APPLICATIONS TO VOLCANOLOGY OF PALAEOMAGNETIC AND ROCK-MAGNETIC TECHNIQUES

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ABSTRACT

Due to the great complexity of volcanic phenomena, it is necessary to combine several disciplines to better understand them. In this work the different ways in which palaeomagnetic and rock magnetic techniques can be used to study volcanoes are reviewed with the purpose of diffusing and popularizing them among volcanologists. The conditions of crystallization, the type and degree of alteration that may have suffered, the cooling history, and the mode of emplacement of igneous rocks are some examples of the type of information that can be obtained with these techniques. Emphasis is placed upon anisotropy of magnetic susceptibility as perhaps the most powerful magnetic tool to study volcanoes. However, examples of the use of magnetic correlation and determination of variation of magnetic properties within a single flow unit have also been included.

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CHAPTER 1. INTRODUCTION

PURPOSE

The character of the problems adressed by volcanology and paleomagnetism have remained separated fields of study since the emergence of both disciplines. Nevertheless, these two sciences have been related to each other, though almost accidentally, since the first works on paleomagnetism in the last century. This relationship has not remained static, but it has become more intimate with time. One of the main purposes of this work is to identify the different types of interaction that are possible between paleomagnetism and volcanology and, at the same time, it attempts to contribute to the popularization of paleomagnetic techniques among volcanologists. In the next section, an overview of the historical perspective of the evolution of both sciences is attempted as an aid in the understanding of some of the present standpoints of workers of both fields. Most of the information on the development of volcanology has been drawn up from the works by Bullard (1971) and Williams and McBirney (1979), and that of paleomagnetism is based in the historical recounts by Merrill and McElhinny (1983) and Tarling (1983). In the next two chapters some of the most important works that use paleomagnetic and rock magnetic techniques in volcanological contexts are discussed. Due to the great importance to volcanological studies of the anisotropy of magnetic susceptibility, chapter 4 focuses on this topic. Chapters 5 and 6 are two examples of the application of paleomagnetic techniques to volcanology carried out in two different parts of the world (the Andean Cordillera and the Trans-Mexican Volcanic Belt, respectively). It should be explained that chapters 2 to 6 were conceived as independent articles and, therefore, some material may appear as duplicated in several chapters; this is especially clear in the case of the magnetic susceptibility tensor. It is also important to mention that chapters 5 and 6 have incorporated the contributions of two members of my committee (Dr. Herrero-Bervera and Dr. Walker) not only in the form of suggestions, but in a more active form, although in each case the bulk of the work has been my responsibility.

PALEOMAGNETISM AND VOLCANOLOGY

As early as the last half of the eighteenth century, two geologists working independently in Auvergne (Desmarest and Guettard, the first geologists to produce any geological maps specifying distribution of rocks and minerals) showed for the first time that basalts are of volcanic origin and that columnar structure is a result of the cooling process of a lava flow. Subsequently, James Hutton proposed that basalts are formed from molten material coming from the interior of the Earth based on the observation of thermal alteration of the rocks surrounding some igneous bodies. At approximately the same time, the basis of the experimental igneous petrology were set down by James Hall in 1805, when he demonstrated that the same crystalline structure of natural rocks was attained from fused rocks at high temperatures, provided a slow rate of cooling was allowed. The term "magma", used to designate natural silicate melts, was first proposed by Scrope in 1825. He suggested the possibility of a single fluid that lead to a variety of compositions through differentiation, and also pointed out the importance of the expansion of volcanic gases on the behaviour of volcanic eruptions.

After these pioneering works, during the second half of the nineteenth century, volcanologists were mainly engaged in the study of the geological and petrological aspects of volcanoes. This situation remained almost unaltered until at least the Krakatoa eruption in 1883, when the role of explosive accumulation of gases was reconsidered. After this time, geochemical and physicochemical methods as well as the relationship between activity of volcanoes and other geophysical phenomena such as seismicity, ground deformation, and electric and magnetic fields have gradually attained importance in the study of volcanoes. At the present, although it is accepted that the complexity of volcanic phenomena is large enough to involve other natural sciences (as for example thermodynamics and chemistry), and more specifically some branches of geophysics (seismology and gravimetry are the most common for volcanologists), the bulk of information and the orientation of the studies still continues to be dominantly of a geological nature.

The first studies on the magnetic properties of rocks were made on volcanic material. The earlier studies by Delesse (1849), Melloni (1853), and Nakamura and Kikuchi (1912), lead to the conclusion that magnetization of volcanic rocks was attained during cooling, and that the direction of the remanence was parallel to that of the ambient field. The study of a number of different volcanic rocks of diverse ages and locations, showing different directions of magnetization (normal and reversed polarities), lead to the creation of a time scale based on the changing directions of the geomagnetic field. After this time scale was more or less well established, magnetic dating of geological materials was undertaken. In these contexts (geomagnetic records and magnetic dating), a great number of volcanic rocks have been studied.

In a different line of work, paleomagnetism proved to be very important in the establishment of the plate tectonics paradigm (for a detailed account on the evolution of these theories an excellent source of information is the book edited by Cox, 1973). Contemporaneous with all these works, more detailed study of the nature of the magnetization aquired by rocks revealed the influence that the magnetic properties of some minerals have on the acquisition of a magnetic record defining the field of rock magnetism.

Throughout this time, some workers in both fields have shared a common interest on volcanic rocks and, at some points, the techniques developed by paleomagnetists and rock magnetists have been applied to the study of the volcanic phenomena as discussed in the following two chapters.

CHAPTER 2. VOLCANOLOGICAL APPLICATIONS OF PALEOMAGNETIC TECHNIQUES

INTRODUCTION

Volcanic phenomena are so complex that their study requires the combined use of many different disciplines. However, until about two decades ago, most of volcanological research focused on two main aspects, the description of field relations between volcanic rocks and the chemistry, mineralogy and petrology of those rocks, leaving aside the physical processes that produce them as well as the application of geophysical methods to the study of the volcanic structures. At present, some branches of geophysics such as seismology and geothermics are widely recognized as useful tools in volcanology, but there are still some other areas whose potential use has not been fully explored yet. This is the case of the paleomagnetic techniques and the intimately related field of rock magnetism. In this chapter, I discuss the different ways in which paleomagnetic techniques have been used to study volcanological problems. The applications of the field of rock magnetism are discussed in chapter 2.

PALEOMAGNETIC TECHNIQUES

The main purpose of paleomagnetism is the study of the magnetic field of the Earth throughout geological ages.

This has been made possible thanks to the property displayed by some rock-forming minerals of recording the strength and direction of the local magnetic field at some point during the history of the rock. Several techniques have been designed to retrieve the magnetic record contained in the rocks and to test wether or not it is the result of one or more periods of magnetization. Also, statistical analysis have been developed to determine how much confidence can be placed in that record. These techniques are here broadly termed paleomagnetic techniques (see e.g. Collinson, 1983; Tarling, 1983; Butler, 1992 for details).

In the case of igneous rocks the magnetic record, or remanence, is usually acquired during their cooling from magmatic to room temperature, although some later remanences can overprint the original record. The physical basis behind the acquisition of a remanence is very complex (see Nagata, 1961; Stacey and Banerjee, 1974 or O'Reilly, 1984), but the main important characteristics for the present purposes can be summarized as 1) there are different types of remanences and each of these types is acquired under different conditions, 2) two or more remanences add together in a vector-like fashion, and 3) the direction of each remanence is usually parallel to the direction of the magnetic field present at its time of acquisition (the Earth's magnetic field in this case). In the following sections, it will be assumed that the primary component of the remanence was acquired during the initial cooling of the rocks (it will be called a thermoremanence or TRM). It will also be assumed that in case of existing overprints these were removed by some means, unless indicated otherwise. The many simplifications made on the theory behind the origin of the remanence and on the palaeomagnetic techniques are necessary to limit this review to a reasonable length and, as stated before, the main purpose of this work is to review the applications of palaeomagnetic techniques in volcanology and not the palaeomagnetic theory behind these techniques.

MAGNETIC DATING

Variations of the geomagnetic field

It is a most fortunate circumstance that the geomagnetic field does not have a static character but changes both in strength and direction with time, because this provides the basis of the magnetic dating and magnetic correlation methods.

Two types of temporal variations of the Earth's magnetic field are of relevance for the magnetic dating. The first type includes changes in the direction of the geomagnetic field of up to approximately 40° taking place in time intervals of tens to hundreds of years termed "secular variation". The second type includes changes that involve longer intervals of time (some thousands to millions of years), and approaches changes of 180° in the direction of the magnetic field. This second type includes the "excursions" and "reversals" of the geomagnetic field (Merrill and McElhinny, 1983).

Use of secular variation in magnetic dating

The record of the secular variation obtained from magnetic observatories extends, at most, 500 years into the past. Linear extrapolation of the observed trends of change to older times during the period of time covered by the direct observations can yield an adequate estimate of the ages of lava flows up to several centuries old. For example, Symons (1975) determined the age of the Aiyansh flow by extending the available magnetic record from direct observations of the Earth's field in British Columbia. The age that he obtained (1650 ±40 a.d.) was in good agreement with dates obtained by C-14 and tree ring counts.

If no data from observatories are available, a latitudinal correction of a nearby record can be used as reference, but the uncertainties in the results can be very large (e.g., Rose et al., 1977). Another possibility is to use rock units of the same locality for which the age is well known, either by historical accounts or by very precise radiometric dates, to construct the curve of secular variation. This reference curve can then be used to date flows whose ages are unknown. Soler et al. (1984) used this methodology on lavas from the Canary Islands. The curve of secular variation that they obtained was compared with the records of magnetic observatories in Europe. The agreement between both curves was excellent, after allowing for latitudinal differences.

In Italy, Chevalier (1925) measured the directions of magnetization of several flows from Mt. Etna. Two flows yielded directions which agreed with observatory records, while five other flows defined a smooth curve that was used to extrapolate the ages of much older flows. More recently, a refinement of the record of secular variation obtained from lavas of the Mt. Etna has been made by Tanguy et al. (1985). Their detailed work resulted in the correction of the ages of several flows that were found to be several centuries older than previously believed. As a consequence, the eruptive history, including the rates of discharge during eruptions of Mt. Etna had to be modified.

In Hawaii, Holcomb et al. (1986) have shown that approximately 70% of the surface of Kilauea volcano is younger than 500 yrs., and 90% younger than 1,000 yrs. Their results also allowed them to establish the coincidence of the filling of a large caldera with a hiatus in volcanic growth. They assumed a rate of secular variation of 4.5°/century based on the directions of the field recorded in Hawaiian lavas of known age, and they were able to obtain a dating precision of ±45 yrs., provided the within-site dispersion of magnetization remained on the order of 2°. The uncertainty on dates assigned to lavas older than 3,000 yrs was slightly larger, mainly due to the repetition of values on the directions of the remanence. Kuntz et al. (1986), also assuming a secular variation rate of 4.5°/century, were unable to accurately differentiate events separated by time periods of less than 100 years in the Great Rift, Idaho, because of the uncertainties introduced in the directions of the remanence by subtle tilting of flow surfaces. However, even with this restriction, they identified at least eight eruptive periods on three lava fields in the region combining the paleomagnetic method with observations of flow distribution and some radiocarbon ages. Similarly, Gardner (1989) defined two major episodes of activity separated by a hiatus of some hundred years at the Mt. Bachelor chain.

Thus, the degree of resolution of the magnetic dating method will depend on the dispersion of the directions of the remanence of individual samples from a single rock unit. The scatter has been discussed by Doell and Cox (1963) who have shown that the main sources are 1) the intraflow variations of the magnetic field at the time of cooling produced by the magnetic anomalies that exist over the old terrain where the flows were emplaced, 2) rotation of blocks after cooling and, 3) orientation errors during the collection of the samples. Holcomb et al. (1986) found additionally a correlation between flow type (pahoehoe or aa flows) and dispersion. Nevertheless, careful selection of the sampling sites may reduce the total uncertainty to an acceptable range.

Another source of dispersion, specially important in thick lava flows and intrusive bodies, relates the rate of cooling of the unit with the variation of the direction of the Earth's magnetic field. For example, Dunn et al. (1971) and Ito and Fuller (1970) have reported large fluctuations on the direction of magnetization (~30°) associated with periods of large secular variation before and after the occurrence of a geomagnetic reversal in a single intrusive. Moreover, Coe et al. (1991) found a progressive change in the direction of the remanence as a function of elevation in one lava flow of the Steens Mountains, that was best explained by assuming a rate of change of 4° to 8° per day in the direction of the local magnetic field during the cooling of the flow. Thus, although the probability of periods of rapid change of the Earth's magnetic field being recorded in a single unit are not very high (see e.g., Schwarz et al., 1979; Dunn et al., 1971), this source of dispersion should not be completely discarded. In any case, an acceptable scatter of the directions of magnetization of individual samples within one cooling unit at the 95% confidence level is usually of 3° to 5° around the mean.

Use of paleomagnetic poles and reversals of polarity in magnetic dating

In the case of long time scale variations of the geomagnetic field, it is convenient to divide the magnetic dating method in two different groups. One of these is based on the change in position of the paleomagnetic poles in time, and the other is based on the chronology of the excursions and reversals of the geomagnetic field.

The direction of the remanence of rocks can be used to calculate the position of a corresponding paleomagnetic pole (Butler, 1992). The paleomagnetic pole is the point where the surface of the Earth is crossed by the axis of the dipole that produces most of the observed geomagnetic field (the dipole is a physical model that fits the observations rather than the true origin of the geomagnetic field). The advantage of calculating a paleomagnetic pole is that it should be the same for all the rocks that acquired their remanence at the same time irrespective of their geographical location. In practice, the paleomagnetic pole positions are an average of the individual poles of rocks of similar age. The age distribution of those rocks should be large enough as to average out the effects of secular variation. The relative movement of different areas of the Earth's surface (tectonic plates) produces the effect of changing the pole position of the blocks relative to one assumed to be fixed. Thus, the changes in position of the poles define a curve called the "polar wandering path" (Tarling, 1983). As the average motion of a plate relative to the pole is typically about 0.3°/ million years, the resolution in the determination of the age of a rock is of about 7 - 10 million years provided the pole can be determined with a precision of 2° - 3°. Tarling (1983) has discussed the different polar wandering paths obtained for the continents as well as their accuracy. An example of magnetic dating using the pole position is given by Abranches et al. (1990). Clearly, the low resolution of the polar wandering paths limits their usefulness for obtaining precise dates of individual units.

It is somewhat more useful to use the changes of polarity recorded in places where the volcanic activity has extended for long periods of time. The chronology of the occurrence of excursions and reversals of polarity of the geomagnetic field are contained in a Geomagnetic Polarity Time Scale (GPTS) which has been modified several times to include new observations from different parts of the world. Cox (1973) compiled key papers that led to the establishment of the earlier versions, and McDougall (1979) and Hailwood (1989) have reviewed some younger versions. The ages assigned to the boundaries between two adjacent polarity zones (periods of thousands of years with the same average direction of the geomagnetic field) are completely dependent on the accuracy of the radiometric method used to determine the ages of the rocks that define a reversal. Cox and Dalrymple (1967) first addressed this problem showing that the limited precision of K-Ar ages introduces some inconsistencies in the pattern of magnetic polarity changes. The older the age of the rock, the larger the error in dating and, consequently, it becomes more difficult to identify the polarity events. For example, Baksi (1988) estimates that errors of 0.85 to 1.0 my for middle-late Miocene times are contained in the time scale of Harland et al. (1982). However, regardless of small differences in very specific parts, a general agreement between different versions of recent GPTSs has been achieved (Harland et al., 1989).

In Iceland and the Hawaiian islands paleomagnetic surveys have been used very extensively (e.g., Doell and Cox, 1961, 1963, 1965; McDougal and Tarling, 1963; Dagley et al., 1967; Kristjansson, 1968; Doell, 1969, 1972a,b,c; Piper, 1971; Doell and Dalrymple, 1973; McDougall et al., 1984) in combination with radiometric dating, mainly to investigate the behavior of the geomagnetic field in time.

It is perhaps illustrative to examine in a little more detail the role that polarity zones have played constraining the age of the Deccan traps in India. McElhinny (1968) suggested that the volcanism that formed the whole traps could not have a duration longer than 5 Ma based in the observation of only one recorded change of polarity of the geomagnetic field within the lava pile (he assumed a maximum duration of a polarity interval to be no longer than 2 my). Kono (1973) combined the statistical properties of the occurrence of geomagnetic reversals and eruptions of lava (both assumed to follow a Poisson distribution, i.e., the probability of a specified number of events in any period of time is equal for all periods of time of equal length) to estimate a maximum duration of 3 Ma for the extrusion of the Mahabaleshwar section. The rate of reversals used by Kono was 2 / my.

Improvements in the knowledge of the reversal time scale (Harland et al., 1982) led to Gallet et al. (1989) to modify Kono's estimate to 6 Ma. However, by extending the statistical approach to include the effects of more than one reversal recorded in the lava pile of the traps, as new evidence suggested (Courtillot et al., 1986), they conclude that the total duration of volcanism is unlikely to exceed 3 Ma. Moreover, using the GPTSs of Harland et al. (1982) and of Berggren et al. (1985) as reference, these authors suggested that the extrusion of the Deccan lavas took place around either chrons 29R or 31R (66 Ma and 67-69 Ma respectively).

Magnetic stratigraphy based on recorded changes of polarity of the geomagnetic field have also been used in other parts of the world either as a direct dating tool or as an aid in constraining the ages of activity of volcanic areas (e.g. Watkins, 1965; Wilson, 1970; Sutherland et al., 1973; Mooser et al., 1974; Swanson et al., 1974; Crossley, 1979; Storetvedt et al., 1978, 1989; deBoer et al., 1980; Sheriff and Shive, 1980; Storetvedt, 1980; Barbetti and Sheard, 1981; Dohrennend et al., 1984; Tanaka et al., 1986; Baksi, 1988; Champion et al., 1988; Mankinen and Cox, 1988; Mitchell et al., 1989; Sherwood, 1990).

MAGNETIC CORRELATION

Slightly different from the magnetic dating method is the correlation of units based on their measured direction of remanence. In this case, it is not necessary to have a previous knowledge of the secular variation or the GPTS because the comparison of the directions between rock units contains all the necessary information. The method has been employed very successfully in the mapping of complex ash flow terrains (Reynolds, 1977; Hoblitt, 1983; Hildreth and Mahood, 1985), ignimbrites (Cox, 1971; Knight et al., 1986) and flood basalts (Bogue and Coe, 1981).

The ash flow province of Nevada and Utah states in North America has been subject of intense work of this type. For example, Grommé et al. (1972) were able to delineate individual cooling units over distances as great as 190 km and areas up to 8 000 km^2. The same general area has been studied by Best et al. (1973), Nairn et al. (1975) and Noble et al. (1984). Each of these works has extended the previously studied areas and contributed to the revision of the old stratigraphy (Makin, 1960) which was based on lithologic observations. The modifications to the stratigraphy had led to a reinterpretation of the estimated volumes, timing and duration of events of individual volcanic centers in the area.

Reynolds (1979) attempted to correlate 13 Pearlette ash beds distributed all over North America with the two youngest tuffs of the Yellowstone group. Seven of the studied ash beds yield directions of the remanence statistically identical to the corresponding directions of the two tuffs. The differences in direction obtained from the other ash beds were attributed to current rotation effects.

Cox (1971) developed a statistical method to evaluate quantitatively the validity of correlations made with the use of directions of remanences. Bogue and Coe (1981) pointed out that Cox's statistics is an estimate of the probability that two randomly sampled directions of the remanence be close enough as to allow an overlapping of their respective circles of confidence, and does not consider the probability of the two directions resulting from a simultaneous acquisition. Thus, these authors proposed a more complete method, and used it to correlate individual and sequences of flows in the Columbia River Plateau.

STRUCTURAL APPLICATIONS

In all the above examples it has been assumed that no significant tilting had affected the studied rock units or that the amount of tilting was well known from the geology. However, it may occur that the field evidence supports the fact that two different localities are exposures of the same unit unambiguously but the degree of tilting remain unclear.

In this case, the direction of the remanence should have the same direction in every point of the unit because it was acquired at the same time; any difference in the direction of the remanence as measured on each outcrop would indicate that some movement occurred in one part of the unit relative to the other. Hagstrum et al. (1982) and Hagstrum and Lipman (1986) have shown that tilting was very important in the development of the Questa caldera in New Mexico. They estimated that most of the tilting occurred after the intracaldera welded tuff and the uppermost portion of the subcaldera magma chamber had cooled and acquired a TRM. Tilting ceased by the time the last stage plutons were acquiring their remanence within the caldera structure and to the south of it, whereas on the north side tilting continued for a longer period of time.

Another example of the use of the paleomagnetic method in the study of the history of calderas is the work by Reynolds et al. (1986) in the Lake City caldera, Colorado, although in this particular case more emphasis was placed on the timing of events than on the study of structural deformations.

Comparison of the directions of stable magnetization of tilted lava flows with that of intruding dikes along the east coast of Greenland was used by Faller and Soper (1979) to discriminate between two alternative models of emplacement of the dikes. Wager (1947) explained the seaward dip observed in the lava flows and the roughly normal dip of the dikes as the result of the emplacement of the intrusives in the convex part of the monocline, due to outer arc extension, defined by the previously tilted flows. Nielsen (1975) proposed an alternative explanation in terms of vertical emplacement of the dikes followed by seaward tilting during rifting. As Faller and Soper (1979) found, the direction of the remanence of the dikes, when corrected to reflect vertical emplacement, do not correspond to any

Tertiary pole position (the assumed age of the dikes) making Nielsen's model very unlikely. Moreover, the non-corrected direction of the dikes was found to be in good agreement with the direction of the remanence of the tilt-corrected remanence of the flows and, additionally, the direction of the remanence of the dikes remained stable during thermal demagnetization while that of one intruded flow became closer to the direction of the dikes after heating to 560°C. Therefore the original model proposed by Wager (1947) was more favored by the paleomagnetic information.

An important implication of the results obtained by Faller and Soper (1979) is that the extrusion of the flows, their flexuring and subsequent intrusion all took place in a short time interval. Another possibility, that seems to be validated by some additional information mentioned by these authors, is that the geomagnetic field direction changed very little during a somewhat long time interval, although this problem was not examined in more detail.

Paleomagnetic arguments have been used to question the transtensional model proposed by Shurbet and Cebull (1984) to explain the origin of volcanic activity in the Trans Mexican Volcanic Belt (TMVB). The inferred counterclockwise rotations of parts of central and eastern Mexico from paleomagnetic data, in combination with other evidence (e.g. seismic and geochemical), seems to associate the TMVB with subduction of the Cocos plate better than with differences in the rate of absolute plate velocities between the North America plate and the southern Mexico microplate (Urrutia-Fucugauchi and Bohnel, 1987), although the geological complexity of the region requires more detailed studies before definitive conclusions can be made.

In a more local scale, tilt has been used to explain some differences in the measured directions of remanence in batholiths (e.g. Irving and Archibald, 1990; Marquis and Irving, 1990), although Beck (1992) has questioned the validity of some of these interpretations based on thermal considerations. Beck's arguments can be summarized by saying that the depth of burial of parts of the batholith before the initiation of tilting may preclude the acquisition of a remanence while in the most superficial parts the TRM was already acquired at that time. By the time the lower part of the batholith could acquire a TRM, some amount of tilt had occurred and therefore, the amount of tilt recorded by paleomagnetic methods is not a measure of the total tilt but rather a minimum value. Moreover, he also suggested how some limitations on the size of the batholith and the rate of tilt can be inferred by dissecting the remanence into its different components. This will be further discussed in the next section.

THERMAL HISTORIES

Acquisition of a thermoremanent magnetization

Our attention has been focused up to this point on the direction of the primary remanence isolated from all the later overprints (if any). However, the different conditions that give place to those overprintings can be discovered by looking at the several remanences that may be present in the rock. Temperature is the most important factor that control the acquisition of a remanence in the present context. Above a certain temperature, the blocking temperature (Tb), no remanence relevant for geological purposes can be acquired. Below this temperature, the remanence will be proportional to the magnetic field to which the rock is exposed during the interval of temperatures Tb - Ti. If Ti is above the room temperature, and the magnetic field changes direction while the rock cools down from Ti to room temperature, the total remanence will be formed by two components. Therefore, the number of components will depend on how many times the magnetic field changes direction during the cooling of the rock. If the rock is reheated to a temperature Tr, the components acquired up to this temperature will be erased, and a new component will be acquired if the rock is cooled down again from Tr to room temperature in the presence of a new magnetic field. In this simplified model (see Stacey and

Banerjee, 1974; O'Reilly, 1984 for more details), we are assuming that the mineralogical composition of the rock did not change by the reheating, but in nature this may not be the case. Nevertheless, the validity of the model may be assessed by examining the textures of the magnetic minerals and, therefore, it will be assumed in the following that the model is valid and that no mineralogical changes occurred as the rock was reheated.

In the laboratory, the gradual removal of components of the remanence by cycles of measurement-heating-cooling-measurement of the samples is one of the methods that allow us to isolate the primary remanence; the measurements between heating and cooling allow us to reconstruct the acquisition of the remanence (Collinson, 1983).

Constraints in cooling histories

It was mentioned in the magnetic dating section that one source of dispersion of the directions of the remanence within a single rock unit is the variation of the Earth's magnetic field during the cooling of the unit. However, this variation may be used in a positive maner. Furlong and Shive (1983) combined the use of a numerical model of the cooling history of sequences of lava flows with the detailed measurement of the direction of the remanence, and the corresponding Tb's, from samples collected at different depths from the top of one unit to estimate the time interval elapsed between two adjacent lava flows. Time resolution was of 100 years for two flows, each of 35 m thick, and of 400 years for two 70 m thick flows. Audunsson and Levi (1988) used a similar approach to determine the extent to which the Roza flow reheated the underlying Frenchman Springs flow in the Columbia River basalt group. These authors concluded that the thermal histories of both basalts was affected by the presence of ground water and an insulating layer at the boundary between flows. This conclusion is simmilar to the results previously obtained by Buchan et al. (1980) which are discussed latter in this chapter.

EMPLACEMENT TEMPERATURES

Pyroclastic deposits

The TRM also provides a method to estimate the temperature of emplacement of pyroclastic deposits. Aramaki and Akimoto (1957) developed a qualitative method to distinguish deposits of nueé ardentes from those of mudflows. The scatter of directions of the remanence was used as the parameter indicating the temperature of emplacement. Well grouped directions meant that the TRM was acquired after emplacement of the flow, when it was still hot; randomly distributed directions would reflect that the remanence of particles was acquired previously to the emplacement of the deposit.

Hoblitt and Kellogg (1979) extended the method to give a quantitative estimate of the temperature of emplacement by studying in detail the different components of the remanence. Kent et al. (1981) introduced a more sophisticated technique of data analysis that allowed a much better resolution than the Hoblitt and Kellogg method. Zlotnicki et al. (1984) suggested the use of several cycles of heat-cooling the samples, inducing a remanence on the laboratory on each cycle, to eliminate the effects of the demagnetizing and interacting field of individual grains within the deposit. Their method is based on that proposed by Thellier and Thellier (1959) to determine the intensity of the geomagnetic field in the past. However, due to the several assumptions that must be made in this method, and the possible risk of alteration of the original mineralogy due to the repeated heating of the samples, the improvement on the resolution of the temperature of emplacement with respect to the method of Kent et al. (1981) do not justify the extraordinary amount of work that is required.

Examples of the application of these methods can be found in Kato et al. (1970), Yamazaki et al. (1973), Wright and Mutti (1981), Urrutia-Fucugauchi (1983), McClelland and Druitt (1989) and Gill et al. (1990).

Intrusive rocks

Determination of the Tb of country rock and the observed thermal effect of an intrusive body of magma on it allowed Schwarz (1977) to estimate the depth of burial at the time of intrusion of the now exposed section of a dike and its surroundings in the Canadian Shield. The thermal effect of the dike was inferred from the directions of the remanence of the country rock collected at increasing distances from the dike. By taking the present geothermal gradient to be valid at the time of the intrusion, the thickness of the layer removed by erosion since that time was estimated to be of 7 Km. Despite the many sources of uncertainty that are associated with the depth of burial, this method may be used to estimate the amount of erosion in a unique manner.

Buchan et al. (1980) attempted to calibrate the method used by Schwarz (1977) by studying the directions of the remanence of two dikes and their surrounding host rock in the Columbia River Plateau, Oregon. Based on geological considerations, the depth below the surface at the time of emplacement of the dike of the sampling sites was known providing an independent estimate of the depth obtained by the paleomagnetic study. However, the theoretically calculated increases in the temperature of the host rock due to the intrusives were found to be greater than those inferred from the measurement of blocking temperatures. The discrepancy of results was better explained by introducing the effects of groundwater, free to move in convective cells upon heating, in the theoretical models. The inferred presence of groundwater is also consistent with the form of the thermomagnetic curves presented by these authors, because they reflect the effects of hydrothermal alteration of the magnetic minerals (see Ade-Hall et al., 1971).

In the two above examples, the effects of the heating time in the Tb's were ignored. McFadden (1977) introduced this in the calculation of the temperature of emplacement of four kimberlite pipes in South Africa. He also showed that the temperatures inferred from thermal demagnetization experiments should be interpreted as overestimates of the actual emplacement temperature, although the overestimate is not gross in general. Dodson and McClelland Brown (1980) and McClelland Brown (1982, as quoted in McClelland Brown, 1982), included the temperature dpendence of the activation energy that had been assumed to be constant by McFadden (1977) in the estimation of the effect of continuosly varying the temperature in the Tb's. This more exact method of calculating the ambient temperatures of the country rock has been used by McClelland Brown (1981), Robinson and McClelland (1987) and Smith et al. (1991). As noted by McClelland Brown (1981), the accuracy in the method of calculation of the maximum temperatures of reheating is not very advantageous in the sense that the estimated temperatures are not an unique solution and therefore, another geothermometer must be used in each particular case.

Robinson and McClelland (1987) and Smith et al. (1991) used the temperature profiles of sediments intruded by igneous bodies to investigate the cooling history of the intrusions. Solutions to several theoretical models changing the geometry of the intrusion, the mechanism of heat transport, and/or the dynamics of the problem (stagnant against flowing magma), were compared with the temperature profiles obtained from the paleomagnetic study. From the results of both works, it is clear that in general a conductive model of heat transport fits better the observations than a convective model, although this latter mode of transport may become more important closer to the intrusion. It is also clear that the geometry and dimensions of the intusion have a major importance in the obtained results (see also McFadden, 1977).

In the case of models that involve flowing magma, the duration of the flow within a dike was found to take values between 5 days and 21 hrs depending on the mode of heat transfer that is used (Smith et al. 1991). Although these results are more or less satisfactory, more detailed work is needed to better constrain the mechanisms of cooling of intrusives, and their effects on the surrounding rocks.

It was mentioned in the last part of the preceding section that some constraints on the size of batholiths that had suffered some tilt can be made by measuring the TRM in different parts of the intrusive. As Beck (1992) has shown, the batholith can be divided into different depth zones each with a different temperature. If we assume that the most superficial of these zones acquired its TRM before the tilting had started, the distribution of the directions of the remanences given by samples that were originally contained in this zone of the batholith will be roughly distributed in a circular pattern. Moreover, the remanence will be found to be single-component in nature. Samples that formed part of the deepest zone of the batholith will not acquire any remanence until later, when its temperature had descended to the appropriate Tb (this is the effect of the uplift produced by the tilting and the cooling of the batholith). By taking into consideration the large amounts of time involved in these processes (at least 10 my), the direction of the remanence is very likely to be very different from each zone to the other. Failure in recognize such differences in the direction of the remanence from different parts of the batholith would indicate either that the original dimensions of the pluton were not sufficiently large as to allow a significant thermal zonation or that the rate of tilt was large enough as to minimize the effect of that thermal zonation.

LIMITATIONS OF THE PALAEOMAGNETIC METHODS

In addition to the assumptions that have been mentioned above, there are some additional constraints of the paleomagnetic methods discussed. These limitations are related with the accuracy of the magnetic record itself. Several types of remanence can be acquired at room temperature and may significant alter the original remanence. Usually, these low-temperature remanences are easily removed in the laboratory, but the "cleaning" process can also erase parts of the remanence which are of interest. Therefore, it is necessary to exert the greatest caution when these techniques are applied.

A more serious problem is the type of remanence that can be acquired at high temperatures erasing all traces of the original remanence. Sometimes not even optical examination of the textures of magnetic grains is able to yield information about if this had occurred (e.g. Geissman and Van der Voo, 1980; Lovlie and Mitchell, 1982). In these cases, it is an anomalous direction of the remanence, as different from what was expected from the age of the rock, which indicates that a complete remagnetization may have occurred. This is a problem that becomes more serious in older rocks because it is more probable that they have suffered some type of alteration due to burial and its related reheating.

The possibility of self-reversal, i.e., when the remanence is antiparallel to the direction of the inducing field, poses another source of error in the interpretation of paleomagnetic results. The phenomenon of self-reversal has been found in several instances (e.g. Nagata et al., 1952; Schult, 1976; Heller, 1980; Heller et al., 1986; Ozima et al., 1992) and may be more common than usually accepted. Once again, it is the combined information of the geology and age inferred from other methods that may help to rule out this possible source of error.

In the case of pyroclastic deposits, the plastic deformation, or small-scale rotations of the magnetic grains, can disperse the directions of the remanence within a single unit (Geissman, 1980; Rosenbaum, 1986), although Hoblitt et al. (1985) have shown that even non welded pyroclastic flow deposits may be reliable recorders of the direction of the geomagnetic field at the time of deposition, and therefore, the various methods discussed here are applicable.

SUMMARY

The paleomagnetic techniques originally conceived to study the past geomagnetic field have turned out to have many applications in the study of volcanic processes. The most common of these applications are the magnetic dating and correlation of units. Age resolutions depend on how old is the rock and how accurately the changes of the geomagnetic field in the locality are known. The use of statistical techniques defines the confidence that can be placed on the results. Correlation of units can be used to lead to the establishment of stratigraphic markers, as an aid in mapping volcanic terrains and in evaluating volumes of extrusion. Magnetic correlation may be neccessary in some cases when the variation in the chemical composition of lavas during one single eruption is suspected (e.g., Tatara-San Pedro Project Team, 1992). Timing of events is also possible at different scales (from repeated eruptions from one single vent to migration of activity on a volcanic field) and this may yield some constraints on the rates of extrusion. The thermal histories of igneous rocks, including emplacement temperatures and identification of reheating events, can be inferred from the paleomagnetic information. More details about the thermal histories of igneous rocks are obtained if the paleomagnetic method is combined with thermal models.

Certainly, the paleomagnetic methods assume a number of conditions that validate them, but these conditions are usually satisfied very easily. In the most complicated cases, the combined use of geological information and of other techniques can solve the problems presented by the paleomagnetic methods and yield much more information about the volcanic phenomena than each of these techniques can individually.

CHAPTER 3 VOLCANOLOGICAL APPLICATIONS OF ROCK MAGNETIC TECHNIQUES

INTRODUCTION

Paleomagnetic and rock magnetic techniques can be used in many diverse ways to study volcanic phenomena although they are not widely recognized as a volcanological tool. In the preceding chapter the applications of paleomagnetic techniques to volcanology are reviewed. Here the uses of the closely related field of rock magnetism in the same context are discussed.

ROCK MAGNETIC TECHNIQUES

The field of rock magnetism deals with the magnetic properties displayed by rocks, which are almost completely determined by the chemical composition, microstructure and concentration (Fig.3.1) of a small fraction (usually 1-5% by volume; Butler, 1992), of their constituent minerals. The majority of the magnetic minerals, the iron-titanium oxides, can be represented in the ternary system $FeO-Fe_2O_3-TiO_2$ of Figure 3.2. Other magnetic groups, the iron-sulphides, iron-manganese oxides and the hydrous iron oxides are generally less abundant than the Fe-Ti oxides, and therefore, have received less attention in the literature. In igneous rocks, the titanomagnetites, represented by the line joining magnetite and ulvospinel in Fig. 3.2, and the

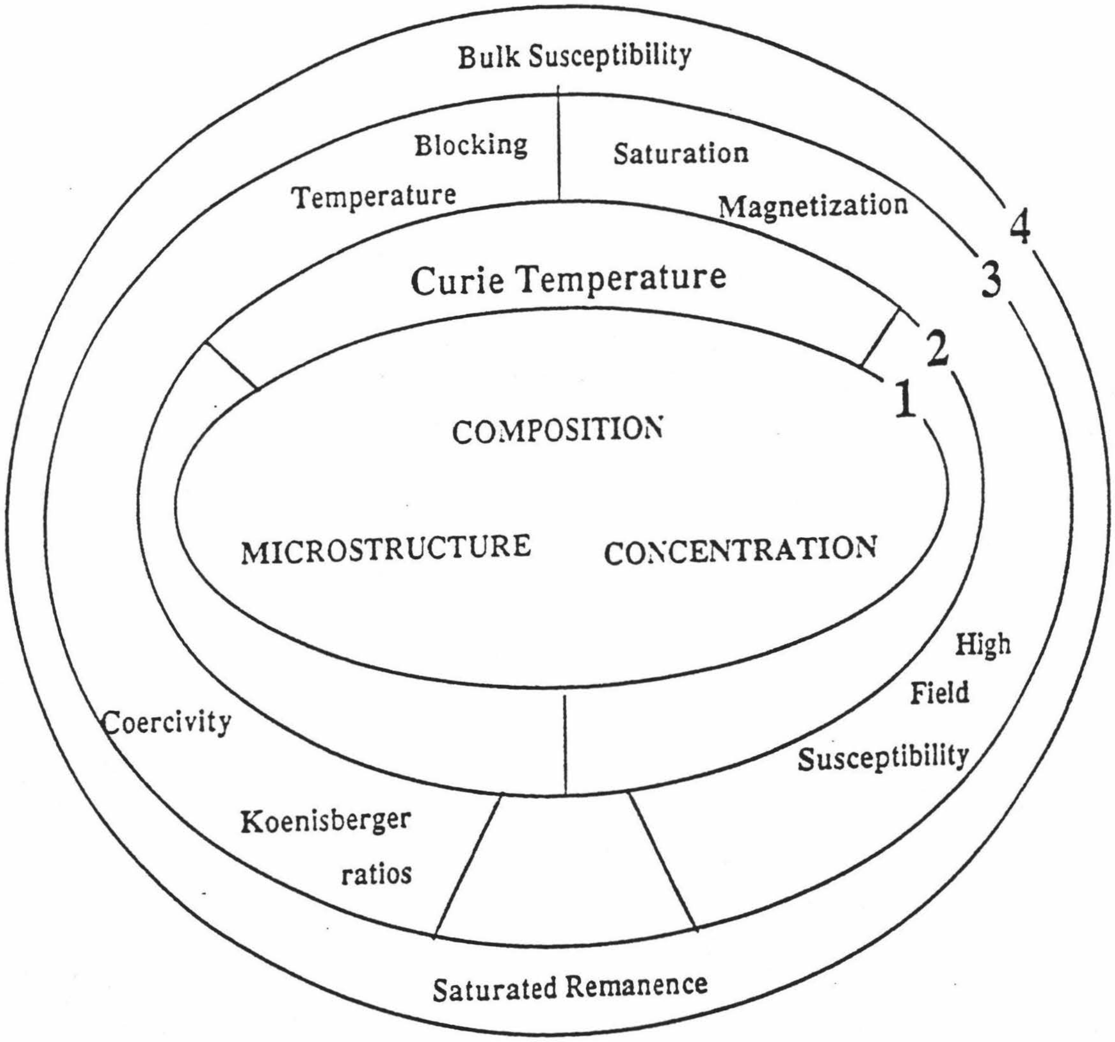


Fig.3.1. The three factors that control the magnetic properties of rocks are listed in the inner ellipse (1); the magnetic properties that are function of only one of these factors are enclosed in the ellipse 2, those that depend on any two factors are enclosed in the ellipse 3 and, finally, those properties that are determined by all three factors are listed in the outermost ellipse (4).

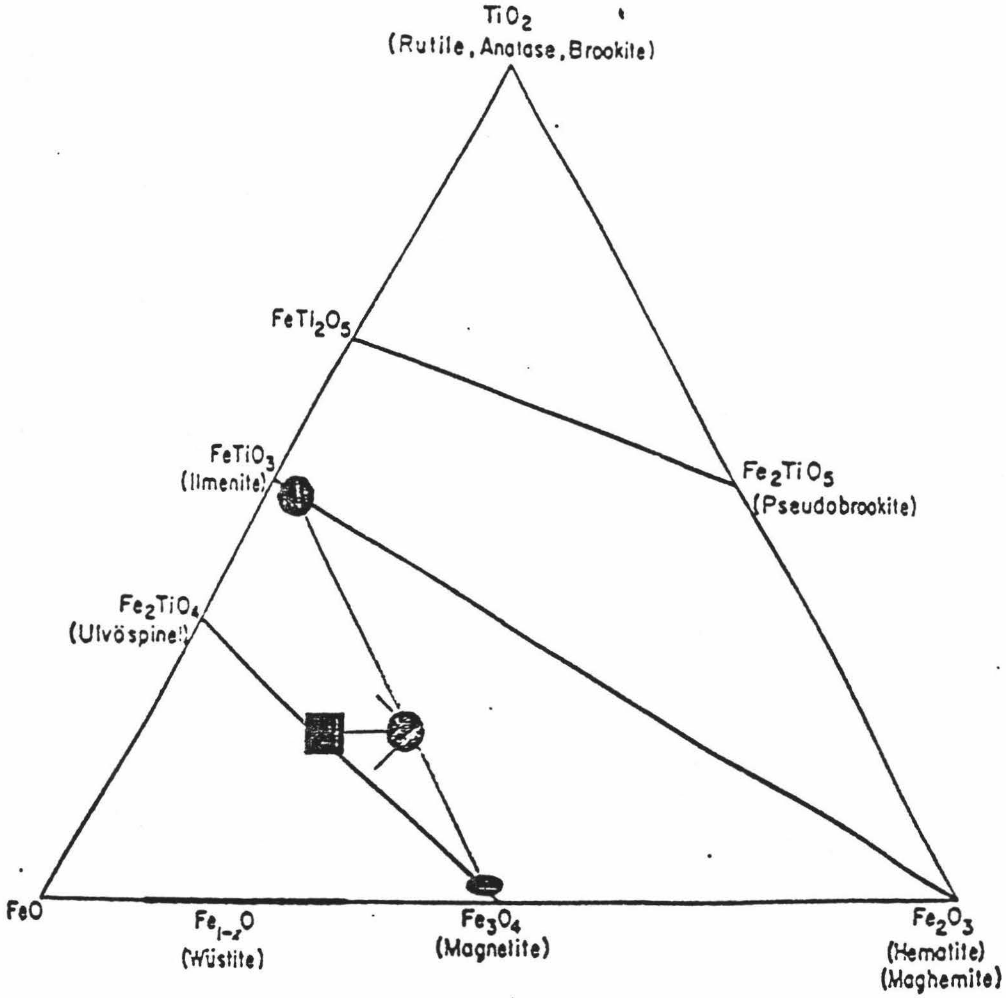


Fig. 3.2. Ternary diagram showing the most important group of magnetic minerals, the Fe-Ti oxides. Solid lines represent solid solution between the corresponding end members. Composition of a primary titanomagnetite (square) changes during high temperature oxidation in the direction of the arrow. The mineral assemblage that forms is shown by the circle and ellipse near the ilmenite and magnetite points, respectively.

ilmenohematites, represented by the line between hematite and ilmenite, are among the first minerals to crystallize (Buddington and Lindsley, 1964). Post-crystallization alteration of the primary magnetic phases occurs at high and low temperatures inducing chemical and structural changes that affect their magnetic properties. For example, members of the titanomagnetite series may undergo high temperature oxidation and "exsolve" ilmenite intergrowths while the host mineral becomes closer in composition to pure magnetite. If the oxidation process takes place at low temperatures it may produce a structural change in the titanomagnetites, leading to the formation of a member of the titanomaghemites which are very similar in composition and magnetic properties to the original titanomagnetites. However, the process that take place in the formation of titanomaghemites, or cation deficient titanomagnetites, are still not well understood (Steinthorsson et al., 1992). Details of the crystal chemistry and structure of the cation-deficient titanomagnetites are extensively discussed in O'Reilly (1984) and Readman and O'Reilly (1972).

One of the original motivations of the field of rock magnetism was to understand better the mechanism of magnetization and acquisition of remanence by rocks, and therefore many of the techniques of this discipline are oriented to yield information about the stability and accuracy of the record of the geomagnetic field as measured in rocks. However, mainly because of space considerations, the studies that involve a more profound knowledge about the structure and composition of the magnetic carriers of rocks are not discussed in detail. Studies of this type and with some relevance to the present purposes include those of Nagata (1961), Lowrie and Fuller (1971), Readman and O'Reilly (1972), Dunlop et al. (1973), Parry (1974), Radhakrishnamurty and Deutsch (1974), Johnson et al. (1975), Day et al. (1977), Radhakrishnamurty et al. (1977), Cisowski (1980), Dunlop (1981), Moskowitz (1981), Senanayake and McElhinny (1981), Bailey and Dunlop (1983), Dunlop (1983), O'Reilly (1984), Hodych (1991).

PETROLOGY, MINERALOGY AND MAGNETIC PROPERTIES

Chemical composition of coexistent Fe-Ti oxides in igneous rocks determine their magnetic properties, and can also yield important information about the temperature and oxygen fugacity conditions at the time of the rock formation (Buddington and Lindsley, 1964). A general decrease in the content of ulvospinel in titanomagnetites and of ilmenite in the ilmenohematites is observed as the silica content of the rock increases (Fig. 3.3), although it may be difficult to draw a definite correlation between rock type and titanium content of their primary Fe-Ti oxides mainly because of the

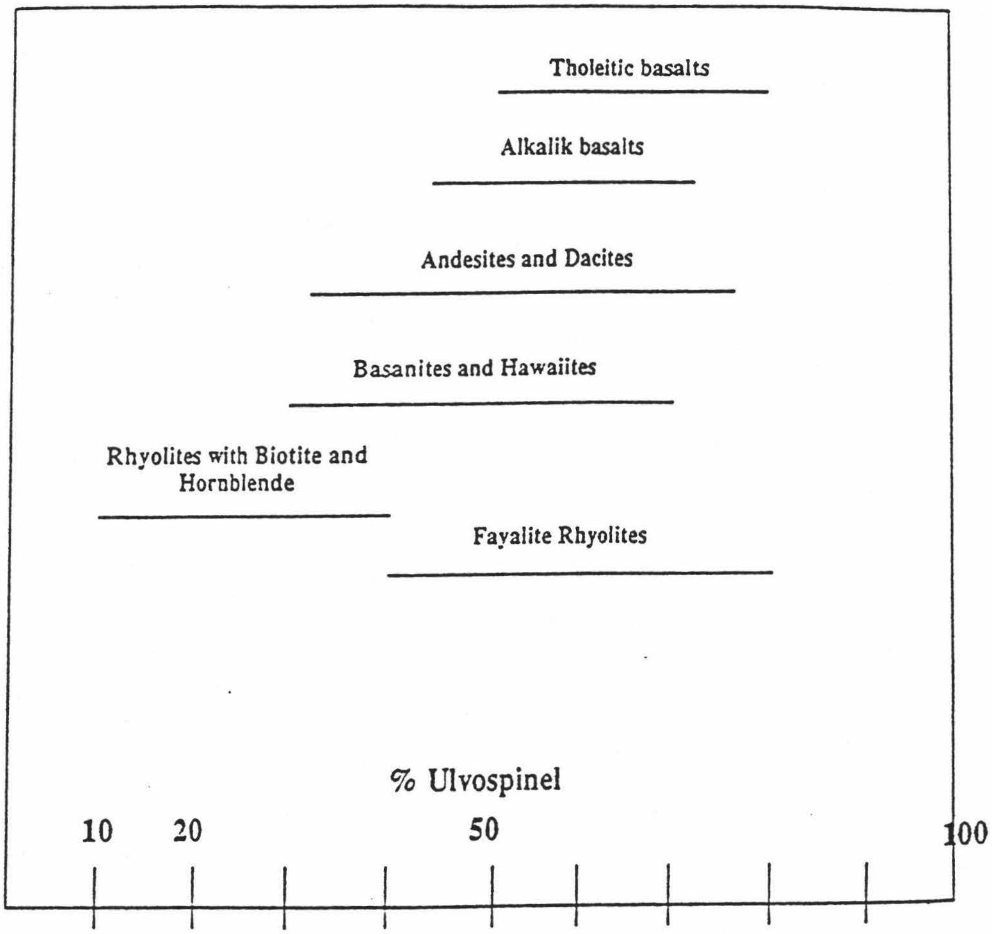


Fig. 3.3. Common ranges of composition of primary titanomagnetites in different types of rocks (data from Buddington and Lindsley, 1964 and Frost and Lindsley, 1991).

complex series of oxidation and re-equilibration processes that takes place during cooling (Frost and Lindsley, 1991).

If magma cools down very rapidly, the composition of the primary minerals will be preserved provided that no extensive weathering occurs. Also, the magnetic grains will be relatively small in size and homogeneous. In any case, the final assemblage of grains will determine the values of some magnetic properties, and therefore it is, at least in principle, possible to infer the characteristics (composition and structure) of the magnetic grains by measuring their magnetic properties.

High temperature oxidation

Some attempts have been made to correlate systematically microscopic observations with magnetic studies of rocks. For example, Watkins and Haggerty (1965, 1967) found that the zones of highest oxidation near the center of several Icelandic lava flows correspond with areas where the intensity of the remanence is higher and more stable; they also found that these zones present higher Curie points than other parts of the flow. Symons (1967) also found a zonation in some magnetic properties such as the intensity of the remanence, susceptibility and Curie temperatures in one basalt column. The parts of the column with higher intensity of the remanence and Curie temperatures corresponded with those exhibiting larger amounts of oxidation.

Larson et al. (1969) associated the presence of two or more Curie points with basic rocks which have been little affected by high temperature oxidation. It is interesting to mention that based on the reversibility of the thermomagnetic curves (Js-T curves), either samples containing high grade Ti-rich titanomaghemite or Ti-poor magnetite were easily differentiated from those barely showing the effects of high temperature oxidation. Samples of the former case are chemically stable upon heating while those of the later case were characterized by large irreversible changes in the Js-T curves.

Wilson et al. (1968) suggested six classes of titanomagnetite grains according to their degree of high temperature oxidation. Class one are homogeneous titanomagnetite grains and class six corresponds to the maximum degree of oxidation characterized by the presence of pseudo-brookite. These workers concluded that high temperature oxidation of titanomagnetites is the most important factor that influences their magnetic properties, because it not only changes the chemical composition of the grains but it also induces changes in their structure (see below). Similar conclusions were reached by Ade-Hall et al.

(1968), Petersen (1976), Lawley and Ade-Hall (1971), Herzog et al. (1988) and Audunsson and Levi (1992).

Intensity of remanence is a good indicator of zones of higher degree of high temperature oxidation that can be used to identify the limits of different units (Watkins et al., 1970; Centeno-García et al. 1986) and finer mapping of these zones within a single unit can be made by other magnetic means such as Js-T curves. In these cases, information that it is not readily detectable in thin sections can be obtained from the thermomagnetic curves.

Larson et al. (1969) correlated the effective grain size of titanomagnetites of igneous rocks for diverse settings and the coercivity spectrum obtained in step by step demagnetization of an induced ARM. Their results indicate that lavas and welded tuffs generally contain a larger number of small grains than plutonic rocks as a result of a faster cooling and more high-temperature oxidation. This type of oxidation is probably the result of the interaction of lava with air or water near the surface and produces the development of lamellae which subdivide the primary magnetic crystals.

The development of high oxidation zones is explained by the interaction of the fluid system of the lava with the Fe-Ti oxides (Buddington and Lindsley, 1964). The fluid system is assumed to be mainly water, although addition of carbon dioxide does not materially affect the proposed model. Preferential escape of hydrogen may enhance oxidation and, according to Petersen (1976), a minimum thickness of 6 m will be required to generate a central zone of increased oxidation state in a lava flow; if the flow is thinner, its uppermost parts will be more oxidized than the base. Also, overlying flows enhance the oxidation of the top of an underlying flow by reheating it.

The presence of sulfur compounds in the fluid phase may inhibit oxidation (Buddington and Lindsley, 1964). Lawley and Ade-Hall (1971), indeed found a positive correlation between the zones with a low degree of oxidation and the presence of sulphides in a thick (35 m) tholeiite flow. By comparing their observations with the opaque mineralogy of submarine basalts and dikes, these authors suggested that hydrostatic pressure may be a decisive parameter preventing the escape of magmatic volatiles containing sulfur compounds. However no further research has been made to quantify the effects of hydrostatic pressure in the oxidation conditions of lavas. Also, the little information available about the magnetic properties of sulfides makes it difficult to quantify these phenomena.

From the very few detailed measurements of magnetic properties on dikes it is apparent that variation of thermomagnetic properties is preferentially controlled by the grain size of the magnetic phases and not by their degree of oxidation as in lava flows. Smith and Prévot (1977) have shown that the central part of dikes have similar properties as those displayed by most subaerially erupted basalts, while the quenched zones resembled more closely those of oceanic basalts. However, Warner and Wasilewski (1990) reported a large influence of the oxidation-induced microstructure in the titanomagnetites in the magnetic properties of a group of diabase dikes. The available data at the moment preclude the possibility of evaluation between which factors are most important in controlling the final state of the magnetic phases in dikes.

Hydrothermal alteration

In addition to the changes in the magnetic mineralogy of igneous rocks suffered by high temperature oxidation, a different type of alteration may occur in the range of 300°-100°C in the presence of water. The response of the magnetic minerals to this type of hydrothermal alteration has been carefully documented by Ade-Hall et al. (1971). It was found that the minerals produced by high temperature oxidation are more resistant to the effects of subsequent hydrothermal alteration, and therefore it is possible to differentiate between both types of alteration by inspection of the thermomagnetic curves. Determination of the Curie temperature of several samples from the same unit was proved to provide a reliable picture of its thermal history, although in the cases of extreme degree of hydrothermal alteration, the magnetic information can not discriminate between high and low temperature oxidation. These authors also proposed a scheme of classification of the various degrees of hydrothermal alteration common to igneous rocks which was in agreement with the alteration zones defined by the presence of secondary minerals.

Burial of a lava may result in the last type of alteration and Lawley and Ade-Hall (1971) used the magnetic properties of rocks to infer a maximum reheating temperature of probably no more than 125°C of a tholeiitic flow in Ireland.

In the case of oceanic basalts, Wooldridge et al. (1990) have shown that the degree of alteration of the magnetic minerals in oceanic crust is very closely related with its depth. Low temperature oxidation is dominant near the surface and high temperature oxidation becomes more important with depth. They also observed that the magnetic properties of massive sulfides depend on their specific mineralogy (pyrite and pyrrhotite), and they concluded that more detailed studies of this type have to be made before a clear picture of the complex relations between magnetic properties and mineralogy of oceanic crust can be obtained.

Magnetite and ilmenite series

In the special case of granitic rocks, Ishihara (1977) introduced a magnetite and an ilmenite series on the basis of the total amount of those minerals as observed in polished sections. The presence of a few grains of ilmenite, or its complete absence, was the main criteria used to define those series. The higher oxygen fugacity necessary for the formation of the magnetite series granitoid was in turn interpreted as indicating a deeper level of generation for these magmas.

In a similar manner, Gastil et al. (1990) proposed a model for the generation of magma in subduction zones that depends on the dehydration of the undergoing slab. Magmas generated within a certain range of depths at which the subducting slab dehydrates, will enhance the formation of abundant ilmenite, while magmas generated above or below these depths (before or after dehydration ocurs) will preclude its formation and will be dominated by magnetite grains.

Correlation of magnetic properties and other parameters

Watkins et al. (1970), related the variations observed on some major and trace elements in a single Icelandic lava with the effects of an oxygen fugacity gradient that were partly recorded by the changes in the magnetic properties. Unfortunately, no other study of this type has been made and it is not possible to compare their results with other cases to see if there is some well established correlation.

An example of the sensitivity of some magnetic properties with respect to some features found in lavas is given in chapter 6 in which a segregation vein that occurs at approximately the middle of a vertical section of the flow unit from Xitle volcano has completely distinctive magnetic properties (higher intensity of remanence and susceptibility). In a second unit of the same lava, the same magnetic signature is observed, and although there is no macroscopic evidence that supports the presence of a segregation vein, it is expected that examination of thin sections may reveal some special characteristic of this part of the flow.

The recent efforts to include the Fe-Ti oxides in some petrogenetic studies (e.g. Frost et al., 1988, Nord and Lawson, 1989, Lindsley et al., 1990, Frost and Lindsley, 1992), in which the oxide and silicate thermometry are used together may promote the detailed study of the magnetic properties of igneous rocks to increase our knowledge of the different ways in which variation in the conditions of equilibrium affect them. These type of studies may establish some correlations between the thermal history of a rock and its magnetic properties that have been undetected until now that may have practical uses constraining some parts of the history of such rocks.

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

Perhaps the most powerful technique of rock magnetism when applied to volcanology is the anisotropy of magnetic susceptibility (AMS). AMS is a global term used to describe the directional variability in the response of matter to a magnetic field (Hrouda, 1982); the value of the intrinsic magnetic susceptibility depends on the chemical composition, but its anisotropy is controlled by additional factors. Bathal (1971) has reviewed the physical basis of the causes of AMS in rocks, concluding that shape alignment of ferromagnetic grains, or in some cases lattice alignments of crystals, seem to control AMS (see O'Reilly, 1984 for details), and Khan (1962) showed that the shape of the titanomagnetite grains of igneous rocks plays an important role in the orientation of the observed anisotropy of the whole rock. He found that the direction of maximum elongation of the grains usually coincides with the direction of maximum susceptibility. However, Hargraves et al. (1991) have shown that the distribution of the magnetic grains within the rock (textural anisotropy) may be of more importance than the shape of individual grains in defining the anisotropy of whole rock specimens.

From the many applications of AMS measurements to geology and geophysics (Hrouda, 1982), some special uses in the study of igneous rocks will be discussed here in more detail.

Petrofabric

A large number of parameters attempting to quantify the magnetic fabric of rocks have been proposed (see Hrouda, 1982; Tarling, 1983), but no one has been widely adopted. In the next chapter an attempt to introduce some guidelines for the selection of parameters based mainly in the fact that no particular geometrical representation of the AMS measurements should be favored is made. Symmetry and definition of the range of possible numerical values for a given parameter are also important factors in the selection of one parameter. Finally, as more than one parameter is usually necessary to perfectly characterize the AMS measurements, the internal congruence between the parameters must be also taken into account. Thus, one of the parameters derived from AMS measurements can be interpreted in terms of a scale that describes the average magnetic fabric of a rock as predominantly foliated, with equally developed foliation and lineation and with a predominant lineation. The number of samples showing either type of magnetic fabric seems to be equal in each case (e.g. Knight and Walker, 1988), although a difference in the relative position of each type of sample relative to the borders of the cooling unit has been found in some instances (Ellwood and Fiske, 1977; Urrutia-Fucugauchi, 1982; chapter 6 this work). The reason why this difference occurs is not clear at this point, but it may be related with the gradient of velocity, with the flow regime of the lava, or with the thermal stresses that take place during cooling (Ellwood, 1979).

Flow direction

Pyroclastic flows

The alignments of particles immersed in a flowing viscous fluid produces the parallel alignment of the longest axis of minerals during movement of lava (Jeffreys, 1922). This alignment of minerals can be associated with the direction of maximum susceptibility of magnetic minerals due to its relationship with the shape of titanomagnetite grains observed by Khan (1962). Ellwood (1982) used AMS measurements to infer the flow direction at the collection site of four welded tuff units in the central San Juan Mountains, Colorado, and hence was able to identify the eruptive source for each. The sources inferred by use of AMS measurements were in good agreement with those known from the geological setting. A study made by Knight et al. (1986) on three Toba ignimbrites also give similar results.

It is important to mention that AMS measurements may be reflecting the flow direction of the depositional layer instead of the direction of the flow as a whole and, therefore, gradual changes in the inclination of the axis of maximum susceptibility with height within an unit may rather indicate changes in the conditions of deposition instead of deformational structures due to post-emplacement compaction (Branney, pers. comm.). One important consequence of the latter is that, under favorable conditions, it may be possible to estimate the underlying topography by detailed examination of the changes in orientation of the maximum axis of susceptibility from the top of a pyroclastic flow towards its lowermost exposed parts.

Dikes

The flow direction of magma in dikes has also been determined by use of AMS measurements. Knight and Walker (1988), have shown the coincidence of the mean direction of maximum susceptibility with the macroscopic lineations observed on some dike margins in the Koolau complex in the island of Oahu. Moreover, in some cases the directions of maximum susceptibility provide a means of determining the absolute magma flow direction as they seem to reflect the imbrication of grains against the margins of the dike caused during deposition in a velocity gradient. More recently, Ernst and Baragar (1992) used AMS measurements to reconstruct the pattern of magma flow in the Mackenzie Dike swarm, Canada. An important result of their work is that dike magmas are derived from mantle material that underlines the near focal region of a swarm and therefore represent local sampling of the underlying mantle, despite the dimensions of the swarm.

Lava flows

In the case of lava flows, AMS measurements have yield contradictory results when used to infer flow directions. Khan (1962) and Symons (1974) reported a large scatter in the observed directions of the maximum susceptibility of lava flows attributable to thermal convection or turbulence patterns that may develop in the frontal or upper parts of the flows. The large scatter made difficult to obtain a significant mean direction that could be associated with the flow direction as inferred from geological evidence. However, the method used to calculate the mean direction of maximum susceptibility was not the most appropriate (see Ellwood, 1978). Jelinek (1978) developed a multivariate analysis technique that allows the calculation of a mean direction, and of a region of confidence around it, appropriate to sets of AMS measurements with large scatter (Lienert, 1991). In chapters 5 and 6 this analysis technique is used to determine the mean flow direction of lava flows from its AMS; the results are in agreement with the flow direction inferred by the geological evidence. Moreover, a good correlation between the direction of maximum susceptibility and the observed vesicle foliation was obtained near the base and top of two flow-units from Xitle volcano. The parallelism of these features is interpreted as a result of the flow patterns in the lava, and therefore it seems reasonable to assume that even in the absence of other indicators of flow direction, AMS is a good estimate of it. Another example of determination of flow direction of subaerial lavas is the work by Kolofikova (1976) reported in Hrouda (1982). Perroud et al. (1991) related their results of AMS measurements of several flows from Almiden, Spain, with emplacement on a gentle slope dipping about 10° towards the southeast. According with these authors, it was not possible to determine the location of the volcanic centers associated with the lava flows mainly because of the deformation suffered during the Variscan orogeny. Although it is certain that the directions of susceptibility showed a somewhat large scatter before and after the introduction of tilt corrections, it is not clear what was the criteria used by these workers to determine the mean directions and therefore it is not possible to evaluate the utility of the technique of Jelinek (1978).

In the special case of columnar basalts, AMS measurements have been used as a criteria to decide wether or not convection cells are responsible for the formation of the columns as was proposed by Lefeber (1956). Thus, Brown et al. (1964) carried out measurements of the AMS in two columns from New South Wales and they found no evidence of convective flow structures. Similar results were found by Symons (1967), Ellwood and Fisk (1977) and Urrutia-Fucugauchi (1982).

Mode of emplacement

Ellwood (1975) suggested that the AMS measurements could be used to distinguish between the extrusive and intrusive types of oceanic basalts. Although until now there is no clear explanation of the reasons why this occurs, he found that in approximately 80% of the cases his parameter F (defined as the ratio $k_1' / (k_2' k_3')^{1/2}$ where the superindex indicate normalized values of the principal susceptibilities using a fixed value of .001 SI) discriminates between both types of basalts (e.g. Ellwood, 1975; Ellwood and Watkins, 1976).

SUMMARY AND CONCLUSIONS

Most of the magnetic properties of the magnetic minerals are strongly dependent on their chemical composition. The original composition of these minerals will be influenced by interaction with volatiles of both magmatic and external origin, and it is the final assemblage that determines the measured magnetic properties of igneous rocks. Certainly, the path followed by a particular rock to arrive at its present state may be extremely complicated, but some insight into its history can be obtained by studying the relationship between chemical composition, structure and concentration of magnetic minerals in igneous rocks, and consequently by the detailed study of their magnetic properties. Careful documentation of the magnetic properties can identify the different types of alteration that igneous rocks suffer during and after their emplacement and may constrain the possible conditions under which magmas are generated. However, work attempting to establish in a more systematic way than until now the relationship between the petrology and the magnetic properties of rocks is needed.

The uses of AMS in the study of movement and emplacement of igneous rocks have proved succesful in several instances. The development of an appropiate statistical technique to determine the mean values of the anisotropy tensor of one rock formation has opened the possibility of use this method even in some instances where the scatter of data is large. Certainly, the interpretation of AMS measurements must be congruent with the geological evidence, but it has all the requirements to be considered a standard tool of study of volcanoes.

CHAPTER 4. GUIDELINES FOR THE RATIONAL SELECTION OF ANISOTROPY OF MAGNETIC SUSCEPTIBILITY PARAMETERS

INTRODUCTION

Due to the interest in the determination of the anisotropy of magnetic susceptibility because of its value as a petrofabric indicator, a large number of anisotropy factors have been proposed (see for example Hrouda, 1982 and Tarling, 1983). Most of them attempting to describe a geometrical entity having well defined spatial dimensions rather than an abstract mathematical representation of a physical property of matter (i.e., a measure of the response of a material to an external magnetic field). Also, many of the "shape" and "degree of anisotropy" parameters were not compared with the original observations that stimulated the use of the magnetic susceptibility as a petrofabric indicator. It is not surprising therefore that two apparently different aspects of the tensor lead to equivalent numerical expressions (see following sections). Fortunately, as will be shown in this chapter, the duplicity in concepts can be avoided and a set of parameters with an internal congruence can be selected if some basic definitions are first established.

Perhaps the two most difficult tasks for the reader are (1) to accept that no geometrical representation is necessary to derive the parameters and (2) to leave aside, at least momentarily, the presently accepted nomenclature because it is extremely dependent on a particular geometry. Therefore, it seems necessary to review in some detail the three commonly used graphical representations of the susceptibility tensor to draw attention to their differences in form.

Very recently Constable (1992) reviewed these geometrical representations, but she failed in clarify that the definition of the "magnitude ellipsoid" involves a change in the frame of reference of the direction cosines used in its derivation. Moreover, although she showed that the three geometrical representations are equivalent in that they are related to the same tensor, she did not emphasize that, precisely because of this equivalence, it will be more convenient to leave aside any reference to a particular representation in order to avoid confusion.

The conditions that promoted the use of anisotropy parameters, together with some of their most popular expressions, are presented following the discussion of the geometrical representations. The two possible methods of calculating the mean susceptibility are compared in the range of experimental observations, and the consequences of selecting each of these methods are examined.

Much of the material in this chapter is drawn from previous works, with the difference that the emphasis is placed on the independence of the susceptibility tensor from a particular geometry, and on the internal congruence of the sets of parameters that are derived.

GEOMETRICAL REPRESENTATIONS

Magnetic susceptibility is mathematically represented by a second order symmetric tensor (Nye, 1960), whose three eigenvalues are positive ($k_1 > k_2 > k_3 > 0$) in the case of ferromagnetic materials, which is the only case that will be referred to in this chapter. The eigenvalues are the values of the principal susceptibilities directed along the corresponding eigenvectors. Defining a system of reference formed by three Cartesian axes (x_i, i=1,2,3) parallel to the eigenvectors of the susceptibility tensor, the components of the magnetization (M_i) that results from an applied magnetic field with components denoted by H_i are

$$\mathbf{M}_i = k_i \mathbf{H}_i, \qquad i=1,2,3$$

(4.1)

One graphical interpretation of the susceptibility tensor is provided by the representation quadric (Nye, 1960)

$$k_1 x_1^2 + k_2 x_2^2 + k_3 x_3^2 = 1 \qquad (4.2)$$

Equation (4.2) has received the name of Susceptibility Ellipsoid (Nye, 1960; Nagata, 1961) because it represents an ellipsoid with semiaxis parallel to the main susceptibilities (if, e.g., $k_3 < 0$ as in diamagnetic materials, the geometrical surface is completely different from an ellipsoid). It should be noticed that the lengths of the semiaxes of this ellipsoid are equal to the inverse of the square roots of the corresponding principal susceptibility. Thus, the orientation of the longest axis of this ellipsoid will coincide with the direction of minimum susceptibility, while the shortest axis coincides with the direction of maximum susceptibility. Therefore, the anisotropy ellipsoid has no direct interpretation in terms of the magnitude of the measured susceptibility with direction (Runcorn, 1967; Ellwood et al., 1988) as shown in Figure 4.1.

Another geometrical surface associated with the susceptibility tensor is described by the magnitude of the susceptibility in a direction parallel to the applied magnetic field

$$k_{||}=M_{||} / H \qquad (4.3)$$

where $M_{||}$ is the component of the magnetization parallel to the applied magnetic field of norm H. $k_{||}$ has been called the directional susceptibility (e.g. Hrouda, 1982). By using the direction cosines (denoted by l_1, l_2 and l_3) of the applied magnetic field, **H** and **M** are given by

$$\mathbf{H} = (l_1 H, l_2 H, l_3 H) \tag{4.4}$$

and

$$\mathbf{M} = (k_1 l_1 H, k_2 l_2 H, k_3 l_3 H) \tag{4.5}$$

With these two expressions it is easy to prove that the magnetization parallel to the field, and the directional susceptibility are,

$$\begin{aligned} M_{||} &= \mathbf{M} \cdot \mathbf{H} / H \\ &= k_1 l_1^2 H + k_2 l_2^2 H + k_3 l_3^2 H \end{aligned} \tag{4.6}$$

and

$$k_{||} = k_1 l_1^2 + k_2 l_2^2 + k_3 l_3^2 \tag{4.7}$$

The surface described by eq. (4.7), as the applied field changes in direction, is very different from an ellipsoid (Fig 4.1; Nagata, 1961; Runcorn, 1967; Hrouda, 1982, Constable, 1992). It is worthwhile mentioning that it is the directional susceptibility what is actually measured in many instruments.

Yet a third geometrical surface associated with the susceptibility tensor has been used in the literature: the magnitude ellipsoid (Nye, 1960; Nagata, 1961), that represents the loci of the magnitude of the susceptibility

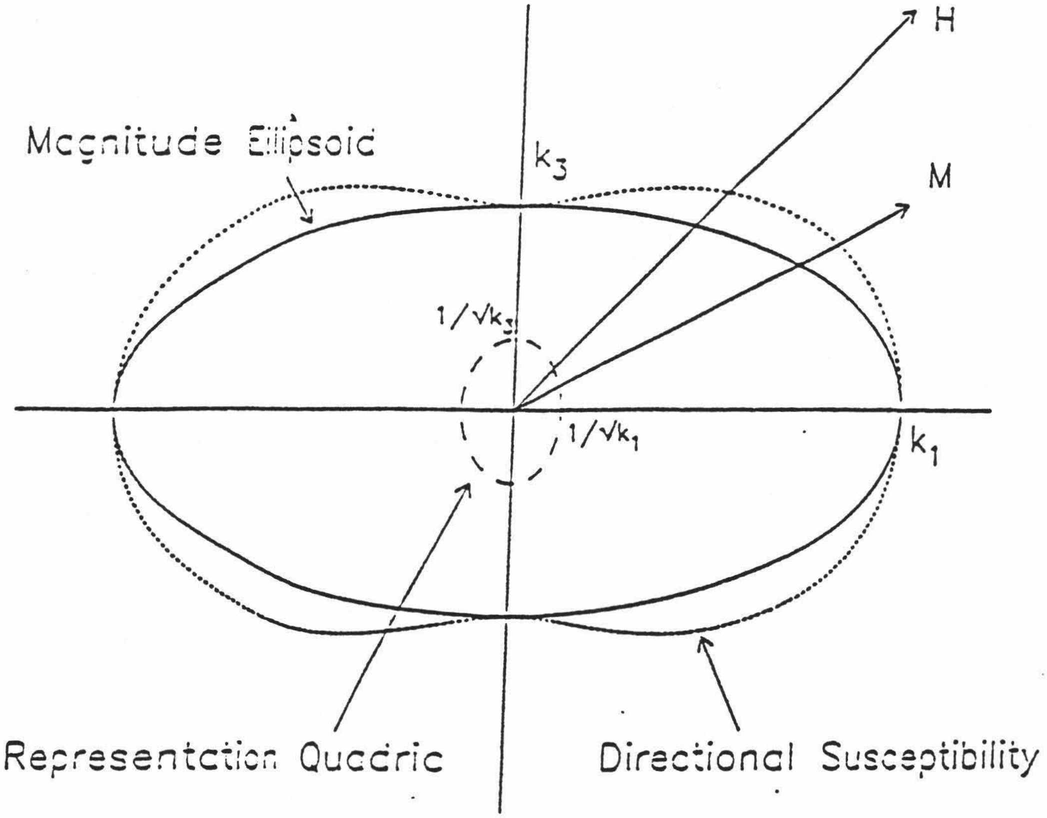


Fig 4.1. Projections of the three principal geometrical representations of the susceptibility tensors on a plane defined by two axis parallel to the maximum and minimum principal susceptibilities (after Constable, 1992).

in the direction of the resulting magnetization. Now, it is necessary to use the direction cosines of the magnetization vector instead of the direction cosines of the applied field. The new direction cosines are

$$L_i = (k_i \; l_i \; H) \; / \; M$$
$$= (k_i \; l_i) \; / \; m \qquad (4.8)$$

where $m = (k_1^2 \; l_1^2 + k_2^2 \; l_1^2 + k_3^2 \; l_3^2)^{1/2}$.

Using eqs. (4.4), (4.5) and (4.8), the square of the magnitude of the susceptibility in the direction of the magnetization is

$$K^2 = (\mathbf{M} \; / \; H)^2$$

$$= \{(L_1^2/k_1^2) + (L_2^2/k_2^2) + (L_3^2/k_3^2)\}^{-1} \qquad (4.9)$$

Equation (4.9) can be interpreted as the length of a radius vector of an ellipsoid (the magnitude ellipsoid) with equation

$$x_1^2/k_1^2 + x_2^2/k_2^2 + x_3^2/ \; k_3^2 = 1 \qquad (4.10)$$

In this case, the lengths of the semiaxis of the ellipsoid and the directions of the principal susceptibilities are directly proportional, i.e., the longest semiaxis of this ellipsoid is parallel to the direction of the maximum susceptibility, and the shortest semiaxis is parallel to the direction of minimum susceptibility. Probably because of this relationship, the magnitude ellipsoid has became the most popular representation of the susceptibility tensor.

If the two ellipsoids, eqs. (4.2) and (4.10), are compared, it is clear that when the susceptibility ellipsoid is oblate, the magnitude ellipsoid is prolate and viceversa. However, it is important to remark that not only these two, but the three geometrical representations discussed above are equivalent in that they constitute a visualization of a tensor, but are not the tensor themselves. In consequence, the parameters that are to be used in the study of the magnetic susceptibility should not rely on any particular geometrical representation because the conditions that are required for describing one particular shape may not be fulfilled if a different representation is used.

SUSCEPTIBILITY PARAMETERS

Mean Susceptibility

Two different forms for calculating the mean susceptibility (k_m) from the principal susceptibilities are

$$k_m = (k_1+k_2+k_3)/3 \qquad (4.11)$$

and

$$k_m = (k_1k_2k_3)^{1/3} \qquad (4.12)$$

the arithmetic and the geometric means, respectively. In Figure 4.2, the values of k_m calculated with eqs. (4.11) and (4.12) are plotted as a function of the ratios k_3/k_1 and k_2/k_1. The upper pair of lines corresponds to the limit

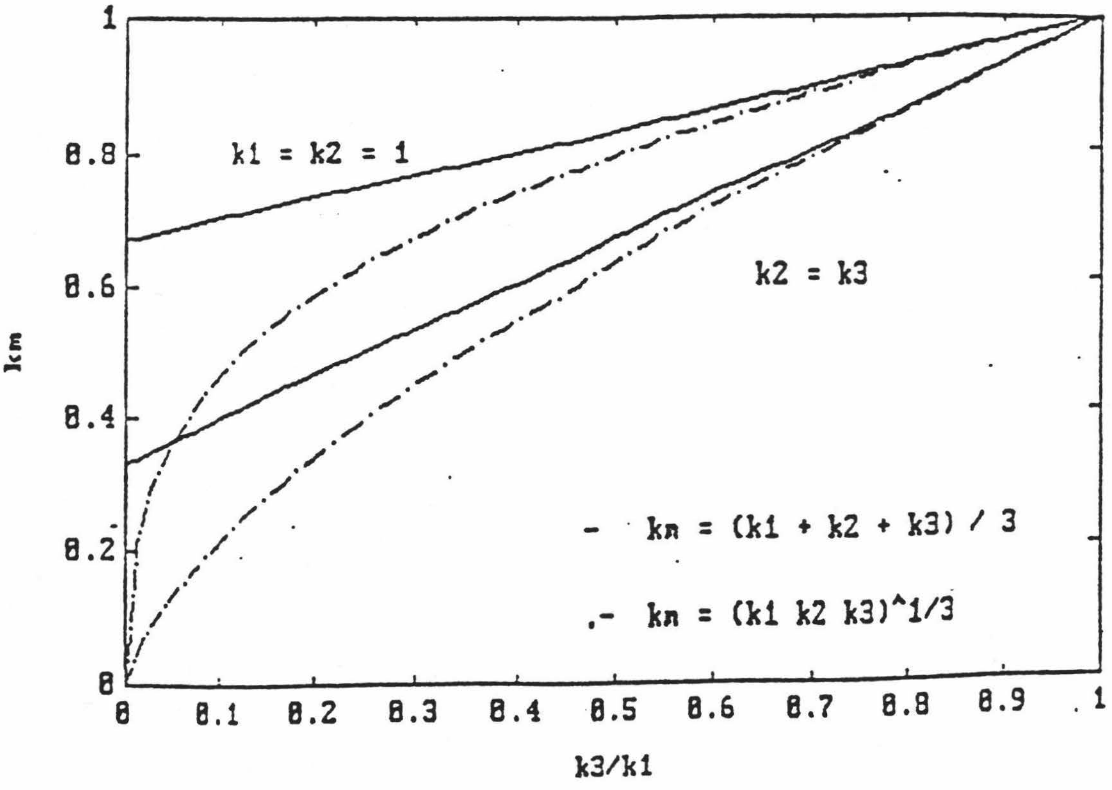


Fig. 4.2. Values of the mean susceptibility (k_m) as a function of the ratios minimum / maximum (k_3/k_1) and intermediate / maximum (k_2/k_1) susceptibilities for two limiting cases: the upper pair corresponds to $k_1 = k_2$. The lower pair represents $k_2 = k_3$. The upper right part of the graphic corresponds to the most common values obtained in measurements.

case $k_1 = k_2$, whereas on the lower pair $k_2 = k_3$. Clearly, for ratios of $k_3/k_1 > 0.5$ there is not much difference between the two means. Although the use of (4.11) has been strongly recommended (Ellwood et al., 1988), while (4.12) is usually neglected, it has been observed experimentally that the ratio k_3/k_1 usually lies between 1 and 0.75 and is rarely below 0.5 (Nagata, 1961). Exceptionally low values of k_3/k_1 (~ 0.2) can be expected when the magnetic phase contained in the specimen is part of the ilmeno-hematite or pyrrhotite series (Nagata, 1961). Nevertheless, even at this extreme, the difference between the arithmetic and geometric means is less than 20% (Fig. 4.2) and, therefore, based on the mentioned observations of ferromagnetic minerals, eqs. (4.11) and (4.12) are both valid and almost equivalent. There is however an advantage of using eq. (4.11), namely that this expression is proportional to the trace of the susceptibility tensor, and consequently, it will have the same value independently of what system of reference (principal susceptibilities, specimen or geographical axis, e.g.) is used.

Foliation-Lineation Parameters

The concept of "magnetic plane" (Granar, 1957; Balsey and Buddington, 1960; Graham, 1966) was derived from the coincidence of planar structures observed in the rock and a plane where the difference of susceptibilities was smaller than the difference between the smallest susceptibility in the plane and the susceptibility normal to it. This definition can be expressed in terms of the principal susceptibilities as the plane that contains k_1 and k_2 provided either

$$k_1 - k_2 < k_2 - k_3 \tag{4.13}$$

or

$$k_1/k_2 < k_2/k_3 \tag{4.14}$$

is satisfied.

From (4.13), Khan's (1962) oblateness and prolateness parameters are easily obtained and from (4.14) two other shape parameters (Stacey et al., 1960 and Hrouda et al., 1971) are also derived (Table 4.1). It is important to notice that both expressions, (4.13) and (4.14), involve all the three principal susceptibilities in the definition of the magnetic foliation, and therefore, it should be clear that any parameter that only uses two of the principal susceptibilities will not be consistent with the original definition. Also, it must be emphasized that either (4.13), (4.14) or any of those parameters listed in Table 4.1 were obtained independently of any geometrical representation of the susceptibility tensor, and that all of them are completely equivalent and satisfy the original definition of magnetic foliation.

It can be seen from eq. (4.14) that the magnetic deformation diagrams analogue to the Flinn (1962) diagrams

Table 4.1 Some of the shape parameters that have been proposed in the literature. All the parameters in this table satisfy the original definition of magnetic foliation.

$(k_1 - K_2) / (k_2 - k_3)$	(Khan, 1962)
$(k_2 - k_3) / (k_1 - k_2)$	(Khan, 1962)
$k_1 k_3 / k_2 2$	(Stacey, 1960)
$k_2 2 / k_1 k_3$	(Hrouda et al., 1971)
$(2k_2 - k_1 - k_3) / (k_1 - k_3)$	(Jelinek, 1981)
$k_3/k_1 - 2k_2/k_1 + 1$	(This work)

are a direct consequence of the definition of magnetic plane if the geometric mean susceptibility is used. Then, if Flinn diagrams are used together with the arithmetic mean susceptibility, the internal consistency of the selected parameters is not mantained.

Expressions (4.13) and (4.14) can be rewritten as

$$(k_1 + k_3)/2 \quad < \quad k_2 \tag{4.15}$$

and

$$(k_1\ k_3)^{1/2} \quad < \quad k_2 \tag{4.16}$$

respectively. From these new expressions, it is more clear that the definition of a magnetic foliation will be immediately satisfied if the value of the intermediate susceptibility (k_2) is larger than either the arithmetic or the geometric mean. An important consequence of this is that depending on the form of calculation of the mean susceptibility the parameter used to quantify the degree of foliation should be selected to maintain the internal consistency.

It has been suggested (Ellwood et al., 1988) that instruments like bridges and cryogenic magnetometers favor the use of parameters that follow (4.14), whereas torsion fiber and spinner magnetometers define more precisely parameters that follow (4.13). However, after the principal susceptibilities have been determined, the interpretation of the susceptibility tensor in terms of any set of parameters is independent of the instrument used to make the measurements. Of course, comparison of results from different instruments should be made very cautiously, due to the differences in the properties that they measure.

The definition of magnetic foliation as expressed above also excludes the possibility of an independent calculation of a lineation parameter. However, it is convenient to extend the numerical limits of (4.13) and (4.14) (by reversing the direction of the inequality) to include the evaluation of lineations as opposed to foliation. In this manner, the magnetic fabrics will be described by the categories: purely foliated, preferentially foliated, foliation-lineation equally developed, preferential lineation and pure lineation. These categories are similar to those proposed by Jelinek (1981) and Hrouda et al. (1988), although once again, their derivation has been made here independently of any geometric representation of the susceptibility tensor. The range of numerical values from each of these categories can be arbitrarily defined, depending on the actual form of the parameter that is used.

It is desirable that the parameter could take defined values throughout all its range, and that this range have finite upper and lower limits. Also it is important that two very different cases led to different values of the parameter. Unfortunately, the parameters listed in Table 4.1

do not satisfy all of these requirements. For example, if $k_1 >> k_2, k_3$, the first and third parameters do not have a finite upper limit. Conversely, if $k_3 << k_1, k_2$, the second and fourth parameters do not have a finite lower limit. One parameter that satisfies all the above conditions, derived from (4.13) is

$$B = k_3/k_1 - 2k_2/k_1 + 1 \tag{4.17}$$

The parameter B takes values only between -1 (purely foliated) and 1 (pure lineation). A value equal to zero will indicate the mixed foliation-lineation. The similarity of B with the difference shape factor U and the shape factor T (Jelinek, 1981) is remarkable considering the different assumptions in their derivation. The B parameter is a simple consequence of the definition of foliation and does not require analogies with the strain ellipsoid.

Degree of anisotropy

There are several parameters that have been proposed with the name of degree of anisotropy, but their contexts of application are very different from each other. Therefore, in this case it is important to be sure what is the purpose of the study before comparing parameters. Nagata (1961), defined a parameter P (k_1/k_2) that allows the calculation of the intrinsic susceptibility of the magnetic grains from the measurements of the apparent susceptibility (this is what is measured in every case), provided that the dimensions of the grain are known. The good agreement with the experimental results (Uyeda et al., 1963) support the use of this parameter in this context.

In a slightly different range of interests, the P parameter has proved to be useful. In the evaluation of the difference between the directions of the external field and the remanent magnetization produced by the degree of anisotropy of the rock. However, for its application it is necessary to evaluate the P factor at the blocking temperature as well as at room temperature to obtain accurate results (Uyeda et al., 1963). Due to this complication a different approach to this problem is probably better. Stacey, (1960) has related the principal susceptibilities to the dimensions of a magnetic grain through the relation

$$5\epsilon\ (1/k_3 - 1/k_1)/8\pi = (1 - b/a) \qquad (4.18)$$

where a and b represent the maximum and minimum semiaxes of an equivalent (to the grain) ellipsoid that is required to produce the observed anisotropy and ϵ is the volume fraction of ferromagnetic material in the rock. The right hand side of (4.18) has been used as a measure of the degree of anisotropy due to shape effects. The limiting value for this parameter of 0.1 assures that the deviation of the remanence with respect to the applied field is less than 3° (Stacey, 1960).

Several other parameters which attempt to quantify the degree of anisotropy have been proposed (Khan, 1962; Graham, 1966; Rees, 1966; Owens, 1972: Jelinek, 1981) mainly with the idea of allowing comparison between different types of rocks with a single parameter. Some of these parameters are listed in the Table 4.2. Once again, the main inconvenience of most of them is the lack of finite upper limits on their ranges, and therefore their limited use in comparing different rock types. An exception is the P' parameter (Jelinek, 1981) but this parameter is defined using the scatter of the natural logarithms of the principal susceptibilities. It has the minor inconvenience that the selected numerical constants depend on the geometry of the susceptibility tensor (its limit values are the same for both oblate and prolate rotational ellipsoids). An alternative to these parameters is given by

$$A = 1 - k_3/2k_1 - k_2/2k_1 \qquad (4.19)$$

The parameter A takes values between zero (isotropic case; $k_1 = k_2 = k_3$) and 1 (the limiting case $k_2 = k_3 = 0$) and depends on the principal susceptibilities rather than in their logarithms, which makes its calculation slightly more simple than the P' parameter. A characteristic of this

Table 4.2 Degree of anisotropy parameters.

k_1/k_3	(Nagata, 1961)
$5\epsilon\ (1/k_3 - 1/k_1)/\ 8\pi$	(Stacey, 1960)
$100\ (k_1 - k_3)/k_1$	(Graham, 1966)
$(k_1 - k_3)/2k_m$	(Khan, 1962)
$(k_1 - k_3)/k_2$	(Rees, 1966)
$(k_1 - k_3)/k_m$	(Owens, 1974)
$\exp\ \{2[(\eta_1-\eta)^2 + (\eta_2-\eta)^2 + (\eta_3-\eta)^2]\}^{1/2}$	(Jelinek, 1981)
$1 - k_3/2k_1 - k_2/2k_1$	(This work)

parameter is that any two susceptibility tensors with the same (arithmetic) mean susceptibility will have the same value of A. The convenience of using A to compare sets of susceptibility tensors instead using directly their mean, is that A has a restricted range of values, and is possible to evaluate how close the tensor is from the isotropic case very easily (the smaller the value of A, the more isotropic the tensor).

Other parameters

Although it is impossible to examine in detail all the parameters that have been suggested, there is one that deserves special mention because of its proved empirical value. The F parameter $(k_1' / (k_2' k_3')^{1/2}$ where the principal susceptibilities are normalized to the constant value .001 SI; Ellwood, 1985) has been used to differentiate between the intrusive and extrusive character of igneous rocks with some success. There is no apparent reason to reject this parameter, although in the other hand there is no physical basis for its validity, and therefore caution should be strongly exercised when this parameter is used.

CONCLUSIONS

The main points of this chapter can be summarized as follows:

1) There are at least three equally valid geometrical representations of the susceptibility tensor which have completely different forms. The differences in the forms are such that a parameter that describes one characteristic of one particular representation may be completely erroneous in describing the form of another representation. Because what is important in the study of the susceptibility tensor is the tensor itself and not one particular representation, it is suggested that the parameters used to characterize it should not reflect a geometrical connotation in either their derivation or their names.

2) Due to the range of observations, it is possible to calculate the mean susceptibility as the geometric or arithmetic mean of the principal susceptibilities. However, the arithmetic mean has the advantage of being proportional to one invariant of the susceptibility tensor (its trace).

3) From the original definition, based on experimental observations, of the magnetic foliation of a rock it is possible to derive a factor, B, that conveniently quantifies it. Some of the old shape parameters are such that satisfy the original definition of magnetic foliation but their ranges of definition are not convenient.

4) The method of calculating the mean susceptibility determines to some extent the form of the parameters that

should be used (or viceversa) if internal consistency is to be maintained.

5) The existing set of degree of anisotropy parameters includes parameters that were conceived with completely different purposes in mind. It is therefore important to select one particular parameter from the correct category to avoid confusion.

CHAPTER 5. PALEOMAGNETIC STUDY OF ROCKS FROM THE AZUFRE VOLCANO, ARGENTINA

INTRODUCTION

The main purpose of paleomagnetism is the study of the Earth's magnetic field through geological times although it may be used to constrain some important aspects of the development of a volcano. The data base for paleomagnetic studies is obtained from the magnetic record contained in rocks from around the world; a global reconstruction of the geomagnetic field at a given time needs data widely distributed over the Earth's surface. Several factors, such as the unequal distribution of land and the relative inaccessibility of appropriate places for collection of rock samples, have produced a limited set of data from the South Hemisphere. For example, only eight studies on South American Quaternary formations (from which only two include results pertaining to the Bruhnes Chron) are included in one recent database (Piper, 1988).

In this chapter, paleomagnetic results from eight lava flows from the Azufre volcano, Andean Cordillera (35.25°N, 289.5°W) are reported. Due to the intermingling of lavas from two volcanoes (Azufre and Planchón, Fig.5.1), it was necessary to use anisotropy of magnetic susceptibility (AMS) measurements to determine flow directions of the sampled lavas in order to assign them an eruptive source. Additionally, a comparison of the obtained directions of magnetization of the Azufre lavas with those obtained from a group of lavas of the Mendoza and

Neuquén provinces, Argentina, was made to constrain to some degree the age of the Azufre lavas.

Preliminary measurements on some of the rock samples showed a large increase on the intensity of the remanence without significant change in its direction after demagnetization at 2.5 mT. These results were interpreted as indicators that a partial self-reversal had taken place in the studied rocks (Cañón-Tapia, 1991). However, the sudden character of the increase in intensity, the large value of the ratio $J_{2.5}$ / J_{NRM} (~1.5-2.0), and the shape of the demagnetization curves, raised the question of whether or not the experimental results were accurately reflecting an actual phenomenon. To eliminate the possibility of accidental magnetic contamination of the samples by a magnetic field during the demagnetization process, the remaining samples were measured on a cryogenic magnetometer which is inside the same field-free space as the three-axis tumbler and oven used for alternating fields (AF) and thermal demagnetization, respectively. The field-free space is provided by the mu-metal room of the Paleomagnetic Laboratory at the University of Hawaii. Results from most of these specimens also show an increment in the initial intensity of magnetization with the first steps of demagnetization, but the ratio J_{MAX} / J_0 is considerably lower (~1.05-1.1) which invalidates the argument of partial self-reversal reported before (Cañón-Tapia, 1991).

GEOLOGICAL SETTING AND SAMPLING PROCEDURES

The site of study is located in a transition zone between andesite volcanoes to the north and basalt-dacite volcanoes to the south (Tormey et al., 1989). Overlapping volcanic products from three volcanoes, Planchón, Peteroa and Azufre, aligned from north to south (Fig. 5.1) have formed a complex structure. A detailed study of the development of the volcanic complex has been made by Tormey et al. (1989) who estimated that the age of the older volcano of the complex, the Azufre, has to be less than 0.55 My. These workers also conclude that the Planchón volcano initiated its activity after approximately 75% of the Azufre lavas had been erupted and inferred that the intervals between extrusion of the Azufre lavas were short because of the lack of sedimentary deposits between flows.

Cores from eight lava flows were obtained using two gasoline powered drills. These eight flows were divided in two groups, North and South, according with their location on the complex (Fig. 5.1). Each group is formed by four individual lava flows; the N-1 flow is a compound flow, i.e., it is formed of several flow units, five of which were sampled. A minimum of 5 cores, subsequently cut in two specimens, were drilled from each flow of the South group while in the North the minimum number of cores was 15. Schematic stratigraphic positions of both groups of flows are shown in Fig. 5.2.

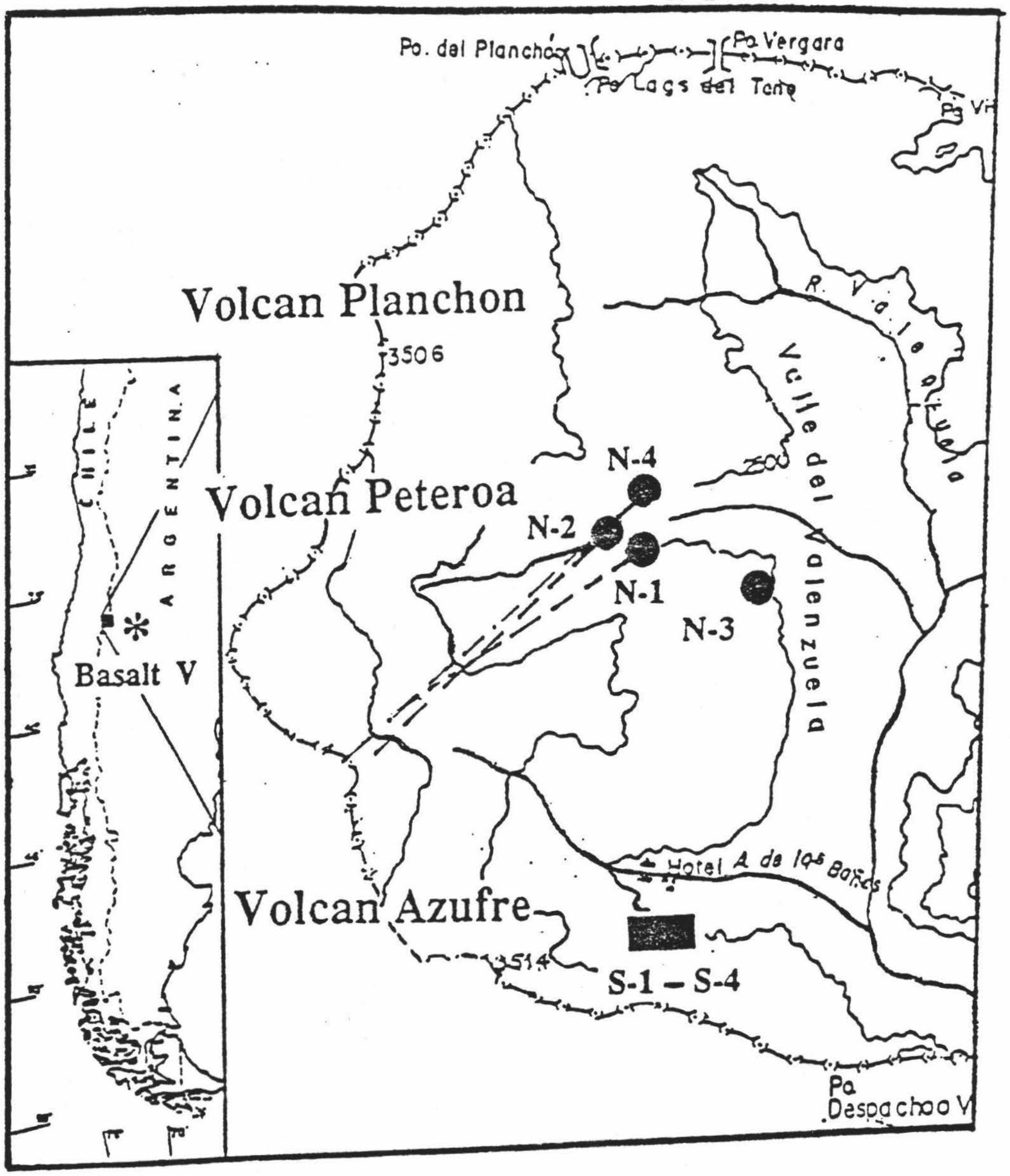


Fig. 5.1. Location of the area of study of this work. Dashed lines indicate the inferred flow direction from AMS measurements in samples of the N-1 to N-3 flows at the site of sampling.

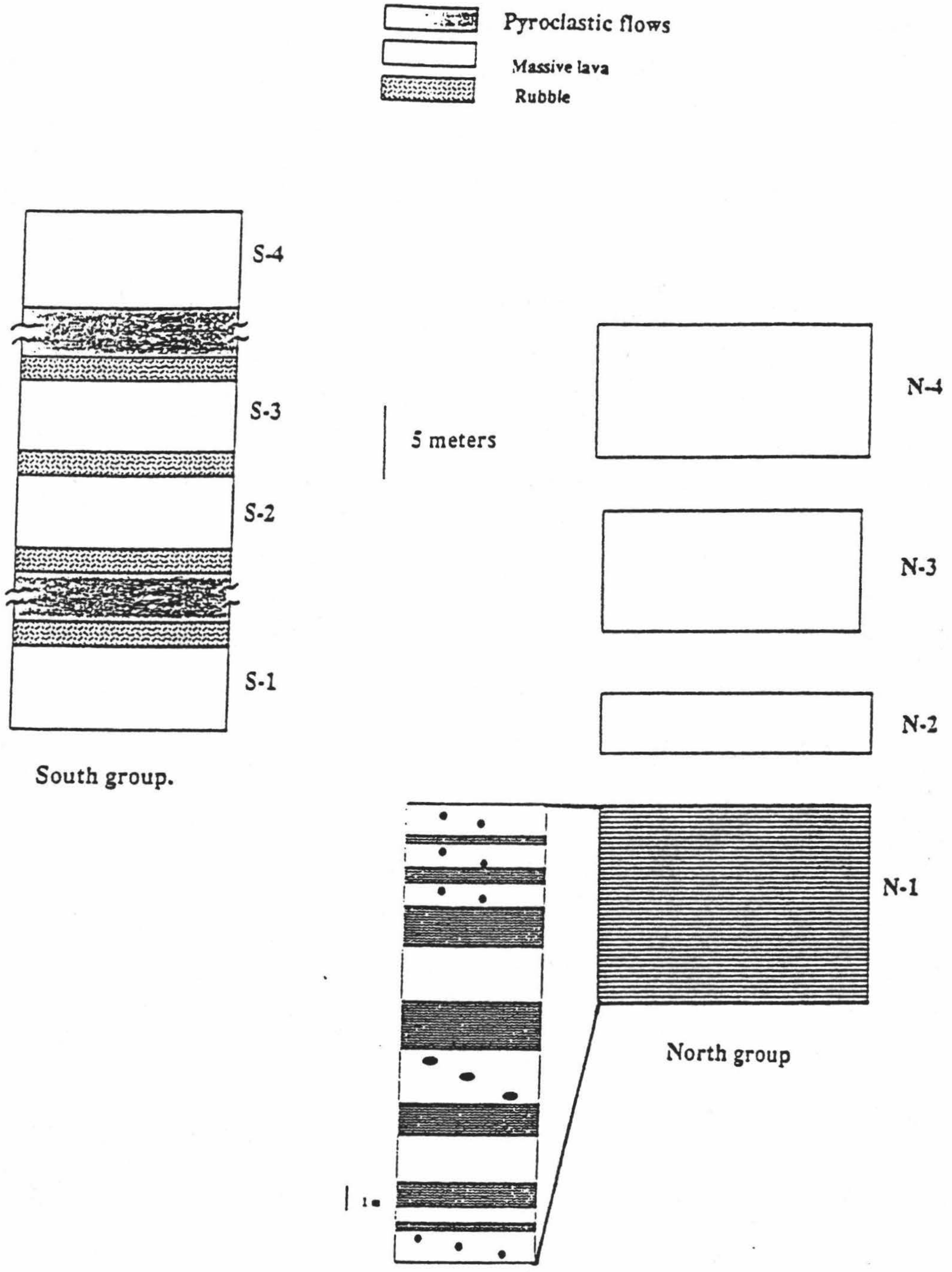


FIG 5.2 Schematic stratigraphic sequence of a) South group and b) North group flows.

Orientation of samples was made with magnetic compass, and additionally in the North group a solar compass was used. The mean difference in the magnetic and solar orientation was 2° after correction for the local declination (10°).

Due to their location, three flows of the North group could be not Azufre but Planchón flows. Because of the chemical and mineralogical similarities between the lavas from both volcanoes (Tormey et al., 1989) a different approach was used to infer their possible source vent.

AMS MEASUREMENTS

Background

The flow of magma influences the distribution of grains, represented as ellipsoidal particles, arranging them in such a way that the long axis parallel the flow lines (Jeffrey, 1922). Khan (1962) showed that the average orientations of the principal axis of the magnetic grains determine, for the most part, the observed differences in the magnetic susceptibility measured along different directions on a rock sample containing magnetite. This assumption seems to be valid in the most general case of magnetic grains with high intrinsic susceptibility (Nagata, 1961; Hruoda, 1982). However, Hargraves et al. (1991) have pointed out that the data presented by Khan (1962) were obtained from a metamorphosed dike and that the preferred orientation of magnetic grains is not necessarily the cause of AMS in pristine igneous rocks. Moreover, the irregular shape of the magnetite grains and the fact that the bulk of the accessory magnetite usually crystallizes after flow of magma has ceased (Park et al., 1988) also made doubtful that forces related to flow alone are the main cause of AMS. Stacey (1960) suggested that the alignment of other minerals by flow forces may control the growth of magnetite minerals, but no further work had been made to validate this hypothesis until very recently. Hargraves et al. (1991) carried out a series of experiments to test the hypothesis that an AMS symmetric with the preexisting fabric is expected from the bulk, late-crystallizing magnetite. Their results showed that AMS measurements provide a direct record of fluid-dynamic histories of igneous rocks because they are a direct, or indirect, reflection of the preexisting silicate fabric. Therefore, the determination of the principal directions of susceptibility on several samples from the same unit as an indicator of the flow direction in igneous rocks has been validated experimentally, in addition to the previous observations made in dikes (Khan, 1962; Knight and Walker, 1988; Ernst and Baragar, 1992) and pyroclastic flows (Ellwood, 1982; Knight et al., 1986).

In the particular case of lava flows, the results of this technique have been somewhat contradictory. Khan (1962) and Symons (1974) found a large scatter on the AMS directions and little or no relationship at all between their means and the flow directions determined from the geological evidence. The observed scatter on the AMS directions was in both cases attributed to the effects of convection patterns or of local turbulence within the flow boundaries. The method used to calculate the mean direction of the principal axis of the AMS tensor did not take into account the tensor nature of the magnetic susceptibility. Jelinek (1978) developed a multivariate analysis technique to compute the mean susceptibility tensor which allows for the variations in the bulk susceptibility as well as the "shapes" of the individual tensors obtained from the measured samples. The utility of this method in characterizing AMS data sets was demonstrated by Lienert (1991) who concluded that the performance of Jelinek's method is extremely good except for a small underestimate of the confidence region size when the directions of the individual samples are almost randomly distributed.

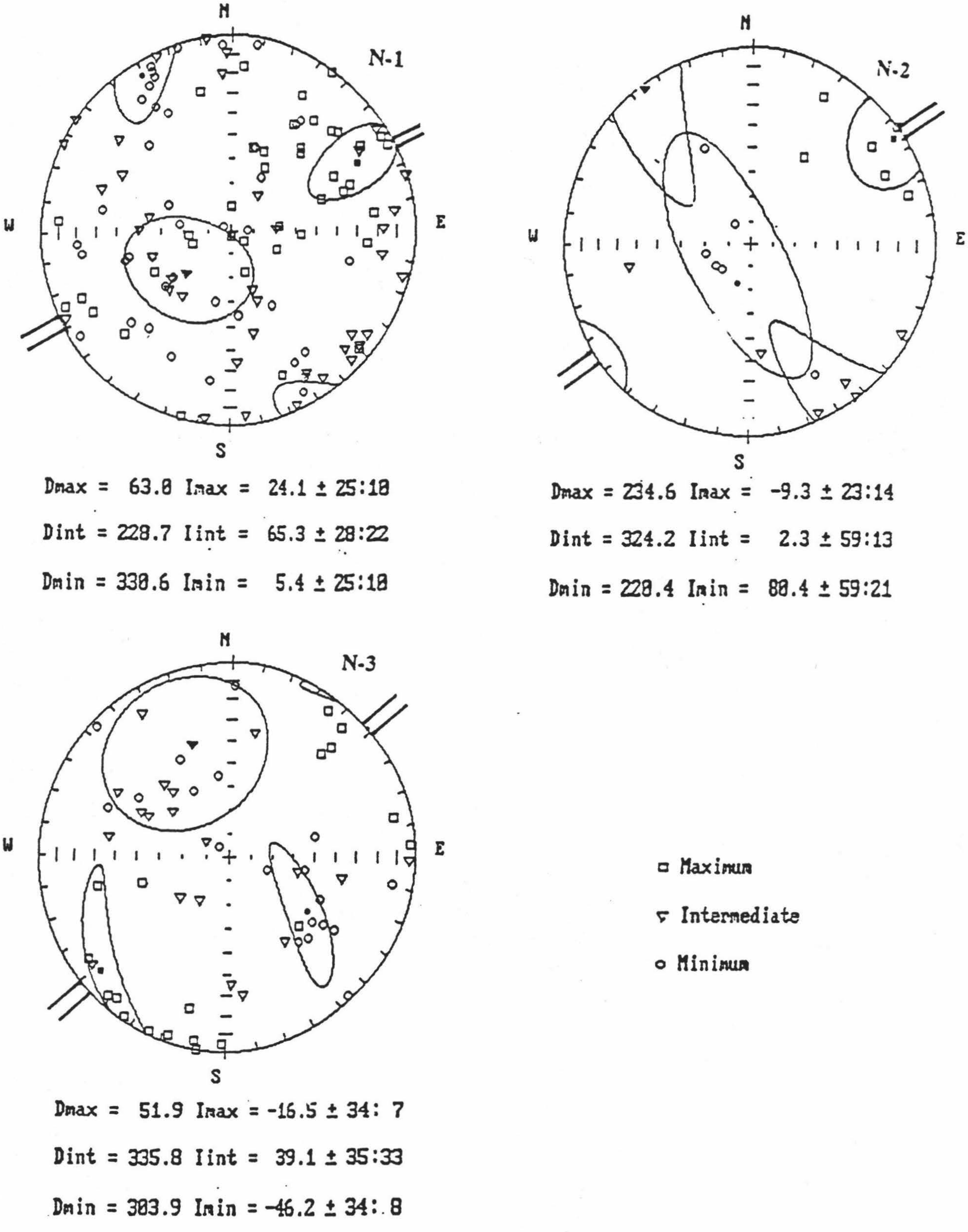
Hrouda (1982) refers to a work by Kolofikova which shows that the maximum axis of susceptibility is very close to the mean flow direction provided the middle parts of the flow, and not its frontal section, are sampled. As will be shown in the next chapter, a close relationship between the maximum axis of susceptibility and flow direction in two units from Xitle volcano was found by applying the analysis technique of Jelinek using Lienert's computer program.

Results

AMS was measured on a Kappabridge KLY-2 instrument, and statistical analysis were made using an updated version of the program made by Lienert (1991). The criteria used to decide the acceptability of the results as indicators of flow direction was established analogous to those used in the determination of the mean directions of magnetization in paleomagnetic studies, i.e., defining sizes of the confidence regions ($\alpha95$, defined by Fisher, 1953, in paleomagnetism and the ellipsoids of confidence in AMS) for which the quality of the results are graded. The difference in the geometry of the $\alpha95$ and ellipses of confidence regions, the two semiaxis of the ellipses, makes modification of the values for different categories necessary. I decided to use the normalized area of the region of confidence obtained by multiplying together the sine of each of its semiaxis (the length of each semiaxis is expressed in degrees and is analogous to the $\alpha95$ parameter; the area of the circle defined by an $\alpha95 = 90°$, divided by the normalizing factor π, is equal to one in the unitary sphere). The following threshold values were defined: < .03 (excellent), < .07 (very good), < .12 (good), < .18 (moderate), < .25 (fair) and, > .25 (poor), which are equivalent to an $\alpha95$ of 10°, 15°, 20°, 25° and 30°, respectively (see Knight and Walker, 1988). Although this scheme gives an objective means of evaluation, it must be noticed that one set of data could be considered as not reliable if one of the semiaxis of confidence is extremely large, despite the fact that the area may be below the limits of the category "good". This is the result of some girdle-like regions of confidence that can be found in the analysis of AMS data (Stone, 1967). Therefore, additional criteria from the particular geologic setting should be used to decide if that set of data is accepted or rejected. Results of AMS measurements of the three North group flows whose source was not clear are shown in Fig. 5.3. The inferred directions of the flows, defined by the mean maximum susceptibility directions all of which have confidence intervals smaller than .12, are marked by the double lines in the equal area projections. In all the three cases the most likely vent of origin implied by the above directions is the Azufre and not the Planchón (see dashed lines in Fig. 5.1).

PALEOMAGNETIC RESULTS

There are no documented paleomagnetic results from this part of the Andean Cordillera, although Creer and Valencio (1969) conducted an extensive paleomagnetic survey on cenozoic volcanic rocks of the Mendoza and Neuquen provinces, close to the site of the present study. Their "basalt V" group will be used as a reference point, and later it will be used to constrain the age of the Azufre flows.



Dmax = 63.0 Imax = 24.1 ± 25:10
Dint = 228.7 Iint = 65.3 ± 28:22
Dmin = 330.6 Imin = 5.4 ± 25:10

Dmax = 234.6 Imax = -9.3 ± 23:14
Dint = 324.2 Iint = 2.3 ± 59:13
Dmin = 220.4 Imin = 80.4 ± 59:21

Dmax = 51.9 Imax = -16.5 ± 34: 7
Dint = 335.8 Iint = 39.1 ± 35:33
Dmin = 303.9 Imin = -46.2 ± 34: 8

□ Maximum
▽ Intermediate
○ Minimum

FIG 5.3 Equal area projections of the AMS measurements from samples of the N-1 to N-3 flows.

NRM and ChRM

Numerical values of the direction of the natural remanent magnetization (NRM) and of the characteristic remanent magnetization (ChRM) are listed in Table 5.1 together with the precision parameter k and the angle of the 95% cone of confidence, $\alpha95$. Equal area projections of the $\alpha95$ intervals of confidence around the average NRM directions are shown in Figure 5.4a. The direction of the ChRM (Fig. 5.4b) is the direction of the remanence after partial AF demagnetization. The value of the field necessary to isolate this ChRM (H in Table 5.1) was determined by examination of the Zijderveld (1967) diagrams of individual specimens; it coincided in most of the cases with the field necessary to halve the initial intensity, i.e., the median destructive field (MDF). It was necessary to thermally demagnetize the samples from the N-3 flow because AF demagnetization barely decreased the intensity of the remanence indicating that significant amounts of hematite could occur among the magnetic carriers on this flow. Representative examples of the demagnetization process are shown in Figure 5.5.

The resultingdirections of the ChRM shown in Figure 5.4b are in agreement with the expected direction of magnetization of the locality assuming a coaxial dipolar mcdel of the geomagnetic field. The obtained virtual geomagnetic pole (VGP) coordinates from the mean direction of the ChRM of the eight flows is compared with the VGP position obtained by Creer and Valencio

TABLE 5.1 Palaeomagnetic results from Azufre volcanic rocks. NRM=natural remanent magnetization; ChRM= characteristic remanent magnetization; S/N=samples collected/number of specimens used in the calculations; D=declination of magnetization measured from the North, in degrees; I=inclination from the horizontal, in degrees; α95=95 % circle of confidence; k=Fisher parameter; H=AF used to isolate the ChRM in mT, except in the N-3 flow where temperature is indicated.

		NRM					ChRM			
Flow	S/N	D	I	α95	k	H	D	I	α95	k
S-4	7/13	340.1	-42.3	16.4	8.7	40	4.1	-42.2	4.3	115.3
S-3	6/ 7	357.1	-44.8	4.3	201.1	30	354.8	-42.8	3.8	254.5
S-2	5/ 9	358.8	-50.2	4.9	112.3	40	355.4	-46.9	4.0	165.4
S-1	7/13	0.4	-60.0	5.4	60.8	10	353.1	-53.5	3.7	124.8
N-4	14/20	12.4	-62.5	4.2	90.7	30	1.9	-66.2	3.3	144.7
N-3	11/16	359.3	-50.3	4.1	125.1	310°	5.4	-46.9	2.5	334.2
N-2	8/ 7	353.7	-39.9	36.1	3.7	7.5	8.7	-35.5	5.5	122.0
N-1	38/52	9.7	-49.4	2.3	198.0	60	10.3	-51.8	2.2	1683

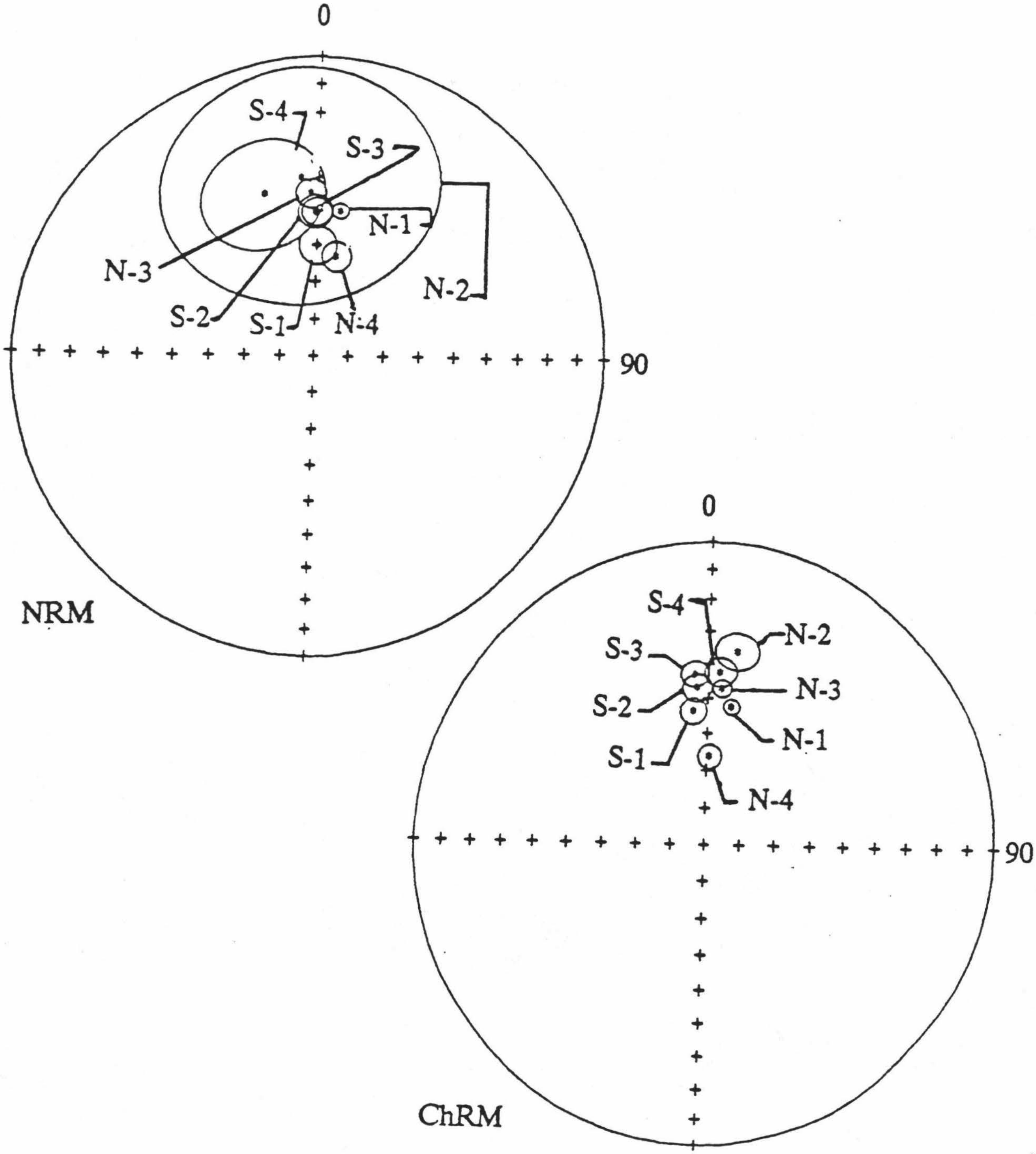


Fig. 5.4 Equal area projections (lower hemisphere) of NRM and ChRM directions.

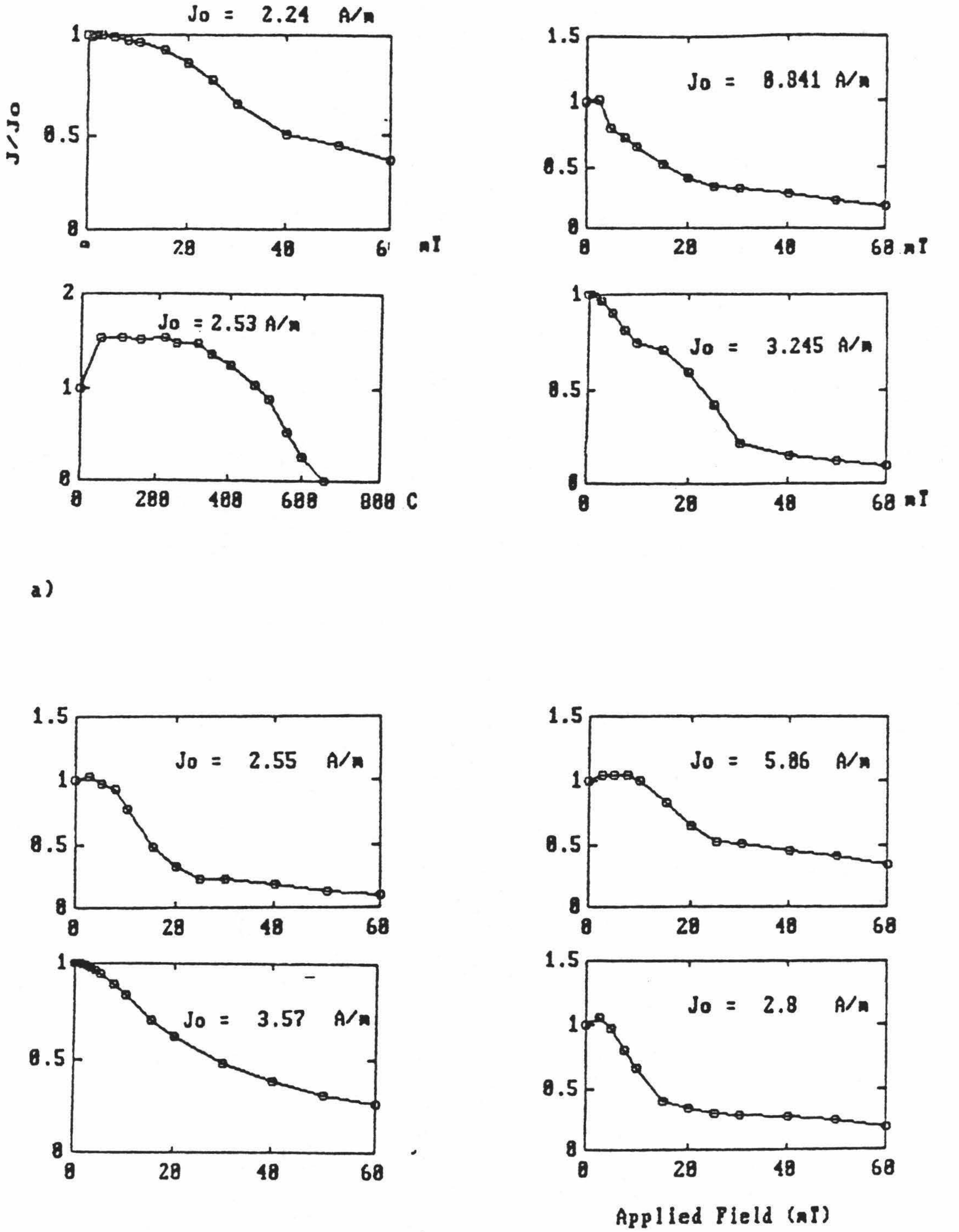


Fig. 5.5 Demagnetization of selected specimens of the Azufre volcano flows. a) Normalized intensity of the remanence against demagnetizing field (Note that one flow of the North group, N-3, was thermally demagnetized).

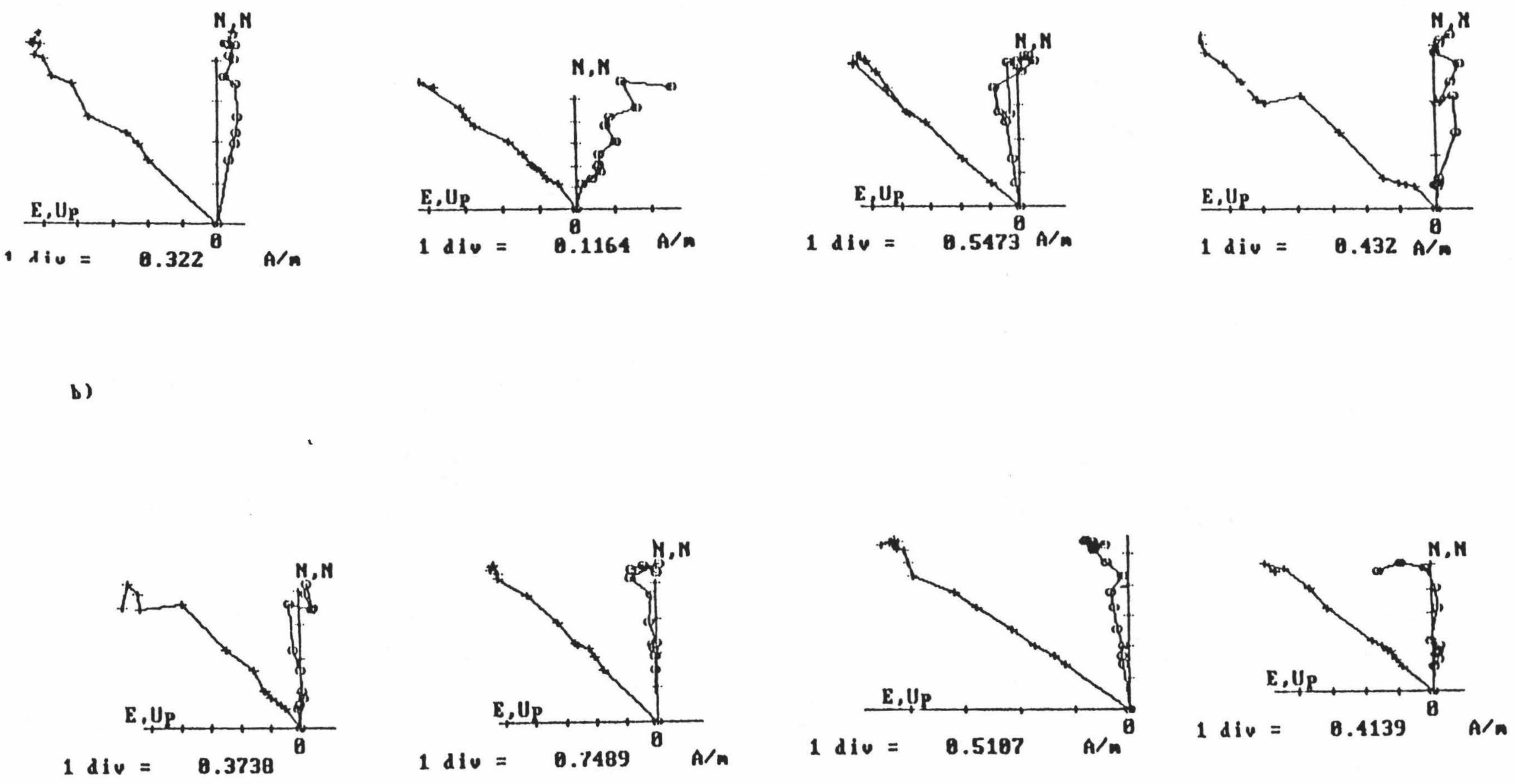


Fig. 5.5 (cont.) b) Zijderveld diagrams (solid symbols: vertical projection; circles: horizontal projection).

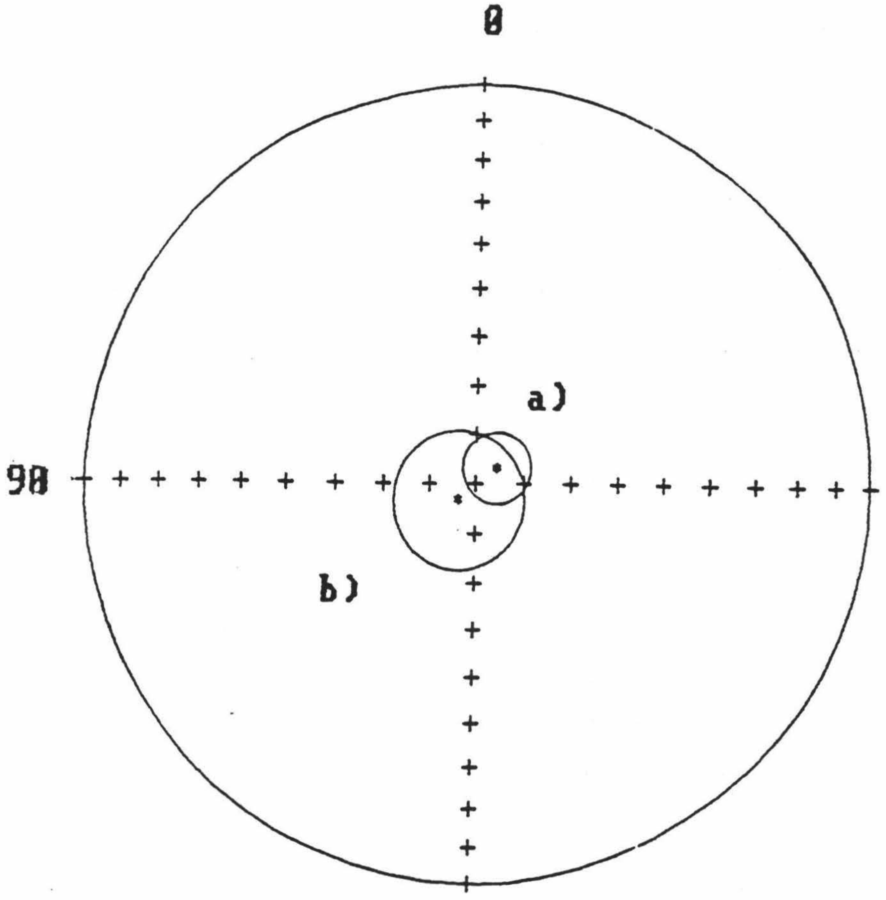
(1969) from several flows of the Bruhnes Chron in Table 5.2 and Figure 5.6. Despite the apparent large difference in the longitude, both locations of the VGP's can be considered equivalent because of their high latitudes.

It is observed in Figure 5.4b that flows S-1 to S-4 define a clear trend in the direction of magnetization with decreasing values of inclination, followed by a change on declination towards the east in the younger flow (S-4). Approximately the same trend is followed by the flows N-1 to N-3 making unlikely that this trend be the result of post-emplacement movement of individual flows. The probability that the four flows of the South group and the three flows of the North group had been erupted during the same period of time, or at least during a short period of time compared with the secular variation was therefore evaluated using the approach of Bogue and Coe (1981). The value of the secular variation used follows that of Creer and Valencio (1969) who used the between-lava flow dispersion to estimate it to be 10° for the Bruhnes Chron in this area. The necessary values of the angular dispersion and relative angular distances of the mean direction of each group to be correlated relative to each other and to the expected field in the region are listed in Table 5.3.

The probability of the simultaneous hypothesis is approximately three times larger than the probability of random sampling of directions of the geomagnetic field. As the

TABLE 5.2 Site coordinates and VGPs location derived a) from this work and b) from Creer and Valencio, 1969.

	Site Coordinates		VGP Coordinates		
	Lat(°N)	Long(°E)	Lat(°N)	Long(°E)	α95
a)	35.25	289.5	84.6	306.2	7.2
b)	35	311	85	131	14.0



VGPs

Fig. 5.6 Virtual Geomagnetic Poles from a) the Azufre volcano and b) that reported by Creer and Valencio, 1969.

TABLE 5.3 Values of a) the mean declination, b) mean inclination, c) angular dispersion and d) angular distance of the mean direction of magnetization with the expected field on the locality (0,-55) of the North group (first line), South group (second line) and group V (third line) basalts. The columns e) to g) are the angular distance, the random sampling probability and the simultaneous sampling probability, respectively; results of the comparisson of the North and South groups, South and Basalt V and, North and Basalt V are shown in the first, second and third lines, respectively, in these columns.

	a)	b)	c)	d)	e)	f)	g)
N-1 to N-4	357.1	-46.4	6.2	8.8	7.9	.170	.571
S-1 to S-3	8.1	-44.8	8.5	11.5	15.1	.500	.145
Basalt V	7.7	-59.8	6.7	6.4	14.8	.500	.075

relative position of the South group is roughly midway up in the volcano and the three flows of the North group occur lower down, the hypothesis of simultaneity is very consistent with the conclusion of Tormey et al. (1989) of a rapid rate of extrusion.

It is also possible to compare in the same manner each of the two groups of this work with the basalt V group of flows of Creer and Valencio (1969) which were dated by radiometric techniques in 0.5 ± 0.3 My by Valencio et al. (1970). In this case it is the random hypothesis that is more strongly favored (see Table 5.3) and therefore it is reasonable to assign an oldest limit of approximately 0.3 My to the age of the Azufre lavas of this study.

SUMMARY

The results of this chapter can be summarized as follows:

1) Despite the large scatter on the AMS observations of multiple samples from the same lava flow, this technique can be used as an indicator of the flow direction of the lava at the point of sampling if the multivariate analysis technique of Jelinek is used to calculate the mean directions of the principal susceptibilities. As a corollary, the discrimination between possible source vents can be assessed in the basis of AMS measurements.

2) The suggested criteria to determine the acceptability of the AMS results has been derived in analogy with the criteria used in paleomagnetism. However, the different nature of the

problem to be addressed may make necessary to use additional information from the geological context to finally accept or reject one given set of data.

3) The mean direction of the ChRM of the lavas of the Azufre volcano is Decl. = 1.9°, Incl. = -48.4°, $\alpha95$ = 7.0°. The corresponding VGP coordinates are lat = 84.6°N, long = 306.2°E, $\alpha95$ = 7.2°.

4) By using statistical criteria it is possible to roughly estimate the extrusion rate of lava flows and to constrain the possible age of groups of lavas when the directions of magnetization and the rate of secular variation are known.

CHAPTER 6. MAGNETIC PROPERTIES OF TWO FLOW-UNITS OF XITLE VOLCANO, MEXICO: STRUCTURAL CORRELATIONS AND FLOW DIRECTION

INTRODUCTION

The magnetic properties of two different basaltic lava flow units from Xitle volcano, Mexico City, are presented. These basalts were erupted 2,400 years ago (Libby, 1951); Xitle is the youngest volcano in the Chichinautzin monogenetic volcano field (Martin del Pozzo, 1982). The Xitle lava in and near the National University of Mexico (UNAM) campus is pahoehoe. It is a compound flow made of a great number of flow units that range in thickness from 0.2 to 13.0 meters.

Previous study of the magnetic properties of the Xitle lavas (Centeno-García et al., 1986), showed that the intensity and the magnetic susceptibility increase towards the upper parts of the units; the higher values of these parameters are associated invariably with areas of larger vesicles. This pattern was preserved across the margins of successive units. In this study the topmost units were selected so as to avoid possible effects of reheating by superposed units. Their heights are respectively 4.7 and 6.0 meters. The unit of the first profile (profile 9) rests on a paleosol. Location of both profiles is shown in Figure 6.1. Profile 9 is a roadcut on the opposite side of Ave.

Insurgentes to Football fields (UTM coordinates 801 368). Profile 22 is a roadcut just northwest of Auditorio "Justo Sierra" of the Facultad de Filisofía y Letras (UTM coordinates 803 377).

Both flow units are highly vesicular in their upper third and almost nonvesicular in their lower two thirds apart from a vesicular layer containing pipe vesicles in the basal 0.5 to 1.0 m. 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 were sampled in profile 9. A total of 13 cores 2.5 cm in diameter distributed from the top to the bottom of the first flow unit were drilled (Profile 9, Fig. 6 1), and eight cores were drilled from the lower part of the second flow unit (Profile 22, Fig. 6.1), allowing a more detailed study of the basal section of the lava.

MEASUREMENTS

The series of magnetic measurements followed the sequence: 1) measurement of bulk magnetic susceptibility and anisotropy of magnetic susceptibility on a KLY-2 Kappabridge; 2) measurement of natural remanent magnetization (NRM) on a Schonstedt spinner magnetometer; 3) demagnetization of the specimens by the method of alternating fields (AF) achieved while rotating the sample along three mutually perpendicular axis, with a maximum peak

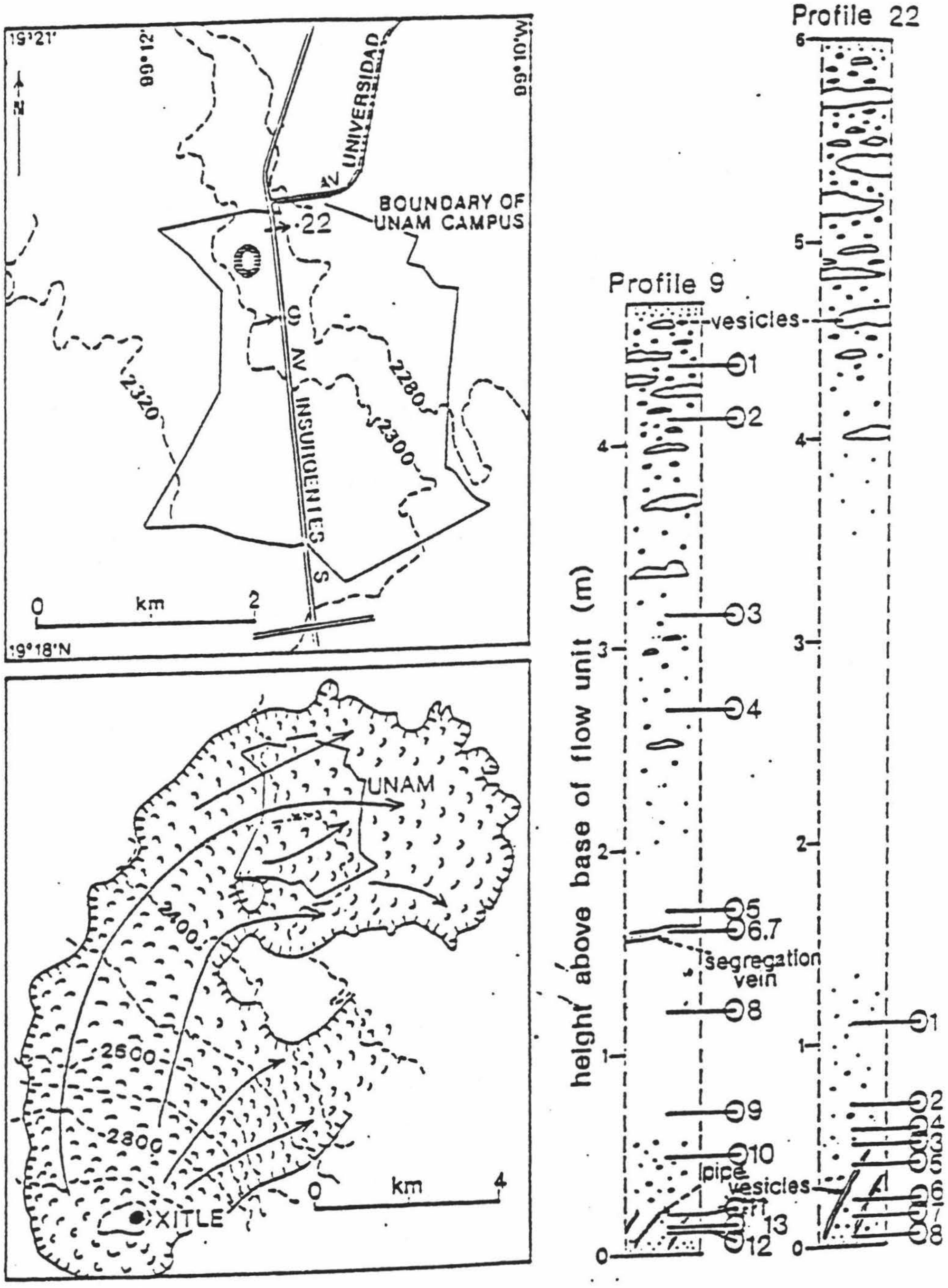


Fig.41 Above left: location of the two sampled profiles in the Universidad Nacional Autonoma de México (UNAM) campus. Arrows give the lava flow direction inferred from geological features. Dashed lines-contours, elevation in meters.

Below left: UNAM campus in relation to Xitle lava flowfield.

Right: the two profiled lava flow units, showing sample location in relation to vesicle zonation and other features.

value up to 60 mT; 4) induction of anhysteretic magnetization (ARM) in a constant field of 0.1 mT (maximum peak value of the alternating field up to 100 mT); 5) AF-demagnetization of the samples; 6) acquisition of isothermal remanent magnetization (IRM), magnetic field up to 0.12 T; 7) AF-demagnetization of the specimens.

Table 6.1 summarizes the results of the magnetic measurements; Figures 6.2 to 6.5 illustrate the variation of the magnetic parameters in the two profiles. In both figures the height in the flow units has been normalized with respect to the maximum height.

RESULTS, FLOW-UNIT 9

Direction of magnetization

Neither declination nor inclination of the natural remanent magnetization show a clear trend of variation with the location of the samples in the profile (Fig. 6.2a), defining an interval of confidence (alpha 95) around the mean of 3° (not shown).

Intensity of the remanence

Low values of the intensity of NRM at the bottom contrast with the high values on the top, although a slight increase takes place very close to the lower margin. A well defined peak of high values, at approximately one third of the total

Table 6.1 Numerical results of the measurement of magnetic properties of studied samples. The order of the parameters is: height of the sample from the base of the unit, intensity, declination and inclination of the NRM, magnetic susceptibility, shape and anisotropy parameters, intensity and median destructive field of ARM, and of IRM.

FLOW 1

		NRM					ARM		IRM	
H (cm)	Int. (A/m)	Dec. (deg)	Inc. (deg)	k x10^{-6} (SI)	A	B	Int. (A/m)	MDF (mT)	Int. (A/m)	MDF (mT)
440	5.42	350.8	39.7	04297	.003	-.002	28.7	29.5	372.5	42.6
413	3.67	359.2	33.6	04851	.008	-.014	19.3	26.1	227.0	29.6
315	1.53	378.2	41.5	03434	.026	-.011	08.7	22.6	120.7	27.0
270	2.23	353.5	40.9	03523	.011	-.013	19.3	26.1	163.0	26.1
170	1.04	353.7	34.5	02871	.020	-.019	15.8	21.7	219.0	21.7
160	5.82	353.0	43.6	07980	.004	.001	33.6	25.2	377.0	20.0
160	6.89	354.9	44.1	10620	.002	-.003	40.4	22.6	807.0	20.0
120	1.04	338.7	29.4	02776	.037	-.041	09.7	06.1	057.3	07.0
070	0.88	340.6	40.5	04198	.041	-.039	10.7	06.1	041.5	06.1
048	1.73	349.2	36.7	04134	.031	-.006	13.4	06.1	061.4	05.3
020	1.53	360.4	32.1	04814	.013	.006	17.2	08.7	073.0	07.0
010	2.20	343.7	35.6	06198	.015	.008	24.9	09.6	079.3	07.8
010	2.58	357.5	35.9	04992	.012	.004	20.8	08.7	066.7	07.8

FLOW 2

		NRM					ARM		IRM	
H (cm)	Int. (A/m)	Dec. (deg)	Inc. (deg)	k x10^{-6} (SI)	A	B	Int. (A/m)	MDF (mT)	Int. (A/m)	MDF (mT)
110	01.50	257.7	37.6	04190	.019	-.029	11.6	12.2	106.0	15.6
070	01.97	360.1	34.5	02570	.014	-.014	10.1	28.7	084.0	33.0
058	01.75	354.3	33.4	02243	.013	-.012	06.4	25.2	080.0	34.8
050	02.51	353.6	33.2	02099	.010	-.015	10.0	32.2	097.5	35.6
040	14.60	357.4	37.3	08335	.015	-.004	45.6	38.3	350.0	38.3
028	29.70	362.3	36.2	17180	.017	.001	103.3	35.6	914.4	31.3
016	14.20	360.3	39.1	09813	.015	-.009	45.1	36.5	223.3	34.8
004	9.97	358.3	41.5	11500	.007	-.001	53.0	31.3	308.0	27.8

height of the flow, defines a narrow section where either concentration of the magnetic minerals, or their oxidation state (e.g. Watkins and Haggerty, 1965), is higher. The same pattern is shown by the intensity of ARM and IRMsat (Fig. 6.2b). These results are very similar to those obtained by Centeno-García et al. (1986). Inspection of the curves of acquisition of both ARM and IRM (Fig. 6.3a) do not reveal any special characteristic of the samples with high intensity. Moreover, these samples perfectly follow the trend of decreasing coercitivity toward the bottom of the flow.

Comparison of the demagnetization curves of ARM and IRM (Fig. 6.3b), may be used to infer the average domain structure of magnetic grains (e.g. Johnson et al., 1975). On the uppermost level of the flow both remanences are very stable, showing a linear dependence with the intensity of the demagnetizing field. In this part of the flow, ARM is more easily removed than IRM but it becomes equally hard at approximately the middle section. A very different type of curve is observed on samples from the lower third. Here, the demagnetization shows an exponential dependence on the field, which reflects the lower coercitivities previously mentioned. The ARM curve usually lies above the IRM curve, but on the lower levels their relative position is switched at weak demagnetizing fields. Thus, a division of the flow

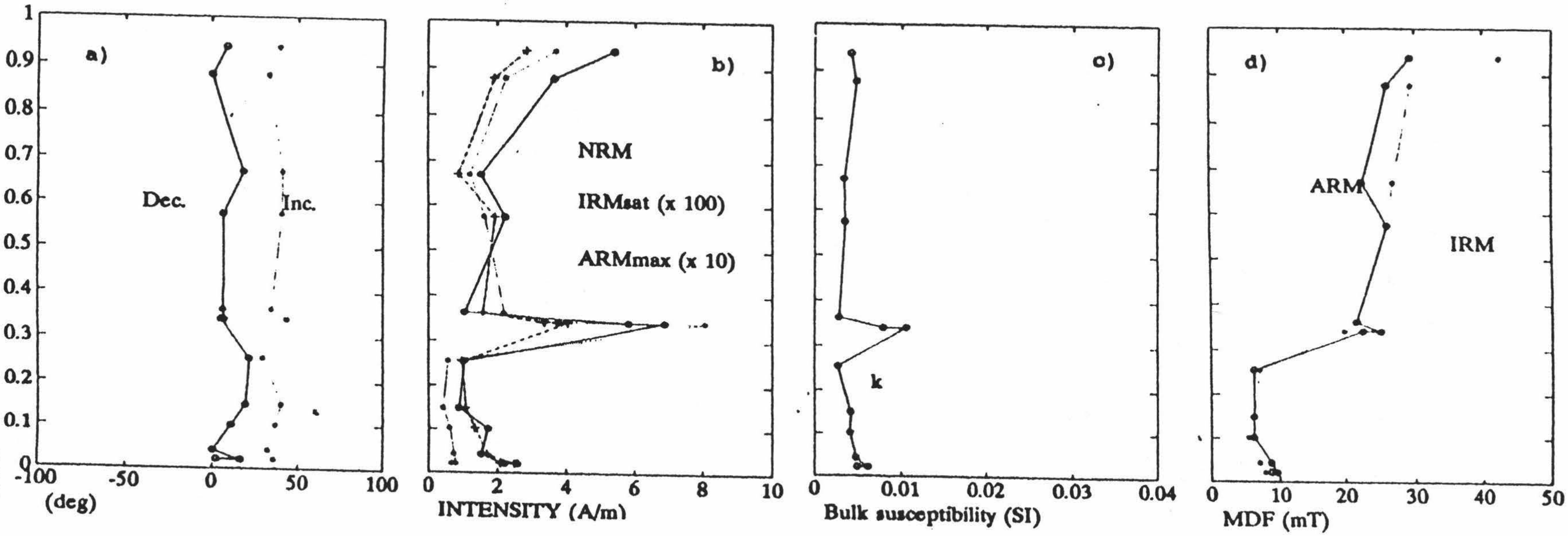


Fig. 6.2. Variation of magnetic properties within the first flow unit (profile 9) sampled in this study. a) Declination and Inclination; b) Intensity of NRM, ARM and IRMsat; c) Bulk susceptibility; d) MDF of ARM and IRMsat;

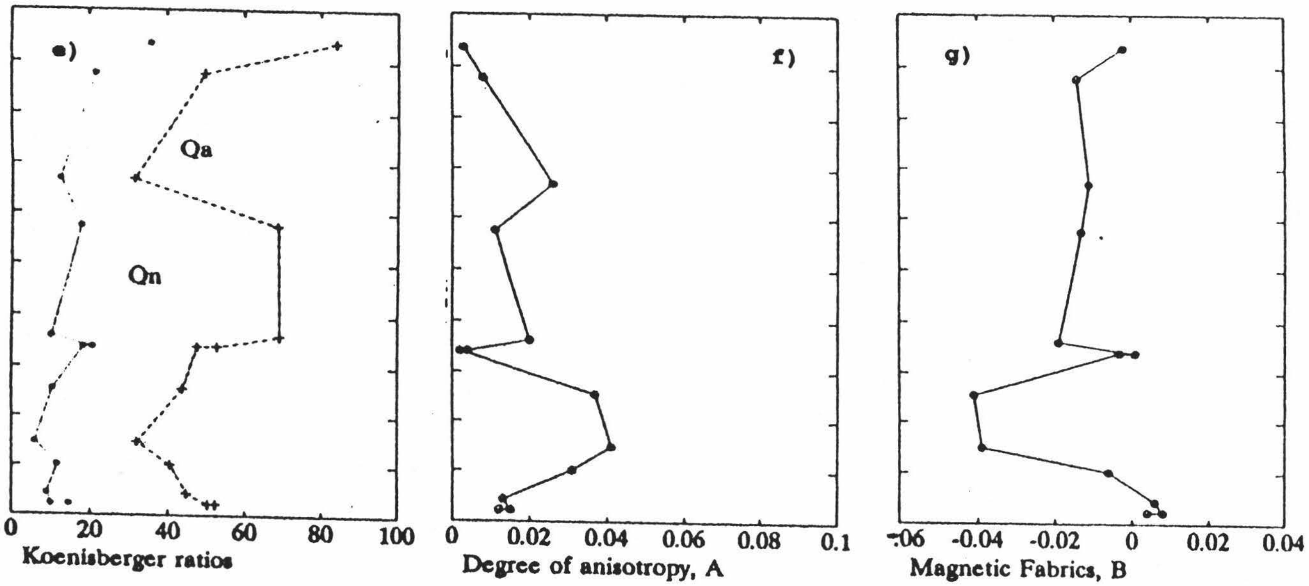


Fig. 6.2 (cont.) e) Koenigsberger ratios using NRM (Qn) and ARM (Qa); f) Degree of anisotropy: A-parameter; g) Magnetic fabrics: B- parameter.

in two parts with distinctive characteristics is clearly defined. The upper part, with rather high coercivities and a mixture of multidomain (MD) and single domain (SD) particles is dominated by the SD fraction (whose relative importance decreases with depth). The lower part, characterized by particles with low coercivity and a predominance of the MD fraction that becomes more clear close to the base of the flow.

Variations on the bulk susceptibility

As shown in Fig. 6.2c, variations of the magnetic susceptibility are parallel to those described of the remanences on the lower half of the flow. In the upper part there is no increment on the values of susceptibility, but rather, a slight decrease is observed. This result, together with the variation of the coercivities, predicts the observation of larger amounts of exsolution, probably of hematite lamellae, produced by oxidation of the original magnetic minerals on the upper part of the flow. Nevertheless, the mineral fraction is expected to be dominated by some member of the titanomagnetite series (see discussion below).

Stability to demagnetization

By comparing the median destructive field, MDF (the field necessary to reduce the remanence to half its initial

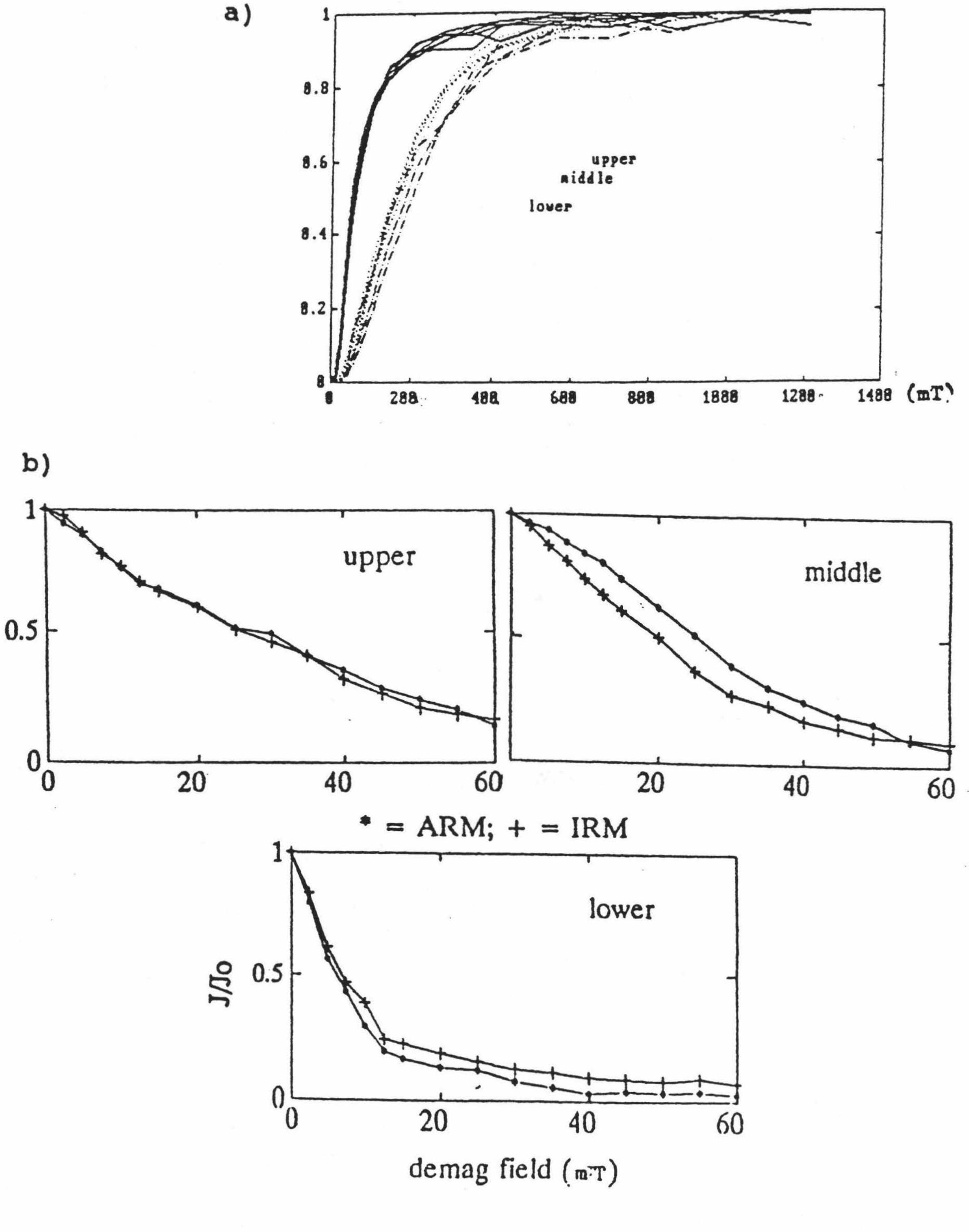
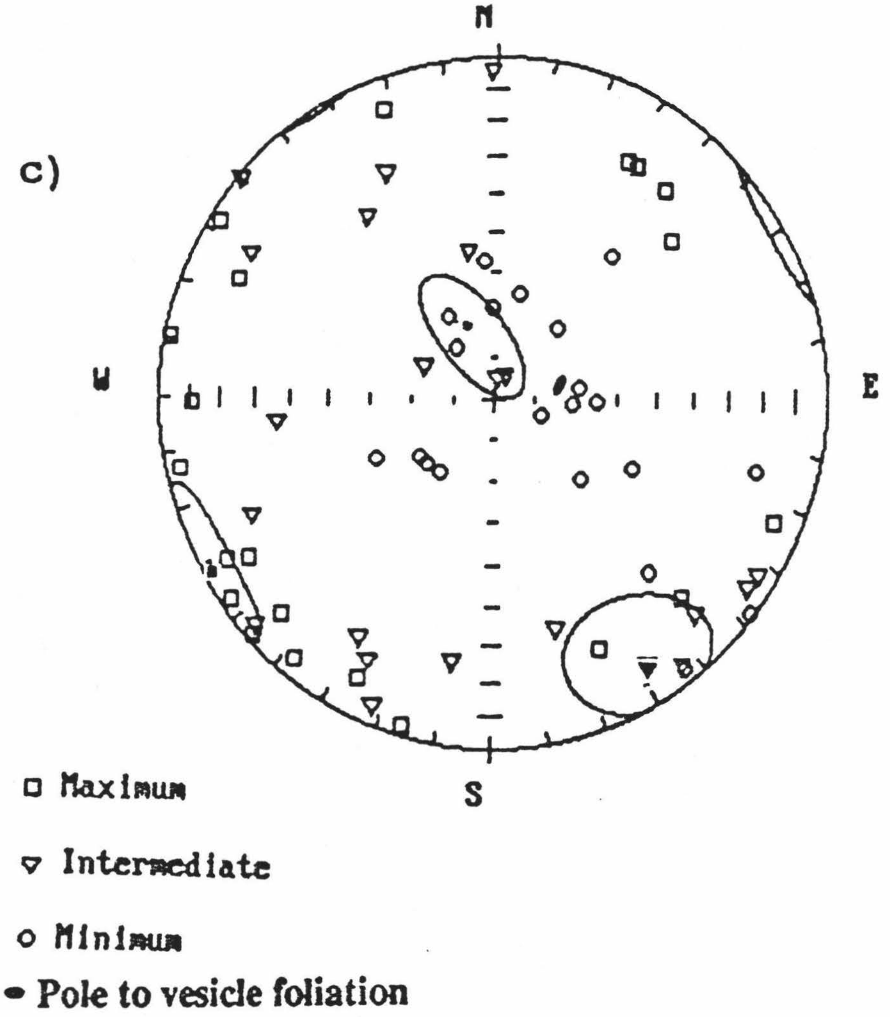


Fig. 6.3. a) Curves of acquisition of IRM. b) Selected demagnetization curves from the top, middle and lower parts of the flow.



Dmax = 239.8 Imax = 2.7 ± 15: 8

Dint = 329.1 Iint = -15.6 ± 18:14

Dmin = 339.4 Imin = 74.2 ± 18: 8

Fig. 6.3 (cont.) c) Stereographic projection (lower hemisphere) of the directions of the principal susceptibilities measured on the profile 9.

value), of ARM and IRM (Fig. 6.2d), the two zones of high (upper half) and low (lower half) coercitivities are clearly observable. The relative position of both curves also reflects the mentioned distribution of the domain state of the magnetic grains.

Koenigsberger ratio (Koenigsberger, 1938)

Two ratios were calculated: one, Qn, using the values of the NRM and an estimated value of the intensity of the magnetic field on the location at the time of formation of the rock (35 A/m), and the other, Qa, using the values of ARM and the known value of the direct field. Qn and Qa should differ only by a constant factor due to the difference on the intensity of the inducing field used in each case. In Figure 6.2e it is clear that this is true except on the central part of the flow. Thus, it seems that the original remanence of this part of the flow has been more altered with time (e.g. decay of the original remanence), which is contrary of what is usually expected.

Anisotropy of magnetic susceptibility

Results of these measurements are expressed in the form of the variation of the parameters A and B (chapter 4) with position on the flow. The parameter A (Fig. 6.2f) is a measure of the degree of anisotropy, and B (Fig. 6.2g) is an indicator of the magnetic fabric. The degree of anisotropy is very low along the profile, with a zone of somewhat higher values around one quarter of the total height, and the lowest values occur near the borders and on those samples with high intensity of remanence. The magnetic fabric corresponds to a mixed foliation-lineation structure, with a development of a magnetic foliation coinciding with the places of higher anisotropy.

The mean direction of the minimum susceptibility is normal to the plane defined by the other two principal susceptibilities (Fig 6.3c). This plane coincides with the plane of emplacement of the flow. The confidence region of the average direction of maximum susceptibility belongs to the category of very good grouping as proposed in the chapter 5, and therefore, the flow direction is assumed to be indicated by the average direction of maximum susceptibilities. Moreover, field evidence supports the conclusion that the flow direction coincides with the NE-SW trend defined by the mean direction of the maximum susceptibilities.

RESULTS, FLOW-UNIT 22

The results obtained from the second profile (Figs. 6.4 and 6.5), offer the opportunity to observe in more detail the variations on the basal parts of the flow. There is an overall agreement with the general patterns observed in the lower parts of the first flow, and therefore no detailed

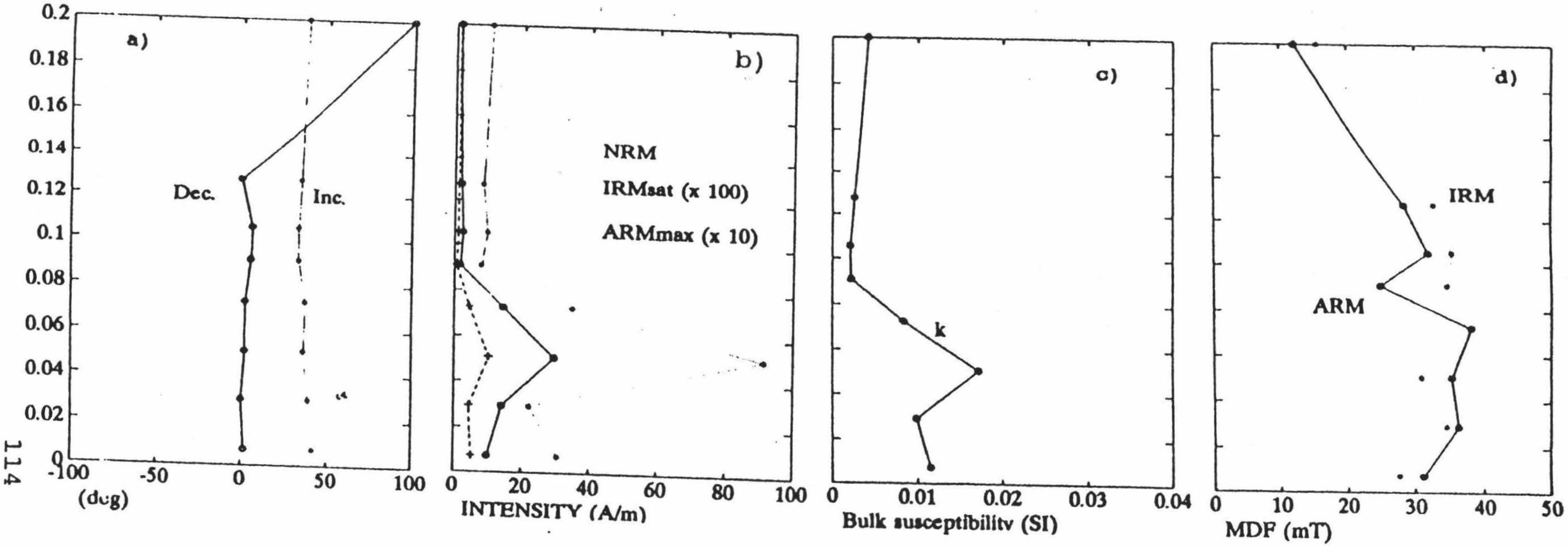


Fig. 6.4. Variation of magnetic properties within the second flow unit (profile 22) sampled in this study. a) Declination and Inclination; b) Intensity of NRM, ARM and IRMsat; c) Bulk susceptibility; d) MDF of ARM and IRMsat;

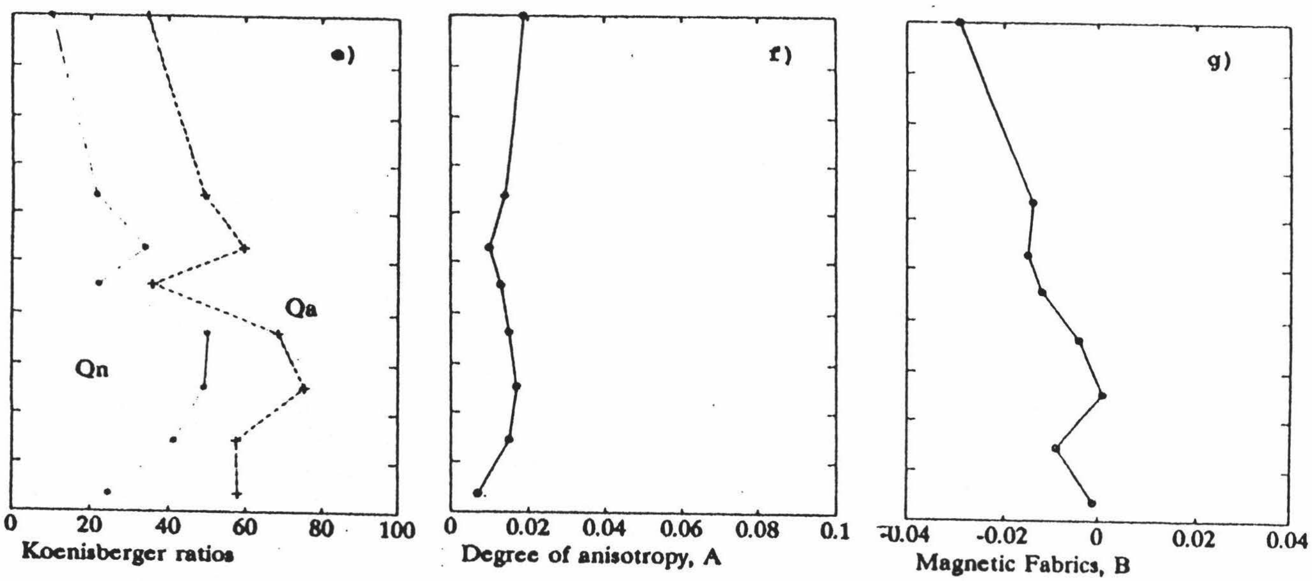


Fig. 6.4 (cont.) e) Koenigsberger ratios using NRM (Qn) and ARM (Qa); f) Degree of anisotropy: A-parameter; g) Magnetic fabrics: B- parameter.

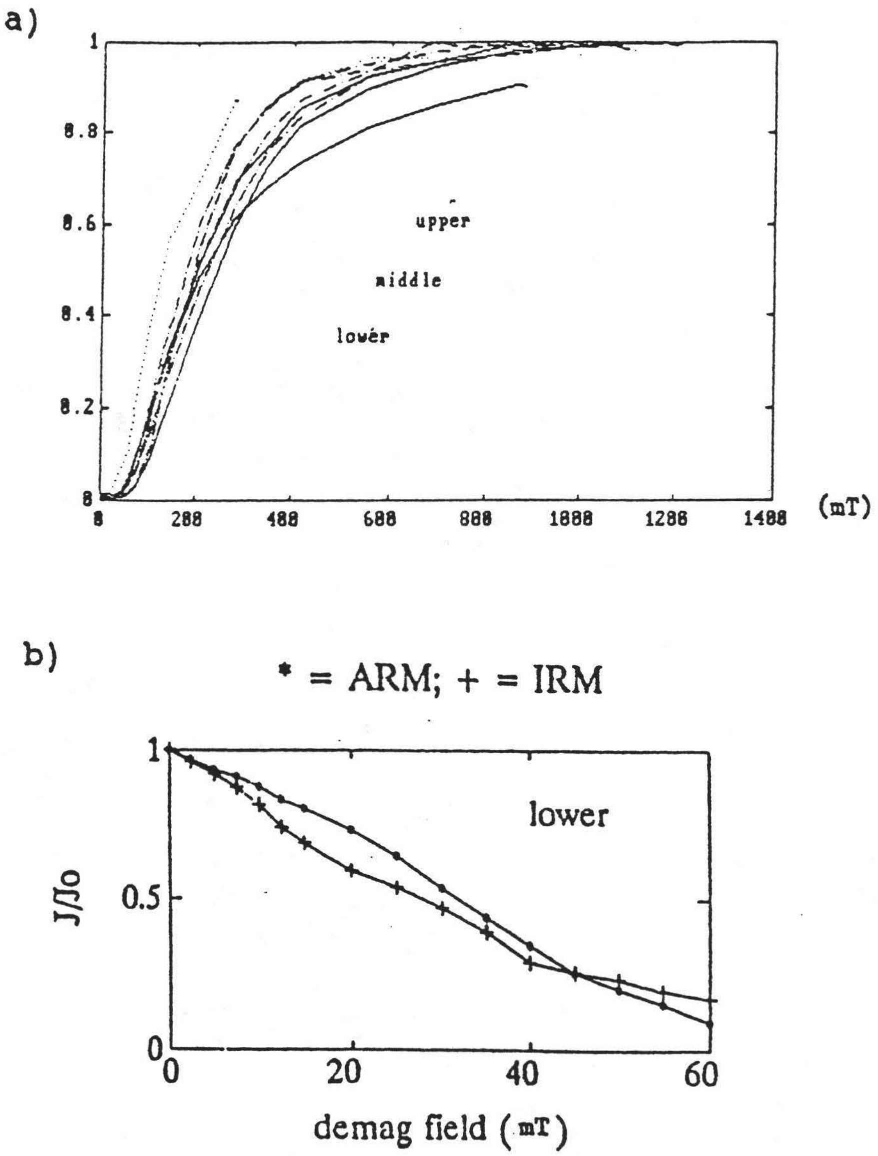
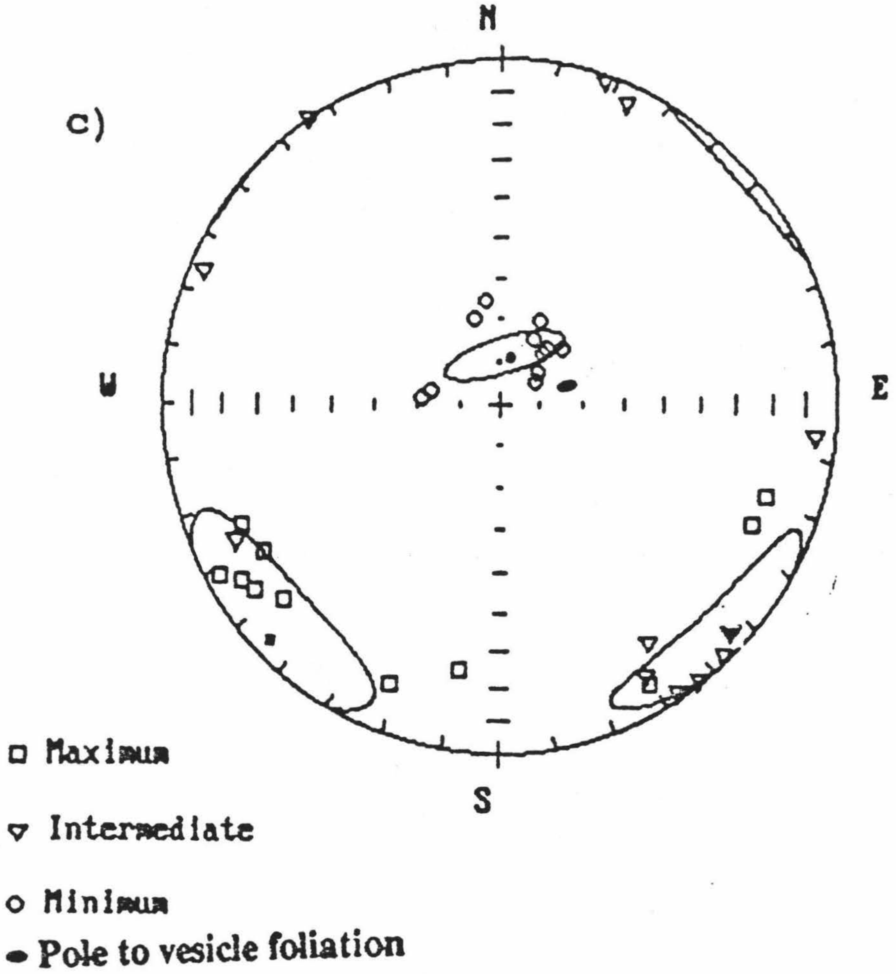


Fig. 6.5. a) Curves of acquisition of IRM. b) Example of a demagnetization curve.



Dmax = 46.7 Imax = -8.6 ± 23:13

Dint = 315.6 Iint = -7.5 ± 23: 8

Dmin = 5.1 Imin = 78.5 ± 15: 4

Fig. 6.5 (cont.) c) Stereographic projection (lower hemisphere) of the directions of the principal susceptibilities measured on the profile 22.

description of the profiles is made. Some important differences are discussed instead. The curves of acquisition of ARM and IRM reflect the effect of some mineral of very large coercivity (e.g., hematite) because saturation is not very clearly attained in most of the samples (Fig. 6.5a). Also the form of the demagnetization curves (Fig. 6.5b) is analogous to that found in the upper part of the first flow, and not to the general form of its lower part. Thus, we interpret this result as indicating that in the second flow the oxidation of the lower levels was higher than on the first flow.

The directions of the principal susceptibilities are also well grouped (the area of the 95 % ellipse of confidence is < .12 in this case) with the maximum anisotropy pointing in the direction of the flow direction inferred from other sructures. The minimum susceptibility is again normal to the plane of emplacement (Fig. 6.5c).

DISCUSSION

Differences in the cooling rate and oxygen fugacity are among the most important factors that induce slight variations in the chemistry and mineralogy of a single lava flow which otherwise would remain homogeneous within its cooling surfaces. Several studies (e.g. Watkins and Haggerty, 1965; Ade-Hall et al., 1968; Wilson et al., 1968; Hargraves and Petersen, 1971; Lawley and Ade-Hall, 1971;

Parry, 1974; Petersen, 1976; Smith and Prévot, 1977; Herzog et al., 1988, Audunsson et al., 1992) have documented the variations in magnetic parameters such as intensity of magnetization, magnetic susceptibility, Curie temperature, coercive force and anisotropy of magnetic susceptibility within the boundaries of basaltic lava flows and dikes. In general, an increase of the intensity of magnetization and Curie temperature is observed toward the upper parts of flows and the margins of dikes, corresponding with the areas of most rapid cooling and finer grain size. Most of these works also find a correlation with the degree of exsolution produced by high temperature oxidation and intensity of magnetization. The larger the amounts of exsolved ilmenite lamellae, the closer the host-mineral composition to pure magnetite and therefore, the stronger the remanence. The occurrence of zones of high degree of oxidation in the central parts of thick lava flows, presumably due to the differential escape of hydrogen (Petersen, 1976), however, produce departures from this basic pattern. In the present case, the intensity of magnetization does indeed increase near the borders of the flow, specially in the upper part of the flow.

The narrow section with large values of remanence and susceptibility that was described in the profile 9 correlates with a segregation vein within the flow. We infer that at this level on the flow there is a larger concentration of magnetic minerals, rather than a distinctive mineralogy independent of the observed trend in the rest of the flow. A similar narrow zone occur in the second profile, although there was no obvious field feature that could be associated with the observed magnetic signature.

It is interesting to note that it is possible to divide the flow in two zones with marked differences, and that the division seems to be sharp rather than gradational. The distribution of vesicles of the studied lavas has also different characteristics along the width of the flow: the upper part has larger vesicles, while those in the lower sections are smaller and less abundant. The observed change in the coercivities of the samples can be correlated with the change in the vesicularity. Therefore, we infer that the conditions that favored the formation of the vesicle distribution also influenced the distribution of the magnetic minerals. For example, the presence of larger vesicles may favour the oxidation of the magnetic phases more than the presence of numerous little vesicles.

One of the main reasons for making this study was to investigate the application of the AMS technique to determine flow direction of lava. Previous work by Khan (1962) showed that the scatter of the three main susceptibilities measured on several specimens from the same unit was very large, although the mean minimum susceptibility was normal, and the mean intermediate susceptibility was parallel to the flow direction. Symons (1975) also found a large scatter on the AMS directions of samples drilled from the surface of the Aiyansh flow. Furthermore, he could not find any significant relationship between the geologically inferred flow direction and the mean direction of the principal susceptibilities. The discrepancy of these results was attributable to the effects that disturb the surface of flows during cooling. The large dispersion on the directions of the principal susceptibilities seems to be a common feature, and lead to Ellwood (1978) to suggest that only those principal susceptibilities whose directions lie within an area of statistical significance should be used in the determination of their mean direction. Unfortunately, the statistical method that he used was applied to each principal susceptibility grouping independently from each other, which could lead to the elimination of a different number of axis in each grouping or other similar problems. An alternative statistical method is the multivariate analysis technique developed by Jelinek (1978). In this method, the effects of the "shape" of the individual tensors are included, and the three mean directions are calculated in an integrated manner. The results of this method yield the sizes and directions of the three principal susceptibilities together with the sizes and orientations of three ellipses of confidence. Lienert (1991) proved the utility of this technique to calculate the mean directions of susceptibility. We used in this study the multivariate analysis technique as suggested by Lienert (1991).

The confidence ellipses of the three principal susceptibilities in the two profiles suggest a good degree of clustering in every case, despite the apparent large dispersion of the data found in the profile 9 (Fig. 6.3c). Approximately half of the samples of each profile have the direction of their maximum susceptibility axis within 15 to 25 degrees of, and therefore regarded as consistent with, the geologically inferred flow direction of about 70°. Thus, the mean maximum susceptibility direction is accepted as the true flow direction on each profile.

The sense of motion (the absolute flow direction) is towards the northeast or east for both profiles, based on the imbricate magnetic fabric, and this agrees with the geologically inferred direction, being the downslope direction.

A macroscopic vesicle foliation, defined by the parallelism of the plane of flattening of vesicles, pervades the lower roughly 0.5 to 1.0 m of Xitle flow units. This foliation dips in a general upflow direction at an angle of up to 20 degrees and appears to asymptote against the base. A lineation defined by the direction of maximum elongation of these vesicles occurs in the foliation plane and plunges in the dip direction. In many flow units a similar vesicle foliation and lineation occurs at the top of a flow unit and plunges in the opposite direction as at the base (the attitude of the foliation and lineation at the top is a mirror image of that at the base relative to a horizontal mirror in the median plane of the lava). The foliation defines an imbrication against basal and top margins of the lava.

The vesicle foliation at the flow base was ascribed (Walker, 1992) to drag against the underlying surface, and at the top to drag against the roof at the point where lava emerged though an orifice. Pipe vesicles also occur in the basal part of each flow unit but plunge more steeply than the vesicle foliation. Their attitude was attributed to drag superimposed on a component of buoyant ascent (Walker, 1992).

The magnetic fabric correlates closely with the macroscopic foliation and lineation (Fig. 6.6). The plane containing the maximum and intermediate susceptibility axes coincides approximately with the vesicle-foliation plane, shown by the clustering of minimum susceptibility axis near the pole to

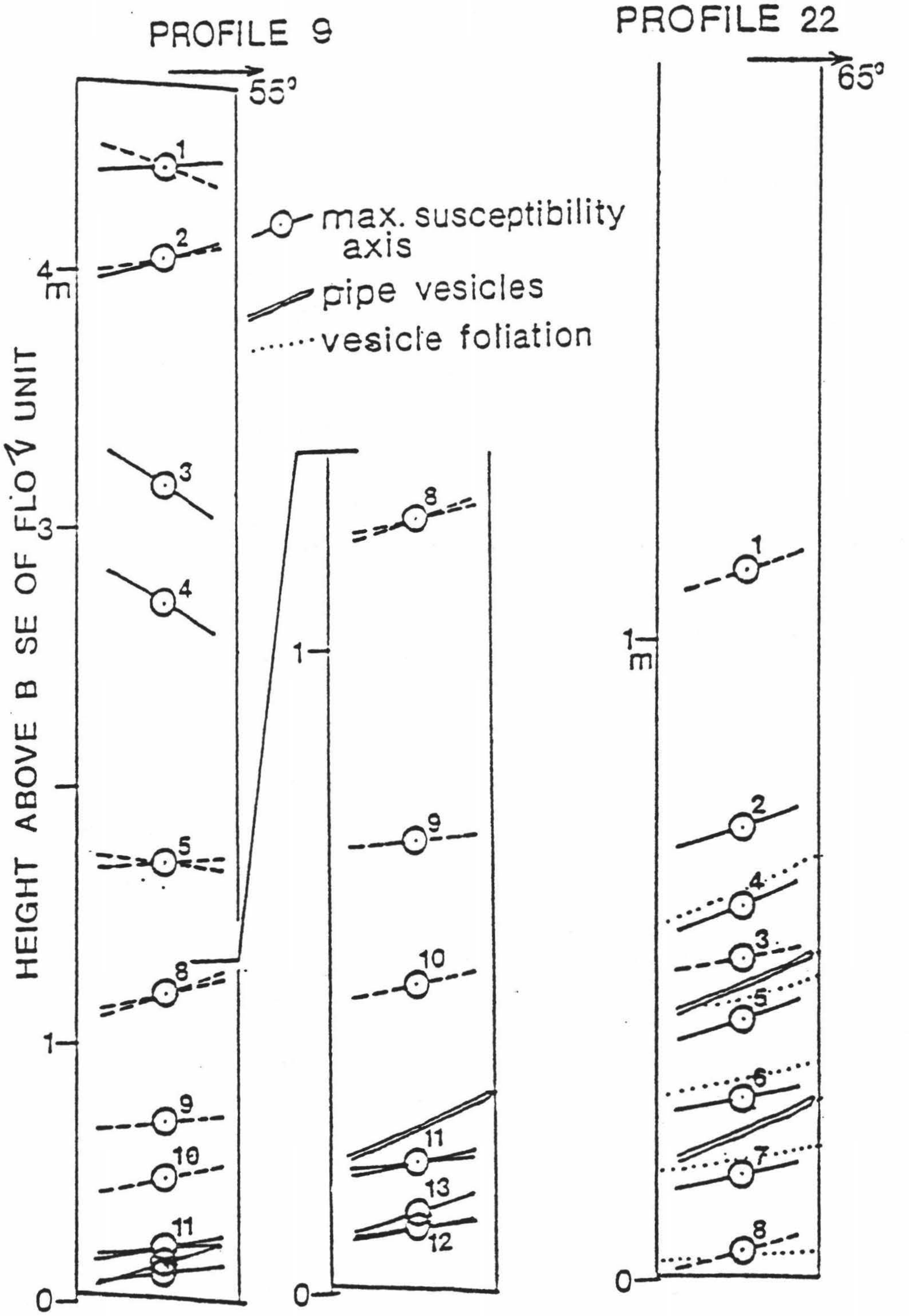


Fig. 6.6. The two profiles showing plunge of the maximum susceptibility axes. Solid lines are the samples for which the axis plunges in a direction within 15° of 55° (profile 9) or 65° (profile 22). Note the parallelism of axis and vesicle foliation; the steeper plunge of pipe vesicles is attributed to their ascending through the lava as the lava flowed laterally.

the foliation (Figs. 6.3c and 6.5c). The maximum susceptibility axis also coincides approximately with the macroscopic vesicle-lineation.

SUMMARY AND CONCLUSIONS

In summary, the study of the variations of the magnetic properties of lava flows, may yield important information about the processes that took place during their emplacement and cooling, and has great potential as a geological tool. In particular, the two Xitle lava flow units studied by us have a magnetic fabric from which the direction of flow can be inferred without ambiguity. In this instance we have independent geological evidence for the direction of flow, but the method clearly might be applied to lavas for which the flow direction is not known.

CHAPTER 7. CONCLUSIONS

Several techniques (paleomagnetic techniques) have been developed with the purpose of studing the magnetic field of the Earth in geological times as recorded in rocks. The need to evaluate the accuracy of that record produced theories that explain its causes and principles that govern it. This, in turn, led to the development of new techniques (rock magnetic techniques) conceived to yield experimental support to these theories. Meanwhile, igneous rocks provided the raw material used in many of these paleomagnetic and rock magnetic studies but were not regarded as the subject of study. This was clearly expressed by A. Cox when he stated that "for paleomagnetists, volcanoes are giant recorders of the Earth's magnetic field" (Cox, 1973).

At present, the accumulated knowledge about the mean aspects of the geomagnetic field and about the phenomena of magnetization and acquisition of a remanence by igneous rocks, allow us to study the giant recorder itself. It enable us, for example, to constrain the conditions of crystallization of igneous rocks, the types and degrees of post-emplacement alteration they may have suffered, their cooling history, their age and the rate and volume of their extrusion. Certainly, the uses of paleomagnetic and rock magnetic techniques in volcanology require the close colaboration of workers having different backgrounds and, although the potential number and variety of applications is very large, the information obtained with these techniques should be always interpreted in combination with the geological evidence to obtain the most insight into the knowledge of the volcanic phenomena.

Besides the relevance of the magnetic techniques in mapping volcanic terranes, an important aspect in the study of the evolution of magmatic systems, there are three areas that, in my opinion, offer the most clear opportunities for the fruitful employment of magnetic techniques: the reconstruction of the thermal histories of igneous rocks, especially if thermodynamical models are used in combination, the reconstruction of the fluid behaviour of magmas and, finally, the determination of the original characteristics of these magmas. All of these areas of application were reviewed in chapters two and three of this work. In chapters four to six, the emphasis was put in the applications of anisotropy of magnetic susceptibility measurements in the study of volcanic rocks. This particular technique may help us to better understand the fluid behaviour of magmas, although much additional work has still to be made to explore this field. Some other aspects of the uses of magnetic techniques (magnetic correlation of units, correlation of magnetic properties with structural features of lava flows) were also exemplified in chapters five and six, and finally, the information obtained about the magnetic properties of the rocks studied in these chapters constitute the basis of a study that may be relevant to the determination of the original characteristics of magmas. In this sense, it is considered that the main purpose of this work, i.e., to serve as a point of reference for further research in the area of magnetic volcanology has been fully acomplished.

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