VERTICAL DETAILED VARIATION OF PETROMAGNETIC PROPERTIES IN BASALT FLOW PROFILES, XITLE VOLCANO, MEXICO: A REVIEW

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Resumen
Se presenta una revisión de estudios de propiedades magnéticas de rocas, microscopía de opacos, AMS y paleointensidades (PIs) usando distintas técnicas, y se discute la confiabilidad de los resultados de PI para flujos de lava del volcán Xitle junto resultados paleomagnéticos de dos nuevos perfiles verticales estudiados en detalle y su comparación con otros más viejos. Nombres y número de núcleos de los perfiles colectados son: RM-46, PC-24 y CU-39. Las propiedades magnéticas son consistentes pero las propiedades paleomagnéticas son más dispares. Se observaron considerables diferencias dentro- y entre-flujos en direcciones características y PIs tanto en nuevos perfiles como en sitios previamente estudiados distribuidos en todo el campo volcánico. Esas variaciones no correlacionan con ninguna de las propiedades físicas o magnéticas medidas de los flujos. La dirección media no esta definida en ningún sitio y solo cuando se consideran colectivamente se reconocen las inconsistencias. Las variaciones dentro- y entre-flujos es grande. Así, es difícil reconocer la mejor estimación basándose en criterios de magnetismo de rocas. Nuestros resultados inducen preguntas sobre la confiabilidad de lavas como registradores paleomagnéticos y enfatizan la importancia de la estrategia de muestreo para obtener parámetros representativos promedio de los flujos.

Abstract
A review of the rock magnetic properties, opaque microscopy, AMS and paleointensity (PI) determinations using different techniques and discussing the reliability of the PI results for lava flows of Xitle volcano are presented, with two new detailed paleomagnetic results of full sampled vertical single lava flows and its comparison with older ones. Profile name and sampled core number is RM-46, PC-24 and CU-39. Rock magnetic properties are quite consistent but paleomagnetic properties are much more uneven. Considerable intra- and inter-flow differences in both the characteristic directions and PIs are observed both in the new profiles and previous studies of sites distributed across the lava field. These variations do not correlate with any of the measured physical or magnetic properties of the flows. At any one site the mean directions are well defined and it is only when considered collectively that the inconsistencies are recognized. Intra-flow and inter-site PI variations are large. So, it is difficult to recognize a best estimate on the basis of rock magnetic criteria. These results raise questions about the reliability of lavas as paleomagnetic recorders and highlight the importance of sampling strategy in obtaining representative flow-mean parameters.

Introduction
Lavas have long been an attractive source of paleomagnetic data, in the main due to their usually strong magnetization and an apparently simple and reliable mode of remanence acquisition. This is generally assumed to involve the acquisition of a thermoremanent magnetization (TRM) as they cool below the Curie temperatures of the resident magnetic minerals. Lavas were employed in the early 1960's to test the accuracy of the paleomagnetic method (Doell & Cox, 1963). Over the next few decades many studies were concentrated on defining the internal variations of magnetic properties within individual lava flows (Watkins & Haggerty, 1965; Ade-Hall *et al.*, 1968; Wilson, et al., 1968; Grommé et al., 1969; Lawley & Ade-Hall, 1971; Petersen, 1976; Herzog *et al.*, 1988; Audunsson, Levi & Hodges, 1992) in order to better know the magnetic evolution of the flows. More recently, attention has returned to the internal variations in the paleomagnetic signal (Castro & Brown, 1987; Tanguy, 1990; Urrutia-Fucugauchi, 1996; Böhnel *et al.*, 1997, Rolph, 1997; Biggin et al., 2003; Alva-

Valdivia, 2005, Morales et al., 2006) and how this affects the precision and reliability of the recorded results. Nevertheless, many attempts to find the possible correlation between these variations and some physical/magnetic parameters have been disappointing. Up to now, any possible explanations are mainly based on distinct oxidation states of opaque minerals throughout the profile or with the thermo-chemical alteration of the sample during the heating.

The importance of the paleointensity (PI) studies for the better knowledge of the Earth's magnetic field is summarized is in the next paragraphs.

The geomagnetic field is generated by convection in the electrically conducting liquid outer core. At the Earth's surface it can be estimated by a time varying dipole field and small non-dipole components. The virtual axial dipole moment (VADM) of present field is $7.9 \times 10^{22} Am^2$ but it is not very well known at distinct geological timescales. Detailed records of the early geomagnetic field are necessary to provide information about the fundamental processes in the Earth's core, and to help understand the historically observed decay in dipole moment of ~10% over the last 170 years. They are also necessary to make better spherical harmonic models of the geomagnetic field and to decipher long standing concerns in paleomagnetism such as the Pacific-non-dipole low and heterogeneous models of palaeosecular variation (PSV). They are necessary to gain new insights into the recently debated topic regarding possible connections between changes in the geomagnetic field intensity and climate variability.

The absolute PI is the most difficult of the geomagnetic parameters to determine. Materials used in PI studies must satisfy rigorous criteria with respect to the nature of the magnetisation and how it was acquired, the magnetic mineralogy and its grain size, and magnetic interactions within the sample.

The most basic requirements that underlie any absolute PI study are:

(1) The material must have retained a primary magnetization of thermo-remanent origin.

(2) Alteration of the magnetic carriers in nature and during the laboratory experiments must be avoided or corrected for.

The absolute PI is studied on rocks (e.g. diabases, gabbros, pyroclastics, and lava flows) because these materials keep a thermo-remanent magnetisation (TRM) from when they were extruded and then cooled down through their blocking temperature (TB) spectrum.

Lava flows give instantaneous spot readings of the geomagnetic field, they can supply semi-continuous records of the geomagnetic field behaviour if they are sampled in sufficient detail through time and if their ages are well constrained. In addition, absolute PI data from lava flows may be used for calibrating relative PI records from sediment cores to absolute value.

The Thellier method and its modifications in combination with additional reliability checks for alteration and multidomain (MD) remanence are regarded by many paleomagnetists as the most reliable absolute PI method. In a Thellier-type experiment, the natural remanent magnetization (NRM) of a rock is gradually replaced by a set of laboratory partial TRM (pTRMs) acquired over successively increased temperatures in a laboratory field of known strength. This carries the assumption that each pTRM segment is independent from the other, which is only valid for grains of single domain (SD) magnetic structure. However, suitable PI recorders are rare in nature, because MD grains and alteration of magnetic minerals in situ or during the laboratory experiment are common in rocks. Thus, failure rates in Thellier-type studies are large, sometimes 80% or higher.

The Thellier method has been tested extensively over the past years on historical lava flows, for which the actual intensity is known from contemporary magnetic observatory data. While these tests yielded the expected intensity in some cases, other studies have revealed more controversial results, indicating significant overestimates of the intensity or large within-flow inconsistencies (this work). So uncertainty has grown regarding the Thellier method, and variants and alternatives have been necessary. Dekkers and Böhnel (2006) used their multispecimen parallel differential pTRM method (MS) to obtain correct paleointensities on the 1945 Paricutin lava flow from Mexico, and in three simulated experiments. This MS method appears to be a feasible alternative for future PI studies.

The Xite volcano is in the Trans-Mexican Volcanic Belt (TMVB), which comprises roughly 8000 volcanic structures, of which several hundred are younger than 2 million years (e.g. Demant, 1978; Gómez-Tuena et al., 2007) and some are like this historical volcanoes, thus offering a superb archive for studying the evolution of the geomagnetic field. The campus of the National University of Mexico is built over ~2000 year-old basaltic lava flows of the Xitle volcano, southern Mexico City. Campus development, along with continuing urban growth, means that the flows are fresh and comprehensively exposed (Fig. 1). A study of the natural remanence directions recorded by the lava field (Urrutia-Fucugauchi, 1996) revealed statistically significant inter-site directional variations. Böhnel *et al*. (1997) sampled a vertical profile (CU) through a single flow-unit, identifying large and reproducible variations in PI and, to a lesser extent, remanence directions, neither of which could be correlated with the physical or magnetic properties of the flow. To see if this variation is typical for the Xitle lavas, one new profile has been sampled (RM). Similar set of experiments has been carried out as for the original profile, along with additional measurements of the anisotropy of magnetic susceptibility (Caballero-Miranda, pers. comm.). The aim of this study was to review and obtain rock magnetic results and microscopic observations of the new profiles and make a discussion with respect to the internal structure of the Xitle lava flows. Finally these results are compared with those previously obtained of the lava field in general.

Sampling and laboratory procedures

We used were the standard instruments in the Mexican and English labs to measure almost all the rock magnetic and PI techniques available all around.

The analyses of results still is in progress for the PC and RM profiles together with opaque mineral identification, but with the available ones we can see that the very old observations of PI inhomogeneity through a profile of a single lava flow remains (Fig. 2, shows results for the RM profile). So, we will try to find the explanation for this and to propose the better part of the flow to get the most reliable (and the best PI technique) PI determinations, and how this can be assessed by the previous rock magnetic and microscopy studies. We are sure that for the meeting time will be ready to discuss the final analyses.

Discussion

In order to get our purposes will make a comparison between the two new profiles studied (RM and PC) with the already published results of CU profile (Böhnel *et al.*, 1997) using all the properties analyzed, including the AMS study.

In a very general way, the three profiles describe large intra-flow variations in PI, which show no correlation with any of the magnetic properties of the flow. Other data are available from 6 sites. Many samples describe a broad range of PI values with a particular distribution. The source(s) of this variation are not clear. The flow morphology is such that there is no evidence for a prolonged period of emplacement. There are no soils or weathered horizons between the various flow units and the composition (both chemical and magnetic) remains uniform across the whole flow field.

For this reason attention is concentrated on the experimental method. PI experiments only work if (a), there has been no significant alteration of the remanence-bearing minerals prior to or during the experiments and (b), if the remanence is a pure TRM. Post-magnetization alteration such as low-temperature oxidation may give rise to a composite NRM, and if the unblocking temperatures of the primary and secondary components overlap this may influence the PI determinations. If the secondary components were acquired in a different magnetic field to the primary, one might expect some curvature in the NRM demagnetization vector. No such curvature is evidenced in the demagnetization plots.

Conclusions

On first appearances, we state that the flows of the Xitle-El Pedregal lava field seem ideal for paleomagnetic purposes; they are reasonably well-dated, freshly and extensively exposed, in the main overly weakly magnetic sediments and sites can be selected where individual flow-units haven't been reheated by successive flows. The rock magnetic properties of profiles through individual flows are uniform and indicate a high degree of homogeneity across the flow field. The paleomagnetic properties, however, appear much more variable.

Each of the site-mean ChRM directions are well-defined, yet are often significantly different. A likely explanation for this is that the variation in direction within individual flow units is such that true flow-mean values have not been recovered at most of the sites. This has implications for paleomagnetic studies of lavas that are less well exposed or sampled. It stresses the need for as spatially distributed a sample set as possible, laterally and vertically, and the need to critically assess the extent to which the degree of outcrop can limit the reliability of the ensuing data set.

Site-mean PI determinations show large standard deviations, whilst the quality of the data (as defined by alteration tests and statistical parameters) is reasonable. There is no clear relationship between the observed PI and any of the measured properties of the flow and it is difficult to recognize the true flow-mean value. A potential source of independent determinations lies in the burnt material immediately beneath the flows. Nagata *et al.* (1965) report PI data for 2 pottery shards found in the baked sediment that had apparently been reheated by the flow. They yielded PI's of 54.2 and 65.3 μT, which support the lower end of the PI range defined by studies of the lavas. There was some suggestion that an Etna lava displayed paleomagnetic properties influenced by TRM-CRM mixtures (Rolph, 1997). The Xitle flow does not show the same correspondence of paleomagnetic and rock magnetic properties and so such a relationship cannot be confirmed in a different lava flow. These results, though, do caution against too simplistic an interpretation of either the magnetization process in lavas or the paleomagnetic method used in their investigation.

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Figure 1

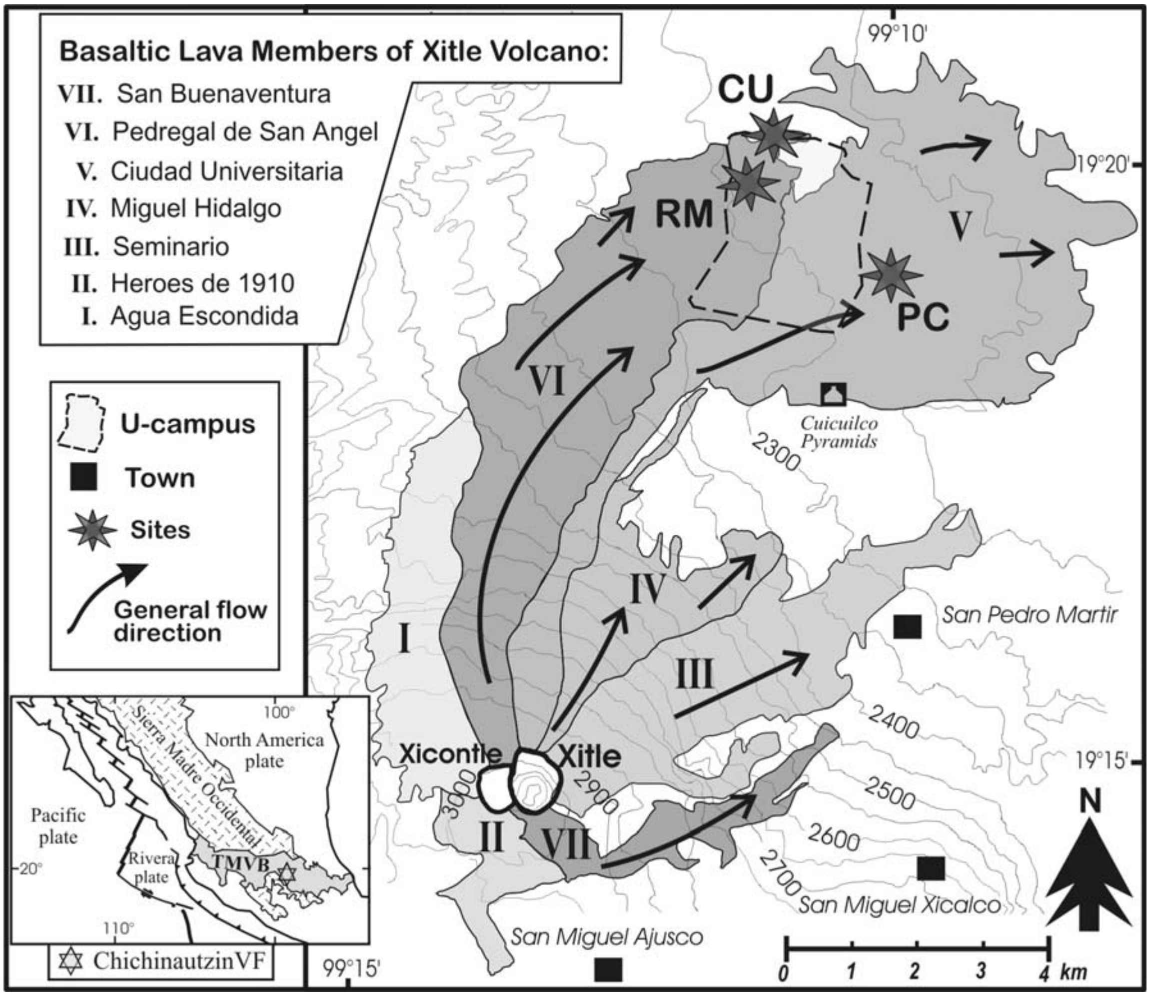
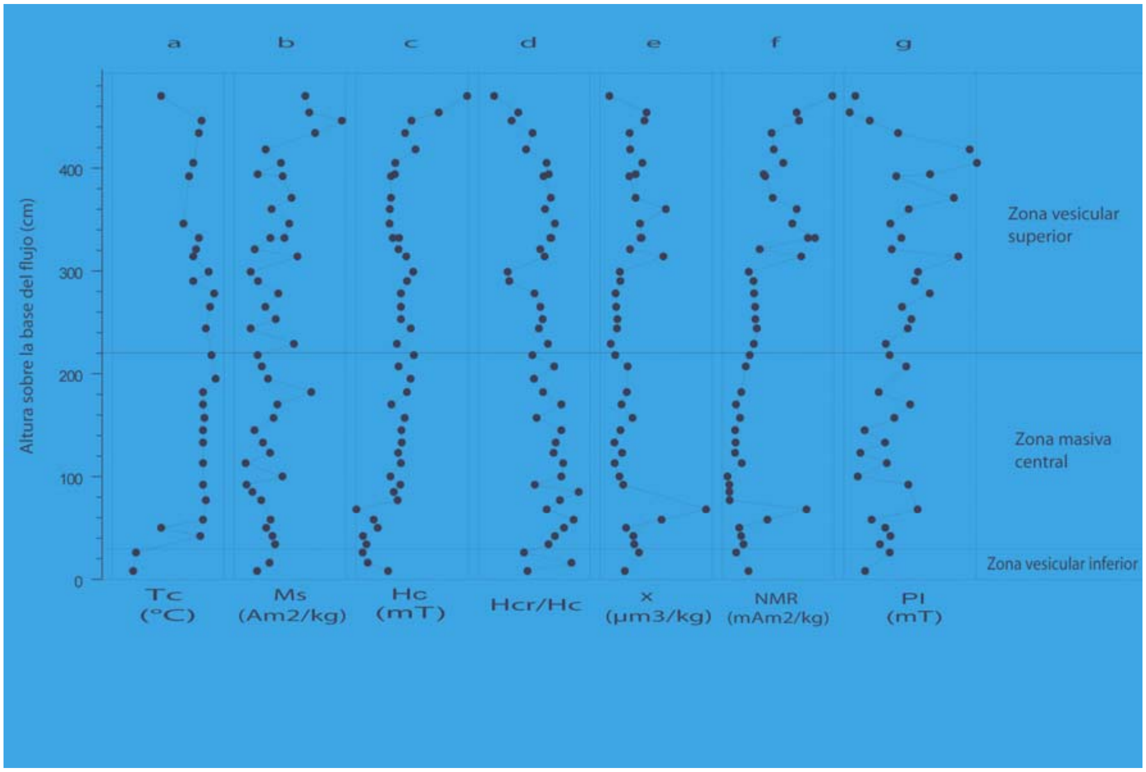

Basaltic Lava Members of Xitle Volcano:
VII. San Buenaventura
VI. Pedregal de San Angel
V. Ciudad Universitaria
IV. Miguel Hidalgo
III. Seminario
II. Heroes de 1910
I. Agua Escondida
U-campus
Town
Sites
General flow direction
99°10'
19°20'
19°15'
99°15'
CU
RM
PC
VI
V
IV
III
II
I
VII
Cuicuilco Pyramids
2300
2400
2500
2600
2700
2900
3000
Xicontle
Xitle
San Pedro Martir
San Miguel Xicalco
San Miguel Ajusco
N
0 1 2 3 4 km
North America plate
Pacific plate
Rivera plate
Sierra Madre Occidental
TMVB
100°
110°
20°
ChichinautzinVF

Figure 2.


a
b
c
d
e
f
g
Altura sobre la base del flujo (cm)
0
100
200
300
400
Zona vesicular superior
Zona masiva central
Zona vesicular inferior
Tc (°C)
Ms (Am2/kg)
Hc (mT)
Hcr/Hc
χ (µm3/kg)
NMR (mAm2/kg)
PI (mT)