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Anomalously shallow palaeomagnetic inclinations and the question of the age of the Canarian Archipelago

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SUMMARY

Extensive geological, geophysical and geochronological data available from the Canary Islands establish conclusively that formation of the oldest subaerial volcanic structure of the islands began during the Miocene. A mid-Cretaceous age for these volcanic formations has been postulated in previous works on the basis of palaeomagnetic determinations. The results obtained in the present palaeomagnetic study of Lanzarote include analysis of the record of variations of magnetic inclination in boreholes that penetrate the whole of the oldest volcanic series. They show that the excessive age previously assigned to these formations is due to the utilization of volcanic units with abnormally low (<15°) magnetic inclinations (LGIs). In Lanzarote, lavas exhibiting LGIs appear interbedded in a volcanic series that, overall, shows a typical Miocene inclination (~45°). The units stratigraphically beneath and above the LGI horizons give, in fact, directions consistent with the Middle–Upper Miocene field direction ($D = 359°$, $I = 45°$, with $k = 29$, $a_{95} = 6.7°$ and a palaeopole of 87°N, 178°E), thereby confirming the Miocene age of the oldest subaerial volcanics of Lanzarote. Short excursions of the geomagnetic field seem likely to be the explanation for these LGIs, since other factors such as tectonic tilting, post-eruptive modification of the primary remanence or errors in sample orientation can be disregarded.

The detection in the Canary Archipelago of volcanic units with abnormally low magnetic inclinations seems to be related to the relatively continuous record of the geomagnetic field in rapidly growing volcanic edifices, as seems to be indicated by the presence of a few (usually one or two) short polarity events in volcanic suites of several hundred metres thickness.

Key words: Canary Islands, geochronology, geomagnetic excursions, Lanzarote, palaeomagnetism.

INTRODUCTION

Palaeomagnetism is a method widely used for the dating of volcanic formations. Recent investigations have shown, however, that volcanic rocks can record anomalously the direction of the geomagnetic field, giving data that can bring about erroneous interpretations in the dating of the volcanic formations in which they are observed. For example, self-reversal phenomena have been observed in pyroclasts from the volcanic eruptions of Nevado del Ruiz in Colombia in 1985 (Carracedo *et al.* 1986; Heller, Carracedo & Soler 1986; Haag *et al.* 1990) and Mt Pinatubo in the Philippines in 1991 (Ozima *et al.* 1992).

Anomalous low magnetic inclinations have been reported in the Old Basaltic Series of the Canary Islands (Storetvedt 1980; Storetvedt *et al.* 1978, 1979; Felix 1989; Carracedo & Soler 1992). In the case of the Canary Archipelago, these anomalous inclinations give palaeopoles that correspond to ages that exceed by more than 40 Ma the ages currently accepted for these islands, based on other geological and geochronological data.

The issues of the age at which volcanism began in the Canary Islands and the time of the building of the first subaerial stages of the insular edifices were the subject of intense debate during the 1960s and '70s. Although some aspects of the chronology of the earliest magnetic history of the Canaries remain unclear, it is almost unanimously agreed that the subaerial construction of the insular edifices took place in the Miocene (approximately <15 Ma). These conclusions have been reached by means of published geochronological K–Ar data (Abdel-Monem, Watkins & Gast 1971, 1972; Ancochea *et al.* 1990; Cantagrel *et al.* 1984; Carracedo 1979; Feraud 1981; Feraud *et al.* 1981; Coello *et al.* 1992 and McDougall & Schmincke 1976) and palaeomagnetic data (Watkins 1973; Watkins, Richardson & Mason 1966).

Storetvedt (1980) and Storetvedt and co-workers (1978, 1979) published several reports concerning palaeomagnetic data gathered in different islands of the Canarian Archipelago. The analysis of these data prompted the aforementioned authors to question earlier geochronological works. The ages they gave in these reports for the Old Series (the original terms Old Series and Basaltic Series I were proposed by Fúster *et al.* (1968) to identify the oldest subaerial formations of the insular edifices) were Upper Cretaceous for Tenerife and Gran Canaria (Storetvedt *et al.* 1978), and the Cretaceous–Tertiary boundary (around 65 Ma) for the islands of Fuerteventura and Lanzarote (Storetvedt 1980; Storetvedt *et al.* 1979). These data strongly contradicted the generally accepted ages assigned to the islands (Table 1). This marked digression from the widely accepted model of the volcanic history of the Canarian Archipelago was contested by Schmincke (1979) on the basis of geological and geophysical data. He also proposed that these discrepant palaeomagnetic results be further investigated through additional palaeomagnetic studies. This work intends to present such a revision, as well as illustrating some important drawbacks of the applicability of the palaeomagnetic dating techniques to the Canarian scenario.

GEOLOGICAL SETTING AND SAMPLING

Two independent edifices (Fig. 1) constitute the first subaerial phase of construction of the island of Lanzarote: the old basaltic edifices of Los Ajaches, active from about 14.5 to 13.5 Ma, and Famara, active from about 10 to 3.8 Ma (Carracedo & Rodríguez Badiola 1991).

Three main volcano-stratigraphic units seem to form the Famara edifice, separated by discordances clearly marked in some outcrops by reddish baked palaeosols, locally called 'almagres'. The lowest unit is composed mainly of lava flows. The intermediate unit shows a greater presence of layers of pyroclasts and baked palaeosols intercalated between the lava flows. A few very thick lava flows form the upper unit. These three volcano-stratigraphic units correspond to the eruptive phases of 10.2–8.3, 6.7–5.3 and 3.9–3.8 Ma proposed by Coello *et al.* (1992) on the basis of K–Ar data. This is consistent with the finding of fossil eggs and bones of the Lower Eocene to Upper Pliocene Odontopterygiform group in a dune deposit intercalated in the lower unit (García-Talavera 1990).

The old Los Ajaches edifice (see Fig. 1) seems to have been built in a relatively short period, in a 'single' volcanic episode from about 14.5 to 13.5 Ma. The radiometric age evidence agrees with field observations, since no marked discordances or palaeosols are present in the 300 m exposed section of the Pico Redondo escarpment.

Volcanic activity resumed after a 2 Myr period of volcanic repose, continuing until historic times, with the last eruptive episode in 1824. During this recent eruptive phase, emission centres and lava fields were dispersed over the whole island, predominantly between the old edifices of Famara and Los Ajaches (Carracedo *et al.* 1992).

The palaeomagnetic determinations used in this work were carried out following standard procedures on 341 rock samples oriented with a sun compass from 57 sites (see Fig. 1). The availability of vertical boreholes with continuous core recovery drilled during the SPA-15 UNESCO Program has allowed the magnetic polarities to be determined flow by flow, by means of portable flux-gate magnetometers. Several

Table 1. Oldest published age determinations (in Ma) from the oldest subaerial stage of building of the different Canary Islands edifices.

ISLAND	*1*	*2*	*3*	*4*	*5*	*6*	*7*
HIERRO	3.0						
LA PALMA	1.5				1.3*		
TENERIFE	15.6	11.6		7.2	5.7*		
GOMERA	12.0		10.2*		10.5*		
GRAN CANARIA	16.1						13.9
LANZAROTE	19.0					15.5	
FUERTEVENTURA	20.6				20.7*		

1. Abdel Monem *et al.* (1971, 1972).
2. Ancochea *et al.* (1990).
3. Cantagrel *et al.* (1984).
4. Carracedo, (1979).
5. Feraud (1981).
6. Coello *et al.* (1992).
7. McDougall & Schmincke (1976).

* Dikes in the Series I (Fúster *et al.* 1983).

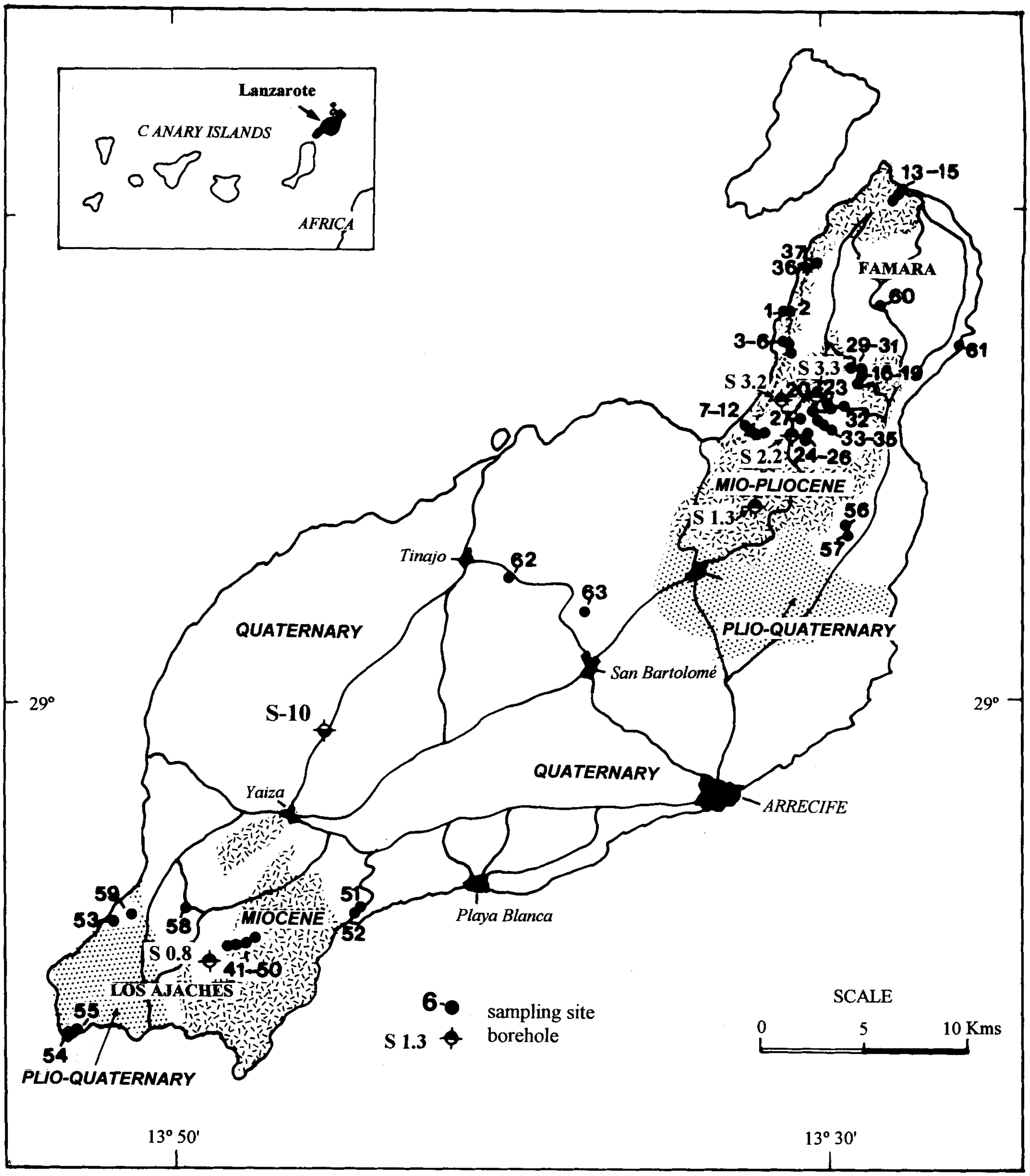

Figure 1. Map indicating the location and extent of the volcanic edifices of Los Ajaches and Famara and the location of palaeomagnetic sampling sites (identification numbers refer to Table 2). Boreholes analysed in this work are also indicated.

of these boreholes that penetrate the entire Famara formation and part of the Los Ajaches formation (see Fig. 1) were sampled to analyse the recorded geomagnetic inclination.

PALAEOMAGNETIC RESULTS

Magnetostratigraphy of the 'old Volcanic series' (Miocene–Pliocene)

The new palaeomagnetic results obtained are in apparent agreement with the geological framework already described. In Famara, a 600 m thick sequence of basaltic lava flows and interbedded pyroclasts of the three units mentioned seems, in fact, to correspond to three magneto-stratigraphic units with different magnetic polarity characteristics (Figs. 2 and 3), a fact already pointed out in an earlier work (Fúster & Carracedo 1979). These units cannot be readily correlated due to the lateral changes that frequently occur in these volcanic formations; nonetheless, the intervals with anomalously low geomagnetic inclinations (L_1 and L_2 in Fig. 2) are effective as 'guide levels' throughout the edifice.

The significance of these anomalous inclinations lies in the fact that, taken as separate palaeomagnetic units, they define mean directions that could be characteristic of Cretaceous or even earlier ages. However, when observed in context, they appear intercalated between formations that show typical Miocene inclinations. The fact that a volcanic formation with a Middle Cretaceous age assigned by palaeomagnetism overlies another similar formation with a palaeomagnetic signature typical of the Miocene is clearly unacceptable, since a stratigraphic inversion is not possible in this geological and tectonic setting.

The observation of the palaeomagnetic inclinations in exposed profiles (Fig. 2) and in borehole columns (Fig. 3) in Famara reveals the slight or negligible stratigraphic representation of these relatively thin horizons of anomalous inclinations. The relative importance of their surficial extent in sectors of the Famara edifice is due to the general concordance in the dipping of these volcanic series and the sloping surface, which favours the extensive outcropping of relatively thin layers.

A careful observation of the outcrop of the volcanic sequence with LGIs shows that it constitutes a well-defined stratigraphic level that correlates with the reverse polarity sections cut by the boreholes. The upper and more significant unit of low geomagnetic inclination (L_2 in Fig. 2) is found in the Famara cliff between 400 and 500 m above sea-level (m.a.s.l.) (see upper right inset in Fig. 2). This same unit L_2 is present at Guinate, a few kms to the north, between 375 and 425 m.a.s.l.; the lateral correlation is compatible with the periclinal dipping of the Famara volcanic edifice. It is found again in Tabayesco (see upper right inset in Fig. 2) at 350–450 m.a.s.l., as a sequence of LGIs with some lava flows with reverse polarity, and in Valle Palomo, to the south, at 325 m.a.s.l., as a thin layer of clearly reverse polarity. This distribution suggests a sequence of lava flows with emission vents centred in the Famara edifice, dipping and thinning periclinally towards the north, east and south, a common feature in these Miocene edifices cut by marine erosion on the windward coast facing trade winds. This volcanic formation of low geomagnetic inclination can be easily correlated with a thick sequence of lava flows and pyroclasts of reverse polarity cut between 300 and 400 m.a.s.l. in borehole S 2.2, located in the centre of Famara (see lower right inset in Fig. 3). This same reverse polarity unit is found as a 70 m thick pack of lava flows at about 250 m.a.s.l. in borehole S 1.3, located at the south edge of Famara. Borehole S 3.2, located very near the Famara cliff, shows a very thin LGI/reverse polarity level at about 300 m.a.s.l. The sharp lateral changes in the thickness of the LGI/reverse polarity level can be easily correlated on field observation with the different degree of erosive removal of the reverse polarity unit, on top of which a 300 m sequence of very thick, relief-filling lava flows rests on erosive discordance.

Only one reverse polarity magnetiztion interval is present in the old edifice of Los Ajaches (see Table 2 and Fig. 4), consistent with the relatively short continuous building period already described. However, LGI events are present between 250 and 300 m.a.s.l. and in a borehole (S 0.8 in Fig. 4) at the base of the subaerial stage of the Los Ajaches edifice, immediately above the submarine tuffs found 20 m below present sea-level.

It is notable that the submarine tuffs at the base of the island also show magnetic inclinations that are in agreement with a Miocene age.

Characteristics of the remanent magnetization

The characteristics of magnetic remanence in the Lanzarote volcanics were analysed using standard procedures. All collected mterial was subjected to thermal and alternating field (AF) demagnetization. At least one sample from each site was tested using thermal and alternating field demagnetization treatments of up to 600 °C and 50 mT. The best fields for cleaning the rest of the samples were chosen after examination of these demagnetization diagrams.

Median destructive fields (MDF, the field at which the original remanence is reduced to 50 per cent) are generally above 20 mT, and median destructive temperatures are above 300 °C, except in the samples with LGIs that show consistent MDFs or MDTs of about 10 mT or 200 °C.

Typical thermal demagnetization diagrams and the corresponding Zijderveld (1967) plots for lavas from the old basaltic edifices of Los Ajaches and Famara are shown in Fig. 5. The samples with 'conventional' values of inclination, either with normal or reverse polarity (Figs 5a and b), show a single stable magnetic component which is generally present after demagnetization at 200 °C or at low alternating fields. In the samples with reverse polarity, a soft secondary component induced by the present magnetic field appears overprinted on the highly stable characteristic magnetiztion and is easily destroyed in the demagnetization process. No indication of a separate high-temperature component is apparent, since the vector paths obtained in thermal and AF demagnetization diagrams are linear and directed to the origin at higher demagnetization steps. Samples with low geomagnetic inclinations show similar characteristics during thermal and AF demagnetization (Figs 5c and d), even at fields as high as 200 mT.

The analyses of thermomagnetic curves from representative samples with normal, reversed and low inclinations

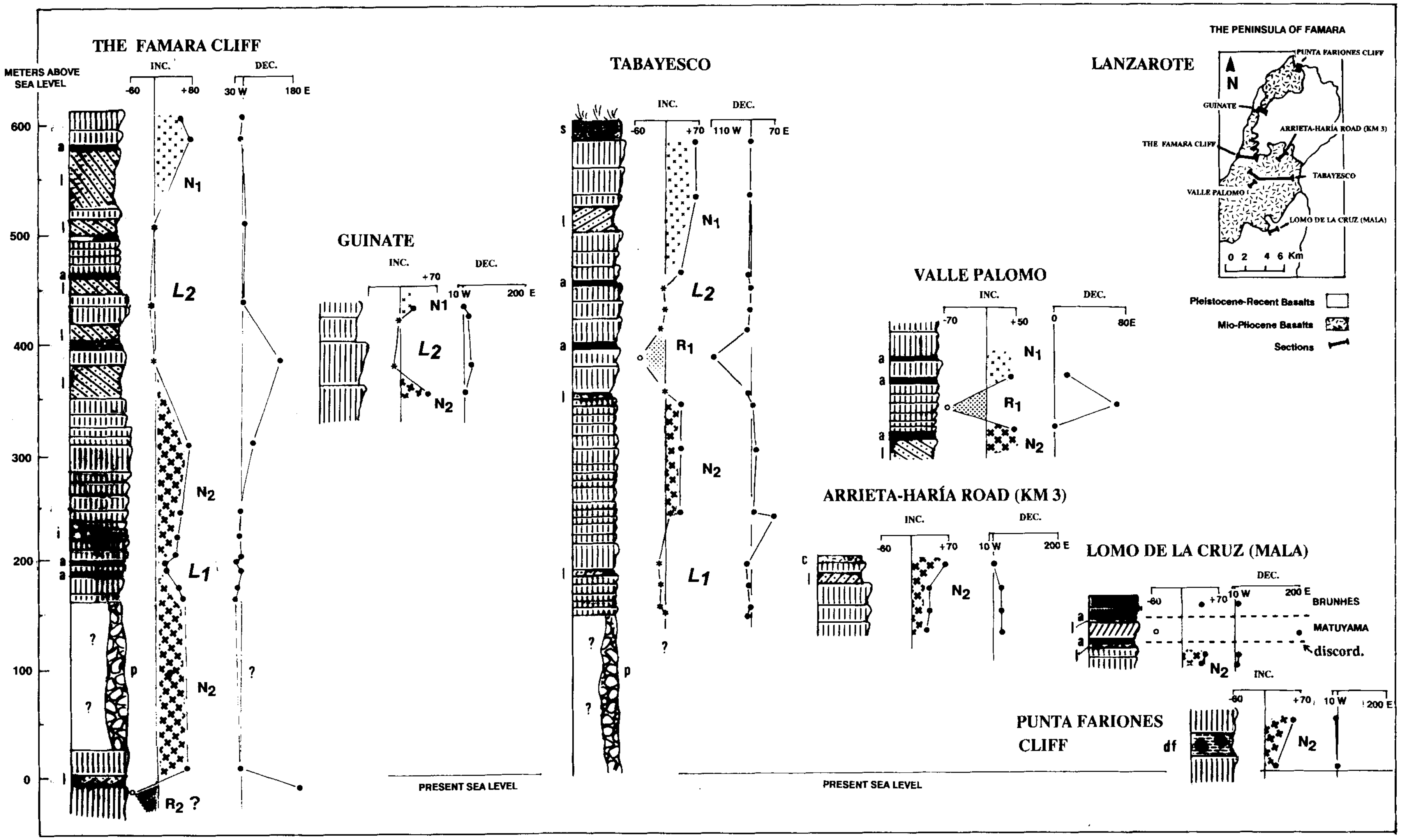

Figure 2. Magnetic stratigraphy of Famara. Positions of sections are indicated in upper right. N and solid circles, and R and open circles indicate normal and reverse magnetic inclinations, respectively; asterisks represent low or transient inclinations; s: soil; p: piedmont deposits; l: lapilli; a: baked palaeosoil; i: dike. Lava flows are shown with vertical stipples. L_1 and L_2: volcanic units with anomalously low geomagnetic inclinations (LGIs in the text). See Tables 2 and 3 and text for further explanation.

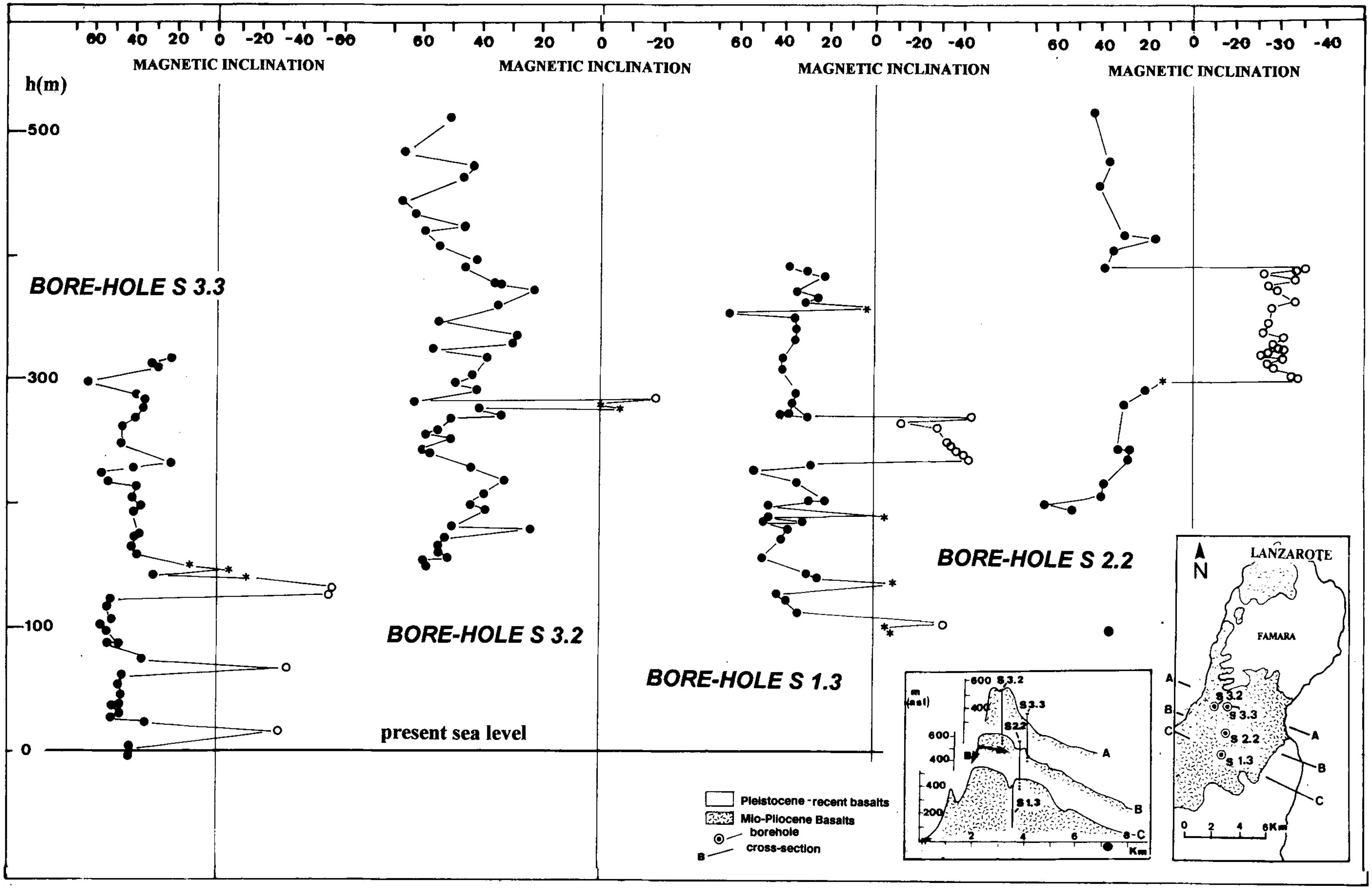

Figure 3. Magnetic inclination recorded in boreholes with continuous core recovery at Famara (positions shown in lower right insets). Magnetic data are after optimal AF and thermal demagnetization. Frequent sharp changes of polarity or aborted transitions are present in boreholes S 3.3, S 3.2 and S 1.3. The chick sequence of lava flows of reverse polarity crossed by the S 2.2 borehole thins out laterally to the south with the slope (see borehole S 1.3 and insets) and disappears to the north (boreholes S 3.3 and S 3.2).

Table 2. Summary of palaeomagnetic data from volcanic series of Lanzarote.

LOCALITY	SITE$^{(1)}$	N$^{(2)}$	CHARACTERISTIC REMANENT MAGNETISM				AGE$^{(5)}$ (Ma)
			DEC	INC	$\kappa^{(3)}$	$\alpha_{95}^{(4)}$	
Miocene Volcanic Series of Los Ajaches, SW Lanzarote.							
Pico Redondo, 330 m	41	4	180.2	-47.0	155	7.4	~14.5**
Pico Redondo, 335 m	42	4	188.5	-45.7	880	3.1	
Pico Redondo, 345 m	43	4	175.8	-45.0	166	7.2	
Pico Redondo, 360 m	44	5	166.4	-39.8	244	4.9	
Pico Redondo, 370 m	45	6	169.2	-40.1	243	4.3	
Pico Redondo, 380 m	46	5	169.7	-44.0	228	5.1	
Pico Redondo, 400 m	47	4	163.8	-20.1	691	3.5	
Pico Redondo, 450 m	48	4	162.2	-12.8	136	7.2	
Pico Redondo, 520 m	49	4	172.3	-45.1	664	4.8	~14.1**
Pico Redondo, 540 m	50	4	186.4	-28.7	371	4.8	~13.6**
Miocene-Pliocene Volcanic Series of Famara, NE Lanzarote.							
Famara cliff 0 m	1	6	174.8	-55.7	1775	1.6	10.2**
Famara cliff 8 m	2	7	351.0	61.3	255	3.8	
Famara cliff 170 m	3	4	339.4	50.2	1577	3.1	8.3**
Famara cliff 175 m	4	7	344.8	45.3	527	2.6	
Famara cliff 195 m	5	5	350.9	19.0	325.0	4.3	
Famara cliff 200 m	6	8	341.1	15.5	287.0	3.3	
Famara cliff 205 m	7	6	350.4	36.7	434.0	3.2	
Famara cliff 220 m	8	4	350.0	43.0	452	2.8	
Famara cliff 250 m	9	4	355,5	49.5	3298	1.6	
Famara cliff 310 m	10	4	32.0	65.4	138	7.9	6.1**
Famara cliff 440 m	11	3	5.6	-9.4	547	2.1	~3.8**
Famara cliff 510 m	12	3	9.2	-2.0	628	1.9	
Pta. Fariones s.l. (below dune)	13	18	0.1	20.8	639	3.6	10.6*, 9.2*, 6.0
Pta. Fariones, 15 m (calcarenites)	14	12	357.9	47.4	194	4.3	Tortonian^{6}
Pta. Fariones, 30 m (above dune)	15	7	1.7	52.0	697	2.3	~5.3*, 5.3**
Haría-Arrieta road, 150 m	16	3	25.3	25.5	2814	2.3	
Haría-Arrieta road, 165 m	17	4	23.8	32.1	1758	2.2	
Haría-Arrieta roas, 185 m	18	3	20.8	33.4	506	5.5	
Haría-Arrieta road, 200 m	19	4	357.3	62.1	1348	2.5	
Tabayesco track, 150 m	20	5	350.1	-0.7	473	3.5	
Tabayesco track, 155 m	21	5	352.0	-9.4	1890	1.8	
Tabayesco track, 175 m	22	5	349.6	-9.8	249	4.9	
Tabayesco track, 195 m	23	7	348.0	-12.7	439	2.9	3.91**
Tabayesco track, 240 m	24	6	2.0	30.6	1317	1.8	
Tabayesco track, 300 m	25	5	13.2	30.0	1291	2.1	
Tabayesco track, 340 m	26	8	6.4	30.7	1912	1.3	
Tabayesco track, 350 m	27	7	351.6	-1.7	1347	1.6	
Tabayesco track, 390 m	28	7	250.8	-54.6	526	2.6	
Tabayesco track, 425 m	29	5	2.9	-2.3	217	5.2	
Tabayesco track, 435 m	30	4	8.2	1.2	249	5.8	
Tabayesco track, 450 m	31	4	5.7	-1.5	567	3.9	
Tabayesco track, 460 m	32	6	352.9	30.7	983	2.1	~6.2**
Peña Pequeña, 330 m	33	4	1.3	44.8	187	6.7	
Peña Pequeña, 350 m	34	3	70.3	-66.6	646	4.9	
Peña Pequeña, 380 m	35	6	13.0	40.1	1627	1.7	~6.7**
Guinate, 400 m	36	5	26.1	-9.3	247	4.9	
Guinate, 420 m	37	8	19.1	-2.2	618	2.2	
Quaternary Volcanics of Lanzarote.							
Playa Quemada, 0 m	51	6	175.7	-30.9	288	4.0	0,99**
Playa Quemada, 20 m	52	5	168.5	-34.8	142	6.4	
Caletón del Río (south of Janubio), 0 m	53	5	191.9	-36.1	233	5.0	0,92**
Punta Pechiguera, 0 m	54	5	198.4	-39.7	380	3.9	0.82 ***
Punta Pechiguera, 5m	55	4	195.5	-35.6	447	4.3	
Guatiza (cemetery of Mala)	56	7	198.7	-50.7	924	2.2	~1,8**

Table 2. (*Continued.*)

LOCALITY	SITE(1)	N(2)	CHARACTERISTIC REMANENT MAGNETISM				AGE(5) (Ma)
			DEC	INC	κ(3)	α_{95}(4)	
Guatiza (cemetery of Mala)	57	10	2.5	36.0	2108	1.0	
Las Breñas (Atalaya de Femés)	58	5	353.5	33.9	163	6.0	
Caletón del Rio (S of Janubio), 15 m	59	6	354.0	31.0	1009	2.1	
Corona Volcano, near cone	60	16	350.5	42.4	361	1.9	
Corona Volcano, at the shore	61	6	354.1	46.3	150	5.5	
Mña. Colorada volcano, 1730 eruption	62	6	342.2	60.0	2592	1.3	
Tao volcano, 1824 eruption.	63	5	336.7	54.6	5953	1.0	

1. Identification of sites in Fig. 1.
2. Number of samples per site.
3. Precision parameter (Fisher 1953).
4. Radius of circle of confidence at 95 per cent significance level.
5. Age (the symbol ~ indicates that the age is stratigraphically close to the level sampled for palaeomagnetism): *Abdel Monem *et al.* (1971); **Coello *et al.* (1992); ***Meco & Stearns (1981).
6. 10–9 Ma (Rothe 1966).

show Curie points typical of magnetite (Fig. 6). After the first heating, a slight variation is observed in relation to a change in the mineralogical composition, resulting in a slightly lower Curie point. In all the samples, this new component remains stable during a second heating (see Fig. 6). Isothermal remanence saturation curves (IRM) indicate that samples become saturated in fields of 0.1–0.2 T (Fig. 6). These results and the transmitted-light thin section observations show that magnetite and titanomagnetite are the main carriers of the magnetic remanence.

Therefore, no meaningful distinction is apparent between the characteristics of the magnetic remanence in samples with inclination conforming to expected values and those with anomalously low values. This conclusion is in accord with the results of Storetvedt and co-workers, who considered the low magnetic inclinations to be original, therefore determining from them a Cretaceous palaeopole for Lanzarote.

ORIGIN OF THE ANOMALOUSLY SHALLOW MAGNETIC INCLINATIONS

Shallow magnetic inclinations of similar characteristics have been found in the Old Basaltic Series of Jandía, on the island of Fuerteventura. A thorough rock magnetism study of these low geomagnetic inclinations (LGIs) (Felix 1989) has not provided a clear explanation for their origin and palaeomagnetic significance.

Simple factors such as tectonic tilting or errors in sample orientation can be discarded when considering the LGIs, since the rest of the volcanic series analysed by the same method shows consistent data. Two models remain as feasible explanations for the cause of the shallowing of the Middle–Upper Tertiary geomagnetic vector in this volcanic unit. The first is that the LGIs represent a primary magnetization produced in the volcanic rocks during short excursions of the geomagnetic field. These short duration oscillations of the inclination of the geomagnetic field can satisfactorily explain the frequent short polarity changes found in the inclination record of the boreholes (see Figs 3 and 4).

Transitional characteristics have been observed in the transits between different polarity states (see Figs 2, 3, 4 and 7). If the duration of the transition is in the range of 20 kyr (Valet, Laj & Tucholka 1986), or in the range of 2 to 10 kyr (Hoffman 1983, 1984), it can easily be accepted that the eruptive frequency in the Canary Islands allows the recording of polarity transitions and, therefore, of related LGIs.

An alternative explanation for the LGIs is the modification of the primary remanence by a process related to post-eruptive mineralogical alteration or weathering. In Famara, a uniformly reversed section of lava flows crossed by the S 2.2 and S 1.3 boreholes (see Fig. 3) is not present in nearby boreholes (S 3.2, S 3.3) and outcropping lava suites. This may be explained by the proximity of the S 2.2 boreholes to the rift where the Famara emission centres are concentrated, and modification of the previous topography by the piling-up of cinder cones and lava flows in successive eruptions, resulting in sharp lateral changes, inversions of relief and heterogeneities.

In the Tabayesco volcanic section of uniform basaltic composition, the LGIs are interbedded between two units of normal and reverse polarities, separated by baked palaeosols (Fig. 7). Palaeosols in these volcanic series indicate eruptive interruptions of at least 10^3–10^4 yr. As shown in Fig. 7, the transitional inclinations are confined between the palaeosols, indicating that they are time-dependent. The presence of normal-transitional-reverse polarities in this Miocene section cannot be explained by a post-eruptive alteration or weathering processes, which should have affected the entire section, and rather suggests the recording of a transition of the geomagnetic field.

PALAEOMAGNETIC DIRECTIONS

The statistical analysis of 341 fully oriented samples from 57 different surface sites allowed the determination of mean

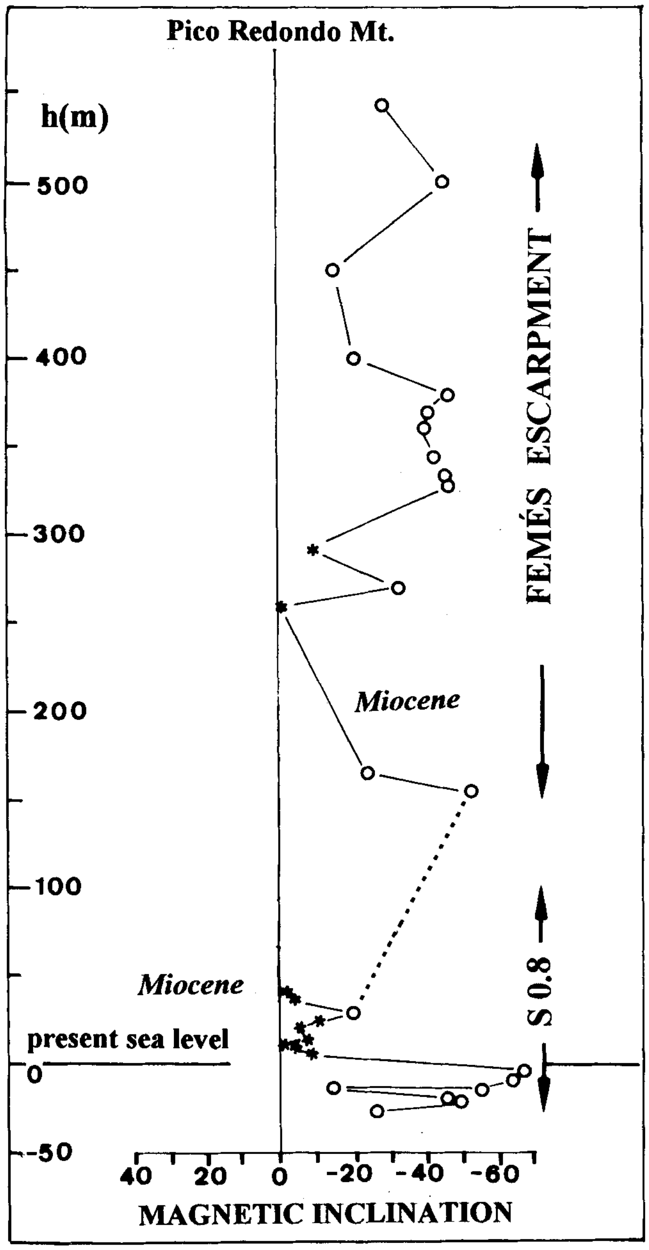

Figure 4. Changes in the magnetic inclination recorded in a section (Femés escarpment, upper part of the figure) and in a borehole (S 0.8, lower part) at the Los Ajaches Miocene volcanic edifice (in southern Lanzarote, see Fig. 1). Symbols as in Fig. 2.

directions and pole positions. A two-step analysis was applied: first with unit weight on samples and then with unit weight on sites. The grouping of the mean directions of 255 samples from 44 sites in Famara and Los Ajaches is substantially improved upon removing those samples corresponding to the anomalous low inclinations, the value of a_{95} changing from 11.4° to 6.7° and the precision parameter k increasing from 5.1 to 29.3 (see Table 3). The wide dispersion shown by the anomalous directions can be explained by different degrees of modification of the original magnetization. These 'cleaned' directions show a close similarity to those obtained from 86 samples (13 sites) of the Recent Series (<1 Ma) of Lanzarote (see Table 2).

Figure 8 shows the virtual geomagnetic poles corresponding to the palaeomagnetic data in Table 3. The poles corresponding to Famara and Los Ajaches overlap at the 95 per cent statistical confidence level with that defined for recent formations. All these poles are located on a sector of the apparent polar wander path for Europe (Doell & Dalrymple 1966; Irving 1977) attributable to the Upper Tertiary–Quaternary. Contrarily, the geomagnetic excursions (L_1 and L_2) diverge clearly at a position of the polar wander path corresponding to the Cretaceous. The Cretaceous positioning of the LGI palaeopoles can only be explained as a mere coincidence, without any chronological significance.

The impossibility of statistically resolving palaeomagnetic directions from the Miocene onwards in the Canaries was reported by Watkins (1973), Watkins *et al.* (1966) and Carracedo (1979), upon comparing the palaeomagnetic poles obtained in the Old Series of the islands with others of known age from Africa and Europe. Watkins *et al.* (1966) compared the polar wander paths of Tenerife, Gran Canaria, Lanzarote, Hierro and Gomera with those of the Eocene in Europe, and concluded that the oldest volcanics analysed in these islands were formed more recently. Watkins (1973), for all the islands, and Carracedo (1979), for Tenerife, concluded that the oldest subaerial edifices in the Canaries give magnetic poles that cannot, in practice, be differentiated from those corresponding to the recent formations, a fact accounted for by these authors as being due to the fact that the African plate became stationary in the Upper Tertiary and the Quaternary, as stated by Burke & Wilson (1972) and Morgan (1972, 1983).

CONCLUSIONS

The anomalously shallow palaeomagnetic inclinations of lavas interbedded in Miocene volcanic suites of Lanzarote reflect the transitions of the geomagnetic field.

It seems evident that the excessive age attributed to the Old Series of the Canaries by using palaeomagnetism (Tertiary/Cretaceous boundary or even Cretaceous) is a consequence of defining pole positions from volcanic units that have registered these abnormally low magnetic inclinations.

Once these anomalous data are rejected, the virtual geomagnetic poles obtained are compatible with the geological and geochronological data, which point to a Middle Miocene–Pliocene age for the building of the Old Basaltic edifices of Lanzarote. It is expected that the anomalously low inclinations, which are well documented in the Old Basaltic Series of Lanzarote, will be traceable throughout the entire Canarian Archipelago, providing 'guide levels' potentially useful in stratigraphic correlations.

The analyses of the mean virtual geomagnetic pole for each volcano-stratigraphic unit in this Old Series unequivocally show that the volcanic formations with abnormal LGIs overlie a volcanic formation with a typically Upper Miocene palaeomagnetic signature.

Virtual geomagnetic poles (VGPs) obtained from samples ranging from the oldest subaerial outcropping volcanic materials to products of historic eruptions, when grouped in Middle Miocene (Ajaches Miocene, 14–15.5 Ma), Upper Miocene (Famara Miocene, 5–10 Ma) and Recent (<1 Ma)

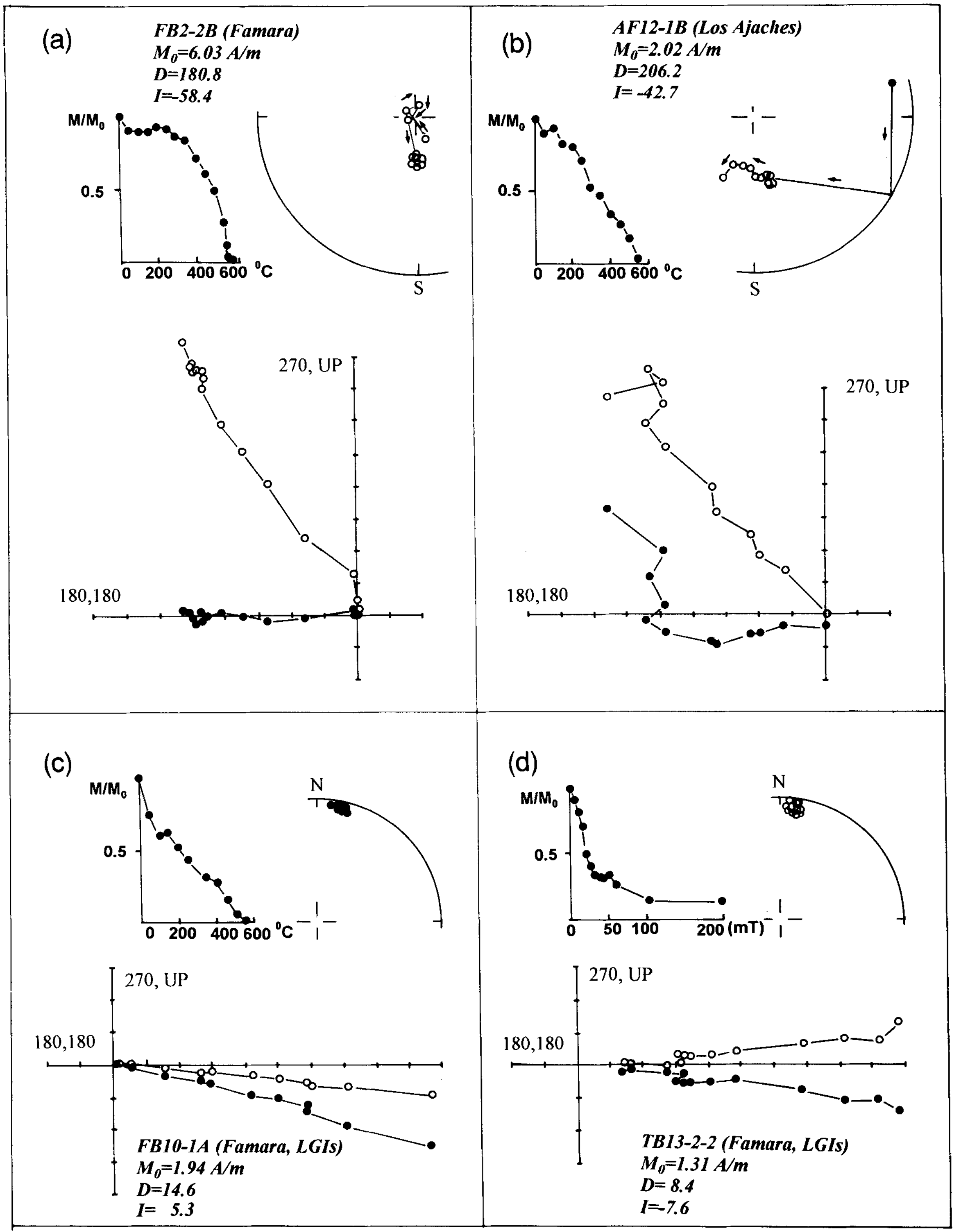

Figure 5. Changes in the intensity (normalized with respect to the maximum value M_0) and direction (stereoplots) of the magnetic remanence after stepwise demagnetization and Zijderveld plots for representative samples from Los Ajaches and Famara old volcanic edifices. (a) and (b) represent samples with 'expected' inclination values. (c) and (d) Samples with anomalously low magnetic inclinations from the Famara volcanic edifice, defined by thermal and alternating field demagnetization. Intensity, declination and inclination of the NRM (natural remanent magnetization) are written below the name of each sample. Note that samples exhibiting low magnetic inclinations show a stable single component during treatment up to 600 °C or 200 mT.

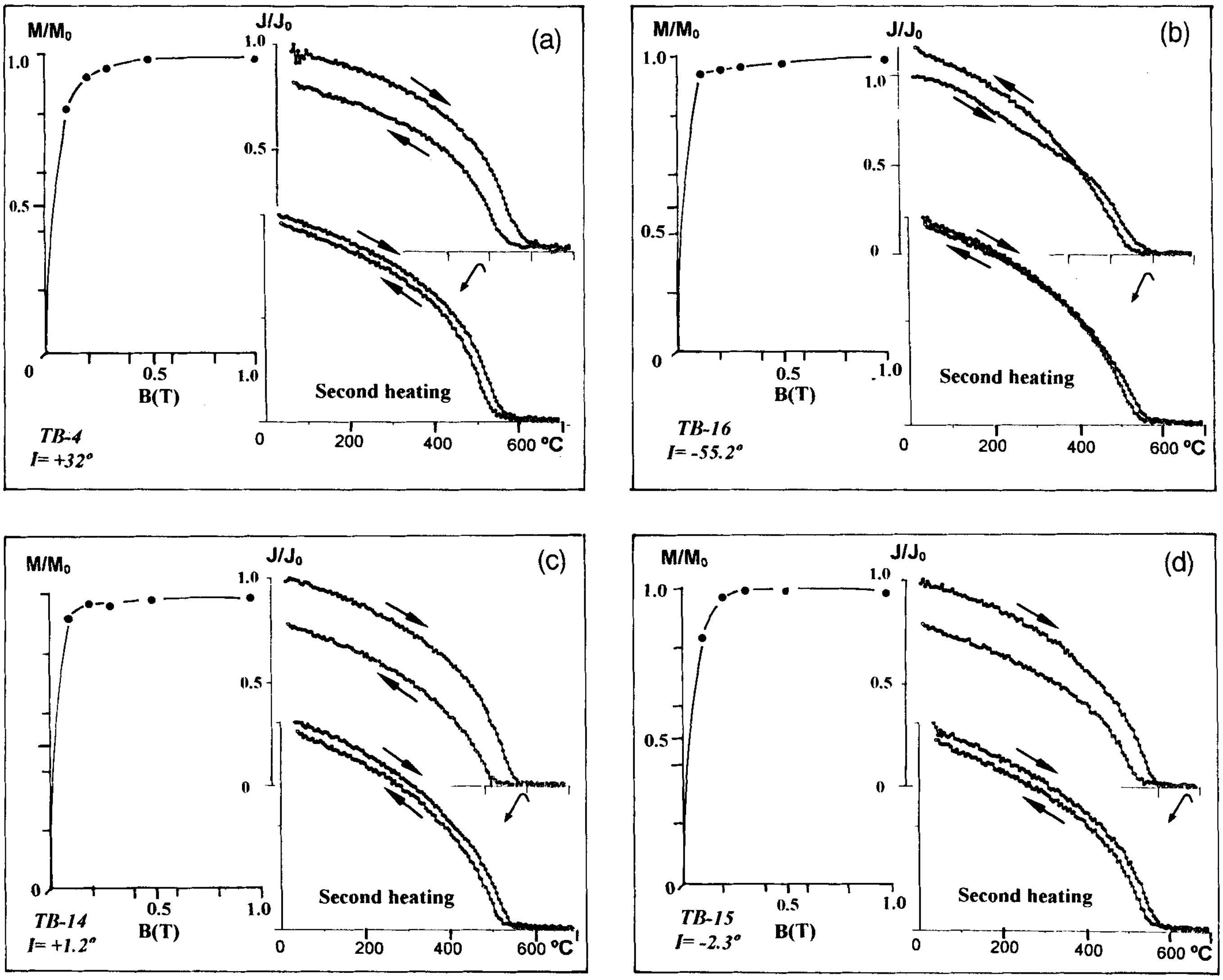

Figure 6. Two-cycle thermomagnetic and isothermal remanent magnetization (IRM) curves. (a) and (b) correspond to samples with normal and reverse polarities,

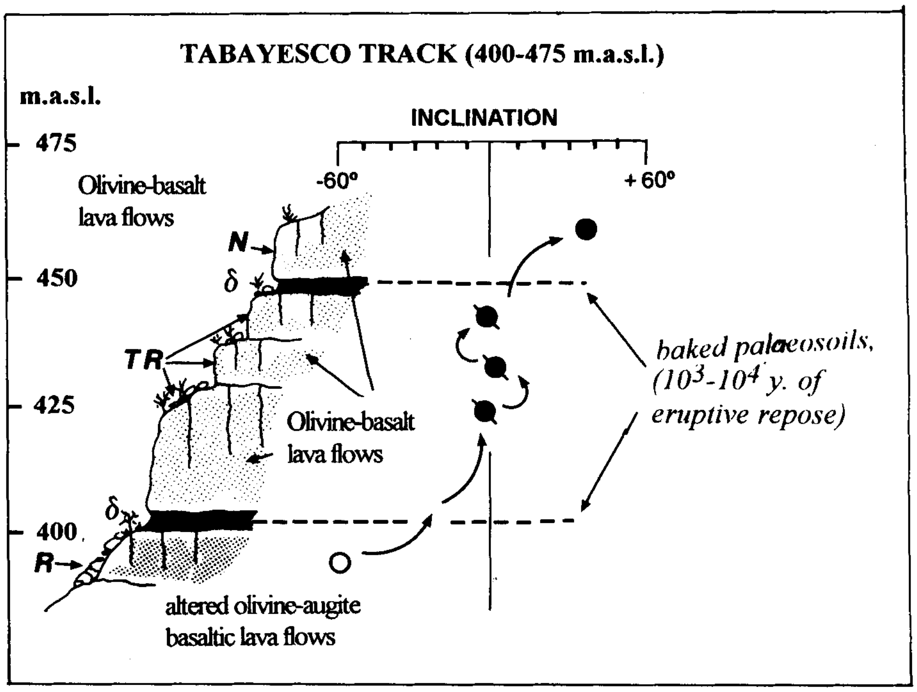

Figure 7. Volcanic sequence in Famara (Tabayesco track) showing lava flows of uniform basaltic composition in which LGIs appear interbedded between two units of normal and reverse polarities, separated by baked palaeosols. The transitional inclinations are confined between the palaeosols, indicating that they are time-dependent, thus suggesting the recording of a change of polarity of the geomagnetic field.

Table 3. Palaeomagnetic results from Lanzarote.

			CHARACTERISTIC REMANENT MAGNETISM				PALEOMAGNETIC POLE	
VOLCANIC UNIT	**AGE[(1)] (Ma)**	**N[(2)]**	**DEC.**	**INC.**	**κ[(3)]**	**α_{95}[(4)]**	**LAT. (δ_{LAT})[(5)]**	**LONG. (δ_{LONG})[(5)]**
FAMARA EDIFICE								
Famara Miocene (all data)	10 to 5.3	38(217) [3]	3.7	25.2	5.1	11.4	73.8 (6.6)	153.5 (12.3)
Famara Miocene (excursions rejected) [6]		17(108)	359.4	45.2	29.3	6.7	87.5 (5.4)	178.2 (8.5)
Excursion 1 (L_1)[7]		10(51)	358.3	13.5	10.6	15.6	67.6 (8.1)	170.9 (15.9
Excursion 2 (L_2)[7]		7(31)	10.1	-3.6	61.7	7.7	57.6 (3.9)	147.8 (7.8)
AJACHES EDIFICE								
Ajaches (all data)	15.5 to 13.4	10(44)	172.9	-37.2	33.1	8.5	79.7 (5.9)	206.5 (8.8)
Ajaches (without sites 47,48) [6]	15.5 to 13.4	8(35)	176.1	-42.2	89.7	5.9	84.4 (4.4)	205.0 (7.2)
LANZAROTE RECENT VOLCANISM								
Pleistocene-Holocene	1.6 to present	13(86)	359.3	41.6	36	7.0	84.9 (5.2)	173.9 (8.6)

[1]Abdel Monem *et al.* (1971); Coello *et al.* (1992). [2]Number of sites per unit (number of samples). [3]Precision parameter (Fisher 1953). [4]Radius of circle of confidence at 95 per cent significance level. [5]Semi-axes of oval of confidence at 95 per cent significance level. [6]Results shown in Figs 4 and 5. [7]See Fig. 4.

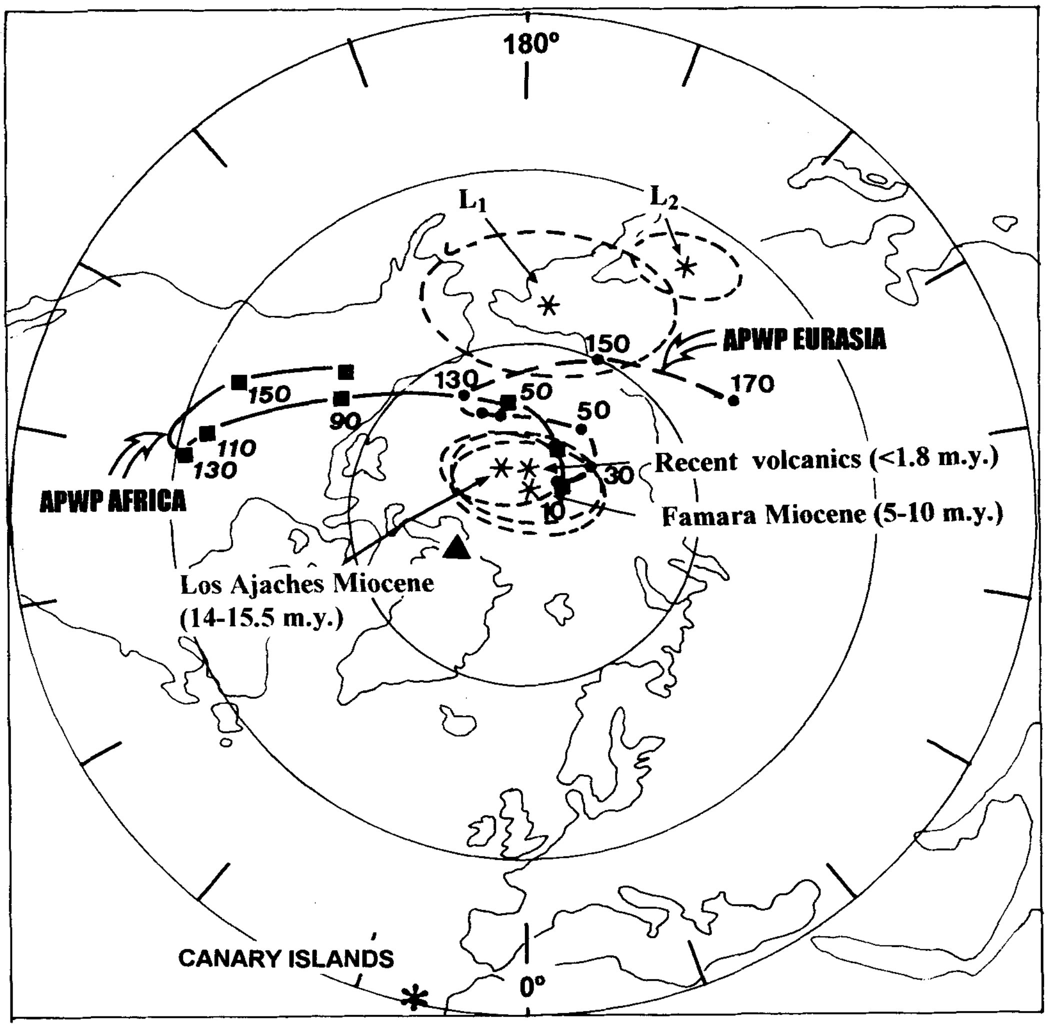

Figure 8. Virtual geomagnetic poles and 95 per cent confidence ovals for the Miocene and recent (Quaternary) volcanism of Lanzarote. L_1 and L_2: geomagnetic excursions. The apparent polar wander curves (Besse & Courtillot 1991) for Eurasia (solid dots, broken line and non-italic numbers) and Africa (solid squares, continuous line and italic numbers) are shown for reference. Numbers indicate ages in Ma. The present geomagnetic pole is indicated by a solid triangle.

units, give poles that fall on the polar path near the present pole position (see Fig. 8). In contrast, pole positions derived from units with low geomagnetic inclinations plot far from the latter, in the zone corresponding to the Mesozoic. However, this fact seems to be a mere coincidence, with no geochronological significance.

This work confirms evidence presented in earlier reports (Watkins 1973 and Carracedo 1979) that it is not possible to differentiate ages from the Miocene onwards by palaeomagnetism alone, since VGPs of that age overlap those derived from recent or even historic volcanics. This fact, probably in relation to the lack of a significant displacement of the African plate during this period, is well documented in the case of Lanzarote and implies important limitations in the utilization of palaeomagnetism as a dating tool in the Canary Islands.

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