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Paleomagnetic directions and K/Ar dating of 0 to 1 Ma lava flows from La Guadeloupe Island (French West Indies): Implications for time-averaged field models

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Abstract. Twenty-six lava flows spanning the last million years were sampled in La Guadeloupe, French West Indies. Because of the lack of continuous volcano-stratigraphic sections in La Guadeloupe, dating is necessary in order to describe the temporal evolution of the geomagnetic field in this time interval. New K/Ar ages ranging from 50 ka to 1 Ma have been obtained on andesites using the Cassignol-Gillot technique at the Université Paris Sud - Institut de Physique du Globe de Paris Orsay laboratory. Additional flows (with K/Ar ages obtained using the same dating technique) were also sampled for paleomagnetic investigations. More than 200 samples were analyzed using both alternating field AF and thermal stepwise demagnetization techniques. Duplicate samplings of two flows at three different sites demonstrate that within-flow dispersion is negligible for the andesitic lava flows sampled in this study. Direct comparison with an earlier paleomagnetic study performed on the island indicates that, for the three investigated flows, modern demagnetization techniques yield much better defined paleomagnetic directions. The Matuyama-Brunhes transition was recorded in a three-flow section and is dated at 781 ± 18 ka, in good agreement with other recent radiometric age determinations. The mean paleomagnetic pole calculated from the 23 normal polarity flows is indistinguishable from geographic north, which implies that no significant persistent axial quadrupole term can be identified at this site for the last million years. This result contradicts earlier results and has important implications for models of the time-averaged field (TAF). An Occam algorithm was used to construct a TAF model from the global volcanic database from the last 5 Ma. Substitution of the mean direction calculated from the earlier study for the Lesser Antilles by our new mean value reduces the quadrupole term by more than 30%. This effect, which was produced by changing data from a single site, demonstrates that older paleomagnetic sites may need to be reinvestigated. Furthermore, it also highlights the limitations of TAF models that can be inferred from paleomagnetic databases in their present state.

1. Introduction

The time-averaged geomagnetic field can be satisfactorily accounted for by a geocentric axial dipole [*Courtillot et al.*, 1992], and second-order features can be resolved only with data of high quality and with well-distributed sites [e.g., *Johnson and Constable*, 1997; *Carlut and Courtillot*, 1998]. Despite recent efforts to reanalyze paleomagnetic data from the last 5 Ma, many data sets that contribute to global databases require revision, and large geographic areas remain devoid of data that satisfy modern criteria [*McElhinny and McFadden*, 1997]. Limitations related to poor site distribution and resulting difficulties in identifying certain terms in time-averaged geomagnetic field (TAF) models have recently been investigated by *Carlut and Courtillot* [1998]. These authors showed that, given the present site distribution in paleomagnetic databases from lava flows, only a 5% persistent axial quadrupole term, superimposed on the axial dipole, could be resolved for the TAF over the last 5 Ma. Deep-sea sediments are not considered because, usually, only inclination is available and because the fidelity of sedimentary records has often been questioned. The time interval that is often used when studying the TAF is 0-5 Ma. This is because biases due to plate motions can be neglected, and the natural remanent magnetization (NRM) is less likely to have been affected by overprints or remagnetizations. Three subdivisions of the data are often made, including data from the Brunhes chron only, which is the most easily recognized in lava flow sequences, and from normal and reverse polarity data from the whole 0-5 Ma interval. However, it would clearly be instructive to investigate geomagnetic field features for data from smaller time intervals. Unfortunately, most studies lack the necessary high-quality age determination which would allow more precise data selection.

The Caribbean plate, and a wide surrounding area, is represented in paleomagnetic databases by only a single study [*Briden et al.*, 1979]. Numerous K/Ar dates obtained for most islands from the Lesser Antilles have demonstrated that a migration of volcanism occurred in the mid-Miocene from the outer volcanic arc toward the inner volcanic arc (Figure 1a). However, the quality of dates obtained for La Guadeloupe Island has been questioned [*Blanc*, 1983]. Individual paleomagnetic directions should also be considered with

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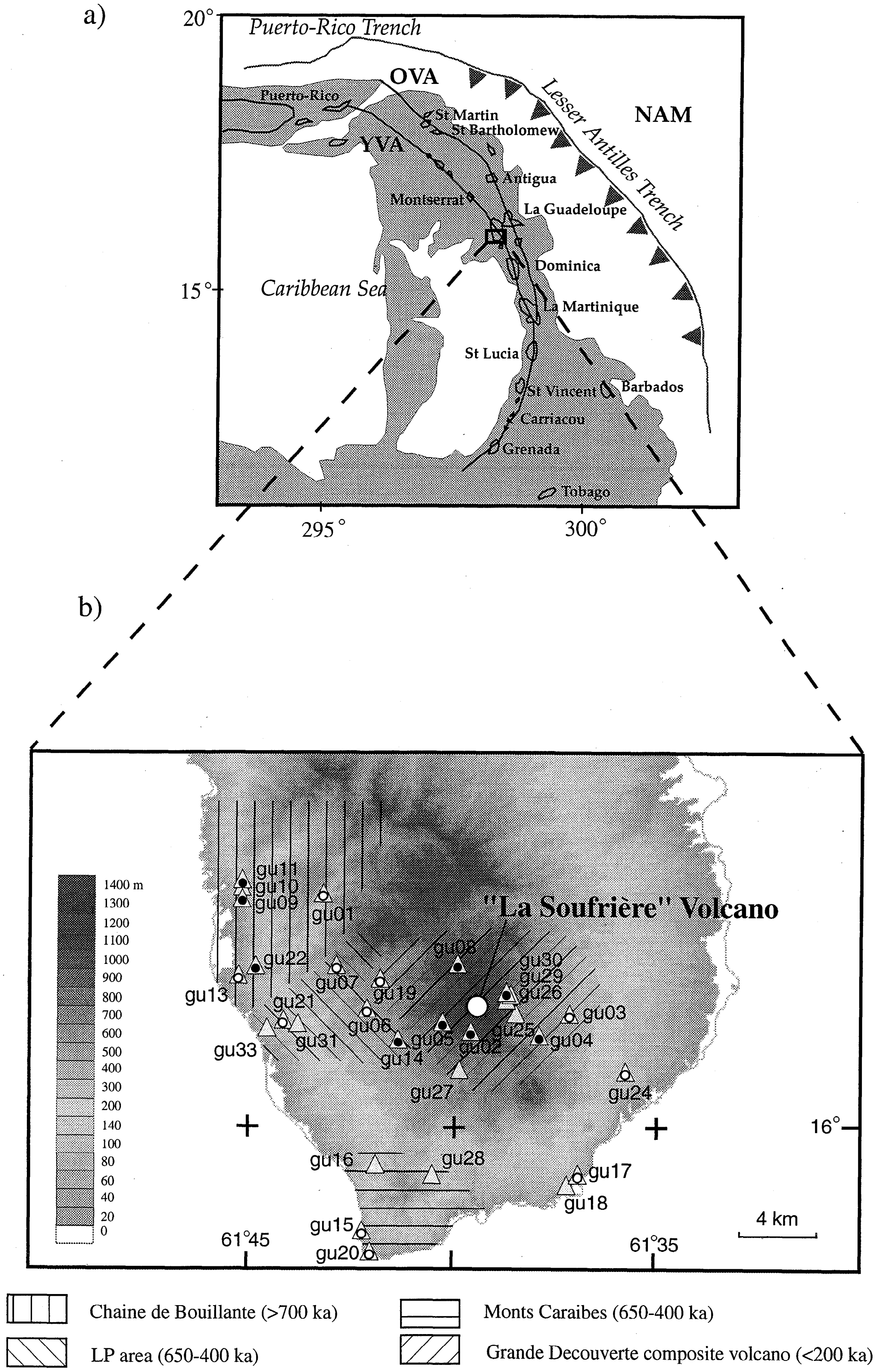

Figure 1. (a) Map of the Lesser Antilles arc which was built by subduction of the North America (NAM) plate under the Carribean plate. Locations of the older volcanic arc (OVA) and the younger volcanic arc (YVA) are shown. Shallower bathymetry is shown in grey. (b) Enlargement of the topographic map (N. Feuillet, personal communication, 1998) of the southern part of Basse Terre, in La Guadeloupe Island, French West Indies. Paleomagnetic sites are shown by open triangles. Triangles with solid dots are dated sites with K/Ar age obtained in this study, open triangles with dots are sites previously dated by *Blanc* [1983]. Also shown are the different volcanic units (see legend) corresponding to successive eruptive stages (see text for details).

caution, since modern stepwise demagnetization techniques, which allow identification of overprints, were not used by the original authors [*McElhinny and McFadden*, 1997].

For the above reasons, volcanics from the last one million years have been sampled for paleomagnetic and geochronologic analyses in Basse Terre (La Guadeloupe Island). Another goal of this data acquisition campaign was to provide a better knowledge of past volcanic history in the island for better assessment of volcanic hazards.

2. Geological Setting

The Lesser Antilles are composed of two distinct volcanic arcs which were built by the subduction of the Atlantic plate under the Caribbean plate [i.e., *Brown et al.*, 1977; *Hawkesworth and Powell*, 1980] (Figure 1). To the north of La Martinique, pre-Miocene volcanics are encountered only in the islands of the older external arc, while late-Miocene volcanics are found in islands of the younger internal arc [*Briden et al.*, 1979]. Near Martinique, both arcs merge into one. During the mid-Miocene, tectonic adjustments probably changed the orientation of the northern part of the subducting slab, initiating formation of the internal arc. Volcanic activity in the younger arc of the Lesser Antilles has been observed since the onset of widespread European settlement [*Roobol and Smith*, 1989], and the presently active Montserrat volcano (immediately north of La Guadeloupe Island, Figure 1) illustrates the potential hazard of these islands. On the other hand, no clues of recent activity are found in islands from the outer arc.

La Guadeloupe Island is built from two adjacent islands, yielding a distinctive "butterfly" shape. The low-relief eastern part, Grande Terre, is composed of Miocene volcanics from the older arc, which have subsequently been covered by Plio-Pliocene limestones. The western part, Basse Terre, belongs to the presently active younger arc (Figure 1). The predominant feature of Basse Terre is La Soufrière volcano (1467 m altitude, highest point in the Lesser Antilles). La Soufrière lava dome is the most recent part of the composite volcano of La Grande Découverte (CVGD) [*Boudon et al.*, 1989]. This volcano results from a succession of edification and destruction (by sector collapse) events [*Boudon et al.*, 1987] which formed an irregular topography. On the southern part of the volcano, the Madeleine eruptive ensemble, which is contemporaneous with the CVGD contains several lava flows and lava domes, of which the most recent are some 10 kyr old. The 1976-1977 phreatic eruption of La Soufrière lava dome [*Feuillard et al.*, 1983] represents the most recent activity of this complex volcano. The CVGD is bounded by the hydromagmatic volcanoes of Monts Caraïbes to the south, for which ages of about 0.5 Ma [*Blanc*, 1983] have been reported, and by the Axial chain to the north, which seems to have ceased activity at about 0.6 Ma [*Blanc*, 1983]. Farther north, the other half of Basse Terre is composed of older volcanic units from the Chaîne de Bouillante and Chaîne Septentrionale, as well as sedimentary formations.

Probably because of poor outcrops and dense vegetation, no detailed tectonic studies of Basse Terre have yet been published. Recently, *Feuillet et al.* [1997] proposed that a rifting system perpendicular to the subduction trench might be responsible for magma ascent within the CVGD (Figure 1b), mainly on the basis of bathymetric data. Following this model, no significant postemplacement motion is to be expected on Basse Terre for lavas from the last million years because the kinematics of plate convergence rates are relatively slow. This hypothesis is supported by the scarcity of large magnitude earthquakes in the vicinity of La Guadeloupe. Nevertheless, care was taken to identify localized fractures within individual flows, which could indicate ongoing tectonic activity.

A wide range of volcanic products are found in the Lesser Antilles, which illustrates the complexity of subduction-related magmatism [i.e., *Hawkesworth and Powell*, 1980]. Mixing calculations indicate that arc magma geochemistry is explained by mixtures of depleted mantle and a small subducted sediment component [*Davidson*, 1986; *White and Dupré*, 1986]. Effusive and pyroclastic events, with a wide range of compositions from basaltic to highly differentiated, have been documented in Basse Terre. Rare earth element (REE) analyses indicate that low-K basalts are explained by simple binary mixing. Alkaline magma formation requires a more complex formation process in which fluid generated by dehydration of subducting sediment and basalt metasomatizes overlying depleted mantle [*White and Dupré*, 1986]. In the present study, only andesitic lava flows covering the time interval 1 Ma to present [*Blanc*, 1983] were investigated.

3. Sampling

Paleomagnetic and geochronological sampling took place on the island of La Guadeloupe (French West Indies) in February 1998. Sampling was concentrated on the southern part of Basse Terre (Figure 1b). In this area the age of volcanism had been constrained to less than 1 Ma from previous dating [*Blanc*, 1983]. Because of the lack of continuous sections, dating of flows is necessary to describe the temporal evolution of the geomagnetic field in this 1 Myr interval. Paleomagnetic sampling was first focused on previously dated lava flows [*Blanc*, 1983]. Thirteen additional flows were then sampled for paleomagnetic studies. From these flows, nine hand-sized blocks were sampled for geochronological investigations, when allowed by freshness of lava. In one case only (GU08), drill cores were sampled for dating. Outcrops were found in road cuts, in streambeds, or on caldera walls. In total, 33 sites from 29 independent flows (including 22 dated flows) from southern Basse Terre have been sampled for paleomagnetic investigations (Figure 1b).

A total of 232 paleomagnetic cores were drilled with a portable gasoline-powered drill and were oriented with a magnetic compass. Sun compass orientation was taken when atmospheric conditions and/or vegetation permitted. The mean magnetic declination of -14.3°±2.8° (calculated from 21 out of 33 flows) is indistinguishable from the International Geomagnetic Reference Field (IGRF) value at the site (-14.3° in 1998), which indicates that there is no local geomagnetic anomaly. When no Sun compass orientations were available for a given flow, this mean value was used to correct the magnetic compass orientation.

4. Laboratory Experiments

4.1. Paleomagnetic Procedure

Measurements and demagnetization of NRM were performed in the magnetically shielded room of the Institut de Physique du Globe de Paris (IPGP) paleomagnetic laboratory. 2G

Entreprises cryogenic and JR5 spinner magnetometers were used for the measurements. Three samples per flow were subjected to alternating field (AF) demagnetization, and three to seven samples underwent thermal treatment. Stepwise demagnetization, with no less than 10 steps, was used for each sample. Evolution of the magnetization vector was scrutinized using *Zijderveld* [1967] diagrams and primary NRM directions were determined using least squares principal component analysis [*Kirshvink*, 1980].

Low-field susceptibility measurements were performed for one sample in each flow using a Bartington Instruments MS2 susceptometer. During the course of thermal demagnetization, susceptibility measurements were performed on selected samples, in order to detect any mineralogical changes. No significant changes were observed, which indicate that no strong oxidation of Fe-bearing minerals took place during thermal treatment.

4.2. K/Ar Procedure

Nine andesitic lava flows from Basse Terre have been K/Ar dated in the UPS-IPGP geochronology laboratory at Orsay, France. The Cassignol-Gillot technique [*Cassignol and Gillot*, 1982], which is based on an atmospheric argon comparison, was chosen because it allows accurate dating of young lavas and/or lavas with low radiogenic content [*Gillot and Cornette*, 1986]. Preliminary examination of petrographic thin sections validated the choice of selected samples. The low K content of plagioclase phenocrysts from calc-alkaline magmas of the Lesser Antilles arc, which probably arise from partial fusion of subducted hydrous oceanic crust, prevented dating of such phase [*Blanc*, 1983]. Early fractional crystallization of amphibole and plagioclase, followed by plagioclase, pyroxene, and Fe-Ti oxides, characterize the differentiation process of magmas from the geodynamic setting of the Lesser Antilles [*Westercamp and Mervoyer*, 1976; *Brown et al.*, 1977]. In order to avoid excess argon phenomena linked to crystallization of amphibole and plagioclase at depth, only the groundmass was kept for dating. Samples were crushed to a 250 - 400 µm size fraction and were ultrasonically cleaned for 1 hour in a 20% nitric acid solution. A magnetic separator was used, in order to remove Fe-Ti oxide rich phases, and then heavy liquids, in order to remove the early crystallizing phases from the microlithic groundmass which was used for both K and Ar measurements. K was measured by flame emission spectroscopy and was compared with reference values of MDO-G and ISH-G standards [*Gillot et al.*, 1992]. Ar was measured with a mass spectrometer identical to the one described by *Gillot and Cornette* [1986]. The interlaboratory standard GL-O, with the recommended value of 6.679×10^{14} atom/g of $^{40}Ar^*$ [*Odin et al.*, 1982], was used for ^{40}Ar signal calibration. Typical uncertainties of 1% are achieved for the ^{40}Ar signal calibration and for the K determination. The uncertainty on the $^{40}Ar^*$ determination is a function of the radiogenic content of the sample. The detection limit of the system is presently of 0.1% of $^{40}Ar^*$, which makes the Cassignol-Gillot technique specially suitable for these samples. In order to avoid isotopic fractionation, no predegassing of the sample was performed. Decay constants and isotopic ratios of *Steiger and Jäger* [1977] were used.

5. Results

5.1. Paleomagnetic Directions

The NRM intensity for most samples is of the order of 10 A/m. A low unblocking temperature, low coercivity overprint, probably held by multidomain magnetite grains, is easily removed at 120 - 200°C or by 10 mT. The magnetization remaining above 540 - 575°C is, in most cases, negligible, which indicates that titanomagnetite, with high unblocking temperatures, is the main remanence carrier. Above 120 - 200°C (or above 10 mT), specimens exhibit simple linear on demagnetization, and determination of the primary remanence directions is straightforward. Only three flows (GU12, GU23, and GU32) did not yield reliable paleofield directions. Flow GU32 shows evidence for an isothermal remanent magnetization (IRM), probably due to a lightning strike (i.e., very high NRM intensity values that are easily demagnetized by AF treatment, while thermal treatment was inefficient). However, despite sampling across a wide area (about 30 m), no reliable mean direction could be determined after AF cleaning. Flow GU12 displays unstable behavior, probably due to high magnetic viscosity. Susceptibility values are significantly lower for this flow, which suggests the presence of multidomain titanomagnetite. Finally, flow GU23 seems to contain displaced blocks. Field observations indicated this possibility, which was subsequently confirmed by paleomagnetic measurements. Results from this flow were therefore discarded. Because of dense vegetation, outcrop visibility is often limited, and postemplacement fractures cannot always be detected in the field, but hopefully can be detected paleomagnetic analyses. Typical *Zijderveld* [1967] diagrams for normal and reverse polarity samples from the southern part of Basse Terre are shown in Figure 2. Paleomagnetic directions are reported in Table 1 and are shown in Figure 3.

5.2. K/Ar Results

5.2.1. Previous work. *Briden et al.* [1979] presented extensive K/Ar geochronological and paleomagnetic data from the Lesser Antilles. There is a marked contrast between K/Ar dates from the outer arc (from 38 to 10 Ma) and the inner arc (less than 7.7 Ma). Fourteen whole rock K/Ar dates, ranging from 0.91 to 2.52 Ma, were reported for Basse Terre. Dates obtained on andesitic flows from Monts Caraïbes and Chaîne de Bouillante are significantly older than those reported by *Blanc* [1983]. This discrepancy can only be explained by potassium loss due to alteration processes leading to overestimation of the K/Ar ages. This hypothesis is supported by the poor correlation between the geomagnetic polarity of dated flows [cf. *Briden et al.*, 1979], when available, and a recent geomagnetic polarity timescale [*Cande and Kent*, 1995].

An important amount of geochronological data from Basse Terre has been reported by *Blanc* [1983]. Two different methods were used. First, thermoluminescence dates of 140 ± 14 ka and 244 ± 18 ka were obtained on quartz from andesitic pumice layers of the Chaîne de Bouillante and 108 ± 10 ka for the early stage of the CVGD. Second, 14 K/Ar age determinations using the Cassignol-Gillot technique were

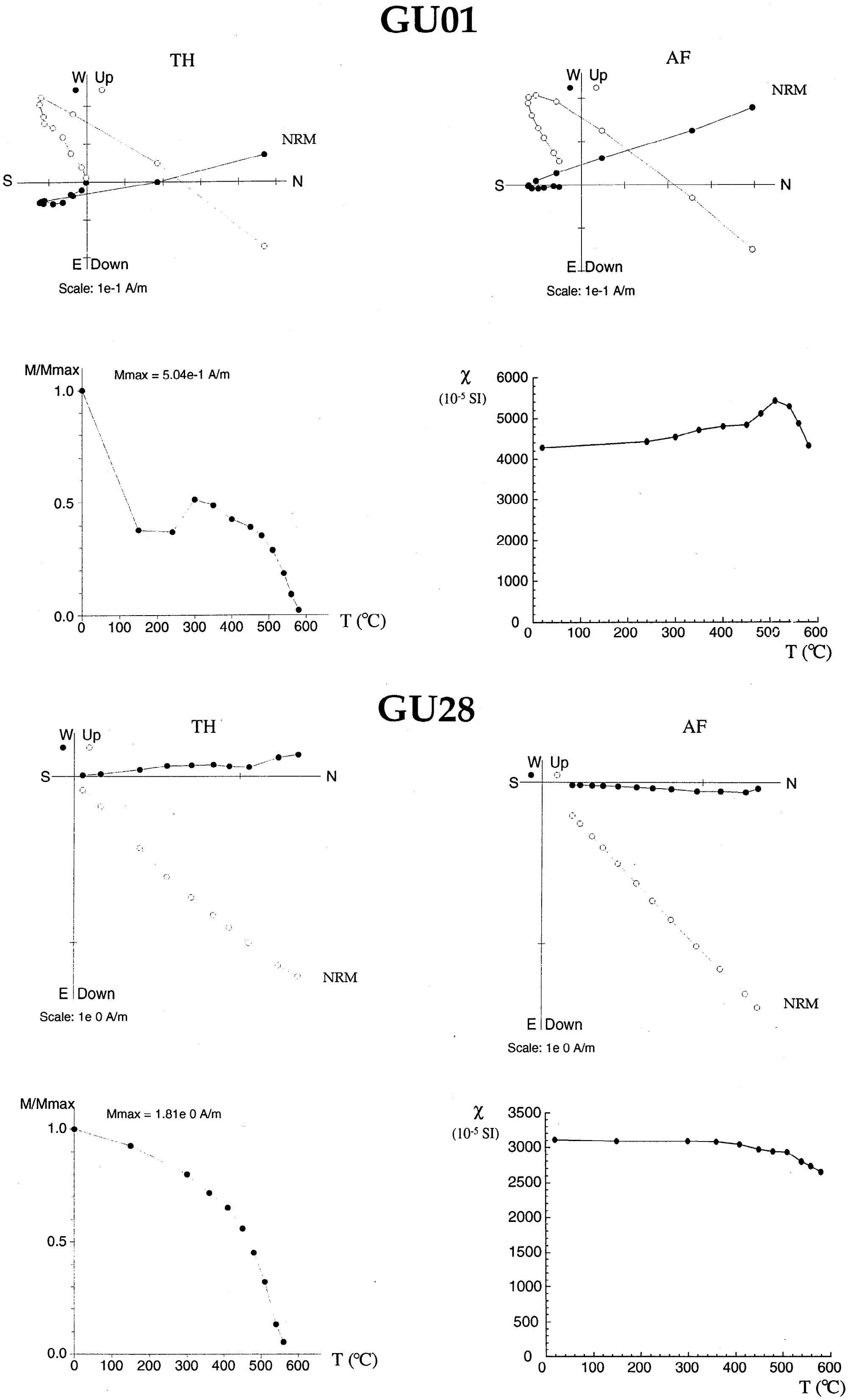

Figure 2. Typical *Zijderveld* [1967] diagrams (one with thermal and one with AF treatment) for normal and reverse polarity data (flows GU28 and GU10, respectively). Solid symbols correspond to projections onto the horizontal plane, while open symbols are projections onto the vertical plane. Also shown for these two flows are the NRM intensity decay (M) normalized to the maximum value (M_{max}), and changes of magnetic suscpetibility χ (in 10^{-5} SI) during thermal treatment.

Table 1. Paleomagnetic Directions From Basse Terre

Site	Flow Location	Lat.	Long.	*n/N*	Dec.	Inc.	α_{95}	λ	ϕ
GU01	Morne Soldat	16° 05.55	61° 43.04	8/9	-6.8	18.5	3.1	80.7	164.2
GU02	Chute du Galion	16° 02.03	61° 39.51	5/5	2.1	24.2	3.9	86.1	86.9
GU03	Carbet (3e chute)	16° 02.84	61° 37.27	8/9	-25.0	24.1	7.7	65.6	203.6
GU04	Grosse Corde	16° 02.41	61° 38.04	8/9	6.1	17.7	2.4	80.8	77.2
GU05	Rivière Noire	16° 02.41	61° 40.32	5/5	1.0	30.2	2.4	89.0	17.2
GU06	Saut d'eau Matouba	16° 02.99	61° 41.99	4/7	-9.5	32.7	4.4	80.7	220.5
GU07	Morne Montval	16° 03.84	61° 42.64	8/8	-1.6	43.8	2.6	80.3	289.7
GU08	Grande Découverte	16° 03.77	61° 39.93	8/9	-23.0	-10.9	3.6	58.6	166.7
GU09	Morne Marigot	16° 05.44	61° 45.28	8/8	241.0	1.7	11.0	-27.5	217.9
GU10	Morne Marigot	16° 05.44	61° 45.28	6/9	162.0	-57.0	9.1	-63.3	85.3
GU11	Morne Marigot	16° 05.44	61° 45.28	9/10	-19.3	31.4	3.8	71.5	213.7
GU13	Grande Rivière	16° 03.49	61° 45.20	9/9	3.6	29.6	3.0	86.5	31.1
GU14	Cascade Vauchelet	16° 02.11	61° 41.18	5/5	13.9	47.7	3.6	71.9	341.1
GU15	Pointe Mazarin	15° 57.68	61° 42.29	7/9	7.2	36.3	4.6	82.0	355.6
GU16	Houëlmont	15° 58.90	61° 41.96	4/5	-0.8	23.9	4.9	86.4	130.9
GU17	Schoelcher	15° 58.88	61° 36.84	8/8	7.5	23.6	1.6	81.9	54.1
GU18	Grande Pointe	15° 58.70	61° 36.95	5/5	9.4	24.5	5.0	80.4	46.2
GU19	Fond Bernard	16° 03.66	61° 41.47	8/9	-8.5	16.9	4.9	78.9	167.5
GU20	Pointe Vieux Fort	15° 57.08	61° 42.22	10/10	-8.1	36.6	4.1	81.1	239.4
GU21	Plessis	16° 02.37	61° 44.69	6/6	0.8	33.7	2.3	87.5	315.8
GU22	Beausoleil	16° 03.64	61° 45.00	6/6	2.5	24.7	2.1	86.1	80.0
GU24	L'Habituée	16° 01.51	61° 35.65	10/10	8.0	33.5	2.6	82.0	10.6
GU25	Carbet (2e chute)	16° 02.74	61° 38.46	6/6	4.8	22.8	6.0	83.7	69.6
GU26	Ravine Longuetau	16° 02.88	61° 38.67	9/9	7.1	34.5	5.0	82.6	4.0
GU27	Bassin Bleu	16° 01.27	61° 39.69	5/5	15.5	23.0	6.9	74.4	41.4
GU28	Bel-Air	15° 58.77	61° 40.18	7/8	-3.4	43.9	3.7	79.8	280.8
GU29	Ravine Longuetau	16° 02.81	61° 38.61	9/10	0.0	32.0	3.6	88.7	298.4
GU30	Ravine Longuetau	16° 02.97	61° 38.75	6/9	-1.7	34.8	2.5	86.5	271.1
GU31	Plessis	16° 02.41	61° 44.30	6/6	1.0	29.6	5.8	89.0	38.9
GU33	Plessis	16° 02.23	61° 44.85	6/6	-2.1	29.0	5.8	87.9	193.4
GU21-31-33	Plessis	16° 02.34	61° 44.64	19/19	-0.1	31.0	2.5	89.3	290.3
GU26-29-30	Ravine Longuetau	16° 02.88	61° 38.70	24/28	1.8	33.8	6.0	87.0	333.1
Mean	All flows except GU08-09-10	16° 01.80	61° 40.80	23/26	0.0	29.6	4.5	89.8	118.3

Column headings indicate site number, flow location, *n/N* (number of data used/total number of samples measured), Lat. (site latitude), Long. (Site longitude), Dec. (declination, in degree), Inc. (inclination, in degree), α_{95} (radius of the 95% confidence cone from *Fisher* [1953] statistics), λ (virtual geomagnetic pole latitude), and ϕ (virtual geomagnetic pole longitude). The mean directions obtained from three sites for the Plessis and Ravine Longueteau flows are indicated. The overall mean direction calculated from 23 out of 26 flows is also given.

obtained at the Centre des Faibles Radioactivités (CFR) laboratory, where the technique was first developed [*Cassignol and Gillot*, 1982]. An additional K/Ar date of 400 ± 20 ka was obtained at the CFR laboratory for flow GU28 (P.-Y. Gillot, personal communication, 1998). Two flows from the recent Madeleine episode [*Blanc*, 1983] have been used for comparison with ^{14}C dating. Radiogenic ^{40}Ar values that are lower than the detection threshold suggest ages lower than 35 ka for a scoriaceous flow and lower than 10 ka for a massive flow. These upper bounds agree with the ^{14}C ages of 10.5 ± 2.0 ka obtained for this episode [*Paterne*, 1980]. Thirteen out of 16 dated lava flows have been sampled for paleomagnetic investigation. The "Morne Goyavier" and "Tuf" flows could not be accessed, and "Habitation Grivelière" displayed indications of fracture. The K/Ar ages of *Blanc* [1983] for which a paleomagnetic direction could also be determined are listed in Table 2.

5.2.2. New age determinations. New K/Ar dating results are reported in Table 3. Potassium contents range from 0.6 to 1%, as expected for groundmass from calc-alkaline lavas. Apart from GU05, which is the youngest dated flow, and GU08, which has a vitreous texture, all flows have radiogenic ^{40}Ar content higher than 2%, allowing relatively small age uncertainties. Dated flows are preferentially located in the CVGD (Figure 1b); the insights brought by these new ages regarding formation of the recent volcanic complex will be discussed elsewhere. New (this study) and older [*Blanc*, 1983] ages are consistent, notably in the northwestern part of the studied area (GU09-13 and GU22-23), where only ages in the 700 - 900 ka range have been found. Indistinguishable ages of 746 ± 13 (Table 3) and 735 ± 47 ka [*Blanc*, 1983] have been obtained for GU22 and D1402a, respectively, which from field observations seem to be from coeval volcanic series. The age of 445 ± 6 ka for GU14, which is located within the GDVC, appears to be rather old compared to GU05 (47 ± 21ka), which is located only slightly higher in La Soufrière massif stratigraphic sequence. However, the very small atmospheric contamination of this sample, as attested by the highest

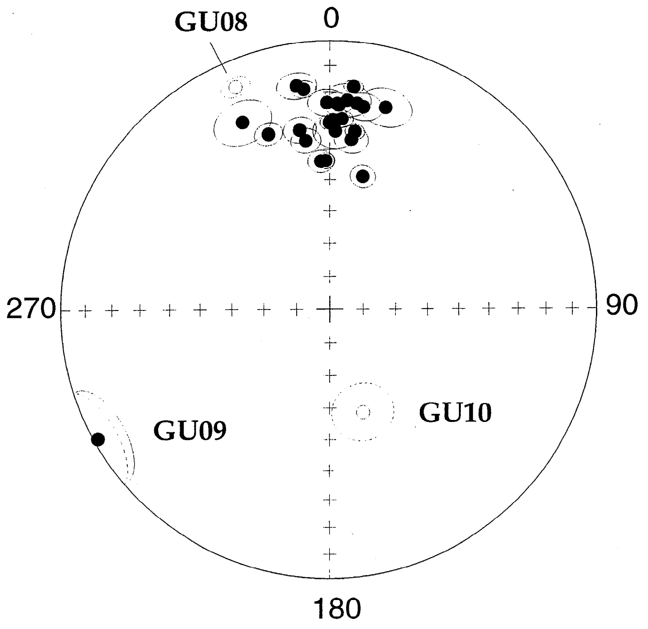

Figure 3. Stereoplot (equal-area projection) of the mean paleomagnetic directions obtained for each flow. Closed and open symbols indicate directions in the upper and lower hemisphere, respectively. The directions of the transitional three flows are labeled (GU08, GU09, GU10).

percentage of radiogenic ^{40}Ar, implies that this age is reliable. It is therefore probably related to an older volcanic series, as revealed by the age of 629 ± 13 ka [*Blanc*, 1983] obtained for the nearby GU06 flow.

All ages agree with the measured paleomagnetic polarity [*Cande and Kent*, 1995], an observation that is also true for previous age determinations [*Blanc*, 1983]. Flow GU08 displays a well defined direction with an anomalous inclination of -11° (Table 1). The relatively low VGP latitude (59°) and the weak NRM argue for a transitional field direction. The obtained age of 205 ± 28 ka places this flow within the age interval estimated for the Pringle Falls excursion [*Herrero-Bervera et al.*, 1994; *Guyodo and Valet*, 1999]. A transitional paleomagnetic direction was recorded by flow GU09. It is overlain by reversed (GU10) and normal (GU11) polarity flows. Age determinations (Table 3) indicate that the Matuyama-Brunhes (M-B) transition has been recorded in this sequence. The indistinguishable ages of 777 ± 14 ka and 785 ± 22 ka, obtained for GU09 and GU11, respectively, are in agreement with a recent geomagnetic polarity timescale [*Cande and Kent*, 1995] and with other dating of this transition performed using the same dating technique [*Valet et al.*, 1999] on lavas from La Palma (Canary Islands).

6. Discussion

6.1. Volcanic Stages

A volcanic chronostratigraphy stands out from the present age data set (Tables 2 and 3). As already observed by *Blanc* [1983], ages obtained for lava flows from southern Basse Terre decrease from north to south. The oldest ages, from about 1 to 0.75 Ma, are only found in the northwestern part of the area and are associated with the Chaîne de Bouillante volcanic stage. The numerous ages found in the 800 - 750 ka interval could represent a burst of activity at the end of this phase. For the 650 - 400 ka interval, lava emissions occurred both south of the Chaîne de Bouillante (in Le Plessis area) and in the Monts Caraïbes (southernmost part of Basse Terre). In between, in a wide east-west trending zone, approximately located at 16°N latitude, there is no evidence for volcanic eruptions during this interval. Only more recent lava flows have been reported there [*Blanc*, 1983]. This zone could correspond to a recent rift system, inferred from regional bathymetric analysis [*Feuillet et al.*, 1997]. A period of relative volcanic quiescence is suggested by the lack of ages for the 400 - 200 ka interval, which following the above hypothesis, could be attributed to inland westward rift propagation. Finally, ages younger than 200 ka are only found within the composite volcano of La Grande Découverte (CVGD [*Boudon et al.*, 1989]) and in the 16°N zone, where recent activity is concentrated. In order to better constrain the different volcanic phases observed in southern Basse Terre, which is beyond the scope of the present paper, geochemical and petrological analyses have been undertaken. Further age determinations are needed to demonstrate that the above observations are not due to insufficient sampling.

6.2. Testing Within-Flow Dispersion

Magnetic variations recorded within a single flow have recently been reported. Up to 10° of directional changes have been measured by *Rolph* [1997] on investigation of the vertical variation of the paleomagnetic vector within two historical flows. Similar variations have been observed by *Bohnel et al.* [1997] on a Holocene flow that was also sampled along a vertical profile. However, few studies have been devoted to the exploration of spatial variations within massive flows exposed on a kilometer scale. In order to quantify the directional within-site dispersion for andesitic lava flows of La Guadeloupe, we sampled two representative flows, "Le Plessis" (LP) and "Ravine Longueteau" (RL), at three distinct locations (GU21-31-33 and GU26-29-30, respectively). The 83 ± 2 ka RL flow (Table 3) is centrally located within the CVGD, while the older LP flow (600 ± 17 ka [*Blanc*, 1983]) is located on the west side of the island and belongs to the Chaîne Axiale volcanism. The topography and position of sampling sites are shown in Figure 4. In both cases, sampling sites are at least 100 m apart. Indistinguishable results were obtained for the three locations from each flow with a confidence parameter (α_{95}) of 4.5° and 6.3° for the LP and RL flows, respectively. Although the mean directions are indistinguishable, the greater uncertainty observed for RL might be explained by the absence of Sun-azimuth orientation for this site, which is located deep in the rain forest. Considering each flow as a single site, all samples from the three locations have been combined to calculate the mean directions given in Table 1.

6.3. Comparison With Earlier Study

Three flows (GU15, GU20, and GU21) had already been sampled in the previous study of *Briden et al.* [1979]. Directions of remanent magnetization obtained for these three flows are reported in Table 4. These directions are quite different and statistically agree only because of the high values of the 95% confidence levels associated with the directions of *Briden et al.* [1979]. The discrepancies observed

Table 2. K/Ar Ages [*Blanc*, 1983] for Lava Flows From Basse Terre for Which a Paleomagnetic Direction Could Also Be Determined

Site	K, %	Rad. ^{40}Ar, %	Age ± 1σ ka	Mean Age, ka
GU01	0.516	7.14	1 030 ± 30	
		8.36	1 017 ± 20	1 023 ± 25
GU03	1.006	3.76	132 ± 6	
		5.55	127 ± 4	129 ± 5
GU06	0.488	12.40	642 ± 13	
		17.10	616 ± 14	629 ± 13
GU07	0.735	11.50	630 ± 15	
		14.80	613 ± 15	620 ± 15
GU12	0.711	2.74	855 ± 50	
		2.81	872 ± 50	863 ± 50
GU13	0.733	12.92	777 ± 18	
		10.72	792 ± 20	784 ± 19
GU15	0.408	3.48	555 ± 26	555 ± 26
GU19	0.926	4.15	149 ± 6	
		3.54	137 ± 6	143 ± 6
GU20	0.644	5.61	469 ± 16	
		5.46	475 ± 16	472 ± 16
GU21	0.745	7.22	600 ± 17	600 ± 17

Column headings indicate site number, K (potassium concentration in percent), Rad. ^{40}Ar (concentration of radiogenic ^{40}Ar in percent), age and one sigma uncertainty (in ka). For each flow, weighted mean age and uncertainty are also indicated.

Table 3. New K/Ar Ages Obtained in This Study

Site	K, %	Rad. ^{40}Ar		Age ± 1σ, ka	Mean age, ka
		%	x10^{10} atoms/g		
GU02	0.694	3.16	5.960	82 ± 4	
		4.55	5.532	76 ± 3	79 ± 3
GU04	0.651	2.41	5.311	78 ± 5	
		3.41	5.193	76 ± 3	77 ± 4
GU05	0.636	0.33	3.058	46 ± 21	
		0.35	3.232	49 ± 21	47 ± 21
GU08	1.063	1.17	24.09	217 ± 28	
		1.05	21.19	191 ± 28	205 ± 28
GU09	0.622	8.38	49.85	767 ± 16	
		11.94	50.91	783 ± 13	
		12.26	50.55	778 ± 13	777 ± 14
GU11	1.031	6.29	83.09	771 ± 20	
		5.13	86.36	802 ± 25	785 ± 22
GU14	0.867	23.08	40.07	442 ± 6	
		29.99	40.53	447 ± 5	445 ± 6
GU22	0.884	9.40	68.86	746 ± 15	
		13.46	68.98	747 ± 12	746 ± 13
GU29	1.048	5.95	8.793	80 ± 2	
		5.54	9.428	86 ± 3	83 ± 2

Column headings indicate site number, K (potassium concentration, in percent), Rad. ^{40}Ar (concentration of radiogenic ^{40}Ar in percent and number of atoms/g of radiogenic ^{40}Ar), age and one sigma uncertainty (in ka). For each flow, weighted mean age and uncertainty are also indicated.

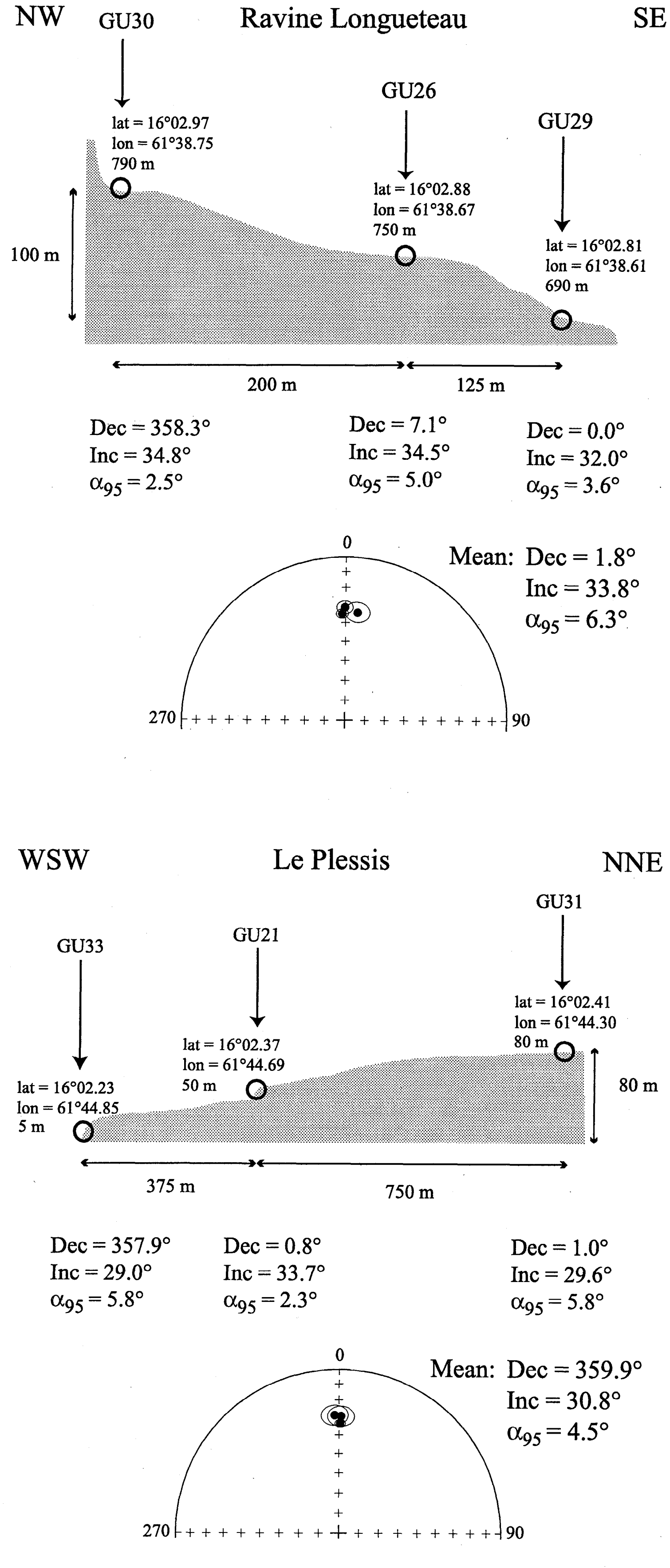

Figure 4. Topography and position of sampling sites for the two flows used for testing within-flow dispersion. For each flow the mean direction and α_{95} [*Fisher,* 1953] obtained for each of the three sites is given and is shown on a stereoplot.

Table 4. Comparison of Paleomagnetic Directions Obtained for Three Flows From This Study and That of *Briden et al.*, [1979]

Flow Location	Site	n/N	Dec.	Inc.	α_{95}	Demag.	Reference
Pointe Mazarin	G23413	9	3	25	13.2	NRM	*Briden et al.* [1979]
	GU15	7/9	7.2	36.3	4.6	AF and TH	This study
Pointe Vieux Fort	G23254	5	n.d.	n.d.		-	*Briden et al.* [1979]
	GU20	10/10	-8.1	36.6	4.1	AF and TH	This study
Plessis	G23201	5	87	23	48.5	NRM	*Briden et al.* [1979]
	GU21	6/6	0.8	33.7	2.3	AF and TH	This study

Column headings indicate flow location, Site number, *n/N* (number of data used/total number of samples measured), Dec. (declination, in degrees), Inc. (inclination, in degrees), α_{95} (radius of the 95% confidence cone from *Fisher* [1953] statistics), Demag. (demagnetization method). NRM indicates that no demagnetization was performed for these flows; AF, alternating field; and TH, thermal.

between the two studies can be explained by the presence of undetected overprints, IRMs due to lightning strikes (in the case of GU15) and by the lack of demagnetization performed for these flows in the earlier study. For each flow, our specimens display straightforward behavior, both in thermal and AF stepwise demagnetization (Figure 5): viscous components are removed after the first few demagnetization steps. The lack of significant susceptibility changes during thermal treatment suggests the absence of dramatic changes in mineralogical properties. This comparison casts doubt onto the accuracy of individual paleomagnetic directions reported in the earlier study of *Briden et al.* [1979]. More generally, it clearly demonstrates the necessity of using only stepwise demagnetized samples when characteristics of the past geomagnetic field are to be inferred.

6.4. Transitional Directions

Because andesitic volcanism is dominantly explosive, sequences of superposed lava flows are rare in Basse Terre. Only one site, exposed by quarry activity, allowed sequential sampling. From the three superposed flows found at Morne Marigot, the lower flow (GU09) is transitional with a VGP latitude of -27.4°, the intermediate flow (GU10) has reversed polarity and the upper flow (GU11) has normal polarity (Table 1). K/Ar dating (Table 3) demonstrated that the M-B transition has been recorded in this sequence, making this site the fifth location on Earth were the M-B transition has unambiguously been identified in lava flow sequences. Each flow is 5 to 10 m thick and is capped by 5 to 10 m of scoria. Possible remagnetization of the underlying reversed polarity flow by the upper normal polarity flow when it was still hot, a phenomenon sometimes observed in transitional records [*Valet et al.*, 1998], is therefore not of concern here. Absolute paleointensity determinations (J. Carlut and X. Quidelleur, submitted manuscript, 1999) indicate that GU10 is associated with low paleointensity and, despite an apparently reversed polarity direction, is well within the transition period [*Lin et al.*, 1994; *Quidelleur and Valet*, 1996].

6.5. Time Evolution

For the 20 dated flows, paleomagnetic directions recorded in Basse Terre have been plotted as a function of age (Figure 6). A relatively good temporal distribution is observed within the Brunhes chron, which indicates that secular variation has largely been averaged in this study. Although declination values oscillate around 0°, a striking difference can be observed in the inclination pattern between the intervals 700 - 400 ka and 200 - 0 ka. In the former interval, all inclinations are above the expected value (under the axial dipole hypothesis) at this site, while in the latter interval, on average, they are shallower. This difference cannot be easily explained in terms of local tectonics because sites from the 700 - 400 ka interval are distributed on both sides and within the CVGD rifting system [*Feuillet et al.*, 1997]. Another argument that may rule out tectonic influence on these data is the relatively low dispersion observed in paleomagnetic directions, especially for inclination values. Such different behavior suggests that it would be instructive to use sub-data sets from different time intervals within the Brunhes chron to compute TAF models. Significantly different mean directions are evident for the two 800 - 400 and 400 - 0 time intervals at Basse Terre. Overall dating in the global database is, unfortunately, not yet of sufficient quality to allow this.

6.6. Normal Polarity Mean

Twenty-six directions from independent paleomagnetic sites are shown on a stereoplot in Figure 3. All flows are of normal polarity except GU10, GU09, and GU08. Although its VGP is not strongly transitional (58.7°N), the latter flow represents an outlier from the overall mean distribution and, as discussed above, could be associated with a geomagnetic excursion. The mean direction ($D = 0.0°$, $I = 29.6°$, $\alpha_{95} = 4.5°$) calculated from the remaining 23 flows is indistinguishable from the expected axial dipole field direction at La Guadeloupe Island ($D = 0°$, $I = 29.7°$, Table 1). Each flow direction has been successively removed from the data set in order to test the stability of this mean direction using a Jacknife approach. Nonsignificant variations result, making this mean direction quite robust (mean declination ranges from -0.7° to 1.2° and inclination from 28.7° to 30.2°).

The angular standard deviation of poles (ASD) has often been used to monitor paleosecular variation [*Cox*, 1970]. The predominant feature associated with this parameter is the significant increase observed as a function of site latitude, from about 12° close to the equator to more than 20° for latitudes higher than 60°. The ASD value of 11.3° obtained at La Guadeloupe is therefore in agreement with this overall picture. Given the small number of sites within the 0° - 20°N

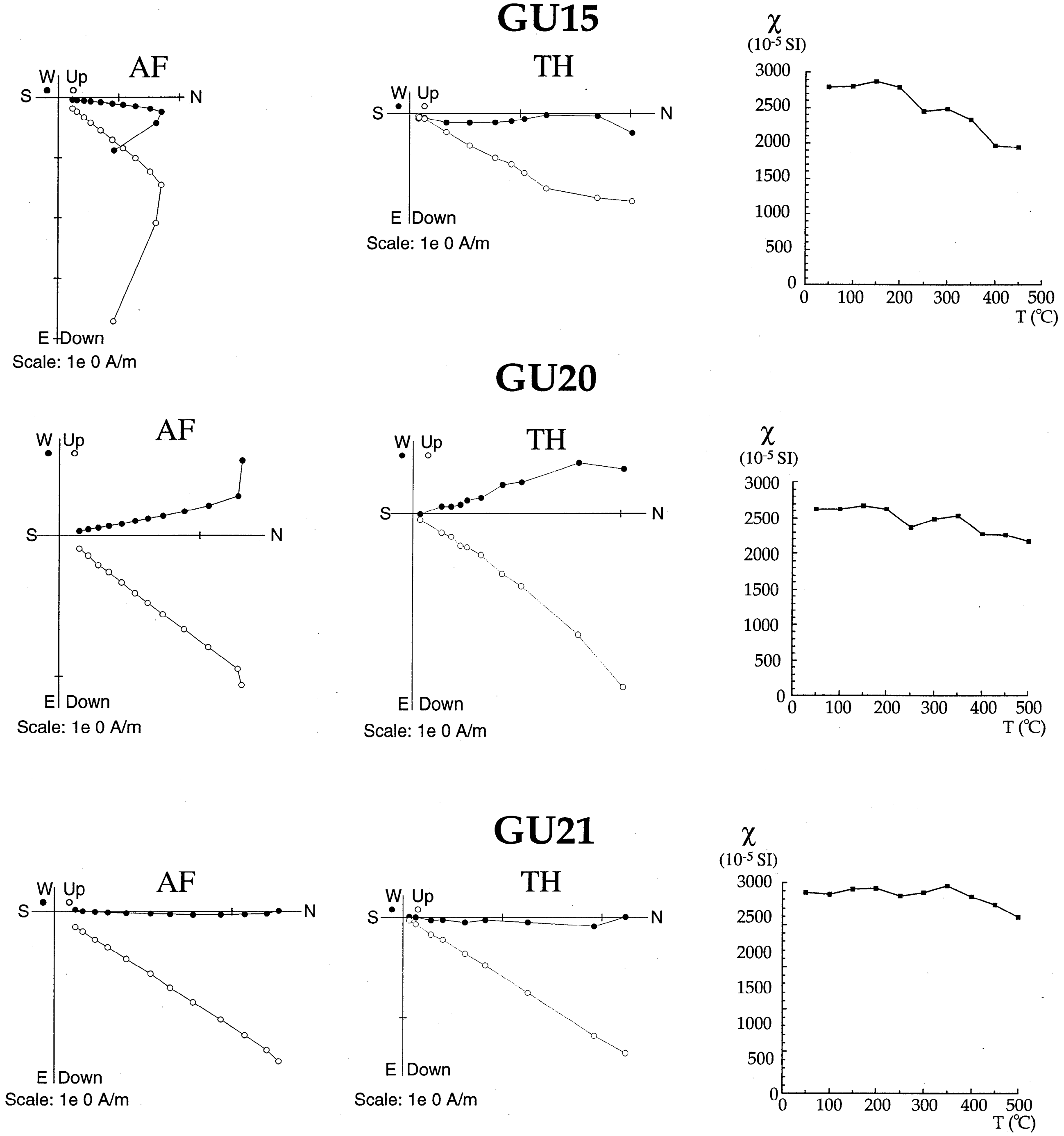

Figure 5. *Zijderveld* [1967] plot of stepwise demagnetization of two samples per flow (one with thermal and one with AF treatment) for the three sites also sampled by *Briden et al.* [1979]. See Figure 3 for convention of plots, and Table 4 for comparison of mean directions.

latitudinal band included in paleomagnetic data sets for the last 5 Myr, this value can be considered representative of the ASD at this site latitude (it is only slightly lower than the expected ASD of 13.5° [*Quidelleur and Courtillot*, 1996]). The wide range of ages available for this study, which are well distributed within the 0 - 1 Ma interval, rules out the hypothesis of insufficient averaging of secular variation. Furthermore, it can be emphasized that, as the number of high-resolution paleomagnetic studies, such as the one presented here, increase, ASD values tend to decrease.

The overall mean direction obtained at La Guadeloupe (this study) for the 0 - 1 Ma interval is therefore indistinguishable from that predicted by a centered axial dipole, and the corresponding mean pole located at the geographic pole. *Briden et al.* [1979] reached a similar conclusion for their whole Lesser Antilles dataset for the 0 - 10 Ma interval. However, when only directions from the last 5 Myr are considered, the mean pole calculated from their data shows a far-sided effect [*Wilson*, 1970] amounting to about 4°. Although this result is not statistically different at the 95%

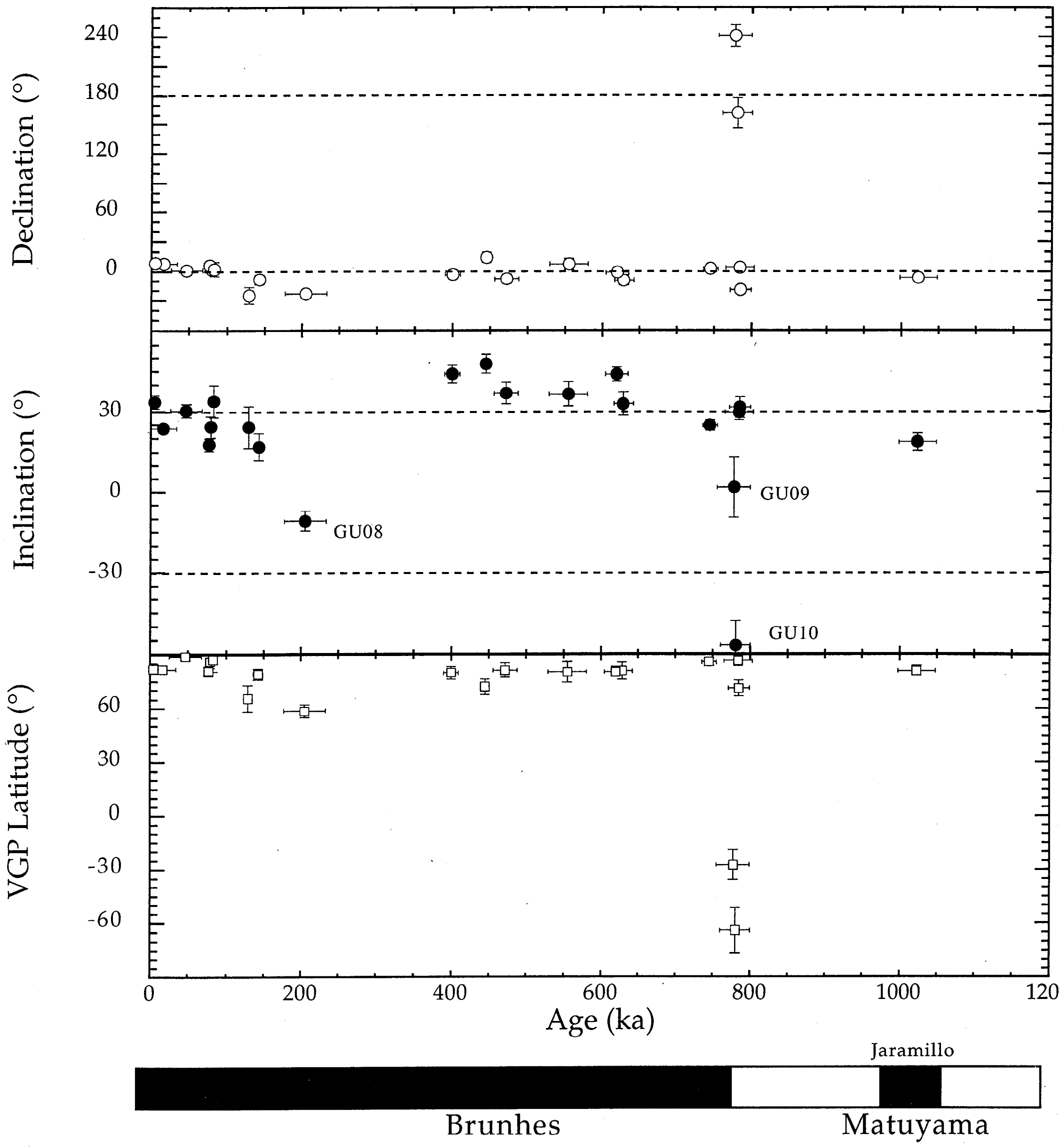

Figure 6. Evolution of paleomagnetic declination, inclination, and VGP latitude as a function of time for the 20 dated flows discussed in this paper. The direction expected for the axial dipole field at La Guadeloupe is shown by dashed lines. A geomagnetic polarity timescale [*Cande and Kent*, 1995] is shown at bottom (black, normal polarity; white, reversed polarity).

confidence level from the 0° far-sided effect that we obtain, this difference has large implications when constructing a TAF model.

6.7. Implications for TAF Models

The far-sided effect, first identified by *Wilson* [1970], has been attributed to the presence of a persistent axial quadrupole superimposed on the main axial dipole [*Wilson*, 1971]. A persistent g_2^0 (axial quadrupole Gauss coefficient) amounting to about 4-5% of the g_1^0 axial dipole term has been reported in most TAF studies covering the 0-5 Ma interval [i.e., *Constable and Parker*, 1988; *Schneider and Kent*, 1990; *McElhinny et al.*, 1996; *Quidelleur and Courtillot*, 1996]. The existence of persistent second-order (nonaxial) terms cannot be established from the present state of available databases [*Carlut and Courtillot*, 1998]. However, *Carlut and Courtillot* [1998] also find robust evidence for a 5% g_2^0 term. These conclusions have been reached from the analysis of directions from lava flows from globally distributed paleomagnetic sites. However, these data sets [i.e., *Quidelleur et al.*, 1994] have a small number of low-latitude northern hemisphere sites, particularly in a wide area around the Lesser Antilles, including the central and southern Atlantic Ocean and South America. This scarcity strongly enhanced the importance of the Lesser Antilles site. There is no general agreement regarding the incorporation of the *Briden et al.* [1979] study in global databases used for TAF models. *Gubbins and Kelly* [1993], *Kelly and Gubbins* [1997], and *Johnson and Constable* [1997] included this study to construct their final TAF model. *Johnson and Constable* [1995] noted its strong influence; yet they included it in one of their models. Based on a jack-knife approach, *Carlut and Courtillot* [1998] rejected the *Briden et al.* [1979] data set.

In order to test the influence of this site on TAF models, we performed two successive numerical calculations using an updated version of the *Quidelleur et al.* [1994] data set (J.

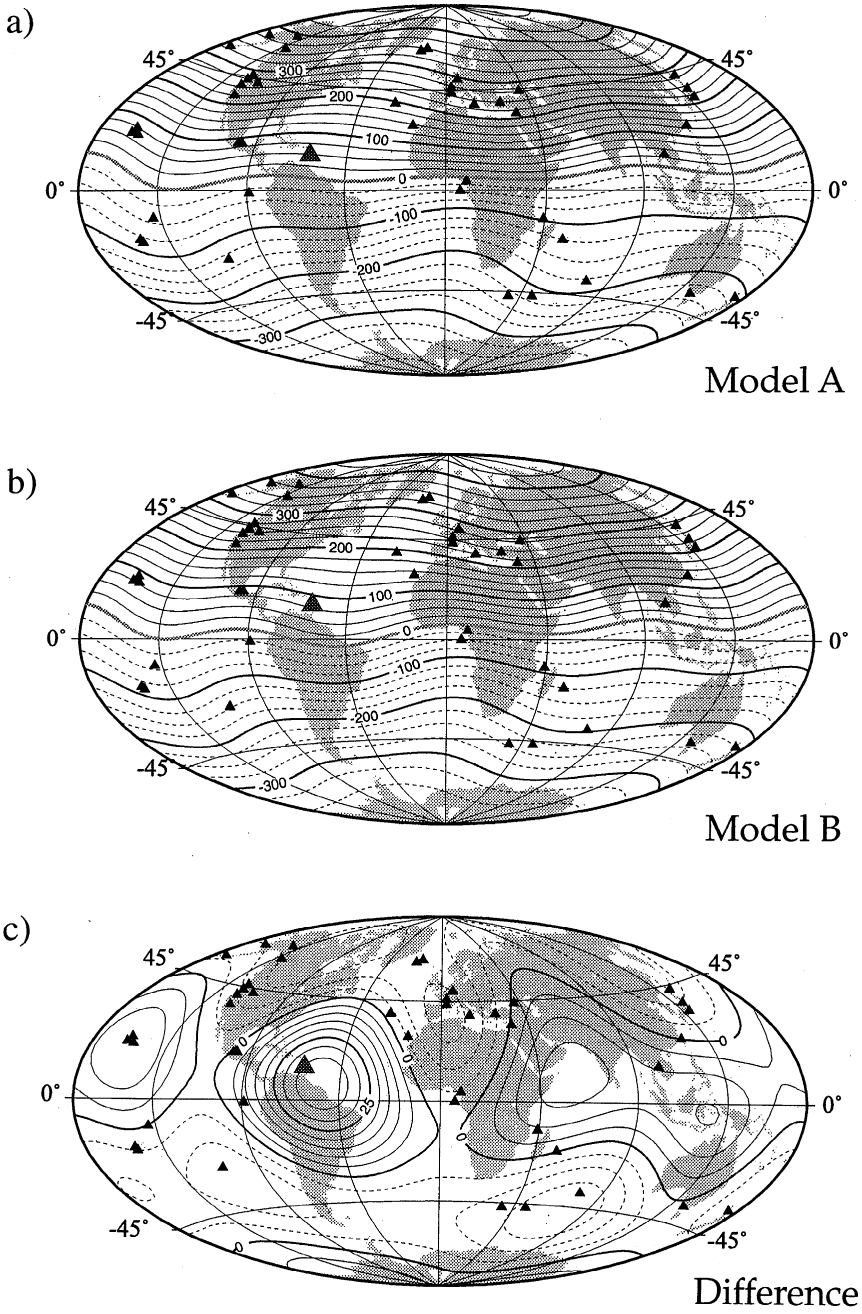

Figure 7. Radial component (B_r, in μT) of the geomagnetic field at the core-mantle boundary obtained by fitting the paleomagnetic database from the last 5 Ma [*Carlut and Courtillot*, 1998] (see text). Geographic location of sites from the database are shown as triangles. The larger triangle shows the location of the Lesser Antilles. (a) Model obtained using the mean direction calculated from *Briden et al.* [1979] for the Lesser Antilles (Model A). (b) Same as Figure 7a but using the mean direction calculated from this study. See Table 5 for listing of the Gauss coefficients obtained for each model. (c) Difference of B_r (in μT) between models A and B.

Carlut and X. Quidelleur, available at http://www.ipgp.jussieu.fr/depts/PALEOMAG/VARSECU/Intro.html). First, the mean direction calculated from the *Briden et al.* [1979] study has been used for the Lesser Antilles site (model A), while in the second calculation (model B), it has been replaced by the mean direction obtained in the present study. TAF models were determined using the Occam algorithm of *Constable et al.* [1987], developed up to degree 4 (see *Carlut and Courtillot* [1998] for a description of the method). The radial component of the field (B_r) at the core mantle boundary (CMB) is shown in Figures 7a and 7b for models A and B, respectively. The most striking change between models A and B is the significant southward displacement of the magnetic equator south of the Lesser Antilles in model B. This corresponds to a lower axial-quadrupole Gauss coefficient (g_2^0) in model B (3.4%) compared to model A (4.8%) (Table 5). The 30% decrease in the g_2^0 term, from -1448 nT to -1034 nT, represents the major change from model A to B. Other terms do not show such strong changes, though they appear, overall, to be slightly smaller. The simpler field configuration obtained for

Table 5. Gauss Coefficients and Energy Spectrum [*Lowes*, 1974] of the Model Fitting the Paleomagnetic Database From the last 5 Ma [*Carlut and Courtillot*, 1998]

		Model A			Model B		
l	m	g_l^m	h_l^m	R_l	g_l^m	h_l^m	R_l
1	0	-30.000			-30.000		
1	1	0.198	0.194		0.053	0.246	
2	0	-1.448			-1.034		
2	1	0.049	-0.275		0.037	-0.304	
2	2	0.250	-0.449	7.315	0.340	-0.264	4.046
3	0	-0.498			-0.402		
3	1	0.133	-0.241		0.177	-0.257	
3	2	-0.145	0.096		-0.100	0.050	
3	3	-0.085	0.006	1.444	0.029	0.056	1.101
4	0	0.079			0.022		
4	1	0.117	0.046		0.092	0.018	
4	2	0.026	-0.068		0.009	-0.087	
4	3	-0.081	-0.095		-0.040	-0.074	
4	4	0.084	0.011	0.249	0.129	-0.009	0.204

For Model A the mean direction calculated from *Briden et al.* [1979] was used for the Lesser Antilles, while in Model B the mean direction obtained in this study was used. Column headings indicate degree (l), order (m), and Gauss coefficients g_l^m and h_l^m in μT, and energy spectrum (R_l) in μ^{2}T^2 (see text).

model B (Figure 7b and Table 5) corresponds to a lower energy spectrum [*Lowes*, 1974] for each degree (l = 2 to 4) of the spherical harmonic representation (Table 5; because the value of the axial dipole coefficient is set to 30 μT, the energy spectrum is not calculated for degree l = 1). The differences between the two models are more easily analyzed using the difference of the B_r component at the CMB (Figure 7c). This shows strong differences of up to 35 μT (9% of maximum B_r at the poles), representing an increase of more than 50% over a wide region centered on the Lesser Antilles. This underlines the strong influence of this site on the TAF model because it is located in an area with no other data. Similar conclusions regarding site distribution effects have recently been drawn by *Carlut and Courtillot* [1998].

7. Conclusions

Paleomagnetic and geochronologic investigations of 23 independent andesitic lava flows have been conducted in La Guadeloupe Island, French West Indies. Previous [*Blanc*, 1983] and new K/Ar ages obtained at the UPS-IPGP laboratory indicate that the time interval covered by the present sampling is between 0 and 1 Ma. In the only sequence of superposed flows, the Matuyama-Brunhes transition, with a mean age of 781 ± 18 ka obtained for two flows, has been recorded. Only one out of three flows displays intermediate directions, with a VGP located in the southern Pacific Ocean.

The mean paleomagnetic direction calculated from the present data set leads to a significant revision of the direction deduced for the last 5 Ma from a previously published study of the Lesser Antilles [*Briden et al.*, 1979]. This is of major importance because for this time interval, it is the only site available in paleomagnetic databases for a wide area surrounding the Lesser Antilles. Iterative calculations which were performed using an Occam algorithm [*Constable et al.*, 1987] indicate that substituting the mean direction obtained in this study for that of *Briden et al.* [1979] significantly changes the TAF model. The major difference is observed for the axial quadrupole term, which is reduced by more than 30%. The resulting g_2^0/g_1^0 ratio is reduced from 4.8 to 3.4%, which compares well with the 3.6% estimate of *Carlut and Courtillot* [1998].

The high-quality dating obtained in the present study suggests that it could be quite instructive to perform analyses of the TAF in smaller time intervals than what is usually done. The difference in inclination found in the Lesser Antilles between 600 - 400 and 200 - 0 ka could indicate characteristic changes in the axial quadrupole over timescales of the order of several hundred thousand years. Unfortunately, the present state of global databases does not allow testing of this hypothesis, and much more temporally well-constrained paleomagnetic data are needed from all over Earth's surface.

Finally, this study strongly suggests that TAF models may be significantly influenced by both the poor site distribution and the use of old studies that require revision [*McElhinny and McFadden*, 1997]. These models are therefore likely to change as more high-quality data are included in global data sets.

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