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K–Ar GEOCHRONOLOGY AND PALAEOMAGNETISM OF VOLCANIC ROCKS IN THE LESSER ANTILLES ISLAND ARC

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CONTENTS

K–Ar age determinations, mainly whole rock, with some corroboration from mineral separates, are presented for lava flows, domes, minor intrusives and blocks in tuffs from 95 localities in the Lesser Antilles. Together with the much smaller number of previously published data, these show a distinction between a range 38–10 million years (Ma) in the outer arc (Limestone Caribbees) and less than 7.7 Ma in the inner arc (Volcanic Caribbees). From southern Martinique southwards, the two arcs are superposed, and the whole range is fragmentarily represented. The observed age ranges in the outer and inner arcs fit between discontinuities in sea floor spreading in the North Atlantic at *ca.* 38 and *ca.* 9 Ma and a causal connection between spreading change and relocation of arc volcanicity is suggested.

Palaeomagnetic directions at 108 localities in ten of the islands fall into normal ($N = 56$, $k = 13.8$, $D = 359°$, $I = +22°$, pole position 229° E, 89° N with $\mathrm{d}\psi = 3°$, $\mathrm{d}\chi = 6°$) and reversed groups ($N = 41$, $k = 14.1$, $D = 178°$, $I = -22°$, pole position 18° E, 88° S with $\mathrm{d}\psi = 3°$, $\mathrm{d}\chi = 6°$) plus six sites of intermediate polarity and five sites indeterminate. The mean dipole axis is within 2° of the present rotation axis and is likely to be identical with it with a probability of 99 %. The data are generally in accord with the established geomagnetic polarity time scale, but there is some suggestion of a normal polarity event at *ca.* 1.18 Ma within the Matuyama Reversed Epoch. The palaeomagnetic data relate mainly to be past 10 Ma and suggest that

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within that time the Lesser Antilles have not changed their latitude or geographic orientation, and that the geomagnetic field has averaged that of a centred axial dipole. The few older palaeomagnetic data are consistent with these same conclusions (though with less certainty) back to *ca.* 20 Ma ago. There is no evidence for oroclinal bending of the arc since then.

1. Introduction

This joint geochronological and palaeomagnetic study of the Lesser Antilles island arc is aimed at (1) providing a time framework for related petrological studies of its volcanic evolution, (2) testing whether palaeomagnetic polarity identification could, in conjunction with the known geomagnetic polarity time scale, reduce uncertainty in age determination below the analytical limits of conventional K–Ar techniques, (3) determining palaeomagnetic poles and interpreting whether any deviations they may have from the present geographic pole are due to geotectonic or geomagnetic effects, and (4) ascertaining whether the new data enable better interpretation of the evolution of the Lesser Antilles island arc and the Caribbean plate, in relation to the Atlantic Ocean and its margins. The Lesser Antilles island arc (figure 1) was not ideal for discerning global aspects of such a study for three reasons. Outcrop is poor. There is only a limited amount of geological mapping of the islands and relations between many of the lava flows and stratigraphically dated pyroclastic sequences are uncertain. There is invariably a lack of sequence control on lava flows from central volcanoes, as compared with that often available from plateau volcanics.

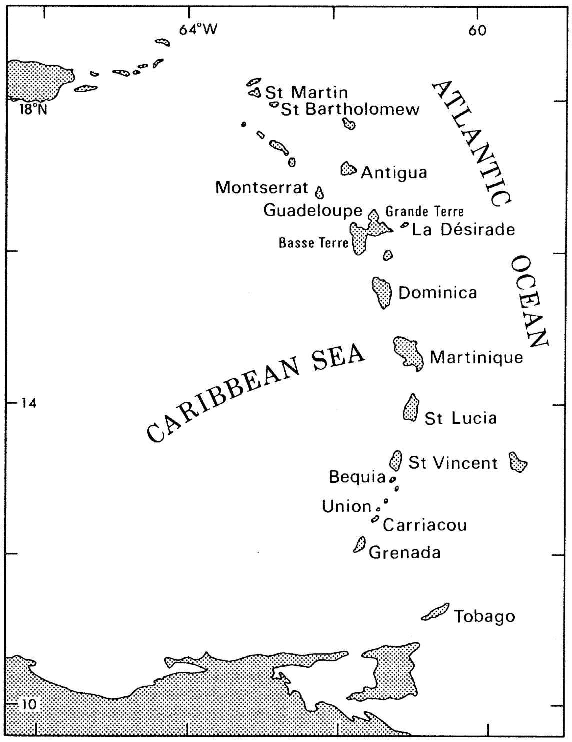

Figure 1. Location map of the islands of the Lesser Antilles. Only the islands studied in this paper are labelled.

Inspection of 'pre-drift' maps of the continents around the Atlantic (e.g. Bullard, Everitt & Smith 1965) shows that the North and South Atlantic 'mainlands' were so closely adjacent prior to the opening of the Atlantic that no Caribbean plate could have existed. North America began to move away from Africa about 200 Ma ago, though large scale spreading did not commence until some 20 Ma later (Pitman & Talwani 1972). The South Atlantic began to open about 127 Ma ago (Larson & Ladd 1973) and if, as seems likely, it opened about a different tectonic rotation pole with respect to Africa than did North America with respect to Africa, then it is from this time onwards that a progressive insertion of additional crust – the Caribbean plate – between North and South America may have occurred. It is important, then, to ascertain the maximum age of material which can be assigned to that plate. By chance, the first radiometric age to be published from the Lesser Antilles area was *ca.* 140 Ma (Fink 1970; Mattinson, Fink & Hopson 1973) but it is now clear that this is an isolated occurrence and in any case doubt has recently been cast upon its validity (Dinkelman & Brown 1977). Marine geological studies of the Venezuelan Basin indicate that it has been an area of pelagic deposition since a period of extensive flood basalt emission about 80 Ma ago (Donnelly 1975). The Greater Antilles have a stratigraphic history extending well back into the Mesozoic (Khudoley & Meyerhoff 1971). Fossil identifications on the islands of the Lesser Antilles indicate ages of marine sediments as old as early Eocene (Lewis & Robinson 1976). These early Tertiary sediments were deposited on a developing island arc where activity has since ceased, and has been succeeded as the site of volcanism by the Volcanic Caribbees. Knowledge of the age distribution of volcanic activity in the Lesser Antilles is essential for an understanding of the tectonic history of the region.

2. METHODS

Most of the palaeomagnetic samples for this study were cored at outcrop using a portable petrol driven drill, and oriented by sun compass. Where circumstances dictated, block sampling and magnetic orientation were substituted, cores subsequently being cut from block samples in the laboratory. The cores were prepared into 25 × 25 mm cylinders with original orientation marks preserved for measurement of remanent magnetization vector by using a PAR SM2-D spinner magnetometer. Alternating field demagnetization was carried out on all samples, with equipment similar to that described by McElhinny (1966). As an example, the treatment of the data from St Lucia is illustrated in figure 2. Site mean directions of total natural remanent magnetization (n.r.m.) show considerable scatter and a tendency to group near the present geomagnetic field direction (figure 2*a*). Optimum fields for magnetic cleaning were selected using the criterion of minimum proportional change in magnetization vector between successive demagnetization steps (Briden 1972), i.e. the figure for which Briden's stability index (s.i.) was a maximum (figure 2*d*, *e*); where there was an ambiguity in maximum s.i., the criterion of minimum directional change between demagnetization steps was used (figure 2*b*) which commonly identifies optimum fields which correspond to a kink in the demagnetization curve (figure 2*f*, *g*). Site mean directions after magnetic cleaning not only show increased internal precision, as indicated by Fisher (1953) analysis (table 7) but are also more closely grouped into normal and reversely magnetized sets (compare figure 2*a*, *c* and see table 14). The wide range of textural types and mineralogical compositions among the basalts is reflected in the diversity of alternating field (a.f.) demagnetization curves. Those with the least low remanence-coercivity material are among the most highly oxidized, but the remanence-coercivity spectra

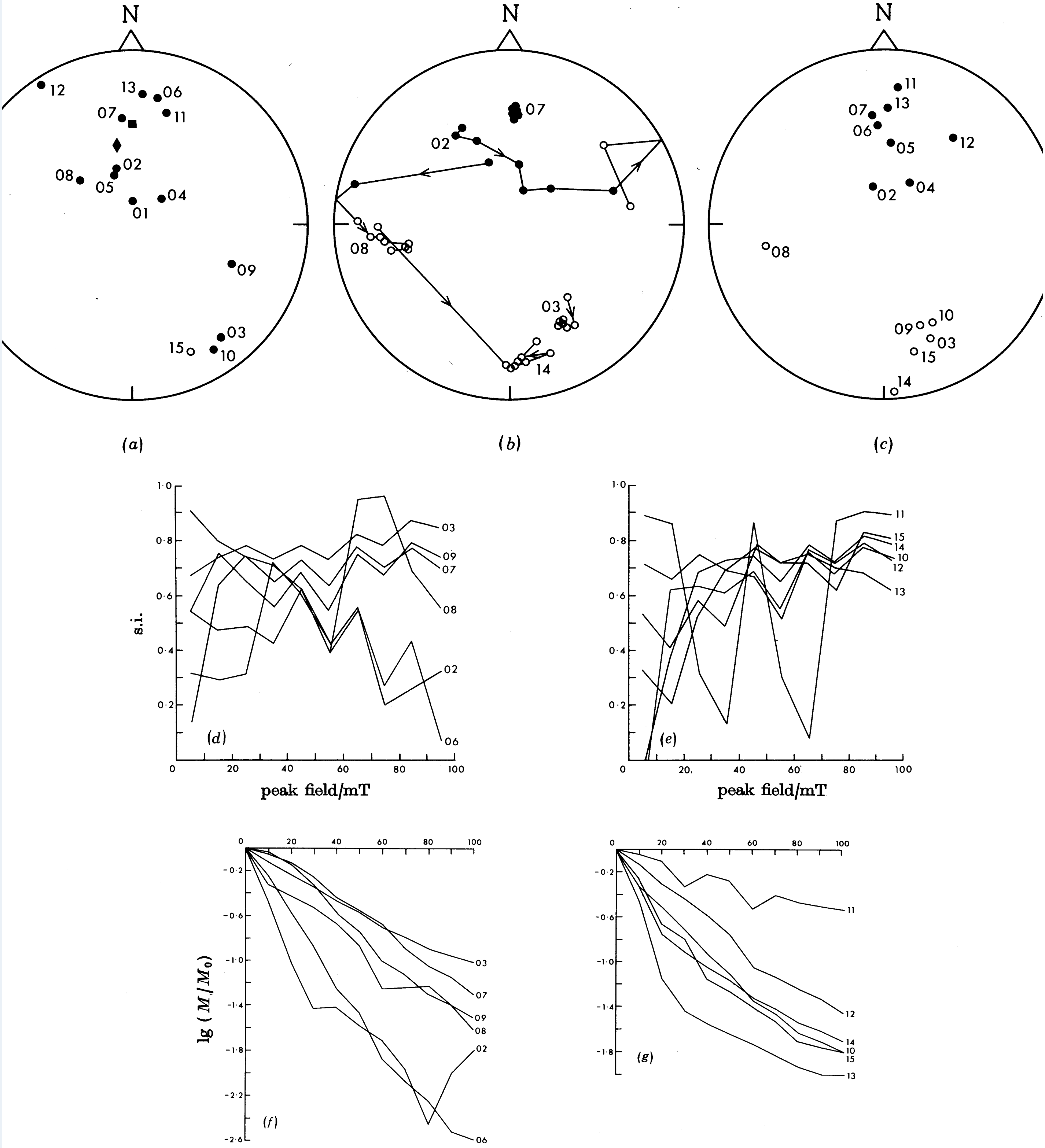

FIGURE 2. Palaeomagnetic data from St Lucia. (*a*) Site mean directions of total n.r.m., (*b*) progressive a.f. demagnetization of pilot specimens and (*c*) site mean directions of stable remanence isolated by a.f. cleaning. These figures are stereographic projections in which solid symbols denote downward (positive) inclinations and open symbols denote upward (negative) inclinations; the numbers refer to sample sites (see table 7; site prefix 7024 omitted from the figures); ◆ denotes the present geomagnetic field and ■ the geocentric axial dipole field direction. (*d*), (*e*) Plots of Briden's (1972) stability index (s.i.) as a function of applied alternating magnetic field for a specimen from each site. Normalized demagnetization curves are plotted on logarithmic scale in (*f*) and (*g*), including those specimens selected for illustration in (*b*).

deduced from nearly all the a.f. demagnetization curves are unimodal and constitute evidence that remanence is commonly carried by a single mineralogical component. Isothermal remanent magnetizations (i.r.m.) were imposed by using a Varian electromagnet with field monitored by Hall probe, and magnetization measured with Forster fluxgates in gradiometer configuration (cf. Helbig 1965). Figure 3 shows an example from Grenada in which although a.f. demagnetization effectively cleans the n.r.m., hysteresis of i.r.m. shows high coercivity haematite to be the dominant bulk magnetic component; the haematite in this rock evidently does not contribute to the remanence.

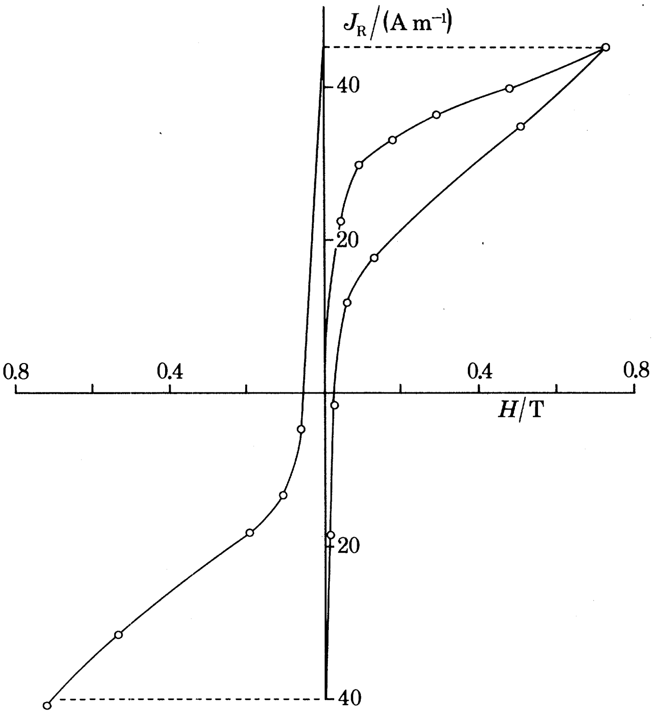

FIGURE 3. Hysteresis of isothermal remanent magnetization (J_R) in preapplied fields (H) for a specimen from site 6928084, Grenada. J_R units are approximate.

The majority of the geochronological determinations were made on crushes of the palaeomagnetic samples themselves (as numbering in the tables in this paper indicates). On the basis of these determinations, specific collections of block samples for K–Ar dating purposes were subsequently made. Criteria for acceptance for analysis were based on thin section examination, namely (1) no secondary calcite or zeolite should be present, (2) feldspars should show no sericitization, (3) the groundmass should contain less than 10% of interstitial glass, and (4) no obvious xenolithic material should be present. The samples were crushed and sieved, the -60 $+90$ size fraction being used for both potassium and argon determinations. Where possible, biotite or hornblende was separated and analysed.

Potassium was determined in triplicate by using an EEL flame photometer (Dodson & Rex 1971). Argon was extracted in a glass vacuum system using ^{38}Ar tracer from an aliquoting system. Special attention was given to the purity of the gas sample before analysis. A two-stage 'clean up' procedure was used, stage one incorporating a Ti-sponge furnace, a Cu/CuO furnace and a liquid N_2 trap. The purified gases were then drawn into a second 'clean up' section on activated charcoal containing a further Ti-sponge furnace. A small aliquot of the gas was then tested on the mass spectrometer for purity before the argon analysis. Argon isotopes were measured on a modified AEI MS10 mass spectrometer fitted with automatic peak-switching and digital output (Rex & Dodson 1970). The percentage difference between replicate determinations of the whole of this collection was plotted as a function of radiogenic ^{40}Ar, and the best curve through these data was used to estimate 1σ errors in the individual analyses, as quoted in the tables. International standards were analysed and atmospheric-argon ratios were determined on a regular routine basis. Ages were calculated using the decay constants and branching ratio agreed by the IUGS Sub-commission on geochronology (Steiger & Jäger 1977). The geomagnetic polarity time scale of McDougall (1979) which is based on these conventions is used as reference standard. Published ages which underwent numerical revision by recalculation to this new basis are denoted in the text by an asterisk. However the Tertiary stratigraphic time scale has yet to be comprehensively revised in line with the new constants and rather than undertake an *ad hoc* revision which is beyond the scope of the present work we have adhered to that of Berggren (1972). This results in the numerical data of figure 19 being calculated according to a formerly accepted K–Ar decay scheme for comparison with the stratigraphy.

3. St Martin and St Bartholomew

Figures 4 and 5 respectively show our new K–Ar data (table 1) for St Martin and St Bartholomew, superimposed on generalized versions of the geological maps of Christman (1953) together with the geochronological data of Nagle, Stipp & Fisher (1976).

The geological relations within St Martin are best expressed with respect to the widespread Pointe Blanche Formation of mainly volcaniclastic sediments of mid to late Eocene age (Christman 1953). According to Christman, the Pointe Blanche Formation was first intruded by andesites and basalts and these in turn were cut by intrusive diorites. We have a single determination of 31.1 Ma for a basalt and ages in the range 31–28 Ma for the cross cutting diorites. These results are, then, entirely consistent with the volcanic history proposed by Christman. They suggest that both andesitic and dioritic activity occurred within an interval of 2 or 3 Ma and that the explosive volcanism represented in the Pointe Blanche Formation is of a separate episode about 10–15 Ma older.

Many of the K–Ar data of Nagle *et al.* (1976) are consistent with this picture. They have determined an age of *31 Ma from close to locality SM16 where our data, at 28.6 Ma, are concordant between whole rock and its component hornblende and biotite. Moreover Nagle *et al.* (1976) have determinations of *33 and *31 Ma for dykes cutting the Pointe Blanche Formation. However they also present two ages of *37 Ma and one of *26 Ma which appear to be in conflict with the remainder of the geochronological data and with Christman's (1953) interpretation of the sequence of events.

On St Bartholomew, Nagle *et al.* (1976) record ages of about *36 and *33 Ma, similar to their findings on St Martin. They also report an age of *24 ± 3 Ma from the same diorite on the southwest coast which we have dated at 26.5 ± 0.8 Ma. It may be then, that the timing of igneous events on St Martin and St Bartholomew are similar, though activity may have continued slightly later on St Bartholomew.

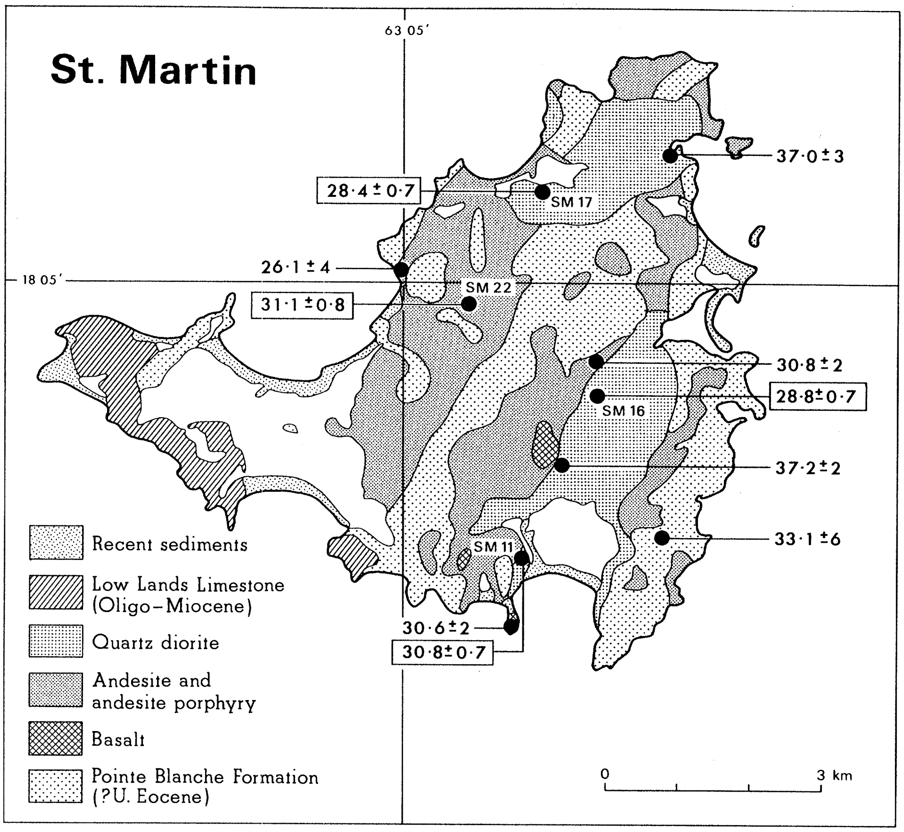

FIGURE 4. Simplified geological map of St Martin (after Christman 1953) with geochronological data added (table 1; Nagle *et al.* 1976). In this and subsequent figures, our new data are summarized in boxes in the order: palaeomagnetic polarity (+, reversed; −, normal; I, intermediate) and K–Ar age and standard error (Ma); at many localities not all of these data are available. Previously published geochronological data are also added (unboxed).

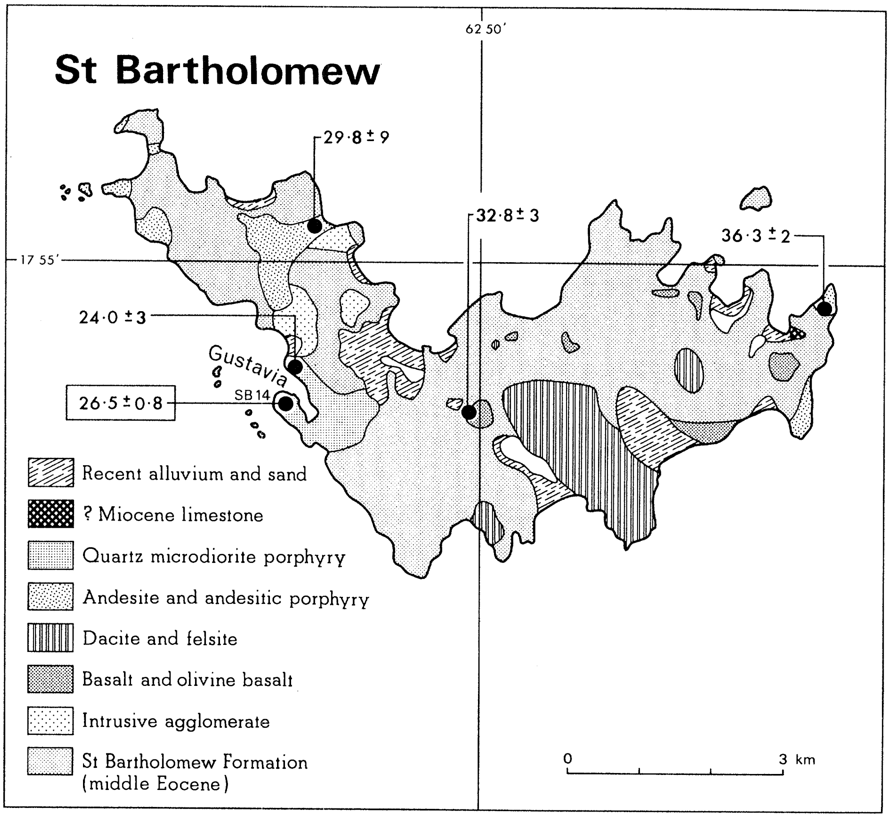

FIGURE 5. Simplified geological map of St Bartholomew (after Christman 1953) with geochronological data added (table 1; Nagle *et al.* 1976). Format as figure 4.

TABLE 1. ST MARTIN AND ST BARTHOLOMEW

(w.r., whole rock; bio., biotite; hb., horneblende)

	sampling details				K–Ar analysis				
	locality	latitude °N	longitude °W	rock type	material analysed	K (%)	vol. ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
Martin									
SM17	Pic O'Reilly	18° 06.1′	63° 03.3′	diorite	w.r.	1.19	1.3197	62.6	28.4 ± 0.7
							1.3267	65.6	
SM16	Belle Plain	18° 03.7′	63° 02.8′	quartz-diorite	bio.	6.57	7.4022	86.8	28.8 ± 0.7
					hb.	2.68	2.9945	80.2	28.5 ± 0.7
					w.r.	1.50	1.7072	66.8	29.0 ± 0.8
SM11	quarry above St Julian	18° 01.9′	63° 03.7′	quartz-diorite	bio.	7.17	8.7164	86.0	30.6 ± 0.7
							8.5055	83.8	
					w.r.	1.22	1.4794	19.1	31.1 ± 1.0
							1.4948	19.7	
SM22	Columbiet	18° 05.2′	63° 04.2′	basalt dyke	w.r.	0.362	0.4436	47.4	31.3 ± 0.8
							0.4378	52.3	
Bartholomew									
SB14	Gustavia	17° 54.1′	62° 51.3′	diorite	w.r.	1.07	1.1355	30.8	26.5 ± 0.8
							1.0902	33.6	

TABLE 2. ANTIGUA

sampling details				stable n.r.m., a.f. cleaned						whole rock K–Ar analysis			
locality‡		latitude °N	longitude °W	rock type	polarity§	peak field mT	number of specimens	R‖	D‖	I‖	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	minimum age Ma
02101	Johnson's Point	17° 01.6′	61° 52.6′	andesite lava flow		20	3	1.50	—	—	—	—	—	—
00014														
02102					+	20	4†	3.71	165	−20	0.768	0.5952	23.7	19.8
02103					+	20	4†	3.80	185	+35	1.530	1.3894	41.1	23.2

† One anomalous specimen or sample has been disregarded.
‡ In all tables, the locality reference is both the palaeomagnetic site number and the geochronological sample number.
§ Normal polarity is conventionally negative, reverse polarity positive.
‖ The palaeomagnetic statistics consist of the site mean direction with declination D, inclination I as the resultant R of N unit vectors, analysed by giving unit weight to specimens, after Fisher (1953).

4. ANTIGUA

We only regarded one locality in Antigua as sufficiently fresh for palaeomagnetic study. This is subdivided in table 2 into three palaeomagnetic sites – three different outcrops probably in the same lava flow – of which two showed reversed polarity and the third was magnetically unstable, and polarity was indeterminable. These lavas were so highly calcitized that we would not normally have attempted K–Ar analyses on them, but did so because they were the only samples from Antigua. The age determinations, which come from the two outcrops of reversed polarity, must be regarded as minimum, i.e. the rocks are older than 23.2 Ma. Our results are similar to ages of *24 and *21 Ma (figure 6) obtained by Nagle *et al.* (1976) which they also regarded as minimum ages for the same reason, and are to be compared with the estimated mid-Oligocene age of related sediments (Christman 1972), i.e. about 30 Ma on the time scale of Berggren (1972).

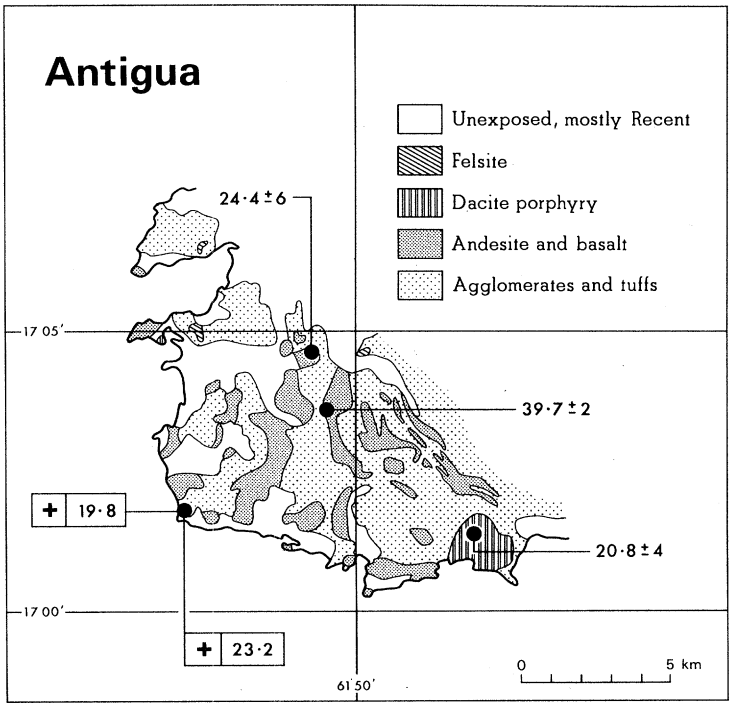

FIGURE 6. Simplified geological sketch map of southwestern Antigua (after Christman 1972) with palaeomagnetic and geochronological data added (table 2; Nagle *et al.* 1976). Format as figure 4. Prefix 70210 is omitted from site numbers.

5. MONTSERRAT

The volcanic geology of Montserrat has been studied principally by MacGregor (1938), Martin-Kaye (1959*b*) and Rea (1974). Rea (1974) recognized five major volcanic centres (figure 7) and the ages reviewed in this section (table 3) were quoted in this paper but the analytical data have not previously been published. The oldest of these centres, in the east-central part of the island, is known as the Harris–Bugby centre from which the age of *4.41 Ma has been obtained. Younger complexes at the northern and southern ends of the island (Silver Hill and South Soufrière Hill respectively) yield single ages at *1.59 Ma (D. C. Rex, quoted by Rea (1974)) and *1.6 Ma; hence they are at least partially contemporaneous. However Rea (1974) also notes that the South Soufrière centre was still active after the emplacement of the Landing Bay Dacite dated at *0.93 Ma. Rea (1974) believes that the Centre Hills volcanic centre (in the west and central parts of the island) was active within this *1.64–*0.93 Ma timespan. The youngest centre, in the Soufrière Hills, has been historically active, and ^{14}C ages of the order of tens of thousands of years have also been reported (Rea 1974).

The stable palaeomagnetic polarity is reversed in the two samples from the Harris–Bugby centre, one of which was the dated sample. Reversed polarity is also observed in the dated sample from South Soufrière Hills, and normal polarity in the Landing Bay Dacite; in both these cases the analytical uncertainty in the ages is such that the coincidence of the quoted mean age with normal polarity events in the Matuyama Epoch is not worthy of detailed appraisal. The remaining polarity determination reported in table 3 is of reversed polarity in a sample some 400 m from the locality on Silver Hill which Rex (in Rea 1974) dated within the Matuyama Epoch (as noted above).

All these palaeomagnetic observations were made on single samples, and hence only polarity is quoted, and not mean direction; nor are these incorporated in the overall compilation in table 14.

Table 3. Montserrat

	sampling details				stable n.r.m., a.f. cleaned		whole rock K–Ar analysis†			
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
M122 (18609)	Bugby Hole	16° 45.0′	62° 10.0′	two-pyroxene andesite lava (?flow)	+	20	0.626	0.1075	17.0	4.41 ± 0.33
M137 (18614)	Pea Gut below Harris Village	16° 44.2′	62° 10.2′	two-pyroxene andesite lava (?flow)	+	20				
M296 (18367)	W Shoe Rock S Soufrière Hills	16° 40.4′	62° 10.2′	basalt lava flow	+	15	0.717	0.0456	5.4	1.64 ± 0.53
M352 (18646)	Silver Hill	16° 48.7′	62° 11.7′	two-pyroxene andesite lava (?) dome	+	20				
M400 (18646)	Landing Bay S Sweeneys Well	16° 41.4′	62° 09.1′	hornblende-hypersthene dacite lava dome	−	10	0.916	0.0330	9.0	0.93 ± 0.38

† Analysis by J. C. Briden at the Department of Geology and Mineralogy, University of Oxford, by using MS10 Spectrometer, quoted by Rea (1974); the Oxford departmental accession series numbers are shown in brackets beneath the field numbers in the first column.

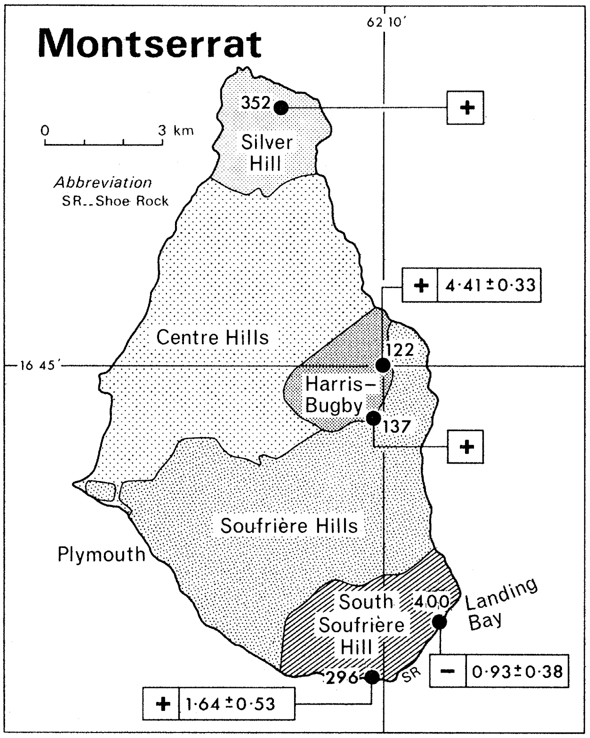

Figure 7. Outline map of Montserrat, showing the main volcanic centres distinguished by Rea (1974), and the palaeomagnetic and geochronological data (table 3). Format as figure 4.

6. Basse-Terre, Guadeloupe

The new data from Basse–Terre (table 4 and figure 8) are described by reference to the stratigraphy of the island described by de Reynal de Saint-Michel (1965), who regarded the older volcanics as Miocene or older, and Mervoyer (1974) who contended that the exposed volcanics were all Pliocene or younger. Our principal findings are that the K–Ar ages agree closely within the various volcano-morphological units described by these workers and their sequence is broadly consistent with the morphological sequences suggested by them. However, the time scale indicated by the K–Ar analyses is compressed by a factor of about ten compared with the age range estimated by de Reynal de Saint-Michel: areas denoted by him as 'pre-Miocene' yield ages in the range 2.52–1.98 Ma, 'Miocene' rocks yield ages in the range 2.28–1.15 Ma, and Pliocene volcanics date in the range 1.77–0.91 Ma.

Mervoyer (1974) distinguished four magmatic units. The first of these, which he regarded as Pliocene, covers most of the northwest quarter of the island and is represented by our age determinations in the range 2.52–1.15 Ma. The older of these determinations come from the extreme northwest and from the coast near Pointe Mahout and the younger ones from further inland between Anse Colas and Morne à Louis; it may that the latter would more properly be grouped with Mervoyer's second unit, which was a belt across the middle of the island, including the Pitons de Bouillante. Mervoyer (1974) regarded this area as late Pliocene, but we have obtained age determinations in the range 1.24–0.91 Ma. He correlated this area with outliers of dacitic ignimbrites in the extreme northwest, which we have not been able to date radiometrically and which were also palaeomagnetically unstable. Third in Mervoyer's chronology was the Monts des Caraibes centre which our analyses (1.77 and 1.37 Ma) would place earlier than his second unit. Both our dated samples have normal polarity and may represent the Gilsa Event (*ca.* 1.62 ± 0.08 Ma, McDougall 1979). Perhaps this is an example where the combination of polarity, K-Ar analyses, and the published time scale can confine an age estimate more closely than any single method can achieve. Finally in sequence of age come the Soufrière and Madeleine centres which are sites of Recent activity and which have not been included in geochronological studies.

The youngest rocks we have dated are andesitic lavas from the coast between the southern end of Basse-Terre town and north of Bouillante. The K–Ar ages range only between 1.24 and 0.91 Ma. All these rocks are normally magnetized except at one locality where polarity is intermediate, although their ages fall within the latter part of the Matuyama Reversed Epoch. It seems most likely that the 0.91 Ma observation at site 2 represents the Jaramillo Normal Event and all other observations represent a brief normal event at *ca.* 1.18 Ma (see § 18).

Nagle *et al.* (1976) obtained no data from Basse-Terre, but dated three samples collected from pyroxene-andesite boulders in a cane field on Grande-Terre, to the east. They were puzzled by their result (*ca.* 11 Ma) as 'it is younger than the suspected age of either the Grande-Terre basement or the overlying conglomerate and older than any volcanic activity on Basse-Terre except for one middle or late Miocene volcanic centre'. They concluded that their samples were probably part of a conglomerate unit with clasts derived from Basse-Terre. However, Andreieff & Cottez (1976) recognized no pre-Pliocene sediments on Grande-Terre; likewise Mervoyer (1974), supported by the results of the present study, suggests no pre-Pliocene outcrop on Basse-Terre either. The problems posed by the Nagle *et al.* (1976) result

TABLE 4. GUADELOUPE

	sampling details				stable n.r.m., a.f. cleaned						whole rock K–Ar analysis			
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	R	D	I	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
702201 (G23201)	N of Anse a Colas	16° 02.4′	61° 45.0′	basalt lava	I	0	5‡§	3.84	87	+23	0.553	0.0253 0.0232	8.4 9.5	1.13 ± 0.08
702202 (G23203)	S of Anse de la Barque	16° 05.4′	61° 45.8′	andesite lava	–	40	2†	1.96	5	+17	0.764	0.0261 0.0277	8.9 11.3	0.91 ± 0.05
702203 (G23254)	Anse du Vieux Fort	16° 21.5′	61° 45.0′			40	5	1.68						
702204 (G23238)	Anse Fillon	16° 12.2′	61° 46.8′		+	0	7‡§	6.71	182	–40	0.761	0.0731 0.0621	10.0 6.8	2.28 ± 0.18
702205 (G23237)	Pte a Zambi	16° 11.2′	61° 46.6′	basalt lava	+	40	2	2.00	157	–38				
702206 (G23225)	1 km N of Bouillante	16° 08.4′	61° 46.1′	andesite lava	–	40	4†	3.27	6	+01	0.947	0.0435 0.0393	10.4 10.6	1.12 ± 0.07
702207 (G23220)	Descoudes	16° 06.3′	61° 46.1′	basalt lava	–	40	4	3.87	328	+47	0.693	0.0310 0.0359	8.1 13.9	1.24 ± 0.09
702208 (G23219)	Petite Anse	16° 05.8′	61° 45.8′		–	40	3	2.94	10	+53	0.546	0.0219 0.0235	8.8 9.2	1.07 ± 0.06
702209 (G23762–4)	Morne Griselle	15° 58.8′	61° 42.6′		–	40	4	3.97	353	+41	0.322	0.0234 0.0210	6.6 5.5	1.77 ± 0.17
G23413	Les Trois Pointes	15° 57.4′	61° 42.3′		–	0	9§	8.19	3	+25	0.323	0.0190 0.0154	4.2 2.7	1.37 ± 0.20
G23307	Morne à Louis	16° 11.1′	61° 44.7′	andesite massive							0.964	0.0432	67.8	1.15 ± 0.04
G23326	D'Aulm	16° 20.2′	61° 44.6′	andesite loose blocks							0.884	0.0710 0.0747	28.8 31.2	2.12 ± 0.06
G23365	Crete Mahaut	16° 11.2′	61° 45.3′	andesite massive lava							0.914	0.0523 0.0451	21.0 19.2	1.37 ± 0.06
G23404	Cafeiere	16° 19.6′	61° 46.1′	andesite loose block							1.18	0.0885 0.0936	30.5 41.3	1.98 ± 0.06
G23405	Riviere du Vieux Fort	16° 19.8′	61° 45.5′								0.975	0.0981 0.0932	38.3 38.1	2.52 ± 0.07
G23451	Pointe à l'Aiguille	16° 12.4′	61° 46.8′	andesite lava flow							0.950	0.0735	16.6	1.99 ± 0.10

† One discrepancy disregarded. ‡ a.f. Cleaned more scattered than total n.r.m. § Total n.r.m. adopted for Fisher calculations.

are, therefore, first finding a source of the boulders and second, explaining how they were transported. The fact that the samples were not taken from blocks which were definitely in place, introduces extra uncertainty.

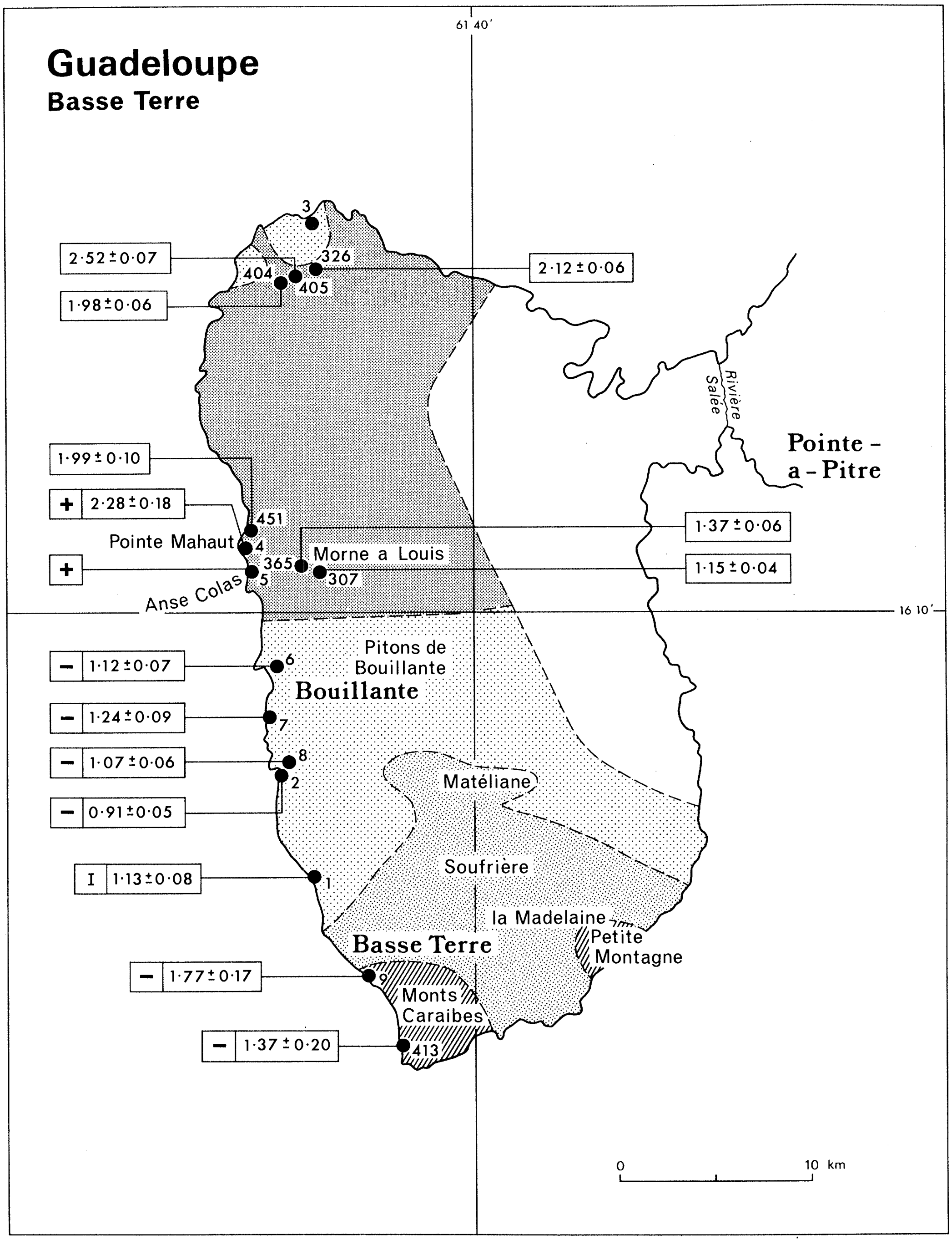

FIGURE 8. Outline map of Basse-Terre, Guadeloupe, showing palaeomagnetic and geochronological data (table 4) and outlining the principal volcano-morphological groups identified by Mervoyer (1974). Coarse stippling shows 'Pleistocene' andesitic centres of north coast and Pitons de Bouillante areas; fine stipple shows 'Upper Pliocene-Pleistocene' calc-alkaline rocks of northwest; medium stipple shows Recent calc-alkaline volcanism of Matéliane, Soufrière and Madeleine; oblique ruling shows tholeiitic products of Mont Caraibes and Petite Montagne; unshaded areas represent deeply weathered plain of the northeast. Prefix 70220 is omitted from all single digit site numbers and prefix G23 from all three digit numbers. Format as figure 4.

7. LA DÉSIRADE

The geology of La Désirade has been described by Fink (1971). The island is capped by Lower Miocene limestones (Barrabé 1934; de Reynal de Saint Michel 1966) which places a younger limit to the igneous complex exposed along the northern coast. This complex comprises massive flows, spilite-keratophyre pillow lavas and a trondhjemitic intrusion. The trondhjemite has been dated (Fink 1970; Mattinson *et al.* 1973) by the K–Ar whole rock method and the U–Pb method on zircon separates and the age estimated at 142 Ma. Neither the precise localities nor the full analytical data have been published and they are therefore not depicted in figure 9, but the K–Ar sample (at least) came from the Rivière Ravine in the

TABLE 5. DOMINICA AND LA DÉSIRADE

	sampling details				whole rock K–Ar analysis			
	locality	latitude °N	longitude °W	rock type	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
Dominica								
SD171	Upper Savane River, Foundland Centre	15° 15.5′	61° 17.5′	basalt	0.422	0.0201	10.4	1.12 ± 0.07
						0.0170	9.7	
						0.0184	12.3	
SD338	Boeri River, Morne Trois Pitons Centre	15° 19.0′	61° 22.4′	andesite	1.12	0.0802	30.6	1.77 ± 0.07
						0.0740	38.3	
La Désirade								
GD20	La Rivière	16° 19.3′	61° 03.2′	trondhjemite	0.332	1.2525	44.2	92.1 ± 3.0
						1.1862	38.7	
GD29	Point Fregule	16° 18.3′	61° 05.6′	keratophyre	0.100	0.3406	25.1	85.0 ± 3.0
						0.3360	29.1	

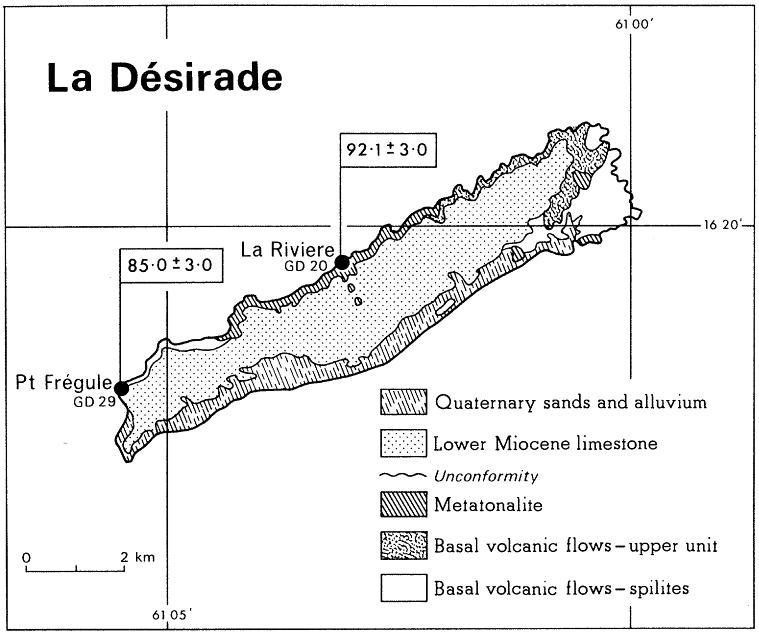

FIGURE 9. Geological map of La Désirade (from Fink 1971) with geochronological data added (table 5). Format as figure 4.

vicinity of our samples from which we obtained whole rock K–Ar ages of 92 Ma on the trondhjemite and 85 Ma from a quartz-keratophyre (table 5, figure 9). Dinkelman & Brown (1977) have reanalysed the material studied by Fink (1970) and Mattinson *et al.* (1973), apparently using their original samples, and treating the data by the K–Ar isochron method. They deduced ages of 87 ± 12 Ma from the quartz-keratophyres and 37 ± 12 Ma from spilites, but could not derive a significant age for the trondhjemite due to data scatter. Dinkelman & Brown (1977) therefore cast doubt on the Jurassic ages previously reported, and regard the quartz-keratophyre age of 87 ± 12 Ma as the best estimate for the age of the Désirade Ophiolite Suite. Our data are fully in accord with this conclusion and further suggest that the trondhjemites as well as the keratophyres have ages in the approximate range of 90–80 Ma.

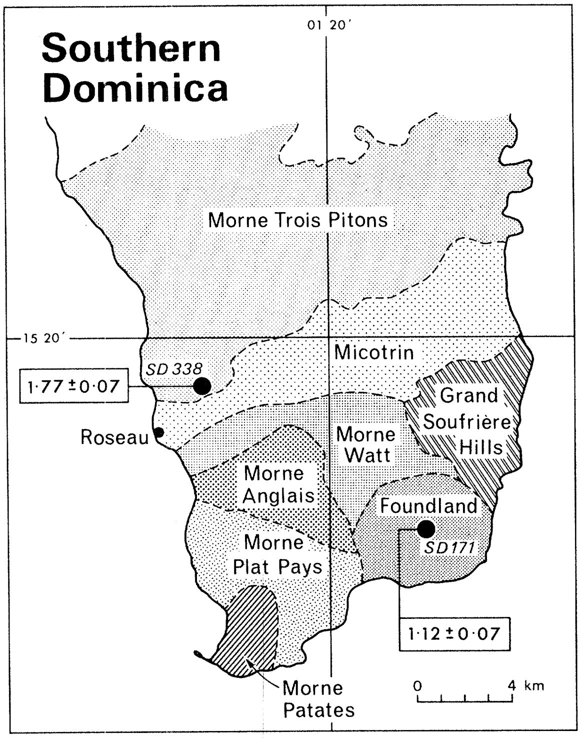

FIGURE 10. Generalized geological map of southern Dominica (after Wills 1974) with geochronological data added (table 5). Format as figure 4.

8. DOMINICA

A preliminary geological map of Dominica was compiled by Martin-Kaye (1959*a*) and the southern part has subsequently been studied in more detail by Wills (1974). Two whole rock samples provided by Dr K. J. A. Wills have been analysed (table 5 and figure 10). The first, from the southeast of the island, yields an age of 1.12 Ma and the second, from *ca.* 3 km northeast of Roseau, yields an age of 1.77 Ma. They were regarded by Wills (1974) as from amongst the oldest exposed parts of the Foundland and Morne Trois Pitons centres respectively and as pre-dating the uplift of the island, which Wills therefore concluded took place between about 1 and 0.5 Ma ago. It remains possible that the northern part of the island is older (it is certainly extremely deeply weathered) and also that older rocks are preserved in the east coast volcanic centres.

9. MARTINIQUE

Martinique has been the subject of extensive geochronological studies (Bellon *et al.* 1974; Andreieff *et al.* 1976; Nagle *et al.* 1976). K–Ar age determinations of 28 rocks have been published previously and the additional 13 newly presented here (table 6) are best discussed in

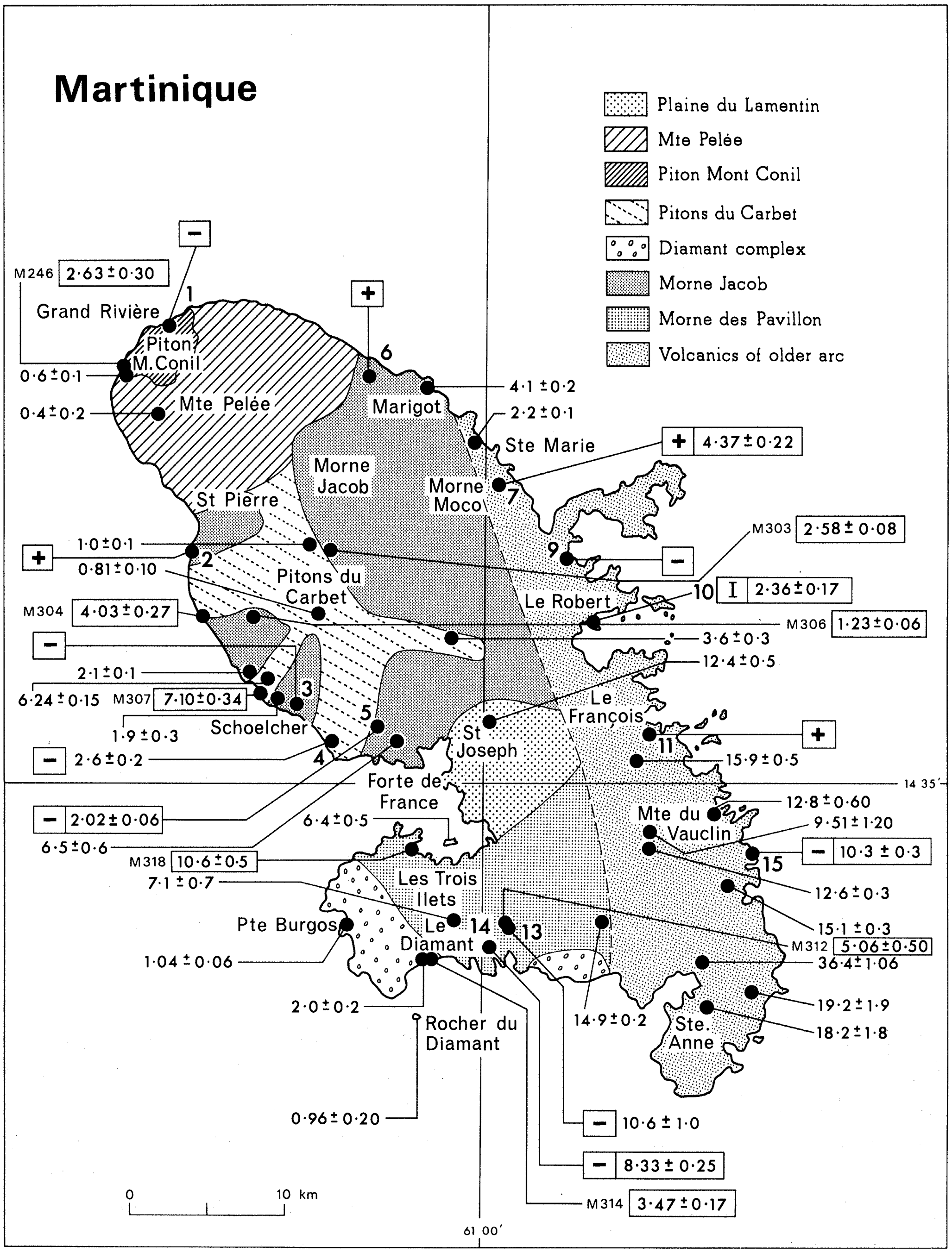

FIGURE 11. Outline map of Martinique showing palaeomagnetic and geochronological data (table 6), and previously published geochronological data (Andreieff *et al.* 1976; Bellon *et al.* 1974; Nagle *et al.* 1976) in the format of figure 4, and outlining the principal volcano-morphological groups identified by Westercamp (1976) and Westercamp & Mervoyer (1976). Prefix 7023 is omitted from all two digit site numbers.

Table 6. Martinique

	sampling details				stable n.r.m., a.f. cleaned						K–Ar analysis				
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	*R*	*D*	*I*	material analysed	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
702301	Grande Rivière	14° 52.1′	61° 10.8′	basalt lava	−	70	20	19.89	353	+13					
702302	St Pierre	14° 43.9′	61° 11.0′	andesite lava	+	70	3†	2.76	182	−52					
702303	S of Fond Lahaye	14° 37.4′	61° 06.9′		−	70	5	3.83	27	+38					
702304	1 km SE Scheulcher	14° 36.5′	61° 06.1′		−	70	4	3.95	0	+13					
702305	Route Desroches	14° 37.1′	61° 04.6′		−	70	6	5.40	2	−08	w.r.	1.25	0.1058	24.4	2.02 ± 0.06
	Fort de France												0.0908	28.9	
702306	Le Lorrain	14° 49.9′	61° 04.0′	basalt lava	+	70	3	2.99	174	−27					
702307	Morne Moco	14° 45.7′	60° 59.5′		+	70	4	3.95	182	−59	w.r.	0.560	0.0868	17.1	4.37 ± 0.22
													0.1038	27.4	
702309	Baie Du Galion	14° 43.2′	60° 57.0′		−	70	5	4.39	0	+23					
702310	Le Robert	14° 40.8′	60° 56.7′		I	70	2	1.99	95	−11	w.r.	0.659	0.0602	11.1	2.36 ± 0.17
													0.0607	7.9	
702311	Le Francois	14° 36.4′	60° 54.0′		+	70	5	4.60	177	−09					
702313	Qr les Coteaux	14° 29.8′	60° 59.2′	pyrox. andesite lava flow	−	70	2	2.00	359	+19					
702314	Qr Tourpiniere	14° 28.9′	60° 59.9′	basalt lava flow	−	70	4	3.87	337	+18	w.r.	1.33	0.4316	56.7	8.33 ± 0.25
702315	S of Le Vauclin	14° 32.3′	60° 50.2′	basalt lava flow	−	70	1	1.00	11	+33	w.r.‡	0.727	0.2845	24.5	10.0 ± 0.3
											w.r.	0.740	0.3046	36.7	10.6 ± 0.3
M303	Morne De Lorrain	14° 43.7′	61° 04.8′	basalt							w.r.	1.02	0.1015	28.8	2.58 ± 0.08
													0.1029	29.1	
M312	Quartier les	14° 29.8′	60° 59.2′	basalt dyke							w.r.	0.770	0.1467	6.6	5.06 ± 0.50
	Coteaux												0.1567	7.2	
M318	Quartier Wallon	14° 32.6′	61° 03.1′	basalt lava flow							w.r.	0.961	0.4011	11.1	10.6 ± 0.5
													0.3926	11.0	
M246	Morne du Ceron	14° 50.1′	61° 13.6′	hornblende andesite							hb.	0.234	0.0212	3.7	2.63 ± 0.34
													0.0271	5.9	
M304	Hotel Latitude	14° 41.6′	61° 11.0′	dacite							hb.	0.283	0.0444	8.8	4.03 ± 0.27
M306	Canton Suisse	14° 42.0′	61° 08.3′	dacite							bio.	5.29	0.2528	12.6	1.23 ± 0.06
M307	Case Pilote	14° 38.1′	61° 08.4′	dacite							hb.	0.259	0.0716	13.0	7.10 ± 0.34
M314	Le Diamant	14° 28.8′	61° 02.0′	tuff							hb.	0.242	0.0327	16.3	3.47 ± 0.17

† One anomalous specimen excluded. ‡ Two separate samples were taken for K–Ar analysis.

the context of the results as a whole (figure 11). Palaeomagnetic data are presented here for thirteen sites, of which we have radiometrically dated five and two were from localities dated by Nagle *et al.* (1976).

In summary, the principal result of the K–Ar work is to compress the geologically inferred time scale considerably, compared with that deduced by Grunevald (1961). Rather than a succession of central volcanic activities with only one or two centres being active at any one time (as depicted by Grunevald), parallel development of a number of centres is indicated. Rather than an island-wide basement being established early on, it now appears that the exposed basement to each centre is not significantly older than much of the superstructure. Thus there are areas of basement, previously regarded as Eocene, which now appear to be Plio-Pleistocene. Moreover, some longer-range lateral correlations on the basis of petrographic type are now seen to be invalid. The results will be discussed regionally and generally in order of increasing age, though this is not practicable in every case. The active centre of Mt Pelée, designated Quaternary by Grunevald has only a single whole rock age determination of 0.4 ± 0.2 Ma (Andreieff *et al.* 1976).

Volcanics of the Piton Mont Conil area have yielded a whole rock age of 0.6 Ma from a plagioclase-phyric andesite (Nagle *et al.* 1976) and 2.63 Ma from a hornblende separate. Excess of hornblende ages over whole rock ages in other parts of Martinique is currently the subject of joint investigation by Rex & Westercamp. Regardless of the outcome, it is clear that the Piton Mont Conil rocks belong to the Plio-Pleistocene activity as suspected by Gunn, Roobol & Smith (1974) on geochemical grounds, rather than to the Eocene as considered by Grunevald (1961). It is not clear, from the limited geochronologic data whether they should simply be regarded as parts of the Peléan pile (cf. Gunn *et al.* 1974), or as an early subcentre of Pelée (Westercamp, personal communication). However the 0.6 Ma whole rock age is preferred, and is consistent with the normal polarity of remanence in a section through Piton Conil lava flows at Grande Riviere (site 702301, table 6).

The Carbet centre was regarded as the immediate precursor of Mt Pelée by Grunevald. All three groups of geochronologists have obtained ages of *ca.* 1.0 Ma from the vicinity of the Piton du Carbet itself. In the vicinity of Case Pilote, northwest of Schoelcher, Nagle *et al.* (1976) and Andreieff *et al.* (1976) have both obtained ages of around 2 Ma. Further south at Schoelcher, Nagle *et al.* (1976) report a 2.6 Ma age from a flow in which we have determined normal polarity (site 702304). Westercamp (1976) has shown that the basement to the Pitons du Carbet centre can be related to an older centre near Morne Jacob. Between the Carbet centre and the coast, this basement has been dated at 4.03 and 7.10 Ma by using hornblendes from dacite pyroclast flows (this work) and 6.2 Ma by using whole rock analysis (Bellon *et al.* 1974). In the vicinity of Fort de France, an age of *6.5 Ma (Andreieff *et al.* 1976) has been determined from volcanics beneath limestones in a borehole. Near St Joseph, Nagle *et al.* (1976) report an age of *3.6 Ma from an andesite boulder in conglomerate mapped as part of the older, eastern Martinique basement by Grunevald (1961) but regarded as part of the Morne Jacob sequence by Westercamp (1976). K–Ar analyses of 2.58 and 2.02 Ma from products of the Morne Jacob centre indicate that its activity overlapped that of the mainly younger Carbet centre. Ages of *4.1 and *2.2 Ma by Nagle *et al.* (1976) from supposed correlatives of the St Joseph conglomerate near Marigot and Ste Marie, and 4.37 and 2.36 Ma (this study) from Morne Moco and Le Robert may indicate that the Morne Jacob structure – or another contemporaneous with it – spread its products more widely and was active more recently than has hitherto been realized.

These last two ages were from rocks mapped as outliers of Vauclin volcanism by Grunevald (1961) but this is refuted by discrepancies in K–Ar ages as indicated in the following paragraphs. The 2.36 ± 0.17 Ma date at site 702310 comes from samples showing intermediate polarity of stable n.r.m., which would most easily be explained if the true age coincides with the Gauss–Matuyama boundary at 2.47 Ma.

In the south of the island a quite different chronology is evident. In relation to Grunevald's (1961) map the simplest point of discussion is the Vauclin centre, from which ages of *15.1 and *12.6 Ma have been obtained by Nagle *et al.*, and 15.9, 9.5 and 12.8 Ma by Bellon *et al.* (1974). Andreieff *et al.* (1976) have argued that these data are in accord with the known relations of these rocks with the Vauclin tuffs and associated fossiliferous sediments. Peripheral to the Vauclin outcrop, similar ages of 10.0 Ma (this work) and *12.4 Ma (Nagle *et al.* 1976) have been obtained from andesite and basalt which Grunevald regarded as basement. It is clear however that this last group is not homogeneous because Andreieff *et al.* (1976) obtain ages of *18.2 and *19.2 Ma from the Ste Anne area, where Nagle *et al.* (1976) report a single, and so far uncorroborated, age of *36.4 Ma. The oldest fossilferous tuffaceous sediments in this area are regarded as early Miocene by Andreieff *et al.* (1976) so ages in excess of 22 Ma can be expected from their underlying basement.

West of the Vauclin region, Grunevald maps Eocene and Oligocene volcaniclastic rocks associated with 'Morne Jacob' volcanics, though he concedes that these latter are unlikely to be true equivalents of the Morne Jacob sequence in the north. K–Ar analyses yield ages of *15.1 and *10.6 Ma (Nagle *et al.* 1976), *7.1 Ma. (Andreieff *et al.* 1976), and 5.06 and 8.33 Ma (this work). The first mentioned of these appears to belong to a unit which predates the Vauclin centre. We regard the remainder as basement to the present day active arc, and it appears that the exposed basement in the south and southwest of the island ranges from about 10 to 5 Ma. This is further reinforced by determinations of 10.6 Ma at Trois Ilets (this work) and *6.4 Ma on the dacite of Gros Ilet (Andreieff *et al.* 1976).

Finally, the Diamant complex is clearly the youngest in this part of the island and is not part of the local basement. Ages ranging from 3.47 to 0.96 Ma have now been obtained. Moreover it is more extensive than previously realized. Bellon *et al.* (1974) obtained 1.04 Ma for a basalt at Pointe Burgos assigned by Grunevald to the early Tertiary basement, and Westercamp (1976) regards a large part of the southwestern peninsula as correlatable with this complex.

10. ST LUCIA

On St Lucia (figure 12 and table 7) there is only isolated Recent volcanic activity, mainly concentrated around the Soufrière area. The young age of 0.26 Ma determined on the prominent dacite dome core of the Petit Piton is of interest. Immediately north of the Petit Piton we have determined intermediate polarity of remanence in an aphyric basalt dated at 5.61 Ma and immediately north of that, positive polarity has also been determined in a lava at the south end of the Soufrière Beach. The age of the rocks of negative polarity in the south of the island (at Laborie and Vieux Fort) is not known but there is another 5 Ma age at Savannes, about 4 km northeast of Vieux Fort and it may be that the bulk of the southern part of the island is about this age. The area around Castries may also be mainly about 5 Ma age as indicated by the andesite plug at Vigie. In Castries itself, two distinct lava flows have positive polarity.

The oldest rocks outcropping on St Lucia are in the extreme north; this is confirmed by the

K–Ar analyses of 10.3 Ma age for a lava at Gros Islet, two ages of about 9.5 Ma for a lava flow and a block in an underlying agglomerate-tuff, and a further analysis at 18.3 Ma of hornblende from a block from a similar tuff. These tuff horizons are associated with the lenses of rubbly reef-type limestone in this part of the island, so that taken at their face value they appear to indicate a middle Miocene or younger age for the limestone. The age determinations of middle Miocene are inevitably minima, being taken from blocks within agglomerates. On the other

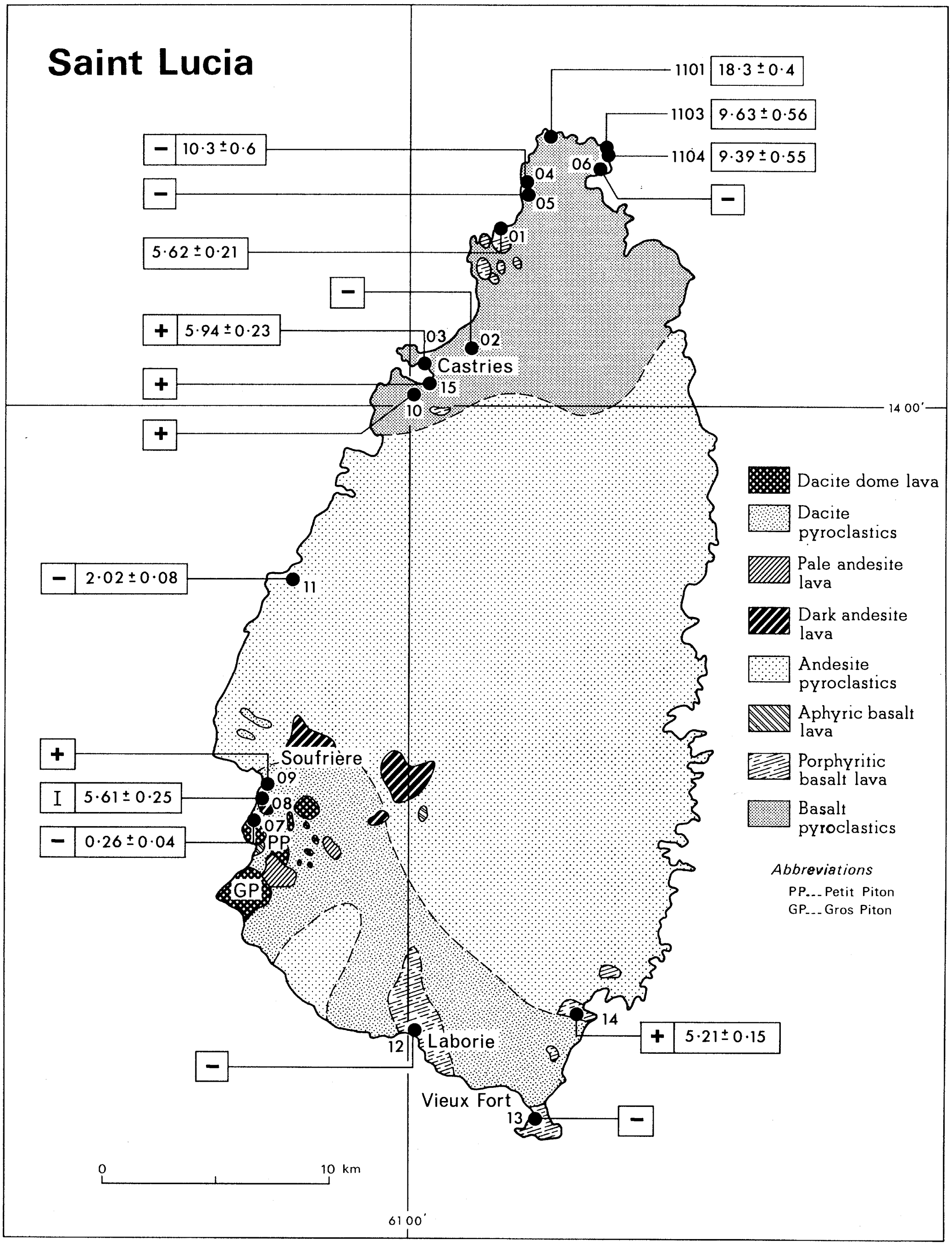

FIGURE 12. Geological sketch map of St Lucia (Tomblin 1964), with palaeomagnetic and geochronological data added (table 7); format as figure 4. Prefix 7024 is omitted from all two digit site numbers.

Table 7. St Lucia

	sampling details				stable n.r.m., a.f. cleaned						K–Ar analysis				
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	*R*	*D*	*I*	material analysed	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	Age/Ma
702401	Mt Pinard	14° 04.2′	60° 57.7′	andesite plug		50	4	2.00	unstable		w.r.†	0.568	0.1242	20.8	5.62 ± 0.21
702402	Bise Quarry	14° 01.4′	60° 58.4′	rhyolite dome	−	40	2	1.91	347	+65					
702403	Vigie	14° 01.1′	60° 59.8′	andesite plug	+	40	7	6.98	157	−20	w.r.	0.274	0.0669 0.0600	17.2 21.2	5.94 ± 0.23
702404	N of Gros Islet	14° 05.0′	60° 57.2′	lava	−	50	6	5.87	36	+58	w.r.	0.207	0.0826 0.0840	10.2 10.2	10.3 ± 0.6
702405		14° 05.5′	60° 57.2′	dyke	−	50	4	3.43	6	+40					
702406	N side Anse Lavoutte	14° 05.3′	60° 55.4′	dyke	−	40	3	2.79	358	+31					
702407	NW flank of Petit Piton	13° 50.7′	61° 03.7′	dacite dome	−	40	6	5.90	355	+26	w.r.	1.30	0.0147 0.0118	4.6 4.2	0.26 ± 0.04
702408	Malgretoute	13° 50.7′	61° 03.8′	aphyric basalt	I	40	3	2.95	260	−22	w.r.†	0.590	0.1289	18.0	5.61 ± 0.25
702409	S end Soufrière beach	13° 50.8′	61° 03.7′	basalt lava flow	+	40	7	6.89	159	−27					
702410	Government House Castries	14° 00.2′	60° 59.9′	basalt lava	+	40	5	4.88	153	−26					
702411	Anse Galet	13° 55.7′	61° 02.8′	basalt lava	−	40	5	4.67	7	+14	w.r.	0.591	0.0462 0.0469	15.6 19.7	2.02 ± 0.08
702412	Laborie	13° 45.0′	60° 59.9′		−	40	3	2.26	40	+25					
702413	Vieux Fort	13° 43.1′	60° 57.0′	andesite intrusion	−	40	6	5.91	3	+23					
702414	Savannes	13° 45.4′	60° 56.4′	basalt lava	+	40	4	3.96	176	−03	w.r.	0.563	0.1106 0.1179	36.1 34.0	5.21 ± 0.15
702415	Castries, St Antoine Hotel	14° 00.3′	60° 59.8′	basalt lava	+	40	4	3.93	166	−17					
L1101	Cap Point	14° 06.3′	60° 56.6′	hornblende rich block in conglomerate							hb.	0.123	0.0869 0.0887	24.1 24.6	18.3 ± 0.9
L1103	S of Point Hardy	14° 06.0′	60° 55.2′	basalt lava							w.r.	0.268	0.1031 0.0982	11.0 10.1	9.63 ± 0.56
L1104	S of Point Hardy	14° 06.0′	60° 55.2′	basaltic block in tuff							w.r.	0.439	0.1692 0.1523	11.1 9.9	9.39 ± 0.55

† Analysed by J. C. Briden at the Department of Geology and Mineralogy, University of Oxford, using MS10 Mass Spectrometer.

hand some of the limestone rubble may itself be secondary – and hence older – than the adjacent volcanics, which would accommodate the early Miocene age of foraminifera reported in these limestones by Martin-Kaye (1961*a*).

11. St Vincent

St Vincent is the only island in the Lesser Antilles for which we know of any previous attempt at palaeomagnetic work. Ten samples collected from the Soufrière by F. D. Stacey with the principal intention of investigating magnetic fabric, were studied by M. Aftab Khan (F. D. Stacey, personal communication). Total n.r.m., widely scattered with positive inclination was discovered before the investigation lapsed.

Geological maps have been compiled by Martin-Kaye (1957) and Rowley (1978). Our new data are listed in table 8. This island is the source of our largest palaeomagnetic collection, 28 sites, of which only 9 were fresh enough for age determination. The palaeomagnetic results show a clear geographic distribution of polarities (figure 13). The products of the active Soufrière volcano in the north all have normal polarity, and those that are dated all have K–Ar ages within the Brunhes Normal Epoch. The youngest, though undated, are likely to be the lower two of the four flows in the Somma Wall (sites 683771 and 683772).

Volcanics believed to be derived from the Richmond or Brisbane centres, sampled at six sites on a traverse along the west coast from Mt Wynne to Coulls Hill all show reversed polarity, and one of these, at 1.33 Ma, dates within the Matuyama Reverse Epoch. Further north at Chateaubelair Point and Richmond Vale, two lava flows which are believed to derive from the Richmond centre (the next volcanic centre southward from the Soufrière) have normal polarity. One of these yields an age of 1.18 Ma. This result, and the age of 1.16 Ma just north of Kingstown on one of four normal-polarity lava flows in that segment, appears to record the normal event in the Matuyama Epoch which is found also in Guadeloupe (see § 6 and 18). The flows around Kingstown are regarded as being at least as old as the reversely magnetized flows to the north and recent volcanism in the south of the island is confined to the cinder conelet at King's Hill; hence an age as young as the Brunhes Epoch is extremely unlikely. Immediately south of Kingstown, a normally magnetized lava *ca.* 1.65 Ma old is taken to represent the Gilsa Event and in the extreme south of the island two reversely magnetized rocks dated at 2.49 and 2.74 Ma, are attributed to the beginning of the Matuyama Epoch, although the latter determination is older than the Gauss–Matuyama boundary at 2.47 Ma by more than 2σ from the calculated mean.

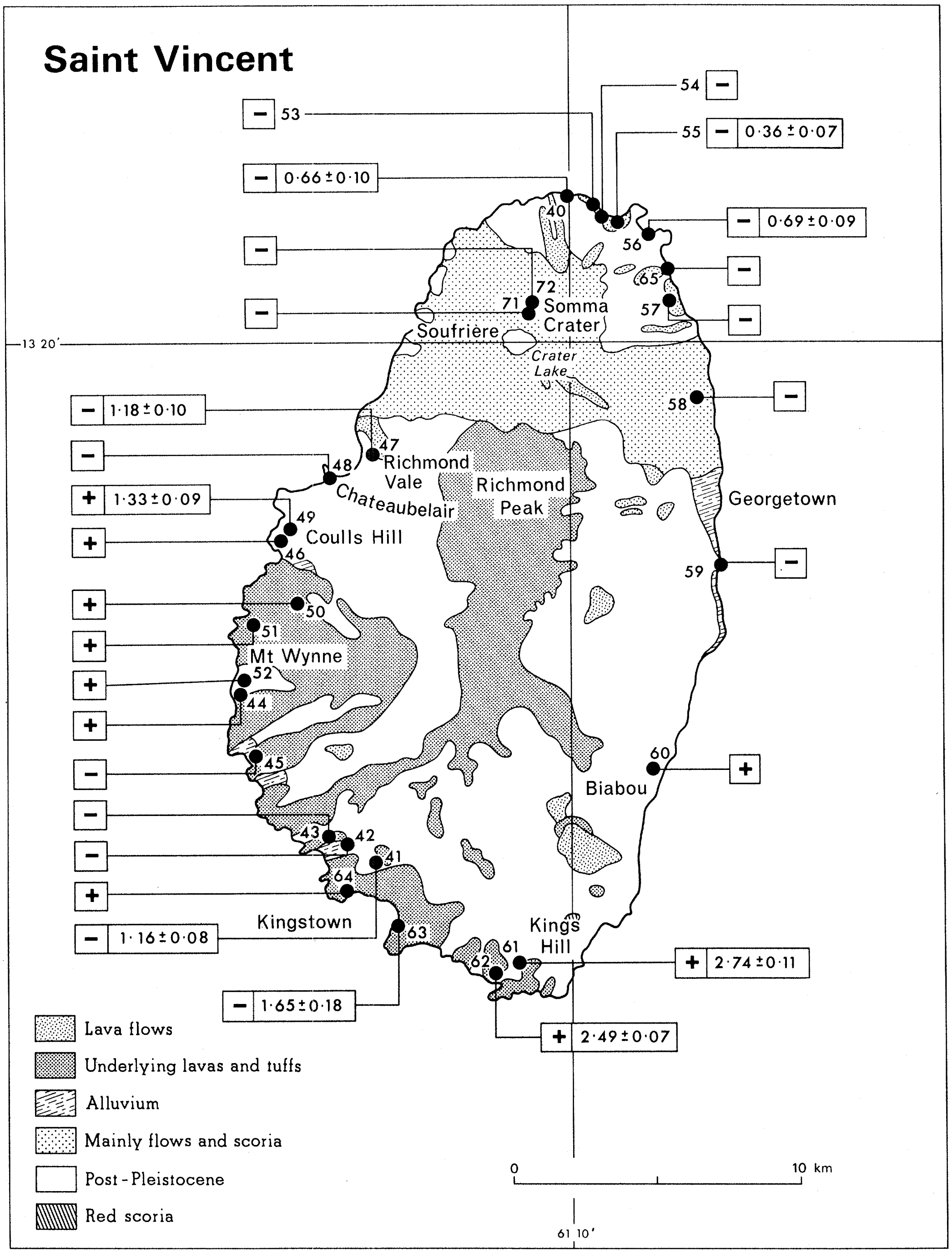

FIGURE 13. Geological sketch map of St Vincent (Rowley 1978) with palaeomagnetic and geochronological data added (table 8). Format as figure 4. Prefix 6837 is omitted from all site numbers.

Table 8. St Vincent

	sampling details				stable n.r.m., a.f. cleaned						whole rock K–Ar analysis			
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	R	D	I	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
683740	Porter Point	13° 22.9′	61° 10.1′	basalt lava	−	20	6	5.97	358.1	+06.4	0.462	0.0108 0.0130	2.1 2.0	0.66±0.10
683741	Lowmans	13° 10.2′	61° 14.1′		−	60	6	5.40	348.4	+13.3	0.491	0.0245 0.0198	8.0 8.9	1.16±0.08
683742	W of Campden Park	13° 10.4′	61° 14.7′		−	18	3	2.74	358.6	+01.7				
683743	Leeward Highway at Clare Valley turn	13° 10.9′	61° 15.0′		−	12	4	3.95	358.8	+11.3				
683744	Mt Wynne	13° 13.0′	61° 16.4′		+	12	3	2.99	169.0	−34.4				
683745	Layou	13° 11.8′	61° 16.1′		−	12	3	2.98	357.2	+20.1				
683746	Westwood	13° 16.3′	61° 15.7′		+	24	2	2.00	(220.5	+33.5)				
683747	Richmond Vale	13° 17.9′	61° 14.6′	andesite lava	−	24	2	2.00	1.5	−13.5	0.852	0.0405 0.0378	9.8 7.8	1.18±0.10
683748	Chateaubelair Point (W side)	13° 17.6′	61° 14.9′	basalt lava	−	12	2	1.96	346.0	+38.8				
683749	Coulls Hill	13° 16.5′	61° 15.6′		+	20	4	3.98	171.6	−06.9	0.608	0.0238 0.0400 0.0309	8.3 9.2 10.1	1.33±0.09
683750	N of New Works	13° 15.1′	61° 15.1′	olivine basalt dyke	+	30	5	4.81	168.4	−20.2				
683751	Keartons	13° 14.4′	61° 16.5′	basalt lava	+	24	1	—	191.0	−08.0				
683752	Mt Wynne (north)	13° 13.4′	61° 16.6′	andesite	+	24	2	1.97	184.5	−06.1				
683753	Kramaku	13° 22.7′	61° 09.6′	basalt lava	−	12	1	—	359.0	+35.0				
683754	Windblow Rock	13° 22.6′	61° 09.5′		−	18	1†	—	(0.0	−25.0)				
683755	Commantawana Bay	13° 22.4′	61° 09.4′		−	20	6	6.00	344.1	+10.6	0.550	0.0074 0.0076	1.5 1.1	0.36±0.07
683756	Rouges Hill (Owia Bay)	13° 22.1′	61° 08.5′	andesite lava	−	40	6	5.99	344.4	+29.7	0.350	0.0088 0.0100	3.3 3.0	0.69±0.09
683757	New Sandy Bay Village	13° 20.9′	61° 08.1′	basalt lava	−	12	2	1.96	355.9	+23.1				
683758	Orange Hill	13° 18.9′	61° 07.6′		−	12	1	—	9.0	+33.0				
683759	Black Point	13° 15.6′	61° 06.6′		−	24	3	2.96	353.8	+37.1				
683760	Biabou	13° 11.8′	61° 08.3′	andesite lava	+	24	2	1.97	189.8	−33.7				
683761	Windward Highway nr. Prospect turn	13° 08.0′	61° 10.9′	basalt lava	+	18	2	1.99	183.5	−16.5	0.439	0.0498 0.0449 0.0458	20.5 15.2 18.1	2.74±0.11
683762	Calliaqua	13° 07.7′	61° 11.8′	basalt lava	+	12	2	1.93	176.4	−10.2	0.373	0.0355 0.0367	19.6 19.1	2.49±0.07
683763	Kingstown, Cane Garden Road	13° 08.7′	61° 13.6′		−	30	6	5.61	329.8	+69.0	0.455	0.0279 0.0306	4.9 13.9	1.65±0.18
683764	Kingstown, Fort Charlotte Road	13° 09.6′	61° 14.5′		+	24	3	2.93	175.3	−27.6				
683765	N of New Sandy Bay Village	13° 21.4′	61° 08.1′		−	40	7	6.97	355.0	+32.7				
683771	Soufrière, Somma Rim, lowest lava	13° 20.5′	61° 10.5′	andesite lava	−	40	3	2.99	341.1	+13.7				
683772	Soufrière, Somma Rim, second lava	13° 20.5′	61° 10.5′		−	30	5	4.97	345.8	−00.2				

† One discrepancy disregarded. The bracketed site mean directions are regarded as anomalous and are not included in the analysis in table 14.

12. Bequia

On Bequia (figure 14 and table 9) all samples west of about 61° 14′ have positive polarity. Three of four ages lie within the Gilbert Reversed Epoch (*ca.* 5.44–3.41 Ma) and though the calculated age of one of these (3.85 Ma at site 18) falls nominally within the Cochiti Normal Event, the uncertainty in its age is greater than the duration of that brief event. Reversed intervals around that time are 4.07 to 3.92 Ma and 3.82 to 3.41 Ma (McDougall 1979) so the optimum compromise between polarity and K–Ar evidence would assign an age to it of just under 3.82 Ma. It is not proven whether the whole of western Bequia is of Gilbert age; a K–Ar date of 8.96 Ma would appear to make this unlikely, but this analysis was obtained from a sample only a few tens of metres away from another sample, identical in lithology, which yields the 3.85 Ma age; confirmation is evidently needed.

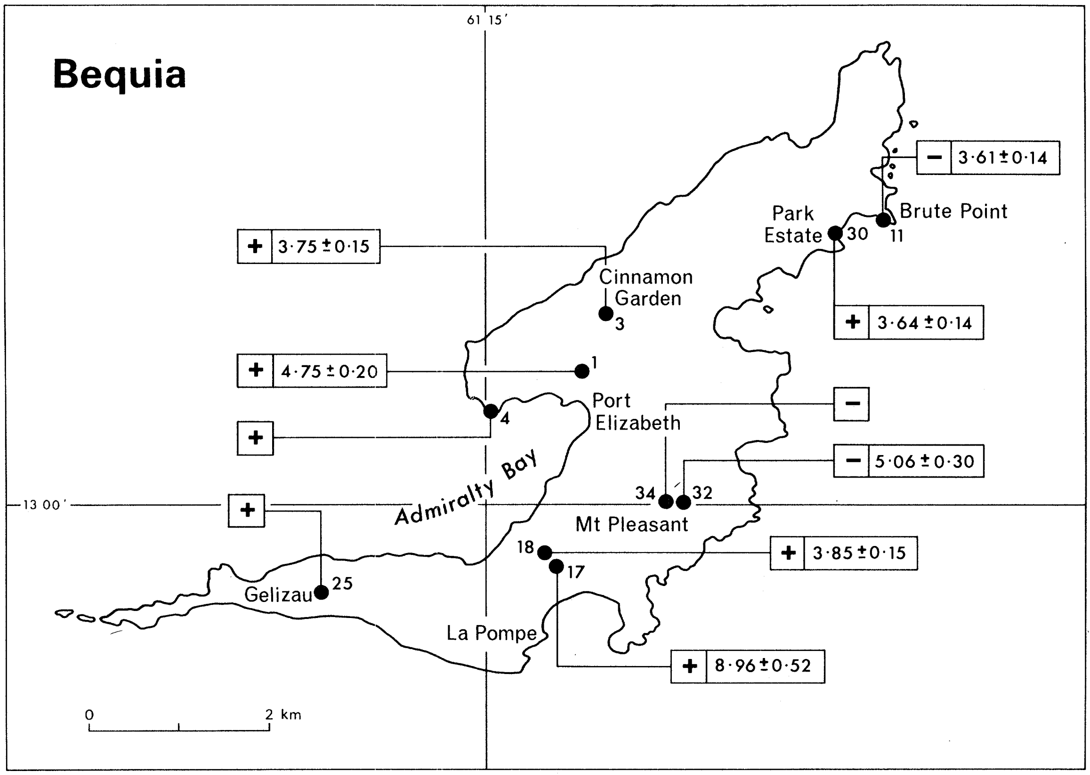

Figure 14. Outline map of Bequia showing palaeomagnetic and geochronological data (table 9) in the format of figure 4. Prefix WBQ is omitted from all site numbers.

Of two normally magnetized lavas on Mount Pleasant, one is dated at 5.06 Ma an age virtually on the Magnetic Epoch 5/Gilbert boundary (McDougall 1979). On the northeast peninsula, lavas at Brute Point and Park Estate have indistinguishable K–Ar ages but opposite polarity. Their ages (3.61 and 3.64 Ma respectively) fall midway through the last reversed interval in the Gilbert Epoch, so superposition evidence would be needed to determine whether the normally magnetized lava west of Brute Point is of younger (early Gauss) or older (Cochiti) age. Whichever proves to be the case, the actual age must differ from our calculated age by slightly more than the quoted 1σ uncertainty.

Table 9. Bequia

	sampling details				stable n.r.m., a.f. cleaned						whole rock K–Ar analysis			
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	R	D	I	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
WBQ 001	Stone Quarry	13° 00.8′	61° 14.4′	andesite lava	+	40	6	5.18	194	−44	0.379	0.0701	21.4	4.75 ± 0.20
WBQ 003	E Cinnamon Garden	13° 01.1′	61° 14.5′	olivine basalt lava	+	40	6	5.26	215	−08	0.348	0.0508	32.1	3.75 ± 0.15
WBQ 004	Old Fort	13° 00.6′	61° 15.0′	andesite lava	+	40	2	2.00	188	−33				
WBQ 011	W of Brute Point	13° 01.8′	61° 12.7′	olivine basalt lava	−	40	5	4.97	12	+24	0.695	0.0976	23.1	3.61 ± 0.14
WBQ 017	La Pompe Road	12° 59.7′	61° 14.6′		+	60	4	3.59	176	−06	0.333	0.1133	10.6	8.96 ± 0.52
												0.1193	10.6	
WBQ 018	La Pompe Road	12° 59.6′	61° 14.7′		+	40	5	4.52	158	−24	0.363	0.0516	13.9	3.85 ± 0.15
												0.0572	16.7	
WBQ 025	Gelizeau	12° 59.4′	61° 16.2′		+	60	5	4.93	177	−24				
WBQ 030	Park Estate	13° 01.6′	61° 12.8′	andesite lava	+	40	6	5.81	169	−01	0.545	0.0773	30.7	3.64 ± 0.14
WBQ 032	Mt Pleasant	13° 00.1′	61° 13.9′	olivine basalt lava	−	40	2	1.99	356	−12	0.291	0.0575	22.6	5.06 ± 0.30
												0.0572	9.8	
WBQ 034	Mt Pleasant	13° 00.1′	61° 14.2′	andesite lava	−	40	5	4.89	9	+37				

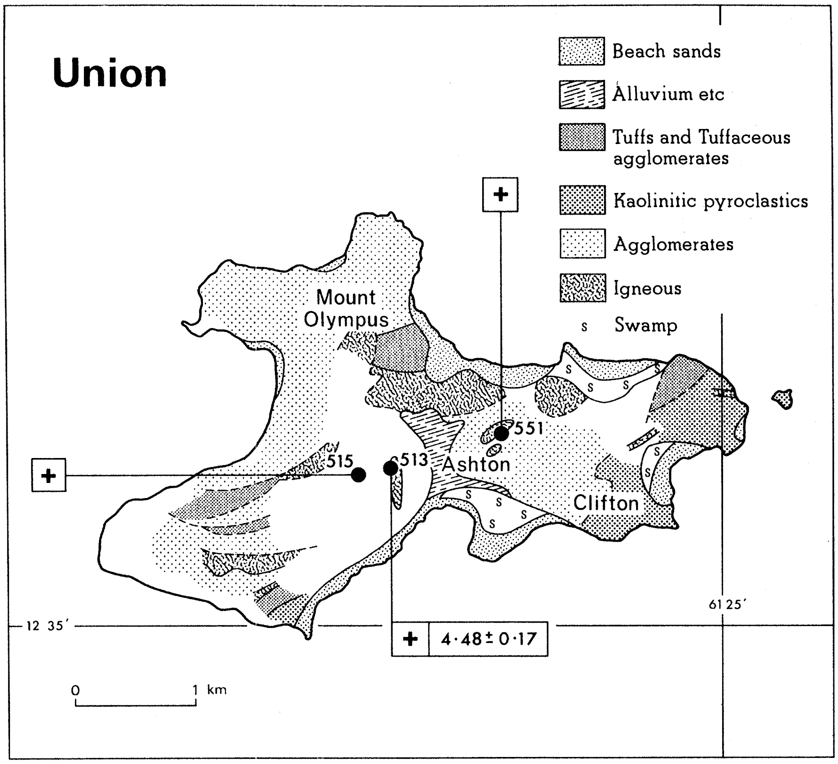

FIGURE 15. Geological sketch map of Union (Martin-Kaye 1956) showing palaeomagnetic and geochronological data (table 10) in the format of figure 4. Prefix WUI is omitted from site numbers.

TABLE 10. UNION

	sampling details				stable n.r.m., a.f. cleaned						whole rock K–Ar analysis			
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	R	D	I	(%) K	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
I 513	Mt Parnassus	12° 35.7′	61° 26.5′	andesite dome	+	40	3	2.94	172	−37	0.847	0.1450 0.1503	34.9 35.1	4.48 ± 0.17
JI 515	E of Mt Taboi	12° 35.6′	61° 26.6′	pyroxene andesite dome	+	50	3	2.96	179	−05	—	—	—	—
JI 551	NE of Ashton	12° 35.7′	61° 26.0′	andesite dome	+	40	2	2.00	147	−20	—	—	—	—

13. UNION

On Union (figure 15 and table 10) we have only three sites, all in the central part of the island and all of reversed polarity. The middle site is dated at 4.48 Ma within the Gilbert Reversed Epoch. Within that epoch, normal events occur at 4.57–4.44 and 4.25–4.07 Ma, so we may provisionally reduce the uncertainty in this K–Ar age to the interval 4.44–4.25 Ma.

14. CARRIACOU

Geological maps of Carriacou have been compiled by Martin-Kaye (1958*b*) and Jackson (1970) and the stratigraphy has been discussed by Robinson & Jung (1972). The K–Ar ages (figure 16 and table 11) range between 18.1 and 2.87 Ma, and fall into three chronological groups. The youngest group (less than 7 Ma old) are found in a pyroxene-hornblende andesite dome at Dumfries (which has intermediate polarity of n.r.m.) and a sill at Sparrow Bay within older volcaniclastics; both ages are corroborated by agreement of whole rock and hornblende analyses. Whole rock ages for two separate lava flows at Belmont and for an andesite dome at Hillsborough Hospital, together with hornblende ages for a hornblende-andesite lava flow at

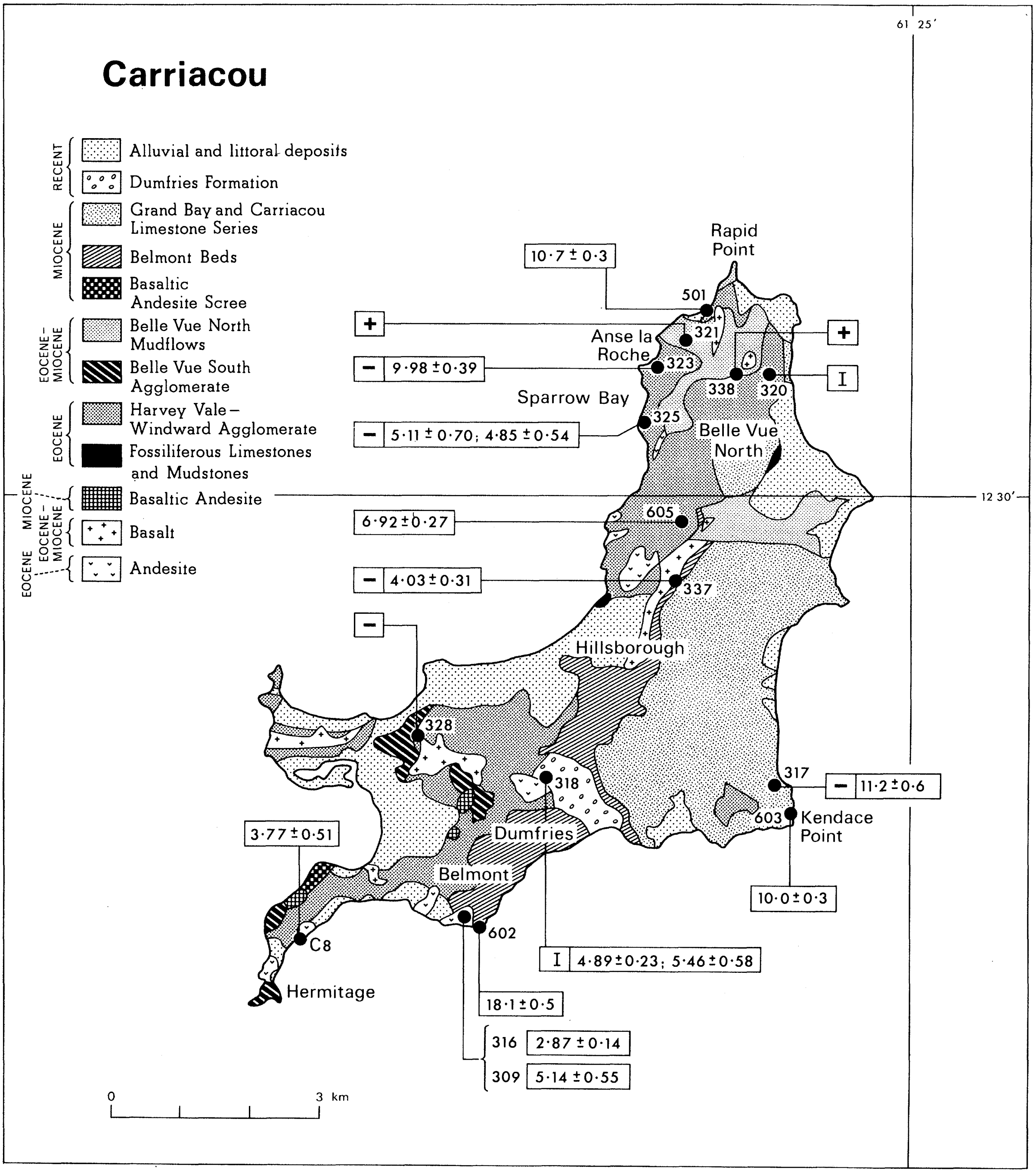

Figure 16. Geological map of Carriacou (Jackson 1970), with palaeomagnetic and geochronological data added (table 11). Format as figure 4. Prefix WCA is omitted from all site numbers except C8 (a sample from J. F. Lewis).

TABLE 11. CARRIACOU

	sampling details				stable n.r.m., a.f. cleaned						K–Ar analysis				
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	R	D	I	material analysed	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
WCA309	Belmont	12° 26.8′	61° 28.4′	hornblende andesite lava flow							hb.	0.304	0.0608	4.1	5.14 ± 0.55
WCA316	Belmont	12° 26.9′	61° 28.3′	olivine basalt lava flow							w.r.	0.430	0.0480	14.1	2.87 ± 0.14
WCA317	N of Kendace Point	12° 27.8′	61° 25.9′	olivine basalt dyke	–	40	3	2.97	338	+17	w.r.	0.667	0.2995 0.2853	13.2 22.0	11.2 ± 0.6
WCA318	Dumfries	12° 27.9′	61° 27.9′	hornblende andesite dome	I	60	3	2.87	286	–54	w.r.	0.928	0.1697 0.1833	20.1 11.7	4.89 ± 0.23
											hb.	0.276	0.0587	4.9	5.46 ± 0.58
WCA320	N of Windward Village	12° 13.1′	61° 26.0′	basalt dyke	I	30	2	2.00	291	–10					
WCA321	SW of Rapid Point	12° 31.4′	61° 26.8′	pyroxene basalt	+	60	3	2.99	167	–12					
WCA323	Anse La Roche	12° 31.2′	61° 27.0′	olivine basalt dyke	–	60	3	2.78	355	+25	w.r.	1.07	0.3987 0.4338	19.3 23.8	9.98 ± 0.39
WCA325	Sparrow Bay	12° 30.7′	61° 27.1′	hornblende andesite sill	–	30	3	2.80	359	+07	w.r.	0.613	0.1292 0.1148	3.4 5.7	5.11 ± 0.70
											hb.	0.308	0.0581	6.0	4.85 ± 0.54
WCA328	L'Esterre	12° 28.2′	61° 29.3′	pyroxene andesite lava flow	–	60	2	1.99	356	+24					
WCA337	Hillsborough Hospital	12° 29.3′	61° 26.8′	andesite dome	–	30	2	1.96	349	+24	w.r.	0.773	0.1208 0.1216	27.3 6.2	4.03 ± 0.31
WCA338	Belle Vue North	12° 31.0′	61° 26.2′	pyroxene basalt	+	60	2	1.94	196	–30					
C8	Hermitage	12° 26.7′	61° 29.6′	hornblende andesite lava							hb. conc.	0.303	0.0445	3.2	3.77 ± 0.51
WCA501	W Side Rapid Point	12° 31.5′	61° 26.6′	basalt block in agglomerate							w.r.	0.726	0.2966 0.3065	54.4 42.4	10.7 ± 0.3
WCA602	Belmont	12° 26.7′	61° 28.3′	basalt block							w.r.	0.377	0.2759 0.2584	38.8 34.8	18.1 ± 0.5
WCA603	Kendace Point	12° 27.6′	61° 25.9′								w.r.	0.504	0.1977 0.1952	39.0 32.2	10.0 ± 0.29
WCA605	W of Belvidere	12° 29.9′	61° 26.7′	hornblende andesite block in agglomerate							hb.	0.301	0.0811	19.8	6.92 ± 0.27

Hermitage and a hornblende-andesite block in the Windward volcaniclastics complete this group. All these data are consistent with stratigraphic age evidence for these rocks.

The second group of ages is in the range 11.2–9.9 Ma. One is for an olivine-microphyric basalt block in agglomerates belonging to the Belle Vue North Mudflows and points to a middle Miocene age – which was the minimum age for that formation suggested by Jackson (1970). Another determination for an olivine basalt dyke intruding the Windward Agglomerates (Jackson 1970) near Anse La Roche gave a similar age. An age of 11.2 Ma is obtained from an olivine basalt dyke cutting the Belmont Formation just north of Kendace Point. However, nearby, a basalt block in Belmont Beds, supposedly below the late early Miocene Carriacou Limestone, yields an age of 10.0 Ma. J. F. Lewis (personal communication) suspects that the stratigraphic position of this sample may have been wrongly attributed, in what is a complicated and poorly exposed area.

Finally the single age of 18.1 Ma for a block from the basal part of the Belmont Formation not only constrains the age of that formation, but helps to confine the age of the overlying Carriacou limestone at *ca.* 15 Ma.

The palaeomagnetically studied rocks on Carriacou all appear to be at least *ca.* 4 Ma old and no extra age constraint can be deduced by consideration of their polarity.

15. GRENADA

Grenada (figure 17) has been mapped geologically by Martin-Kaye (1958*a*, 1961*b*) and Arculus (1976); the K–Ar data on unoriented specimens in table 12 (i.e. those with no associated palaeomagnetic data) are from samples collected by R. J. Arculus. Palaeomagnetic collection was concentrated on more prominent lavas in the southeast, around St Georges, and it emerges (table 12) that these were all younger than 4 Ma. They show well-defined normal and reversed stable remanence. The youngest K–Ar ages of 0.98 and 0.94 Ma are associated with normal polarity and appear to record the Jaramillo event. Next in order of increasing age are four determinations between 1.43 and 1.68 Ma in the Matuyama Reverse Epoch. Finally, two reversely magnetized lavas correlate with the last part of the Gilbert Reverse Epoch between 3.4 and 3.8 Ma (the last lavas having polarity determined on only one specimen due to erroneous treatment of the remainder of the collection in the laboratory).

Arculus' samples were selected to ascertain the extent of this Pliocene and younger volcanicity in critical areas and to identify older volcanic events. Plio-Pleistocene ages were obtained in the north and centre of the island and may represent some of the earliest activity associated with the centres in the Mt St Catherine and Fedons Camp areas. The pre-Pliocene ages come from formations identified by Arculus as basement to the younger structures. It would be intriguing to know whether the apparent hiatus in age between 21 Ma (Mt Craven) and *ca.* 2 Ma nearby, and 14–10 Ma (South East Mountain – Mt Maitland region) and less than 2 Ma nearby, is real or a reflexion of the limited number of samples. The synchronism of a major amount of igneous activity on Grenada with that at 11–10 Ma on nearby Carriacou is of note.

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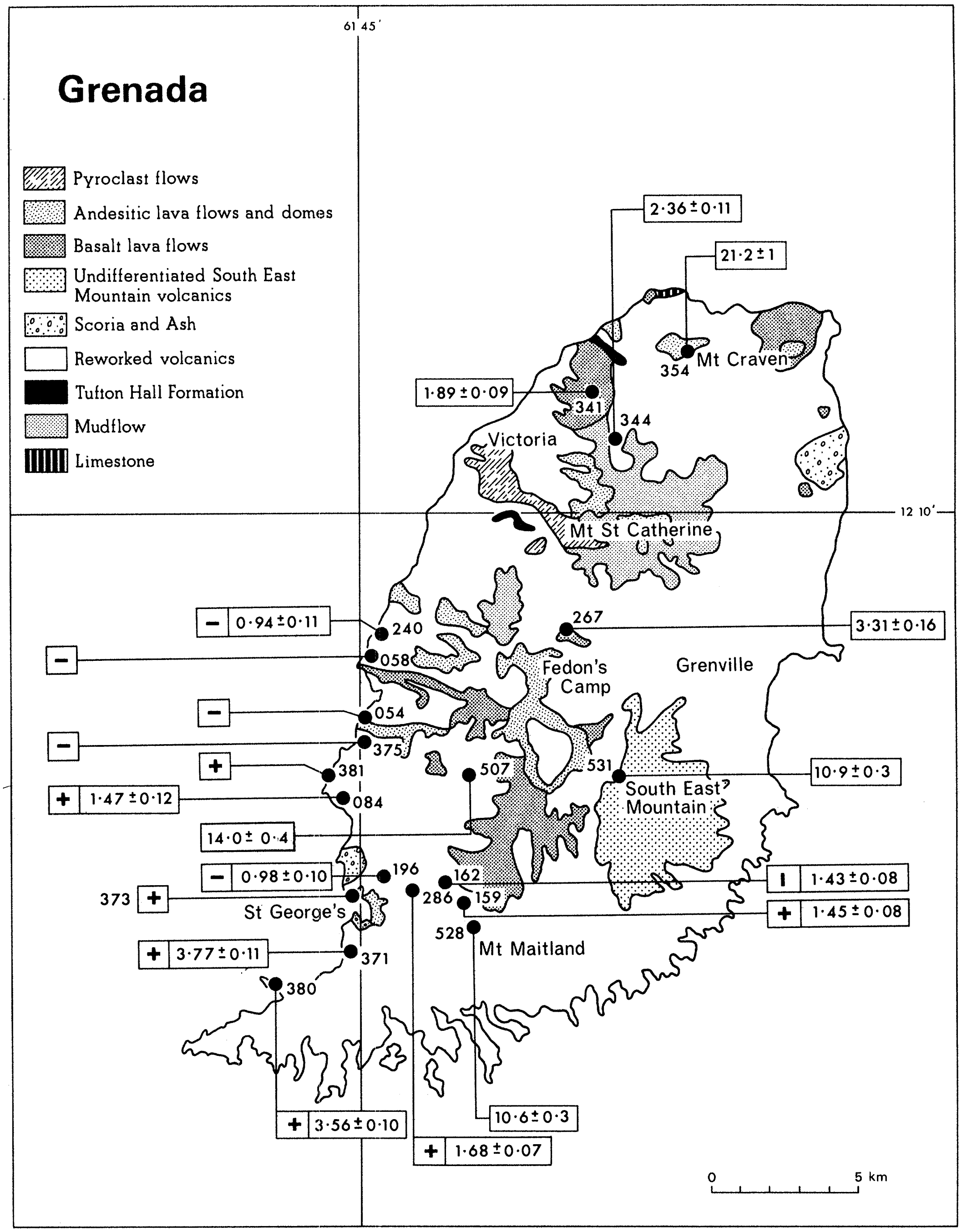

Figure 17. Geological map of Grenada (Arculus 1976) with palaeomagnetic and geochronological data added (table 12). Format as figure 4. Prefixes 6928 and RJA omitted from site numbers (see table 12 for details).

Table 12. Grenada

	sampling details				stable n.r.m., a.f. cleaned						K–Ar analysis				
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	R	D	I	material analysed	K (%)	volume ^{40}Ar rad. 10^{-6} cm^3 g^{-1}	^{40}Ar rad. (%)	age/Ma
6928054	Brisant	12° 06.5′	61° 45.6′	andesite lava	–	30	6	5.96	14	+32					
6928058	Black Bay River	12° 07.0′	61° 44.6′	olivine basalt lava	–	30	6	5.92	4	+08					
6928084	Grand Mal	12° 04.6′	61° 45.2′		+	30	6	4.34	215	–21	w.r.	0.554	0.0310 0.0325	2.6 12.2	1.47 ± 0.12
6928159	La Borie	12° 02.5′	61° 43.6′		+	60	6	5.93	187	–32	w.r.	0.633	0.0372 0.0342	3.7 18.0	1.45 ± 0.08
6928162	St Pauls	12° 02.9′	61° 43.7′		I	60	3†	3.00	105	+11	w.r.	0.633	0.0352 0.0353	4.8 14.2	1.43 ± 0.08
6928196	N of Mt Royal	12° 03.4′	61° 44.7′		–	40	4	3.93	20	+14	w.r.	0.707	0.0273 0.0264	2.3 9.2	0.98 ± 0.10
6928240	Marigot	12° 07.7′	61° 45.0′		–	40	6	5.97	1	+13	w.r.	0.763	0.0257 0.0297	3.0 8.7	0.94 ± 0.11
6928286	Richmond Hill	12° 03.0′	61° 44.3′		+	40	2	2.00	184	–28	w.r.	0.552	0.0375 0.0348	16.3 21.5	1.68 ± 0.07
6928371	S of Ross Point	12° 02.2′	61° 45.3′		+	50/80	1	—	194	–51	w.r.	0.928	0.1358 0.1369	38.3 49.5	3.77 ± 0.11
6928373	St Georges	12° 02.9′	61° 45.3′	andesite lava	+	40	6	5.75	209	–27					
6928375	Brisant	12° 05.9′	61° 45.1′	olivine basalt lava	–	50	6	5.90	12	+11					
6928380	Goat Point	12° 01.4′	61° 46.6′		+	60	6	5.94	178	–02	w.r.	0.816	0.1114 0.1149	29.5 27.2	3.56 ± 0.10
6928381	Flamand Bay	12° 05.6′	61° 45.4′		+	60	3	2.99	182	–17					
RJA 267	Near Belvidere	12° 07.7′	61° 41.1′								w.r.	0.710	0.0915	22.0	3.31 ± 0.16
RJA 344	Mt Ellington	12° 11.3′	61° 40.5′								w.r.	0.450	0.0413	15.1	2.36 ± 0.11
RJA 507	Annandale Falls	12° 05.2′	61° 43.1′								w.r.	0.316	0.1706 0.1737	25.6 29.7	14.0 ± 0.4
RJA 528	Morne Delice	12° 02.4′	61° 43.0′								w.r.	0.382	0.1568 0.1589	49.1 41.8	10.6 ± 0.3
RJA 531	South East Mtn.	12° 05.9′	61° 40.2′								w.r.	0.666	0.2846 0.2795	48.1 45.5	10.9 ± 0.3
RJA 341	Diego Piece Crayfish	12° 12.2′	61° 41.0′	basalt							w.r.	0.788	0.0578	12.6	1.89 ± 0.09
RJA 354	Mt Craven	12° 12.9′	61° 39.2′	andesite dome							hb.	0.391	0.3418 0.3059	47.8 38.5	21.2 ± 1.0

† One discrepancy disregarded.

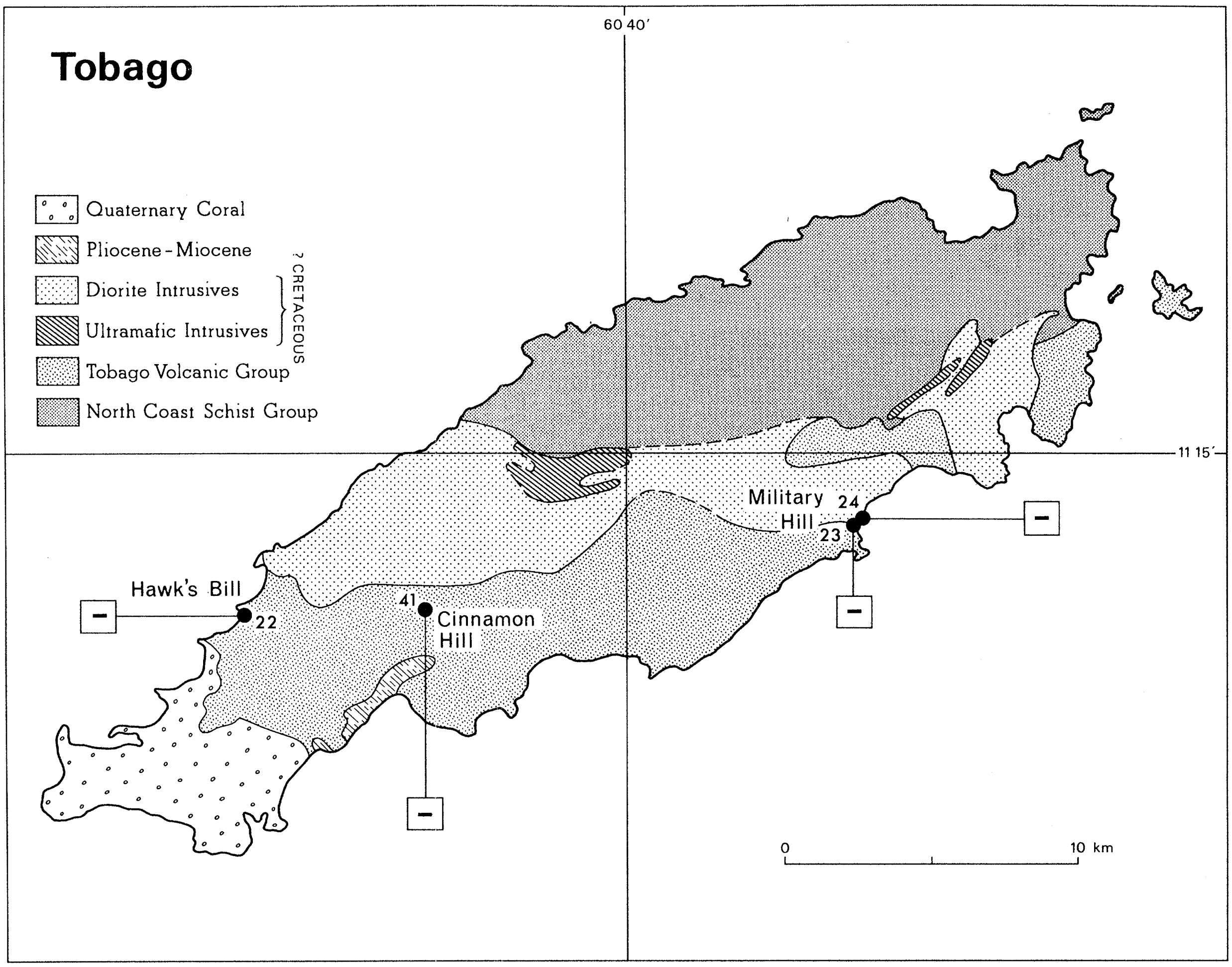

Figure 18. Simplified geological map of Tobago (after Maxwell 1948), showing palaeomagnetic data (table 13) in the format of figure 4. Prefix Y290 is omitted from site numbers.

Table 13. Tobago

	sampling details				stable n.r.m., a.f. cleaned					
	locality	latitude °N	longitude °W	rock type	polarity	peak field mT	number of specimens	R	D	I
Y29022	Hawks Bill	11° 12.2′	60° 47.1′	dacite lava flow	−	80	4	3.90	350	−09
Y29023	Military Hill	11° 13.6′	60° 35.9′	diorite batholith	−	0†	5	4.10	342	+40
Y29024	Military Hill	11° 13.8′	60° 35.8′	diorite batholith	−	20	2	2.00	18	−17
Y29041	Cinnamon Hill	11° 12.2′	60° 43.7′	andesite porphyry lava flow	−	20	5	4.89	2	+09

† n.r.m. direction preferred to a.f. cleaned.

16. TOBAGO

Palaeomagnetic results have been obtained from four sites (table 13, figure 18). These come from the batholith (Military Hill) and both older and younger volcanics (Cinnamon Hill and Hawks Bill respectively). All show normal polarity. Stratigraphic estimates (Maxwell 1948) and geochronological studies now in progress (D. C. Rex & K. Rowley, personal communication) are both consistent with ages within the long Cretaceous normal polarity interval (*ca.* 110–80 Ma) for all these rocks.

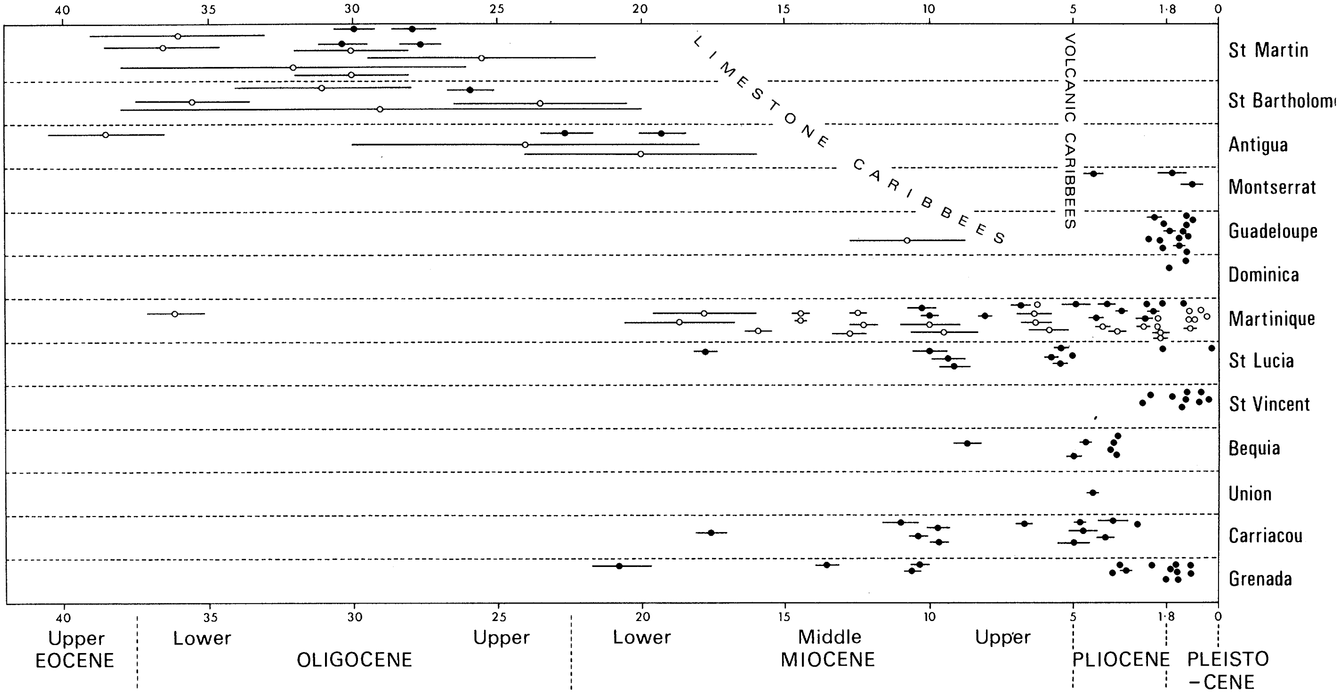

FIGURE 19. Schematic illustration of the geographic distribution of K–Ar ages of igneous rocks among the islands of the Lesser Antilles related to the Cainozoic time scale of Berggren (1972). Data of this paper are denoted by solid dots, and those of other authors by small open circles. Bars denote 1σ errors; for the sake of clarity bars are omitted when the errors are less than 0.15 Ma. For compatibility with the Berggren (1972) time scale the data are calculated by using potassium decay constants $\lambda_\beta = 4.72\times10^{-10}$ per year; $\lambda_e = 0.584\times10^{-10}$ per year; $^{40}\mathrm{K}/\mathrm{K} = 0.0119\%$.

17. GEOCHRONOLOGY

The age determinations are consistent with the recognition of an older arc (Limestone Caribbees and their continuation as basement from Martinique southward) and a younger arc (the Volcanic Caribbees, which deviate west of the older arc north of Dominica) (figures 1 and 19). Ages referred to the 'older arc' range between 30 and 19 Ma (*37 and *10 Ma if the data of Nagle *et al.* (1976) are accepted); those from the younger arc are predominantly less than 5 Ma; ages in the range 9–6 Ma have been found only in Martinique along with isolated examples from Bequia (8.96 ± 0.52 Ma) and Carriacou (6.92 ± 0.27 Ma). Baker (1969) also quotes a single whole rock K–Ar age of *7.7 ± 2.0 Ma from South Olivées Gut in St Kitts, but this appears to be in conflict with a number of determinations of *ca.* 2 Ma (Baker 1969; D. C. Rex unpublished) from other parts of the island which are believed to be older on geological and geomorphological grounds.

The preponderance of Pliocene–Recent ages is partly a consequence of the availability of samples suitable for dating and partly an expression of the extent of young volcanic cover where the two arcs are superimposed. This is mainly due to the extreme youth of the present volcanic arc, a fact which was not fully appreciated prior to this study. Thus in the presently inactive islands of Grenada and the Grenadines, selective sampling has been necessary to establish the extent of pre-Pliocene volcanicity; in St Lucia pre-Pliocene rocks have been identified only in the extreme north; on St Vincent all traces of pre-Pliocene activity are obscured. Pre-Pliocene rocks are more widely exposed on Martinique, where there is a general progression of age from the oldest in the southeast to the active Mt Pelée centre in the northwest. North of Dominica, the separation of the arcs and of their ages is quite complete. In the volcanic islands, the ages are exclusively Pleistocene in Dominica and Basse-Terre, and the only pre-Pleistocene ages reported are those of 4.41 ± 0.33 Ma from Montserrat and of *7.7 ± 2.0 Ma on St Kitts mentioned critically above. In the Limestone Caribbees, the range is *ca.* 30–20 Ma plus isolated determinations of *37 Ma in St Martin and *11 Ma in Grande Terre (Nagle *et al.* 1976) and the Mesozoic ages of La Désirade, all of which have been questioned to greater or lesser extent.

18. PALAEOMAGNETISM

The palaeomagnetic data are predominantly of Pliocene–Recent age (93 of 108 sites). Miocene data are probably confined to Martinique (3), Carriacou (5?) and Bequia (1), the uncertainties arising because not every palaeomagnetic site has been radiometrically or stratigraphically dated. The Oligocene has only been sampled palaeomagnetically in Antigua; the Eocene remains unsampled. The data are all grouped about the geocentric axial dipole field (figure 20). In Grenada and St Vincent, mean poles appear to be significantly different from the geographic pole, but the separation is marginal and the deviations are in the opposite sense: little significance is to be attached to these differences. Taking all the Pliocene–Recent data together, the normal and reversed directions are perfectly anti-parallel within the precision limits of the data (table 14, last line). Each group is insignificantly different from the geographic pole and their mean is only $1\frac{1}{2}°$ away from it. There is no indication that the palaeomagnetic poles are systematically 'far-sided', i.e. on the opposite side of the geographic pole from their source locality, and hence the hypothesis of a displaced axial dipole (Wilson 1970) finds no support in these data. The dispersion of stable r.m. directions, by using the circular standard deviation $81°/\sqrt{k}$ as a measure, is 22° which is similar to present day dispersion of the geomagnetic field along the latitude of the Lesser Antilles.

Six sites show intermediate polarity, interpreted as recording polarity transitions. The number of such observations is in accord with current estimates that the geomagnetic field may have been in a polarity-transitional state for about 5% of the last 5 Ma, while surprisingly, the virtual geomagnetic poles (v.g.p.) for all six of these sites lie within 30° of the zero meridian, suggesting that some of them record the same polarity transition.

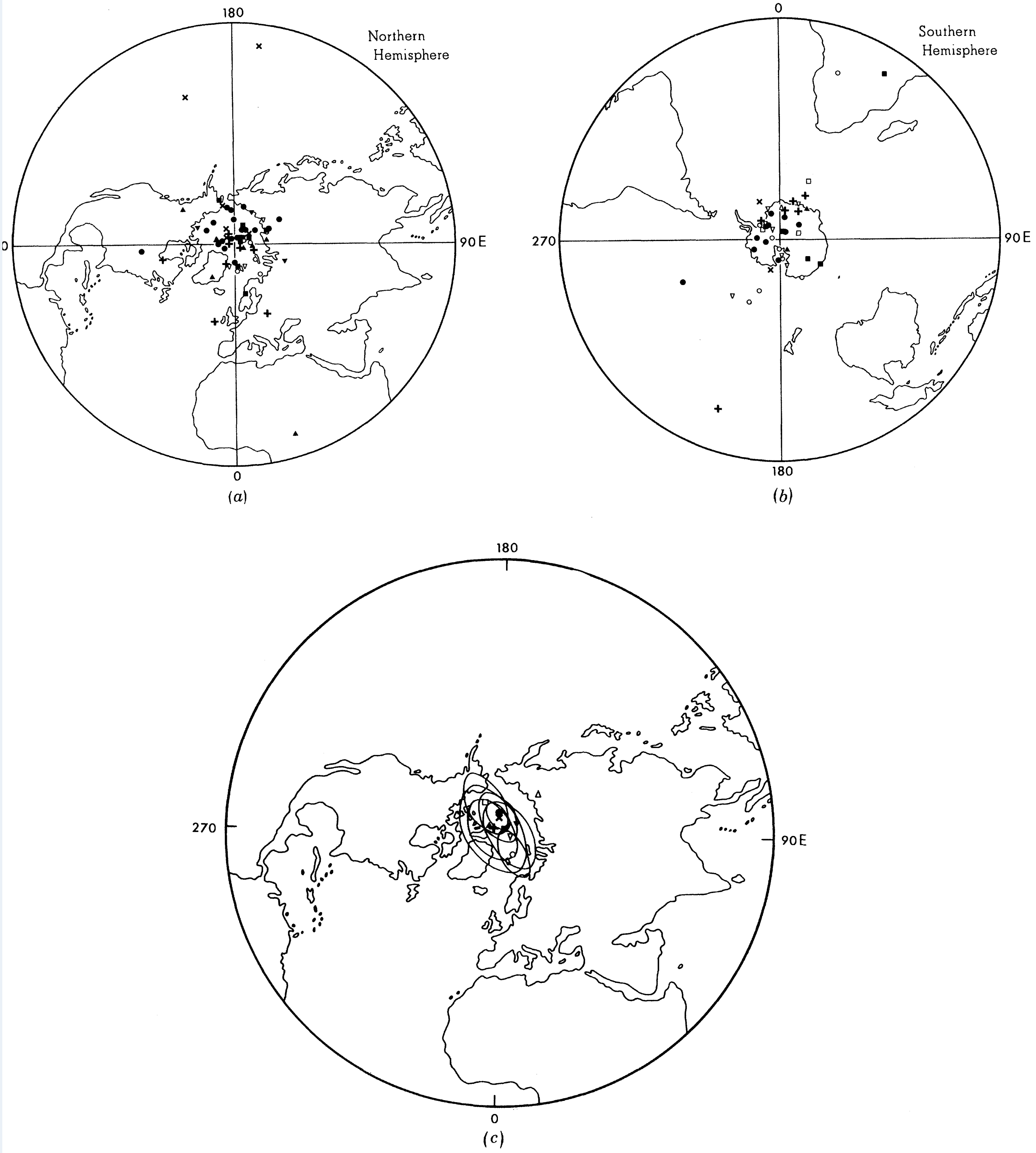

FIGURE 20. Polar stereographic maps of palaeomagnetic poles from all of the islands. Results from different islands have different symbols: △, Antigua; ▲, Guadeloupe; ■, Martinique; +, St Lucia; ●, St Vincent; ▽, Bequia; ×, Carriacou; □, Union Island; ○, Grenada; ▼, Tobago. (*a*) Site mean poles, normal polarity, north polar projections; (*b*) site mean poles, reverse polarity, south polar projection; (*c*) mean poles for each island with ovals of 95% confidence where more than 5 sites were sampled, standardized to normal polarity on north polar stereographic projection.

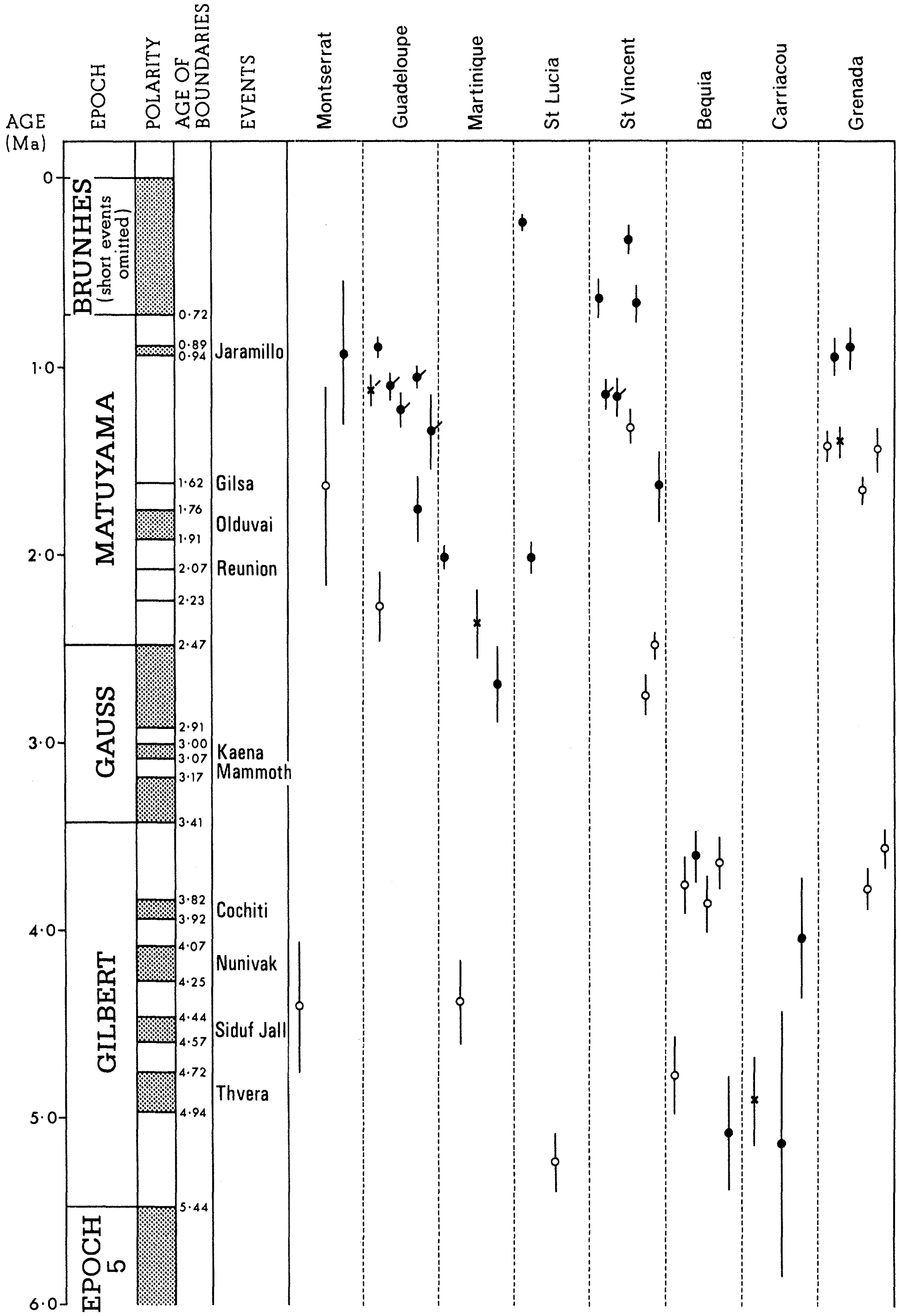

Figure 21. Pliocene to Recent K–Ar age determinations and palaeomagnetic polarity (normal black, reverse open, intermediate ×) together with the geomagnetic polarity time-scale of McDougall (1979) (normal polarity, stippled). The error bars are 1σ in length; where both whole rock and mineral ages were determined from the same sample, the more precise determination only is illustrated. The data which appear to indicate a normal polarity event at *ca.* 1.18 Ma are distinguished by oblique tags.

TABLE 14. MEAN STABLE n.r.m. DIRECTIONS AND PALAEOMAGNETIC POLE POSITIONS FOR EACH ISLAND

	normal								reversed								combined ('normalized')										
						pole								pole								pole					
	N	D	I	k	α_{95}	lat.	long.	$(d\psi, d\chi)$	N	D	I	k	α_{95}	lat.	long.	$(d\psi, d\chi)$	N	D	I	k	α_{95}	lat.	long.	$(d\psi, d\chi)$	intermediate	random or excluded from computation	total
Antigua	0	—	—	—	—	—	—	—	2	174	+07	—	—	315E	68S	(—, —)	2	354	−07	—	—	135E	68N	(—, —)	—	1	3
Guadeloupe	6	359	+31	12.3	19.8	246E	88N	(13, 22)	2	170	−39	—	—	62E	78S	(—, —)	8	356	+34	15.1	14.6	243E	86N	(10, 17)	1	1	10
Martinique	8	0	+19	18.1	13.4	114E	85N	(7, 14)	4	178	−37	—	—	103E	84S	(—, —)	12	0	+25	14.6	11.8	126E	88N	(7, 13)	1	—	13
St Lucia	8	9	+36	12.7	16.1	315E	79N	(11, 19)	5	163	−19	39.7	12.3	16E	73S	(7, 13)	13	358	+30	11.7	12.6	251E	87N	(8, 14)	1	1	15
St Vincent	17	353	+21	15.7	9.3	193E	83N	(5, 10)	9	177	−18	36.6	8.6	340E	85S	(5, 9)	26	354	+20	19.8	6.5	184E	84N	(4, 7)	—	2	28
Bequia	3	5	+17	—	—	69E	83N	(—, —)	7	182	−20	11.9	18.2	264E	86S	(10, 19)	10	3	+19	12.4	14.3	77E	86N	(8, 15)	—	—	10
Carriacou	5	351	+20	56.5	10.3	193E	81N	(6, 11)	2	181	−22	—	—	264E	88S	(—, —)	17	354	+20	35.9	10.2	189E	84N	(6, 11)	2	—	9
Union Island	0	—	—	—	—	—	—	—	3	166	−21	—	—	23E	76S	(—, —)	3	346	+21	—	—	203E	76N	(—, —)	—	—	3
Grenada	5	10	+15	44.2	11.6	51E	80N	(6, 12)	7	192	−26	17.3	15.0	199E	78S	(9, 16)	12	11	+21	22.5	9.4	32E	79N	(5, 10)	1	—	13
Tobago	4	359	+06	—	—	128E	82N	(—, —)	0	—	—	—	—	—	—	—	4	359	+06	—	—	128E	82N	(—, —)	—	—	4
Total	56	359	+22	13.8	5.3	229E	89N	(3, 6)	41	178	−22	14.1	6.2	18E	88S	(3, 6)	97	358	+22	14.2	4.0	192E	88N	(2, 4)	6	5	108

k, α_{95} are Fisher's (1953) precision estimate and circle of 95% confidence about the mean direction D, I. $d\psi$, $d\chi$, are the semi-axes of the oval of 95% confidence about the mean palaeomagnetic pole. N is the number of sites in each island.

Within the last 5 Ma one would not expect to be able to detect apparent polar wander of plate tectonic significance, and our data are in accord with this. It is more notable that our pre-Pliocene data from the Lesser Antilles show no significant deviations of the palaeomeridian, nor do the Cretaceous rocks from Tobago (table 13). The three palaeomagnetically stable sites in Tobago appear to indicate a slightly lower latitude in Cretaceous times than now, but with orientation unchanged. This indicates that the arc has not been oroclinally bent during its evolution, and that Tobago has not changed its orientation with respect to the pole since the Cretaceous.

At the outset of this study it was evident that we could not hope to contribute substantially to the refinement of the geomagnetic polarity time scale due to the inherent imprecision of single whole rock K–Ar age determinations, in comparison with the known (short) duration of constant-polarity time intervals and in the absence of the extra sequential control which is available in continuous lava piles. Our observations are mainly isolated 'spot readings' of both time and palaeomagnetic field, from central volcanoes for which the sequence of eruption of the various mappable deposits is rarely determinable without ambiguity. None the less the bulk of our K–Ar and polarity data are concordant with the known geomagnetic polarity time scale (figure 21). The principal exception to this concerns seven sites in Guadeloupe (702201, –6, –7, –8; G23413) and St Vincent (683741, –7) where normal polarity is observed along with age determinations between 1.07 ± 0.06 and 1.37 ± 0.20 Ma (unweighted mean 1.18 Ma). These appear to suggest a normal polarity event at about 1.18 Ma within the Matuyama Reversed Epoch and about 0.20 Ma prior to the Jaramillo Normal Event. Watkins & Abdel-Monem (1971) have suggested a normal event at this time on the basis of a single whole rock K–Ar age determination of 1.18 Ma on a normally magnetized basalt from the island of Madeira and suggested that it might be correlated with a short event found in some deep sea cores from the Southern Ocean by Watkins (1968). It is conceivable that most or all of these observations record the same event, or perhaps more than one event is represented. On the other hand no events in the time interval 1.25–1.00 Ma have been consistently observed either in ocean floor magnetic anomaly records, or from deep ocean cores. If the suggested new normal event at *ca.* 1.18 Ma is ever confirmed, many current identifications of the Jaramillo Event might well be reappraised. The data which appear to suggest this are all from basaltic andesitic lava flows, but they appear to have few other characteristics in common; their matrices are all crystalline though some are exceedingly fine grained; they have a variety of phenocrysts but only in two cases is there any suspicion of alteration of feldspars. It must, however, be pointed out that our samples from four of the seven sites in question have been reanalysed for argon by essentially similar methods to ours by Dr I. McDougall, in whose laboratory many of the undisputed cornerstone data for the polarity time scale originate; much younger (Brunhes) ages were obtained in all four cases. In contrast, two of these same four samples have been analysed by Dr J. Mitchell using an Omegatron, and results consistent with ours were obtained; three of the four have been reanalysed in Leeds by using an argon-38 tracer less than one tenth of the volume used in the initial runs, with essentially identical results. All of the data at issue involve argon analyses with 90 % or more atmospheric contamination, so that the differences in determined argon isotope ratios which give rise to these discrepancies are small. They cast uncertainty on only a minority of our data. If a normal event at *ca.* 1.18 Ma is admitted, only three of our 45 determinations shown in figure 21 are in conflict (when 1σ errors are allowed for) with the polarity time scale. Two of these are from single lavas from St Vincent and Bequia which are both mentioned in the text; they may be explained as due to small proportions of argon loss, or 1σ errors quoted here may underestimate actual error in these particular instances. The third is from Grenada; it is stated to be of intermediate polarity – an observation which is capable of more than one interpretation.

Of greater interest are the many cases where we use the polarity observation, calculated age and published time scale together to identify which polarity interval is likely to be represented by a given sample. When the duration of that polarity interval is less than the standard deviation in the K–Ar age, it can then replace the statistical estimate of error as a measure of uncertainty in the age determination. Examples are cited from Guadeloupe, Martinique, St Vincent and Grenada (§ 6, 9, 11 and 15). Where only the statistical error and the compatible polarity interval overlap, the interval of that overlap may be taken as the age uncertainty – though in such situations it is difficult to formulate a proper statement of probability to attach to that uncertainty. Examples arise in Bequia (§ 12).

19. Implications for the plate tectonic evolution of the Central Atlantic

In the early generalized plate models (Le Pichon 1968; Morgan 1971; Le Pichon, Francheteau & Bonnin 1973), North and South America and the whole of the Atlantic west of the Mid-Atlantic Ridge (M.A.R.) were regarded as part of a single plate. This 'Americas' plate dwindled in width to a narrow neck in the Central Atlantic where the Caribbean plate nosed into it, and it was difficult to construct an evolutionary model to account for interaction between the Caribbean and Americas plates. Distinct North and South American plates are now inferred and relative motion between them has been determined to be small but real (Minster, Jordan, Molnar & Haines 1974; Phillips & Forsyth 1972; Harrison & Ball 1973). Thus the Caribbean plate is in a critical position between the large North and South American plates and might be expected to respond sensitively to their differential motion. Marine geophysical studies have shown that the growth of the Atlantic has been complicated. Long periods during which rate and direction of ocean floor spreading remained steady, were interrupted by relatively rapid changes in tectonic rotation vectors (Pitman & Talwani 1972; Ladd 1976). It is therefore of interest to see whether changes in character or location of volcanism in the Lesser Antilles are correlated with plate tectonic readjustments elsewhere.

According to Pitman & Talwani (1972) steady ocean floor spreading was interrupted in the North Atlantic at 38 Ma and again at 9 Ma. The K–Ar ages show a distinction between a range 37–10 Ma in the outer arc (Limestone Caribbees) and less than 7.7 Ma in the inner arc (Volcanic Caribbees), whereas from southern Martinique southwards the two arcs are superposed and the whole age range 37–0 Ma is fragmentarily represented. The spreading direction of the western Atlantic floor relative to the Mid-Atlantic Ridge shifted anti-clockwise at about 9 Ma, as did the orientation of the active volcanic arc, and the two events appear to have occurred together. The jump in arc location *away* from the mid-ocean ridge which occurs in the Lesser Antilles is the opposite of the oceanward migration which is common in Pacific island arcs and may be unique. Perhaps the older arc itself was initiated about the time of the 38 Ma sea floor spreading change; the only evidence that it was volcanically active or uplifted from the ocean floor substantially earlier than 38 Ma depends on the assignment of early or middle Eocene ages to carbonate and volcaniclastic formations on St Martin, St Bartholomew, and the Grenadines (Lewis & Robinson 1976) – some of which may be open to some readjustment.

Despite recognition of separate North and South American plates on global kinematic grounds (Minster *et al.* 1974), their common plate margin in the Central Atlantic has not been located. It is not obvious topographically and the seismicity does not indicate a clear line. Jordan (1975) tentatively locates it as traversing eastward from the southern terminus of the Lesser Antilles arc towards the M.A.R. as a transform fault compatible with the tectonic rotation pole for this plate-pair predicted by model RM1 (Minster *et al.* 1974). Le Pichon *et al.* (1973, figure 27) hint at a possible location of a transform margin running from the northern end of the Lesser Antilles arc, perhaps on the line of the Barracuda Fracture Zone. Harrison & Ball (1973) invoke a family of small transform faults – westward extensions of M.A.R. offsets between 12° N and 18° N – to account for the weak and dispersed seismicity. Neither the M.A.R. offsets nor, of course, their postulated extensions, are concentric with the North America–South America tectonic rotation pole of Minster *et al.* (1974) and those authors have suggested that the small relative motion is taken up by anelastic creep.

We now note that the St Vincent–St Lucia–Martinique segment of the Lesser Antilles arc at about 14° N is critical in several respects. The tectonic rotation pole for the North America–Caribbean plate-pair is about 50° S 64° W (Jordan 1975). Its meridian is fixed by the normal to the Puerto Rico trench where it passes westward from an extremely oblique subduction zone into a pure transform. St Lucia and Martinique lie in the area where the slip vector is straight down the subduction zone, i.e. the arc is meridianal to the tectonic rotation pole at this point: to the south there is southward oblique slip and to the north, oblique slip is northward. It is between St Vincent and St Lucia at 13° 30′ N that the geochemical discordance occurs between more alkaline, less silicic rocks in the south and calc-alkaline, more silicic rocks to the north (Tomblin 1975; Brown *et al.* 1977) occurs. This geochemical evidence, together with the change in bathymetry and Bouguer gravity anomaly patterns east of the volcanic arc (Westbrook 1975) and seismic evidence (Tomblin 1975) at about 14 °N, indicate a change in the nature of subduction in this vicinity. It seems kinematically impossible that the pre-9 Ma subduction zone could be succeeded by another on its inner side, of which the jump in arc location would be the surface expression. It is equally improbable that such a new subducting slab could have penetrated deep enough in the few million years, at most, which were available, to act as the source for the foundation of the younger arc. Nor does bifurcation of younger and older subducting slabs, matching the bifurcation of the arcs seem geometrically feasible.

Migration of the northern part of the arc due to varying dip of the subduction zone, or to a change in the depth range from which the magma for the northern part of the arc was being tapped, both seem more plausible explanations. Both might in turn have been caused by the variation in *relative* spreading rate along the arc which occurred in the Atlantic at about 9 Ma and which could have favoured increased curvature of the subducting margin. Further geophysical and geochemical work would be needed to evaluate these suggested mechanisms, and further search is needed for a fracture zone or zones between the M.A.R. and the Lesser Antilles which are the most likely expression of the North American–South American plate margin. The existence of such fractures would be compatible with the partial arc-migration mechanisms suggested here.

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