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Tectonic and structural controls of magma genesis in the Lesser Antilles*

J.F. TOMBLIN

Seismic Research Unit, University of the West Indies, Trinidad

Abstract

The island arc of the Lesser Antilles between Grenada and Saba consists of Tertiary to Quaternary volcanic piles built at intervals along the crest of a submarine tectonic ridge. The magmas belong to the calc-alkaline assemblage, distinguished chemically by a large proportion of silica-rich rocks, and a decrease in iron/magnesium ratio with increasing silica. Potassium-rubidium ratios in the more acid rocks attain relatively low values, whilst $\text{Sr}^{87}/\text{Sr}^{86}$ ratios which exceed the level normally accepted as typical of recent mantle differentiates, have been reported in certain of these rocks.

Tectonic earthquakes are common in the eastern Caribbean region, where about 400 hypocentres, belonging to events of magnitude (Mb) 3 or greater, are determined annually by the Seismic Research Unit. Most of the epicentres lie in a belt 200 km wide, bordering the eastern side of the arc. The foci are at depths of up to 250 km, and a trend of depth increase westward, towards the arc, is often discernible. This asymmetrical pattern of focal depths is matched by the asymmetry of topographic features and of gravity anomalies in a section east-west through the arc.

Magnetic anomaly patterns in the Atlantic indicate that the western Atlantic ocean floor is spreading westward, and recent studies of focal mechanisms of Caribbean

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earthquakes suggest that this western Atlantic Ocean floor is actively under-thrusting a resistant Caribbean crustal plate. If oceanic crust (believed to be mainly basaltic) is being thrust downward beneath the arc to depths at which partial melting takes place, it is not surprising that the magmas generated are mainly andesitic in composition.

The basaltic magmas of the Lesser Antilles appear to be derived mainly by total or near-total fusion of ocean-floor basalt, although there is evidence that, at the southern end of the arc, low-silica, highly mafic magma has been derived directly from the mantle. The general tendency for the volcanic products to become more siliceous with time reflects the progressive accumulation of oceanic crust plus continental detritus beneath the island arc.

Introduction and Acknowledgements

This paper reviews the structure, major element geochemistry and present-day tectonics of the Lesser Antilles. It attempts to relate the various observations to one another and to the broad picture of global tectonics in the Atlantic-Caribbean region.

The geochemical summary is based upon all published data known to the writer, the more important sources of which are BAKER 1968; FLETT, 1908; HUTTON, 1968; LACROIX, 1904; LACROIX, 1926; MACGREGOR, 1938; ROBSON and TOMBLIN, 1966; TOMBLIN, 1968a; and TOMBLIN, 1968b. Data on eastern Caribbean earthquakes are from the Seismological Bulletins and recent, unpublished data files of the Seismic Research Unit in Trinidad.

The author's work on the petrology and geochemistry of the region began in 1961 as a research project at the University of Oxford under the late Professor L.R. WAGER and Professor G.M. BROWN, with the cooperation of Dr. G.R. ROBSON

at the University of the West Indies. From 1964 onward, the author has continued this research at the University of the West Indies, where over 200 whole rock, colorimetric analyses have been made. Since 1967 the author has collaborated with Professor G.M. BROWN and Dr. J.G. HOLLAND (University of Durham) in a project for the comprehensive study of the geochemistry of the Lesser Antilles, under which large numbers of whole rock analyses are being made by x-ray fluorescence spectrometry. None of these XRF data are used in the present paper, although it is clear that when this project is completed and the data fully processed, a much more detailed picture will be obtained of the geochemistry of the region.

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Structural Setting of the Lesser Antilles

The volcanic islands of the Lesser Antilles (Fig. 1) are Tertiary to Quaternary piles built at regular intervals along the crest of an arcuate tectonic ridge. This ridge and the external trench coincide with a seismically active belt which approximately surrounds the Caribbean Sea and which, at its western ends in northern Colombia and Mexico, joins the circum-Pacific orogenic belt. The Lesser Antilles represent the youngest part of the circum-Caribbean tectonic belt and the only part which is still volcanically active. The characteristic island-arc gravity pattern is present, with high positive anomalies along the volcanic island chain and an axis of negative anomalies following the external trench and passing through the island of Barbados.

There is no evidence of ancient continental crust beneath or adjacent to the arc: no such material either outcrops in the region or occurs as xenoliths in the lavas, although it is clear that sediments of continental origin from adjacent South America are continuously being deposited alongside the arc, especially in the external trench. It therefore appears that there is no direct or exclusive supply of continental material for conversion into magma. At the same time it is observed that no peridotite or olivine nodules are erupted from the Lesser Antillean volcanoes, and this suggests that the magmas are not derived directly from the mantle; the latter is confirmed by the geophysical evidence, e.g. the seismic refraction profiles of OFFICER et al. (1959), that the Mohorovicic discontinuity is at least 20 km deep below the islands.

Composition and Distribution of Lesser Antillean volcanic rocks

The products of the Lesser Antillean volcanoes are typical members of the calc-alkaline assemblage. Petrographically they range from olivine-augite basalt, through hypersthene or two-pyroxene or hornblende andesite, to amphibole-biotite dacite, and occasionally to rhyolite. Basalts, defined here as all rocks with silica up to 55%, account for only 25% of surface outcrops. Andesite ($\text{SiO}_2 = 55-63\%$) forms an estimated 67% of all outcrops. Dacite ($\text{SiO}_2 = 63-70\%$) accounts for approximately 8%, and rhyolite ($\text{SiO}_2 > 70\%$) for 0.1%. The basalts are rather variable in composition, with two principal types. The first is augite-olivine-phyric and the second, olivine-microphyric. A third, subordinate type consists of aphyric basalt with relatively low alumina and high iron content (i.e. tholeiitic affinities): this occurs only in the island of St. Lucia, in small volume. The andesites and dacites are all strongly porphyritic, with calcic plagioclase (cores An_{90-80} , outer parts oscillatory-zoned between An_{70-40}) as the predominant phenocryst.

The distribution of rock types along the arc according to area of outcrop is illustrated in Fig. 2, which contains four groups according to age and four divisions according to composition. This represents the most detailed level of subdivision which can meaningfully be made at the present time. The diagram shows that the basalts tend to be more common among the older rocks in a given island, and are distinctly more abundant in the southern two islands of the arc. The dacites and rhyolites occur almost exclusively in the central part of the arc, between St. Lucia and Guadeloupe.

In addition to their high mean silica content, the Lesser Antillean rocks are distinguished by their high abundance of alumina and lime, low titanium, and by the marked decrease in the iron/magnesium ratio with increasing acidity. BROWN and SCHAIRER (1968) used the $MgO/\text{total iron oxide}$ diagram to illustrate the distinctive characteristics of the calc-alkaline series of the Lesser Antilles and other regions in relation to the alkaline and tholeiitic series of Hawaii. A similar diagram, illustrating a larger number of analyses from the Lesser Antilles, is presented in Fig. 3. There is a marked contrast between the Lesser Antillean rocks and the Hawaiian tholeiitic series, which BROWN and SCHAIRER (1968, p.463) attribute to "the probable effect of increasing oxygen fugacity in the calc-alkaline basalts, resulting in iron oxide formation at the site of crystal fractionation". The present author, whilst in complete agreement with BROWN and SCHAIRER over the importance of high oxygen fugacity, suggests that it may in fact be not the early growth of iron oxides during solidification of magma, but rather the reverse process, i.e. the late melting, or failure to melt, of the oxide minerals during the partial melting of basaltic parental material. The Lesser Antillean trend is much more comparable in iron:magnesium ratios to the alkaline series of Hawaii, although the proportion of iron remains distinctly lower

throughout the Lesser Antillean suite. Tie lines are shown in Fig. 3 connecting whole rocks and corresponding groundmasses: these closely parallel the whole rock trend, demonstrating that the separation of high and low temperature components, by either fractional crystallization or partial melting, could produce a succession of liquids along the calc-alkaline trend. The point marked Z in Fig. 3 is the plot of the mean mid-Atlantic ridge basalt quoted by MELSON et al. (1968) which, although called a tholeiite, contains markedly less iron than the Hawaiian tholeiites. This mean composition is of great interest with regard to the question of magma genesis in the Lesser Antilles, since the mid-Atlantic basalt falls exactly on the Lesser Antillean trend, and thus, in terms of its iron and magnesium contents, represents an eminently suitable parent for the Lesser Antillean magma series.

Potash to silica ratios in the Lesser Antillean volcanics are illustrated in Fig. 4. This diagram shows uniformity in most of the islands, but a marked anomaly in the very low-silica rocks from Grenada and the Grenadines, which are relatively rich in potash. A less striking divergence, in the opposite direction, is seen in the andesites from St. Kitts which have comparatively low ratios of potash to silica. The diagram also illustrates the special position of St. Lucia, which is noteworthy for its large number of high-silica, high-potash rocks. The high abundance of both oxides suggests a high degree of fractionation, involving the selective removal of the earliest-melting fraction of a basalt, and possibly also the incorporation of acid continental material from recent sediments¹.

¹The case for continental material having contributed to the formation of siliceous andesites and dacites in the islands of St. Lucia and Dominica has been made by PUSHKAR (1968) on the basis of three strontium isotope analyses showing moderately high Sr 87/86 ratios of between 0.707 and 0.709. The remaining eight strontium isotope analyses reported by PUSHKAR (1968) for other islands in the Lesser Antilles all have Sr 87/86 ratios below 0.705, i.e. compatible with a fairly recent mantle origin.

The mean mid-Atlantic tholeiite, indicated by the symbol Z in Fig. 4, lies near the K_2O -poor end of the main West Indian trend: any low-melting derivatives from such a tholeiite ought to be relatively enriched in potash and silica, and this is exactly the relationship of the majority of Lesser Antillean rocks to the mid-Atlantic tholeiite. The chemical relationship of the very low-silica lavas from Grenada and the Grenadines to the mean mid-Atlantic basalt is more remote: the Grenada rocks contain less silica but more potash. Thus, if any genetic link were to be postulated between these and the mid-Atlantic basalts, a mechanism would be required which raised the potash but lowered the silica content. In the augite-olivine macrophyric basalts, it is easy to explain the low silica as the result of crystal accumulation in the magma before eruption, although it is difficult to see how the accumulation of augite and olivine could account for the high potash relative to other West Indian basalts and to the mean mid-Atlantic basalt (c.f. Fig. 4). The olivine-microphyric basalts from Grenada, which also have a relatively high potash content, contain no obviously accumulative phenocrysts, and may therefore represent an ultramafic magma. Thus it is concluded that the Grenada basalts were probably not generated from oceanic crust, but developed as direct differentiates from a part of the mantle relatively rich in K_2O .

Tectonics and Structure of the Lesser Antilles

The high ratio of sea to land in the region, and the relatively poor geological exposures in the land areas mean that only a very rudimentary picture of the regional structure can be obtained from direct observation of the geology. Information on the tectonics and structure of the Lesser Antillean arc has therefore depended to a larger degree than usual on geophysical measurements such as seismic refraction profiles and earthquake studies. The refraction profiles of OFFICER et al. (1959) show that the Caribbean crust is essentially similar to typical

Atlantic oceanic crust, the largest difference being that it appears to grade into the mantle rather than possess a sharp boundary with it. Beneath the volcanic arc, however, the crust is at least twice as thick as in adjacent oceanic areas. The greater part of this thickened crustal section has a seismic velocity of 6.4 - 6.8 km/sec, which is equivalent to the velocity of the main portion (layer three) of the oceanic crust. This lends further support to the hypothesis that the thickened crust beneath the arc is oceanic basalt or its metamorphosed equivalent.

The study of regional earthquakes in the eastern Caribbean is being carried out by the Seismic Research Unit of the University of the West Indies, which has published seismological bulletins containing regional hypocentre determinations since 1952. This network currently determines about 400 hypocentres per year, representing almost complete coverage for regional events of magnitude (Mb) down to 4.5, and partial coverage for magnitudes down to 3.0. About 10% of these events are also located by the World-wide Standardized Seismograph Network of the United States Coast and Geodetic Survey; data from the latter source for the period 1950 through 1964 have been recomputed and briefly reviewed by SYKES and EWING (1965).

The hypocentres determined by the Seismic Research Unit¹ are plotted on a routine basis by quarter years, and examples of the resulting epicentre maps are presented in Figs. 5 and 7. Most of the hypocentres are shallow and lie in a belt 200 km wide, bordering the eastern side of the arc. Focal depths almost never exceed

¹Experiments with the computer program indicate that, for at least 90% of typical input, errors in latitude and longitude do not exceed 0.1 degree for every degree mean hypocentre to station distance (e.g. at a mean distance of 3 degrees, errors are less than 0.3 degrees), whilst depths are usually accurate to $\pm 50\%$ of the figure obtained, and origin times are in error by up to one second for every degree mean hypocentre to station distance.

Fig. 5 illustrates a crude tendency for hypocentres to cluster within the so-called Benioff zone (BENIOFF, 1954), with shallower foci concentrated outside and deeper foci beneath and inside the arc. Events in the northern half of the arc for this quarter have been projected onto a cross-section perpendicular to the arc (Fig. 6) which illustrates that hypocentres beneath and to the west of the arc are consistently deeper, although there is still a considerable scatter in depth and the Benioff zone is very poorly defined. A general relationship between the depth to the Benioff zone and magma composition has been pointed out for other island arcs, notably Japan (KUNO, 1959), and DICKINSON and HATHERTON (1967) have shown that the potash to silica ratio in certain island arcs varies as a function of the depth to the Benioff zone. In the Lesser Antilles this ratio is distinctly higher at the southern end of the arc, although no tendency for foci to be deeper in this part of the arc has been observed in earthquake data for the last 15 years. It is possible that the pattern of earthquake activity during this short historic period may not be representative of the last several million years during which the magmas in question were erupted, and indeed the considerable variation in the geographic distribution of epicentres which has been observed during the last decade favours such a conclusion. The relatively short length of section perpendicular to the arc along which volcanic rocks are seen in the Lesser Antilles effectively prevents any comparisons from being made between earthquake depths and lava compositions across the arc, of the kind made in Japan by KUNO (1959).

The correlation between hypocentres and physiographic features of the region is illustrated by Fig. 7. The pattern during this quarter is dominated by the occurrence of hypocentres in strings perpendicular to the arc, including intermediate depth earthquakes far to the east of the arc where foci are usually all shallow. Bathymetric contours have been inserted on part of this map, and these

show that the northern two strings of earthquakes correspond closely with steep submarine slopes. These slopes presumably represent the escarpments formed by active faults. It is concluded that the faults form boundaries between slabs of Atlantic lithosphere which break up into independent units, subject to different stresses and moving at different rates, as they are carried downward beneath the Caribbean crustal plate. Thus at least two structural elements seem to be responsible for the distribution of earthquake foci: firstly, a westward-dipping thrust plane striking parallel to the arc, which is the Benioff zone; and secondly, a number of planes striking perpendicular to the arc which are faults across which vertical offsets are demonstrable, and along which minor transcurrent movements have probably also occurred. The distribution of the Lesser Antillean volcanoes in a north-south, arcuate line indicates that the actual genesis of magma is closely connected with the thrust plane. However, the faults perpendicular to the arc would allow adjacent blocks of lithosphere to move independently, and each block could thus develop its own stress pattern which in turn would affect the earthquake distribution, the depth of magma genesis, and the timing of volcanism within that block. Differential movement would also affect the physiography of the external trench, hence the thickness of the sediment deposited in any one part of the trench, and ultimately, perhaps, the composition of the magma produced.

In addition to the regional tectonic earthquakes, swarms of shallow earthquakes occur from time to time beneath dormant volcanoes of the Lesser Antilles. Characteristically these volcanic earthquakes are of small magnitude, and at the shallow depths of between 1-15 km. In five out of sixteen historic examples in the Lesser Antilles, such a crisis has ended in an eruption. An account of the most recent of these crises, in the island of Montserrat, is given by SHEPHERD, TOMBLIN and WOO (in press). The earthquakes are interpreted as the result of rock fracture in the vicinity of rising magma, and illustrate that magma is frequently

intruded into the upper crust. However, no data on hypocentres have yet been obtained in the Lesser Antilles from the very beginning of such a crisis, and thus there is no seismological evidence upon which to base an estimate of the depth from which the magma initially began to rise.

Focal mechanism studies on a few of the larger magnitude, tectonic earthquakes in the region carried out by MOLNAR and SYKES (1969), and the fault plane solutions determined by these authors have been inserted in Fig. 1. Although the total number of slip vectors shown for the eastern Caribbean is only small, the majority of these confirm the pattern of transcurrent movement, left-lateral along the northern side and right-lateral along the southern side of the Caribbean crustal plate, whilst two fault plane solutions along the eastern margin of the Caribbean correspond appropriately to westward-dipping thrust movements in this sector of the arc.

Sea-floor Spreading and Rates of Magma Genesis

The reality of sea-floor spreading at the mid-ocean rift zones has been convincingly demonstrated on the basis of magnetic anomaly patterns, to which attention was first drawn by VINE and MATTHEWS (1963). More recently, DICKSON et al. (1968) have estimated that the western half of the south Atlantic lithosphere has spread westward at mean rates of between 1.5 and 2.5 cm/year, during the last 10 million years. They also show that anomalies have been traced outward from the ridge for nearly 1,500 km which would correspond, by extrapolation of the recent rate, to sea-floor spreading at the mid-Atlantic ridge through the last 75 million years. It appears from the concentration of seismicity and vulcanism in the Lesser Antilles that the complementary process to sea-floor spreading, involving the disposal of oceanic crust, is taking place along this island arc. Assuming that material is being consumed in the Lesser Antilles at a rate equivalent to its rate of generation in the mid-Atlantic, a rough calculation can be made of the balance between materials consumed and erupted in the island arc region:

in an interval of 100 years, for example, at a spreading rate of 2 cm/yr, a strip of crust 2 metres wide would be consumed. With a crustal thickness of 10 km, and an arc 600 km long, this amounts to a total volume consumed of 12 cubic kilometres per 100 years. The estimate for total erupted magma during the last 100 years, almost all of which came from St. Vincent and Martinique, is about 3 cubic kilometres (ROBSON and TOMBLIN, 1966). Hence a volume equivalent to roughly 25% of the amount consumed has melted and been re-ejected, whilst a further, possibly similar volume of magma must have been intruded into the upper crust to form dioritic to granodioritic plutons.

Conclusions

Data on ocean floor spreading in the South Atlantic (DICKSON et al., 1968) suggest that the crust which reaches the Lesser Antillean island arc was generated some hundred million years earlier along the mid-oceanic rift as the lowest-temperature, partial melt from the upper mantle which it now overlies. This upper mantle segment therefore consists of material which would not begin to melt at least until more or less complete melting of the nearby crust had occurred. The upper part of the former ocean floor must have been thoroughly permeated by sea water before it was driven downward beneath the island arc, and the presence of this water would further lower the melting point of the crustal material. The mantle, on the other hand, can be expected to have remained relatively dry. Thus it is concluded that the andesite magmas represent crust-partial melts, whilst the island arc basalts in most cases represent total melts of the wet crust, rather than partial melts from the dry mantle. It seems probable that newly formed liquids will normally migrate upward from depth before complete melting has been achieved. Thus andesite magmas, representing the partial melts of oceanic crust, are more abundant than basaltic magmas which would represent crust-total melts.

The dacite and rhyolite magmas, which form a relatively small proportion of the total volume of volcanic products in the Lesser Antilles, are interpreted either as the products of the earliest, highly differentiated melts from ocean floor basalt, or alternatively as partial melts from oceanic crustal basalt plus more acid detritus of continental origin, of the kind which is found, for example, among the early Tertiary flysch sediments in Barbados.

There is little evidence in the Lesser Antilles that andesites and dacites were extensively produced by the fractional crystallization of basaltic liquids in high level magma chambers. The only island where such a process appears to have taken place to a significant degree is St. Vincent, which is notable for its relatively abundant accumulative blocks (LEWIS, 1964), and also for the complete absence of rocks more acid than basaltic andesite. The highly explosive character of the St. Vincent basalt magmas indicates a high volatile content, and supports the notion that they were derived from wet crust rather than dry mantle. The violence of this basaltic vulcanism is in marked contrast with the relative mildness of typical mid-oceanic, volatile-poor, basaltic eruptions. In Grenada and the Grenadines, at the southern end of the Lesser Antilles, the style of the basaltic vulcanism is notably milder and corresponds closely with the mid-oceanic type. The abundance of olivine microphyric basalts of picritic composition, erupted mildly from numerous scoria conelets, suggests that a substantially different magma-generating process takes place in this part of the arc. It is probably significant in this context that the level of present-day seismicity is notably lower at the southern end of the volcanic island chain, and that there is an outer ridge east of here, in the Barbados region, whilst other embryonic submarine ridges southeast of Barbados are suggested by the gravity anomaly map of BUSH and BUSH (1969). These features imply that crustal shortening is taking place over a much longer east-west profile at this

end of the arc, and that oceanic crust is not being consumed beneath the southern section of the present volcanic arc as rapidly as it is beneath the central and northern islands. Thus it is concluded that the highly mafic magmas produced at the southern end of the arc are more likely to be primary mantle differentiates than the products of complete fusion of basaltic crust followed by crystal accumulation.

In the world at large, calc-alkaline magmas are produced only in the circum- or intra-oceanic tectonic belts where crustal shortening is the dominant process. This in itself is compelling evidence that the tectonic process is the critical factor, whilst the relative uniformity of the oceanic crust ensures that wherever it is subject to this process, the same distinctive magma series will be generated.

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	K (8)	F (2)	G (3)	D (4)	M (6)	L-A (2)	V (47)	X (27)	M-A (33)
SiO ₂	51.01	52.01	52.60	48.14	49.80	52.96	51.89	46.14	49.21
Al ₂ O ₃	19.46	19.37	19.61	19.72	18.91	15.68	18.40	14.76	15.81
Fe ₂ O ₃	3.74	2.79	4.11	2.73	4.62	3.75	3.44	4.79	2.21
FeO	5.41	5.70	5.06	7.20	5.60	7.64	5.39	5.10	7.19
MgO	4.82	4.65	2.82	4.24	6.16	3.39	5.53	10.63	8.53
CaO	10.69	10.13	9.21	10.99	9.57	7.55	9.75	11.61	11.14
Na ₂ O	3.16	2.88	3.49	2.54	2.24	3.41	2.99	2.36	2.71
K ₂ O	0.46	0.88	0.59	0.64	0.71	0.60	0.54	0.79	0.26
H ₂ O ⁺	0.38	0.24	0.68	1.95	0.69	1.37	0.67	1.99	
H ₂ O ⁻	0.12	0.24	0.37	0.00	0.19	0.84	0.24	0.29	
TiO ₂	0.96	0.75	0.98	0.82	1.34	1.04	0.93	0.90	1.39
P ₂ O ₅	0.07	0.12	0.32	0.10	0.18	0.11	0.11	0.19	0.15
MnO ₂	0.16	0.14	0.18	0.21	0.08	0.25	0.18	0.16	0.16
CO ₂	0.00	0.00	0.00	0.00	0.00	1.42	0.00	0.00	
Other	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	
TOTAL	100.44	100.21	100.02	99.28	100.09	100.01	100.08	99.71	

TABLE 1. Mean composition of basalts from islands of the Lesser Antilles, and from the mid-Atlantic ridge. K = St. Kitts; F = Montserrat; G = Guadeloupe; D = Dominica; M = Martinique; L-A = St. Lucia aphyric basalts; V = St. Vincent; X = Grenada; M-A = Mid-Atlantic. Islands are listed in sequence from north (column K) to south (column X). Figures in brackets at the top of each column indicate the number of analyses contributing to the mean. Data for columns K through X are from Tomblin (1968). Data for column M-A are from Melson et al. (1968).

	K (17)	F (5)	G (7)	D (12)	M (46)	L (12)	V (17)	V-BG (10)	X (6)
SiO ₂	59.30	58.87	57.83	60.49	60.12	59.69	55.60	57.11	59.14
Al ₂ O ₃	18.39	18.50	17.28	17.94	18.32	17.62	18.79	17.38	16.14
Fe ₂ O ₃	3.48	2.33	3.90	2.72	2.68	2.27	3.00	3.55	3.59
FeO	3.52	4.07	3.99	3.25	3.88	3.63	4.92	4.42	3.32
MgO	2.24	3.13	2.99	1.97	2.93	2.20	3.41	2.84	2.60
CaO	6.74	8.02	6.56	6.80	6.94	6.85	8.10	7.12	6.98
Na ₂ O	3.86	2.96	3.31	3.33	3.05	2.83	3.41	3.80	4.37
K ₂ O	0.63	0.84	1.14	1.46	1.03	1.17	0.65	0.85	1.52
H ₂ O ⁺	0.92	0.32	1.50	1.05	0.66	1.53	0.72	0.62	1.46
H ₂ O ⁻	0.25	0.26	0.25	0.17	0.02	1.00	0.27	0.00	0.24
TiO ₂	0.59	0.48	0.83	0.59	0.49	0.56	0.85	1.03	0.53
P ₂ O ₅	0.11	0.10	0.15	0.11	0.10	0.11	0.12	0.15	0.18
MnO ₂	0.17	0.13	0.16	0.15	0.02	0.14	0.19	0.20	0.15
CO ₂	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00
Other	0.00	0.00	0.00	0.00	0.02	0.00	0.07	0.10	0.00
TOTAL	100.20	100.01	99.89	100.03	100.26	99.75	100.10	99.17	100.22

TABLE 2. Mean composition of andesites from islands of the Lesser Antilles. K = St. Kitts; F = Montserrat; G = Guadeloupe; D = Dominica; M = Martinique; L = St. Lucia; V = St. Vincent; V-BG = St. Vincent basalt groundmasses; X = Grenada. Islands are listed in sequence from north (column K) to south (column X). Figures in brackets at the top of each column indicate the number of analyses contributing to the mean. Data are from Tomblin (1968).

	G (2)	M (6)	L (8)	L-R (1)	G-R (3)
SiO ₂	64.02	64.07	64.24	70.66	73.06
Al ₂ O ₃	15.73	17.79	16.66	13.38	14.53
Fe ₂ O ₃	2.54	2.29	0.82	1.20	1.50
FeO	3.66	2.72	3.13	2.50	1.30
MgO	1.85	1.98	1.73	0.00	0.53
CaO	4.94	5.49	6.42	2.82	1.78
Na ₂ O	3.74	3.53	3.10	4.85	4.69
K ₂ O	1.30	1.27	1.50	2.00	1.15
H ₂ O ⁺	1.30	0.42	1.27	1.85	0.97
H ₂ O ⁻	0.08	0.14	0.27	0.47	0.29
TiO ₂	0.47	0.36	0.47	0.28	0.19
P ₂ O ₅	0.08	0.10	0.12	0.04	0.03
MnO ₂	0.04	0.05	0.09	0.28	0.03
CO ₂	0.00	0.00	0.01	0.00	0.00
Other	0.00	0.01	0.00	0.00	0.00
TOTAL	99.75	100.22	99.83	100.33	100.05

TABLE 3. Mean composition of dacites and rhyolites from islands of the Lesser Antilles. Dacites: G = Guadeloupe; M = Martinique; L = St. Lucia. Rhyolites: L-R = St. Lucia; G-R = Guadeloupe. Figures in brackets at the top of each column indicate the number of analyses contributing to the mean. Data are from Tomblin (1968).

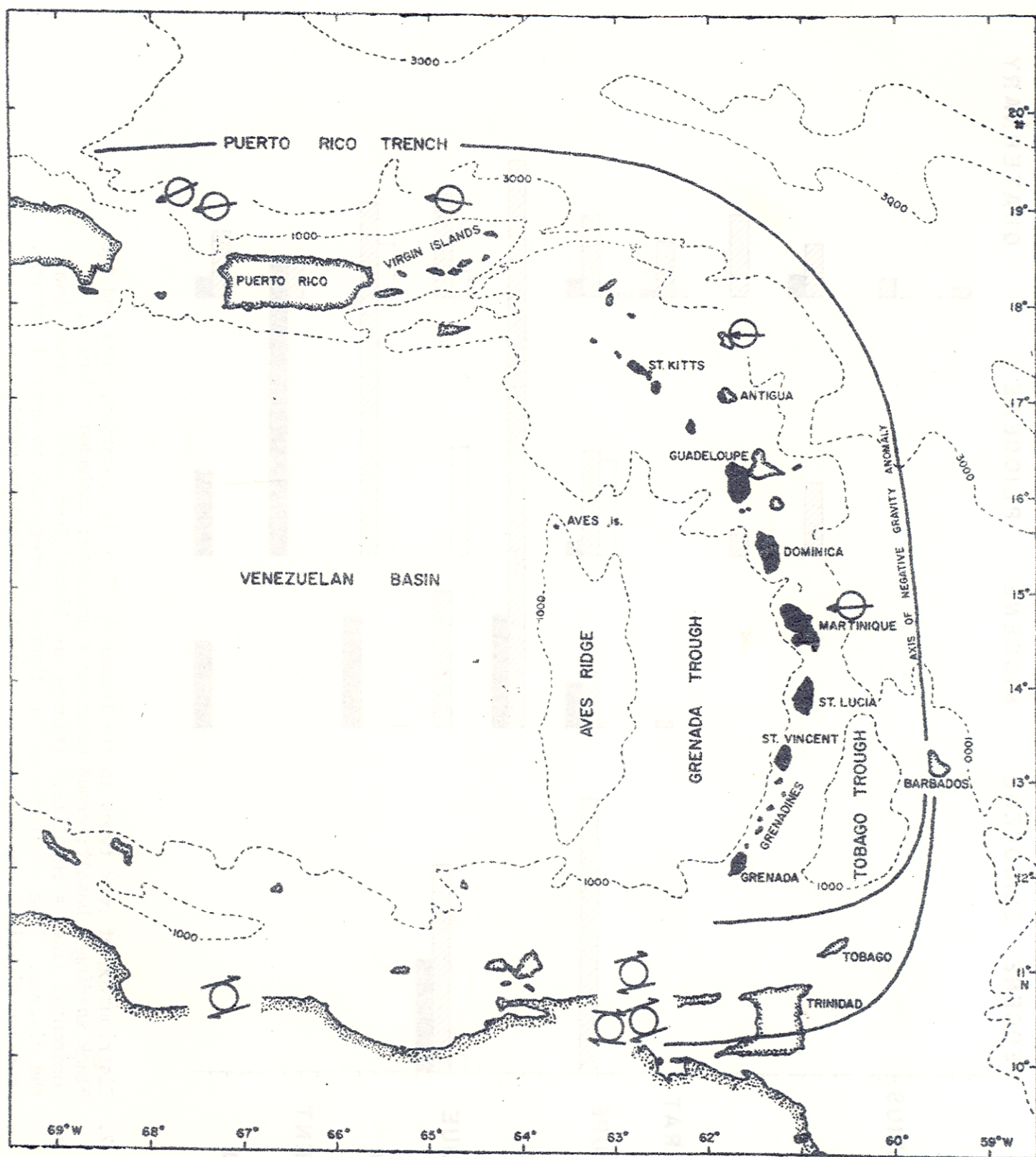


Fig. 1. Map of the eastern Caribbean, showing main bathymetric features (contours in fathoms), volcanic islands (black shading), axes of negative gravity anomaly and slip vectors for earthquake mechanisms (circles, with single arrow indicating thrust and double arrow indicating transcurrent movement). Slip vectors are from Molnar and Sykes (1969).

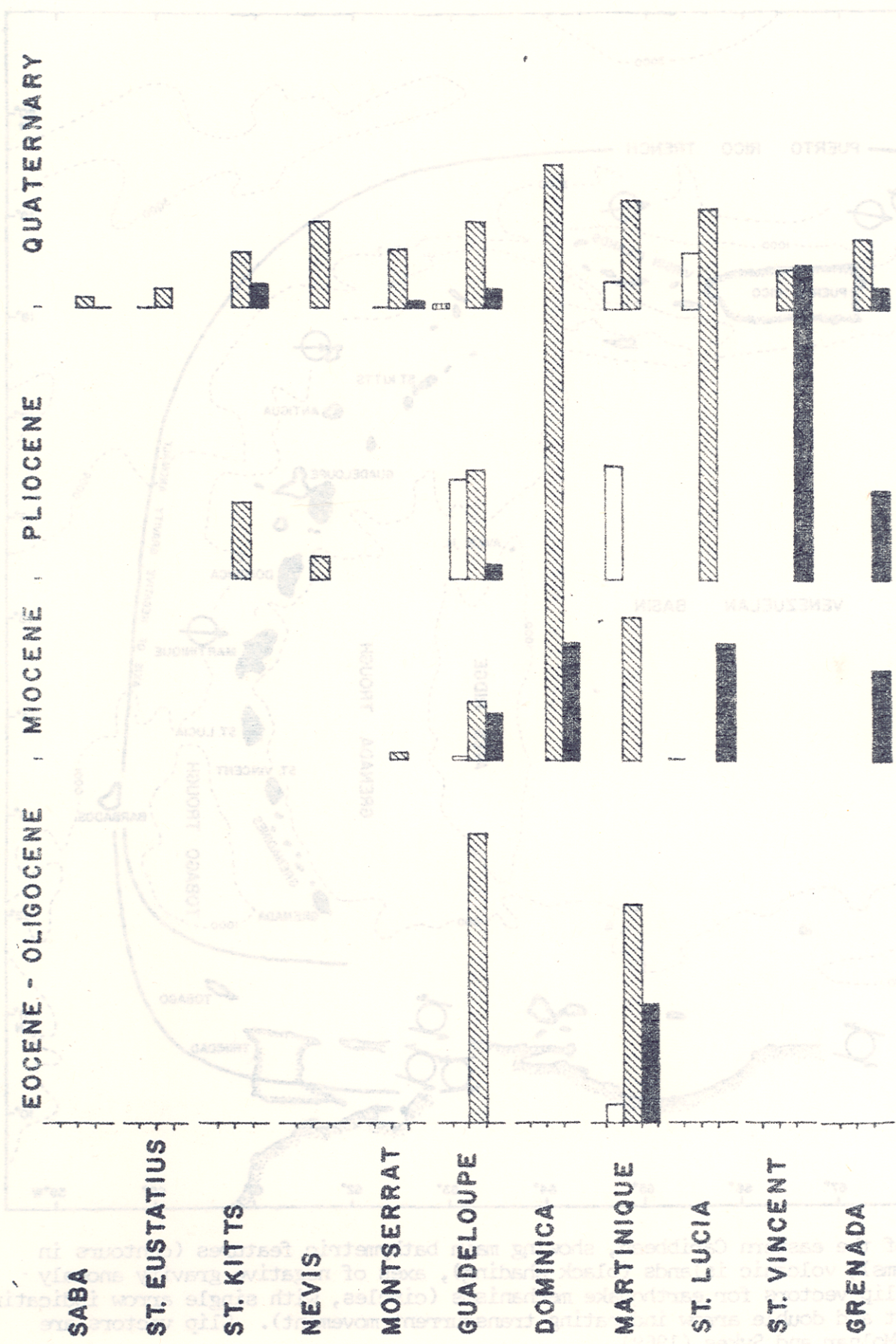


Fig. 2. Distribution of rock types in the Lesser Antilles by location, area and age. Black shading = basalt; cross hatching = andesite; unshaded = dacite; horizontal lines = rhyolite. Islands are listed from north to south down the diagram. Area of blocks on the diagram corresponds to area of outcrop. Four age divisions are indicated, younging from left to right.

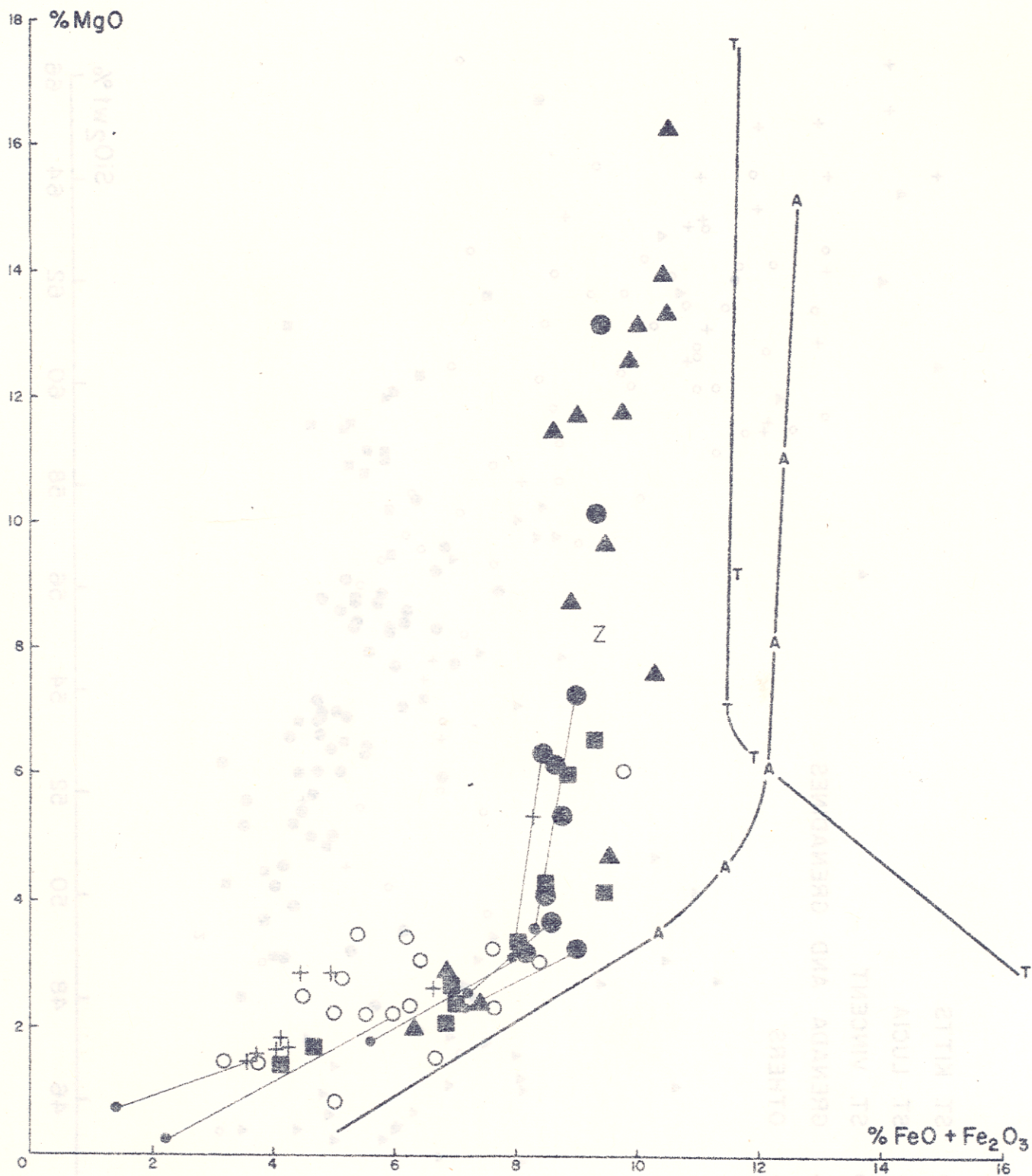


Fig. 3. MgO: total iron oxide ratios in representative rocks of the Lesser Antilles. Triangles = Grenada; large solid circles = St. Vincent; crosses = St. Lucia; squares = St. Kitts; open circles = other islands; small solid circles = groundmasses. A tie line is drawn between whole rock and corresponding groundmass. Heavy lines through points marked A represent Hawaiian alkali, and through points marked T represent Hawaiian tholeiite series from Tilley, Yoder and Schairer (1968). The symbol Z indicates the mean mid-Atlantic basalt of Melson et al. (1968).

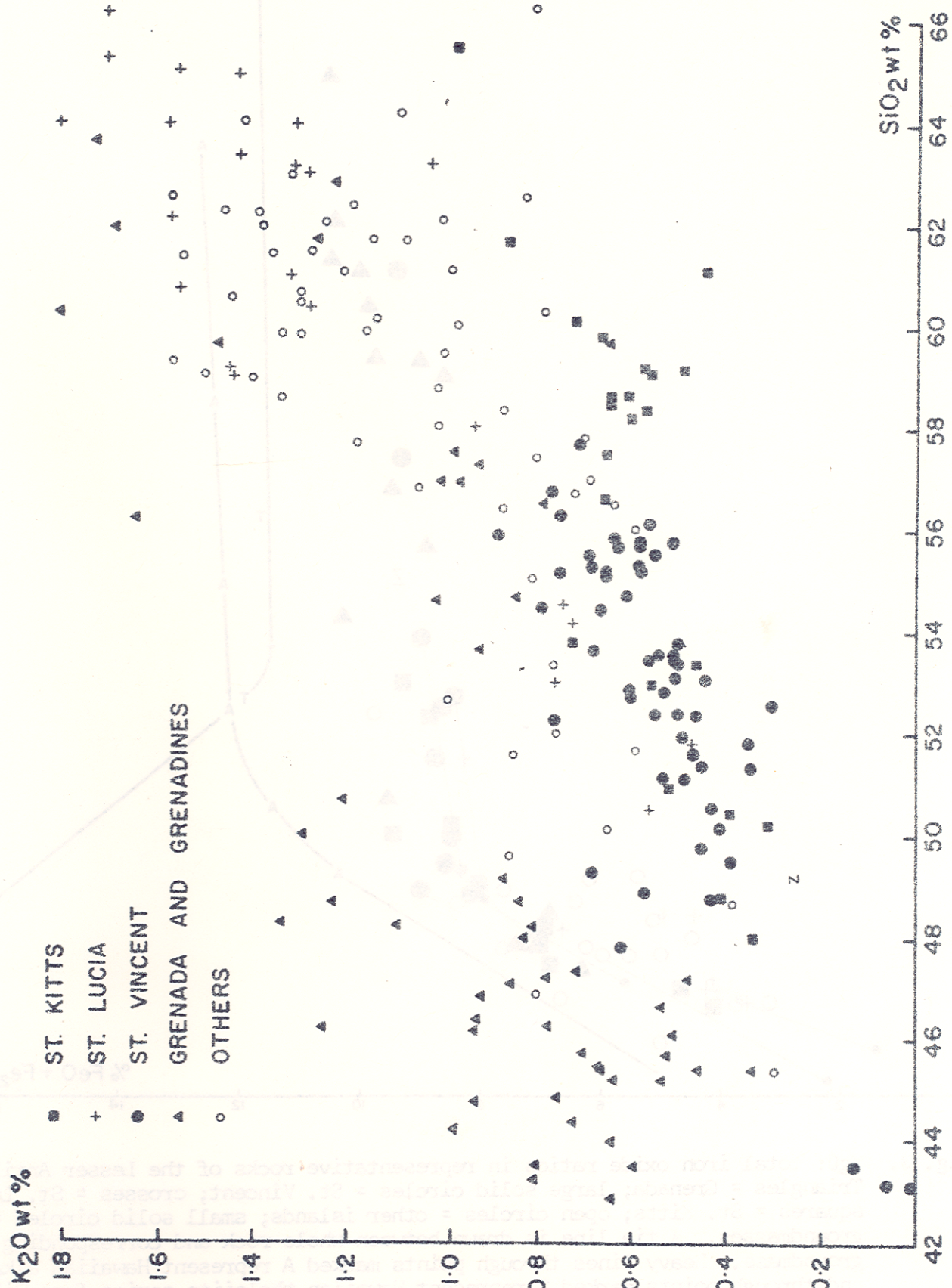
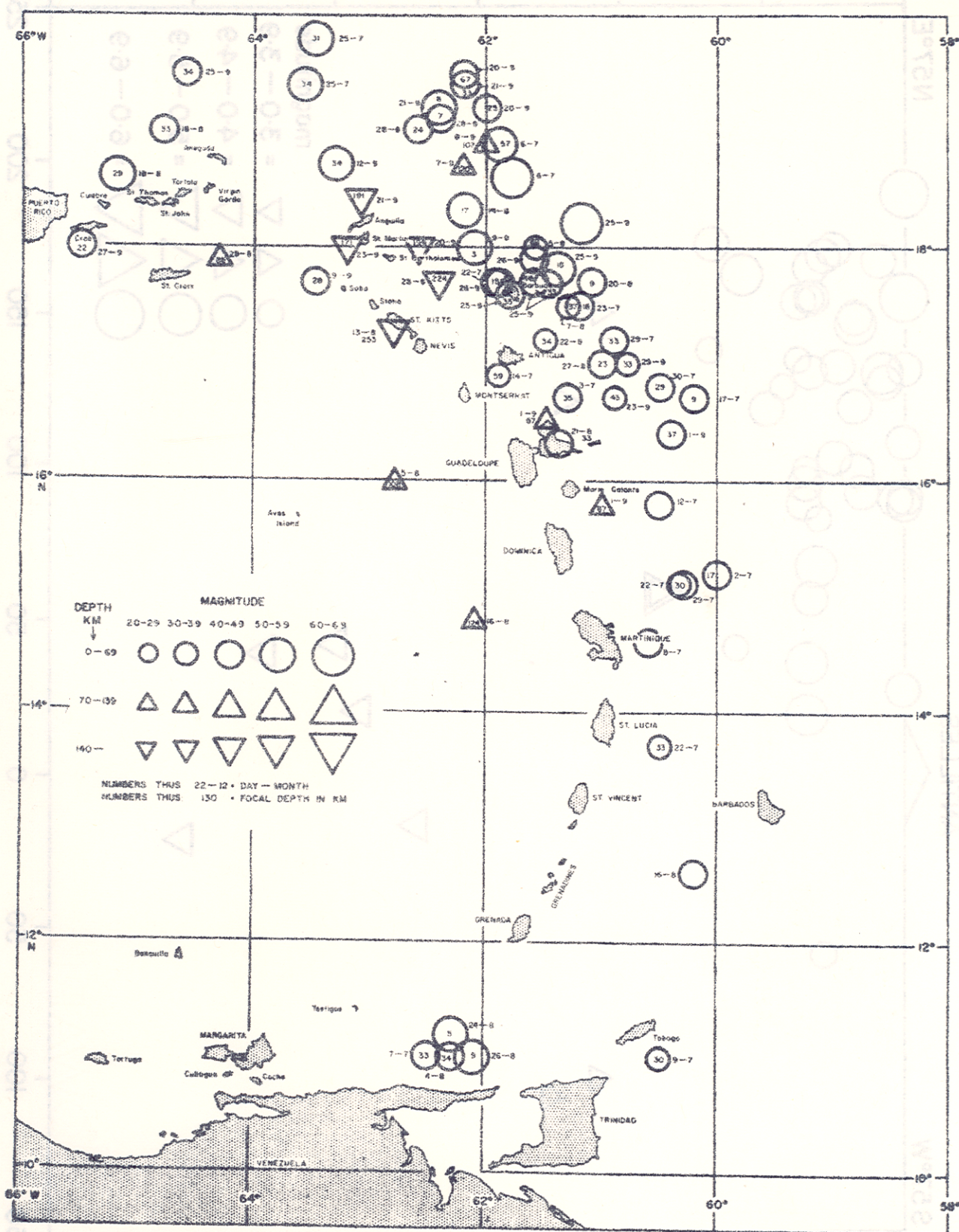


Fig. 4. Potash:silica ratios in rocks of the Lesser Antilles.

Fig. 5. Eastern Caribbean earthquake epicentres, July-September 1967.



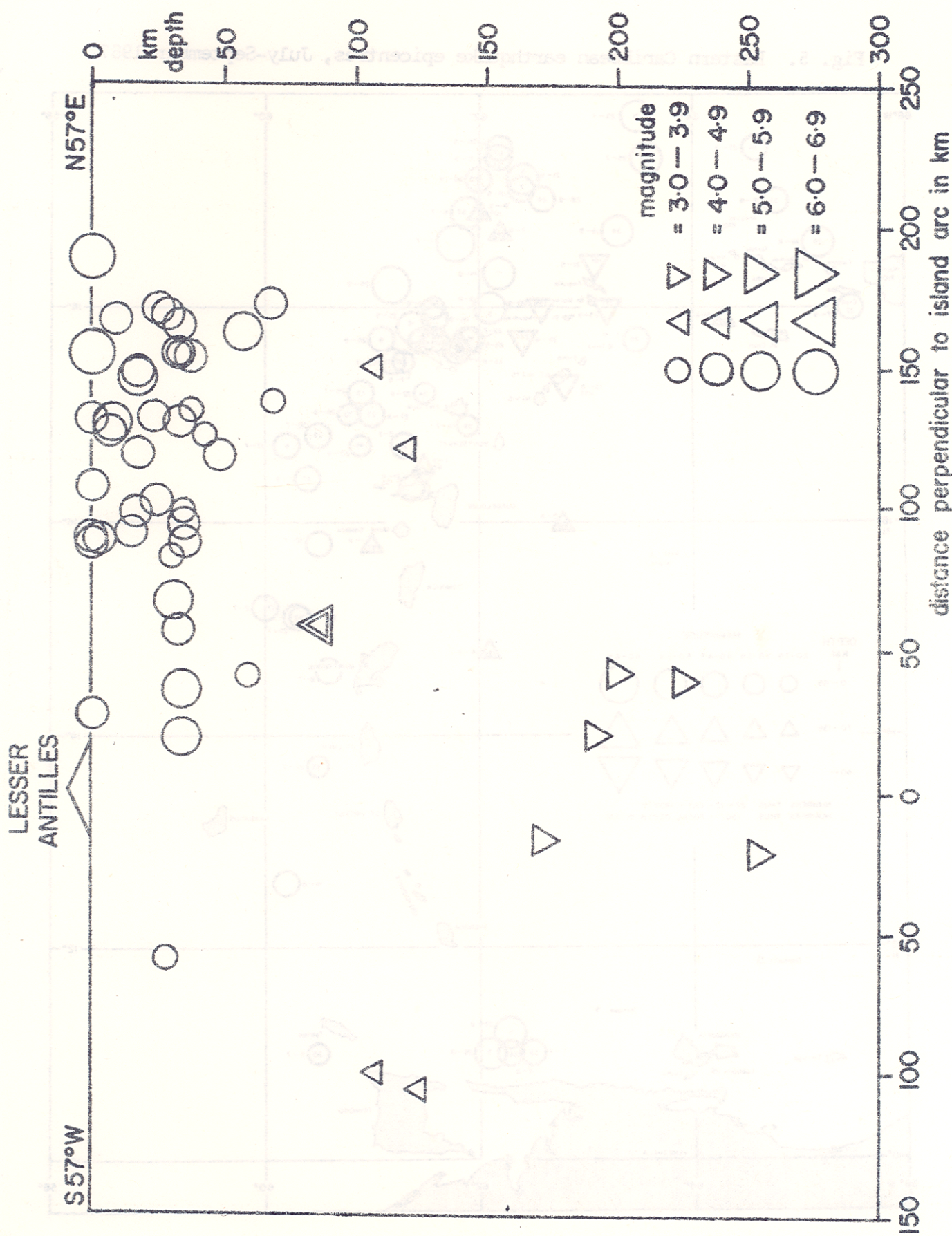


Fig. 6. Cross section through Fig. 5, showing hypocentres for the Leeward Islands projected into a single vertical plane.

Fig. 7. Eastern Caribbean earthquake epicentres, July-September 1966.

