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Relations between fracture patterns, seismicity and plate motions in the Lesser Antilles

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Abstract—Measurements of orientations of joints that have been made on the Leeward and Windward Islands (Lesser Antilles) from St. Martin to St. Vincent are reported. The preferred orientations of the joints have been determined by a statistical analysis. Assuming the joints to be shearing phenomena, the principal directions of the stress field that caused them, can be calculated. The latter are in very good agreement with the principal stress directions obtained by a statistical analysis of fault plane solutions of earthquakes in the area; the inferred maximum compression direction being NW–SE (*ca.* N 130°E). This corresponds to a model which assumes that the American plate is subducted in that direction beneath the Caribbean plate.

INTRODUCTION

JOINT orientations have been measured in the island arc complex of the Lesser Antilles from St. Martin to St. Vincent and Barbados. The results of previous surveys in Guadeloupe (Bonneton & Scheidegger 1980), Martinique (Bonneton & Scheidegger 1981) and Barbados (Scheidegger 1978) have already been reported and hence they are only briefly quoted here. Figure 1 shows the region surveyed in this and the previous surveys; the aim of the surveys being to measure the orientations of joints. Care was taken to investigate only joints which are not filled with intrusive igneous material, which transect pebbles in conglomerates, which are steeply dipping, and which are planar and smooth. Evidence was previously presented to support the proposal that such joints are of neotectonic origin and represent some sort of shearing phenomenon (Scheidegger 1979). Inasmuch as there is a considerable scatter in the joint orientations of individual outcrops or groups of outcrops, only the statistical behaviour of the joints can have any significance. For this purpose, an evaluation procedure devised by Kohlbeck & Scheidegger (1977) was used. It involves the superposition of two Dimroth–Watson distributions which are fitted to the data by means of a maximum-likelihood procedure carried out on a computer. This yields two 'preferred' planar orientations for any one set of orientation data. If the assumption is correct that the joints are shearing phenomena, then the bisectrices of the preferred orientations must be the principal directions of the tectonic stress field that caused the joints. The smaller quadrant should enclose the largest compression (σ_1). However, it is a common observation that the angle between preferred planar joint orientations is generally close to 90°, so that the identification of the maximum compression direction is seldom certain. The large angle indicates that joints cannot be Mohr-type fractures, but are probably associated with the planes of maximum shear in a triaxial stress state (c.f. the discussion by Scheidegger 1979.)

DESCRIPTION AND ANALYSIS OF THE FIELD DATA

St. Martin

St. Martin (Sint Maarten) is the northernmost island which was visited. A large part of the island is affected by a major fracture system which strikes NE–SW and is marked by intrusions of dacite, andesite and dacitic porphyry. A total of 439 orientations of joints were measured in 16 outcrops. The locations of the latter are shown in the sketch map of Fig. 2(a). The western half of the island is underlain by mainly Oligocene to Miocene sediments (with some dacitic intrusions); in the eastern half of the island there are volcanic mountain ranges dating back to the Oligocene. The joint pattern (Tables 1 and 2, Fig. 3(a)) is completely independent of rock type or folding.

St. Barthélémy

Next to St. Martin lies St. Barthélémy, a mountainous island consisting of sedimentary and magmatic rocks; the latter are mostly older (middle to upper Eocene) volcanics; the island, however, is considered as part of the 'calcareous' arc. The principal fracture systems strike

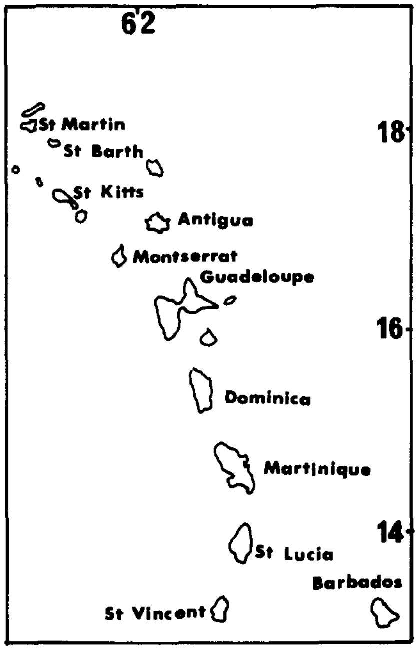

Fig. 1. Sketch map of the region investigated.

NE–SW and NW–SE. The NW–SE fractures contain dykes which may be the products of tensional tectonics. In all, 293 joint orientations in 10 outcrops were measured (Tables 1 and 2, Fig. 3b). The locations of the outcrops are given in Fig. 2(b).

Antigua

The next island investigated in the outer ('calcareous') arc was Antigua. This island also consists in part (the SW) of older (Oligocene) volcanics, and only in part of limestone (the NE). A total of 254 joints were measured (Tables 1 and 2, Fig. 3c) at 12 outcrops, whose locations are shown in Fig. 3(c).

St. Kitts

Turning now to the 'volcanic' island arc, we attempted to investigate joints on St. Kitts. Unfortunately it was very difficult to find suitable outcrops, most of the accessible parts of the island are in washouts of volcanics and in lahar deposits. Thus, only few locations with joints (Tables 1 and 2, Figs. 2d and 3d) were found.

Monserrat

The conditions on Monserrat were better than on St. Kitts. Although there are many lahar deposits there are also exposures of recent lava flows. Thus, it was possible to measure 179 joint orientations at 7 good outcrops (Tables 1 and 2, Fig. 3e). Their locations are shown in Fig. 2(e).

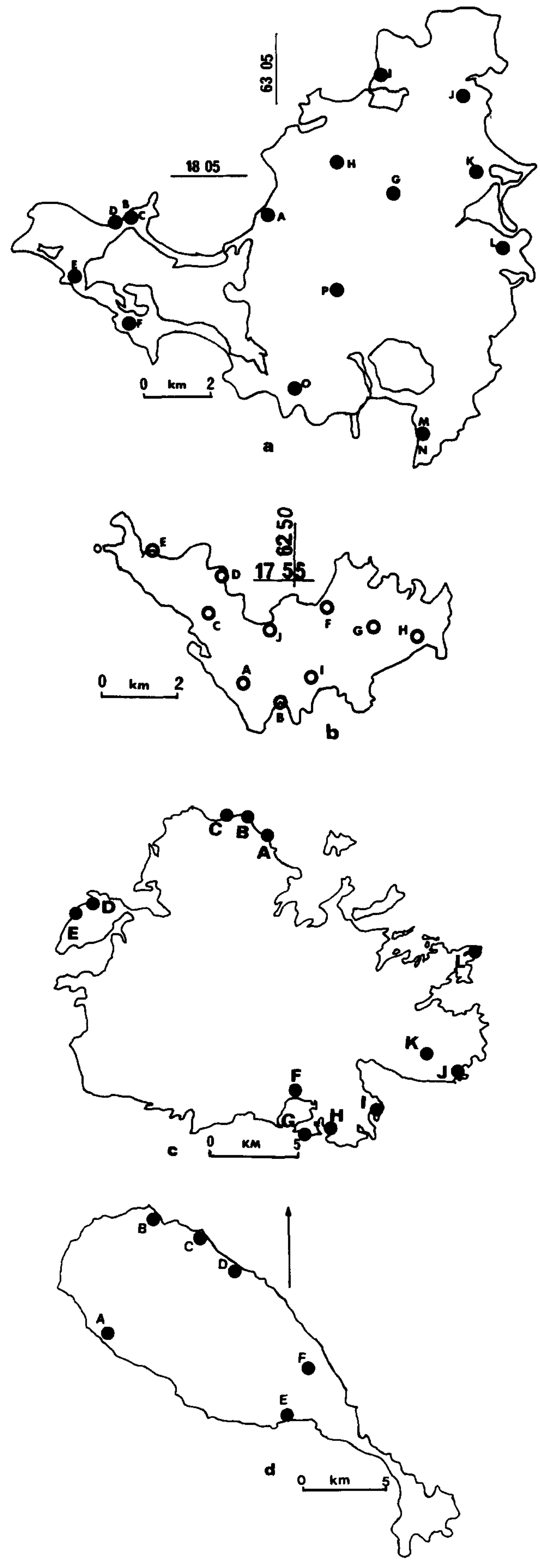

Fig. 2. (a)–(d). Caption on facing page.

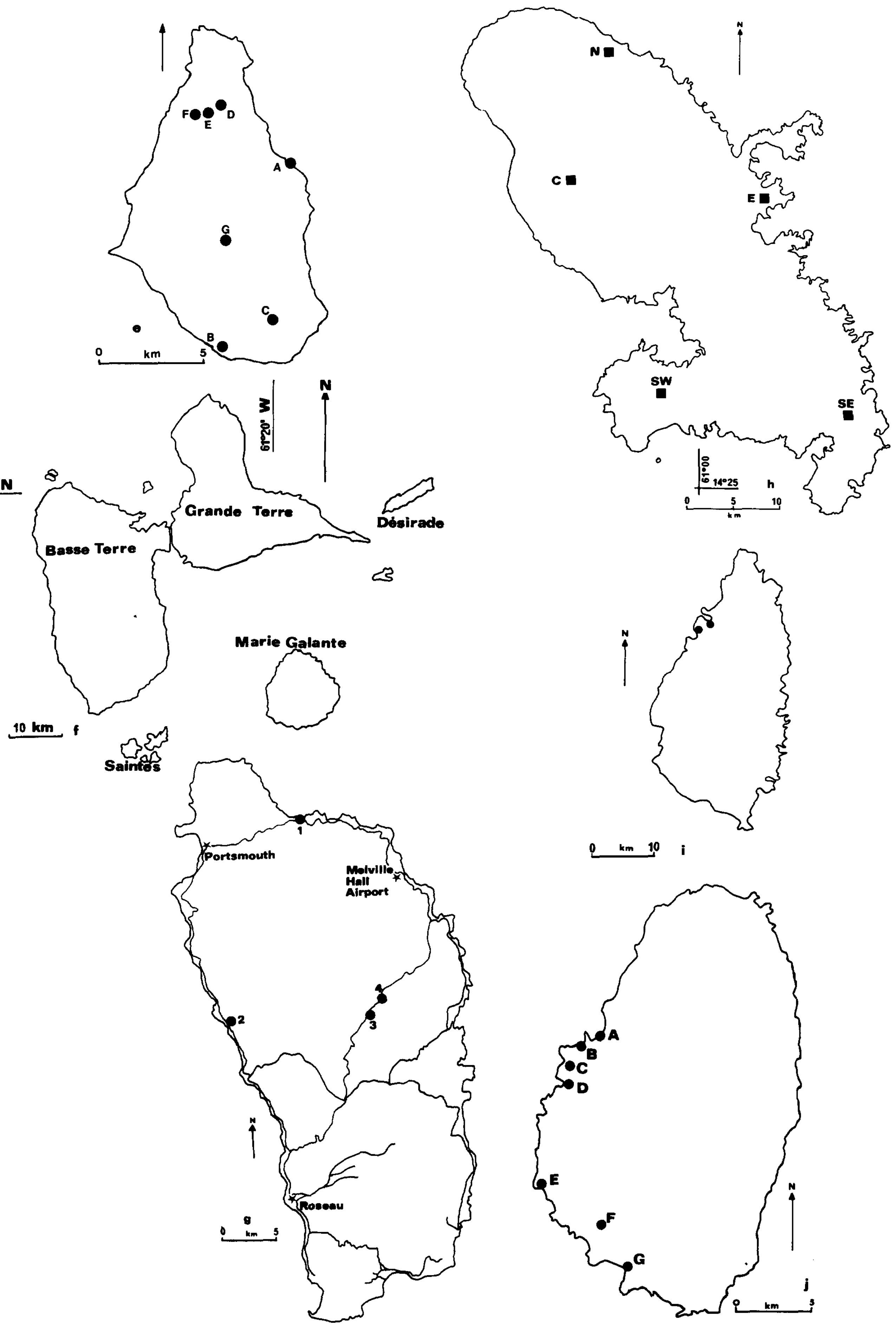

Fig. 2. Locations of joint measurements. (a) St. Martin. (b) St. Barthélémy. (c) Antigua. (d) St. Kitts. (e) Montserrat. (f) Guadeloupe Archipelago. (g) Dominica. (h) Martinique. (i) St. Lucia. (j) St. Vincent.

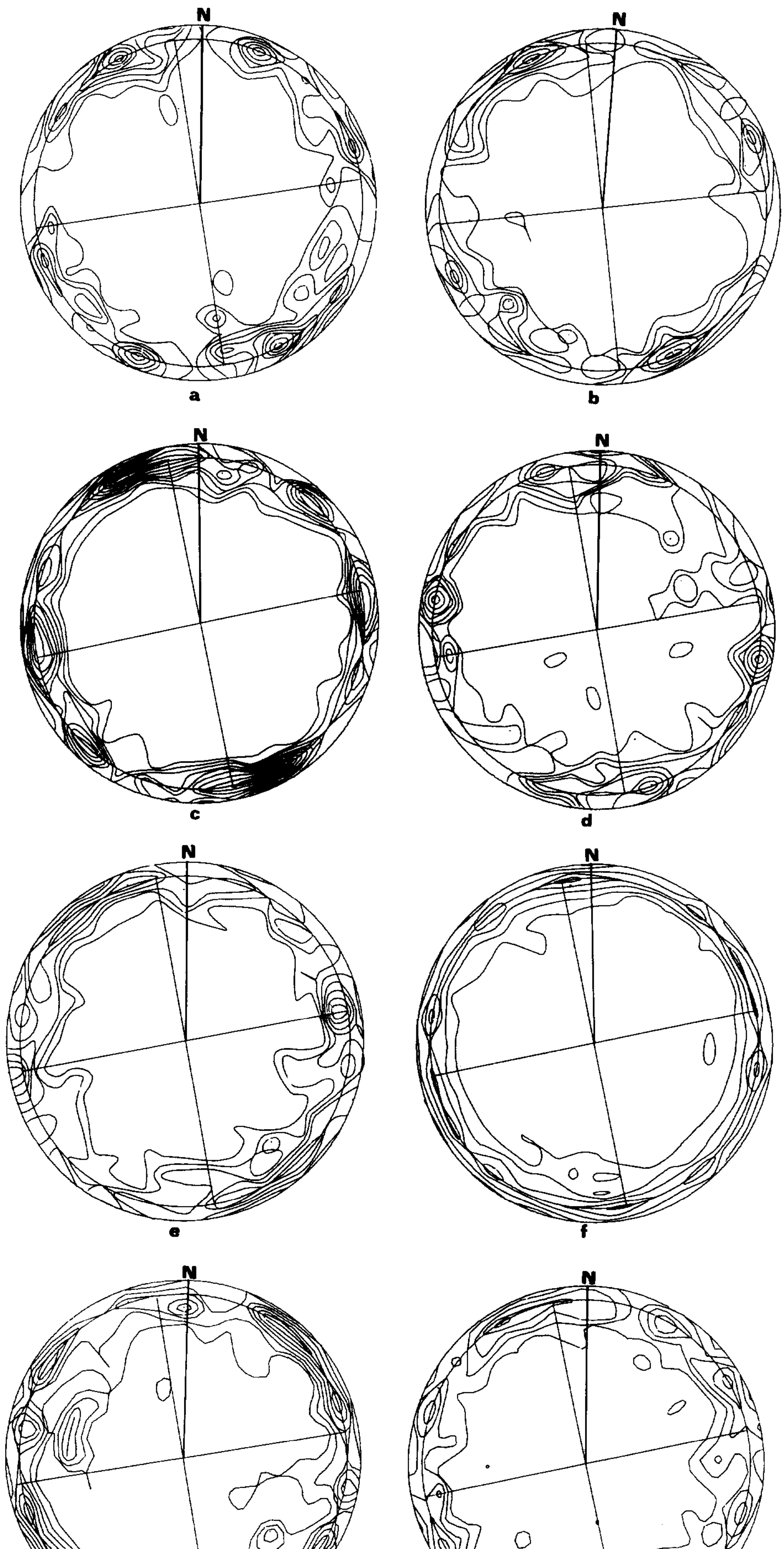

Fig. 3. (a)–(h). Caption on facing page.

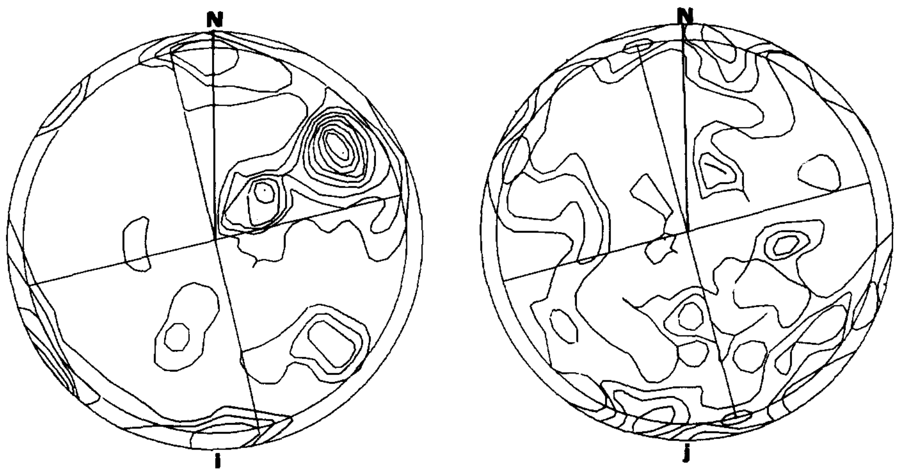

Fig. 3. Pole density diagrams of joints. (a) St. Martin. (b) St. Barthélemy. (c) Antigua. (d) St. Kitts. (e) Montserrat. (f) Guadeloupe Archipelago. (g) Dominica. (h) Martinique. (i) St. Lucia. (j) St. Vincent. The diagrams are Lambert projections of the lower half of the unit sphere, the inner circle corresponds to the unit sphere, the outer circle is a 10° overlap. The density lines are at 1% intervals.

Table 1. Individual results

Loc.	No.	Max. 1	Max. 2	Angle	σ_1	σ_3
			St. Martin			
A	24	67±18/85±16	358±28/84±17	68	122/2	213/7
B	31	307±21/86±19	27±17/86±14	80	77/6	167/5
C	27	21±18/89±16	320±12/89±11	61	81/0	171/1
D	26	59±24/88±24	334±12/79±11	84	106/7	197/9
E	22	160±13/86±12	257±22/90±19	83	28/3	298/2
F	25	173±20/86±16	273±19/87±17	80	43/6	313/0
G	34	56±16/86±14	333±15/79±13	83	104/5	195/10
H	25	233±8 /74±7	346±33/71±25	75	109/30	200/2
I	26	38±18/84±17	322±12/89±13	76	270/4	180/4
J	26	224±15/79±13	149±19/85±18	74	97/5	6/10
K	31	52±9 /85±9	335±24/79±20	76	103/5	194/10
L	27	241±21/84±20	330±18/85±18	89	16/1	106/7
M	25	73±34/75±29	348±9 /87±10	84	301/9	210/12
N	24	45±25/76±22	150±19/34±11	87	19/25	258/48
O	35	250±34/86±21	331±20/88±14	81	21/2	111/4
P	31	271±22/81±20	342±14/82±11	70	37/10	127/11
			St. Barthélemy			
A	33	68±16/88±16	155±15/90±14	87	201/1	291/1
B	35	239±23/88±14				
C	33	36±9 /88±9	298±18/83±16	82	167/7	77/4
D	26	257±12/88±10	330±24/83±19	72	204/4	113/6
E	33	38±9 /76±9	328±10/88±9	71	274/10	182/9
F	34	48±14/76/12	317±14/81±13	89	273/4	182/16
G	24	250±16/78±13	145±18/84±16	77	17/15	108/3
H	24	189±26/88±20	110±15/79±12	79	238/7	330/8
I	24	54±30/84±19				
J	27	53±36/90±28	129±9 /86±8	76	1/4	271/3
			Antigua			
A	21	318/13/79±12	41±19±85/16	82	89/5	180/11
B	21	340±20/88±15				
C	21	60±22/81±15				
D	23	65±19/87±12				
E	24	56±21/89±16	331±20/85±16	85	103/3	193/4
F	21	197±11/75±10	120±13/88±12	77	69/11	337/11
G	22	199±22/85±19	87±9 /86±9	69	323/8	53/1
H	21	160±18/82±17	274±14/90±13	66	38/7	307/4
I	16	45±18/89±15				
J	21	159±14/89±12				
K	21	0±24/87±17				
L	22	74±42/89±29	347±12/87±10	88	121/2	211/3

Table 1. (continued)

Loc.	No.	Max. 1	Max. 2	Angle	σ_1	σ_3
			St. Kitts			
A	25	213±14/89±12				
B	18	260±14/88±13	337±14/82±14	77	209/1	118/3
C	40	272±16/90±16	347±29/83±20	76	220/5	130/5
D	2	indef.				
E	27	185±12/86±11				
F	32	237±34/77±36	158±8 /89±8	79	108/10	17/9
			Montserrat			
A	29	357±20/87±15				
B	23	100±18/85±15				
C	22	204±34/85±30	311±21/77±20	74	77/15	168/5
D	23	89±10/84±9				
E	31	324±18/89±14				
F	28	60±10/88±10	157±25/89±22	82	289/2	199/0
G	23	243±20/84±15	153±26/85±22	88	108/1	18/8
			Guadeloupe Archipelago			
Basse Terre	614	67±11/85±6	342±9 /89±6	85	294/3	204/3
Grande Terre	275	354±8 /85±6	86±8 /89±6	88	220/4	130/3
Désirade	196	236±17/86±10	153±15/84±9	82	284/1	14/7
Saintes	300	200±28/87±14	114±18/89±10	87	67/2	337/3
Marie Galante	172	202±18/90±10	124±18/88±9	79	273/1	343/1
			Dominica			
1	21	302±15/89±14				
2	22	29±8 /87±8	106±37/86±26	77	337/1	247/5
3	36	190±11/85±11	104±15/64±14	83	234/15	329/20
4	32	337±27/86±21	69±14/89±12	88	203/4	113/2
			Martinique			
C	62	282±26/82±18	184±13/80±11	83	53/13	323/2
N	60	222±35/87±15	313±27/89±12	88	87/2	357/2
E	182	164±10/86±8	261±13/89±10	83	32/4	302/2
SE	172	245±11/86±8	352±17/90±11	74	119/3	28/2
SW	246	247±14/82±8	337±17/87±9	90	22/3	112/8
			St. Vincent			
ABCD	32	353±14/76±12				
EFG	61	completely undetermined				

The location, the numbers of joints analyzed, the two preferred joint orientations, the angle between them and the inferred σ_1- and σ_3-directions are given in sequence. The orientation of a joint set is given by stating its dip direction (azimuth N → E in degrees) and its inclination in degrees separated by a solidus. A straight line (stress direction) is given by the azimuth (N → E in degrees) of its plunge and the plunge angle, again separated by a solidus. Errors are indicated by ± and represent 90% confidence limits.

Table 2. Summary results for the islands investigated

Loc.	No.	Max. 1	Max. 2	Angle	σ_1	σ_3
St. Martin	439	55±8 /88±6	330±7±/85±5	85	103/2	193/5
St. Barthélémy	293	53±8 /88±6	323±8 /89±6	90	278/1	188/2
Antigua	254	83±13/87±6	175±10/89±6	88	309/3	219/2
St. Kitts	144	253±14/86±11	348±9 /90±7	83	119/3	29/2
Montserrat	179	260±12/90±8	344±13/88±8	84	212/2	122/1
Guadeloupe	1557	346±9 /89±4	78±11/88±4	88	212/2	302/1
Dominica	111	198±17/86±10	109±16/84±11	89	243/2	334/7
Martinique	722	252±7 /86±5	165±8 /89±5	87	118/2	28/4
St. Lucia	45	236±17/61±16	347±40/74±37	80	115/36	20/7
St. Vincent	93	103±18/57±23	348±32/69±26	83	220/44	317/7
Barbados	261	205±14/89±6	303±12/90±6	87	74/1	164/0

Notation as in Table 1.

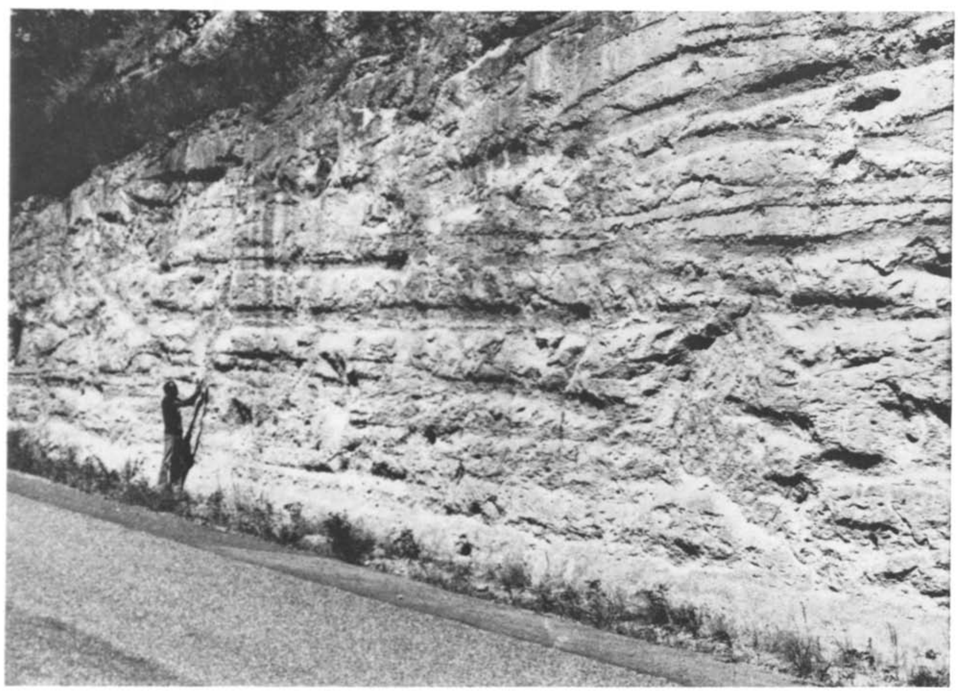

Fig. 4. Clay surface on an outcrop at location 2 on Dominica.

Guadeloupe

Several studies have already been reported on the Guadeloupe Archipelago (Bonneton & Scheidegger 1980). The archipelago includes Grand Terre and Basse Terre as the two parts of the Island itself, as well as Les Seintes, Désirade and Marie Galante (Fig. 2f). The geology of the various regions is entirely different; on Désirade, the basement, consisting of volcanics and ophiolitic rocks (142 $\pm$ 10 Ma) on a trondhjemite intrusion into volcanics which consist of spilite pillow lavas and quartz–keratophyres, (Fink, 1968, 1972) is unconformably overlain by Pliocene limestones; Grande Terre and Marie Galante are entirely calcareous, whereas Basse Terre and the Saintes are volcanic. The orientation of the stress field obtained by microtectonic studies in Basse Terre permits us to identify the principal compression and tension directions; these agree with major tensional and compressional features related to the recent volcanism.

Dominica

A brief visit was made to Dominica during which joint orientations were measured in road-side outcrops. Unfortunately, like on St. Kitts, the material in many parts of the island consists of lahar deposits; where bed-rocks crop out they are pale-coloured andesites with large phenocrysts. Commonly, the andesites are much weathered to clay (Fig. 4). Thus, in spite of a wide-ranging tour around the island, only four good outcrops were encountered; these are marked 1–4 in Fig. 2(g). The results of the analysis of the joints are shown in Tables 1 and 2 and Fig. 3(g).

Martinique

As noted in the introduction, a large programme of joint orientation measurements was undertaken in Martinique, the results of which have been reported elsewhere (Bonneton & Scheidegger 1981). The results are statistically highly significant. As the details are given in the cited paper we supply here only a summary (Tables 1 and 2, Figs. 2h & 3h).

St. Lucia

A number of joints were also measured on St. Lucia. The locations of the outcrops are shown in Fig. 2(i). Too few joints were measured to analyse each outcrop individually and thus they were analysed together (Table 2, Fig. 3i).

St. Vincent

A total of 93 joint orientations were measured on the island of St. Vincent at the locations shown in Fig. 2(j). On account of the paucity of the data, it was not possible to evaluate the outcrops singly. An attempt at forming two groups (ABCD and EFG) yielded rather indeterminate results (Table 1). The combined evaluation, however, was statistically significant (Table 2, Fig. 3j).

Barbados

Finally, it should be recalled that 261 joint measurements had been made already on Barbados (Scheidegger 1978). Because they have been discussed in detail elsewhere, we only summarize them in Table 2.

SYNTHESIS

Table 2 and Fig. 7 summarize the results from all the islands. It is clear that there is a general orientation of one of the principal stress directions in the NW–SE quadrant, with perhaps an indication of a turning from WNW to NW from the northernmost to the southernmost islands.

It should be noted that the sign of the stresses can never be taken as certain; the angles between preferred joint orientations being too close to 90° to identify the σ_1 and σ_3 directions with statistical certainty. Nevertheless, in a majority of cases the σ_1-direction lies in the NW (SE) quadrant. One would therefore guess that the NW–SE direction is in all cases that of the maximum compression, a proposition which is supported by the NW–SE orientation of the volcanic tension-fissures at the Soufrière in Guadeloupe (Jeremie & Bonneton 1979).

One can compare the above results with those from fault plane solutions of earthquakes. Dorel (1978) has collected data from 17 earthquakes (listed in Table 3). The locations of the events and the respective fault plane solutions are shown in Fig. 5. We have treated these data statistically. Figure 6(a) shows the density diagram of the

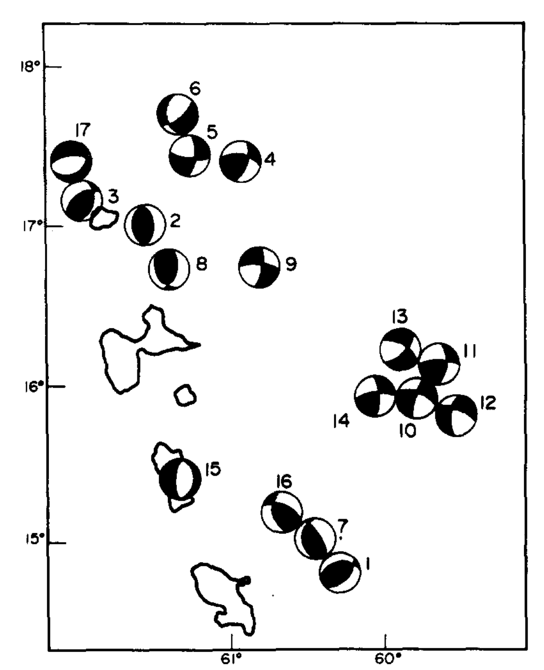

Fig. 5. Fault plane solutions of 17 Antillean earthquakes: Black indicates the σ_3 quadrants, that is an initial compression in the seismic record, modified after Dorel (1978).

Table 3. Fault plane solutions of earthquakes in the Lesser Antilles (after Dorel 1978)

No.	Date	Lat N	Long W	σ_1-axis	σ_3-axis
1	20.08.64	14.9	60.4	153/21	280/74
2	15.07.66	16.99	61.49	85/9	291/68
3	13.11.66	17.05	61.94	309/13	189/66
4	14.10.67	17.33	60.89	146/2	237/34
5	24.12.67	17.42	61.19	321/18	227/11
6	24.12.67	17.61	61.26	352/53	118/24
7	19.03.68	15.06	60.47	73/19	215/59
8	15.05.69	16.75	61.39	90/21	320/65
9	01.12.69	16.68	60.80	232/16	141/3
10	25.12.69	15.79	59.64	149/22	245/14
11	25.12.69	16.08	59.79	318/3	226/31
12	26.12.69	15.74	59.59	151/39	60/2
13	29.12.69	16.13	59.74	266/29	174/4
14	07.01.70	15.86	59.78	129/6	220/14
15	22.03.73	15.34	61.29	92/75	271/17
16	07.09.74	15.10	60.63	48/4	145/58
17	08.10.74	17.34	62.00	170/75	335/15

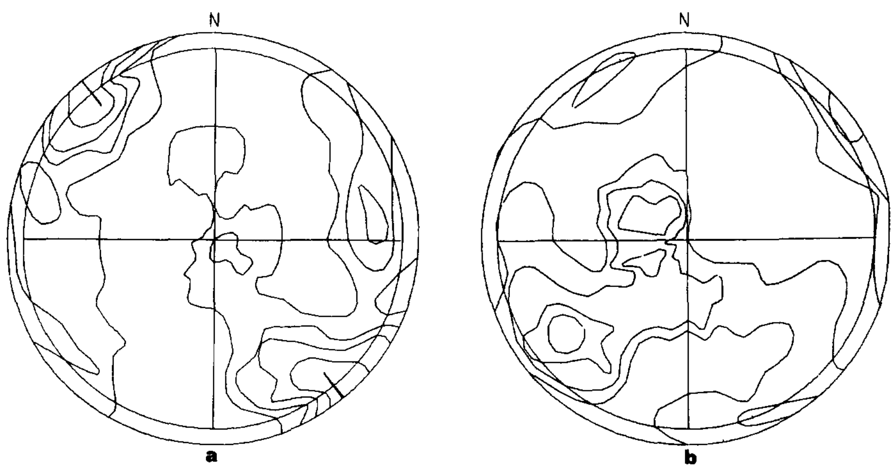

Fig. 6. Density diagrams of (a) σ_1- and (b) σ_3-axes obtained from fault plane solutions of earthquakes. Representation as in Fig. 3.

σ_1-directions and Fig. 6(b) the corresponding density diagram for the σ_3-directions. Looking at them entirely non-parametrically, the preferred σ_1-direction is NW–SE and the preferred σ_3-direction is NE–SW. The parametric evaluation (by means of fitting a Dimroth–Watson distribution) yields (azimuth NE and plunge):

$$\sigma_1:\text{-}\quad 123 \pm 34/10 \pm 32$$

$$\sigma_3:\text{-}\quad 233 \pm 46/41 \pm 31.$$

The confidence limits are rather large, the preferred σ_1-direction being better defined than the preferred σ_3-direction. The preferred σ_1-direction inferred from the fault plane solutions fits very well with the prevailing preferred σ_1-directions inferred from the joints. The directions of the compression are tangential to the small circles of relative movement between the Caribbean and Atlantic plates (Molnar & Sykes 1969).

There is therefore an excellent agreement between the seismic and joint analysis data and, incidentally, with the morphology of volcanic fissures on Guadeloupe. At the present stage of the investigations we note that the effects of the compression are essentially identical in the whole

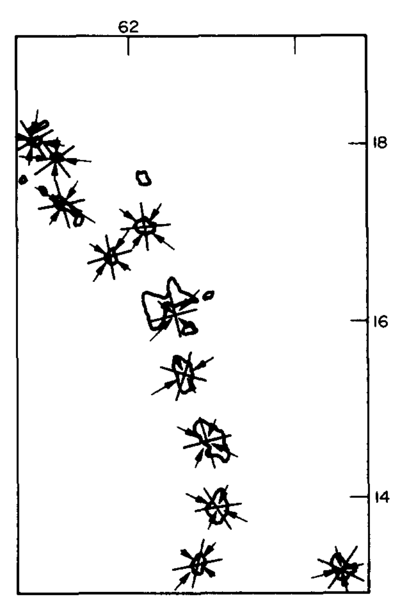

Fig. 7. Plot of the preferred joint strikes and principal tectonic stress directions in the Lesser Antilles. Heavy arrows, σ_1; light arrows, σ_3. Note, however, that identification of σ_1 and σ_3 is not certain (see discussion in text). Thus, the arrows in Guadeloupe should probably be the reverse of those shown as calculated from the joint orientations.

arc of the Antilles, except at its southern end (Grenada), where the alkaline series are probably related to subduction. Thus, the orientation of the maximum compression corresponds to a model involving subduction from the southeast of the American at the Caribbean plate.

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