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Morphotectonics of the Mascarene Islands

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Abstract
A study is made of the orientations (strikes/trends) of joints, valleys, ridges and lineaments, *i.e.* of the (potentially) morphotectonic features, of the Mascarene Islands (Réunion, Mauritius and Rodrigues) in the Indian Ocean. It turns out that a connection exists between these features on all islands. For the joints alone, the results for Mauritius as a whole agree closely with those for Rodrigues as a whole, and also partially with those of Réunion. Inasmuch as the trends of the valleys, ridges and lineaments are related to the trends (strikes) of the joints, a common morphotectonic predesign seems to be present for all features studied. The morphotectonic orientations on the island also agree closely with the trends of fracture zones, ridges and trenches in the nearby ocean bottom; which has had a bearing on the theories of the origin of the Mascarene Islands. Generally, a hot-spot origin is preferred for Réunion, and may be for Mauritius as well, although differing opinions have also been voiced. The dynamics of a hot-spot is hard to reconcile with the close fit of the joint strikes in Réunion with the trends of the Madagascar and Rodrigues fracture zones. The closely agreeing joint maxima in Mauritius and Rodrigues – across the deep Mauritius trench – also agree with the trend of that trench and with the trend of the Rodrigues fracture zone. Thus, it would appear as most likely that the trends of joints and of fracture zones are all part of the same pattern and are due to the same cause: *viz.* to action of the neotectonic stress field.

Key words *Mascarenes – Indian Ocean floor – neotectonics – hot spots – oceanic islands*

1. Introduction

The Mascarene Islands (fig.1; bottom topography and tectonics compiled from Heezen and Tharp, 1965a,b and Bonneville *et al.*, 1997) form a volcanic archipelago in the Southern Indian Ocean that stretches from Réunion (shape elliptical, 2512 km^2; capital St. Denis, 20°52′S, 55°27′E) for about 1000 km to the ENE. Apart from Réunion, the archipelago includes Île Maurice or Mauritius (shape more or less circular, 1865 km^2; capital Port Louis 20°10′S, 55°27′E), Rodrigues (E-W elongated shape, 104 km^2; capital Port Mathurin 19°41′S, 63°25′E) and some further smaller islands.

Geographically, the islands lie more or less on a straight line, although they may genetically not be connected. They are located on a rather fractured, but aseismic part of the Indian Ocean floor. Their topography is rugged-volcanic, and, in a first instance, is dominated by volcanic forms such as shield volcanoes with slopes degraded to deep ravines and cirques. Nevertheless, there are also prominent fracture lines present that separate specific parts from others on each island: thus, the archipelago exhibits important morphotectonic aspects.

The local neotectonics can generally easily be assessed by the study of joint orientations

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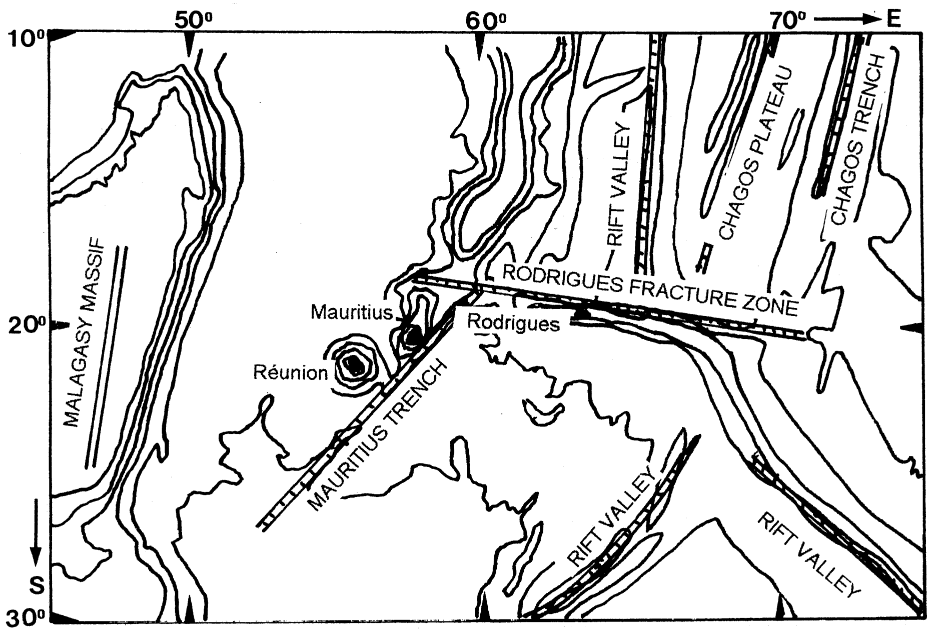

Fig. 1. Topography/tectonics (collated after Heezen and Tharp, 1965a,b and Bonneville *et al.*, 1997) of the Indian Ocean bottom in the Mascarene region with the locations of the islands shown.

which can then be compared with prominent morphological features of the islands. The joint orientation data are treated by the statistical method of Kohlbeck and Scheidegger (1977). In order to determine the prevalent directions in joint systems, it is assumed that the polar axes representing joints are *a priori* distributed according to so-called 'Dimroth (1963) – Watson (1966)' probability distributions, which correspond, on a sphere, to Gaussian distributions on a plane. Applied to a practical problem, the procedure consists in the determination of the best-fitting parameters of the theoretical distribution (*s*) by minimizing the mean-square deviation sum of predicted/measured values by an iterative procedure. For a joint system representing two conjugate joint sets (*i.e.* forming a grid), two Dimroth-Watson distributions are assumed and the best-fitting parameters (representing joint set 1 and joint set 2) are determined by computer; a similar procedure applies for three assumed joint sets. The calculations have to be performed using polar or dip-axes, but for geological purposes the strike/trend values or strike/trend-rose diagrams are more convenient. Azimuths are given in degrees N > E. The bisectrices of two conjugate joint sets are the principal stress directions of the stress field (P = compression; T = tension) that caused them.

This kind of «parametric» statistics is not free of *a priori* assumptions, *viz.* of the assumption of the *existence of a set number* of Dimroth-Watson distributions (and therefore of the existence of a set number of parameters for describing the latter). Non-parametric statistics can, on occasion, be more to the point: the directions of the (absolute) maxima on a direction-rose are independent of any *a priori* assumptions.

This paper investigates joint orientations on the Mascarene archipelago and relate them to the neotectonic environment. This procedure may also contribute to the solution of the problem of the still-controversial origin of the islands.

2. Réunion

2.1. *Geology/geomorphology*

Réunion (fig. 2) is the westernmost of the volcanic islands of the Mascarene group. As befits a mid-oceanic island, the volcanism, with one exception (see below) is and has been essentially basaltic. The formation of Réunion began about 5 Ma ago; the main activity occurred about 2.1 Ma ago. Thus, the main body is an old volcanic mass; it ceased its main activity 200 ka ago (Pliocene shield volcano); its last lava flow has been dated as 13-12 ka old. Towards the end of its activity, the flows became somewhat andesitic, through age-differentiation in the magma chamber.

The «old» volcanic mass is in an advanced state of dissection by short torrential rivers. In the west-central area (*cf.* fig. 2) there is a mountain massif, left from the top of the old volcano, with three high summits: the Piton des Neiges (3070 m), Le Gros Morne (2891 m) and Le Grand Bénare (2896 m). Around them three wide basins have been excavated on account of the higher rainfall rate in the island's interior than at its periphery (Nunn, 1994, p. 193): the Cirque de Cilaos in the S and the Cirques de Salazie and de Mafate on the N, all draining through narrow gorges down the

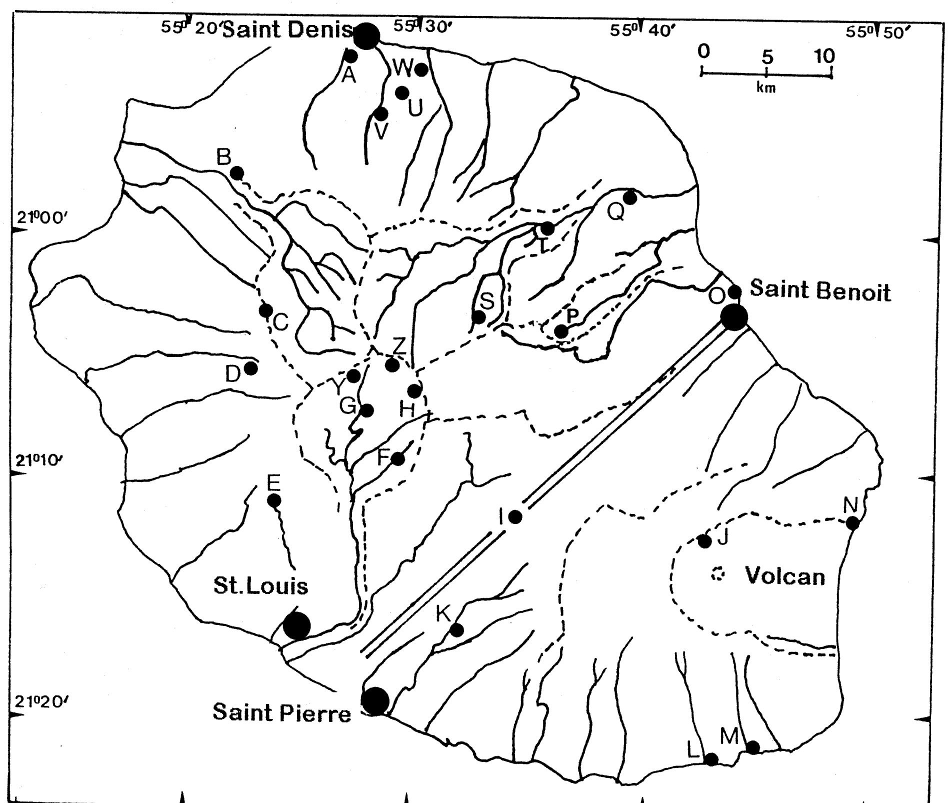

Fig. 2. Topography/tectonics of Réunion with measurement locations (dots), river valleys (solid lines), crests (dotted lines) and the lineament (double line) shown. A = St. Denis; C = border of Cirque de Mafate; F, G, H, Y, Z: in Cirque de Cilaos; K, I, O «disturbance», O = St. Benoit; P = Takamaka; Q, S, T: in Cirque de Salazie; U, V, W near Ste. Clotilde.

outer slopes. Around these «amphitheatres» are a series of plateaus, table-like facets of the uneroded slopes of the former cones (Brookfield, 1966).

Separated from the main (old) volcanic mass by a straight geological disturbance trending N45°E and linking St. Pierre and St. Benoit is a volcanic area in which volcanism has been more recently (during the last 200 ka) active, and in the extreme E is «Le Volcan», one of whose craters, Piton de la Fournaise, was inactive from 1860 until 1925, but has been active several times since then (last times in 1976, 1977 and 1986). Le Volcan (2577 m) and its eastern lava slope, Grand Brûlé, are entirely enclosed within a huge parabolic mountain-wall about 50 km long, the whole basin being a large caldera refilled by recent lava flows (Montaggioni and Nativel, 1988). The massif descends steeply on all sides, but everywhere except in the E it is bordered by a narrow coastal plain/shelf 1-5 km in width. The coast consists mainly of cliffs and has no natural harbors (Brookfield, 1966). All recent lava flows are significantly of the ropy (pahoehoe) type.

2.2. *Origin*

For the origin of Réunion, two hypotheses (Montaggioni and Nativel, 1988; Rivals, 1989) have been proposed:

a) The «hot-spot»-theory, according to which Réunion is currently on top of a mantle-plume. Indeed, Bonneville *et al.* (1988) found that thickness decreased away from the supposed Réunion Hotspot in the Western Indian Ocean, from which they argued that Réunion, Mauritius and the Nazareth and Cargados-Carajos banks of the Mascarene plateau had been formed as a result of passing over this hot-spot (Nunn 1994, p. 47). The hot-spot origin of Réunion was further supported by heat flow measurements on the Mascarene ridge (Bonneville *et al.*, 1997). In a more extreme form, McDougall and Chamalaun (1969) argued that not only the three Mascarene Islands, but also the Deccan traps have been caused by plate-passing over a hot-spot, although the three Mascarene Islands do not seem to belong to the same geological system in spite of their geographical proximity.

b) A tectonic origin by the position at a plate margin or by the reactivation of a paleorift (Schlich, 1982). Indeed, the hypothesis of reactivation of a zone of weakness in the Indian Ocean crust corresponds to similar instances elsewhere on the globe. Although no formal proof exists, the location of Réunion is not accidental, it could be on the prolongation of a ancient ridge dated as 60 Ma old.

2.3. *Joint orientation measurements*

General remarks – A total of seven regions were visited for the purpose of joint orientation measurements. The individual locations are marked by the letters between A and Z in fig. 2. We shall describe the various areas in the order in which they were visited.

Region of the north-west coast – The capital of the Département, St. Denis, lies on the N coast at the foot of the old shield volcano: it stretches from a narrow coastal plain up the slopes of the mountain and into the valley of the Rivière St. Denis. The banks of the latter are very steep and present the aspect of cliffs with well-exposed, jointed rock (Loc. A). A road-spur runs from la Possession on the coastal road up a ridge (Dos d'Âne) forming the right bank of the Rivière des Galets. In roadcuts of the winding road solid rock was exposed (Loc. B). The road led to a «window» (Cap Noir) with a view into the Cirque de Mafate. Another «window» into the Cirque de Mafate is reached at Le Maido at the end of a forestry road starting in St. Paul. From the rim of the Cirque de Mafate (Le Maido viewpoint) one has a spectacular view of the Cirque; joints are seen everywhere on the rim (Loc. C). A forestry road (Forêt des Bénares) rounds the old shield volcano southwards from le Maido towards Tévelave, along which joints were measured in a ravine above Trois Bassins, in volcanic conglomerates (Loc. D). A similar outcrop was found at a road cut within the confines of the town of Tévelave (Loc. E).

Cirque de Cilaos – As noted, the Cirque is considered as a huge erosion-amphitheatre with a narrow entrance from the S through which a road winds itself in numerous curves. Outcrops occur on the road-sides (Loc. F), some with zeoliths; the village of Cilaos lies on a mesa or Îlette. Inside the Cirque de Cilaos, joints were measured on the road to Îlet à Cordes (Locs. G and Y) which cuts some rocks assumed to be basaltic lava flows (*cf.* map by Vincent and Billard, 1974). However, a closer inspection at the location shows that the outcrops consist of (poorly dated) cemented breccias (brèches cimentées), not lava flows. Further joints were measured at the Roche Merveilleuse (Loc. H) and in the gorge of the Rivière des Étangs on the trail to the Col du Taibit (Loc. Z).

Disturbance line St. Louis/St. Pierre - St. Benoît – As noted earlier, the presently active region of «le Volcan» is separated from the old main volcanic mass (Pliocene) of the island of La Réunion by a roughly NE-SW trending geological disturbance-lineament. On it, joint orientations were measured near Le Tampon (Loc. K) in the Plaine des Cafres (Loc. I) and at St. Benoît (Loc. O) on a lava flow near the sea.

Region of «le Volcan» – The easiest access to «le Volcan» can be gained from the west (Plaine des Cafres). From there, a forestry road approaches le Volcan, ending at a parking area at the rim of an inner caldera in whose center the actual volcano and the currently active crater, Piton de la Fournaise, are located. Joint orientations were measured on the inner caldera wall (Loc. J). The volcano can also be accessed from the east coast which, between St. Joseph and Rivière de l'Est (W of Ste. Rose) lies entirely within the parabolic outer caldera wall mentioned above. The whole coast has been shaped by the volcano and a large part of it is a nature reserve (Reserve du Grand Brûlé); thus, the wall of Basse Vallée is obviously an old internal caldera-wall (Loc. L); Cap Méchant is a spur of an old lava flow. In the lava, blow-holes (Souffleur d'Arbonne; Loc. M) were formed. At the N exit of the Reserve, further joints were measured at an older lava exposure (Loc. N).

Valley of Takamaka – Proceeding anticlockwise around Réunion from the volcano region, one crosses the geological disturbance discussed earlier past St. Benoît (see above) and then, at Pointe à Bourbier, the mouth of the Valley of Takamaka (Rivière des Marsouins) is reached. The latter, in effect, issues from an «incipient cirque» with deep gorges, huge cliffs and giant waterfalls. A road leads to the site of a hydro development of the Électricité de France; cliffs at the end of this road provide an opportunity for joint orientation measurements (Loc. P).

Cirque de Salazie – The cirque of Salazie was (alledgedly) formed by the Rivière du Mât whose mouth is not far from St. André; it is accessible by road. Right at the turnoff of the road to Salazie (Route D48) from the coastal highway (at the *village* of Rivière du Mât) there is an outcrop which permits joint orientation measurements to be made (Loc. Q). Proceeding upstream, one enters a narrow «cluse», in which further joint orientation measurements were made (loc. T). More joints were measured on a side road to the Îlet à Vidot (Loc. S).

Ste. Clotilde – Near the Université de la Réunion in Ste. Clotilde, outcrops were inspected and joint orientation measurements made at three locations. One (Loc. U) was in Moufia, just above the University, the second (Loc. V) at the end of the bus line in Les Flibustiers, and the third on the University Campus itself, just above the Science faculty building (Loc. W). The outcrops showed lava flows; the locations were on the slope of the ancient shield volcano and the cover was everywhere very thin, so that practically any building-excavation reached bedrock.

Evaluations – The data collected in the various regions were evaluated according to the method of Kohlbeck and Scheidegger (1977). The results for each region as well as the results for Réunion as a whole are given numerically in table I; the strike-rose diagram for Réunion as a whole is shown in fig. 3a.

Table I. Strike/trend directions of morphotectonic features in the Mascarene Islands.

Two distributions

Localities	#	Max. 1	Max. 2	Ang.	*P*	*T*
Réunion						
Joints:						
W-Side (A,B,C,D,E)	118	117 ± 08	32 ± 11	85	74	164
C. Cilaos (F,G,H,Y,Z)	92	72 ± 17				
C. Salazie (Q,S,T)	63	2 ± 14	88 ± 14	86	44	134
Takamaka (P)	21	0 ± 16	90 ± 13	90	45	134
Disturb. (I,K,O)	63	125 ± 20	46 ± 24	79	85	176
Volcano (J,L,M,N)	84	116 ± 12	27 ± 09	89	73	161
S. Clotilde (U,V,W)	63	101 ± 14	21 ± 13	80	61	151
All joints	504	105 ± 03	20 ± 03	84	63	153
River links	571	115 ± 06	29 ± 00	86	72	162
Crests	222	146 ± 00	64 ± 00	82	105	195
Lineament	1		45			
Mauritius						
Joints:						
SW-Mts. (A-H,M,N)	182	154 ± 04	57 ± 03	84	15	106
Center (L,O,P)	28	182 ± 08	92 ± 24	90	137	47
SE-Coast (I,J,K)	66	161 ± 13	79 ± 06	83	120	30
Moka-Reg. (Q,R,S)	63	170 ± 11	59 ± 12	70	24	114
All joints	359	159 ± 06	66 ± 06	86	22	112
River links	339	142 ± 03	44 ± 00	83	3	93
Crests	81	160 ± 01	64 ± 07	85	22	112
Lineaments	2	140	70			
Rodrigues						
Joints:						
Pte Coton (A,B,C,D,E)	105	168 ± 11	74 ± 10	86	31	121
Pt. Mathurin (1,2,3)	63	169 ± 12	84 ± 11	86	126	36
Mt. Limon (4,5,6)	63	166 ± 16	75 ± 00	89	30	120
NW-Coast (W)	22	110 ± 17	44 ± 18	65	77	167
All joints	253	170 ± 02	80 ± 00	90	35	125
River links	68	161 ± 05				
Crests	18		51 ± 13			

Three distributions

Localities	Max. 1	Max. 2	Max. 3
Réunion			
Joints	141 ± 00	88 ± 03	26 ± 03
River Links	118 ± 00	48 ± 04	5 ± 00
Crests	128 ± 00	67 ± 00	175 ± 00
Mauritius			
Joints	157 ± 04	87 ± 03	48 ± 01
River links	158 ± 02	14 ± 03	34 ± 00
Crests	160 ± 02	77 ± 06	43 ± 03
Rodriguez			
Joints	166 ± 02	95 ± 00	51 ± 00
River links	161 ± 05		
Crests			50 ± 13

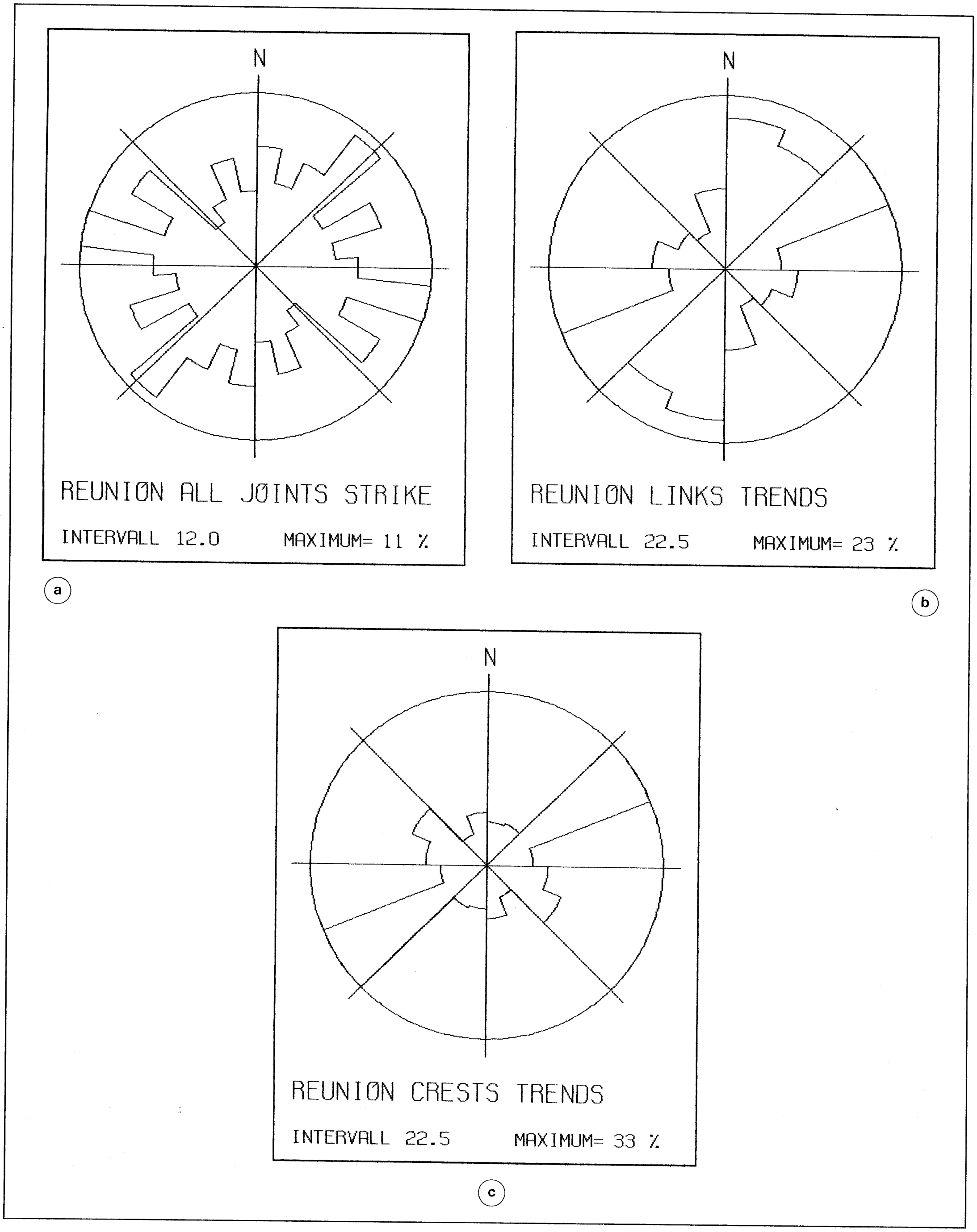

Fig. 3a-c. Strike/trend roses for joints (a), valleys (b) and ridges (c) of Réunion.

2.4. *Morphotectonic features*

General remarks – Apart from the joints in a region, potentially morphotectonic features are the river valleys and the crest lines. In fig. 2 we have indicated the rivers by solid and the crests by dotted lines. In addition there is a prominent disturbance lineament separating the new, active volcano from the old massif: it strikes roughly SW-NE from in-between St. Louis/St. Pierre to St. Benoît. Furthermore, for the *whole* region one can refer to the map of bottom topography shown in fig. 1, according to which the neighbourhood of La Réunion is dominated by two conjugate fracture zones: the Malagasy and the Rodrigues fracture zones. In fact, these two fracture zones are part of a whole system of fractures and ridges in the Indian Ocean (*e.g.*, Owen Fracture Zone, Chagos Trench, Ninetyeast Ridge, Diamentina Fracture Zone): one system strikes about N100°E, the other N20°E. The aim is now to compare these various morphotectonic features with each other.

River valleys – We have digitized the orientation of the rivers by approaching their course by straight «links» of 1 km length. Their orientations were measured and treated by the same Kohlbeck-Scheidegger (1977) method as the joints. The results of the evaluations are also given in table I; fig. 3b shows the corresponding trend-rose.

Crest lines – A similar procedure was applied to the crest lines shown in fig. 2. In this, it will be seen that the «crests» are not necessarily mountain ledges, but also abrupt crests at the top of deep gorges, particularly in and around the cirques. The numerical evaluation values are shown in table I and the trend-rose in fig. 3c.

2.5. *Evaluation of orientation measurements*

It remains now to compare the orientation structures of the joints, valleys and crest lines with each other.

Regarding *joints*, one notes that the values for the joint strikes vary between 72 and 125° for Maximum 1 and between 2° and 46° for Maximum 2. These values can be compared with the tectonic make-up of the region. First of all, the directions of the oceanic fractures/ridges are reflected very well by the joint orientation maxima found for *Réunion as a whole*: strikes are directed N105°E and N20°E. This shows that the joints fit statistically with the overall tectonic pattern prevailing in the region.

In detail, the value fitting the general pattern least is that from the *geological disturbance* (Locs. I, K, O). The latter trends about N45E which agrees very accurately with the *local* joint orientations (strike of Maximum 2: 46°). Thus, even at the local level, the orientations of the joints and of the geological lineaments again agree with each other. One would assume, therefore, that both types of features are caused by the same stress field; whatever the origin of the latter may be.

The *river links* are fairly closely orientated like the joints. This is quite obvious by the coincidence of the non-parametric trend maxima around N48°E seen in the rose diagrams; the parametric statistics give a correspondence within 9-10°.

Even more striking is the coincidence of one non-parametric trend maximum (fig. 3a-c) in the trend roses for the *crests* with the corresponding one for the river links (at N56°E); in this case, the parametric procedure gives a slightly less satisfactory result. The second non-parametric crest-orientation maximum is then simply normal to the first; this is an eminently reasonable result. The rivers in Réunion are therefore normal or parallel to the crests. The latter statement implies that crests are doubling the river courses (particularly evident in the gorges around the cirques).

In *summary*, one can say that joints, river valleys and crests are all similarly oriented. The disturbance-lineament agrees *locally* with the local joints. Therefore, all these features are most probably caused by the same neotectonic stresses.

3. Mauritius

3.1. *Geology/geomorphology*

Mauritius is (after Bold, 1966a) a wholly volcanic island. There is a block of high country in the SW, another in the SE and a third just S of the capital, Port Louis (fig. 4). A trench-like depression trending N145°E runs from Port Louis to the SE to Mahébourg which separates the high block in the SW from that in the SE. Another very broad basin trending N70°E from Flic-en-Flac to Poste de Flacq separates the mountain blocks near (*i.e.* just

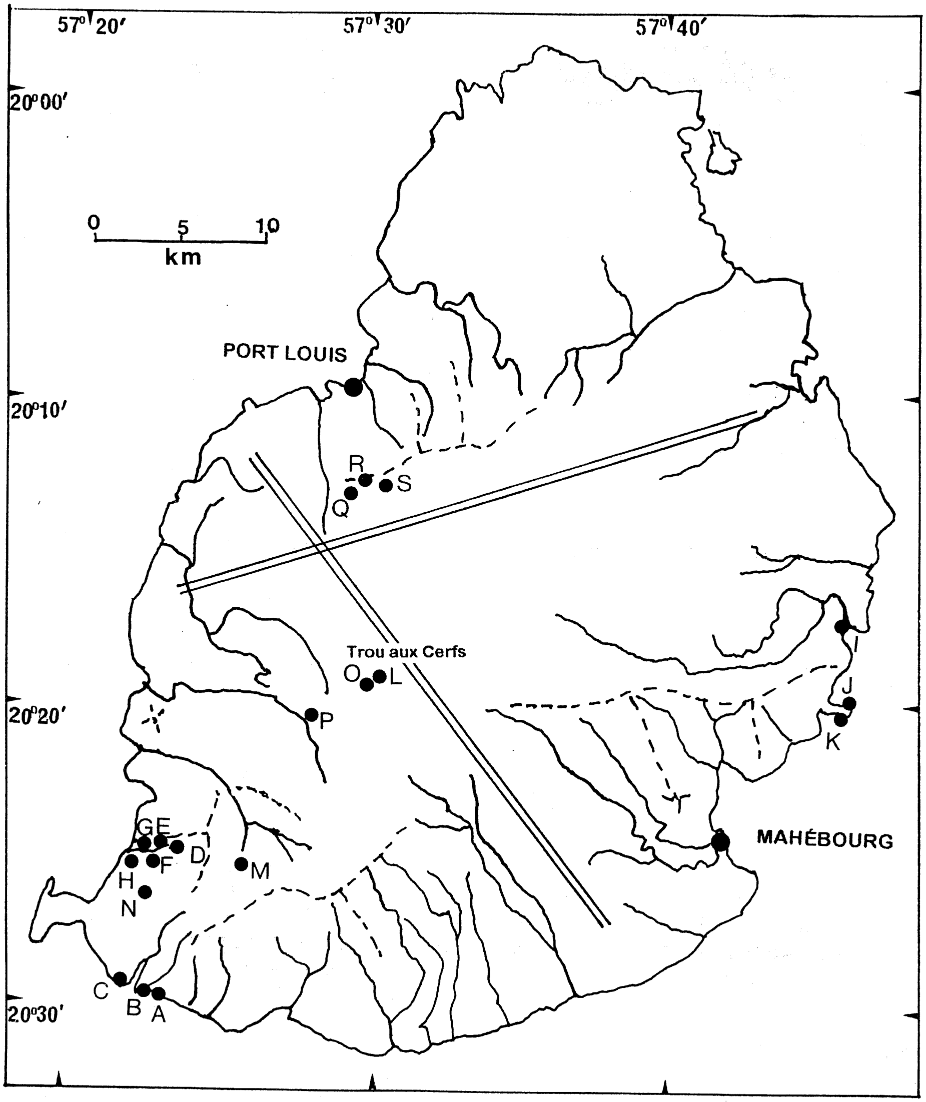

Fig. 4. Topography/tectonics of Mauritius with measurement locations (dots), river valleys (solid lines), crests (dotted lines) and lineaments (double lines) shown.

S of) Port Louis from those in the SE-SW. The rest of the island is plateau-like, sloping particularly in the N gently towards the sea. The highest summit, the Piton de la Rivière Noire, in the block of high country in the SW of the island, reaches only 813 m, but in other parts of the mountain ring there are peaks almost as high. In the jagged chain behind Port Louis are the Pieter Both (807 m) and Le Pouce (798 m). The abruptness of the Mauritian mountains, rising above the smooth slopes of the newer lavas, makes them more impressive than their small elevations would suggest.

Mauritius was built up during three periods of volcanism. In the Cretaceous or Early Tertiary a vast volcanic dome was formed, but the center of this either foundered or was blown out in a paroxysmal eruption, so that only a series of jagged, tooth-like stumps survive around the edges to form the grotesque bordering mountain blocks of the island. In the Late Tertiary there was a second outpouring of lava, followed by a third in the Pleistocene, in which flow after flow of basaltic lava poured out from a series of low craters aligned around the center from the NNE to the SSW. These later lavas formed a vast, gently sloping dome from which the stumps of the older series protrude.

The surface of the newer lavas is slightly trenched by erosion; only the Grand River South East, which with a length of 16 km is the principal stream of the island, has cut down to form a sizable gorge: also by morphotectonic predesign. Some of the volcanic craters still contain lakes and the small streams falling over the western escarpment, on older lavas, have impressive falls. There are some underground streams in lava tunnels. The whole coastline is girt by a coral reef, and there is raised coral at several points on the coast, up to 12 m above sea level. These formations are ascribed to high sea levels in the Pleistocene and are taken to indicate that most of the volcanism ceased about 100 ka ago. Last vestiges are seen in the «Trou aux Cerfs», an old crater near Curepipe; according to information received from the University of Réunion, volcanism was still active there about 30 ka ago.

3.2. *Origin*

The origin of Mauritius is intimately connected with two major structural elements in the Western Indian Ocean: The Mascarene plateau and the Island of Réunion (Perroud, 1982; fig. 1). The East-Indian and the Carlsberg ridge with trends of N100°E arose 50 Ma ago along the Chagos-trench transform-fault which is the cause of the origin of the Mascarene plateau (first volcanic series). Volcanism began 20 Ma ago at the zone of weakness at the junction of the East Indian ridge and the Chagos-Laccadives transform fault which generated Mauritius 10 Ma ago. The N100°E trending rift generated the first («second volcanic series») Mauritian volcanoes at right angles to the ridge whose position it fixed. About 10 Ma ago, the Central-Indian ridge was formed. It is displaced by the large faults (*e.g.*, the Rodrigues faults) affecting the Mascarene plateau. Thus, the fracture zone trending N20°E at the west of Mauritius coincides with the Indian ridge. The reactivation of a paleoridge, which had been inactive for 60 Ma, around 3.5 Ma ago lies at the origin of the volcanism of Réunion. These movements were triggered by a reactivation of the transform fault which passes SE of Réunion and extends to Mauritius along an axis oriented N20°E. This rejuvenation would have caused the «second» volcanic series. Its activity lasted until the beginning of the Recent (third) volcanic series (Montaggioni and Nativel, 1988).

3.3. *Joint orientation measurements*

General remarks – From a geological point of view the most interesting parts of Mauritius are naturally the three blocks of high country. In addition, the central depressions (lineaments) are also of interest; thus four «regions» were investigated. The locations visited are indicated by the letters A-S on the map shown in fig. 4.

South-western high country – From a geological point of view, this is probably the most interesting part of the Island. The first locations visited were near Baie du Cap: Loc. A in a basalt flow at the roadside by the bus stop, Loc. B in an adjacent limestone-shore platform and Loc. C at the Cap du Diable somewhat further W. Next, the coast was reached over a low pass, at which there was a road-cut (Loc. D). Two further locations were found in road curves (Loc. E; Loc. F); upon descent towards the sea the outcrops become more and more lateritized (Loc. G in a further curve; Loc. H at the exit of the road from the hill-country into the plain). Finally, the center of the SW mountain block was visited. At a lookout point (indicated as Loc. M in fig. 4), a view of the falls of the Rivière Noire was obtained; the basalt flow causing these falls was criss-crossed by joints whose orientations were measured. Finally, the Terres colorées (Loc. N) near Chamarel are mainly formed by small gulleys, whose directions were evidently predesigned by joints.

South-eastern high block – Sets of measurements were taken along the coast of the SE high block: in the region between Grande Rivière Sud-Est and Pointe du Diable. The first was at Loc. I, at the Beauchamps Bridge, the second (Loc. J) at the Pointe du Diable near fortifications and the third (Loc. K) at the N-side of Anse Bambou.

Moka (Pieter Both) region – As noted earlier, another range of mountains is located between Port Louis and Moka. Near the bus station at Moka on the road towards Port Louis, after crossing the river, a huge road-cut presents itself in a curve (Loc. Q). Further measurements could be taken along a side road doubling the Moka river; quite a number of data were obtained by making sightings along the face of the Pieter Both range (Loc. R). Finally, an opportunity offered itself to actually encounter bedrock when ascending a new development road to its end (Loc. S): this was a lava flow.

Central Mauritius region – Finally, some joint orientation measurements were taken in the central region of Mauritius. The side of the road leading to the Trou aux Cerfs skirts a cemented lahar flow (Loc. L); the lava itself is cut through at the crater rim (Loc. O). The Trou itself is, as noted earlier, a perhaps 30 ka years old crater and presently has a small lake in its center. Finally, near Henrietta, the Tamarin river flows in a deep gorge; it cascades in many waterfalls over a succession of lava traps. It was not possible to get to these falls, but the trap rock surfaced on the plateau, and measurements could be taken on cracks in the roads across it (Loc. P).

Evaluations – The joint orientation measurements were collected, grouped according to the regions discussed above, and evaluated according to the statistical method of Kohlbeck and Scheidegger (1977) for the individual groups as well as for the island as a whole. The results of the evaluations are summarized in table I; the strike roses for the Mauritius joints is given in fig. 5a.

3.4. *Morphotectonic features*

General remarks – Mauritius is cut by some sort of lineaments (double lines in fig. 4) trending N70°E and N140°E. The river directions seem to form subparallel sets, and so do the mountain crests.

River valleys – To study the orientations of river valleys, the rivers were again approximated by straight links of 1 km length and then treated statistically by the parametric Kohlbeck-Scheidegger (1977) procedure. Nonparametric maxima can be taken from the corresponding trend-rose on fig. 5b.

Crest lines – A similar procedure was applied to the crest lines. The steps were again 1 km; the evaluation data are shown in table I and fig. 5c (trend rose).

3.5. *Evaluations of orientation measurements*

As far as *joints* are concerned, the orientations for the individual regions in the SW mountains and the SE coast are almost the same; this is also true for the results from the Center and from the Moka (Pieter Both) area, so that it appears that there is a small change of orientation N of the two southern mountain massifs. For Mauritius as a whole one obtains

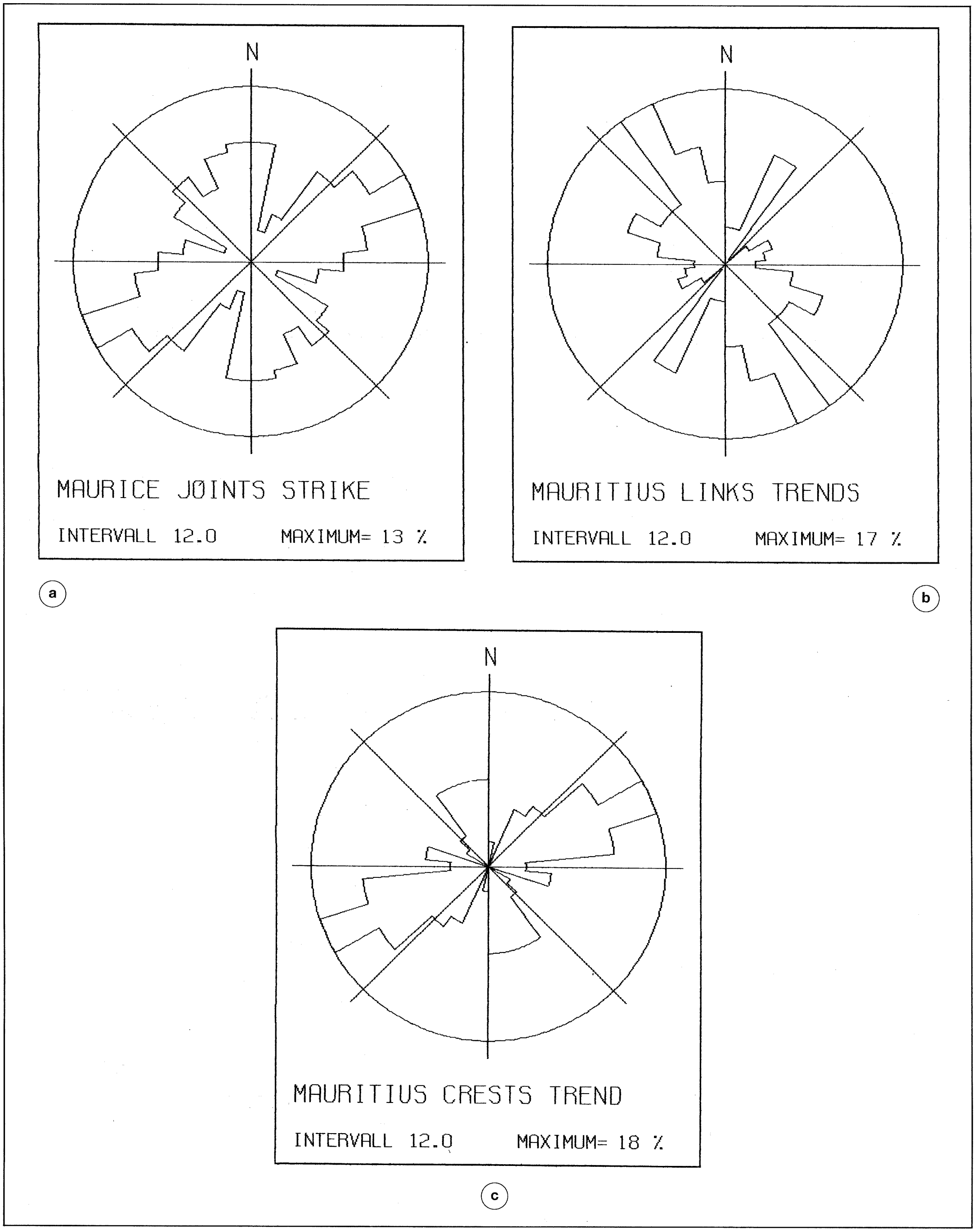

Fig. 5a-c. Strike/trend roses for all joints (a), valleys (b) and ridges (c) of Mauritius.

parametrically two well-defined maxima (at 159° and 66°), which are also borne out by the rose-diagram (fig. 5a).

The rose diagram of the *river links* (fig. 5b) seems to indicate that there are more than two sets. Thus, if the statistical evaluation is forced into only two sets, the results are not too meaningful. If, however, the evaluation is made for three maxima, the main maximum of the river directions (at 157°) agrees within 2° with that of the joint-strike directions (table I). The subsidiary maxima are relatively small and most possibly spurious.

The two maxima (at 160° and 77°) of the *crest-line directions* agree closely with those of the joint strikes; the rose diagram in fig. 5c also bears out that only these two maxima exist in reality.

Regarding the *lineaments*, one sees that one of them agrees with one of the joint- and crest-maxima, the other with one of the river-links maxima.

Thus, *in summary*, one sees that there is a close connection between the orientations of joint- river-, crest- and lineament-directions. This would seem to indicate that there is again a pronounced common (neo)tectonic control of these features.

4. Rodrigues

4.1. *Geology/geomorphology*

Together with Mauritius and Réunion, Rodrigues lies (after Bold, 1966b) on a submarine ridge trending NE-SW. Like the other Mascarene Islands (*cf.* sections on Mauritius and Réunion), it is wholly volcanic in origin, being composed of a central ridge of doleritic lava reaching 387 m at Mt. Lubin, partly surrounded by a raised coral reef, studded with islets and separated from the land by a shallow lagoon of varying width (fig. 6).

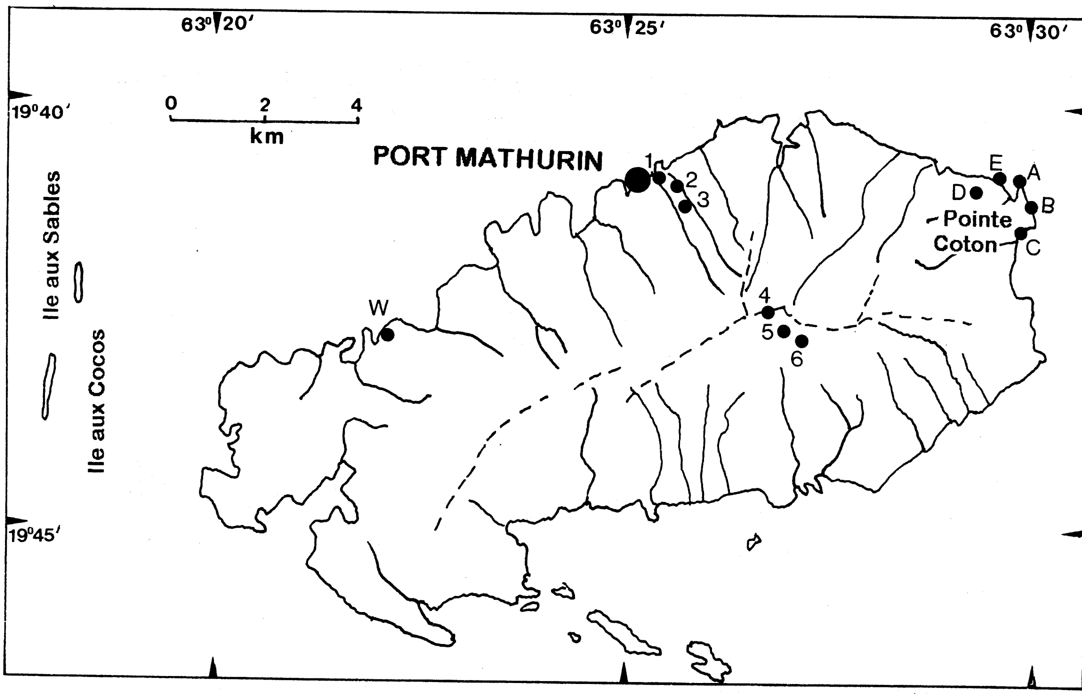

Fig. 6. Topography/tectonics of Rodrigues, showing joint measurement locations (dots), river valleys (solid lines) and crests (dotted lines).

4.2. *Origin*

According to Nunn (1994, p. 28), Rodrigues is an example of an island formed near a triple plate junction along a mid-ocean ridge: Bonneville *et al.* (1988) have proposed a mid-ocean ridge rather than intraplate origin of Rodrigues.

4.3. *Joint orientation measurements*

General remarks – The points/outcrops visited are shown on the map in fig. 6 indicated by the letters A-E, W and the ciphers 1-6. They were in groups, one at Pointe Coton (Locs. A,B,C,D,E), one around Port Mathurin (Locs. 1,2,3), and one on the central ridge around Mt. Limon/Mt. Lubin Locs. 4,5,6). Finally, a set of measurements were taken by aiming the compass from a launch when doubling the NW coast (Loc. W).

Vicinity of Pointe Coton – Outcrops around Pointe Coton included the following: Loc. A was coral limestone on the bay east of Pointe Coton; Loc. B on the spur adjoining the bay. A bit further inland from the coast there was raised coral (Loc. C); the former volcanic activity is attested to by a volcanic bomb found nearby. Typical pyroclasts were found nearby upon ascending Mont au Sel (Loc. D). Finally, an outcrop of a basaltic lava flow was seen on the beach at the Pointe itself (Loc. E).

Vicinity of Port Mathurin – Three outcrops were investigated on the road leading from the capital Port Mathurin to the central ridge of the island. The first of these (Loc. 1) was at the town-exit in volcanic tuff, the next (Loc. 2) near the look-out point of «the Monument» (to «Our Lady, Reine de Rodrigues») consisting of similar material and the third (Loc. 3) a slightly higher up in a road-curve.

Vicinity of Mt. Lubin – The next group of outcrops visited was located around Mt. Lubin-Mt. Limon. Thus, Loc. 4 was on the flanks of Mt. Lubin, Loc. 5 on the flanks of Mt. Limon and Loc. 6 on the crest road near Grand Montagne.

Northwest coast – Finally, a set of measurements were taken by sighting joints from a launch on a trip from Baie du Nord to Cocos Island. Rather prominent hills, as yet inaccessible by road, were seen here (Loc. W).

Evaluations – As mentioned above, joint orientation measurements were taken on the outcrops indicated above. These were then evaluated according to the method of Kohlbeck and Scheidegger (1977) in the groups described above, as well as a single unit for the entire island. Table I gives a summary of the results; fig. 7a shows the strike rose diagram for the joints.

4.4. *Morphotectonic features*

General remarks – The prominent morphotectonic features on Rodrigues are the valleys and the central mountain ridge with its ramifications. There are no obvious lineaments as on the other Mascarene Islands. Thus, the orientation studies have to be restricted to valleys and crests.

Valley trends – The valley courses were again approximated by links 1 km long. Because of the much smaller size of Rodrigues in comparison with the two other Mascarene Islands, the total number of links is naturally also much smaller and the statistical evaluation less decisive. In effect, only one maximum is meaningful: table I gives the values for the Kohlbeck-Scheidegger (1977) evaluation of the data and fig. 7b the trend rose diagram.

Crest lines – Similar remarks apply to the valley trends. There is only *one* meaningful maximum; the ramifications represent splay-splits of the central ridge. The numerical values are given in table I and the trend rose diagram in fig.7c.

4.5. *Evaluations of orientation measurements*

An inspection of the Rodrigues data in table I shows that there is a good consistency between the values for the individual groups of *joints* (except for the NW-coast, where there

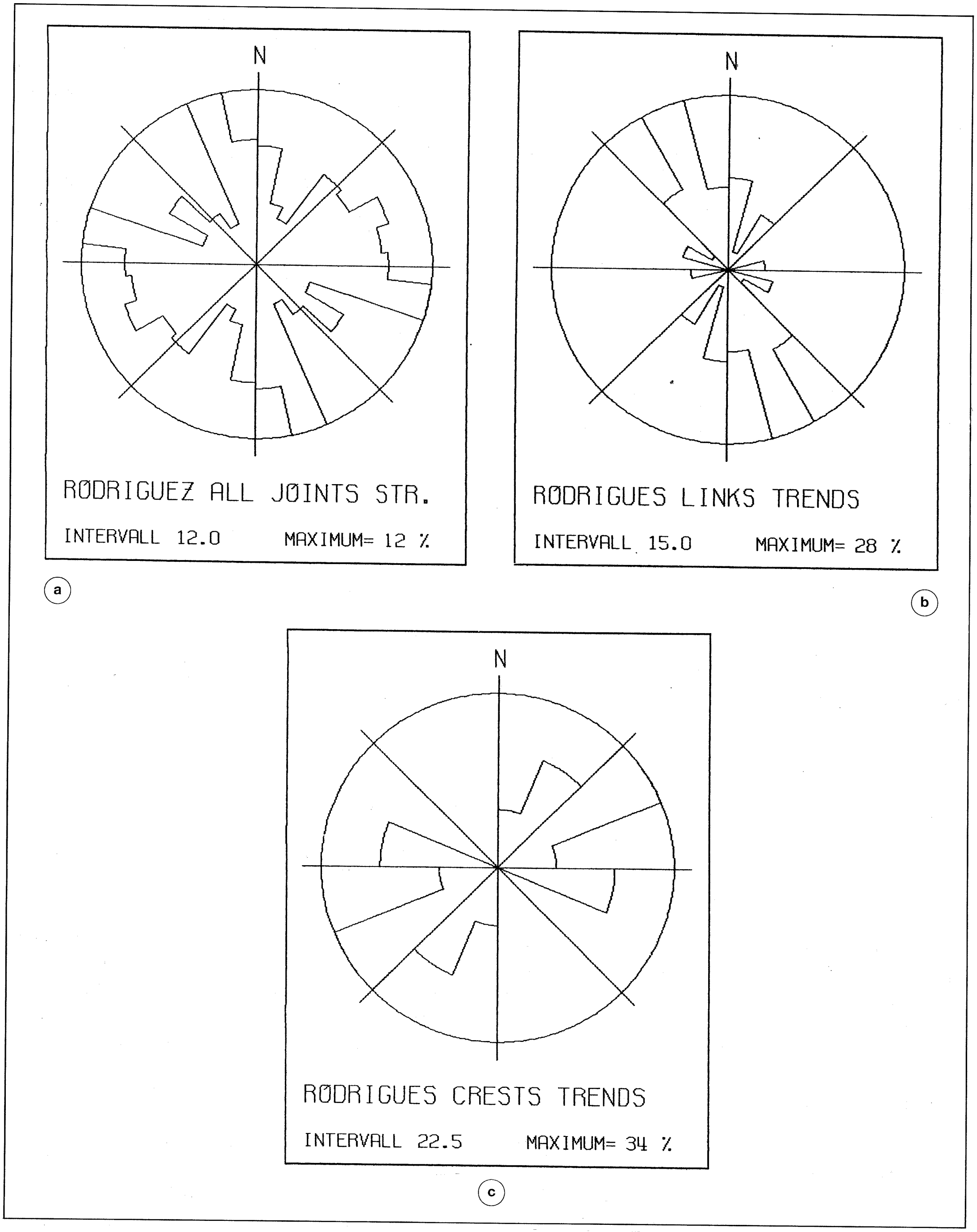

Fig. 7a-c. Strike/trend roses for all joints (a), valleys (b) and ridges (c) of Rodrigues.

were only 22 values taken by sightings, which is probably a somewhat inaccurate procedure) and also with the results for the entire island.

The *river trends* agree with one of the joint maxima, accurately by inspection of the non-parametric trend roses, within 9° with regard to the parametric Kohlbeck-Scheidegger (1977) evaluations.

The *crest-line* maximum agrees again accurately by inspection of the non-parametric rose diagram with one of the joint-maxima; they do this also numerically, if three Dimroth-Watson distributions are taken. The crests are also more or less (11° discrepancy) at right angles to the river directions, which would be expected from a purely exogenic process.

In *summary*, there is again a reasonably close correspondence between the various geomorphic features with joint strikes, so that again a common predesign can be postulated.

5. Conclusions

Upon inspection of the orientation statistics of (potentially) morphotectonic features, a connection exists on all islands between the joint orientations and the orientations of prominent geomorphological features (valley courses, crest lines, lineaments). For the joints alone, we note that the results for Maurice as a whole agree closely with those for Rodrigues as a whole. However, with only two distributions, there is not much relation between the results of Maurice/Rodrigues with those of Réunion. Nevertheless, if the evaluation is made for *three* distributions, one sees that two of these agree with two (corresponding ones) of Réunion. In particular, the strike of the Rodrigues fracture zone and others (*ca.* E-W) is very well reflected by the Max 2 if three distributions are taken. On the other hand, the strike of the Madagascar fracture zone (N26°E) is only reflected in the Réunion joints, presumably because the latter island is closest to it. Inasmuch as the trends of the valleys, ridges and lineaments are related to the trends (strikes) of the joints, a common morphotectonic predesign seems to be present for all the features studied.

Such are the morphotectonic facts. The next question concerns the origin of the various islands of the Mascarene archipelago. In this instance, a hot-spot origin is generally preferred for Réunion, and may be for Mauritius as well, although different opinions have also been voiced (see sections on the individual islands). If one keeps the close fit of the joint strikes in Réunion with the trends of the Madagascar and Rodrigues fracture zones in mind, one cannot but wonder how the latter could affect the dynamics of a hot-spot. The joint maxima in Mauritius and Rodrigues agree closely with each other, across the deep Mauritius trench; they also agree with the trend of that trench and with the trend of the Rodrigues fracture zone. Thus, it would appear as most likely that these trends (of joints and of fracture zones) are all part of the same pattern and are due to the same cause: *viz.* to action of the neotectonic stress field. The Indian Ocean floor (like, incidentally, also the floor of the Pacific) is criss-crossed by what almost appears as a grid of conjugate lineaments (ridges and fractures) which do not point to a formation by plate-drift, but rather to a formation as shearing lines in a stress field. An analogy between the Mascarene «line» (Rodrigues-Mauritius-Réunion) with, *e.g.*, the Society Islands «line» (Bora Bora-Huahine-Moorea-Tahiti) is certainly unthinkable and has never been suggested: Réunion would have to be a single anomalous hot spot at its present location. Such anomalies also occur in the Pacific: the Samoan «line» Tutuila-'Upolu-Savai'i (the latter island is active today) simply does not fit any idea of a plate drifting over a hot spot at all; similarly, the failure of the plume theory for explaining midplate volcanism in the Southern Austral Islands has been admitted (McNutt *et al.*, 1997). Thus, our data from the Mascarenes join the growing list of difficulties arising in connection with «classical» plate tectonics (*cf. e.g.*, Shields, 1997; Storetvedt, 1997). Of course, *ad hoc* hypotheses can *always* be found to save the preconception that *every* feature has to be explainable by plate-tectonics, but they lead into difficulties in other contexts, and it might be wise to at least consider the possibility of alternative mechanisms: island chains like the

Mascarenes could be connected with failure lines of the neotectonic stress field – whatever the cause of the latter may be.

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