Geol. Soc. Malaysia, Bulletin 31, July 1992; pp. 113–131

Geology of Taman Bukit Tawau, Semporna Peninsula, Sabah

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Abstract: The volcanic mountains crowned by the peaks Magdalena (1,320 m), Lucia (1,210 m), and Maria (1,090 m) consist of Quaternary pyroclastics and lava flows of dacitic, andesitic and basaltic character. Some of these products have become silicified, probably through hydrothermal action. High silica content is also evident in the "basaltic" and "andesitic" volcanic rocks that we analysed. On the other hand, nephelinite was determined among the basaltic rock of Bukit Tiger. Evidence of the most recent volcanicity consists of a 24 ka old carbonised tree trunk embedded in a lava flow. In spite of its geologic youth, the complex, including the extensive lava surfaces, is transacted by numerous long lineaments that occur either as single strands or as zones several kilometres wide. Common lineament directions are 340°, approximately north, 10-15°, 75°, and east. Several of the volcanic peaks are also aligned along three of the mentioned directions, spanning distances between 4 km and 22 km. Along a few northerly trending lineaments, normal faulting downthrowing to the west, is suggested by triangular facets (more than a hundred metres high) and scarps facing west. A major fault zone, 3 km across and traceable over almost 30 km is indicated by strongly developed lineaments trending approximately 10° across Mount Magdalena. This interpreted fault zone is transacted by many east-striking lineaments that reach lengths of 5 km.

Indications of widespread hydrothermal processes affecting the volcanic rocks of the Taman Bukit Tawau area suggest the occurrence of mineralisation and geothermal sources. The lineament map of the Lucia-Maria-Magdalena complex may prove useful for delineating mineralisation targets and geothermal centres.

Abstrak: Pergunungan volkano yang berkemuncak Magdalena (1,320 m), Lucia (1,210 m) dan Maria (1,090 m) terdiri daripada piroklas serta aliran lava dasit, andesit dan basalt yang berumur Kuaterner. Sebahagian daripada batuan tersebut telah menjadi kaya dengan silika, mungkin kerana tindakan hidrotermal. Contoh batuan yang kononnya bersifat "basalt" dan "andesit" didapati berkadar silika melebihi 60 peratus. Sebaliknya, di antara basalt Bukit Tiger telah dikenal batuan nefelinit. Petunjuk aktiviti volkano yang paling muda ialah batang pokok terkarbon dan berumur 24 ka di antara aliran lava. Walaupun batuan Taman Bukit Tawau begitu muda, namun seluruh kawasan, termasuk permukaan lava yang luas, direntasi banyak lineament panjang yang wujud sebagai utas tunggal atau sebagai zon berkelebaran beberapa kilometer. Arah lineamen yang umum adalah 340°, hampir utara, 10-15°, 75° dan timur. Sejumlah kemuncak volkano juga menunjukkan kedudukan sepanjang tiga arah lineamen yang tersebut, dan mencapai jarak antara 4 km dan 22 km. Beberapa sesar normal dengan bongkah sesar sebelah barat yang menurun, didapati berjurus mengutara dan ditandai faset segitiga menghadap ke barat dan juga oleh tubir. Sebatang zon sesar utama berkelebaran 3 km dan yang boleh dikesan sejauh hampir 30 km ditandai lineamen jelas berjurus sekitar 10° memotong tubuh Gunung Magdalena. Zon sesar ini pula dipotong oleh banyak lineamen menjurus ke timur; setiap; satu zon boleh berkepanjangan hingga 5 km. Petunjuk mengenai tindakan hidrotermal yang meluas di Taman Bukit Tawau mencadangkan kemungkinan wujudnya permineralan dan punca geotermal di sana. Peta lineamen daripada komplek Lucia-Maria-Magdalena akan berguna bagi menentukan sasaran permineralan dan pusat geotermal.

INTRODUCTION

The Taman Bukit Tawau area is underlain by Miocene to Pleistocene andesitic, basaltic and dacitic volcanic rocks with sedimentary rocks of the Kalumpang Formation which is of Early Miocene age. Figure 1 summarises the stratigraphy of the area. The oldest volcanic rocks form Bukit Tinagat in the southern part of the area. The Kalumpang Formation crops out in the northwest along Sungai Junap. Gunung Andrassy and Gunung Magdalena are the major topographic features and consist of Late Miocene to Pliocene andesites, while Gunung Lucia and Gunung Maria are of Pleistocene dacites (Figure 2). The youngest dacite and basaltic volcanic rocks in the Tawau area erupted 27,000 years ago covering extensive low-lying ground but occur as patches upon older volcanic rocks of higher elevations. Andesitic-basaltic volcanic products are mainly of Pliocene age. Deep dissection of these rocks occurred in the Late Pliocene and Early Quaternary after uplift and faulting. At the same time dacite erupted from Gunung Maria.

Present field observations

In the later part of 1989, our brief, geological field survey of Taman Bukit Tawau, was part of an extensive collecting expedition by seventy biologists, earth scientists and supporting technical personnel. The expedition was organized by Sabah Parks and Universiti Kebangsaan Malaysia, Sabah Campus. In the 10 days allocated for fieldwork, the geological party restricted its survey to the south part of the park, but included Mount Maria, and small volcanic units outside the park's boundaries: Bukit Tiger, Bukit Quoin, Bukit Bald and Bukit Kawa, and a river section of Sungai Junap in the northwest corner.

The present report is mainly on structural geology and petrography of volcanic rocks of the Taman Bukit Tawau area.

Stratigraphy and structure

The morphology of the Semporna Peninsula is dominated by the presence of (probably) Pliocene to late Quaternary volcanic forms of which the largest complex includes Taman Bukit Tawau (Figure 2). Except for the ?Upper Miocene Umas Umas Formation, the older stratigraphic units of the Peninsula also contain large amounts of volcanic material (Kirk, 1962). The older stratigraphic unit, the so called Chert Spilite Formation of late Cretaceous to Eocene age, contains spilite basalt in addition to generally deep-sea sediments with two major lenses of massive limestone. The formation is chaotically deformed and displays a sinuous WNW to W trend. The limestone dips at moderate angles towards N and NE and disappears beneath a wide zone of brecciated, partly Eocene, chaotically disposed sedimentary and volcanic rocks. Along its southern boundary, Kirk mapped a 3-km wide zone of mainly tectonically brecciated basic igneous rocks and serpentinised intrusions forming sheeted structures. These are most probably sheeted dykes of ophiolite complexes. The next younger stratigraphic unit is the Kalumpang Formation that contains pelagic foraminifera of late Oligocene to Tf

AGE	TERTIARY LETTER CLAS. (Adams 1970)	SEDIMENTARY VOLCANIC ROCKS	IGNEOUS ROCKS & ACTIVITY	PALAEOGEOGRAPHY & DIASTROPHISM
HOLOCENE		RECENT ALLUVIUM: coastal and fluviatile	Siliceous sinter from hot springs	Relative sea level drop
PLEISTOCENE		HIGH LEVEL ALLUVIUM & INLAND VALLEY DEPOSITS mainly tuffaceous + clastics ?— — — — — —?	Olivine basalt Hypersthene andesite G. Maria: dacitic lava G. Wullersdorf: dacitic volcanism & microgranodiorite porphyry G. Magdalena & G. Andrassy: andesitic volcanism & microdiorite porphyry	Uplift and faulting
PLIOCENE	Tgh			
LATE MIOCENE	Tf_3			Nondeposition/ Erosion
MIDDLE MIOCENE	Tf_{1-2}	KALUMPANG FORMATION: tuffite, shale, mudstone	Volcanism associated with the Kalumpang Formation	Strong folding and faulting
Early Miocene	Te_5	tuffaceos sandstone conglomerate		
Late Oligocene	Te_{1-4}	limestone		

Figure 1: Stratigraphy of the Bukit Tawau area.

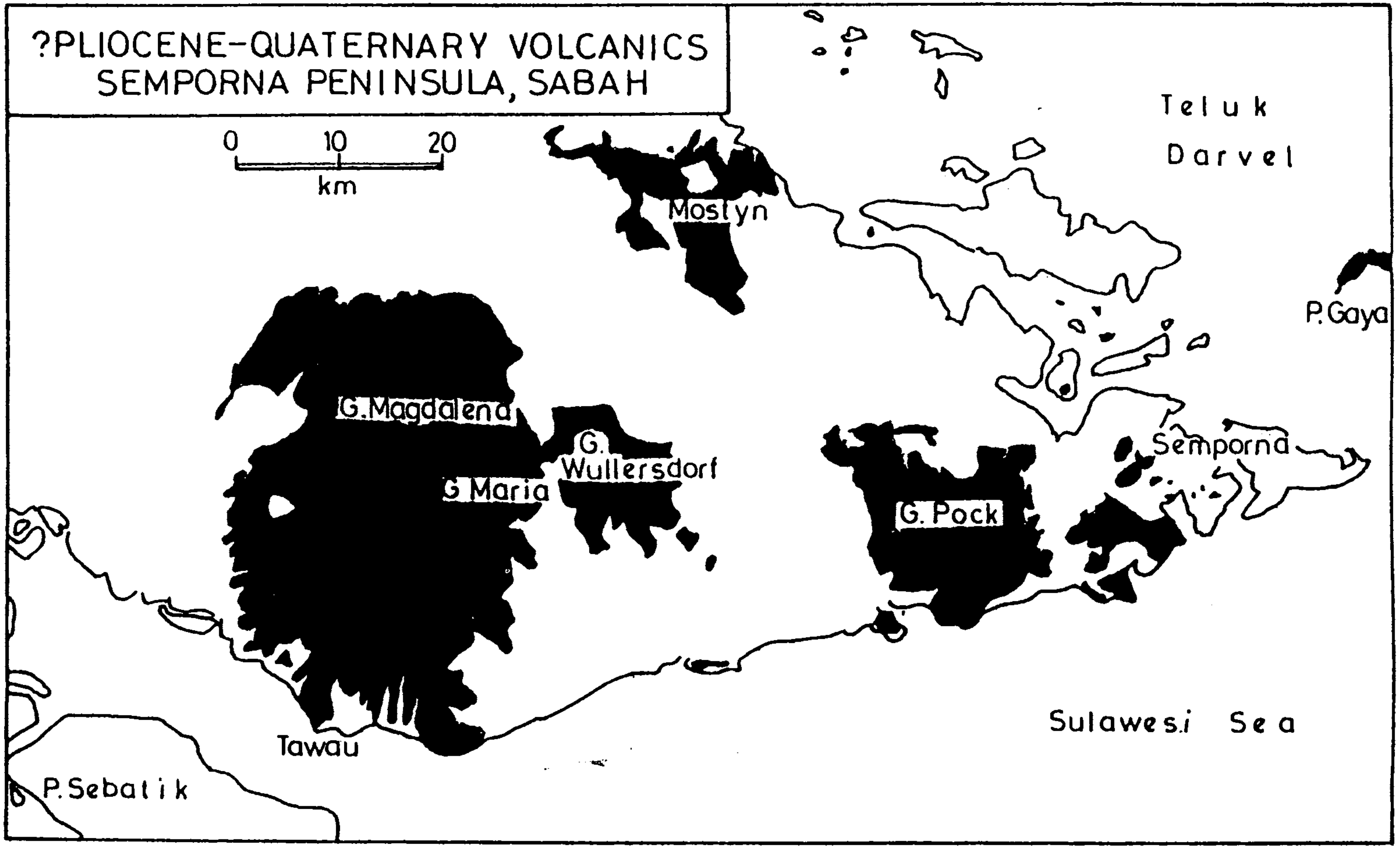

Figure 2: The distribution of ?Pliocene-Quaternary volcanic and subvolcanic rocks in the Semporna Peninsula. Data is from Kirk's (1962) geological map.

or middle Miocene age (in Kirk's original report Tf was considered equivalent to late Miocene). Its sedimentary rocks are mixed shelf and deep-sea deposits consisting of massive limestone and sandstone-shale associations, in which can be recognized a volcanic facies and a sandstone-chert facies. Kirk reports that the Kalumpang rocks are also chaotically deformed, in structural style similar to that of the Chert Spilite Formation. Structural trends in the Kalumpang Formation are W and NW. However, on Sebatik island, this formation forms a regular, although asymmetrical anticline verging southwest. Leong (1974) has included into the Kalumpang Formation the sandstone-mudstone sequence in the Umas-Umas, Binuang and Tingkayu areas. The Kalumpang Formation in this report refers to the folded and faulted sequence of dominantly Early Neogene volcaniclastic sediments. In the map area the formation consists of interstratified tuff, tuffite, mudstone, shale, tuffaceous sandstone and conglomerate. It is well-bedded with a major northerly strike. Most of the fine-grained beds are laminated and show faint graded bedding. Bluish-green tuffite interbeds with layers of green and black volcanic fragments and sedimentary clasts. The pyroclastic and tuffaceous beds are very similar to those of the Middle Miocene volcanic sequences of the Dent Peninsula. Some tuffaceous layers are yellowish green and contain volcanic rock fragments up to a centimetre across with crystals embedded in a fine-grained matrix. The fragments are vitric tuff, interlocking quartz grains, iron oxide and carbonaceous matter. Thick conglomerate beds outcrop along Sungai Junap. Individual beds range from 2 cm to more than a metre thickness. Small scale folds and faults are common. The tuffite layers are intercalated with tuffaceous sandstone and conglomerate.

The Kalumpang Formation was deposited in marine environments at different depths. Foraminifera from the limestone facies at milestone 31 on the Kunak-Tawau road (outside the map area) are *Operculina* sp., *Lepidocyclina* sp. and other reworked benthonic forms indicating shallow-marine surroundings of typical fore-reef shoal or open marine conditions. However, planktonic foraminifera present in some clacareous beds indicate deeper water.

The Kalumpang Formation is the oldest lithostratigraphic unit in the map area. Its base and upper part are nowhere exposed in the map area. Moreover, the intense folding and faulting preclude a reliable estimate of its thickness.

Recently, the chaotic deposits of Sabah represented by the Chert Spilite Formation, parts of the Paleogene Trusmadi and Crocker formations, and the Oligocene-lower Miocene sedimentary units (including the Kalumpang Formation) were interpreted as tectonic and sedimentary melanges that delineate a wide plate boundary, the so-called Kinabalu Suture Zone, between mainland Borneo and the East Sabah accreted terrane (Tjia, 1988). The north fringe of the Semporna Peninsula had already been included into the suture zone on the basis of the presence of Chert Spilite rocks. In view of the fact that the Kalumpang Formation in the Peninsula (with the exception of its occurrence on Sebatik island) is chaotically deformed, it appears that the Semporna Peninsula, with the exception of a narrow south fringe now occupied by young volcanoes and Quaternary deposits, is also part of the suture zone. Faults are common between the Chert Spilite Formation and the Kalumpang Formation. Kirk has interpreted that strong earth movements in Semporna culminated in late Tf time. General vergence seems to have been south.

Kirk states that among the Tertiary stratigraphic units in the peninsula only the 450 m thick Umas Umas Formation of sandstone, shale and mudstone is without volcanic components or detritus. This formation stratigraphically overlies the Kalumpang Formation and Kirk thinks that the Umas Umas beds are possibly of late Miocene or Pliocene age. The formation was warped into an open basinal structure, similar to the structural basins Melibau, Maliau and Bangan.

Two groups of granitic rocks occur as small bodies in the peninsula. One group is of pre-Mid Miocene age and consists of a few small granite bodies associated with ultrabasic and basic rocks of the Chert Spilite Formation and those that are not. This group is characterized by showing the effects of dynamo-metamorphism and some by having been cataclastically deformed. The younger group consists of small bodies of undeformed leucogranite and silicic intrusives in the Timbun Mata area.

The major volcanic units consisting of igneous rocks and sediments are of late Tertiary (?Pliocene) to Quaternary ages. Lim (1981) mapped a geologically similar area, Gunung Wullersdorf to the east of Taman Bukit Tawau. Kirk's geological map covers the entire Semporna Peninsula and shows that the main volcanic and subvolcanic centres are aligned in two parallel east-west zones. The north zone comprises the Mostyn area, east side of Pulau Timbun Mata and the partially submerged caldera of the Gaya islands. The south zone consists of the large Magdalena-Lucia-Maria complex north of Tawau, G. Wullersdorf, G. Pock, and scattered hill complexes west and southwest of Semporna town. Both zones are part of the Semporna-Sulu-Southwest Mindanao volcanic belt. Kirk (1962: p. 130 etcetera) reports the following contacts phenomena between the volcanic rocks and older stratigraphic units. North of G. Magdalena, volcanic rocks were downfaulted against the Kalumpang Formation. Near G. Wullersdorf, silicified dacite exhibits steep margins with folded sediments and the igneous rock may be an exposed volcanic neck. East of the Balung valley and north of G. Pock, volcanics unconformably overlie Kalumpang beds. The older volcanic masses of andesitic and dacitic composition are transected by many large, steep-sided silicified volcanic rocks, some of which reach diameters of 8 km. These silicified complexes may have been old volcanic vents where the original rock became silicified by hydrothermal fluids.

Kirk observes that during the ?Pliocene to early Quaternary the main volcanic products were of andesitic and dacitic composition. During the late Quaternary, olivine basalt volcanism dominated. Blocky lava flows covered large areas on the west and east borders of Taman Bukit Tawau, and in the Mostyn region. Small breached craters can still be seen on the summits of G. Bombelai at the Park's entrance and on Bukit Quoin. The soil upon basalt flows may be exceptionally thick and reaches more than 6 metres. Kirk does not think that this is because the original material was lahar overlying the basalt. He argues that there is no stratification and that all the fragments are basaltic without other types of volcanic rock. However, both arguments are invalid, since stratification is generally absent in lahars and the type of rock fragments in a deposit (lahar) overlying basaltic lavas could very well be that of the underlying rock only. Kirk (1962: 72, 99-100) states that the ?Pliocene to Quaternary volcanic products are of typical calc-akaline basalt-andesite-dacite association and originated from the same parental magma: a basalt type. He interprets further that the diversity in volcanic products during the ?Pliocene-early Quaternary activity was the result of differentiation when the region was under compression, whereas the younger olivine basalt flows represented a tensional tectonic regime.

The volcanic flows of the Tawau area have been determined by the K/Ar method at 9 Ma (Rangin *et al.*, 1990), while the foraminiferal assemblage in the Kalumpang Formation indicates Early to Middle Miocene (Muller in Rangin *et al.*, 1990). Zircon grains from hornblend andesite of the Tinagat area were analysed by fission-track that yielded an age range from 13.6 to 70.7 Ma and clustering in three groups: 13.6-21.4 Ma, 32.1-37.8 Ma, and 55.7-70.0 Ma (M. Ueno in Leong, 1987). The K/Ar age of andesite from the vicinity of Mt. Andrassy is 6.4 Ma, while dacite from Mt. Maria is 1.62 Ma (Leong, 1987).

A carbonized tree trunk in a dacite breccia near Tawau was dated at 27,000 ± 500 BP (Kirk, 1968). Recently, Bellwood (1988) published similar radiocarbon dates (24 ka) of other wood specimens collected from the basaltic flows that once dammed Tingkayu Lake in the Mostyn area. It seems clear that, in the Peninsula, volcanism was still active until the late Pleistocene. Numerous hot springs and gas seepages occur near or in outcrops of the youngest volcanic rocks and, therefore, are related in Kirk's opinion. During his surveys, two mud cones were also present.

Older Quaternary sediments and redeposited volcaniclastic sediments form strata that dip at angles not exceeding 20° in various directions. This suggests that the inclinations may be depositional dips. In our fieldwork along the headwaters of Sungai Junap, Merotai, in the northwest corner of the Park, we saw an outcrop of well stratified, little consolidated mudstone having an attitude of 310/20. The appearance of the mudstone, that acquires brown staining upon exposure, is similar to that of the Neogene-Pleistocene tuffaceous mudstone so common in Java. In the lower Balung and Apas areas, such young deposits show gentle regional dips southward and very probably indicate regional tilt.

The younger Quaternary sediments consisting of coastal alluvium and redeposited volcaniclastic beds are horizontal and occur exclusively in the coastal zones. Terraces built of such sediments indicate differential uplift along the axis of the peninsular.

Reef limestone forming the 3-3.5 m high (above mean sea level) platform on which Semporna town stands, is 19,030 ± 450 BP (Tjia *et al*, 1972). Taira &

Hashimoto (1971) dated several coral specimens and oyster shells from the reef limestone on Bangau Bangau island near Semporna town and reported that the bulk was between 30 ka and 36 ka old. Other researchers have experienced that such old radiocarbon dates of coralline material are suspect and the actual ages may be much older than the radiocarbon ages. However, one younger date of a coral of 18,400 ± 350 BP that probably represents a later attachment to an old reef complex, may indicate a true age. This particular specimen was collected from a position of circa 2 m above high tide. It is widely accepted that 20 ka to 18 ka ago during the peak of the Last Glacial, sea level stood at least a hundred metres lower than today. If that is the case, the two dated samples referred to above, suggest average rates of uplift in the range of 5.6 mm to 7 mm annually.

PETROGRAPHY

We collected and studied petrographically a variety of volcanic rocks, including andesites, basalts and a nephelinite from the map area and its vicinity (Table 1). The chemical compositions of fifteen samples were also analysed by X-ray fluorescence (Table 2). These samples can be grouped into acid volcanic rocks (silica content exceeds 60 per cent; samples 1, 2, 8, 11 and 13). The high silica content for samples 2, 8 and 13 is most probably due to silicification by hydrothermal action. The other samples contain less than 60 per cent silica and are grouped as intermediate rocks.

STRUCTURAL GEOLOGY

Structures in volcanic rocks

The occurrence of late Quaternary volcanic products associated with hot springs, mud cones, tilted Quaternary sediments, and rapid rates of crustal movements attest to tectonic mobility of the Semporna Peninsula. During present fieldwork, we came across one, at least 12 metres wide, shear zone in ?Pliocene andesitic lava along Sungai Tawau, some 3 km upstream from the entrance to Taman Bukit Tawau (Figure 3.). A moderately large H_2S hot spring marks one boundary of the 210°-striking shear zone that contains numerous N-S vertical, en echelon fractures. On one of the vertical planes of the shear zone are subhorizontal fault striations across which are spalls. Corrosion by the acidic vapours emanating from the hot spring made it impossible to determine if the spalls are accretion (which would indicate left slip motion) or stoss types (this would indicate right slip). The subhorizontal striae definitely indicate transcurrent motion, and the N-S en echelon fractures within the shear zone suggest left slip motion.

In the dark coloured, upper lava flow unit at the 7-8 m fall at the Taman Bukit Tawau entrance are regular sets of fractures and some warps (Figure 4). The 2-m thick upper flow unit at the fall displays an open anticline and syncline of 6-m wave length. The folds rest upon a lower flexured flow unit. These structures are shown by deformed flow planes, of which the majority consists of

Table 1. Petrography of samples collected during present survey.

Note Rock names in each subheading are from Kirk's map.

1. **Andesite at Camp 2, SW mid-slope of G. Maria.**
Crystalline to cryptocrystalline rock. Minerals are probably augite, unspecified pyroxene, cryptocrystalline plagioclase.

2. **Silicified Volcanic Rock**
Plagioclase, anhedral quartz, unspecified pyroxene, and augite as micro-phenocrysts. Overall texture is hypocrystalline, most crystals are euhedral to subhedral. Occasional seriate texture and vesicles. Groundmass of fine plagioclase laths and cryptocrystalline ferromagnesian? minerals. Zoning in plagioclase common; pyroxene forms inclusions in plagioclase. Pyroxene also shows strong oscillatory and sector zoning.

3. **Basalt at Base Camp, entrance to Taman Bukit Tawau**
In hand specimen this appears as acidic volcanic rock. In thin section: cryptocrystalline rock with perlitic fractures. Most feldspars are alkaline feldspar, some contain glass enclaves; opaque minerals not uncommon.

4. **Andesite at Bukit Botak (Bald Hill)**
It contains plagioclase, olivine, clinopyroxene, and vesicles. Pyroxene with some plagioclase enclaves. Some show corona texture; quartz rimmed by hornblend? Also embayed quartz.

5. **Scoria at Bukit Tiger**
The rock is mainly composed of plagioclase and olivine forming megacrysts; groundmass is cryptocrystalline clinopyroxene. Flow texture shown by alignments of plagioclase laths. Embayed plagioclase also present. Vesicles filled by glass, sometimes also rimmed by pyroxene.
Rock is porphyritic with seriate texture.

6. **Lava Basalt at Bukit Tiger**
Trachytic texture. Groundmass and microphenocrysts of plagioclase. Phenocrysts of olivine and some of the plagioclase. Corona texture in olivine with hornblend rims.

7. **Lava from Baked Boundary at Bukit Tiger**
Nephelinite.
Fine-grained rock composed of pyroxene microphenocrysts in seriate textured aggregate of pyroxene-nepheline and ore mineral(s).

8. **Scoria at Gunung Bombalai**
Mostly opaque material and perhaps silica-rich material filling vesicles.

9. **Lava Basalt at Bukit Quoin**
Most minerals are plagioclase phenocrysts and groundmass. Olivine and pyroxene form microphenocrysts. Texture mainly equigranular with subhedral to euhedral crystal shapes. Many vesicles.

10. **Scoria at Bukit Quoin**
Zoned plagioclase, vesicles filled with glass or quartz; brown background of glass.

13. **Basalt at Waterfall 2, between Base Camp and Gunung Glass**
Fine-grained silicate minerals/quartz. Probably silicified by hydrothermal action.

14. **Andesite at Waterfall at Base Camp**
Trachytic texture of plagioclase laths and orthopyroxene; many vesicles.

Table 2. X-Ray Fluorescence Analysis of Sampled Volcanic Rocks

	Samples														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	89.99	95.02	53.7	56.7	53.34	52.74	56.64	62.56	53.11	52.1	87.11	52.07	85.45	51.56	50.61
Al_2O_3	2.4	1.77	15.11	17.46	14.48	16.86	17.86	16.67	19.52	15.56	1.86	16.79	2	15.83	17.52
Fe_2O_3	0.14	1.07	10.89	5.94	12.97	8.56	7.98	5.45	8.33	10.78	6.98	9.23	6.86	9.35	9.94
MgO	0.46	0.38	4.29	3.54	5.03	7.95	2.84	3.67	3.79	5.33	0.19	4.32	0.34	5.6	4.93
CaO	0.52	0.37	7.1	6.11	6.88	7.81	7.04	5.62	9.39	7.81	0.34	7.73	0.34	8.14	8.11
Na_2O	0	0.46	4.61	2.97	3.38	2.75	3.92	0	2.49	4.04	0.63	4.83	0.94	8.14	8.11
K_2O	0.16	0.12	1.15	2.46	0.84	1.89	1.58	2.65	1.3	1.3	0.12	1.65	0.097	1.55	1.91
TiO_2	1.51	0.07	1.91	0.61	2.28	0.93	1.28	0.49	0.9	1.84	1.47	1.84	1.46	1.57	1.7
P_2O_5	0.069	0	0.49	0.38	0.44	0.53	0.43	0.37	0.63	0.52	0	0.49	0	0.54	0.48
MnO	0.005	0.004	0.14	0.19	0.16	0.14	0.14	0.12	0.15	1.5	0.007	0.15	0.006	0.15	0.15
LOI	0.91	0.52	0.17	2.5	2.37	1.9	0.48	3.76	0.97	1.69	0.1	0.54	4.79	0.95	0.3

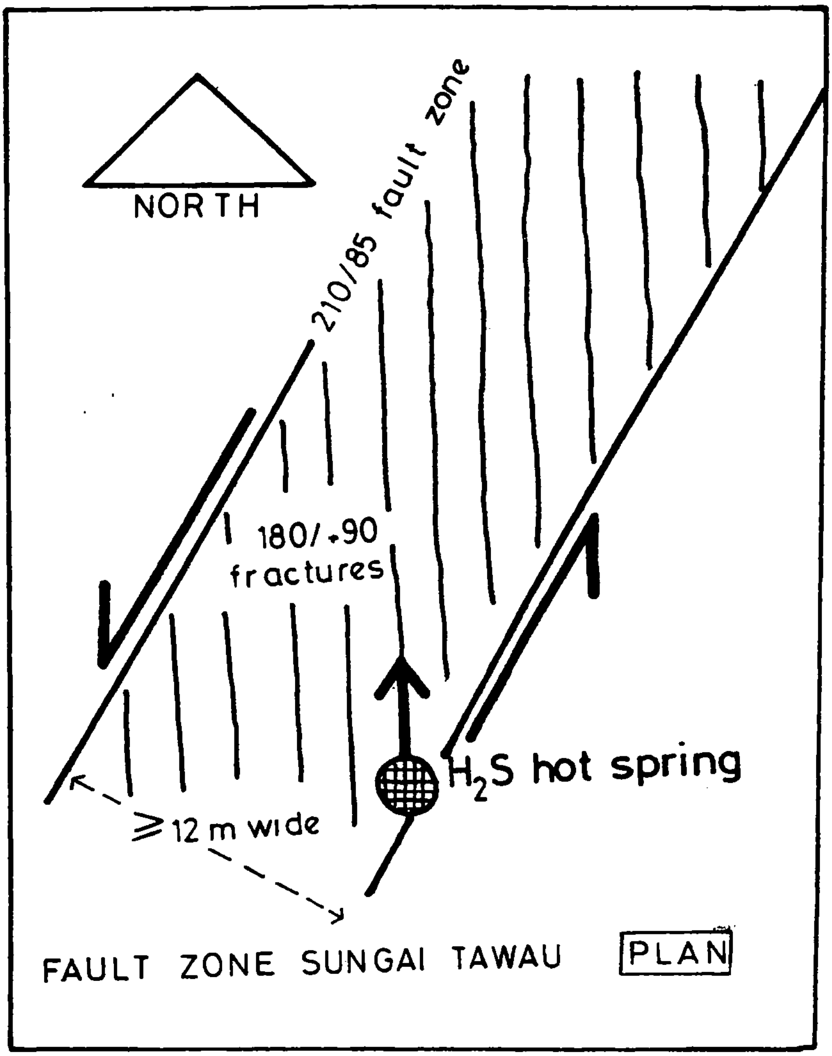

Figure 3: A wide transcurrent fault zone through ?Pliocene lava at the hot spring on Sungai Tawau, some 3 km north from the Park's entrance.

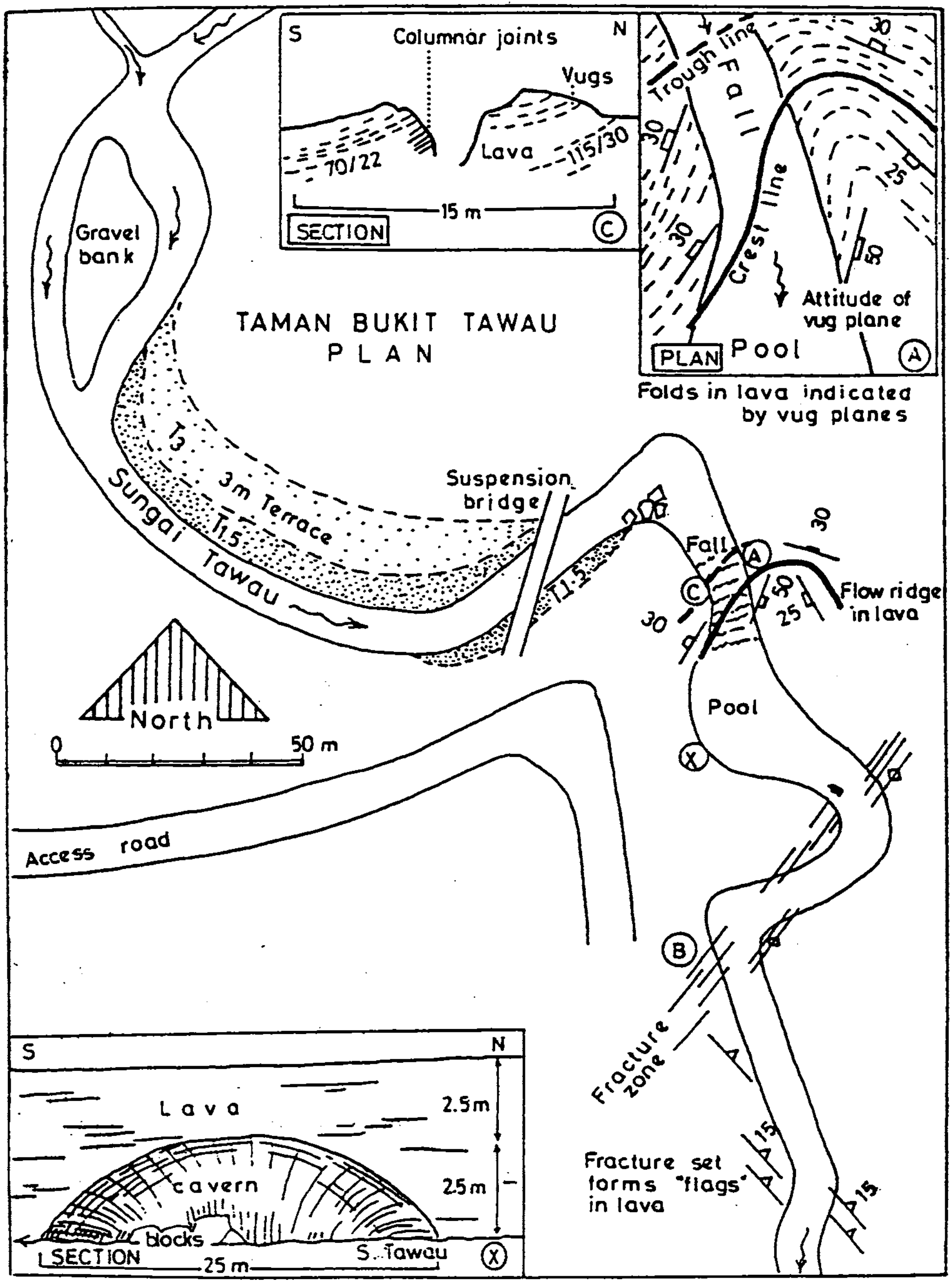

Figure 4: Plan map of the entrance to Taman Bukit Tawau. Lava flows are exposed at the water fall and in the valley downstream from it. The terraces at 1.5 m and 3 m above the river may indicate former levels of a narrow valley lake dammed by lava flows. Inset in the lower left corner shows a 5-m thick lava flow containing a cavern which may have been part of a lava tunnel. Further discussions are in the text.

empty vugs in the lava. In plan view (Figure 4, inset at upper right) the anticlinal crest line curves concavely towards SSE. These signs of ductile deformation should be interpreted as results of impeded flowage southward. Resistance to flow could have been caused by a protruding part of an earlier lava flow or by a topographic high of basement rock. All the structures in the lava mentioned earlier are certainly of non-tectonic origin and were related to flowage of the lava. Also of non-tectonic origin are the short columnar joints parallel to the vug planes (Figures 4, inset upper centre).

Downstream of the water fall is a prominent set of long, NE-striking, vertical fractures that cut across dark coloured aphanitic lava (Figure 4). On the basis of size and consistency in strike, these are major fractures that most probably resulted from tectonic stresses. In spite of being major fractures, the structure is not penetrative and appears to be restricted to certain flow units. One probable explanation is that the nonpenetrative nature is due to physical differences between lava flow units. Fractures would less likely develop in plastic or in competent material. Fracture sets in other directions but spaced widely transect the prominent fracture zone. Figure 5 is an equal-area projection of the fractures in the area shown by Figure 4. At the lower end of this figure, gently inclined parallel fractures produced slabs of the dark coloured, aphanitic lava. These fractures may represent flow planes.

Lineaments

Kirk (1962) already noted that the volcanic centres are aligned in east-west direction. His geological map shows many other lineaments. Among these are three hills of hypersthene diorite (Gemuk, Middle and Kukusan) near Tawau aligned over a 4.5-km stretch in NNW direction; the SE-striking, 21-km long alignment from G. Magdalena over G. Maria and G. Andrassy to G. Kinabutan Besar; and the E-striking, 20-km long lineament across Bukit Tiger-G. Maria-Bukit Quoin. Figure 6 shows that most volcanic centres are aligned in the sectors 340°-350°, 20° and 70°-90°.

Lineaments on aerial photographs covering the central and southern parts of Taman Bukit Tawau and neighbouring areas were mapped. A fragment of the photo-lineament map thus produced is shown in Figure 7. The photo-lineaments that are longer than circa 4 km and/or occur as distinct sets were interpreted to represent fault zones. The fault zones running across or along the axis of the Peninsula were named numerically (1-15) and alphabetically (A-M), respectively (Figure 8). The fault zones show preferred orientations within the sectors 350°-20° and 70°-80° (Figures 6 and 8). The N-S direction is especially prominent and is represented by fault zones 3, 5, 6 and 7. The east-west trending faults are shorter. Triangular facets on fault 1 and fault E indicate the downthrown sides. On fault 1 the heights of triangular facets suggest the downthrown component in the order of a few scores of metres. The alignment of several volcanic/subvolcanic centres are clearly shown on Figure 8. Figure 6 shows generally good correlation between strikes of volcano-lineaments and those of fault zones. A comparison between Figure 6 with Figure 5 indicates that only the 70° direction is represented

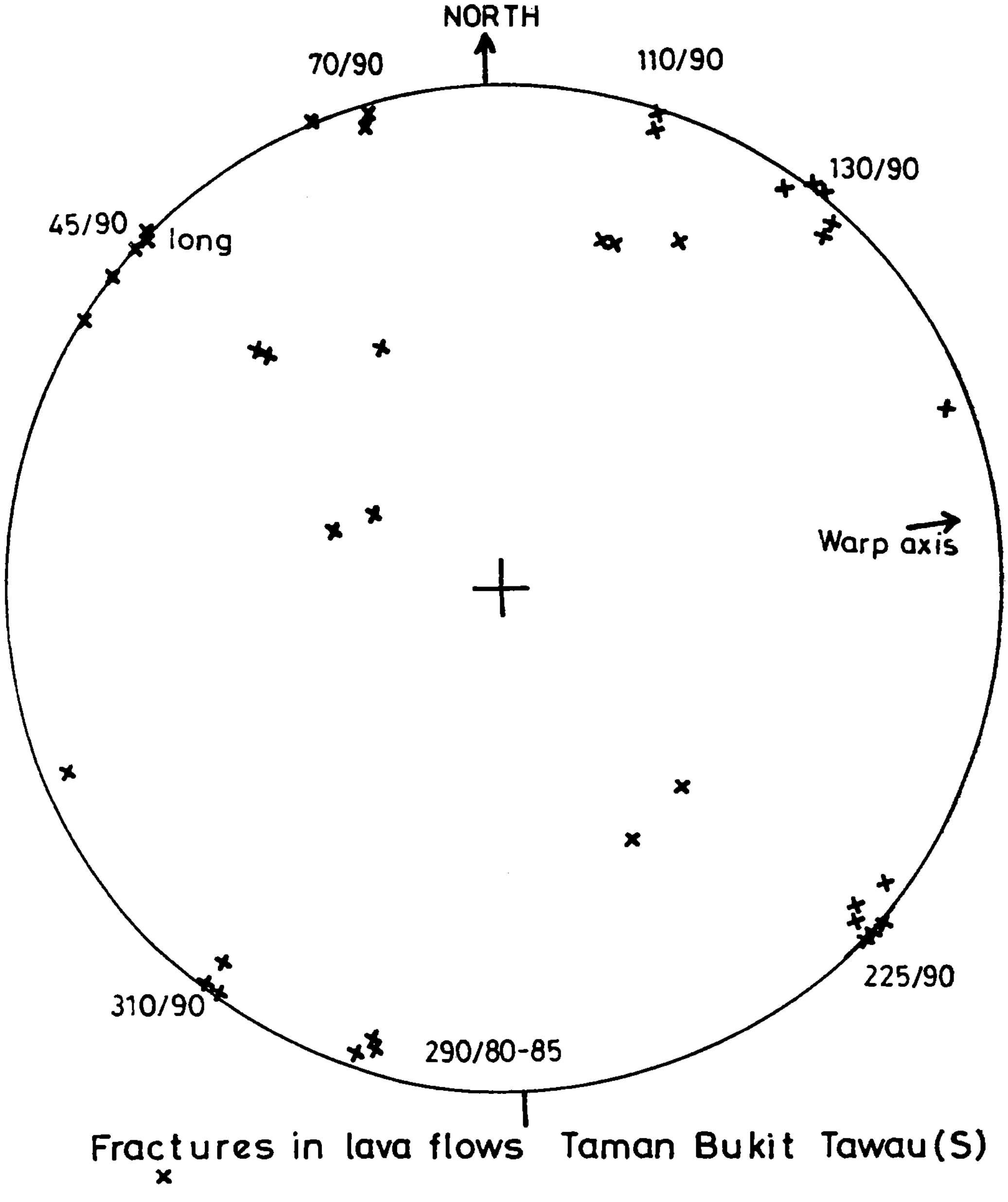

Figure 5: Lower hemisphere, equal-area plot of fractures in lava flows at the entrance to Taman Bukit Tawau (see Figure 4). The warp axis is exposed in the valley wall at the fall. The low-angle fractures may represent flow planes. The SE-SW vertical fractures form a prominent set.

Figure 6: Histogram of running averages of total lineament or total fault lengths versus their orientations.*

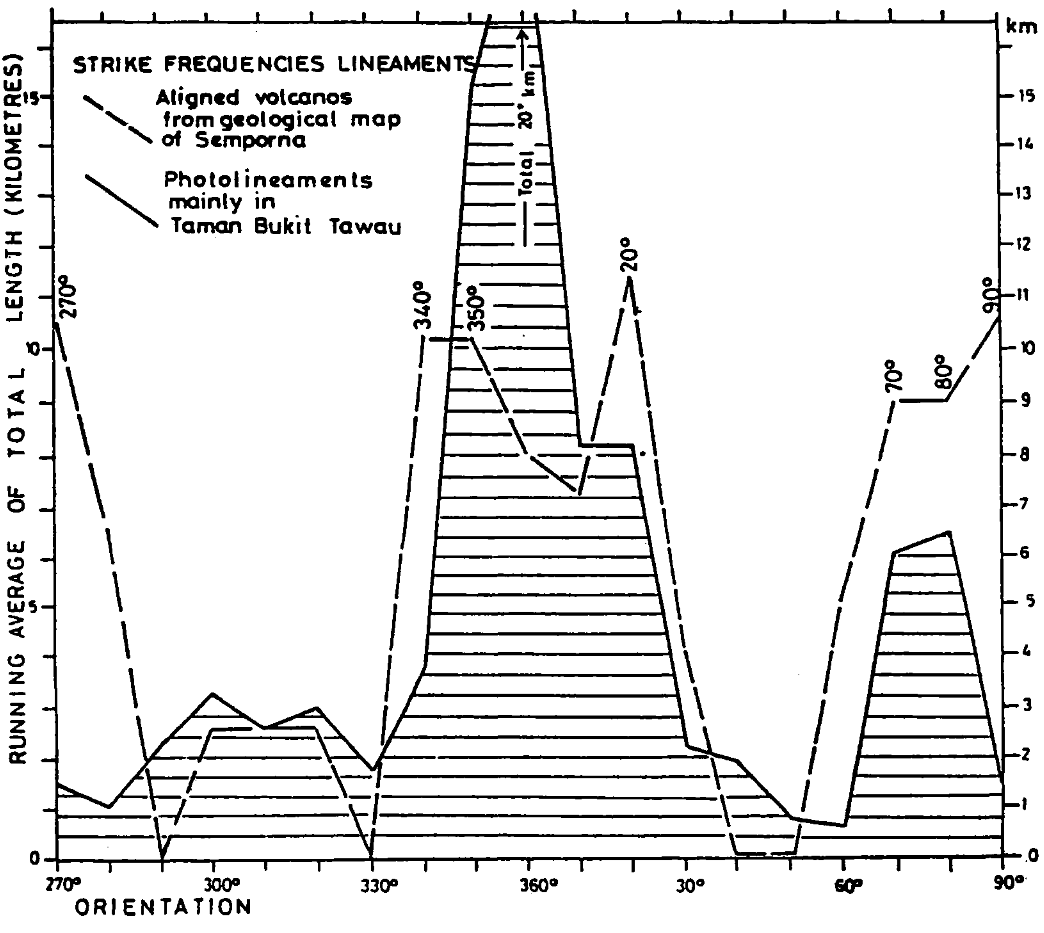

Figure 7: Fragment of photo-lineament map at an original scale of approximately 1:31,000. The bold lines are interpreted faults, the thin lines are probably major joints. Stunted trees cover the high ridges and also occur along the foot of the scarp inside the Maria crater.

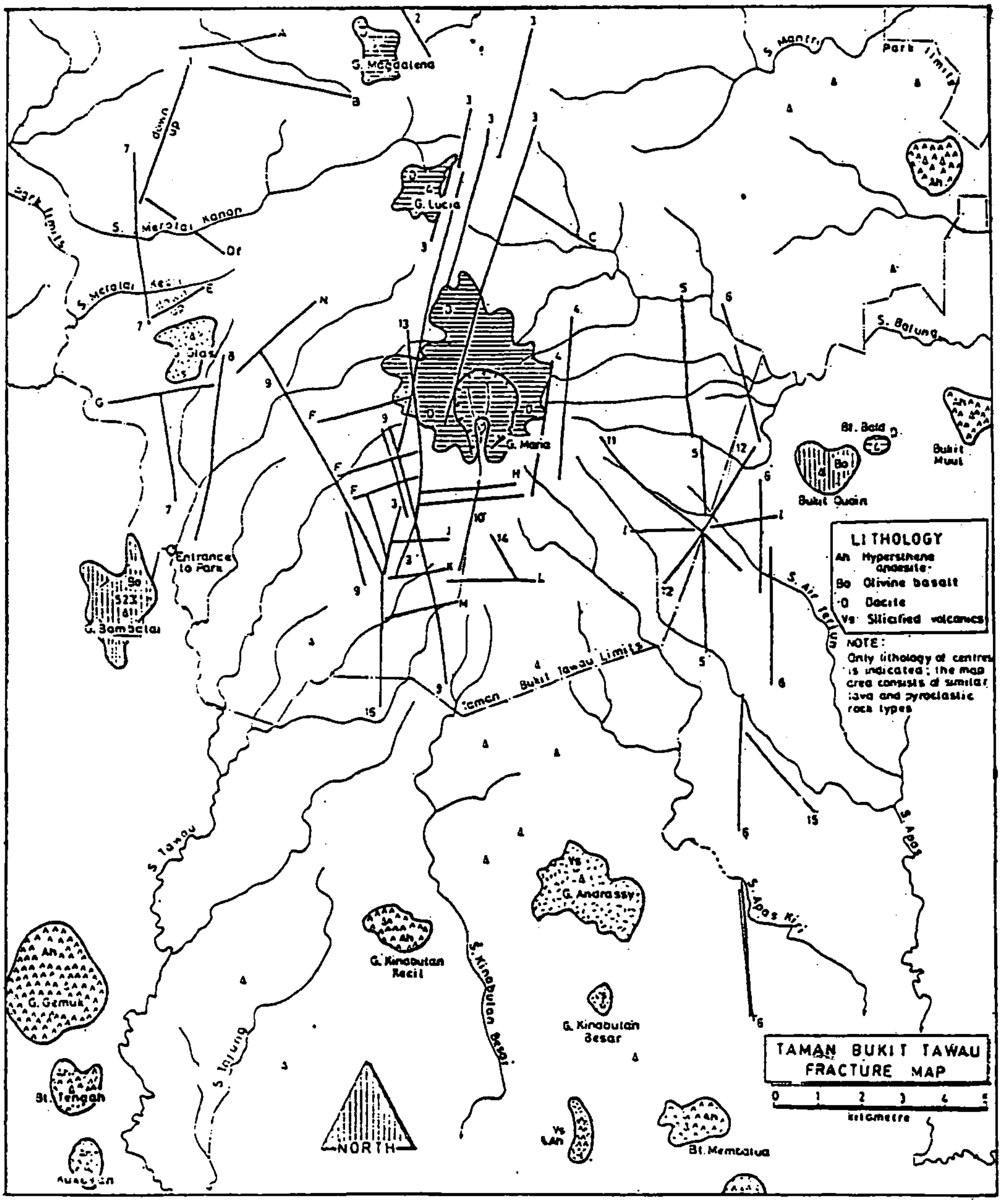

Figure 8: Fault map of Taman Bukit Tawau. The faults were interpreted from aerial photographs. Note the aligned volcanic/subvolcanic centres. Information on lithology is from Kirk (1962).

by volcano lineaments, fault zones as well as major joints. In other words, the major joints are most probably of tectonic origin. On the other hand, the prominent 45/90 fracture attitude in the lava at the entrance to Taman Bukit Tawau (Figure 4) is not or is only weakly represented in the larger structures. The other vertical fracture directions of Figure 5 are less prominently represented in the larger structures. Therefore, those fracture directions have also been influenced or caused by tectonic stresses. This means, that tectonic processes have been active until at least subrecent times. The NNE-striking transcurrent fault zone in ?Pliocene lava along Sungai Tawau (Figure 3) may be interpreted to have resulted from approximately N-S tectonic compression during or after the ?Pliocene.

CONCLUSIONS

The petrographic study generally confirms the volcanic rock types identified on the published geological maps. The only new rock type is the nephelinite of Bukit Tiger. The chemical compositions of sampled volcanic rocks show high silica content which is most probably the result of hydrothermal action. It seems probable that hydrothermal alterations have been widespread in the volcanic areas of Bukit Tawau and this suggests that the area may have mineralisation and suitable geothermal sources. The fracture map of Figure 8 defines more clearly that the major orientations are NNW, N, NNE and approximately east. The pattern of fractures/faults and the fact that the structural grain of the Peninsula is east-west, suggest the following probable relationships.

(1) The NNW and NNE orientations are those of shears and, consequently, movements along such faults should be essentially strike slip. The dihedral angle is small, that is slightly over 40 degrees. We have shown above that the 30°-striking, wide fault zone on the Tawau river (Figure 3) is probably a left lateral shear. The regional compression should have been north-south, a direction that is consistent with the youngest structural grain of the region.

(2) The north-south faults are extension directions which bisect the dihedral angle of the NNW and NNE shear directions. Movements on faults in the extension direction can be expected to be mainly normal.

(3) The east-west faults follow tension directions which also favour normal fault movements.

The lineament map of the Lucia-Maria-Magdalena complex should prove useful for delineating mineralisation targets (along certain lineament directions, at lineament intersections, in densely fractured terrain or otherwise, and/or in certain rocks types) and determining geothermal centres that may be associated with one or a number of the earlier mentioned indicators. Moreover, geothermal centres may also be associated with radial and/or polygonal lineament patterns.

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Manuscript received 9 August 1991