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VOLCANOES AND ROCKS OF ST ANDREW STRAIT, PAPUA NEW GUINEA

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ABSTRACT

When Tuluman volcano in St Andrew Strait (northern Bismarck Sea) erupted between 1953 and 1958, it produced acid rocks similar in major element chemistry to those of three other islands in the Strait - namely, Lou, Pam Lin, and Pam Mandian. These acid rocks - termed the 'TLP' series - are thought to be derivatives of a parental magma produced by melting of crust (about 25 km thick beneath St Andrew Strait). TLP rocks have agpaitic indices ranging between 0.86 and 0.96. Acid lava also makes up 3 of the 4 Fedarb Islands at the northern end of St Andrew Strait, but its composition appears to be unrelated to that of the TLP series, and its origin is uncertain.

Q-normative basalts (quartz tholeiites) make up the fourth island of the Fedarb group, and *ol*- and *hy*-normative basalts crop out on Baluan Island at the southern end of the Strait. These basalt types do not appear to be directly related to one another, although both may have been derived from parents that originated in the upper mantle. Andesitic rocks have not been found on any of the islands in St Andrew Strait.

Tuluman and the volcanoes of Lou Island form an arc which may be part of a developing (or completed) ring fracture whose centre coincides with the line between Baluan Island, the Pam Islands, and the Fedarb Islands. The ring fracture may be the result of sagging of crust above a zone of crustal melting that produced the TLP magma. It is possible that collapse could take place along this ring fracture, producing a caldera.

INTRODUCTION

In Papua New Guinea the period 1951-58 was notable for a pronounced increase in the frequency of volcanic eruptions. It was during this period, in 1951, that Mount Lamington, for example, (Fig. 1) produced classic Peléan-type activity (Taylor, 1958).

Another, less well-known, active volcano was Tuluman. It erupted between 1953 and 1958, and formed new islands among the older volcanic islands of St Andrew Strait in the northern Bismarck Sea (Figs 1, 2). Two of the new islands were still present in 1971. This paper is concerned with the St Andrew Strait volcanoes - their geology and petrology and their capacity for further eruption. A second paper (Smith & Johnson, in prep.) will be concerned with trace element geochemistry, and will extend the discussion of petrogenesis given here.

Five volcanoes along the southern margin of the Bismarck Sea were also active during 1951-58. These were: Bam (1954-58), Manam (1957-58), Long (1953-55), Langila (1954-55), and a submarine volcano northeast of Karkar Island (1951) (Fig. 1). All five centres coincide with a belt of intense seismicity that covers New Britain and the northern ranges of mainland Papua New Guinea (Johnson, Mackenzie & Smith, 1971). This seismic belt defines the southern margin of a 'South Bismarck' plate (Johnson & Molnar, 1972) or 'New Britain' plate (Curtis, 1973), whose northern boundary is a well-defined seismic zone trending east-west across the Bismarck Sea (Denham, 1969).

The northern margin of the Bismarck Sea has also been interpreted as an active plate boundary (see, for example, Johnson & Molnar, op. cit.), but here the frequency of earthquakes is much less and the seismic belt is diffuse and ill-defined. Moreover, during this century there has been only one known episode of volcanic activity that might have been related to the northern plate boundary. This was the series of eruptions from Tuluman volcano in 1953-58.

The magma of Tuluman volcano was highly siliceous (69-71 wt percent silica). It formed pumice deposits and, in its later stages, viscous lava flows which solidified above sea level as flow-banded pitchstone and obsidian. The volcanic rocks of Tuluman are therefore of considerable interest, not only because the eruptive period that produced them was a singular event, but because they are much more silica-rich than any of the rocks produced by the southern Bismarck Sea volcanoes during 1951-58.

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DISTRIBUTION AND AGE OF THE ISLANDS

St Andrew Strait is about 45 km south-southeast of Lorengau on Manus Island (Fig. 1). Most of the islands border the south-eastern side of the Strait where they define a prominent, 30 km-long chain bearing about 045° (Fig. 2). All the islands are volcanic except St Andrew and San Miguel Islands, which are coral but which probably rest on volcanic submarine foundations. On the northwestern side of the Strait are Lou (pronounced 'low') Island and the two islands formed in 1953-58 - Tuluman Island and a nearby unnamed islet (Fig. 2); these islands form an arc whose centre of curvature coincides with the line of islands on the southeastern side of the Strait (see Fig. 9 and later discussion).

No isotopic ages or fossil dates are available for the St Andrew Strait volcanoes, but the absence of deep dissection suggests that their subaerial parts, at least, are no older than Quaternary, and that probably most are Late Pleistocene to Recent.

LOU ISLAND

The rocks of Lou Island appear to be exclusively high-silica types. They were produced from 12 principal eruptive centres, numbered 1 to 12 in Figure 6, which form an arcuate chain about 12 km long.

The two largest volcanoes - centres 1 and 3 - are composite cones, both consisting of pumice deposits and lobate flow-banded lava flows similar to those on Tuluman Island. Each volcano has a summit crater filled by a lava flow; at centre 1 the lava spilled over the crater rim. Centres 2, 4, 5, and 6 are comparatively small volcanoes, two of which have remnants of summit craters. Centre 7 forms the highest point on Lou (270 m above sea level), and is the third-largest volcano on the island. It appears to consist mainly of pumiceous pyroclastic deposits, but lava flows are thought to cap ridges on the northern flank. Centres 9, 10, and 11 all appear to be single lava flows or coulees. The southern tip of Lou Island is made up of the remnants of a small pyroclastic cone, centre 12 (Fig. 6).

A prominent thermal area of bubbling mud pools and fumaroles is present in the low-lying area south of centre 5, and a warm spring (40°C) emerges at one point along the north coast (Fig. 6).

Although the evidence is ambiguous, it appears that Lou Island has evolved by eruptions from centres which migrated southwestwards, or anticlockwise, along an arcuate fracture. Centres 1 and 3 in the north are the largest and most complex of the volcanoes, suggesting that they were active longer than those farther south. Centres 7 and 8 are smaller composite cones, and centres 9 to 12 in the extreme south each appear to have formed during single eruptions. If this decrease in degree of complexity is taken to indicate a southwestward decrease in age of the first eruptions from any one volcano, then activity can be said to have migrated southwestwards, even though eruptions may have continued at the northern volcanoes while new vents were being opened in the southwest. Support for this interpretation of southwestward migration is given by the Tuluman eruptions of 1953-58, which represent new activity from a thirteenth principal centre off the southwestern end of the Lou volcanic chain (Fig. 2).

TULUMAN AND CONE-3 ISLANDS

The 1953-58 Tuluman eruptions were a complex series of submarine and subaerial explosive and effusive events. The eruptions up to August 1955 were described by Reynolds & Best (1957; see also Taylor, 1956, and Fisher, 1957), but an account of the later events when the lava flows of Tuluman Island were extruded (Fig. 4), is found only in an unpublished report by Reynolds (1958), produced by the Bureau of Mineral Resources (BMR), Canberra.

Reynolds & Best (op. cit.) and Reynolds (op. cit.) identified eight principal eruptive centres over Tuluman volcano, and named them cones 1 to 6, 7A, and 7B, in order of initial activity. At some centres islands were built above sea level, but many of these were subsequently destroyed by marine erosion or volcanic activity, or by both.

Tuluman Island, however, remains (Figs. 3 and 5), It was built up by eruptions mainly from cones 2, 4, and 7B. Cones 2 and 4 produced bedded pumiceous deposits and at least one lava flow, which formed the southwestern half of Tuluman when the area was visited in 1971. In late 1956 to early 1957, cone 7B gave rise to lava flows which make up the northeastern half of the island (Figs. 3, 4, and 5). Cone 3 also produced an island, but its only remnant is the islet a few hundred metres northwest of Tuluman (Figs. 2 and 5). This islet will be referred to as 'cone-3 Island'.

In July 1971 the maximum width of Tuluman Island was about 520 m from west-southwest to east-northeast, and its highest point, in the south, was about 23 m above sea level. The pumice deposits in the southwest were exposed in coastal cliffs which, as a result of marine erosion, had receded up to 160 m from the position of the shoreline in 1962 reported by F.E. Decker (unpublished BMR data, 1962). A zone of subsidence, or 'breach' (Reynolds, 1958), which formed in the clastic deposits in late 1956 to early 1957 (Figs. 3 and 5) was still present. The lava flows, consisting of aphyric, flow-banded pitchstone and obsidian, were also more or less still intact. In 1971, all that remained of cone-3 Island was a near-horizontal remnant of a pitchstone lava flow, about 60 m in diameter and 3-4 m high, covered by a discontinuous layer of pumice clasts. Neither thermal emission points nor basic or intermediate rocks were found on either island, and sporadic grass tufts and low shrubs were the only prominent types of vegetation.

BALUAN AND PAM ISLANDS

Baluan Island is the southernmost and largest single volcano in St Andrew Strait (Fig. 2). It is a simple cone, rising to 243 m above sea level, at whose summit is a 1 km-wide central crater (Fig. 7). In contrast to Lou and Tuluman Islands, acid rocks seem to be absent from Baluan; only basalts have been found there. However, the outer flanks of Baluan show very little dissection, the island is largely covered by rainforest, and rock outcrops are common only at the coast. Consequently, only a small part of the volcano has been sampled.

Several satellite centres are present on and around Baluan Island, the most prominent of which are: in the north, a crescentic remnant of a pyroclastic cone and crater, most of which has been eroded away by the sea; and off the northern coast, two islands which are palagonitic pyroclastic cones (see Fig. 7 for other volcanic features of the island). Thermal emission points are found on the western and northwestern coasts of Baluan, and near a satellite cone (e) southwest of the summit crater.

Pam Mandian and Pam Lin are volcanic islands less than 750 m in diameter, 5 and 7 km respectively northeast of Baluan Island (Fig. 2). Both islands appear to be single lava extrusions, similar in form and composition to some of those on Lou Island. An outlier of acid lava forms a small islet a few hundred metres northeast of Pam Lin.

FEDARB ISLANDS

At the northern end of St Andrew Strait are the four Fedarb Islands (Fig. 2). The three smallest islands - Chokua, Malapin, and Small Sivisa (Fig. 8) - are flat-topped, and consist of silica-rich, columnar-jointed lavas that appear to be parts of the same flow. On Chokua Island the flow dips northwest, but on Malapin and Small Sivisa it dips south.

Sivisa, in the east, is the largest island of the Fedarb group. It has a surface that dips between east-northeast and east-southeast. On its southwestern side a cliff 35 m high, which appears to be the eastern remnant of a crater or caldera wall, reveals a stratified succession of basaltic lava flows, scoria, and lapilli. Parts of a raised coral reef form islets close to the eastern shore of Sivisa (Fig. 8).

The geological relation between Sivisa and the other Fedarb Islands is uncertain, but the most likely interpretation is that Sivisa is the eastern remnant of an older basaltic volcano in whose crater (or caldera) the acid lava flow ponded. The central area was probably domed and severely modified by collapse and marine erosion, and only remnants of the original volcano were preserved above sea level.

The surfaces of all four islands are covered by a discontinuous layer of unsorted, unbedded, volcanic rudaceous material. This has a maximum thickness of about 5 m, and contains blocks up to 1.5 m across. The material may have been deposited by lahars, perhaps during submarine volcanic eruptions that accompanied the doming and collapse of the volcano's central area.

EVIDENCE FOR A NASCENT CALDERA

Because Lou and Tuluman Islands define an active volcanic arc whose centre of curvature falls on the line between Baluan Island and the Fedarb Islands (Fig. 9), there are implications regarding future volcanic events in St Andrew Strait.

It is suggested that the volcanoes of Lou and Tuluman represent magmas fed from part of a nascent ring fault, 16 km in diameter and centred on the Baluan-Fedarb line (Fig. 9). As discussed earlier, volcanism may have migrated southwestwards along the Lou volcanic chain, which suggests that a ring fracture is developing by anticlockwise propogation. Future eruptions in the Strait could therefore take place at new sites on the southern extension of the Lou-Tuluman arc. In addition, it is visualized that if the ring fracture developed fully through 360° of arc, collapse could take place along the completed circle (Fig. 9). The Pam and St Andrew Islands would subside, a caldera 16 km wide would form, and the Lou Island volcanoes would be truncated by the caldera escarpment - in the same way, for example, that cumulodomes on the rim of Crater Lake caldera, Oregon, were cut by cauldron subsidence (Williams, 1942).

Lou and Tuluman Islands show that the ring fracture covers only 92 degrees of arc (Fig. 9). However, to the writers' knowledge there are no detailed bathymetric maps of the St Andrew Strait area, and it is possible that submarine volcanoes are present on other parts of the postulated ring fracture. These would indicate that the fracture is developed to a greater extent than is shown above sea level. If eruptions again take place in St Andrew Strait, attention should therefore be directed not only to the immediate site of eruption but to other parts of the nascent ring fault (Fig. 9), where submarine volcanoes might also be active. If the ring fracture is, or remains, incomplete, cauldron collapse cannot be regarded as an imminent, or possible, event. But if a complete ring fracture was recognized, St Andrew Strait should be considered a potential site for a caldera whose formation could have serious effects on life and property.

These interpretations are based entirely upon the evidence presented by the islands of St Andrew Strait. Alternative explanations may have to be adopted if additional data became available on the bathymetry and submarine geology of the Strait and its surrounds.

INTRODUCTORY PETROLOGY

The rocks of St Andrew Strait are of two principal types: (1) basalts, and (2) acid rocks whose silica range straddles the boundary between dacite and rhyolite, which is here drawn at 69 wt percent silica. Twenty-eight rocks have been chemically analysed for major oxides. They show that the difference in silica content between the most siliceous basalt and the most basic acid rock is 16.15 wt percent. No andesites have been found in St Andrew Strait, and the distribution of volcanic rocks therefore appears to be strongly bimodal.

Two types of basalt and two types of acid rock are present in St Andrew Strait. The basalts are either quartz-normative, or hypersthene- and olivine-normative. The two types of acid rocks are (1) dacites, showing high Na_2O/K_2O ratios, and (2) alkali-rich rhyolites, which are more voluminous than the dacites and which show comparatively low Na_2O/K_2O ratios.

The rhyolites make up Tuluman and cone-3 Islands (the Tuluman group), Lou Island, and Pam Lin and Pam Mandian Islands (the Pam group). For convenience, these rocks will be referred to as the 'TLP series'. TLP rhyolites are absent from Baluan Island and the Fedarb Islands, the hy- and ol-normative basalts are present only on Baluan Island, and the dacites and Q-normative basalts are found only on the Fedarb Islands. These details are summarized in Table 1.

Chemical analyses and CIPW norms of 7 of the 28 rocks are given in Table 2. Copies of the other 21 analyses are available on request from the authors, or from the Director, Bureau of Mineral Resources, Canberra. The principal chemical features of all 28 rocks are illustrated in the accompanying variation diagrams, for which weight and molecular percentages have been recalculated volatile-free. In the basalts, the ferric/ferrous ratio is low, and no adjustments for the oxidation-state of iron have been made.

RHYOLITES OF THE 'TLP SERIES'

Petrography and classification

In hand specimen, the TLP rhyolites are aphyric obsidian, pitchstone, pumice, and fine-grained lava. Phenocrysts are rare, but in thin section crystals larger than normal groundmass size are observed in many crystalline rocks. These crystals are zoned plagioclase, clinopyroxene, iron-titanium oxides, and, less commonly, pleochroic orthopyroxene and amphibole. In a few rocks, particularly in some from Lou Island, phenocrysts are visible in hand-specimen. These are mainly sodic plagioclase, but rare pyroxene phenocrysts (mostly clinopyroxene) are also seen. Without exception, these phenocrysts constitute no more than 2 or 3 percent (volume) of the porphyritic rocks examined; in most rocks, the amount is less than 1 percent. The groundmass phases of the TLP rocks are glass, plagioclase, iron-titanium oxides, alkali feldspar, high-temperature polymorphs of silica (cristobalite and tridymite), pyroxene, and - probably - rare apatite. This phenocryst and groundmass mineralogy is typical of that shown by many non-peralkaline acid rocks.

The alkali-content is lower in the TLP rocks than in peralkaline rocks, such as those from the D'Entrecasteaux Islands (Papua; Fig. 1) and Mayor Island (New Zealand) (points B and C respectively in Fig. 10). Moreover, as the TLP rocks are comparatively high in alumina (between 13 and 14.5 wt percent) their agpaitic indices (atomic ratio Na + K / Al, or molecular ratio $Na_2O + K_2O / Al_2O_3$) are correspondingly lower than those of peralkaline rocks. Agpaitic indices for the TLP series range between 0.86 and 0.96, indicating that although the series is not peralkaline some of its members are nearly so.

Acid rocks are found elsewhere among the Quaternary volcanoes of the Bismarck Sea area, but to the writers' knowledge none are as high in total-alkali content as those of the TLP series. This is illustrated in Figure 10 where the TLP rocks are shown to be more alkalic than, for example, the rhyolite obsidian from Talasea, New Britain (Fig. 1; point A in Fig. 10).

Crystal fractionation

Plagioclase fractionation appears to be capable of accounting for the chemical variation within the TLP series. This is illustrated in Figure 11 which shows two of the ternary faces bounding the quaternary system quartz-albite-orthoclase-anorthite. These four components account for at least 90 wt percent of the constituents in the acid rocks of St Andrew Strait. Descriptions of the phase relations in this quaternary system were given by Carmichael (1963), James & Hamilton (1969), and others.

In the ternary system Q-Ab-Or (Fig. 11, upper), the TLP rocks form a short trend in the soda-rich part of the feldspar field, directed towards the ternary minima at 500 and 1000 kg/cm^2 water vapour pressure. The Pam rocks plot closest to the minima; those of Tuluman are nearest the Ab corner. In the system Ab-Or-An (Fig. 11, lower) the TLP rocks fall in the one-feldspar field, and define a trend whose direction is shown to be controlled by separation of sodic plagioclase. As in the Q-Ab-Or diagram, the Pam rocks are shown to be the most fractionated members of the TLP group: they lie closer to the two-feldspar/quartz boundary curve at 1000 kg/cm^2 than do the other rocks. The Pam rocks plot on the two-feldspar boundary curve at 5000 kg/cm^2, but there is no evidence that they crystallized two feldspars at this pressure.

Although plagioclase fractionation was probably the major cause of chemical variation within the TLP series, it was not the only cause. As shown in Figure 12, the rocks from each of the Tuluman group, Lou Island, and the Pam group have compositions successively depleted in total-iron and, to a lesser extent, in MgO. This implies fractionation of ferromagnesian minerals - probably iron-titanium oxides and pyroxene or amphibole, or both (separation of iron-titanium oxides was probably dominant because, in addition to the decrease in iron content, there is a pronounced decrease in TiO_2; see samples 4-7 in Table 2). Because the changes in total-iron and MgO are small compared to those shown by the normative components Q, Ab, Or, and An, it is concluded that separation of ferromagnesian minerals played only a minor role in the development of this rock series.

The rocks of St Andrew Strait have also been plotted in the quaternary system mol. SiO_2-Al_2O_3-K_2O-Na_2O (Figs. 13, 14, and 15). In addition to illustrating the features normally shown on a weight percent basis in the normative tetrahedron Q-Ab-Or-An (Fig. 11), this quaternary system has the advantage of clearly illustrating changes in the ratio of alkalis to alumina. In particular it illustrates the trends of rocks towards peralkaline compositions, and shows variations in composition within the peralkaline field (Bailey & Macdonald, 1969). This is especially relevant to the rocks of the TLP series, as they have high agpaitic indices and may therefore have the potential to produce residual liquids of peralkaline composition. This possibility is considered in a later section. Here, using the method described by Bailey & Macdonald (1969), and developed by Gill (1972), the position of the TLP acid rocks within the SiO_2-Al_2O_3-Na_2O-K_2O system is described.

Figure 13 shows the relevant portion of the <u>ternary</u> system mol. SiO_2-Al_2O_3-Na_2O+K_2O. The TLP rocks plot close to, but on the aluminous side of, the alkali feldspar-silica join; i.e. they have high agpaitic indices, but are not quite peralkaline. In Figure 13, the projections of plagioclase compositions fall along the line AN-AF. In the central diagram of Figure 13, the trend of the TLP rocks coincides approximately with the straight line drawn from a point on AN-AF representing the molecular plagioclase composition $An_{25}(Ab,Or)_{75}$. This line is shown extrapolated to an arbitrary point C in the field of peralkaline compositions. Ideal separation of a plagioclase containing about 25 mol. percent anorthite (oligoclase) would therefore give rise to the trend shown by the TLP rocks.

The stippled plane in Figure 14 represents the surface which, projected into the ternary system of Figure 13 traces out the tie-line between An_{25} and C. It is the surface containing all feldspars of An_{25} composition, and it is the plane that best illustrates the trend of the TLP rocks within the quaternary system. The plane is a quadrilateral whose limits are shown in Figure 15. The rocks of the TLP series form a curved trend in Figure 15, shown schematically by the dashed line in the left-hand diagram. Whereas the central diagram of Figure 13 indicates that the 'average' composition of the feldspars separating from the TLP magma was oligoclase (An_{25}), the curvature of the dashed trend lines in both Figures 13 (right) and 15 (left) show that the fractionating feldspars changed composition, and became successively depleted in anorthite-content and progressively lower in Ab/Or.

Other variations within the TLP series

Each of the variation diagrams in Figures 10, 11, 12, 13, and 15 (see also Fig. 17) demonstrates that the rocks of the Pam Islands are more fractionated than those of Lou Island, and that the rocks of the Tuluman group are the least fractionated of the entire TLP series. Closer examination of the chemical analyses shows that there are also consistent, though generally more subtle, differences in degree of fractionation within each of the Lou and Tuluman groups. This is illustrated in Figure 16 where four standard parameters, each of which may be taken as a measure of degree of fractionation, are shown for the 19 analysed rocks of the TLP series.

The eleven rocks of Lou Island, from 5 of the 12 eruptive centres, show a general decrease in degree of fractionation between centres 3 and 11, and an increase between centres 1 and 3 (compare Figs. 16 and 6). If, as suggested earlier, the Lou Island volcanoes decrease in age between centres 1 and 12, the data of Figure 16 demonstrate that the magmas erupted from centres 1-3 became more fractionated as eruptions proceeded, and that later magmas, erupted from centres 7-12, became progressively less fractionated. This trend of decreasing degree of fractionation between centres 3 and 12 is continued by the rocks of the Tuluman group (Fig. 16).

The analysed Tuluman rocks are: three samples from cones 2, 3, and 4, formed during the earlier part of the 1953-58 eruptive period; and two from the later lava flows erupted in 1956-57 from cone 7. As shown in Figure 16, the two younger samples are less fractionated than the three older ones, demonstrating that a slight, but definite, decrease in degree of fractionation took place during the course of the 1953-58 eruptions.

Generation of peralkaline liquids

When extrapolated to higher silica values, the trends of the TLP rocks in Figures 13 and 15 reach the field of peralkaline compositions.

The possibility of deriving residual peralkaline liquids from magmas of TLP composition appears to depend largely, if not entirely, on whether the melt contains sufficient calcium. Ternary feldspars, in which mol. $Na_2O+K_2O <$ mol. Al_2O_3, could continue to separate from the TLP magma only so long as calcium is present. This separation would increase the alkalis/alumina ratio of the residual liquid to a stage where mol. $Na_2O+K_2O \geqslant$ mol. Al_2O_3. Peralkaline compositions would therefore be generated by the 'plagioclase effect' (Bowen, 1945). This possibility may be examined by reference to Figure 17, a plot of mol. CaO <u>versus</u> agpaitic index.

In Figure 17, the rocks of the TLP series define a zone of negative slope: rocks showing the highest agpaitic indices have the lowest CaO values, and <u>vice versa</u>. Extrapolation of this zone to the horizontal axis demonstrates that if <u>all</u> the calcium were removed from the magma by ideal fractionation of ternary feldspar a residual liquid showing an agpaitic index of 1 $\pm$ about 0.025 could be generated. It appears, however, there is no mechanism involving feldspar fractionation that could produce a strongly peralkaline liquid from the TLP magma - that is, one showing an agpaitic index appreciably greater than 1.

In fact it is unlikely that liquids showing an agpaitic index of 1 would be generated. This is because, as fractionation proceeds, residual liquids will reach the two-feldspar boundary surface in the system <u>Q-Ab-Or-An</u> (Fig. 11), and alkali feldspar will co-precipitate with the plagioclase. The separation of <u>both</u> kinds of feldspar would probably produce a trend which becomes more or less parallel to the alkali feldspar-silica join (Fig. 13), but which does not quite reach it.

<u>Partial melting</u>

An important implication of Figure 17 is that the composition of the parent magma that gave rise to the TLP series appears to have been buffered with respect to the molecular proportions of CaO, Al_2O_3, and

Na_2O+K_2O. Figure 17 shows that when ternary feldspar fractionation has removed the last remaining calcium from the melt, the residual liquid contains more or less equal molecular proportions of alumina and total-alkalis. It appears to be difficult to account for such a magma by fractionation of basalt. This is because minerals containing lime, alumina, and alkalis can fractionate in various proportions, at various times, and with different compositions, during crystallization of basic and intermediate magmas. It would seem, therefore that their separation from the magma would easily disturb any simple proportionate relation between CaO, Al_2O_3, and Na_2O+K_2O.

A favoured alternative explanation is that the parental magma of the TLP series is a crustal melt. This interpretation accounts for the buffering effect, for the abundance of acid material in St Andrew Strait, and for the strongly bimodal distribution of rock types. It is also consistent with geophysical data from the area.

Using the unpublished Bouguer gravity results of a BMR marine geophysical survey and seismically determined crustal thicknesses for the New Britain region (Finlayson et al., 1972), J.B. Willcox (pers. comm., 1973) has computed crustal thicknesses beneath the Bismarck Sea, using a simple slab model. An average crustal density of 2.85 g/cm^3 was computed for the New Britain area by Finlayson & Cull (1973) from the relation between Bouguer anomalies and seismically determined crustal thicknesses. This value was assumed to apply to the Bismarck Sea, although seismic velocities in the New Britain region (Finlayson et al., op. cit.) indicated that parts of the crust may be as dense as 3.0 g/cm^3. Beneath St Andrew Strait the thickness of crust is thought to be about 25 kilometres.

It is proposed that partial, or possibly near-complete, melting of crustal rocks of intermediate composition beneath St Andrew Strait has given rise to a salic parental TLP magma. This magma would contain sufficient calcium and sodium to plot in the plagioclase volume in the quaternary system Q-Ab-Or-An (Fig. 11), and under crustal P/T conditions it would fractionate plagioclase, giving rise to the TLP series. If all the calcium was removed by feldspar fractionation, a residual liquid consisting mainly of normative alkali feldspar and quartz would form. It would approximate to a quaternary minimum composition in which mol. Na_2O+K_2O = mol. Al_2O_3.

The concepts of crustal anatexis and of crustal contamination of mantle-derived magmas have been tested using strontium isotope data (for example, Faure & Hurley, 1963). In a recent reconnaissance examination of Sr^{87}/Sr^{86} ratios of rocks from Papua New Guinea volcanoes, Page & Johnson (in prep.) showed that two TLP rocks had initial ratios of 0.7043 and 0.7044. These values are the highest of 37 available isotopic ratios of rocks from volcanoes in the Bismarck Sea area (including the volcanic islands northeast of New Ireland; Fig. 1). Both values are higher than those of many rocks considered to have originated in the upper mantle (compare, for example, 0.702-0.703 for ocean floor basalts; Peterman et al., 1970). On the other hand, they are lower than the Sr^{87}/Sr^{86} ratios of acid lavas thought to have formed or to have been modified by melting of continental crust (for example 0.7045-0.7068; Ewart & Stipp, 1968). The isotopic values for the two TLP rocks appear to be intermediate between these extremes, which is perhaps not unexpected in view of the fact that the Bismarck Sea crust is neither oceanic nor truly continental. At this stage, however, it is considered that interpretation of these preliminary isotopic results should be postponed until additional isotopic data are obtained for other rocks - especially basaltic ones - in St Andrew Strait. If the basaltic rocks are mantle-derived (see following sections) and the TLP rocks are the derivatives of the partial melt of old crustal material, marked differences in Sr^{87}/Sr^{86} values can be expected.

BASALTS OF BALUAN ISLAND

The Baluan Island basalts contain the following phenocryst assemblages: (1) plagioclase (alone), (2) plagioclase + olivine ± rare clinopyroxene, (3) plagioclase + olivine + clinopyroxene. Modal analyses of six rocks representing each of these assemblage types are given in Table 3. The assemblages indicate that the order of phenocryst crystallisation was plagioclase (An_{65-83}), followed by olivine, followed closely by clinopyroxene.

Plagioclase, clinopyroxene, olivine, and iron-titanium oxides are the principal groundmass minerals. Groundmass orthopyroxene and phenocrysts of orthopyroxene and iron-titanium oxides appear to be absent. Although the generally fine grainsize of the groundmass prevents recognition of pigeonite by normal optical methods (low 2V), the pyroxene is invariably augite where clear interference figures are obtained. The groundmass pyroxenes of one Baluan basalt have also been examined with the electron microprobe and no calcium-poor pyroxenes (pigeonite or orthopyroxene) were found (R.N. England, pers. comm., 1973). The olivine phenocrysts have no coronas of pyroxene, and olivine is present in the groundmass. These petrographic features are characteristic of alkali basalts.

Five analysed Baluan basalts all show <u>hy</u> and <u>ol</u> in the CIPW norm (see sample 1, Table 2). In the iron-free 'basalt tetrahedron' of Yoder & Tilley (1962), therefore, the rocks fall within the 'olivine tholeiite' volume. Some of them lie very close indeed to the critical plane of silica undersaturation (see Fig. 18, where the Ol-Cpx-Pl plane can be taken as the equivalent of this critical plane). In addition, as shown in Figure 10, the rocks plot below, but close to, the line of MacDonald & Katsura (1964) which separates an upper field of Hawaiian alkali basalts from a lower one of Hawaiian tholeiites. Although on these strictly chemical grounds the Baluan basalts are tholeiites, this term seems inappropriate because their mineral assemblages are not obviously tholeiitic. Instead, the nomenclature of Coombs (1963) is adopted, and the five Baluan rocks are termed 'mildly alkaline and transitional basalts' (Table 1).

Titania contents range between 1.11 and 1.64 wt percent. These values are consistent with those for basalts from other circumoceanic areas, most of which, according to Chayes (1965), contain less than 1.75 wt percent TiO_2. Alumina contents are extremely variable. They appear to be directly related to the abundance of plagioclase phenocrysts (Table 3) suggesting that the high Al_2O_3 values are due to plagioclase accumulation (see later). Because of the low MgO values, the ratios 100 Mg/(Mg+Fe^{2+}) (where Fe^{2+} is the atomic ferrous-iron content of the rock analysis on a volatile-free basis) are 60, or less (52-60). It therefore seems unlikely that the Baluan basalts could have been in equilibrium with the Mg-rich olivine of upper mantle peridotite under anhydrous or low PH_2O conditions (Green 1971, and the accompanying discussion by O'Hara and by Green). If the Baluan basalts originated by partial melting in the upper mantle under these conditions, they must have fractionated on the way to the surface to produce compositions low in 100 Mg/(Mg+Fe^{2+}).

Because of the highly porphyritic nature of some of the Baluan rocks (Table 3), it is possible that low-pressure crystal fractionation has contributed to the differences in chemistry between the five analysed basalts. This possibility has been examined by plotting the rocks in the normative pseudo-quaternary system Olivine-Clinopyroxene-Plagioclase-Quartz, following the method adopted by Cox & Bell (1972; after O'Hara 1965, Clarke 1970, and others). Figure 18 shows the Baluan basalt compositions projected from each of the tetrahedral corners onto the opposite faces of the tetrahedron. Also shown are 'natural cotectics' ('natural phase boundaries', which are pseudounivariant equilibria) drawn from the results of dry melting experiments at 1 atmosphere on basalts by Tilley et al. (details are given in the caption of Fig. 18).

The Baluan rocks form a well-defined trend in each of the four projections (Fig. 18a,b,c,d). Two samples, 38 and 42, have compositions which are more-or-less 'cotectic', but which plot just within the plagioclase volume. The three other samples also lie within the plagioclase volume, and define a curved trend from the 'cotectic' compositions. This trend is consistent with low-pressure fractionation of the phenocryst minerals which are present in these basalts.

As shown earlier, the order of phenocryst crystallization is plagioclase-olivine-clinopyroxene. This is also the order of crystallization of all liquids which plot on the Baluan trend in Figure 18. In Figure 18d, the rocks lie in the Pl+liquid field. They therefore crystallize plagioclase first, and follow a course towards the Ol+liquid field where olivine precipitates. Liquids move down the Pl+Ol+liquid 'cotectic' and reach the Cpx+liquid field where plagioclase, olivine, and clinopyroxene crystallize together.

The 'cotectic' samples 38 and 42 in Figure 18 have accumulated no phenocrysts; they are virtually aphyric (Table 3). On the other hand, samples 39 and 45 are extremely rich in plagioclase phenocrysts, and also contain some olivine and clinopyroxene; sample 43 contains less plagioclase and no clinopyroxene (Table 3). The trend away from the 'cotectic' compositions in Figure 18 is therefore consistent with a low-pressure crystal fractionation process involving accumulation of plagioclase phenocrysts, and relative separation of some olivine and possibly (but to a lesser extent) clinopyroxene.

The plagioclase control-line for the Baluan rocks in Figure 13 indicates that the average composition of the fractionating feldspar has a molecular anorthite percentage of about An_{85}, or An_{75} wt percent. This value falls within the range An_{65-83} wt percent (mainly bytownite) determined optically by the Carlsbad-albite twin method for plagioclase phenocrysts in the Baluan rocks.

ROCKS OF THE FEDARB ISLANDS

Only four rocks from the Fedarb Islands have been chemically analysed. These, however, appear to be representative of all the exposed rocks. Two analyses of basalts from Sivisa Island (Fig. 8; Table 1; see sample 2 in Table 2) show that the rocks are Q-normative, rich in Al_2O_3, and similar in composition to many basalts from volcanoes along the southern margin of the Bismarck Sea (Johnson, unpublished data). They may be satisfactorily termed quartz tholeiites (after Yoder & Tilley, 1962). They contain abundant phenocrysts of calcic plagioclase, clinopyroxene, and olivine, which, in some samples and especially where their grainsize is small, is rimmed by fine-grained pyroxene (probably a low-calcium variety) with or without iron-titanium oxides. Phenocrysts of orthopyroxene and iron-titanium oxides seem to be absent. The groundmass is fine-grained and consists mainly of feldspar, iron-titanium oxides, and clinopyroxene. Low-calcium groundmass pyroxenes are almost certainly present, but because the grains are small they have not been identified optically.

Compared with the ol-normative basalts of Baluan Island, the Sivisa rocks contain more silica and less total-alkalis (Figs. 10, 13, and 18); this allows Q, rather than ol, to appear in the CIPW norm. Titania contents are low. 100 $Mg/(Mg+Fe^{2+})$ values are 67 and 69 indicating that these basalts could have been in equilibrium with the olivine of upper mantle peridotite (Green 1971), although it is difficult to envisage that, between the time of their generation in the upper mantle and the time of their eruption, no crystals (especially olivine) separated from, or were added to, these highly porphyritic magmas. Because they have compositions distinct from those of Baluan Island, and because they were erupted from a different volcano, it is concluded that magmatic evolution of the Sivisa basalts was independent of that of the Baluan rocks.

In the field and in thin section, the acid rocks of Chokua, Malapin, and Small Sivisa Islands (Fig. 8) all appear to be of the same type. The rocks are uniformly grey. They contain phenocrysts of sodic plagioclase, clinopyroxene, orthopyroxene, and iron-titanium oxides. Small crystals of apatite are also prominent. The groundmass is fine-grained and consists of feldspar, high-temperature silica minerals, some iron-titanium oxides, and rare pyroxene. Chemical analyses of two samples - one from Chokua, the other from Small Sivisa - show them to be dacites which are more or less indistinguishable chemically. Thus, it is thought likely that all the acid rocks of Chokua, Malapin, and Small Sivisa belong to the same flow, in which case it is the only acid lava flow represented in the Fedarb Islands.

The Fedarb dacite is chemically distinct from the rocks of the TLP series. It lies off the TLP trends in almost all the variation diagrams presented earlier, and its origin therefore does not appear to be directly related to that of the TLP series. Compared with the TLP rocks, the Fedarb lava has less silica and less total-alkalis; it falls below the cluster of TLP rocks in Figure 10 (see also Fig. 13). It contains more Al_2O_3 and more TiO_2, and P_2O_5 values are much higher, corresponding with the presence of conspicuous apatite crystals (see sample 3, Table 2). The ratios Na_2O/K_2O (see Ab/Or relations in Fig. 11) and MgO/FeO (Fig. 12) are also higher than those of the TLP series.

The available petrological data are too few to permit a conclusion on the origin of the Fedarb acid lava. One possibility is that it is a crystal fractionation product of the mafic magma that also gave rise to the quartz tholeiites of Sivisa Island. If so, intermediate members of the fractionation series are not exposed above present sea level. Alternatively, and by analogy with the TLP rocks, the lava may be the product of crustal fusion. If so, melting conditions and subsequent fractionation followed a course distinct from that of the TLP rocks.

DISCUSSION

Based on the conclusions of the previous sections, a working model is presented in this final section to account for the composition, relative abundances, and distribution of the volcanic rocks exposed above sea level in St Andrew Strait. This model will serve as a basis for discussion on trace element geochemistry to be given elsewhere (Smith & Johnson, in prep.). Firstly, in summary, three important aspects of the geology and petrology are emphasized:

(1) The St Andrew Strait Islands define a volcanic zone, trending 045°, the greater part of which is submarine and of unknown composition.

(2) Basaltic rocks on Baluan and Sivisa Islands are interpreted as the derivatives of partial melts of upper mantle peridotite. There is no evidence that fractionation of these melts has yielded andesitic liquids.

(3) Acid rocks of the TLP series are abundant. The interpretation preferred here is that these rocks are the derivatives of a crustal melt, and that they are not directly related to the basaltic rocks of St Andrew Strait. The origin of the acid lava of the Fedarb Islands is unknown.

Crustal melting was perhaps initiated by formation of a linear fracture, part of which is marked at the present day by the line between Baluan Island and the Fedarb Islands (Fig. 2). The fracture may have extended where it intersected an area of high-temperature geoisotherms, caused release of total pressure, and initiated crustal anatexis. Alternatively, St Andrew Strait may be underlaid by high-temperature geoisotherms which form an elongate, northeast-southwest, geothermal high. This thermal upwelling or 'plume' may have produced the crustal melting and given rise to a line of volcanoes along its axis.

Above the zone of melting in the central part of the volcanic line, it is envisaged that the crust sagged and formed at least part of a ring fracture. Magma of TLP composition ascended the ring fracture from the zone of melting, and gave rise to the volcanoes of Lou and Tuluman Islands (Figs. 2 and 9). It also rose up conduits between Baluan Island and the Fedarb Islands, producing the Pam Islands (Figs. 2 and 9).

Finally, attention is drawn to two other parts of Papua New Guinea where similar linear volcanic structures are associated with relatively abundant acidic volcanic rocks.

One area is Willaumez Peninsula, a 60-km north-south chain of volcanoes extending northwards from New Britain, in the central part of which, near Talasea (Fig. 1), are numerous extrusions of rhyolite (including obsidian). These rocks were described by Lowder & Carmichael (1972; see Figs. 10 and 12). The second area is in the D'Entrecasteaux Islands (Fig. 1), where peralkaline acid rocks (including obsidian; Fig. 10) define a prominent north-south line of volcanoes (Smith, unpublished data).

All three volcanic lines - in St Andrew Strait, on Willaumez Peninsula, and in the D'Entrecasteaux Islands - have trends which form high angles with the surface traces of the nearby plate margins (see Johnson & Molnar, 1972). As their structural settings are similar, how similar are the modes of origin for the acid rocks of each volcanic line? If the TLP acid rocks of St Andrew Strait originated from crustal melts, how did those of Willaumez Peninsula and the D'Entrecasteaux Islands originate? Work in progress may provide answers.

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Table 1. Four magma compositions of St Andrew Strait islands

Island	Acid magma-type	Basalt magma-type
TULUMAN & CONE-3: LOU; PAM LIN & PAM MANDIAN } 'TLP series'	rhyolite, low Na_2O/K_2O	not observed
BALUAN	not observed	*hy* and *ol* in CIPW norm ('mildly alkaline & transitional' basalts of Coombs, 1963)
FEDARB GROUP Sivisa	not observed	Q in CIPW norm ('quartz tholeiites' of Yoder & Tilley, 1962)
Chokua, Malapin, & Small Sivisa	dacite high Na_2O/K_2O (probably only one lava flow represented)	not observed

Table 2. Chemical analyses and CIPW norms of seven selected rocks*
from St Andrew Strait

	1	2	3	4	5	6	7
SiO_2	49.51	51.74	68.16	70.31	69.57	72.85	73.40
TiO_2	1.40	0.79	0.83	0.44	0.45	0.28	0.26
Al_2O_3	15.87	17.62	15.28	14.01	13.91	13.74	13.32
Fe_2O_3	1.91	2.36	1.63	1.08	0.89	0.58	0.48
FeO	8.51	5.78	2.20	2.41	2.73	1.44	1.53
MnO	0.20	0.15	0.14	0.09	0.10	0.07	0.06
MgO	6.86	6.59	1.08	0.54	0.84	0.34	0.13
CaO	11.99	11.31	3.01	1.78	1.95	1.11	0.96
Na_2O	2.67	2.52	5.84	5.26	5.29	4.94	4.77
K_2O	0.45	0.32	1.45	3.21	3.21	4.01	4.20
P_2O_5	0.15	0.12	0.24	0.06	0.07	0.04	0.02
H_2O+	0.34	0.17	0.08	0.19	0.23	0.19	0.28
H_2O-	0.21	0.11	0.08	0.10	0.10	0.09	0.13
CO_2	0.05	0.05	0.04	0.14	0.14	0.22	0.14
Total	100.12	99.63	100.06	99.62	99.48	99.90	99.68
Q	-	2.98	21.10	21.40	20.95	25.96	27.30
or	2.67	1.90	8.58	19.20	19.13	23.78	25.00
ab	22.68	21.45	49.44	46.06	45.12	41.94	40.64
an	30.12	36.06	11.22	4.36	4.78	3.50	2.56
di	23.16	15.59	1.55	2.34	3.06	0.32	1.06
hy	8.65	16.66	3.52	3.59	4.32	2.53	1.88
ol	6.81	-	-	-	-	-	-
mt	2.78	3.44	2.37	1.32	1.30	0.84	0.70
il	2.67	1.51	1.58	0.87	0.86	0.53	0.50
ap	0.36	0.29	0.57	0.31	0.17	0.10	0.05
cc	0.11	0.11	0.09	0.55	0.32	0.50	0.32

1. Basalt lava flow, northwestern coast of Baluan Island; BMR sample number 38**.
2. Basalt lava flow, cliff on southwestern side of Sivisa Island, Fedarb Islands (68C).
3. Acid lava flow, northeastern coast of Chokua Island, Fedarb Islands (61).
4. Acid lava flow in cliffs composed of materials from Cones 2 and 4, southeastern side of Tuluman Island (see Fig. 3) (11).

Table 2 cont.

5. Acid lava flow erupted in 1956-57, northeastern coast of Tuluman Island (17A).
6. Acid lava flow of centre 7, northwestern coast of Lou Island (03).
7. Acid lava, southeastern side of Pam Mandian (55).

* 25 samples were analysed by I.E. Smith using mainly X-Ray fluorescence methods. Sodium values were obtained by flame photometry and ferrous iron was determined by wet chemistry. The 3 additional analyses were supplied by the Australian Mineral Development Laboratories, Adelaide.

** All BMR sample numbers, including those shown in parenthesis for samples 2-7, have the prefix 25NG00.

Table 3. Al_2O_3 and modal-phenocryst contents of six basalts from Baluan Island

BMR sample no. (prefix 25NG00)		42	38	43	45	39	48*
wt. percent Al_2O_3		15.29	15.95	18.26	20.47	20.69	-
Plagioclase	vol. % phenocrysts	<0.25**	<0.25**	14.6	46.2	50.1	28.2
Olivine	vol. % phenocrysts	-	-	0.6	0.5	1.1	6.0
Clinopyroxene	vol. % phenocrysts	-	-	-	0.1	0.4	5.6

* examples of rocks rich in ferromagnesian phenocrysts, such as sample 48, have not been chemically analysed because they contain secondary minerals, and because they come from weathered coastal outcrops of clastic deposits that have almost certainly been leached by rain and sea water.

** visual estimate - all other modal values obtained from counts of about 3000 points per sample, exclusive of vesicles.

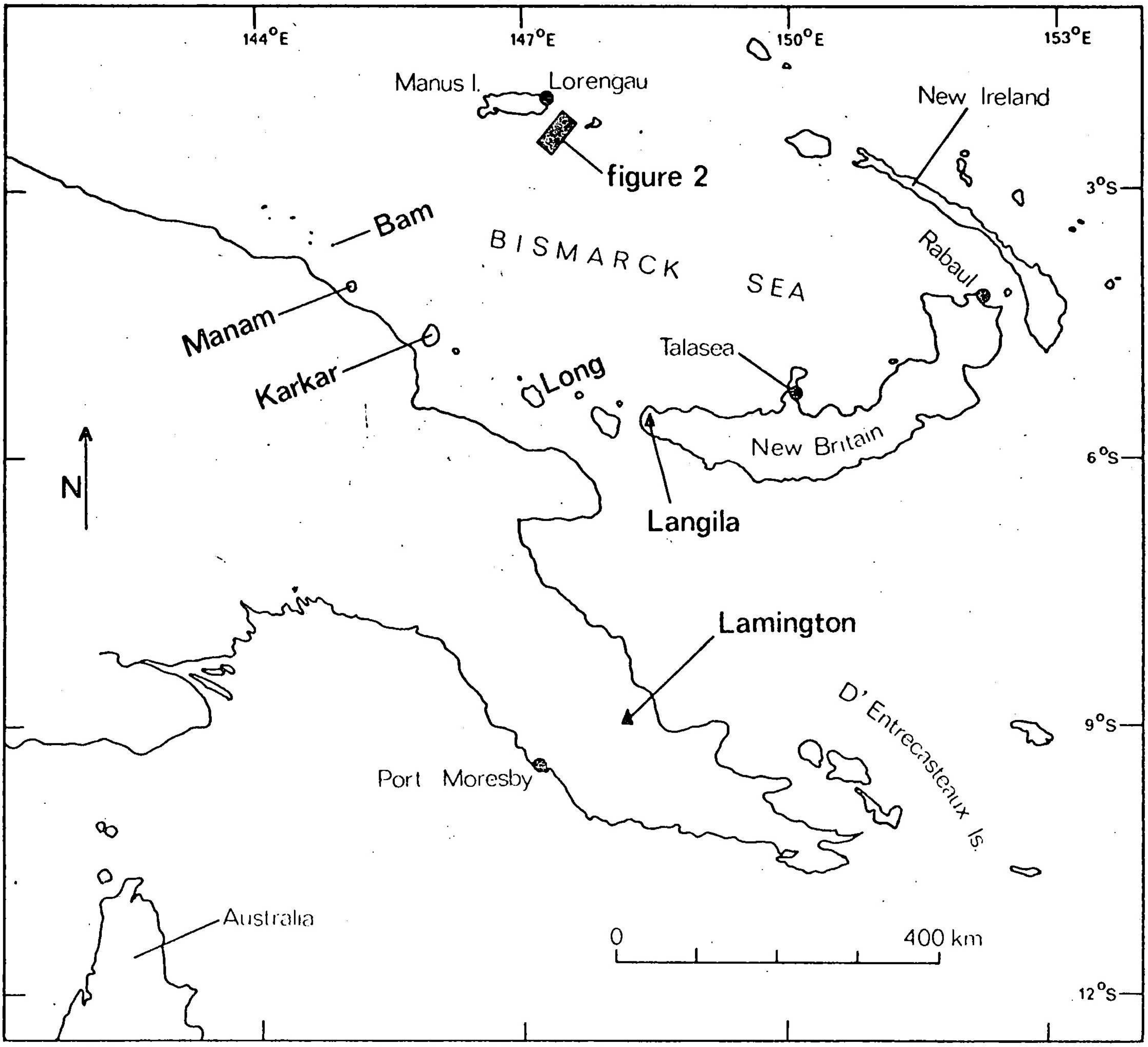

Figure 1. Locality map for Papua New Guinea (excluding Bougainville Island). St Andrew Strait area in Figure 2 is shown as solid rectangle. Filled circles are settlements. Triangles are inland volcanoes.

To accompany Record 1973/180

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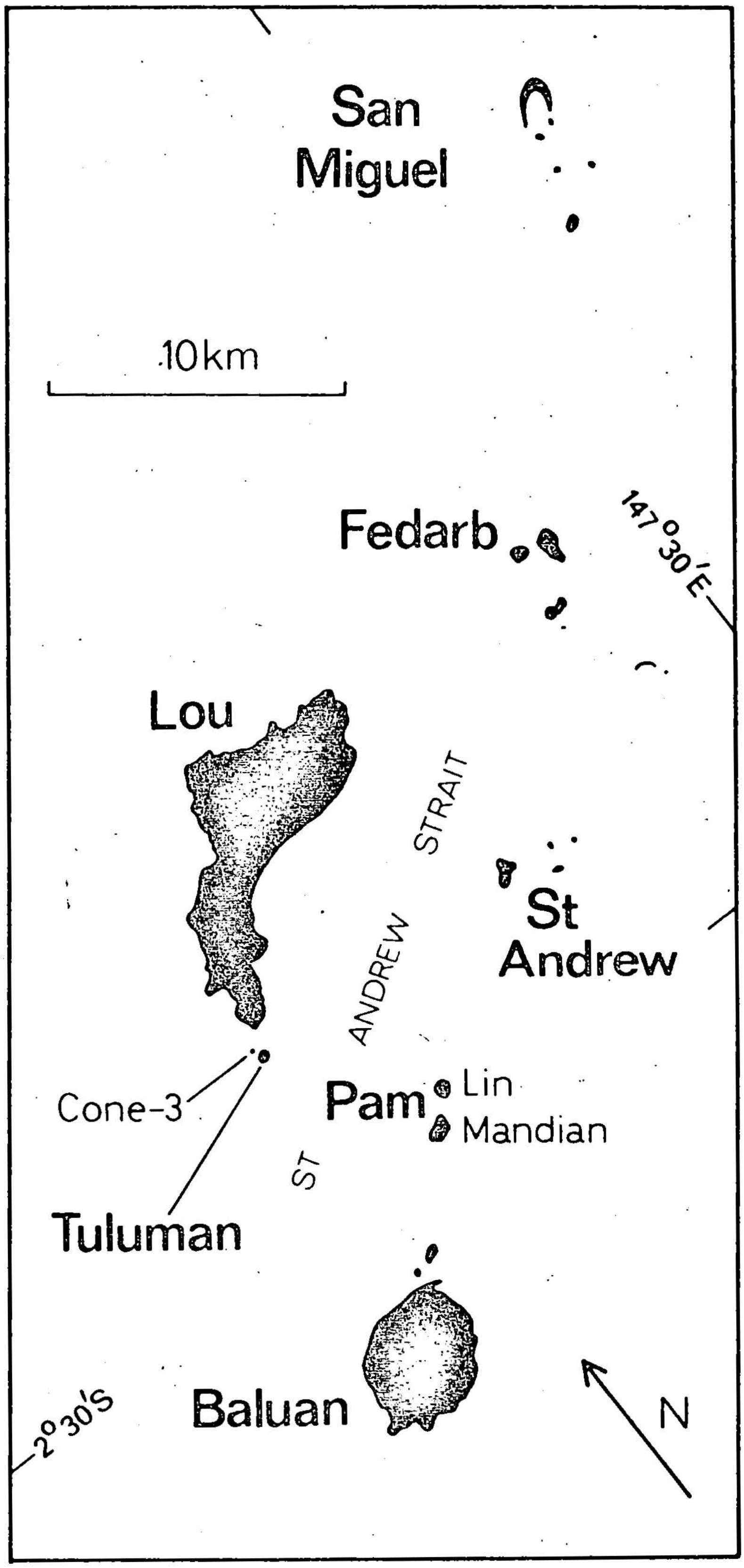

Figure 2. Islands and island groups of the St Andrew Strait area. All are volcanic except for the San Miguel and St Andrew Islands, which are coral.

To accompany Record 1973/180 A 55/A11/14

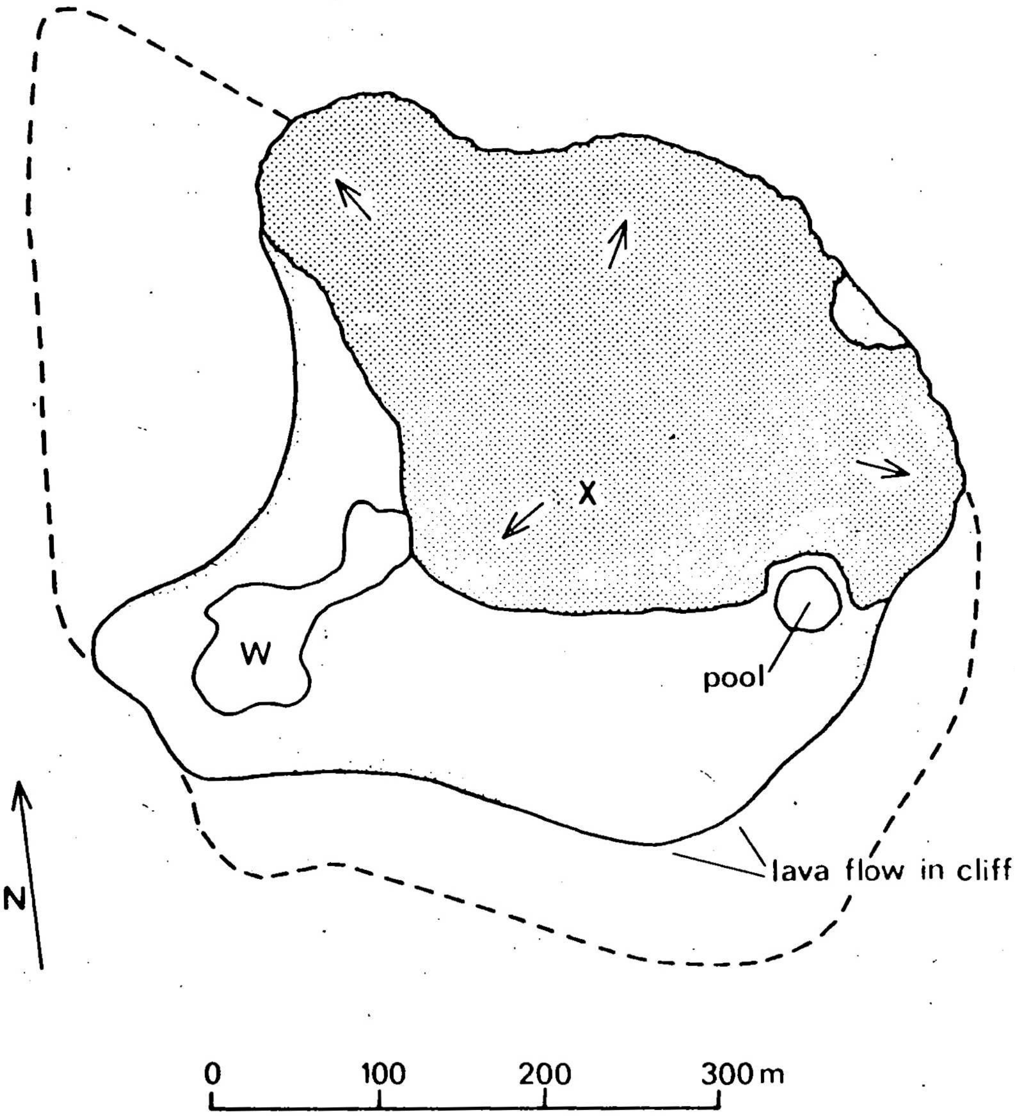

Figure 3. Tuluman Island, as observed in 1971. Dashed line is the position of the shoreline in 1962. Coarse stippling shows the area of 1956-57 lava flows; inferred flow directions, given by arrows, radiate from a high point, X, which probably marks the eruptive centre of the fl ('Cone 7B' of Reynolds, 1958). Fine stippling shows principal beach deposits. Remainder of island, shown blank, is made up of materials produced mainly from Cones 2 and 4. W is a water-filled area at the bottom of a zone of subsidence (or 'breach'; Reynolds, 1958).

To accompany Record 1973/180 A 55/A11/15

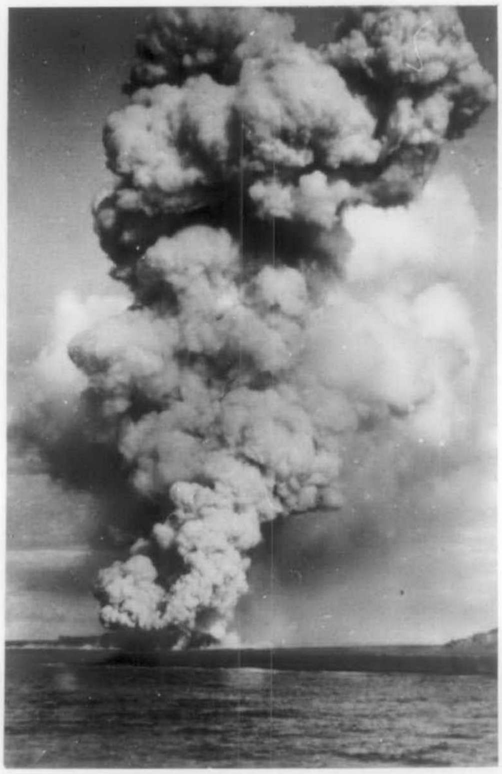

Figure 4. Subaerial eruption of viscous lava from 'Cone 7A' (Reynolds, 1958), Tuluman volcano, on 5 December 1956. Photograph taken from the west by J.H. Kemsley, Master of PNG Administration trawler 'Eros'. In the foreground is the western part of the precursor to Tuluman Island, consisting mainly of deposits from Cones 2 and 4. About one month after this photograph was taken, the lava flows shown in Figures 3 and 5 were extruded from 'Cone 7B' (Reynolds, 1958) a few hundred metres south-southwest of Cone 7A (see point X in Fig. 3).

Figure 5. Tuluman Island from the southwest. Photograph taken by C.D. Branch in 1964. Zone of subsidence (or 'breach'; Reynolds, 1958), partly filled by water, is shown between dashed lines. X marks the highest point of the 1956-57 lava flows (see Fig. 3). By comparing with Figure 3, the amount of erosion of the deposits of Cones 2 and 4 (light-coloured) between 1964 and 1971 can be judged.

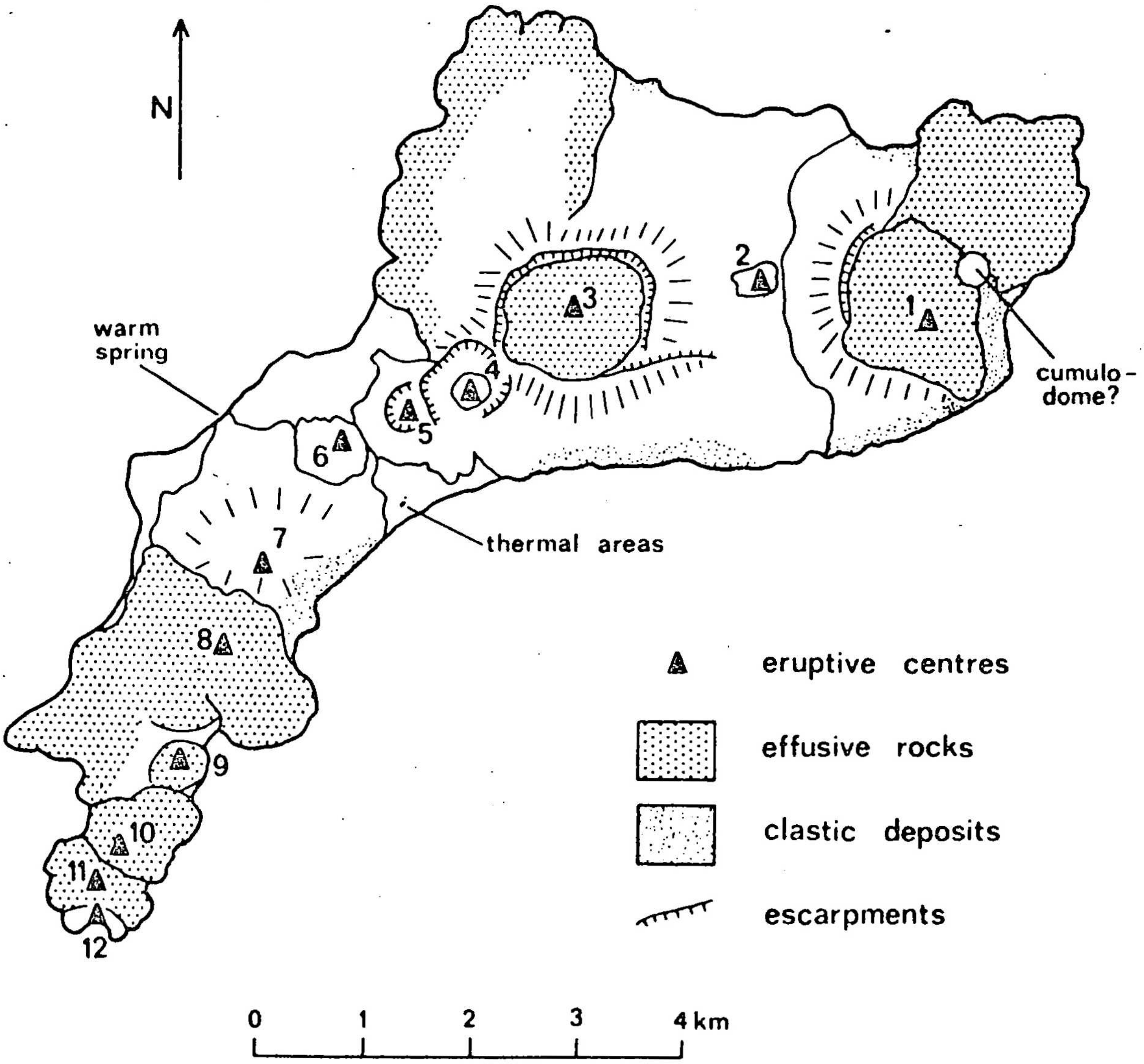

Figure 6. Lou Island, showing 12 principal centres of acid volcanism. The short-line pattern shows slopes radiating from summit areas.

To accompany Record 1973/180 A 55/A11/16

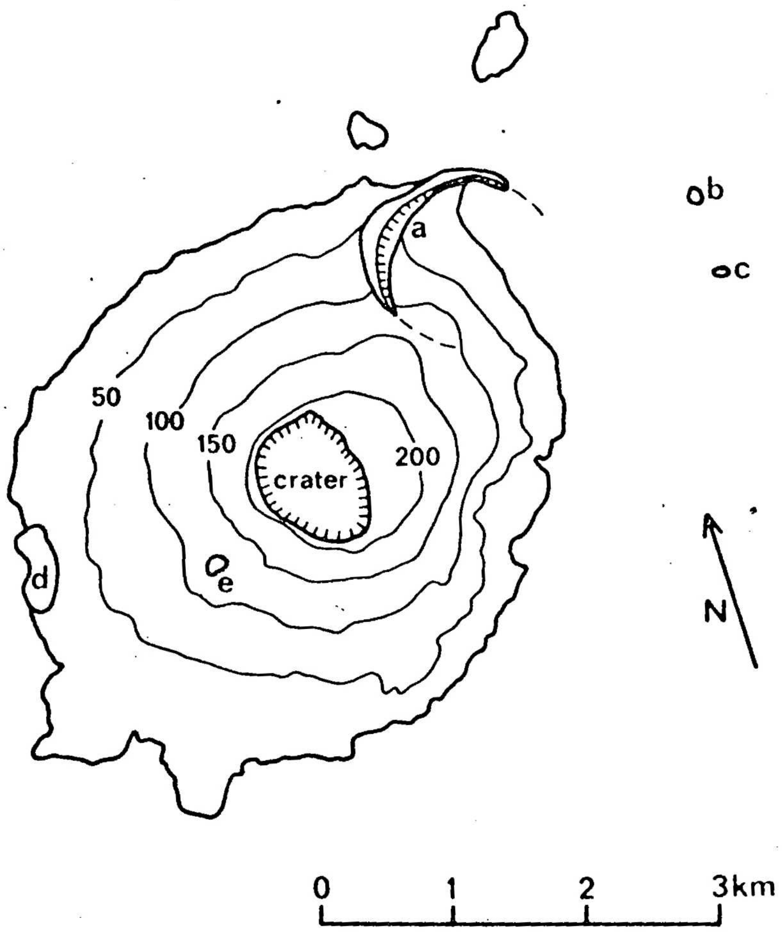

Figure 7. Baluan Island, showing 50-m contours. a is the northwestern remnant of a pyroclastic cone and crater. The two islands to the north are each palagonitic pyroclastic cones. Islands b and c consist of bedded clastic deposits and coral, respectively. d is a twin-peaked hill of scoria. e is a timbered satellite cone.

To accompany Record 1973/180 A 55/A11/17

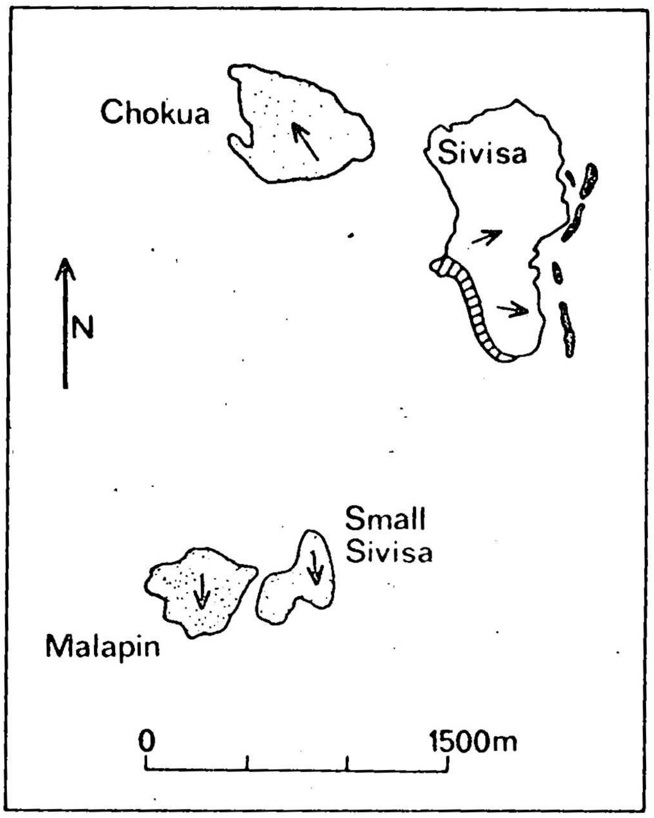

Figure 8. The Fedarb Islands. Stippling shows islands of dacite lava which may be parts of a single lava flow. Arrows indicate dip slopes. Off the eastern shore of Sivisa (basaltic island), coral raised above sea level is shown black. The remnant of a possible crater (or caldera) wall is shown by the lined pattern.

To accompany Record 1973/180 A 55/A11/18

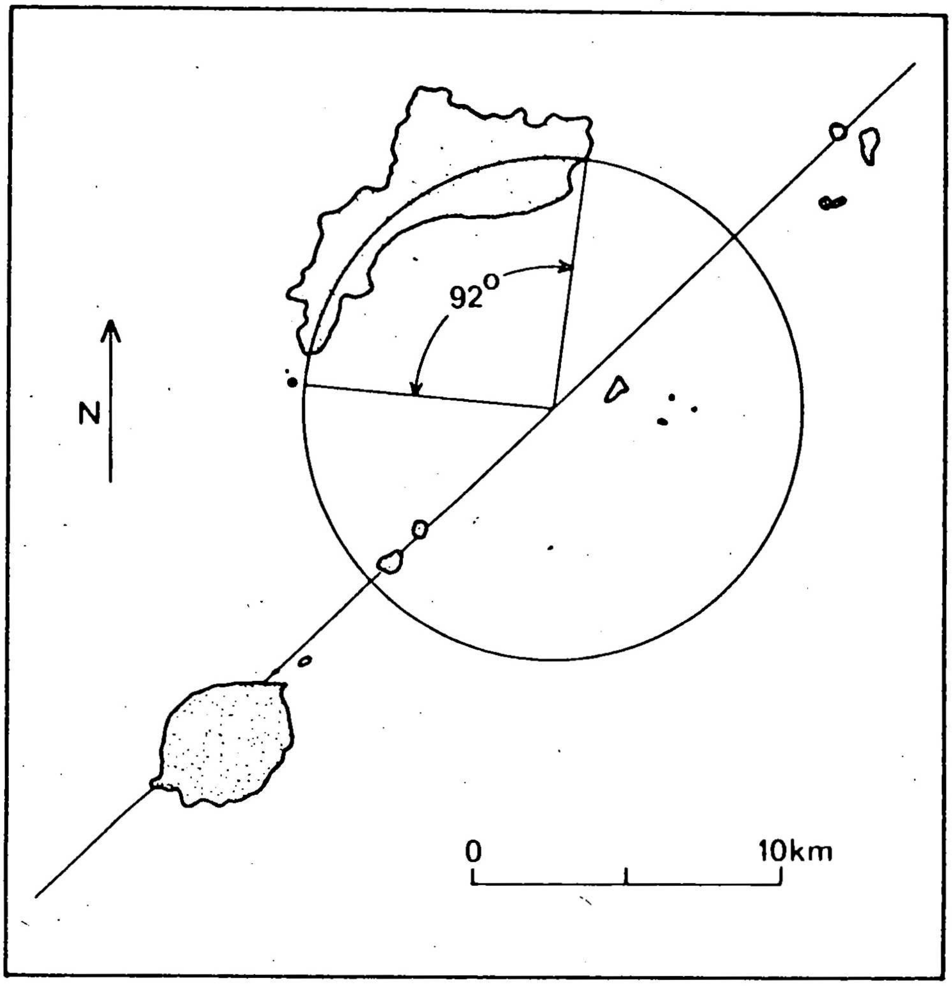

Figure 9. Diagrammatic trace of proposed nascent ring fault in St Andrew Strait. 92 degrees of arc are roughly defined by the arrangement of eruptive centres on Lou Island (see Fig. 6) and Tuluman Island. The centre of the circle coincides with the line between Baluan Island and the Fedarb Islands.

To accompany Record 1973/180 A 55/A11/19

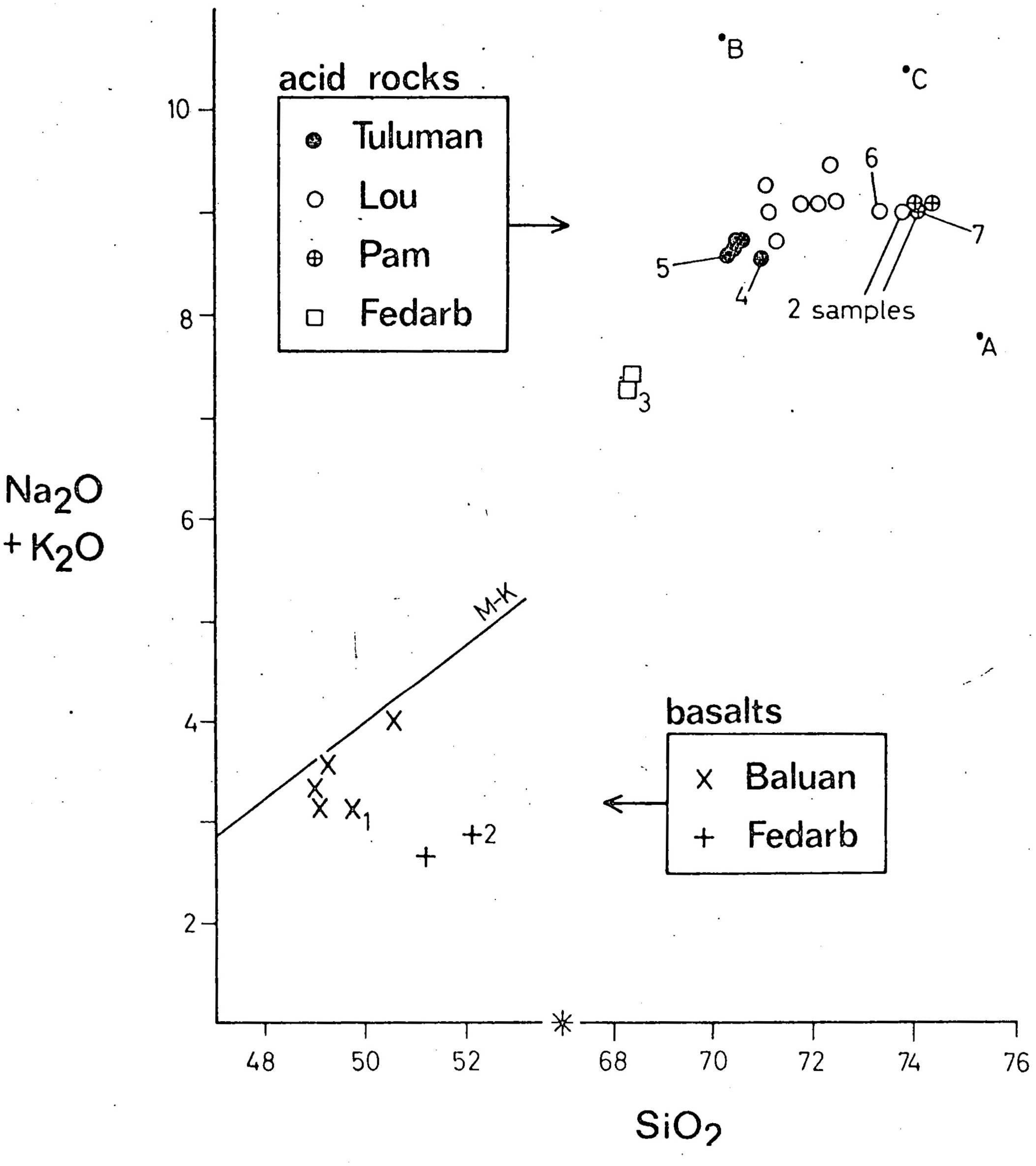

Figure 10. Wt percent Na_2O + K_2O _versus_ SiO_2 for rocks of St Andrew Strait. Note the large silica gap on the horizontal scale (*). The sample numbers of the seven rocks in Table 2 are shown as 1, 2, _etc_. M-K is the MacDonald & Katsura (1964) line, below which plot tholeiitic rocks from Hawaii. _A_ is an obsidian from Talasea, New Britain (Fig. 1; Lowder & Carmichael, 1970). _B_ is the average of three peralkaline acid rocks from D'Entrecasteaux Islands (Fig. 1; Morgan, 1966). _C_ is the average of 8 pantellerites from Mayor Island, New Zealand (Ewart _et al._, 1967). All analyses plotted on a volatile-free basis.

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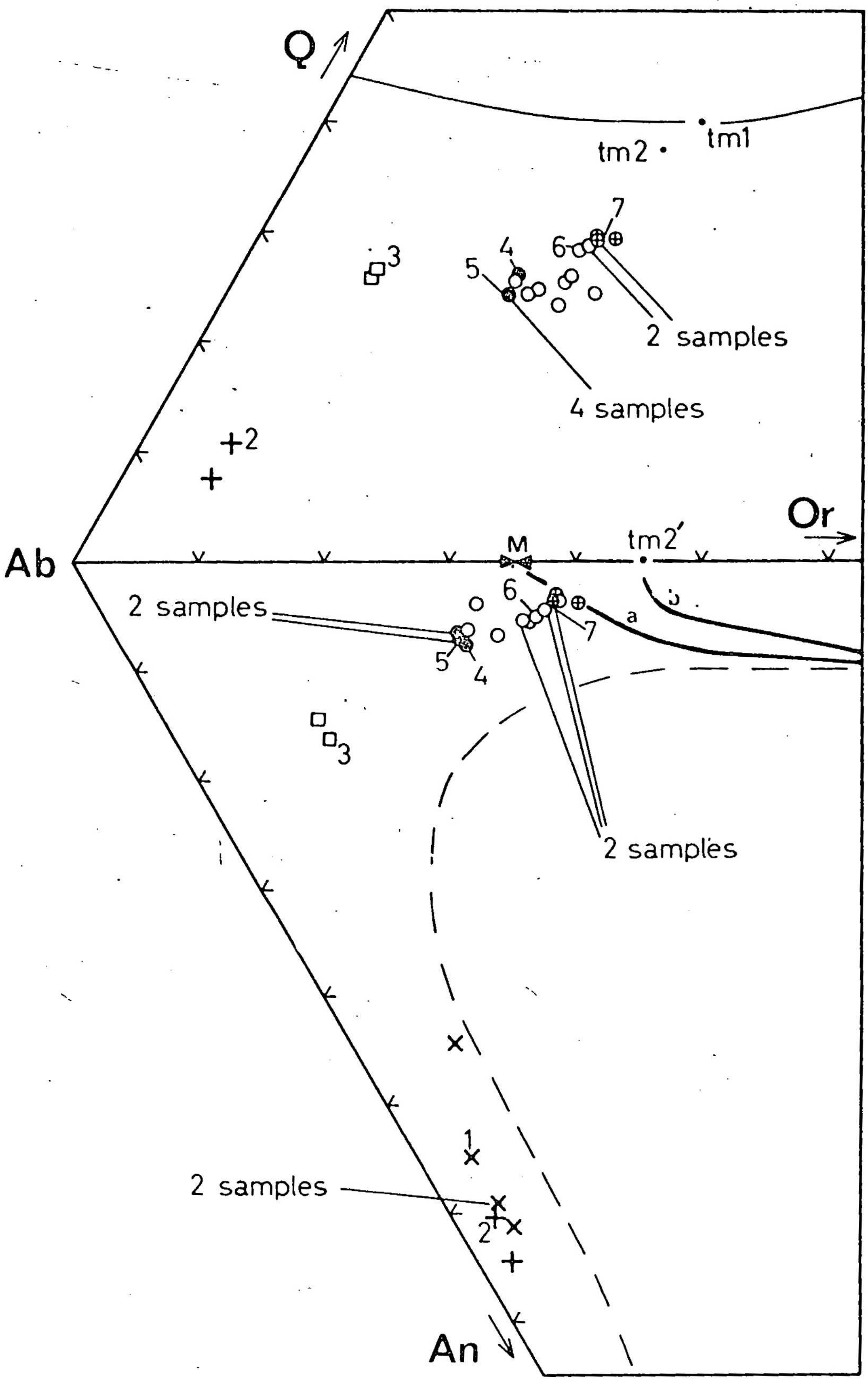

Figure 11. Parts of the ternary system Q-Ab-Or (upper) and Ab-Or-An (lower) (wt percentages). Sample notation as in Figure 10. Q-Ab-Or shows the quartz/feldspar field boundary and its ternary minimum, tml, at 500 kg/cm^2 water vapour pressure; tm2 is the ternary minimum at 1000 kg/cm^2 (Tuttle & Bowen, 1958). The dashed line in Ab-Or-An is the limit of ternary solid solution in natural feldspars (Smith & Mackenzie, 1958). M is the alkali feldspar minimum (Tuttle & Bowen, op. cit.). Curve a is the locus of liquids in equilibrium with two feldspars and water vapour at 5000 kg/cm^2 (Yoder, Stewart, & Smith, 1957). tm2' is the projection of tm2 from the Q apex; curve b is the locus of liquids in equilibrium with two feldspars, water vapour, and quartz, at 1000 kg/cm^2 (James & Hamilton, 1969).

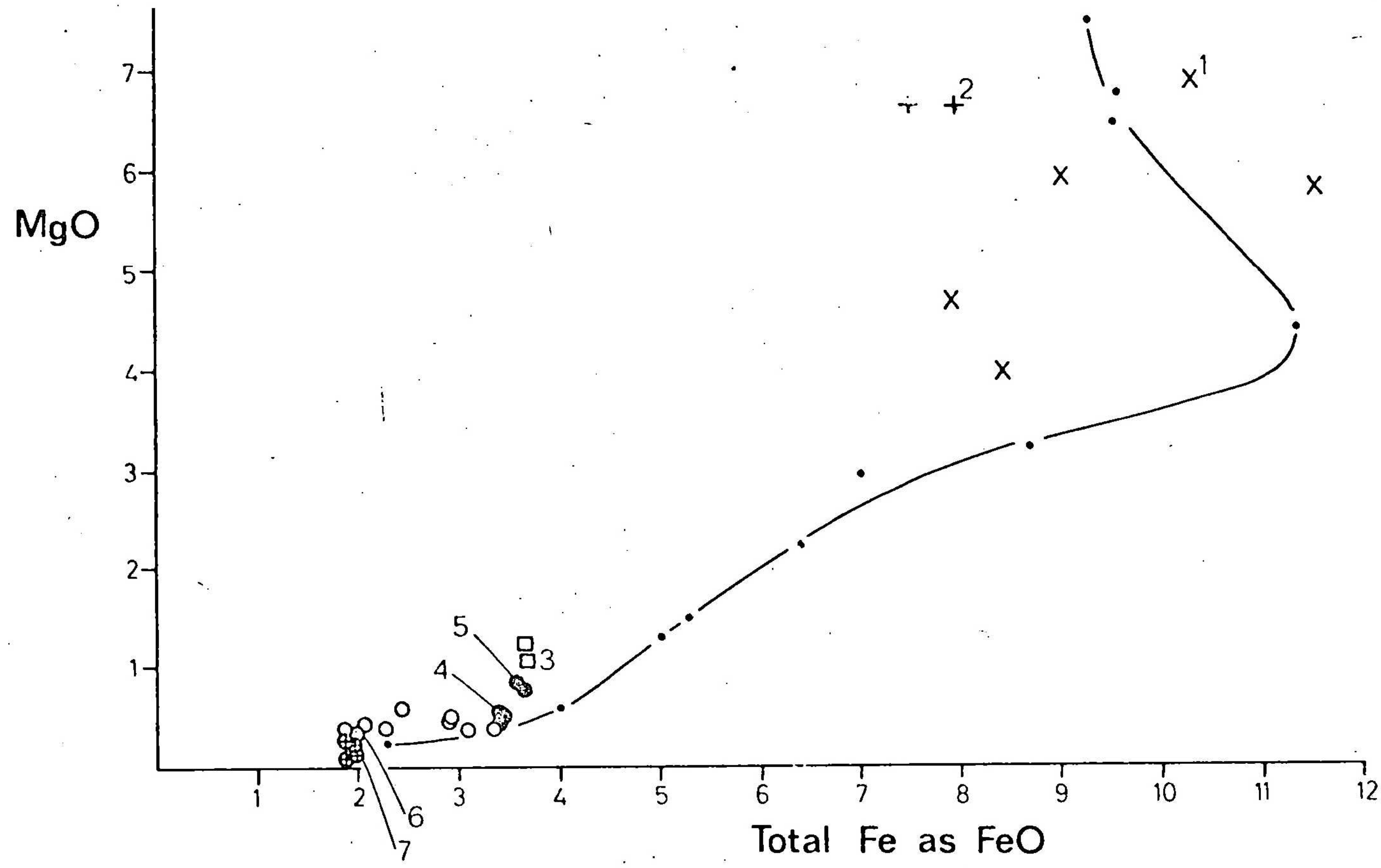

Figure 12. Wt percent MgO versus total-iron (as FeO) for rocks of St Andrew Strait. Sample notation as in Figure 10.
The dot-dash line is the trend of 'moderate iron-enrichment' shown by volcanic rocks from the area north of Talasea, New Britain (Lowder & Carmichael, 1970); dots represent sample points.

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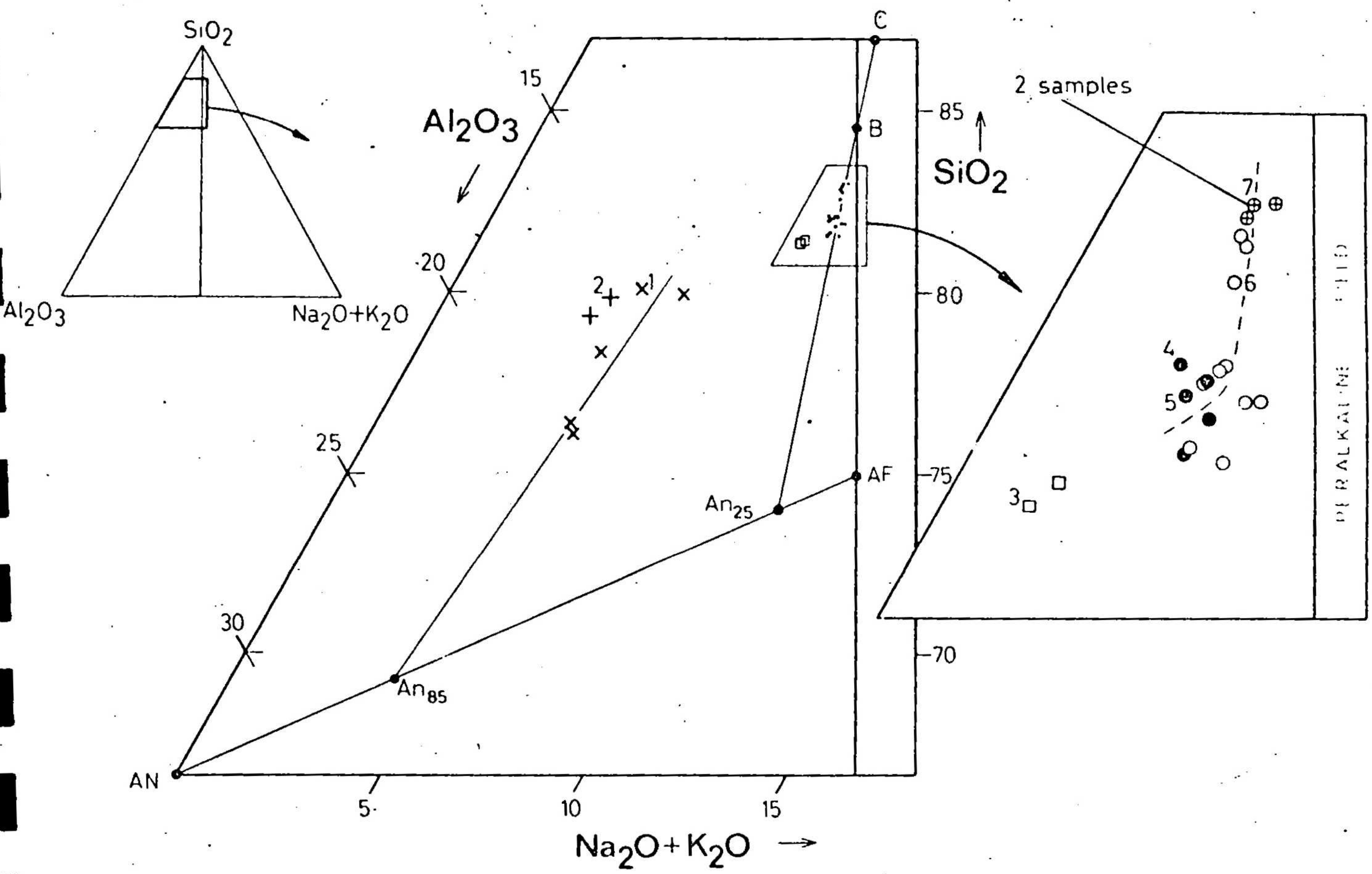

Figure 13. Parts of the ternary system SiO_2-Al_2O_3-Na_2O + K_2O (molecular percentages). Sample notation as in Figure 10, except that in the largest diagram all the rocks of the TLP series are shown as small dots. AN is anorthite. AF is alkali feldspar. Between AN and AF are compositions of the plagioclase solid-solution series, showing the molecular anorthite-contents of some members (e.g., An_{25}). The trend of the TLP rocks, considered as one group, lies roughly on the line An_{25}-B-C, where B is a hypothetical residual liquid showing an agpaitic index of 1, produced by ideal separation of a feldspar of An_{25} composition. The dashed line in right-hand diagram is a generalized trend extending from the Tuluman rocks, through those of Lou Island, to the rocks of the Pam group. The rocks of Baluan Island cluster about a control line for a plagioclase composition of about An_{85}.

To accompany Record 1973/180 M(Pt) 156

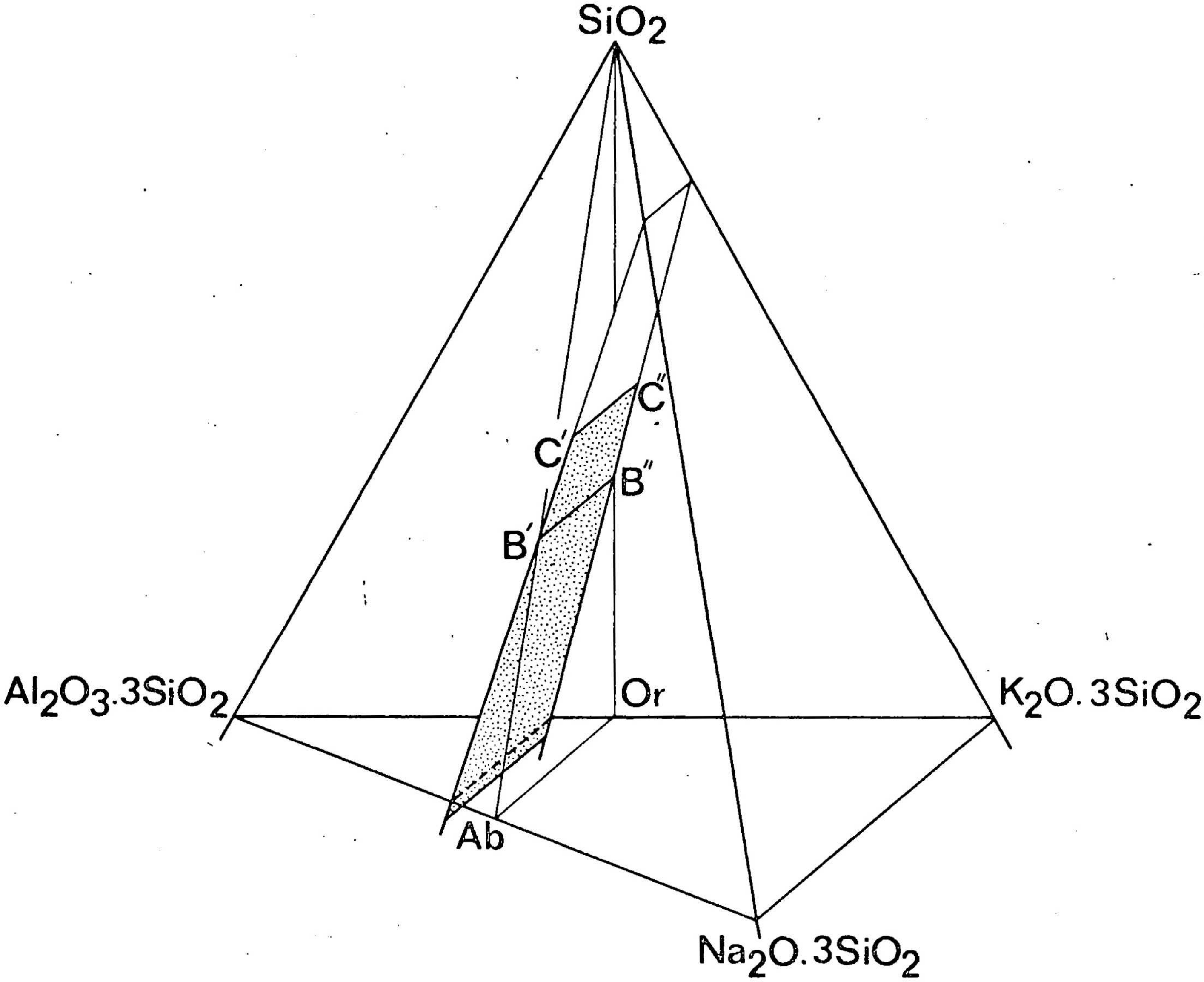

Figure 14. Silica-rich corner of the quaternary system SiO_2-Al_2O_3-Na_2O-K_2O (molecular proportions). Ab and Or are albite and orthoclase, respectively. The stippled plane is the compositional quadrilateral shown in Figure 15. When projected into the ternary system SiO_2-Al_2O_3-Na_2O+K_2O in Figure 13, this plane plots as the line An_{25}-B-C. The area B'-B"-C"-C' is the peralkaline part of the plane.

To accompany Record 1973/180

M(Pt) 157

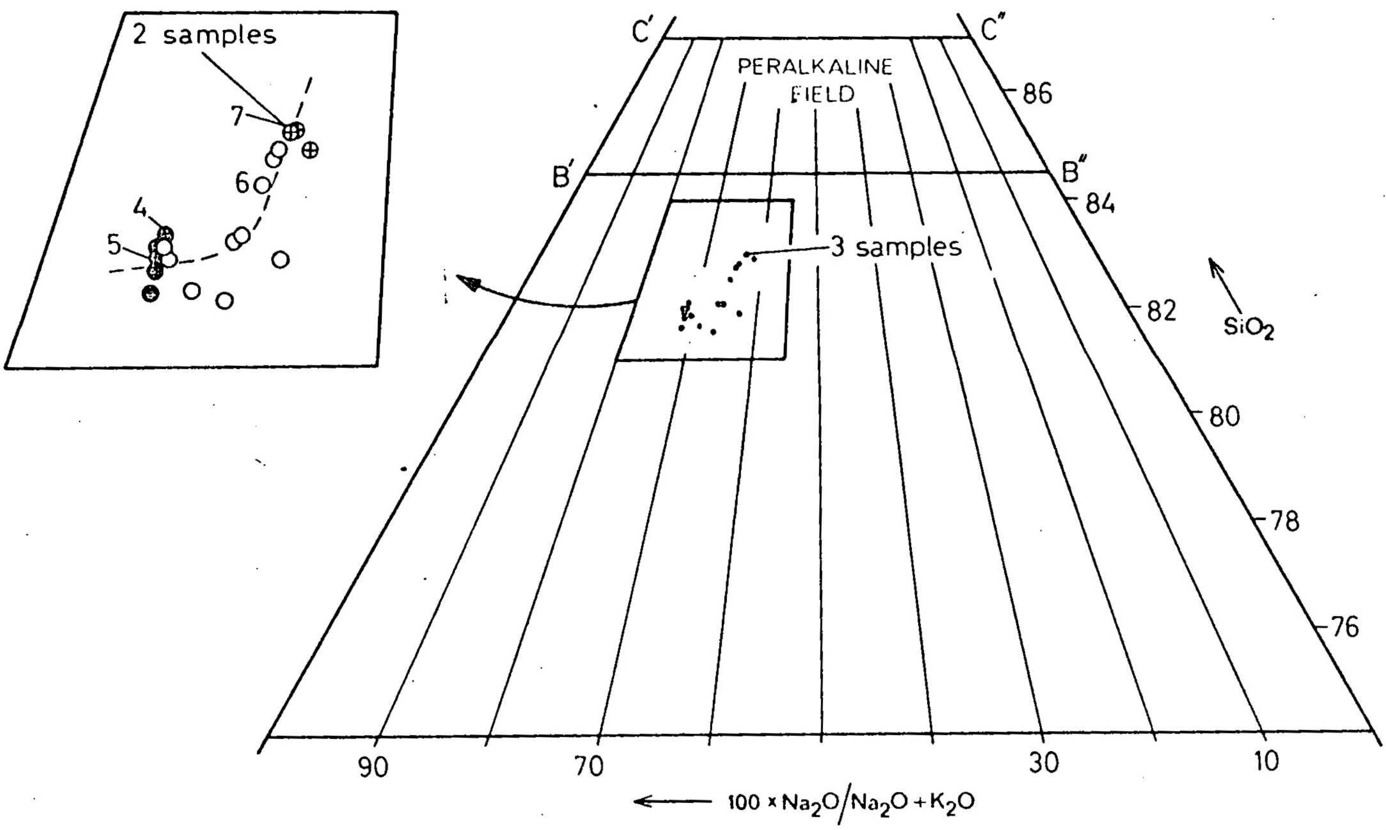

Figure 15. Rocks of the TLP series plotted (in molecular percentages) in the plane whose position in the quaternary system SiO_2-Al_2O_3-Na_2O-K_2O is shown in Figure 14. Sample notation as in Figure 13. Dashed line in the left-hand enlargement is a schematic trend for the TLP series.

To accompany Record 1973/180 M(Pt) 158

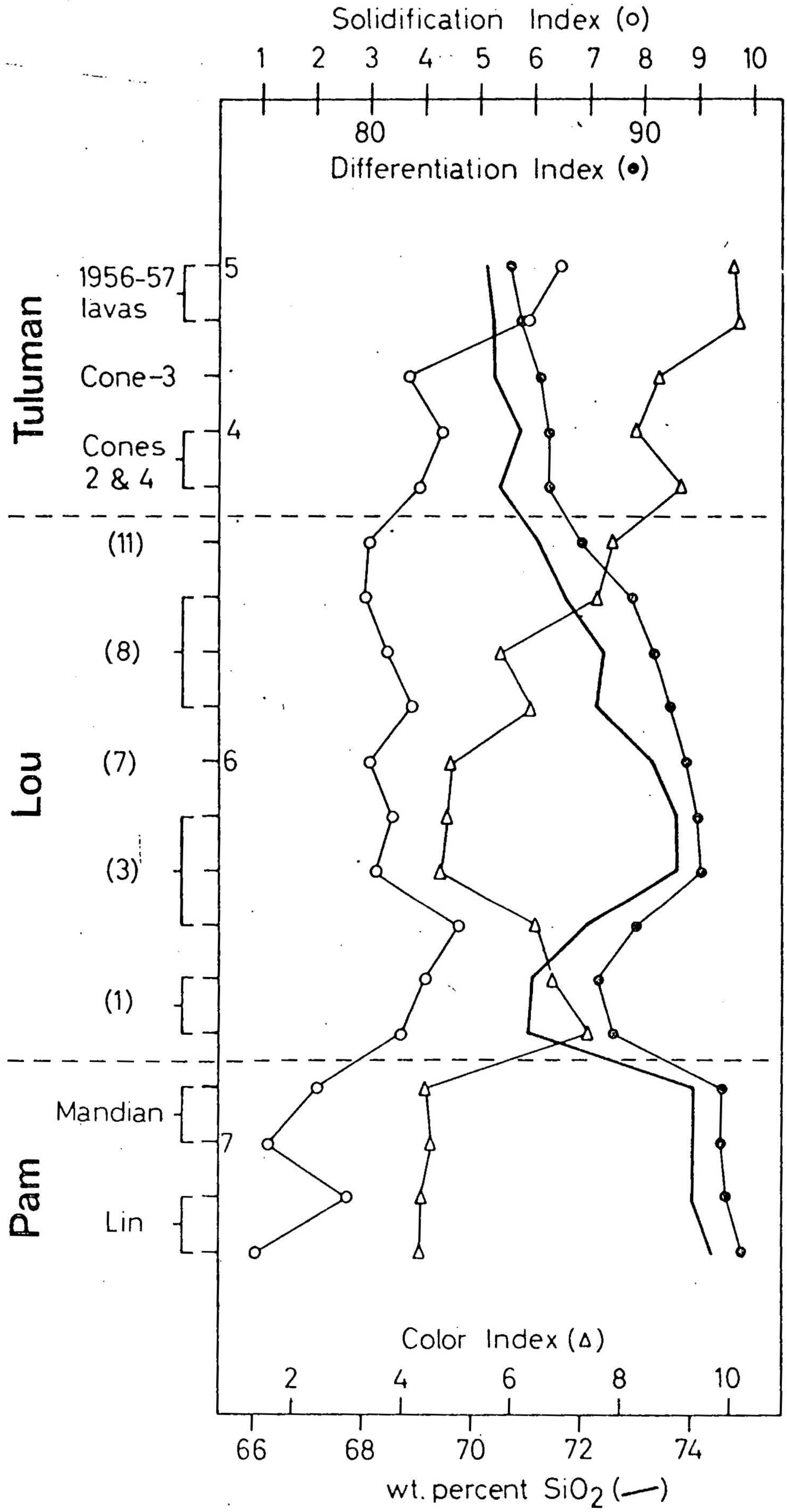

Figure 16. Nineteen TLP rocks plotted against Solidification Index (Kuno et al., 1957), Differentiation Index (Thornton & Tuttle, 1960), Colour Index (wt percent femic minerals in CIPW norm), and silica content (wt percent). Figures in parenthesis refer to the numbers of the eruptive centres on Lou Island (see Fig. 6). Figures right of the left-hand vertical axis are the numbers of samples whose analyses are given in Table 2.

To accompany Record 1973/180

M(Pt) 159

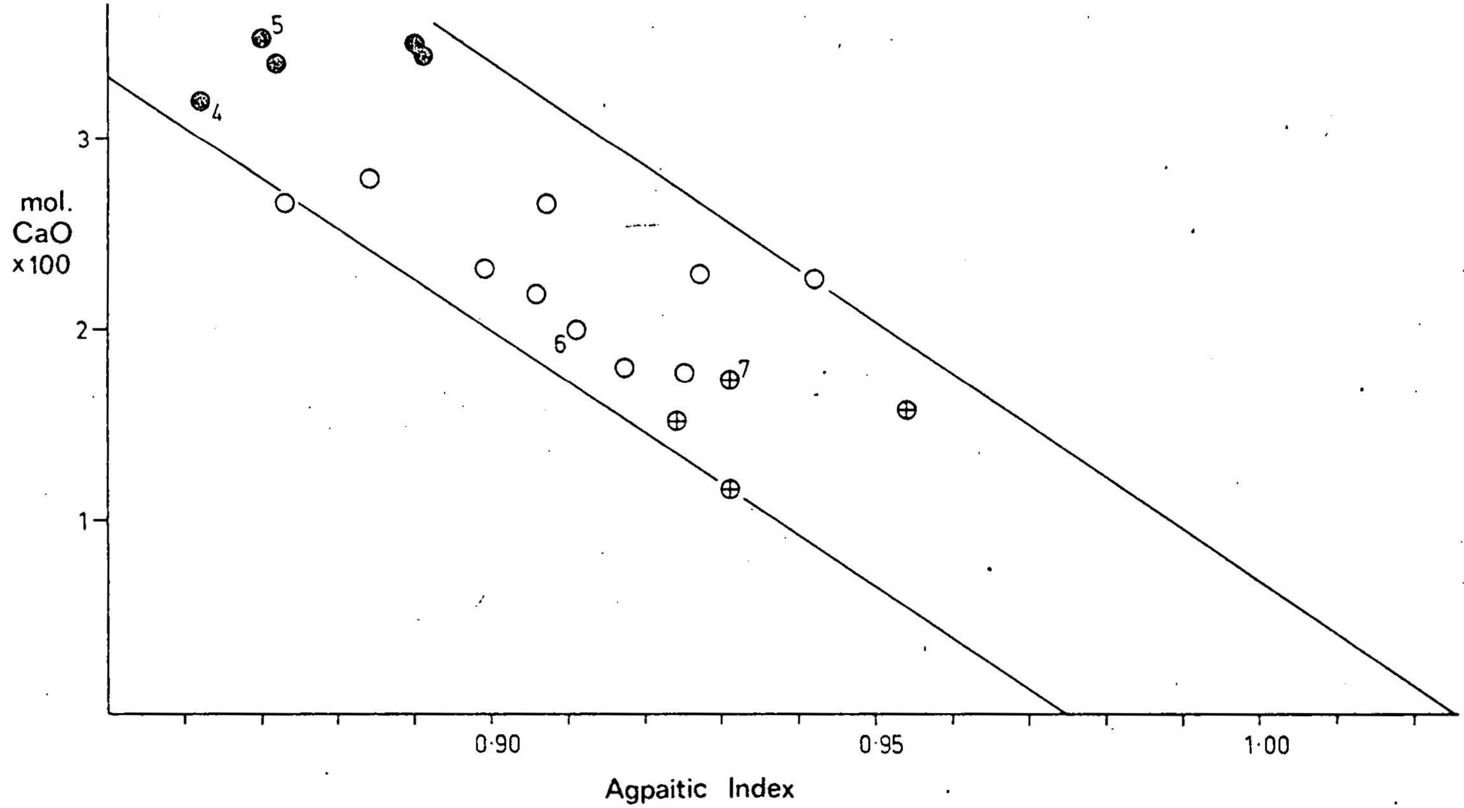

Figure 17. Mol. percent CaO (x100) <u>versus</u> agpaitic index for rocks of the TLP series. Sample notation as in Figure 10. The rocks define a zone which, extrapolated to zero CaO, shows an agpaitic index of 1±0.025.

To accompany Record 1973/180 M(Pt) 160

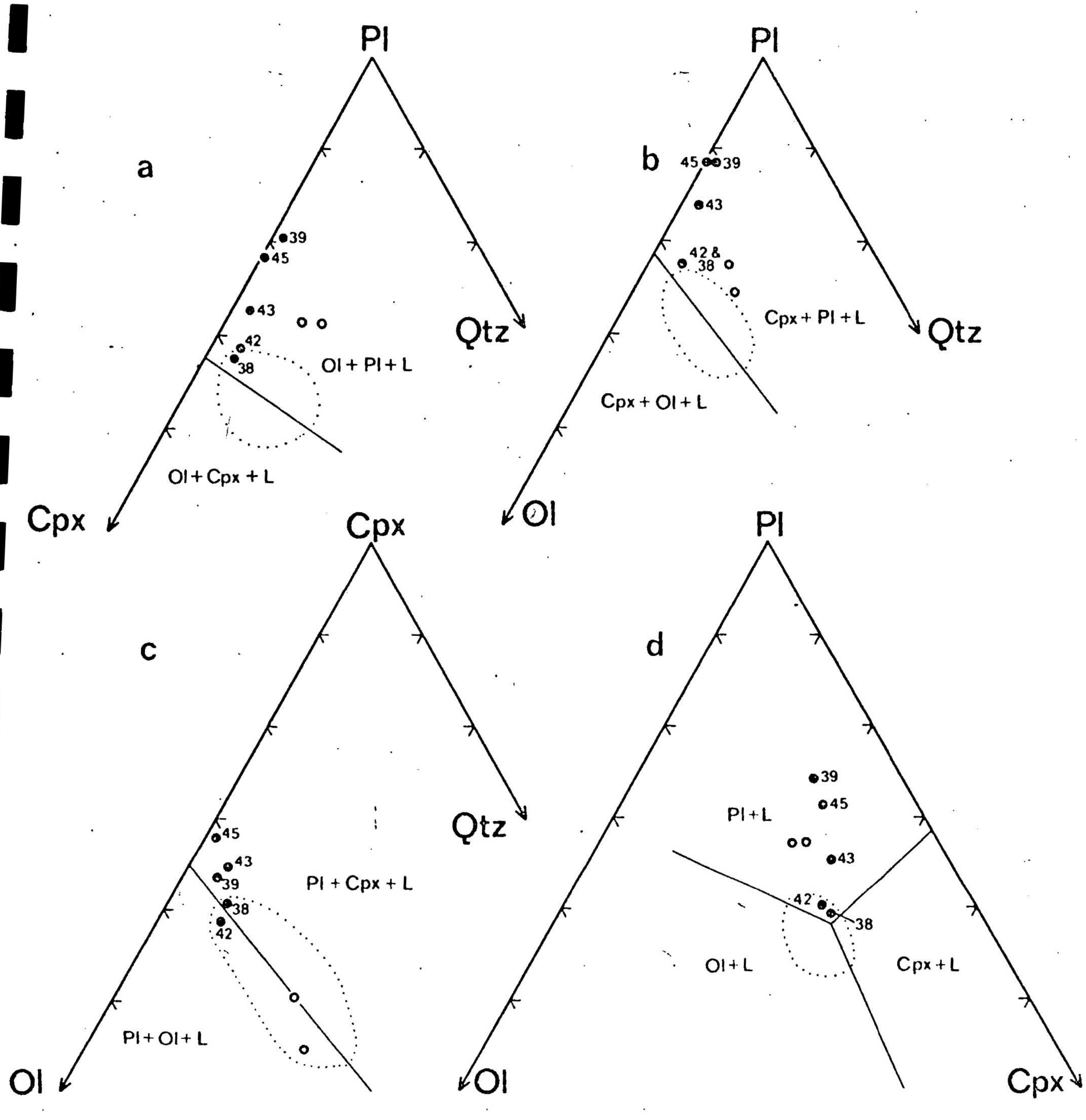

Figure 18. Projections of Baluan and Fedarb basalt compositions onto the faces of the normative (CIPW) pseudo-quaternary system Olivine (<u>Ol</u>) - Clinopyroxene (<u>Cpx</u>) - Plagioclase (<u>Pl</u>) - Quartz (<u>Qtz</u>), from the <u>Ol</u>(a), <u>Cpx</u>(b), <u>Pl</u>(c), and <u>Qtz</u>(d) apices. Solid dots are the rocks of Baluan Island, showing the sample numbers of Table 3. Open circles are the Fedarb quartz tholeiites. All additional data are from Cox & Bell (1972). The unbroken lines are the approximate positions of 'natural cotectics' obtained from the dry, 1-atmosphere melting experiments of Tilley et al. (1963, 1964, 1965, 1967). The dotted lines define areas of those melted rocks which, on crystallization, showed (1) the appearance of all three phases, <u>Ol</u>, <u>Cpx</u>, <u>Pl</u>, within a 30°C temperature interval, and (2) the entry of second and third phases within a 30°C interval, in which case the data points were projected (by Cox & Bell) only from the apex of the first phase to appear. L = liquid.