THE TONIGALA GRANITE, N. W. CEYLON

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A pink, microcline granite at Tonigala in north-western Ceylon occurs as a concordant sheet, one to two miles wide and about 10 miles long, in a complex of migmatitic and granitic biotite and biotite-hornblende gneisses belonging to the PreCambrian Vijayan Series.

The granite is composed of quartz, microcline-microperthite, subordinate oligoclase, and biotite. It is traversed by an anastomosing system of veins of red granite and by dykes, veins and patches of pegmatite, aplite, and microgranite. A parallel swarm of pre-granitic dykes is also present. Enclaves of biotite schist in the form of lenses, bands, and foliae are found within the granite, and corrugations of thin biotitic foliae with a constant axial direction and plunge are scattered throughout.

Field and petrographic evidence suggests that the Tonigala granite was formed by microclinisation of pre-existing synkinematic rocks, possibly granodioritic in composition. In its petrochemistry the granite resembles in many respects the late-kinematic granites of Finland and West Africa, but in certain other important characteristics it is similar to the synkinematic granites of Finland. It is thought that the Tonigala granite acquired its late-kinematic character by metasomatism.

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Introduction

A pink, microcline granite at Tonigala, 15 miles southeast of Puttalam in the north-western sector of Ceylon (Fig. 1, inset) was originally described as a »coarse-grained variety of the Tonigala gneiss» (Coates, 1935, p. 157) which covers an area of 1.600 sq. miles in this part of the island. Detailed mapping, on the scale of 2 inches = 1 mile, intermittently between 1953 and 1963 has shown that this pink granite occurs mainly as two concordant sheet-like bodies, several miles long, in migmatitic and granitic gneisses, the more southerly of the two sheets being known as the Tonigala granite, *sensu stricto*. Such a mode of occurrence is thought to be interesting enough in the comparative study of basement complexes to warrant a description of the granite and its associated country rocks and a consideration of its emplacement.

The area in which the granite is found forms

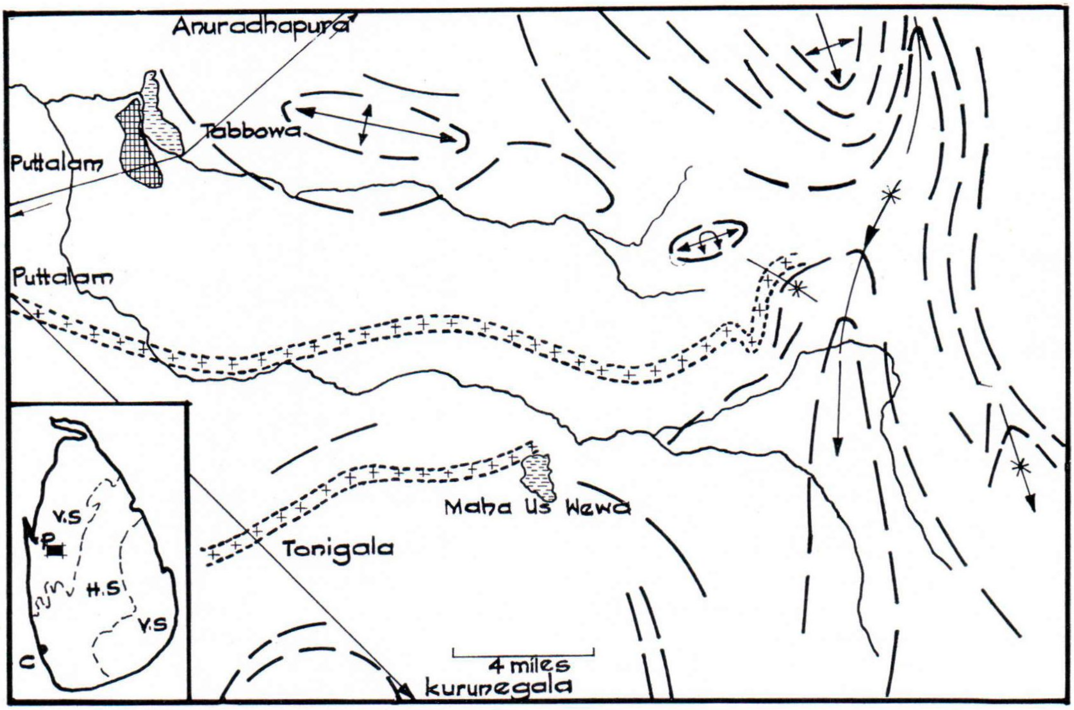

Fig. 1. Sketch map of the Tonigala granite (crosses) showing its relationship to surrounding gneisses and migmatites, the trend lines and major fold axes of which are indicated. *Inset:* Ceylon, showing position of map area and main PreCambrian units. H. S., Highland Series; V. S., Vijayan Series; C, Colombo; P, Puttalam.

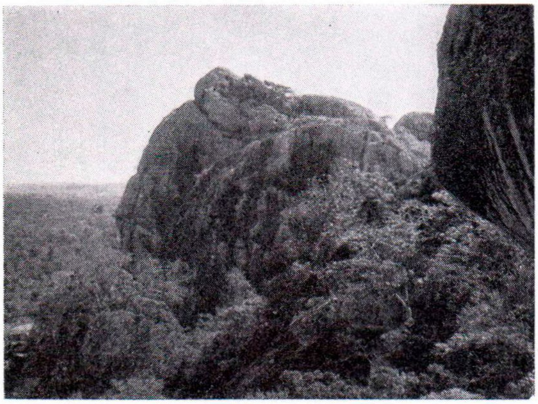

Fig. 2. Paramakande (534′), an inselberg of granite near Tonigala.

part of the crystalline complex of Ceylon occupied by rocks of the Vijayan Series (Fig. 1). The latter lie to the west and east of the granulite facies Highland Series (metasediments and charnockites) which occupy a broad zone running through the centre of the island. The Vijayan rocks in the north-west are mainly migmatitic and granitic gneisses formed under amphibolite facies conditions, and some, at least, are thought to represent Highland Series rocks altered during a later metamorphic episode(s) (Cooray, 1962a). Scattered within the gneisses are relatively rare bands of marble, calc gneiss, and biotite schist of sedimentary origin, remnants of a once more extensive supracrustal series. They now exhibit a »ghost stratigraphy» within this migmatite complex.

The Tonigala granite *(sensu stricto)* is between one and two miles wide and crosses the road from Puttalam to Kurunegala at Tonigala (Fig. 1), being well exposed in a large number of quarries, where the major part of this study was carried out. It crosses the road in a WSW-ENE direction but continues in a roughly W-E direction for about 8 miles, as far as Maha Us

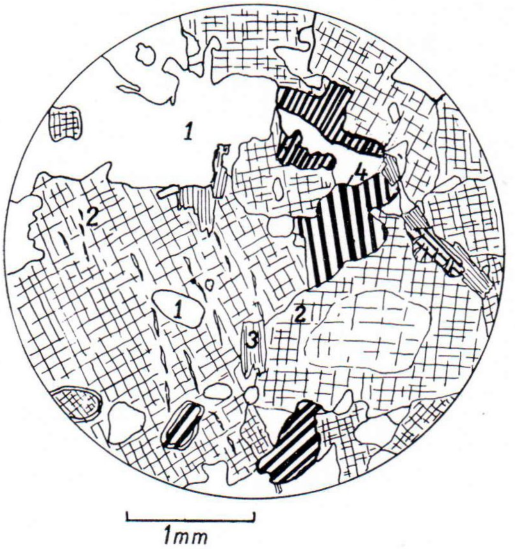

Fig. 3. Drawing of thin section of microcline granite from Tonigala (K. 881). 1-quartz, 2-microcline microperthite, 3-biotite, mostly chloritised, 4-plagioclase.

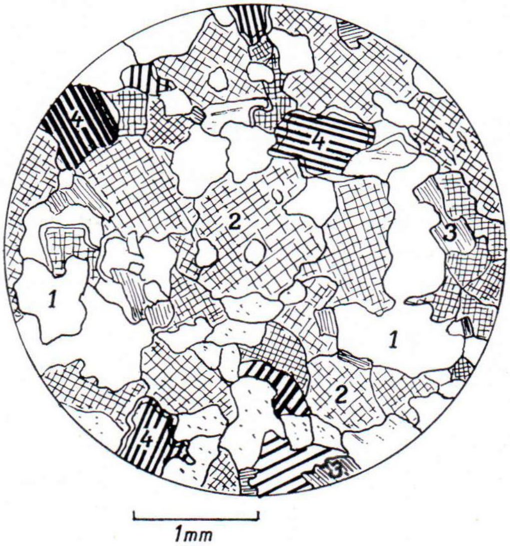

Fig. 4. Drawing of thin section of microcline granite from Tonigala (K. 888A). 1-quartz, 2-microcline, 3-biotite, mostly chloritised, 4-plagioclase.

Wewa, beyond which the granite cannot be traced. About four miles to the north is a similar sheet of pink granite which runs for about 20 miles in a parallel direction but is folded in a N-S direction at its eastern end. The total length of the two granite sheets is, therefore, about 30 miles, and nowhere along this length does either granite body transgress the surrounding gneisses.

Low, exfoliated, turtle-backed outcrops and a few prominent inselberges which rise to several hundreds of feet above the surrounding plain mark the outcrop of the granite (Fig. 2). Owing to the extent of the colluvial mantle and to the relative paucity of outcrops, exposures of the contact between granite and country rock are few, but the indications are that this contact is gradational.

Field relations and petrography

The Granite Proper

The granite at Tonigala is predominantly a pinkish, medium-grained, unfoliated rock, but it may vary in colour from greyish pink to red, and in texture from fine-grained aplitic to coarse-grained pegmatitic. Scarce biotite is the only ferromagnesian mineral present. Scattered through the rock are small ocelli of chloritised mica, 1 to 1½ inches across, surrounded by quartzo-feldspathic rims. A medium-grained grey granite occurs in a band 100 to 150 feet wide within the pink granite. It is more homogeneous than the pink granite. Also present within the pink granite are patches and bands of (a) trondjhemite, (b) dark pink foliated granite, (c) pinkish hornblende granite gneiss associated with hornblende schists and gneisses, and (d) leucocratic granite or granodiorite. These types are found in the surrounding country rocks as well.

The *pink granite* is composed essentially of quartz (34—40 %), microcline-microperthite (49—57 %), plagioclase (8—14 %) and biotite (1—3 %) (see Table 1). The microcline is highly perthitic to microperthitic, the sodium-rich phase being in the form of strings, rods, and veins. It occurs generally as well formed crystals

TABLE 1
Modal analyses of Tonigala granite

	Pink G.			Grey G.
	1 *	3	4	6
Quartz	35.1	39.5	33.5	36.5
Microcline—microperthite	51.1	48.7	56.9	48.5
Plagioclase	12.3	8.7	7.9	13.8
Mica	1.5	3.1	1.7	1.2
Others	tr.	tr.	tr.	tr.
Total	100.0	99.8	99.8	99.9

* See Table 3 for descriptions of specimens.

in which the typical cross-hatched twinning may be uniformly developed over the whole crystal or variable and in patches (Fig. 3).

The plagioclase is oligoclasic in composition (An$_{15-25}$ from optics, An$_{5-6}$ in the norm) and is well twinned, bent twin lamellae being present in specimens from the southern margin of the granite. The crystals commonly have rims of clear albite (Figs. 3 and 4), and marginal lobes of myrmekite often encroach on and replace the adjacent alkali feldspar. Intergranular veinlets of plagioclase are seen in some sections. A brownish red pigmentation, common to both feldspars, is the cause of the reddish colour characteristic of the granite, and kaolinization and sericitization of the feldspars are frequent. The relations of the feldspars to each other and to quartz are complex. Microcline very frequently has inclusions of plagioclase but at times the reverse relation is seen. Early quartz may be contained in later quartz, and microcline may also be enclosed by quartz (K.3002B)*. Microcline may itself enclose an earlier untwinned feldspar.

Biotite (X-yellow, Z-dark green) is almost the sole mafic mineral in much of the granite and occurs as wisps and small stubby flakes (Figs. 3 and 4). It is generally chloritized (at times to a penninitic variety) either completely or along cleavages and margins. Accessory minerals are scarce and include zircon, apatite, iron ores, and sulphides. Chemical analyses of the granite are shown in Table 3.

The *grey granite* (K. 882A) is almost identical to the pink granite in chemical composition (Table 3 no. 6) but differs from it in thin section. Microperthite, with undulose extinction and poorly defined patches of cross-hatched twinning, is the dominant feldspar; some oligoclase is present. A little vein albite and local patches of myrmekite can be seen. Biotite (X-yellow, Z-dark brown to reddish brown) is partly chloritisied, droplets of magnetite being liberated in the biotite-chlorite transformation. The feldspars are slightly altered, selective sericitization of alternate lamellae being common in the plagioclase crystals.

Within the grey granite are inclusions of a dark, fine-grained granulitic rock which is composed of comparatively fresh microperthite and plagioclase, subordinate quartz (mostly as secondary, rounded blebs) and biotite. The latter mineral may be fresh or altered to messy-looking patches of chlorite, iron ores, muscovite and epidote. Apatite is an accessory mineral. The contact between the grey and pink varieties of granite is gradational, with pinkish grey or greyish pink varieties between. A series of sections across the contact showed that the change from grey granite to pink is accompanied by (i) the development of albitic rims round plagioclase and cross-hatched twinning in microcline, (ii) increasing alteration of minerals, (iii) the loss of the even-grained texture, and (iv) progressive change in the colour of biotite from brown to green.

The *trondjhemitic* variety of the granite (K. 892) has quartz, oligoclase with albitic rims, hornblende, and biotite. In thin section, hornblende occurs in aggregates of large poikiloblastic platy crystals, and biotite (X-yellow, Z-dark brown) is in sieved laths intergrown with hornblende and replacing it The dark pink *foliated granite* is made up of quartz, oligoclase with albitic rims, and microperthite in crystallo-

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* Refers to Rock and Thin Section Collection, Geloogial Survey Department, Ceylon.

blastic growth, in which are set crystals of sphene and slightly sodic, partly chloritised hornblende. Sphene is almost an essential mineral and is found around the iron ores (chiefly magnetite) or associated with hornblende. Apatite is in large platy grains and a little zircon and accessory biotite are also present.

The *granodioritic* patches in the pink granite have biotite as a prominent mineral, microcline subordinate to oligoclase, and some antiperthite (K. 900B).

Veins and dykes

Anastomosing veins

The pink granite is traversed by an anastomosing system of narrow veins of darker colour and slightly coarser grain-size than the granite. The margins of these veins are diffuse and the difference between granite and vein material is so slight that the veins are often almost imperceptible. Scattered biotite flakes are present in the veins, larger flakes being present in the marginal zones. The granitic wall rock in contact with the anastomosing veins is often more basic than the rest of the granite.

The veins are identical with the granite when seen in thin section, except in respect of grain size, and the same complex relations of quartz and feldspar are present.

Pegmatites

Pegmatites having no visible connection with the anastomosing veins are common the in the granite. They sometimes occur as vertical to inclined dykes (Fig. 5) generally running N 70°E and N 20°W, but most of the pegmatitic material is in irregular discontinuous patches or lenses varying from a few inches to several feet across. Their margins are diffuse and the dykes often thin out and disappear in the granite.

The pegmatitic material is either pink or leucocratic; both types carry coarse biotites within them and have biotite-rich borders. Each type has patches of the other within it and the leucocratic pegmatites may occasionally pass along their length into completely pink pegmatites.

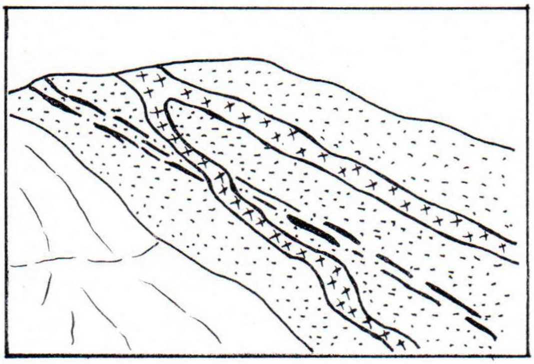

Fig. 5. Cross-cutting and conformable pegmatite dykes in pink granite at Tonigala.

The pink pegmatites, like the anastomosing veins, are very similar to the granite in mineralogical composition. The chemical composition of the one such pegmatite is given in Table 2, No. 1. A leucocratic pegmatite in pink granite (K. 953) has large crystals of microperthite which are traversed by veins of clear albite and are set in a groundmass of strained quartz, plagioclase, and microcline with cross-hatched twinning. A greyish pegmatite in the grey granite has slightly altered antiperthitic plagioclase and highly altered potassium feldspar with undulose extinction; iron ores are conspicuous, occurring as irregular grains and skeletal, sagenite-like growths.

Red micrographitic dykes

Fine-grained dykes of brick-red colour, 2 to 8 inches wide, also cut the granite, but generally lose themselves in fine-grained granitic patches. They commonly have marginal zones of red pegmatite, though leucocratic zones are present in some. They may pass into leucocratic pegmatites but cut across the pink pegmatites.

In thin section these micrographitic dyke rocks are seen to be composed of quartz, plagioclase, microcline, biotite and chlorite. (*e.g.* K. 897,

K. 898, K. 942C), and this feature, together with the high degree of alteration often makes the identification of the feldspars difficult. As in the granite, the red microgranitic dyke rocks are seen in thin section to have clear albitic rims to oligoclase grains, vein perthite, and cross-hatched twinning in the vicinity of brownish stained cracks. In one thin section (K. 898) microcline-microperthite grains are rimmed by clear zones with a higher refractive index. The chemical analysis of one of the micro-granitic dyke rocks is given in Table 2, No. 2.

TABLE 2

Chemical Analyses of Dyke Rocks and Xenolith in Granite

	1	2	3	4
SiO_2	72.42	72.81	72.01	62.53
TiO_2	0.19	0.10	0.41	0.73
Al_2O_3	15.13	15.43	13.70	16.85
Fe_2O_3	1.03	0.74	1.56	0.74
FeO	1.41	0.72	1.45	4.82
MnO	0.17	0.12	0.57	0.62
MgO	0.05	tr.	tr.	2.08
CaO	1.27	0.89	1.36	3.48
Na_2O	4.63	3.09	3.42	4.98
K_2O	3.25	5.30	4.98	2.75
P_2O_5	nil	nil	tr.	0.11
H_2O+	0.32	0.35	0.53	0.44
H_2O-	0.06	0.04	0.04	0.05
Total	99.93	99.59	100.03	100.18
Sp. Gr.	2.58	2.60		2.74
Niggli values				
si	370	413	380	243
al	45	51	42	35
fm	14	7	15	29
c	7	5	8	13
alk	34	36	35	23
c/fm	0.5	0.8	0.5	0.5
alk/c	4.9	5.2	4.4	1.8

Description of specimens

1. Pegmatite (K.3001) with large red feldspars, from quarry behind P.W.D. quarters, Tonigala.
   Well twinned, antiperthitic oligoclase dominant, more altered than microcline; chloritised biotite.
2. Brick-red microgranite dyke rock (K.898) from quarry behind P.W.D. quarters, Tonigala.
   Quartz as rounded grains and blebs in sieved feldspars; altered microcline-perthite with clear rims, subordinate plagioclase, chlorite.
3. »Purple» pre-granitic dyke rock (K.887) from behind P.W.D. quarters, Tonigala.
   Strained quartz, microcline-microperthite, plagioclase with bent lamellae; much altered feldspars; biotite, some chloritised, pale yellow monazite associated with biotite, and pale yellowish-green, zoned orthite?
4. Basic xenolith (K.895A) in pink granite, from quarry east of culvert 15/2, Puttalam—Kurunegala road, Tonigala. Biotite schist with little hornblende, biotite (X-yellow, Z-dark green); plagioclase the sole feldspar, well twinned and slightly altered; scarce quartz; platy apatite grains, ores, and zircon.

All analyses: J.P.R. Fonseka, M.Sc., D.I.C., A.R.I.C.,
Geological Survey Department, Ceylon,
1958.

The red microgranitic dykes appear to be of tectonic origin, probably formed by shearing along narrow zones which coincided with earlier zones of weakness occupied by pegmatites. Somewhat similar brick-red rocks have been noted on the margins of the Closepet Granite of Mysore where they are said to be restricted to zones of intense shearing (Radhakrishna, 1956, p. 25).

Pre-granitic dykes

A parallel swarm of narrow, purplish coloured dyke-like bodies is present in the quarries at Tonigala. They cut across veins, pegmatites, and inclusions in the granite but are themselves crossed by later pegmatites and veinlets. These dyke-like rocks are mineralogically similar to the granite except that monazite is a characteristic accessory mineral and the feldspars are much altered. The feldspars in the leucocratic margins of the »dykes» are oriented roughly parallel to the contact, and the quartz grains have irregularly shaped cores with dust-like inclusions and clear rims. The boundaries between the dykes, their leucocratic margins, and the granite are interdigital and gradational. The chemical composition of one of these dykes rocks is given in Table 2, No. 3.

The »purple» dykes are thought to have been intruded early in the history of the granite along an embryonic joint system and during a long period of pegmatisation; they have undergone the same metasomatic changes as affected the granite in the later stages of its history (see Cooray, 1962 b, for fuller description).

Enclaves in the granite

Enclaves in the granite, where present, are generally confined to narrow zones, as at Labugala (Fig. 6) and are seen to be relics of more extensive and continuous bands which have undergone transformation to granite. They are either lenses of biotite and/or hornblende schist or biotite-rich foliae in the granite.

Schist lenses

At Tonigala, lenses of biotite schist about 3 feet wide and 30 feet long were seen to form part of a small anticlinal fold structure plunging to the south-west. The schist was veined and permeated with pink feldspathic material (Fig. 7) and could be traced into zones of granite gneiss with biotitic foliae (Fig. 8 A, B) with the same orientation as in the schist; the gneissic patches finally passed into homogeneous granite.

In thin section, the schist lenses are seen to be made up of fresh, well oriented biotite (X-yellow, Z-dark green, almost black), quartz, slightly altered plagioclase, alkali feldspar, and a little hornblende (possible slightly sodic); large apatite crystals, zircon, allanite, and iron ores are accessory. Potassium feldspar is conspicuous in the pinkish veins of the more gneissic lenses. The contact between schist and granite is marked by a concentration of biotite. The chemical analysis of a typical biotite schist enclave is given in Table 2, No. 4.

Lenses of hornblende schist (as well as of biotite schist) are present at the foot of Mahagala, Paramakande, the lenses being veined by granitic material and separated from each other by patches of pegmatite (Fig. 9). Above the schist zones are lenticular patches of fine-grained granite simulating the shape and structure of the schistose enclaves below (Fig. 8 C, D). In thin section (K. 937A,B), hornblende (X-yellowish green, Z-brownish green) is associated with clinopyroxene, and long laths of reddish brown biotite traverse the other minerals. Plagioclase is the sole feldspar and sphene and apatite are the accessory minerals. In the more gneissic varieties (*e.g.* K. 973 C) biotite increases at the expense of pyroxene and sphene, and plagioclase is still the main feldspar.

Biotite-rich foliae

These are common in the granite and are of two kinds. Some are long and irregular, generally 0.2 inches wide, which either pass into coarse

Fig. 6. Lenses and irregularly shaped bodies of basic rock occurring in well defined, parallel zones in microcline granite at Labugala. Basic zones dip at about 50° to south. Height of hill about 100 feet.

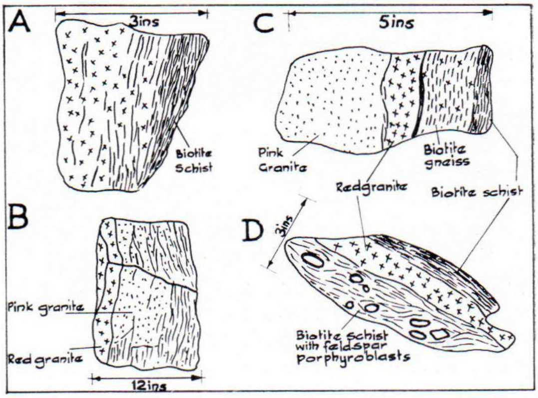

Fig. 7. Enclaves of biotite schist in granite at Tonigala, showing feldspathisation and various stages of transformation to granite gneiss and granite.
A, B: Granite gneiss with relic foliae. C: Red granitic veins in schist; note schist, gneiss, granite, and granitic vein in same hand specimen. D: Pink, microcline porphyroblasts in biotite schist.

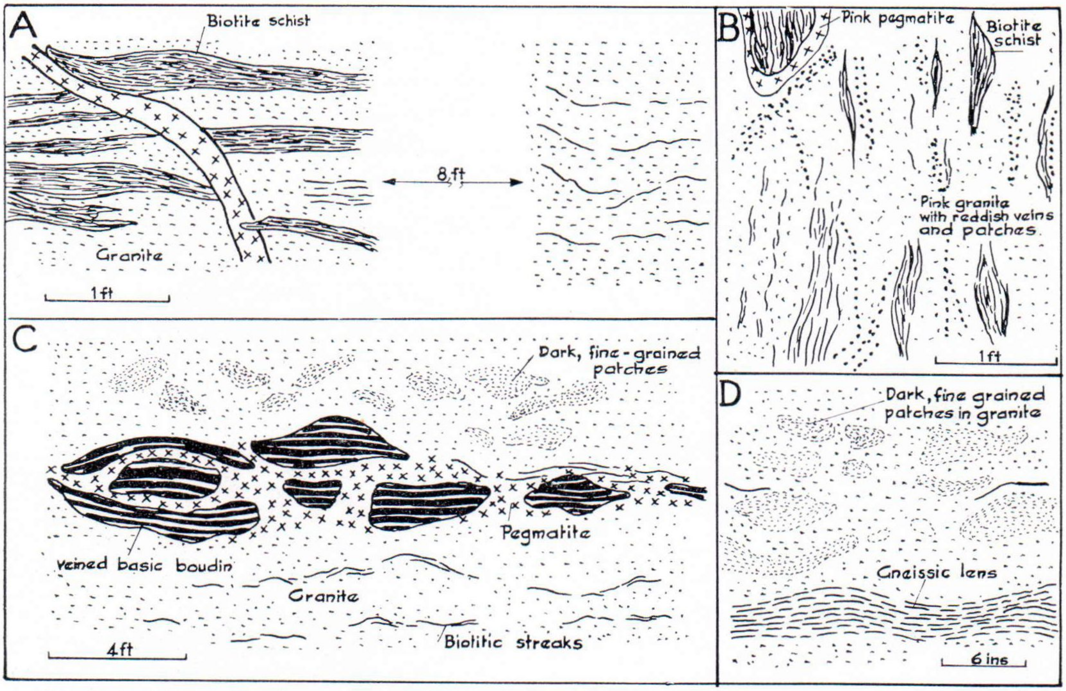

Fig. 8. A: Schist lenses in granite passing into granite gneiss with narrow biotitic foliae, Tonigala. B: Inhomogeneous pink granite with streaks and lenses of biotite schist and red granitic veins and patches, Tonigala. C: Microcline granite with boudins of gneissic basic rock; dark, fine-grained patches similar to the boudins; and biotitic streaks. Paramakande. D: Detail of fine-grained patches in granite, Paramakande.

Fig. 9. Hornblende schist lens in granite, at foot of Paramakande.

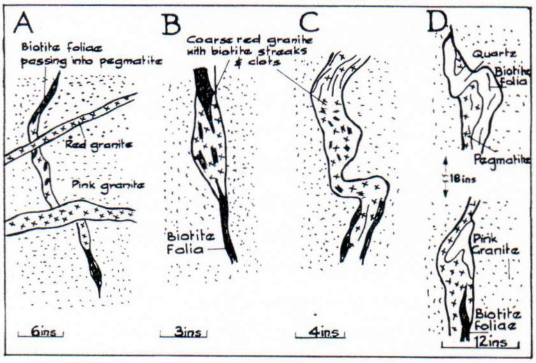

Fig. 10. A, B, C: Biotite-rich foliae in granite passing into red granite veins with wisps and aggregates of biotite. D: Biotite-rich folia terminating in pegmatitic and quartz-rich segregation.

red granitic veins with recrystallised biotite and then reappear as foliae (Fig. 10 A, B, C) or, more commonly, end in the granite as pegmatitic patches or as quartz segregations (Fig. 10 D).

Other foliae are in the form of folds or corrugations a few inches to about a foot in amplitude, and are only noticeable when their planar surfaces are exposed (Fig. 16). The axial traces of these folds and corrugations are an important structural element in the granite (see below).

The country rocks

The granite sheets are emplaced within a varying succession of migmatitic and granitic gneisses, the foliation planes of which are more or less parallel to the inferred boundaries of the granite and to the few foliation planes within it. The country rocks have undergone considerable recrystallisation but division into two broad groups is possible. These are (a) an earlier formed *supracrustal group* now represented by metasediments, amphibolites, and charnockitic rocks, and (b) a later formed *infracrustal* group of migmatitic and granitoid rocks. Both groups are cut by a profusion of aplitic and pegmatitic dykes and veins.

Supracrustal group

Metasediments: Marbles, calc gneisses, biotite schists, and biotite granulites occur several miles to the east and north-east of the granite but are rare in its immediate vicinity. About 1 ½ miles north of the granite, at Uriya Wewa, a well banded black-and-white gneiss has regular schistose bands of calcareous composition (containing brown phlogopite, clinopyroxene, green hornblende, apatite, sphene, quartz, microcline, and plagioclase). Narrow zones of intense granulation are indicative of shearing within the bands. In fact the frequent presence of hornblende, clinopyroxene, much sphene, and apatite in many of the gneisses of the area suggests that lime and magnesia-rich sediments were widespread in the original succession.

Basic rocks: These are mostly amphibolitic in composition and occur throughout the area as discontinuous bands, lenses, blocks, and irregularly shaped masses in all stages of transformation to the gneissic and granitic rocks in which they occur (Figs. 11, 12). The basic rocks are composed essentially of hornblende and plagioclase with or without biotite and/or clinopyroxene, the minerals occurring in varying proportions even within a single thin section (*e.g.* K. 964B).

Fig. 11. Amphibolitic enclaves surrounded by pegmatitic material in trondjhemitic granite gneiss, Galkadawala.

Fig. 12. Discontinuous gneissic bands disrupted by mobilisation of enclosing granite gneiss.

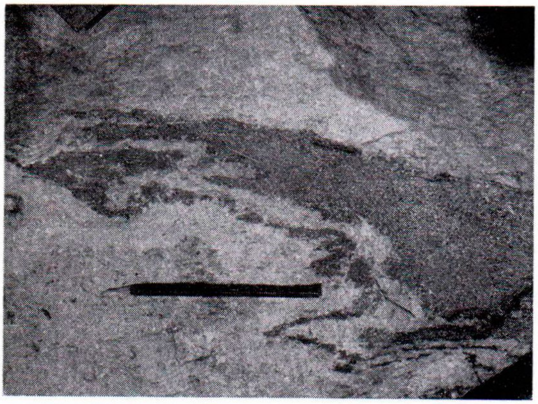

Fig. 13. Folded basic enclave in granitic rocks showing recrystallisation of margins.

These basic rocks pass into several types of gneisses and granitoid rocks in which recrystallisation of the mafic constituents of the basic lenses at their contacts with the granitoid rock is a marked feature (Fig. 13). As in the granite, the hornblende and plagioclase in most of the basic enclaves are very fresh, whereas in the slightly migmatised basic rocks both minerals are altered and hornblende can be seen developing from clinopyroxene. This suggests that many of the basic rocks were originally pyroxene-bearing, that the migmatisation was accompanied by the conversion of pyroxene to hornblende, and that some basic fixation took place in the basic rocks themselves during the migmatisation.

Charnockitic rocks: Dark grey, greasy-looking gneisses, charnockitic in appearance, form a broad band near milestone 14 ½ on the road from Anamaduwa to Andigama (Fig. 1). They have been »intruded» by pink granitic material, the resulting rocks being veined, banded, or streaky migmatites, dark greyish pink in colour, and pink granitoid rocks with aggregates of mafic minerals. The several types pass into each other through intermediate types both along and across the strike.

These charnockitic gneisses (K. 958A) have plagioclase and pyroxene or hornblende, with microcline in the more acidic parts; large zircons, iron ores and sphene are plentiful. The more granitoid types (K. 958B) are composed of perthitic microcline, quartz and a little plagioclase with aggregates of hornblende or clinopyroxene, generally altered. Orthopyroxene is very scarce and in a highly altered state but the macroscopic and microscopic characters of the least migmatised types are clearly charnockitic. Similar types were noted in the granite at Paramakande.

Infracrustal group

Most of the rocks surrounding the granite are granitic, granodioritic, or trondjhemitic in composition, and vary from well banded to streaky, blotchy, or granitoid in appearance. In many of the rocks two phases of migmatisation can be recognised—an earlier leucocratic phase, and a later pink microcline phase which has often completely obliterated evidence of the former. Relics of the earlier formed supracrustal rocks can be recognized in some of the migmatites, but in many of them homogenization has proceeded to such an extent that the original nature of the host rocks cannot be determined.

One common type is a fine- to medium grained gneiss, light pinkish in colour, in which a prominent foliation is caused by the presence of green hornblende. Another common type is a streaky reddish granite gneiss in which are found bands and lenses of hornblende schist, permeated and injected with varying amounts of pink microcline-rich granitic material.

Rocks unaffected by the later microcline migmatisation are found at Uriya Wewa and Galkadawala (see p. 27). At the former locality, streaky, granitic gneisses have been formed by the injection and permeation of basic schists by leucocratic granitic material in which the biotite is often chloritised. The gneissic and granitoid rocks at Galkadawala (Fig. 1) are mainly trondjhemitic in composition and they form a band that can be traced for over 4 miles along the strike. Very little or no microcline is present in these rocks.

Dykes and veins

Pegmatitic and aplitic dykes and veins occur in great profusion in the country rocks and they are both concordant and cross-cutting. Most of these dykes and veins have been emplaced metasomatically (see Cooray, 1961), and pink, microcline-rich pegmatites can be seen replacing the earlier leucocratic pegmatites, as at Uriya Wewa.

The rocks surrounding the granite are thus a heterogeneous group of dominantly migmatitic gneisses with some remnants of earlier formed rocks. As in the granite itself, an earlier migmatisation, chiefly granodioritic in composition was followed by a later microclinisation. The field relations and microscopic characters of the rocks show that these processes have been by selective replacement along bands and veins in the country rocks rather than by an extensive, forcible intrusion of granitic magma.

Structure

There are three major structural elements in the granite, namely, joints, linear structures, and planar structures.

Joints: In the absence of a major planar structure such as is found in the Flamanville Granite (Martin, 1952), the joints in the Tonigala granite are related to the granite sheet and may be classified as follows: —

A joints	— parallel to the length of the granite
BC joints	— transverse to the length of the granite and at right angles to the A joints
D joints	— oblique to the length of the granite.

The orientation diagram (Fig. 14), based on over 200 joint readings, shows that (i) the BC joints are the most conspicuous and have a constant NW-SE orientation, and (ii) that the A joints, trending E-W, although more numerous, have a wider scatter. The BC joints form a set of small, close-set parallel joints (Fig. 15) which is seen in nearly every quarry. A small amount of slip appears to have taken place along the joint planes, and the joints are post-pegmatitic in age. The A joints exert a controlling effect on the physiography of the granite as seen in the presence of numerous, long boat-shaped rock pools and in the elongate nature of many

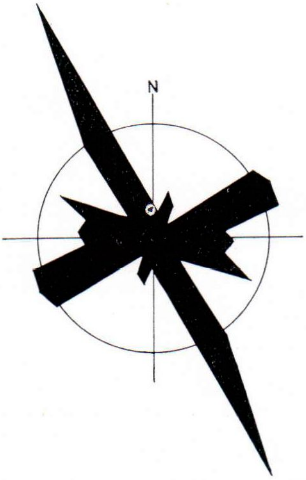

Fig. 14. Rose diagram of joints in Tonigala granite (over 200 readings).

Fig. 15. Close-set, parallel BC joints in Tonigala granite.

TABLE 3

Chemical analyses of granites from Tonigala.

	1	2	3	4	5	6	7	8	9
SiO_2	73.20	72.43	72.21	71.90	72.44	72.88	72.80	74.67	73.04
TiO_2	0.14	tr.	tr.	tr.	tr.	tr.	0.08	tr.	0.22
Al_2O_3	14.75	15.43	15.20	14.93	15.08	14.29	14.31	12.33	14.03
Fe_2O_3	0.78	0.54	1.36	1.71	1.10	1.32	1.01	1.57	0.61
FeO	0.90	0.55	0.60	0.76	0.70	0.61	0.91	1.67	1.16
MnO	0.01	0.13	0.52	0.07	0.18	0.05	0.01	—	0.02
MgO	0.08	0.12	tr.	0.10	0.08	0.20	0.14	tr.	0.36
CaO	1.46	1.12	1.14	1.46	1.30	1.29	1.70	1.24	1.14
Na_2O	5.04	3.76	4.98	3.38	4.29	4.15	4.98	2.34	2.78
K_2O	4.02	5.50	4.74	5.12	4.85	4.47	2.89	5.85	6.07
P_2O_5	tr.	nil	tr.	tr.	tr.	tr.	tr.	0.07	0.08
H_2O+	0.12	0.07	0.10	0.10	0.10	0.19	0.10	0.42	nil
H_2O-	n. d.	0.01	0.05	0.09	0.05	0.17	0.17		0.51
Total	100.50	99.66	100.90	99.62	100.17	99.62	100.10	100.16	100.02
Sp. Gr.	2.63					2.64	2.64		
K_2O:Na_2O mol	.53	.95	.63	1.00	.75	.72	.51		
K_2O:CaO mol	1.65	2.9	2.46	2.09	2.27	2.08	1.36		
Niggli values									
si	381	391	392	390	389	360	346		
al	45	49	45	48	47	42	40		
fm	8	6	10	9	8	16	17		
c	8	7	6	8	7	7	9		
alk	39	38	39	35	38	35	34		
c/fm	1.0	1.2	0.6	0.9	0.9	0.4	0.5		
alk/c	4.9	5.5	6.5	4.4	5.3	5.0	3.8		
C.I.P.W. Norms									
Quartz	24.78	26.58	22.62	28.92		28.32			
Orth.	23.91	32.25	27.80	30.58		22.69			
Albite	42.44	31.96	41.92	28.82		35.11			
Anorth	5.84	5.56	5.28	6.23		6.39			
Cor.	—	1.22	—	1.02		.20			
Diop.	.96	—	.25	—		—			
Wo	.12	—	—	—		—			
Hyp	.50	1.22	.66	.43		.96			
Mag	1.16	.70	2.09	2.55		1.86			
Ilm	.30	—	—	—		—			

Descriptions of specimens

1. Pink granite (K.881), type specimen from quarry near culvert 15/3 on Puttalam—Kurunegala road, Tonigala. Irregular quartz, and microcline-microperthite; subordinate oligoclase with clear albite rims, myrmekite encroaching on alkali feldspar, and narrow intergranular veinlets of plagioclase; rounded zircons; feldspars altered and biotite chloritised.
2. Pink granite (K.969C), from south-western end of Maha Us Wewa, on pathway from old bungalow to spillway; eastern end of granite.
3. Pink, fine-grained granite (K.888A), representative sample from quarries between culverts 15/1 and 15/2 on Puttalam—Kurunegala road, Tonigala.
   Irregular quartz, dominant microcline enclosing quartz and plagioclase, oligoclase with clear albite rims, chloritised biotite.
4. Greyish-pink granite (K.943A) from Pinwewa, about 1½ miles on Karambewa road; southern margin of granite.
   Conspicuous quartz, well twinned microcline, some microperthite; well twinned oligoclase with bent lamellae, albitic rims, and inclusions of microcline; chloritised biotite.
5. Average composition of Nos. 1 to 4.
6. Grey granite (K.882A), fine to medium-grained, from quarry north of road to Uriyawa, near Tonigala junction.
   Quartz, oligoclase, microperthite (with shadowy extinction) nearly equal to plagioclase; feldspars relatively fresh, chloritised biotite and other chloritic patches, monazite, droplets of dark blue mineral.
7. Grey granite (K.998A), from quarry south of road to Uriyawa.
8. Fine-grained pink granite, Closepet, India (Radhakrishna, 1956, Table I, No. 8).
9. Microcline granite, S. Finland, average of 18 samples. (A. Simonen, 1960, Table XXIX).

Analyses 1 & 6: O. C. Wickremasinghe, B.Sc., Geological Survey Department, Ceylon, 1956.

Analyses 2, 3, 4, 5: J. P. R. Fonseka, M.Sc., D.I.C., A.R.I.C. Geol. Surv. Dept. Ceylon, 1956.

of the outcrops. The majority of the joints are vertical or very steeply inclined and quartz and epidote often develop along the joint planes.

Linear structures: These are the most significant structural element in the granite and are mainly the axial traces of minor folds (Fig. 16) and corrugations of biotitic foliae (see p. 26). A plot of 30 readings taken from the Tonigala quarries and from Maha Us Wewa shows that these axes have a pronounced orientation in a SSW direction (Fig. 17). The plunge of the axes varies from 10° to 30°.

Similar axes are present throughout the country rocks and a plot of 25 readings shows that there is a wider scatter than in the case of the granite, with a preferred orientation to the SSE and a secondary orientation to the SSW. The readings are admittedly insufficient to give a true picture of the structure of the region, but they suggest that (i) the granite is part of a southward-plunging structure, and (ii) that the surrounding migmatites are also folded into a dominantly southward-plunging structure, though this is less definite, possibly because of the greater amount of plastic deformation which the country rocks have suffered.

Planar structures: The foliation planes of the schist and gneiss enclaves and of isolated biotite-rich foliae provide the main planar structural element of the granite. In the latter they run slightly north of east and dip to the south-east at about 40°. In the country rocks, those on the west dip to the east, those in the centre dip to the south, and those on the east dip to the west. Their attitudes support the earlier suggestion that the migmatites surrounding the granite are folded into a major southward plunging synformal structure and that the granite itself is part of the same structure.

Petrochemistry

The modal composition of the Tonigala granite is given in Table 1 (see p. 22) and chemical analyses of the granite and associated rocks are given in Tables 2 and 3. Table 3 contains analyses of four specimens of the pink microcline granite (Nos. 1—4), the average composition of the granite (No. 5), and analyses of two examples of grey granite (Nos. 6 & 7). Analyses of the Closepet granite of India (No 8) and the average composition of 18 late-kinematic

Fig. 16. Folded biotite folia in granite, Tonigala.

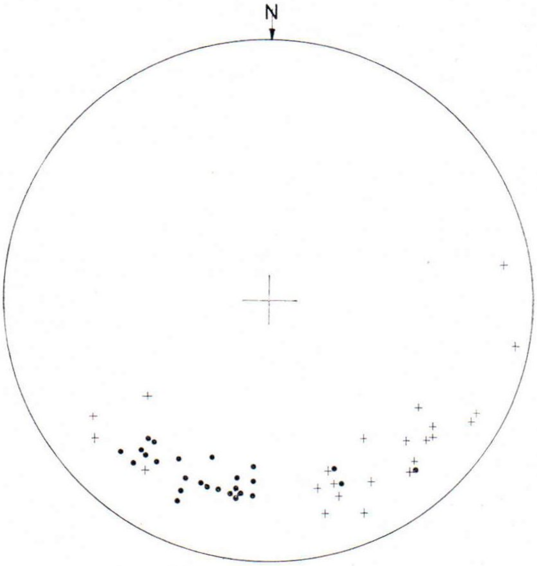

Fig. 17. Stereogram of minor fold axes in granite (dots) and in surrounding migmatites (crosses). (Schmidt net, lower hemisphere).

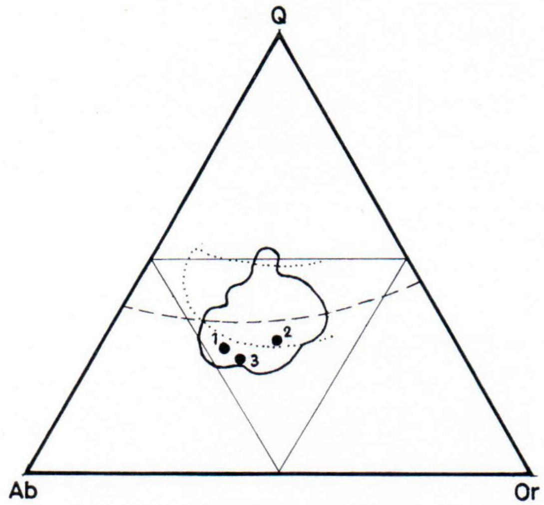

Fig. 18. Plot of normative proportions of analyses 1, 2, and 3, Table 3, on Ab—Or—Q diagram showing their position with respect to the field occupied by 75 % of 1190 granites plotted by Winkler and von Platen (Winkler, 1967). Dotted line, field of most common anatectic melts; dashed line, cotectic line of system $Q+Ab+Or+H_2O$ at $P_{H_2O} = 2\,000$ bars (Tuttle and Bowen, 1958).

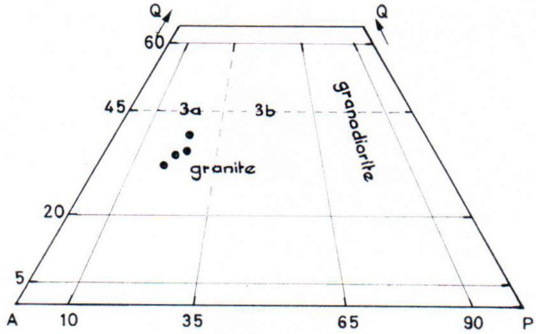

Fig. 19. Plot of Tonigala granite composition on QAP diagram (after Streckheisen, 1967).

granites from Finland (No. 9) are included for comparison. Analyses of the dyke rocks and of a basic inclusion in the granite are shown in Table 2.

It can be seen from these analyses that the Tonigala granite contains more than 80 % of the normative constituents albite-orthoclase-quartz, and that it lies in the central part of the Ab—Or—Q triangle (Fig. 18). The three plotted analyses (Table 3, Nos. 1, 2, 3) fall on the outer margin of the field occupied by 75 % of the 1190 granites plotted by Winkler and von Platen (Winkler, 1967, Fig. 50) but lie outside the field containing 53 % of the same granites. The Tonigala granite can be said therefore to be a true granite within the strict petrological meaning of the term. At the same time, the three plotted analyses show certain interesting relations which tend to support the field evidence regarding the origin of the granite. For example, the analyses plot away from the cotectic line of the system $Q+Ab+Or+H_2O$ at $P_{H_2O} = 2\,000$ bars as determined experimentally by Tuttle and Bowen (Tuttle & Bowen, 1958). Again, when plotted on the QAP diagram (Fig. 19) they lie in sub-field 3a, *(i.e.* essentially potash feldspar granites) which, by implication, does not contain the eutectic compositions of most magmatic solutions leading to granitic melts (Streckheisen, 1967, p. 167). Finally, they lie outside the field of most common anatectic melts (Fig. 18) as delineated by Winkler (Winkler, 1967, Fig. 51).

Marmo (1955 a, p. 404) has shown that the PreCambrian granites of Finland and West Africa can be empirically classified into four groups, on the basis of the relationship

$$SiO_2 \text{ mol: } \frac{K_2O + Na_2O}{CaO} \text{ mol.}$$

The granites in Group I of this classification (Fig. 20) have a ratio >3.5 and an SiO_2 mol. value which is never less than 116. The alkali: lime ratio of the average composition of the Tonigala Granite is 5.2 (Table 3, No. 5) and it has an SiO_2 mol value of 122; it therefore falls within Group I of Marmo's classification, as do all the individual analyses.

The molecular ratio of K_2O:Na_2O for the Tonigala Granite lies between 0.5 and 1.0, with an average value of 0.75 (Fig. 21). The granite is therefore not unduly rich in potash, Na_2O being greater than K_2O in some specimens. It may be classed as a sodi-potassic variety of granite. Although microcline is the dominant feldspar, the preponderance of perthite accounts for the relatively high sodic content of the granite. The combined values of the alkalies, however, is greater than 10 in all the analysed specimens (average value 12.1) and consequently the granite is comparable to the potassic subgroup of the late-kinematic Svecofennidic granites (Marmo, 1955).

The petrochemical similarly of the Tonigala granite to the late-kinematic granites of Finland is in fact very striking and is brought out in a number of relationships. In Fig. 22 for example, the values of $CaO:SiO_2$ and of $K_2O+Na_2O:SiO_2$ have been plotted on the double variation diagram plotted for the West African Pre-Cambrian granites (Marmo, 1956). It is seen that the values of the Tonigala granite correspond closely to those of the late-kinematic granites. In the case of the Finnish granites, as in the West African granites, the late-kinematic granites are separated by a sharp discontinuity from the synkinematic granites and granodiorites (Simonen, 1960).

The molecular ratio $K_2O:CaO$ is also useful in distinguishing between the synkinematic and late-kinematic granites of Finland. According to Wahl (1936) this ratio is characteristically more than 2 for serorogenic (= late-kinematic) granites and less than 1 for the primorogenic (= synkinematic) granites. The K_2O/CaO ratio is more than 2 in three out of the four specimens of pink Tonigala Granite analysed (Table 3), the average value being 2.3.

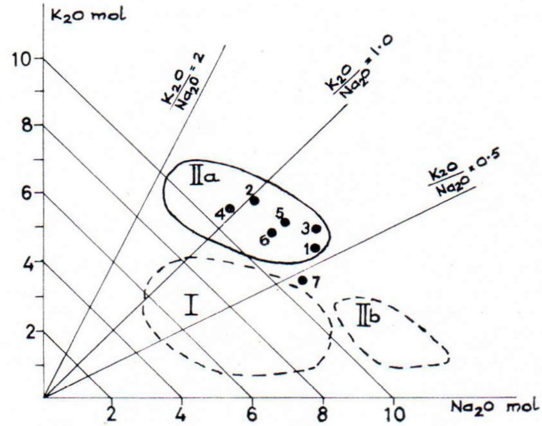

Fig. 21. Plot of Tonigala granite composition on K_2O: Na_2O mol variation diagram of granitic rocks of W. Africa (after Marmo, 1955). I — Synkinematic granites and granodiorites, II a — Late-kinematic granites, potassic sub-group, II b — Late-kinematic granites, sodic sub-group.

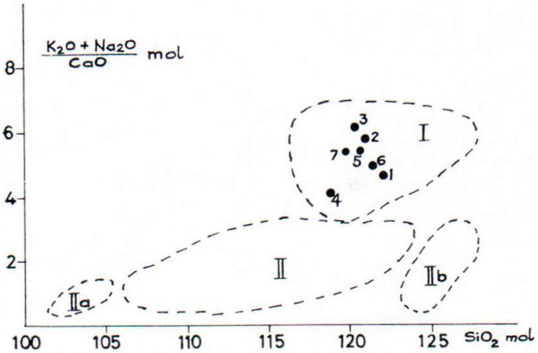

Fig. 20. Plot of Tonigala granite composition on SiO_2: $\frac{K_2O + Na_2O}{CaO}$ mol diagram (after Marmo, 1955) showing that they fall within Marmo's Group I for Finnish and West African granites in which SiO_2 mol > 116 and ratio > 3.5.

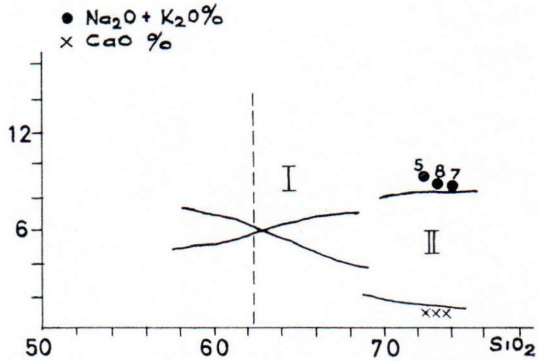

Fig. 22. Plot of Tonigala granite composition on double variation diagram of West African PreCambrian granites (after Marmo, 1956). I — Granites corresponding petrochemically to synkinematic granodiorites and granites, II — Granites corresponding petrochemically to those of late-kinematic origin. Dots, Na_2O+K_2O: SiO; crosses, $CaO:SiO_2$.

Again, when the Niggli values *al*, *alk*, *fm*, and *c* are plotted against *si* (Fig. 23) they are seen to fall within the fields of the late-kinematic Finnish granites (Simonen, 1960), and the *si: al* ratios of the Tonigala granite specimens are comparable to both those of the late-kinematic Finnish and West African granites (Fig. 24) but are not similar to the values for the »urganites» of Central Sweden. Finally, the *alk:c* ratio which is more than 3.5 in all analysed specimens of the Tonigala granite falls within or close to the field occupied by the Finnish late-kinematic granites (Marmo, 1955).

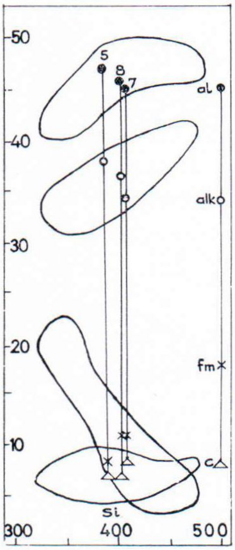

Fig. 23. Plot of Niggli values *si:al*, *alk*, *fm* and *c* for average pink Tonigala granite (5), grey granite (7), and Closepet granite (8). Areas outlined show corresponding fields occupied by Finnish late-kinematic granites (after Simonen, 1960, Fig. 37).

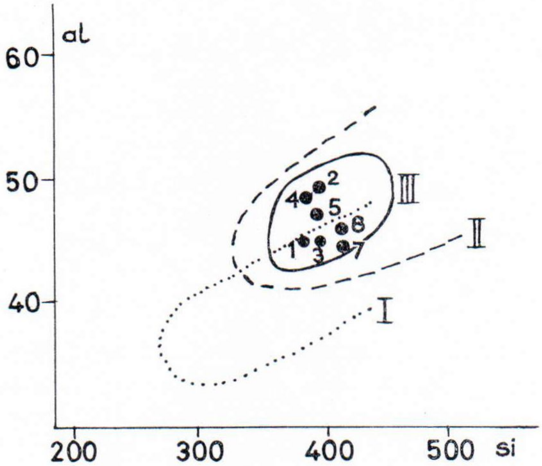

Fig. 24. Plot of *si:al* ratios of Tonigala granite. I — Field of Urgranites of Central Sweden, II — West African granites, III — Svecofennian late-kinematic granites.

The Tonigala Granite may thus be said to belong to the potassic sub-group of the sodipotassic granites, and it approximates most closely in its chemical composition and petrochemical characteristics to the late-kinematic granites of West Africa and of the Svecofennidic chain of S. Finland. Petrochemical similarity cannot, however, by itself determine the tectonic environment of a granite, since even the synkinematic plutonic rocks of S. Finland, though dominantly granodioritic in composition, also contain some granites which approximate to the late-kinematic granites in chemical composition. The tectonic position of the Tonigala granite can therefore be estimated only by taking into account other factors as well (see below).

Emplacement of the granite

Mode of emplacement

The bulk of the field and petrographic evidence presented, supported by the petrochemical evidence, suggests that the Tonigala granite was to a large extent formed by the replacement of pre-existing rocks, and not by crystallisation from a magmatic or anatectic melt.

Among such evidence might be mentioned:

a) the presence of scattered enclaves of basic schist and gneiss within the granite which appear to be undisturbed and which are parallel to basic bands outside it;

b) the presence of fine-grained patches in the granite simulating the size and shape of existing enclaves;

c) the incipient feldspathisation, veining, and ultimate conversion to granite of enclaves within it;

d) the presence of corrugations of biotite foliae with constant axial directions both in the granite and in the surrounding country rocks;

e) the undisturbed nature of pre-granitic dykes and folds in the granite;

f) the replecement origin of small intrusive bodies of pink granite and of cross-cutting pegmatite dykes in the surrounding country-rocks;

g) the textural relations of the feldspars, particularly the replacive character of microcline; and

h) the presence of patches of trondjhemite and granodiorite in predominantly granitic rocks.

The nature and predominance of well-formed microcline, not only in the granite proper but also in the schist enclaves, the pegmatites, and the pre-granitic dykes, and the frequent presence of microcline-bearing gneisses and patches of granite in the country rocks suggest that a widespread potassium metasomatism or »microclinisation» was the last major episode in the plutonic history of the area. It was, in fact, a regional phenomenon which reached its culmination in the zones now occupied by the pink granite. This was followed or accompanied by a minor sodic phase, possibly due to the sodium replaced by the previous potassium metasomatism, and took the form mainly of albitic rims around oligoclase grains in the granite *(cf.* Coombs, 1950), of replacement myrmekite, and of intergranular films of plagioclase. At the same time, the cafemic elements released in the microclinisation were fixed in the biotites and hornblendes of the enclaves in the granite proper, thus explaining their remarkable freshness.

Time of emplacement

An attempt has been made in Table 4 to list the characteristic features of synkinematic and late-kinematic basement granites as defined by Eskola. It is based largely on the recent revised study of granite by Marmo (Marmo, 1967).

If the features of the Tonigala granite as described in the foregoing sections are compared with this table, it will be seen that although the granite resembles the latekinematic granites in many respects, it does possess certain features characteristic of the synkinematic granites.

In its petrochemical properties, its size, the presence of well formed microcline, the absence of sphene and epidote, and the absence of genetically related basic and intermediate rocks, for example, the Tonigala granite is tectonically a late-kinematic granite. The presence of microperthite is, however, unusual for such granites. According to Marmo (1967) the plagioclase of most late-kinematic granites tends to be albite having a composition of An_{1-15}. In the Tonigala granite, the plagioclase is oligoclasic in composition, ranging from An_{15} to An_{25}, though when calculated from chemical analyses the normative plagioclase contains 5.3 to 6.4 anorthite. In this respect as well as in the commonly occurring albitic rims round more basic plagioclase, the Tonigala granite resembles synkinematic granites.

It is thus clear that the Tonigala granite must fall in time between the synkinematic and the late-kinematic granites and may be classed either as »late synkinematic» or »early late-kinematic», thus underlining the fact that a clear distinction between the two magmatectonic types suggested by Eskola and others is not always possible. Even in Finland it has sometimes been found impossible to draw a sharp division between synkinematic and late-kinematic granites (see Simonen, 1960, p. 31), and this is to be expected by the very nature of the continuity of the orogenic process.

The Tonigala granite occurs in an environment of synkinematic gneisses, migmatites, and granitoid rocks of varying composition, and it is probable that, as in the Bartica Assemblage of British Guiana (Cannon, 1965), it has acquired its late-kinematic characteristics and true granitic composition through subsequent potassium metasomatism. Such a time sequence appears to be supported by recent Rb-Sr age data (Craw-

TABLE 4

A comparison of Synkinematic and Late-kinematic granites (after Simonen (1960) and Marmo (1967)).

	Synkinematic	Late-kinematic
Equivalents	Prim-orogenic Synorogenic Harmonious Autochthonous	Ser-orogenic (Wahl) Late-orogenic (Saksela) Disharmonious (Walton) Intrusive (Read)
Time of emplacement	Middle stages of orogeny	Late stages of orogeny
Size	Batholithic	Variable: veinlets, *dykes* bosses, stocks.
Relation to surrounding country rock	*Concordant*	Discordant, intrusive; forms migmatites with country rocks
Composition	Granodioritic to quartz-dioritic; minority granitic; $\frac{K_2O}{CaO} < 1$	Chemically near »ideal» granite. $\frac{K_2O}{CaO} > 2, \ > 4$
Plagioclase	*Characteristically oligoclase,* An_{25-30}. *Albite rims common*	Characteristically albitic, An < $_{10}$
Alkali feldspar	*Microperthite usual.* Microcline interstitial— in veinlets or replacing plagioclase	Perthite usual. *Microcline in well-formed grains* comparable with plagioclase and quartz
Epidote	Frequent, but not typical or abundant	*Uncommon or sparse-* except in some
Mica	*Biotite predominates over muscovite* and hornblende	Characteristically muscovite granite; hornblende seldom seen
Associated rocks	Have genetically related basic rocks like gabbro, quartz-diorite etc.	*Do not have genetically related basic and intermediate rocks.*

(Features shown by Tonigala granite in *italics*).

ford, 1969, p. 383) which shows that the Vijayan retrogressive metamorphism and migmatization took place at 1 150±50 m.y. and that the Tonigala granite was emplaced at 985±30 m.y. The nearest neighbour of the Tonigala granite of which a detailed description is available is the Closepet granite of Mysore (Radhakrishnan, 1965). This is said to have been emplaced in Peninsular Gneisses of South India and formed by progressive granitisation of trondjhemites to granodiorites and ultimately to granite by the microclinisation of older plagioclase. Although the Rb—Sr ages given by Crawford (Croawford, 1969, p. 381) are very different from the Ceylon rocks *(e.g.* Peninsular Gneisses of Bangalore 2 590±40 m.y.; Closepet Grnaite 2 380±40 m.y.), the field settings and petrological characteristics of the two granites are comparable and they appear to have had similar plutonic-tectonic histories.*

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* Crawford warns, however, that the »Closepet Granite» is a complex and heterogeneous body likely to have components of different ages.

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