THE GEOLOGY OF TEHILLA IGNEOUS COMPLEX,
KASSALA PROVINCE, SUDAN.

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THESIS SUBMITTED FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY IN THE UNIVERSITY OF KHARTOUM

AUGUST, 1972.
Panoramic View of Tehilla

granite-porphyry enclosing

the core-troctolite intrusion.

TGP = Tehilla granite-porphyry.

CT = Core-troctolite.

CR = Country rocks.
ABSTRACT

The geology of Tekilla complex and the surrounding basement rocks is described. The latter are mainly meta-sedimentary schists and granitic gneisses with syntectonic intrusions of adamellites.

The Tekilla complex shows great resemblance to Younger Granites of Northern Sudan and North Africa. It forms shallow-level, post-tectonic, ring-shaped outcrops of acid and basic intrusions of possible Lower Palaeozoic age. The basic rocks comprise an early phase of troctolites and norites emplaced in the form of a lopolith and sill-bodies respectively. The acid rocks (mainly granites) have been emplaced later as high-angle cone-sheet bodies. Contact relationships indicate a short evolutionary cycle for Tekilla igneous intrusions, since no chilled zone is detected.

The complex has a general alkaline character and the predominance of basic rocks over the acid ones, coupled with petrographic and chemical evidence suggest a consessional origin for the basic and acid rocks. Consequently a basic (basaltic ?) alkaline magma has been proposed from which both rocks have evolved by a process of differentiation. The parent magma seems to be relatively dry and could have differentiated slowly underneath prior to intrusion.
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I. INTRODUCTION

1. PURPOSE OF THE STUDY

The present study is a continuation of a detailed research work on the Younger Granites of northern Sudan. The Younger Granites were first recognized as the latest subdivision of the Sudan basement complex by Andrew (1948), and subsequently have been investigated by many workers: Delany (1955, 1958), Gass (1955), Almond (1967, 1971), Ahmed (1968), Almond et al. (1969), Gindy and Andrews (1969), Gindy and Amazis (1970), Vail and Rex (1970), Whiteman (1971) and Vail (1971 a, 1971 b and 1972). The Younger Granites group is mainly made of alkali granites and syenites associated with minor basic intrusions and volcanic extrusives. They are emplaced mainly in the form of ring-complexes, possibly during the Ordovician period (Vail and Rex, 1970). These rocks are closely comparable with other rock groups described from Nigeria, Zinder, Niger, Air, Tibesti, Ahaggar, Egypt, Saudi Arabia, etc., which together constitute one of the largest petrographic provinces in the world — the North African Province.

The Younger Granites apart from being economically interesting are of economic potentiality, since some are associated with important mineralization; a tin-tungsten-niobium mineralization is commonly associated with Nigerian complexes. Similar occurrences have been reported from Sahara (Dukun, 1965), Egypt (Ainin, 1947) and Sudan (Almond, 1967). Therefore, the interest in the study of the Younger Granites of Sudan has greatly increased since 1967 and it was decided
to study one of these complexes (Tehilla) in detail.

2. LOCATION AND ACCESS

Tehilla complex lies in the central part of Kassala Province at 17°47' N and 36°06' E, 84 km south of Kairou railway station. It forms an oval-shaped outcrop with axes 16 km (NE-SW) and 11 km (NW-SE) and covers an area of about 81.5 km². The complex is traversed by Kassala – Port Sudan railway and lorry track, therefore, it is readily accessible. Across the complex itself is a network of minor routes constructed by the British army during the Second World War. These routes have made the complex more accessible and thus enabled the author to visit and investigate most parts of the intrusion.

3. PREVIOUS WORK

Delany (1955) was first to recognize Tehilla complex and other intrusions in Sudan as ring structures. He again (Delany, 1956) paid attention to the geology of Tehilla complex while doing a regional geology work during 1951-1955 in the vicinity of Derakib (20 km south of Tehilla). Delany has provided a geological map for the complex using aerial photographs, with short accounts on the lithology of the rock-types recognized.

Omer Ahmed and two other geologists from the Geological
Survey Department of the Sudan Republic in 1963-1964 visited the same area mapped by Delany prospecting for economic mineral deposits and water supply. They submitted an unpublished report in 1964 which includes general remarks on the geology, structures and economic potentialities of the region. They noted two localities of ilmenite-titanomagnetite ore-minerals within Tehillah complex, but the present author was not able to detect more than one locality (Fig. 2).

According to Omer Ahmed and his colleagues (1964) M.I. Gumaa had visited Tehillah complex in 1957 to investigate the ilmenite-titanomagnetite ore-deposit.

4. PRESENT WORK

Aerial photographs on a scale of 1:40,000 were used for field mapping, which totalled about six months, spread over the field seasons of 1968, 1969 and 1971.

Laboratory investigations occupied 14 months spent at the Department of Earth Sciences in the University of Leeds to do microscopic studies as well as chemical analyses of 45 rock samples. A universal stage was used to determine the extinction angles of the plagioclases and the optic angles for the olivines and pyroxenes. Chemical analyses were done by X-ray fluorescence (XRF) method using Phillips machine supplemented by wet chemistry and Planochromatography methods.
The C.I.P.W. norms were calculated using an Algol computer programme written by K.H. Hey and R.H. Le Maitre of the British Museum and E.G.M. Butler of Oxford University.

3. ACKNOWLEDGEMENTS

The author is indebted to his supervisor, Professor J.R. Vail, for his guidance and helpful assistance in the field and during the preparation of this thesis. I am also indebted to my external supervisor Dr. P.E. Baker of the Department of Earth Sciences at the University of Leeds for supervising the laboratory work and critically reading parts of the thesis during my stay in Leeds.

Grateful thanks are due to Dr. D.O. Almond of Kingston College of Technology, U.K., who allowed me to make use of his unpublished chemical analyses of the Sahulok complex, and for reading and commenting on some parts of the text. I wish to express my gratitude to Prof. A.M. Daminova of People's Friendship University, U.S.S.R. for identifying one of my rock samples at her laboratory.

I am grateful for Prof. R.M. Shackleton and Prof. P.G. Harris, University of Leeds, who kindly permitted me to use their departmental facilities. Sincere thanks are also due to the staff and members of the Department of Earth Sciences at Leeds University, especially: Prof. T.N. Clifford, Dr. G. Hormung, Mr. T. Padfield, Mr. F. Buckley,
Dr. J.H. Rook and Mr. T.F. Johnston for helping me in carrying out
the chemical analyses and petrographic investigations. I should
like to acknowledge that the computer program used for the C.I.P.W.
norm calculation was written by Dr. M.H. Hoy and Dr. R.W. Le Maitre
of the Department of Mineralogy, British Museum (Natural History),
and Dr. E.C.M. Butler of the Department of Geology and Mineralogy,
Oxford.

I wish to express my gratitude to Dr. S.N. El Rabaa of the
Geology Department, University of Khartoum, for making useful suggestions
and to Dr. N.A. Shargawi of the same department, who has greatly
helped in opaque-minerals identification of the Younger Granite basic
phase and the massive ilmenite-titanomagnetite deposit.

Financial support for the research is greatly acknowledged
from the Postgraduate Studies Committee of the University of Khartoum,
and I thank Dr. I.M. El Boschi, head of the Geology Department, for
authorizing departmental funds to meet part of the expenses needed
for completion of extra copies of the thesis.
II. PHYSIOGRAPHY

1. CLIMATE AND VEGETATION

The complex lies in an arid region which is warm and dry for most of the year. The rains are few and confined to the 'Kharif' season (July, August and September). The average annual rainfall ranges between 100 and 150 mm (Sudan Topographic Survey 1:8,000,000 Rainfall Map, 1965 Ed.). The rains fall mainly in thunderstorms.

Short-lived grasses usually cover the plains during the rainy season and the few succeeding months. Perennial Acacia trees grow along water courses (Khor beds). Sufal trees are occasionally observed on top of the mountains.

2. POPULATION

The inhabitants are Hadendowa who lead a nomadic life wandering about for pasture and water. During the dry season they usually settle near big Khores around Tekilla and dig temporary open wells for water supply. The depth of water-table in these Khor-wells may vary from few metres up to several metres (26 m maximum) and they usually get deeper towards the end of the dry season (June). The Hadendowa are mainly camel-owners and may keep a few sheep, goats and cattle for milk.
3. GEOMORPHOLOGY

The Tehilla complex constitutes a subcircular or oval group of close hills and ridges that rise about 300–350 m above a central plain. The surrounding basement rocks have been preferentially eroded leaving residual outcrops of the Tehilla igneous rock suite. The basic rocks of Tehilla are more eroded than the granites. The central plain gently slopes to the north, south and west, and is crossed by few seasonal streams (Khor) draining westwards, southwards or northwards in a subradial pattern (Fig. 2). The streams are in part controlled by fault and joint systems. The plain is made of quartz pebbles and rock float mixed with clayey sands and silt. The Khor beds are covered by rock debris or shingle and fine-to coarse-sands sometimes mixed with black grains of dark minerals.

The common weathering features include well exfoliated boulders (onion-skin weathering) and bare slabs (boiler plate weathering) - Plate 1.a,b.
III. REGIONAL GEOLOGY

1. INTRODUCTION

Talha igneous complex constitutes the most southerly of a series of ring-complexes approximately aligned N-S along longitude 36° on the western flank of the Red Sea. The complex is situated in a region mainly dominated by 'basement complex' rocks with few outcrops of Rubaia Sandstone Formation rocks and minor younger volcanic lava flows of basalts and rhyolites. Data on the geology of this region has been obtained from Delany (1952, 1958); Delany (1956) Geological Map of Derudab, Sudan Geological Survey Sheet 46-I, 1:250,000; Omer Ahmed et al. (1966); and personal observations by the author. A photogeological interpretation map on a scale of 1:250,000 based on the above informations has been constructed (Fig. 1).

2. GEOLOGICAL SUCCESSION

The basic subdivisions made by Delany and Omer Ahmed et al. (op.cit.) were modified, and the rocks are tentatively classified into the following successions: -
2.2. The Early Procambran Rocks

The early Procambran rocks within this area (Fig. 1) include, mainly, granitic gneisses and metasediments that belong to the 'basement complex' of Sudan which Whitman (1971, pp. 11) defined as "... those igneous rocks, metamorphic, and sedimentary rocks, that are overlain by horizontal and subhorizontal Palaeozoic or Mesozoic sedimentary or igneous rocks." This basement group was claimed to be of Procambran
age (Andrew, 1948; Busston, 1956; Almond, 1957; Whitman, 1971) while
the youngest subdivision that comprises the Younger Granite series
is assigned to a Lower Palaeozoic age (Almond, 1957; Vail and Rox,

The granitic gneisses and metasediments of low to moderate
metamorphic grade are highly folded and give rise to well-developed
trends dominated mainly by an early N-S and late E-W or ENE directions
(Fig. 1). Locally the strike may vary considerably. These trends
could, possibly, correspond with two periods of early and late folds
designated here F₂₈ and F₄ respectively.

The granitic gneisses are deep-seated metamorphic rocks ranging
from moderate to low-grade facies, while the relatively high-level
metasediments are entirely of low metamorphic grade. The igneous
rocks were emplaced into these low-grade, high-level metasediments,
and are, therefore, considered to be shallow intrusions equivalent
to the episone granites of Baddington (1955). These rocks will be
considered in more detail in Chapter IV.

2.b. Syntectonic Igneous Rocks

The syntectonic rocks consist mainly of granites and adamellites
together with small discrete bodies of metasomatized syeno-diorite
and diorite. The latter two probably invaded the country rocks.
during the early fold movements since they are, more or less, conformable with the N-S structural trend and their present character when examined suggests a repeated cataclastic effect. On the other hand, granites and adamellites were probably emplaced after the commencement but before the conclusion of the late phase of folding ($R_L$). Therefore, there is a close time relation between the late folding movement ($R_L$) and the early tectonic igneous activity. The granite-adamellite bodies seem to occupy the basins and probably the domal structures that result from the intersection of the two folds. These major igneous masses now occur as small subcircular or elliptical batholiths and plutons injected as transmagmatic solutions along foliation planes of the early rocks (metasediments mainly) to produce granitized rocks by process of magmatic replacement in a similar way advocated by Korzhinskii (1960). The formation of magmatic solutions is presumably connected with the thermo-tectonic activities that accompanied the processes of folding. The different intrusions show a definite relation to the regional structure, that is, they keep their foliation in continuity with that of the country rocks. Rocks of the syntectonic nature that lie within the thesis area will be discussed fully in Chapter IV.
2.0. The 'Younger Granite' Basic Phase

The basic phase comprises minor intrusive bodies of troctolites and norites (gabbros?) commonly associated with and predating the Younger Granite complexes. Delany (1955) and Omar Ahmed et al. (1964) claimed that these rocks were not affected by the regional metamorphism or the early igneous activity and they are, therefore, post-tectonic probably of Lower Palaeozoic age. Basic rocks, especially within Tuhilla area, were subjected to slight degree of thermal metamorphism possibly due to the thermal rise that accompanied the late igneous activities.

2.1. The 'Younger Granite' Acid Phase

The youngest subdivision of the 'basement complex' (Andrew, 1968) that includes alkali granites (pink-granites) and syenites, in some places adamellites, and generally emplaced in the form of complex ring-structures or small plutons. They cut sharply across the country rocks and rarely show any foliation. However, Younger Granites from Tuhilla may show a weak primary planar structure, but chilled contacts are rarely observed. Absence of chilled margins in Tuhilla could be attributed to the general condition of the country rocks being relatively hot at the time of igneous invasion. The emplacement and distribution of the Younger Granite masses within this region were, mainly, controlled by the structural setting.
of the area; arcuate fissures and weak zones may have resulted during
the formation of the basins and domal structures as a result of $P_E$
and $P_L$ cross-folding. Through these fissures acid magmas have been
drawn from below at late stages to form Younger Granite intrusions.

2.e. Minor Intrusions Connected With Younger Granites

Minor intrusions represent the latest phase of the Younger
Granite igneous activity. They consist of acid (granitic and adamellite)
and basic (dolerite) dykes with abundant quartz veins. The dykes
are commonly disposed in swarms with two distinct trends E-W and N-S
approximately. NE and NW trends are not uncommon. The dykes
generally initiate the regional trend pattern and the master joint
planes (Fig. 1).

2.f. The Nubian Sandstone Formation

The Nubian Sandstone Formation in this region forms a narrow
strip of land exposed in the extreme east centre of the area (Fig. 1).
It overlies the 'basement complex' rocks and is overlain by the
Tertiary basalts so that it is considered to be of Lower Cretaceous
defined the Nubian Sandstone Formation to include:
"These bedded and usually flat-lying conglomerates, grits, sandstones, sandy mudstones, and mudstones that rest unconformably on the Basement Complex and Palaeozoic Sandstone Formation and are older than the Hudaydah Chert Formation (early Tertiary) and the 'early Tertiary' lavas." He considered the Rubian Sandstones in general to be a continental deposit rather than a marine one (Whitman op.cit.) having his assumption on many criteria which include: the absence of marine fossils, presence of plant fossils; the lithological variations; and the presence of locally derived conglomerates at the base of the formation associated with fossil trees, some in the position of growth. However, since not much work was carried out on this rock formation in the Tushila region, there is little that can be said concerning its lithological character or genesis.

2.4. Basic And Acid Lava Flows

These were extruded at the surface as basaltic and acidic lavas respectively. They are exposed close to and overlie the Rubian Sandstone Formation in the extreme east of the map area. These lavas are believed to be of Tertiary age. The amount of lava extruded is quite small; according to Delany (1955) basalt is relatively more abundant than rhyolite. Although no petrographic details are available to tell the type of basalt, one sample examined from an outcrop near Tushila complex suggests an alkali-olivine type.
Late Dolerite Dykes

In the field these dykes are indistinguishable from the similar ones associated with the Younger Granite intrusions. They, however, seem to be quite numerous, and mainly emplaced in swarms of parallel or subparallel trend. The rock is dark, dense looking, with phenocrysts of olivine and plagioclase. The dykes could therefore be closely connected, and possibly derived from the basaltic lavas.

2. STRUCTURAL HISTORY OF THE AREA

The region under consideration (Fig. 1) has been subjected to a series of intense fold and fault movements. Folding occurred at early times but has only affected the early Bremanbian rocks, while faulting appears to have been operating over a long period extending to post-Tertiary volcanic replacement times. These fold and fault movements imply that the region was under mechanical and thermal instability for a considerable period of time which may correspond with the Pan-African orogeny of Kennedy (1964). As previously mentioned, these movements have, in one way or another, greatly influenced the structural setting and evolution of the different rock-types present in this region. It can, therefore, be argued that the early (syntectonic) and the late (Younger Granites) igneous activities owe their origin to the late tectono-thermal activities prevailing at the time of their formation. Neil and Rex (1970)
suggested the same factors for the origin of the foliated (syntectonic) and unfoliated ('Younger Granites') basement granites of the Sudan. However, isotopic age determinations for some basement rocks from Sudan and Egypt suggest an igneous (tectono-thermal) activity around 420–620 m.y. in Sudan (Vail and Rex, 1970) and at about 400–590 m.y. (Afanas’ev, 1960) or 450–550 m.y. (Shackleton, 1970) in Egypt. This period corresponds with the Pan-African orogeny of Kennedy (1964). The presence of Pan-African orogeny in these regions, Egypt and Sudan, could indicate the northern extension of the Mozambiquan belt into northeastern Sudan and Egypt (Shackleton, 1970; Vail and Rex, 1970).

3.a. Folds
directions

Two main fold types were recognized within this region; early folds (F₁) whose axes trend N-S, succeeded and affected by a late folding (F₂) whose axes trend, approximately E-W and in places NE-SW. Local fold-axes may show a great degree of variance. The effect of cross-folding, as mentioned before, has resulted in a series of local domes and depressions which were occupied, in places, by igneous bodies. Metasediments commonly occur as infolded outliers (basins?).

3.b. Faults

Faults are very abundant, and observed to affect all rock formations in the area including the Tertiary lava flows (basalts). The main faults trend generally N-S, NE-SW, NW-SE, and less commonly E-W. Extensive faults form a regional pattern rather than being
connected with the igneous intrusions. Faults have greatly influenced the drainage system, and streams usually follow the fault planes (Fig. 1). Age relations are not easy to determine from a limited regional coverage.
IV. THE GEOLOGY OF TEHILLI IGNEOUS COMPLEX

1. INTRODUCTION

Tehilla igneous complex is mainly built of acid and basic rocks, followed by late minor dyke intrusions of basic and acid compositions. Acid and basic rocks are closely related in space and time; the former mainly emplaced as high-angle cone-sheets and are seen to cut into the basic rocks. This cross-cutting relation indicates the presence of a liquid phase at the time of intrusion. The country rocks into which the complex was emplaced comprise metasedimentary rocks that occupy a local basin structure believed to be a result of two intersecting folds (P_B and F_L).

The acid rocks are mostly granites with subordinate masses of adamellites. They are exposed on the surface as closely spaced hills and ridges mainly in the form of high-angle partial cone-sheet bodies. One of these bodies, Tehilla granite-porphyry, makes a prominent and rather continuous topographic ridge separated, in places, by low cols which indicate subsequent faults. Other units include from outside inwards; Halokwan granite, Hamlab granite-porphyry, and Thainat granite which are poorly exposed and disposed concentrically on the outside of Tehilla granite-porphyry. To the inside of Tehilla granite-porphyry an eccentric, narrow, and discontinuous anorogenic microadamellite body is exposed. The present shape of the acid
Intrusions indicates that each of the preceding intrusive bodies was partially destroyed by the succeeding one and that the centre of each intrusion was displaced successively westwards.

The basic rocks range between troctolites and norites. Troctolite is mainly surrounded by the Tahilla granite-porphry and it is, therefore, referred to as ‘core-troctolite’. Core-troctolite is exposed as low isolated hill masses characterized by scree-covered surfaces (Plate 2). Troctolite intrusion is surrounded by two crescentic partial sill-like bodies of norite: the outer exposed as stream bouldery patches while the inner is completely hidden and wholly covered by the Tahilla granite-porphry.

Field data is not sufficient to give precise estimates for relative ages of Tahilla rock-types since geological boundaries are almost everywhere hidden by scree and thin alluvial cover. However, the available data support the following proposals:

The early Proterozoic rocks (metasediments and granitic gneisses) are presumably the oldest rocks in the area, followed by the late syntectonic adamellites which were, partly, originated by granitization of the metasediments. The Younger Granite complex rocks were intruded as post-tectonic bodies, the basic phase being emplaced first, and succeeded by the acid phase; veins of acid
rocks cut into the basic rocks. The minor intrusive dykes affect most of the major younger igneous rocks. The enorogenic microadamellite which forms the latest member of the acid phase, cuts and, therefore post-dates the minor basic dyke intrusions.

Field study suggests that igneous activities and tectonic events which occurred within this area are closely related in time; also, post-tectonic igneous members could have evolved under the same conditions, that is, they evolved successively and in a very short time-interval. This proposition is mainly based on the contact zones being relatively coarse-grained throughout and on the less contrasting composition of the post-tectonic members.

2. GEOLOGICAL SEQUENCE

From the above discussion a tentative classification of Tehilla rocks can be proposed in the order outlined below:
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**LOWER PALAEOZOIC OR LATE PRECAMBRIAN**

- o) Quartz veins.
- n) Granitic (or acid) dykes
  - ii) Local acid dykes
  - i) Regional acid dykes
- m) Anorogenic adamellites:
  - ii) Minor adamellite intrusions (dykes),
    - i) Microadamellite cone-sheet.
- l) Basic dykes (dolerites).
- k) Tehilla granite-porphyry.
- j) Teinaat granite.
- i) Hesabi granite porphyry.
- h) Halokwan granite.
- g) The middle olivine-microcortite.
- f) The outer olivine-microcortite.
- e) The core-proctelite.

**PRECAMBRIAN**

- d) The orogenic adamellites:
  - iii) Microadamellite
  - ii) Tehilla adamellite
  - i) Durudob adamellite.
- c) Metabasic rocks (minor syeno-diorite and diorite bodies).
- b) Metasediments (mainly low-grade green schists).
- a) Undifferentiated granitic gneisses.

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Younger Granite Younger Granite Acid Phase
Minor Intrusive Phase

Early Pre-cambrian rocks.
2.3.d. **Country Rocks**

The country rocks include metasediments and undifferentiated granitic gneisses presumed to be of early Proterozoic age, and late syntectonic intrusions mainly adamellites with few outcrops of metamorphosed syeno-diorite and diorite. The adamellites are believed to have originated by process of magmatic replacement or granitization of the country rock schists. The syeno-diorite and diorite may represent early igneous intrusions.

2.3.b. **The Early Proterozoic Rocks**

The early Proterozoic rocks include metasediments and granitic gneisses. The gneisses occupy the northern part of the mapped area while the metasediments cover the rest of the area (Fig. 2). As mentioned before, metasediments occur mainly as infolded green-schists which occupy a basin-shaped structure and constitute the host rocks for Tohilla complex.

a. **Undifferentiated Granitic Gneisses**

Gneisses are mostly thinly covered by alluvium, and when exposed they form low bouldery outcrops. The rock is grey, dark-grey or dark-brown in colour, weakly foliated and displays two well-developed sets of joints running N-S and E-W approximately. It is coarse-to medium-grained, composed mainly of feldspars, quartz and biotite. A few
crystals of garnet may develop in gneisses lying north of the railway line to form garnetiferous gneiss. Narrow bandings of pegmatites and splites commonly cut into the gneisses, and the latter usually show slight pytymelitic folding due to regional stresses.

Microscopic examination reveals that biotite-gneisses are essentially made up of oligoclase, quartz and lesser amounts of feldspar. The coloured minerals are generally less abundant and slightly variable in proportions; they include smoky to dark brown biotite, green actinolite and chlorite with accessory opaques and sphene which may mantle the opaque grains. Chlorite and actinolite could be an alteration products after hornblende which seems to have been a primary component. Garnetiferous gneiss contains abundant potash feldspar (mainly microcline) and muscovite in addition to garnet. Biotite appears to be the only dark mineral present.

Many feldspar and quartz crystals exhibit patchy extinction probably as a result of deformation during metamorphism. The plagioclase has complex twinning which may show slight twisting at places. Rocks close to the late intrusive bodies or fault zones always show sign of crushing and deformation that are believed to be due to post-tectonic movements associated with the late granite.
intrusions, and the subsequent faulting.

2.b. Metasediments (mainly low-grade schists)

Metasediments constitute an originally bedded succession mainly of pelites intercalated with small lenses of psammites and calcareous sediments. Psammites and calcareous pelites are not infrequent.

The sediments interbedded with minor dark quartzite and white-grey marble bands were intensely folded and regionally metamorphosed to a low-grade green schist facies. The regional strike and dip of foliation close to the Tchilla complex may locally change and show conformity with the attitude of the igneous contacts. This conformity can mainly be attributed to the nature of the metasediments which are presumed to occupy a basin structure and, therefore, exhibit high inward dips. However, it is clear from consideration of strike and dips adjacent to the intrusions that it has, in part, been forced into conformity with igneous contacts by magma pressure. Marble bands in contact with igneous intrusions show variable degree of deformation from crystal bending and twisting to high contortion of calcareous and siliceous lamellae which may result in complex sets of drag folds. The siliceous material mixed with calcareous bands is most probably of detrital origin. Mild magmatic pressure
is commonly indicated by slight fault-slip along fracture zones of the metasediment enclaves.

The **green schists** are dark green in colour, fine-grained, and well-foliated rocks very rich in green minerals and mica, with few feldspars and quartz. Foliation is emphasized by the parallel alignment of the mineral components especially the dark mineral suite. In thin section, the schist rock is seen to be composed of well-twinned albite, orthoclase and quartz together with abundant irregular plates of green to bluish-green actinolite. Few crystals of dark brown biotite, green chlorite and granular epidote are present in some places; the biotite is mainly secondary after actinolite. Crystals of opaques and sphene are frequent accessories with sphene mantling the former in many cases. Rare grains of garnet, apatite and zircon are occasionally observed.

It should be noted that the proportions of the mineral constituents vary from the more siliceous to the more calcareous schists; actinolite and plagioclase are much abundant in the latter, commonly associated with few grains of epidote, chlorite and more sphaene. In siliceous schists the amount of coloured minerals is generally low and the rock normally shows an increase in potash feldspars, quartz and biotite.

The mineral assemblages of the schist recorded above correspond
with the low-temperature subfacies-albite-quartz-orthoclase-actinolite
(+ epidote - biotite - sphenol) - of Turner and Verhoogen (1960).

Quartzites form dark bands or lense measuring few metres across. They are, often, exposed at the surface as low, narrow topographic ridges which usually delineate the regional trend pattern. The rock is compact, of fine granular texture, largely made of stout grains of quartz with few crystals of plagioclase and potash feldspars. The dark minerals, when present, may constitute sparse shreds of brown biotite, (rutile ?), discrete grains of ophocrysts and occasional crystals of sphen. Opaques are very frequent and in many cases they are present alone beside quartz minerals.

Marbles form sporadic lense-shaped outcrops with greyish or dark-grey colour, in some places sugary white when pure. They vary greatly both in texture and mineral composition; the texture grades between medium and coarse, and the composition from pure marble composed by crystalline calcite to impure marbles mixed with detrital material in which develop occasional crystals of garnet and corundum.
An average partial analysis of three samples is given below:

\[
\begin{align*}
\text{SiO}_2 & \quad \text{..................} \quad 2.94\% \\
\text{Al}_2\text{O}_3 & \quad \text{..................} \quad 0.96 \\
\text{Total iron} & \quad \text{.............} \quad 0.18 \\
\text{FeO} & \quad \text{..................} \quad 1.90 \\
\text{CaO} & \quad \text{...............} \quad 96.20
\end{align*}
\]

The high calcium content is due to the abundance of calcite. The amount of silica, magnesia and alumina derived from politic schists is very small.

The relation of metasediments to the late igneous intrusions is of particular interest. Thermal effects and contact relations deserve to be considered in more details.

Thermal Effects Of The Late Igneous Activity

There are no regular metamorphic zones traceable around the complex as a whole. In general, however, the thermal effect was mainly confined to country rocks lying within or immediately in contact with the igneous bodies. The marginal effect of the wall rock is not found to a significant degree more than 100-200 m from the contact.

The green schists were generally retrograded to fine-
grained, granoblastic calc-silicate hornfels which corresponds to biotite in isograd of Winkler (1970) and in which foliation is commonly preserved. Hornfels is composed of potash feldspar, albite and quartz with variable amounts of biotite and few grains of opaques and spherule. Actinolite may be present besides biotite possibly in more calcareous schists. Garnet, zircon, and apatite are very rare. The amount of dark minerals is notably low, and in some cases totally absent. Potash feldspar are mostly porphyritic and include both orthoclase and microcline; the latter is partly secondary after plagioclase.

Around Tohilla granite-porphyry porphyritic hornfels may develop with porphyroblasts of potash feldspar (mainly orthoclase) and occasional crystals of plagioclase and quartz. Porphyroblasts may vary in number and grain-size, and are believed to have developed by process of recrystallization. However, whole crystal diffusion may take place along the contact zone, where pink orthoclase crystals identical in every respect to those of the granite intrusions developed in schists. These crystals are of variable size and shape, usually keep within the general attitude of similar crystals in granite.

Xenoliths and enclaves within igneous bodies generally show more advanced stages of metamorphism. Small xenoliths are commonly
transferred to medium-grained granitoid rocks with sparse grains of opaques but no dark minerals. Bigger masses may produce porphyroblastic dark granitoid rocks with few minerals and relic foliation. Two inclusions of schist and another of calcareous schists were enclosed in the core-trachyte and Tertiary granite-porphry respectively; both were converted to intermediate basic rocks (quartz diorite) with more basic and zoned plagioclases. The dark minerals constitute brown biotite and green actinolite mainly.

Quartzites and pure marbles have both undergone simple recrystallization with no essential changes in mineral constituents. Impure marble bands especially when in contact with igneous bodies have produced skarn minerals which include: granular diopside, periclase, brucite, forsterite, wollastonite, garnet (grossularite), opaques, and occasionally dolomite may develop. Brucite and forsterite minerals are common along marble/trachyte contact, while diopside, wollastonite and garnet are more abundant along marble/granite contacts. Locally large euhedral crystals of garnet may develop in immense numbers on marble faces. It should be mentioned that the occurrence of the above mentioned skarn-minerals is not necessarily solely attributed to the thermal effects of the late igneous intrusions since some are observed to grow in rocks situated far from these bodies.
Contact Zone

Basic and granitic intrusions have faithfully followed the local trend and attitude of the host metasediments in most parts. Contact is generally sharp and unchilled, but in details it shows some degree of meandering. Along contact margins granites have been intimately permented into the metasediments.

Calc-silicate marble bands in contact with granites are highly deformed. Complex drag folds seen in these bands appear to be in part due to compression caused by the intrusion of the late igneous bodies; the frequency and complexity of such drag folds increase towards the contact of intrusions. Trends of such fold axes are rather irregular and bear little or no relationship to the major fold axes.

2. c-d. The Late Synformic Intrusions

The presence of rocks which are of igneous nature may suggest the existence of an early phase of igneous activity associated with regional tectonism. The rocks include subordinate masses of metabasic diorite and syeno-diorite which were probably succeeded by acid magmas invaded along foliation planes of the host schists to produce adammellites. Diorite and syeno-diorite form small bodies commonly stretched parallel to the N-S regional trend and could,
therefore, be considered to have originated during the times of early folding period (P2).

2. Metadiorite And Syeno-Diorite

Metadiorite forms small lenses or bosses elongated N-S and mainly exposed at the southern corner of the mapped area. They are too small to be shown on the map. The rock is foliated, black to dark green in colour, and of fine-grain granoblastic texture. It is composed mainly of plagioclase and green hornblende with few grains of opaques. Some partly unaltered olivine and pyroxene crystals are recognizable.

The syeno-diorite comprises low boudary outcrops normally lying close to the basic or granite intrusions as small lens-shaped masses elongated parallel to the N-S regional trend. The rock is melanocratic in parts speckled with white-pink feldspars to give pseudophyric texture. Texture may vary from fine to coarse and more rarely very coarse. The rock is mainly composed of green hornblends with few grains of apatite and chlorite interspersed with cloudy plagioclases and alkali perthites. Quartz is present in small amounts and calcite, corundum or garnet are occasionally observed. The original habit of the rock is not easy to recognize, but it is probably of magmatic origin. However, the rock seems to have been subjected to repeated cataclastic effects and a series of metasomatic
changes that led to metamorphism of plagioclases to produce albite, sausite and sorcrite. Chlorite, actinolite and leucorane were possibly developed after hornblende or plagioclases. Replacement of plagioclase by dark minerals has proceeded very peacefully with the preservation of form and twin lamellae of the original crystal. Solutions responsible for metamorphic reactions were probably derived from the local acid or basic magma; rocks located close to granites are relatively high in felsic oxides while those near to the basic intrusions are low in felsic oxides but relatively high in total iron and lime.

2. Orogenic Adamellites

The syntectonic adamellites (referred to here as orogenic adammellites) fall into three subgroups: Borudob adammellite, Tehilla adammellite, and microadamellite. Each of them form independent structural units quite distinct in the field. Borudob adammellite forms a small batholithic outcrop of which only part is included in the thesis area (Fig. 2). It exhibits weak foliation coinciding with the N-S regional direction, and could, therefore, be regarded as an early intrusion associated with early folds (Fig.). On the other hand, Tehilla adammellite forms a circular stock 5-6 km in diameter, partially surrounded on the outside especially in the northwest by a narrow arenite body of microadamellite facies. The formation of the Tehilla and microadamellite bodies was probably correlated with
the late folding (F₄). They seem to occupy a basin structure that is believed to be the result of fold interference. Their foliation pattern is more or less in accord with the regional attitude of the occupied basin, that is, concentric and relatively weak in Tehilla variety, but strong with slight curving in the microadammellite body (Fig. 2).

The three rock-types outlined above are closely related and most probably have a common genetic origin. They show close similarity in lithology and chemistry, and are mainly composed of quartz and plagioclase (albite-oligoclase) with variable proportions of alkali perthites. The alkali perthites include microcline, an uncommon mineral in the Younger Granites of Tehilla complex. The dark minerals constitute prominent green hornblende with few a flakes of biotite. Mineral components may vary both in quality and quantity from one rock-type to another and even within the same rock group. When compared chemically with 'anorogenic' adammellite of Tehilla complex, the orogenic adammellites are generally higher in silica, relatively low in alumina and total iron while the anorogenic rocks (magnetic ?) are low in silica and high in alumina and total iron (Table 7). Other oxides like alkalies, lime and magnesia show no significant differences. Orogenic adammellite rocks when plotted on variation diagrams (Figs. 3, 4, 5 and 10) with post-tectonic igneous rocks of Tehilla complex
commonly tend to cluster separately and do not match with Tehilla rocks. This may suggest that they bear no relation to Tehilla complex rocks and have a separate origin.

d.i. Derudab Adamellite

The southwest corner of the mapped area is occupied by Derudah type adamellite which crops out as a low dissected plateau in which two master joints run N-S and E-W approximately. Drainage is mainly controlled by these joints. Xenoliths and scree of schists, quartzite and metabasic rocks are very common and their relation to adamellite rocks suggests an extensive degree of transformation; complete transition from country rock (schists and quartzite mainly) to permented gneisses and to adamellite is nicely demonstrated in the field. Homogeneous adamellite exists away from the contact with the country rocks. This homogeneity is due to the high concentration of granitizing agents.

The rock is grey in colour, coarse- to medium-grained, and composed of feldspars and quartz with little amount of dark minerals; mainly green hornblende. Some quartz crystals are opalescent with characteristic light-blue colour. Hornblende when altered gives the rock a greenish colouration, hence the name 'green Derudah granite' suggested by Dalsky (1955) for this type of rock.
Under the microscope adamellite is of even grain-size commonly between 1 and 2 mm. The rock is predominantly made of feldspars and quartz with small amounts of interstitial dark minerals and few opaques mainly replacing the dark minerals. Average modes are given in Table 1; (A) represents homogeneous adamellite and (B) less granitized rock.

Feldspars are mainly soda plagioclases of albite–oligoclase composition, with few replaceable microcline microperthites. Feldspar crystals are partially altered to dirty kaolin and sericite, and commonly show patchy extinction due to regional stresses. Plagioclase crystals present the normal multiple twinning which is accompanied by Carlsbad twins in some cases. Quartz is typically anhedral, strained and often tends to occur in aggregate crystals with sutured margins, some with indistinct boundaries. It occasionally forms myrmekitic intergrowths with plagioclase.

The dark minerals are notably very few and occur as sporadic grains interstitial to felsic components. Green hornblende and brown biotite are the principal variants always crowded with accessory minerals which include opaques, zircon and apatite. Biotite may be secondary after hornblende and in some cases developed after sericite (muscovite?) which is an alteration product after plagioclases.
d.i. Tehilla Adamellite

A small pluton largely covered by alluvium and washwash with some exposures is formed by a rock here referred to as the Tehilla adamellite. The pluton possesses three distinct joint systems trending N-E, E-W, and NE. Tehilla adamellite shows many similarities to Berudeh adamellite. It has most probably evolved by a process of granitization through magmatic replacement; boundary zones with country rocks are irregular and gradational, and xenoliths occur in all stages of resorption, that is, gradation exists between adamellite and the enclosed enclaves of green schists and quartzite. Quartzite bands seem to have suffered mild granitization, and many stand as hard ridges of quartzo-feldspathic gneisses easily distinguished on air photographs by their dark tone. On the other hand, schist xenoliths have been highly attacked, soaked and abraded into small rounded fragments and may be entirely absorbed. The slices of schists exposed on the eastern margin of the pluton are highly permeated and show slight lateral displacement indicated by inconsistency of strikes and dips of the foliae even within a small area. This could suggest an invasion along the foliation planes of the schists by magmatic liquid which later caused granitization of these rocks. Absence of pytgmatic folds from splitters found in this rock may indicate that Tehilla adamellite was formed at a very late stage of the tectonic phase.
The rock is grey or light in colour, coarse-to medium-grained, and mostly composed of feldspar, quartz and biotite. Texture is notably coarse at the centre of the pluton where big crystals of euhedral feldspar developed which measure up to 3.6 cm in length. This feldspar is most probably magmatic formed prior to the intrusion of magma; it can, therefore, further indicate the presence of magmatic fluid which invaded the country rocks in a semi-liquid or partly crystalline state and caused granitization.

The rock when examined under the microscope looks granular, medium-to coarse-grained and principally made up of interlocking crystals of feldspar and quartz measuring 1 to 4 mm in length (average about 2 mm), with little amounts of interstitial biotite. Quartz and feldspar may occasionally produce tiny myrmekitic intergrowths.

The feldspars are mainly sodic plagioclase (oligoclase) with subordinate amounts of replacement microcline and orthoclase microperthite. Feldspars are partly and in places completely decomposed in dusty kaolin and sericite (muscovite), and granular epidote. Plagioclase crystals are twinned and slightly zoned. Quartz forms anhedral grains, often grown in aggregates and show extensive fracturing and undulatory extinction. It carries numerous fluid inclusions enclosed within the fractures. Similar fluid inclusions are also developed in feldspar.
feldspars and occupy the fracture zones. This liquid was probably derived from the granitized green-schists and it could have helped largely in alteration reactions.

Biotite occurs as dark brown flakes, some have grown in crystal aggregates with tiny grains of feldspars and quartz; this assemblage could represent ghost xenoliths. Big crystals may carry accessory components and show pleochroic haloes around zircon. Biotite has in part developed after secondary sericite or muscovite, and is itself partly replaced by green chlorite or opaques. Sericite (muscovite?) results from the decomposition of the feldspars. Accessory minerals include opaques, zircon and apatite.

d.iii. Micromammellite

A body exposed as a continuous low ridge, highly jointed and characterized by loose scree-covered surface is composed of micromammellite in the north of the map-area. Joints recognized run N-S, E-W, radially and tangentially and show vertical or steep dips. Segregations and small veins of quartz and pegmatites are common invaders.

The micromammellite body encloses abundant xenoliths and rafts mainly of green-schists. Along the convex margin of this body erosion was very drastic and has exposed green-schist bands
intervened by parallel sill-like bodies of microdiamellite. This mode of occurrence could demonstrate the way in which the magma attacked the country rock schist; in this part the amount of magma seems to be insufficient to cause granitization on as large a scale as in the case in the other adammellite bodies. A conclusion could, therefore, be drawn that the magma invaded the country rocks along foliation planes in the form of multiple sills and caused granitization (or adammellitization) by magmatic replacement of the green-schists. These sills might also occupy horizontal fracture zones and thus have intensified the granitization effects.

The rock is light gray or pink in colour, medium-to fine-grained. It is relatively finer than the other adammellites and composed of feldspars, quartzs and a few dark minerals (mainly green hornblends), the latter commonly aligned parallel to the foliation planes.

Microscopic examination shows the microdiamellite to be an inequigranular rock with grain-size ranging between 0.1 and 1.0 mm. The mode presented on Table 1 shows very low colour index with increase in amount of free silica over the other adammellite units, and relative decrease in feldspars and dark mineral content. Feldspars are mainly soda plagioclase (oligoclase) with variable content of microcline and orthoclase microperthites. Feldspars are highly kaolinized and sericitized. Quartz is quite abundant, often segregated into patches.
with mosaic texture and patchy extinction. The dark minerals are unevenly distributed and usually gather in clusters. They are interstitial to the felsic constituents and include green or bluish-green hornblende and dark green or dark brown biotite, which commonly replaces hornblendes. Occasionally or the secondary muscovite. Occasional grains of hornblende are seen replacing the secondary muscovite; this relation might indicate that hornblende is mainly derived by alteration after the muscovite. Dark minerals are invariably altered to opaques. The accessory minerals are frequently associated with the dark minerals and include sphene, opaques, zircon and apatite. Sphene in places mantles the opaque grains.

Certain specimens, particularly those collected from near the contact with xenolithic rafts, show a decrease in amount of sodic plagioclase and quartz, with an increase in content of replacive microcline and sericite-muscovite minerals; microcline in some slides may account for up to 11 per cent of the rock composition. The incoming of microcline and muscovite points to an influx of potassium material and hydroxyl possibly derived from the granitized schists (Marzo, 1956). Hydroxyl helped in promoting the metasomatic reactions.

Origin Of The Orogenic Adammellites

Orogenic adammellites have most probably originated by a process
of magmatic replacement or granitization (Korchiniski, 1960). The magmatic solutions were derived from below and possibly associated with the tectonic episode. During folding slow seepage of magma and transmagnetic solutions through foliation or bedding planes of the country rock schists probably took place. These solutions caused magmatic replacement (or granitization) of the intervening schists and led to growth in situ of perhaps most of the adamellite masses. In places the continued supply of magma resulted in complete conversion, while in some parts partial resorption is indicated in every stage of transformation; in the latest subdivision, the microadamellite, the amount of magma seems to have been very limited. Fig. 10 shows that rocks of orogenic adamellite plot on the quartz side of the system Al₂O₃-O₂-H₂O (Tuttle and Bowen, 1958) and this might refute the transformation origin of the adamellites already established from field observations.
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*Table 1: Average daily emission of organic aerosol.*
2.6-6. The Younger Granites

The Younger Granites constitute three major phases: an early basic phase succeeded by acid phase and minor intrusive phase consecutively. The basic rocks are most dominant and cover an area of about 44.5 km² against 36.5 km² covered by acid rocks or granites. The basic and acid intrusions are closely related in the field and they show progressive variations in petrology and chemistry to suggest a common genetic origin. Consequently they are presumed to have evolved by process of differentiation from a basic magma.

2.6-2. The Younger Granite Basic Phase

Introduction

This basic phase of Younger Granites constitutes the earliest intrusions of post-tectonic igneous activity in the region. Since they are commonly associated with the Younger Granite complexes, they are, therefore, considered as part of these complexes. In this complex, the basic phase is more abundant than the acid phase.

A three-fold division of the basic phase, first suggested mainly on the basis of the structural setting of the units, has been confirmed and positively supported by petrographic and chemical data. The units include: the ore-troctolite, the olivine-norite, and
the middle olivine-micronorite. The core-trachytes occupies an area of 40 km² and the outer norite about 5 km²; the areal extent of the middle micronorite is not easy to estimate. The term core-trachytes is used here to denote all trachytes rocks encompassed by Tehilla granite-porphyr. The outer and middle basic bodies form concentric rounded roll intrusions around the northeastern part of the core-body. The middle micronorite body is now replaced by the Tehilla granite-porphyr, and its presence is only predicted from the exposed scree within the granite intrusion.

General Description

The basic rocks appear to share several physical features in common. The rocks are melanocratic and usually show a dark or black colour when fresh. The outcrops are characterized by a loose scree-cover normally of rounded or subrounded boulders of various sizes derived from the effect of weathering on the well-jointed basic rocks (Plate 2). In many places three sets of joints are indicated cutting N-S, E-W and horizontally. This pattern of jointing breaks the rocks into cubic blocks which are later trimmed and rounded by spherical weathering of the 'onion-skin' type (Plate 1.b). Rocks exposed in streams or Wadi beds have their joints filled by white calcareous material (Plate 1.c) which could have been derived from weathered calcic plagioclases of the basic rocks. Boulders of the basic rocks usually ring when hammered and are
usually characterized by pitted surfaces (Plate 1.d) which are probably due to the etching of the less resistant minerals (olivines) during weathering.

The mineralogical composition of the basic rock suite is simple with plagioclase, olivine and orthopyroxene (bronzite ?) the principal constituents, together with subordinate amounts of augite and opaque minerals. The rocks show remarkable uniformity in mineral components, but are variable in modal ratios and texture. On the basis of these variations the three units can be classified into: the core-troctolite which grades by decrease in olivine and increase in orthopyroxene to olivine-norite of the outer body. The middle intrusion is characterized by steady decrease in plagioclase and olivine proportions and counter increase in orthopyroxene with a general reduction in grain-size, so it is here classified as olivine-microxenite.

The chemistry of the outer norite is more or less identical to that of the core-troctolite, and this, together with the closely similar mineral composition of the two rocks might suggest that the outer body could be a minor intrusive emplaced contemporaneously or closely following the intrusion of the core-body. The middle microxenite shows a distinct variation in chemistry and relative abundance of
hydrors minerals and apatite so that it could possibly have been derived from the volatile enriched upper levels of a differentiated basic magma.

Since there is no apparent contact between the three basic units, the order of intrusion and age relations between them could not be determined. However, a tentative sequence of intrusions based on petrographic studies can be given as follows: (a) the core-troctolite, (f) the outer olivine-norite, and (g) the middle olivine-micronorite.

Thermal Metamorphism

The basic rocks were subjected to mild thermal metamorphism as a result of rise in local temperature associated with the late granite invasions. The effect of metamorphism is indicated by the thermal clouding of the plagioclases, replacement of early anhydrous minerals (olivine and pyroxenes) by hydrous ones such as biotite, hornblende, actinolite, etc., and in more affected parts by the partial recrystallization of the mineral constituents. In general, the middle parts of the intrusive bodies are only slightly affected, while the marginal zones, especially those in direct contact with granites are more affected. The middle olivine-micronorite unit being completely occluded by Tehilla granite-porphry was highly affected.

e. The Core-Troctolite

The core-troctolite produces hummocky ground rising from the
central plain with many narrow screens of country rock green schists (Fig. 2). The intrusion appears to be concordant, and emplaced by sill injections which spread laterally into the country rocks possibly at several levels. The nature of dips being conformable with the country rocks foliation planes may indicate a lopolith intrusion possibly occupying a local basin structure. The sills usually bifurcate into narrow fingers on the marginal zones. The rock, in general, shows reduction in grain-size and in places may be porphyritic towards the margins.

Petrography

The trachydotite is generally a medium-grained, granular gabbroic rock with average grain-size of 1 to 3 mm. In hand specimen the rock shows tabular crystals of dark glassy plagioclase; small rounded grains of yellowish-green olivine; few pyroxenes and many grains of opaque minerals. Since no good vertical section is exposed only lateral variations are considered. Towards the margin the texture becomes doleritic and in some places ophiitic with a few slightly zoned plagioclase phenocrysts normally 2 or 3 mm long, but locally some crystals may measure up to 7.5 x 25.4 cm. The marginal samples show a relative increase in secondary hydrous minerals which include red-brown biotite, brown hornblende and serpentine with more opaque granules largely from the
decomposition of early minerals. Apatite is occasionally seen. This indicates slightly greater concentration of fugitives compared with the inner parts.

The core-troctolite is essentially composed of labradorite, olivine and orthopyroxene (bronze ?) with a small amount of augite and opaque minerals (mainly ilmenomagnetite and sulphide minerals). Red-brown biotite and brown basic hornblende are the frequent alteration minerals often developed around olivine or pyroxenes forming a coronal structure. More commonly they form reaction rims around the opaque grains. Serpentine commonly develops along cracks of some olivine crystals. Pseudomorphs are normally observed on olivine and plagioclase crystal boundaries.

The plagioclase is labradorite (An 47-55) consisting of subhedral to anhedral lozenges or flattened tabular crystals normally less than 5 mm in length. It is slightly turbid and always charged with submicroscopic granules and regular lamellae of opaque minerals probably ilmenomagnetite. Clouding is more marked on the boundaries, and it could thus be ascribed to thermal metamorphism. The crystals usually exhibit a complex twinning; Albite twins are most common, accompanied by Carlsbad and Pericline.

Olivine occurs as rounded, corroded grains with an average
diameter of 1 to 2 mm. Some olivine crystals enclose early laths of plagioclase in poikilitic fashion. Clinoenstatite is rather common. Thin mantles of pale pink-green pyroxene, commonly orthopyroxene, usually develop around olivine in corona form. It seems possible that orthopyroxene could have been produced by reaction of olivine with the surrounding melt. Locally olivine may show symplectic intergrowth with the ilmenomagnetite due to exsolution of iron at relatively lower temperatures. Olivine crystals may be replaced along the margins or fissure cracks.

The pyroxenes comprise orthopyroxene (bronzie ?) and augite; the former is normally greatly dominant over the latter. As previously mentioned, they usually rim the olivine crystals and themselves being surrounded and marginally or patchily replaced by the late hydrous minerals in a corona pattern. Pyroxenes may in some places partly or completely enclose early plagioclase laths to produce an ophitic or subophitic texture; a feature commonly displayed on the margins of the intrusion. Both pyroxenes may occur as discrete, wedge crystals grown between the plagioclase laths. They usually carry opaque inclusions of ilmenomagnetite arranged on definite planes to produce schiller structure and infrequently sagenitic texture. The opaque inclusions could have been developed as a result of thermal metamorphism affecting the early basic rocks or they may represent
normal exsolution lamellae. Orthopyroxene has a common pale pink to green, weak to moderate pleochroism and low birefringence. It gives a positive optic angle with large 2V measuring about 75° on average. The large optic angle could designate a bronzite variety rather than hypersthene. Augite is very pale green, non-pleochroic and usually highly birefringent. Bronzite and augite are both seen replacing the olivine, and bronzite may in some cases replace the augite. Augite has, therefore, most probably crystallized prior to bronzite, and partly simultaneously with the late plagioclase laths as it interferes with some of them.

The accessories include mainly opaque minerals (iron-oxides and sulphides), rare apatite crystals and few replacive minerals of red-brown biotite, basaltic hornblende and serpentine. This may suggest that the bulk of troctolite has crystallized under comparatively dry conditions. Opaques are partly primary and partly secondary after olivines and pyroxenes. They include iron-oxides and sulphides which have crystallized simultaneously with the silicate minerals. Iron-oxides constitute magnetite, ilmenite and spinel. The latter may occur as exsolved lamellae in magnetites, and is arranged parallel to (111) cleavage plane. Magnetite appears to be more abundant in norites than in troctolites.

The sulphides are mainly pyrrhotite with subordinate amounts
of chalcopyrite, pentlandite and pyrite. Pyrrhotite occurs as discrete rounded grains, though sometimes it is enclosed by the oxide minerals.

f. The Outer Olivine-Norite

The intrusion forms patchy isolated low-lying rounded outcrops or clumps of scattered boulders. It forms discontinuous partial sills-intrusions which are paralleled by the later granitic bodies and presumably have been intruded along the weak junction-zone between the green schists and the granitic gneisses. There is no conclusive evidence about the amount and direction of dip of the norite body; however, the country rocks near to the intrusion show steep foliation dip. Norite usually carries abundant xenoliths of country rocks and is itself being assimilated partially or completely by the later granites, to produce a hybrid rock of gabbroid or granodioritic composition.

Petrography

Apart from the modal variations considered before, the olivine-norite closely resembles the core-troctolite in mineral compositions and mutual relationship between the mineral components. Texturally the rock is normally medium-grained, subphyric with average grain-size of 0.5 - 2 mm. Towards the margins and roof zone the norite becomes relatively finer as well as porphyritic with more clouded plagioclases
forming the phenocrysts. The plagioclase is labradorite (An$_{52-53}$) which may show a very slight and narrow zoning in few cases.

5. The Middle Olivine-Micronorite

A discontinuous, arcuate outcrop of olivine-micronorite can be traced within the intrusive body of Tehilla granite-porphyry. The basic rock thus seems to form a distinct intrusion which was later almost obliterated by Tehilla granite-porphyry which possibly occupies and follows the old channel way previously invaded by the early micronorite body. The Tehilla granite porphyry, therefore, owes its present form to the underlying micronorite body. In many places the micronorite is seen to underlie horizontally intruded granitic rocks of the later sill intrusions (Fig. 7).

Petrography

The base of micronorite intrusion has not been exposed, and the part now available for study is mainly the roof segment, though one or two samples were collected from a few metres beneath this. The roof is fine-grained, trachy-porphyritic with phenocrysts of plagioclase (andesine, with a narrow outline of more sodic composition) measuring 1-2 cm in length, but crystals as large as 7.5 cm are not uncommon. Samples from below the contact with overlying granites are identical in composition, non-porphyritic, fine-grained
intergranular (0.5 - 1 mm) and mostly altered, so only one sample was found suitable for modal analysis. In fact this unit has suffered more from the thermal metamorphism following the later granite intrusions than the other two units; most of the olivine, pyroxenes and plagioclases are highly altered and replaced by an aggregate of red-brown biotite, actinolite, hornblende, tremolite, serpentine and peninlite. The plagioclase has been marginally metasomatised and crystals show peripheral resorption with the development of more sodic irregular narrow zones on the margins. As a result of this process part of the Ca$^{2+}$ and Al$^{3+}$ ions were presumably released and combined with fugitives to produce more hydrated minerals.

The plagioclases are small, closely packed anhedral laths measuring 1-2 mm in length, highly twinned and commonly zoned. They are endemine (An$^{32-39}$) and always highly clouded with opaque inclusions disseminated throughout them.

Olivine is less abundant, and occurs as small rounded grains averaging 1 mm in diameter. Some of the unaltered grains observed bear the same relations to other minerals as described before.

Pyroxenes are granular and have the same mode of occurrence as in the outer norite and core-troctolite.

Opaeque (ilmenomagnetcite and sulphides) are extremely abundant,
much of them being derived from the breakdown of the mafic minerals. Opaques may concentrate in places to produce segregated patches commonly observed in the rocks. The abundance of accessory apatite, occurring as cathedral prisms or broad needles, is a characteristic feature of the microlite.

History of Crystallization of Minerals

The sequence of crystallization is identical in the three basic units. It appears to be as follows: olivine is generally the first mineral to crystallize, though it is sometimes slightly preceded by plagioclase, small laths of which are often included in olivine. Plagioclase followed later, and before its final crystallization part of the clinopyroxene (augite) started to form. Bronzite however, was not precipitated until after the cessation of plagioclase crystallization. Opaques may appear at any stage in the sequence of crystallization, sometimes preceding even olivine; some of them however, have clearly developed as a reaction product after olivine and pyroxenes. The sequence may be summarized graphically below:

Opaques

\[\begin{array}{c}
\text{Olivine} \\
\text{Plagioclase} \\
\text{Clinopyroxene} \\
\text{Orthopyroxene} \\
\text{Alteration minerals}
\end{array}\]

\[\text{Time} \rightarrow\]
Conclusion

1) In all the basic units order of crystallization is the same and fairly constant, that is, olivine $\rightarrow$ plagioclase $\rightarrow$ pyroxenes $\rightarrow$ biotite and hornblende. The latter two are probably an alteration product after the early minerals which commonly mantle them.

2) Although crystallization was slow, equilibrium was not quite reached as indicated from the presence of corona structure.

3) Late intrusives are relatively low in modal olivine and rich in bronzite; due to the early crystallization of olivine and plagioclase the magma became impoverished in magnesium and calcium to crystallize bronzite rather than clinopyroxene (augite).

4) The magma is generally poor in volatiles and silica so no acid residuum is ever observed, and the content of hydrous minerals is comparatively low. The late intrusion, microgabbro, is evidently more hydrous and it might be expected to have been drawn from the residual liquid of the basic magma.

5) Petrology and field studies indicate that troctolite was emplaced by repeated sill injection from a differentiated magma reservoir, and possibly the other units which are probably marginal facies of the same body.
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**Number of samples analysed**

**Column Index**

**Total**

**Average**

**Minimum**

**Maximum**

**Table 2: Average Modulus of Elasticity (%) of the Traction Bar**
2.h-k. The Younger Granite Acid Phase

Introduction

The acid phase of the Teshila complex comprises four main units emplaced as partial sill bodies (or high-angle cone-sheets) probably in the order: Halkawan granite, Hamlab granite-porphyry, Thainat granite and Teshila granite-porphyry from oldest to youngest. The units are all of granitic composition with small petrographic range and rather similar chemical affinities. They could, therefore have evolved successively at short time intervals. The areal extent of the granite units expressed in square kilometres is approximately as follows: Halkawan granite (5.4), Hamlab granite-porphyry (1.3), Thainat granite (7.5), and Teshila granite-porphyry (12.3). They collectively cover an area of 36.5 km².

The sequence of intrusions proposed above is from the outside inwards and is suggested mainly from the overall shape of the major intrusive bodies which indicates that each preceding body was partially destroyed by the succeeding one; the centre of intrusions has progressively been displaced westwards (Fig. 2).

General Description of the Individual Granite Units

In this part introductory remarks will be given on each rock group separately with special emphasis on their field relations. Other criteria of the granite intrusions will be dealt with under the
appropriate headings which include here common field characters, petrography, mineralogy and chemistry.

h. Halokwan Granite (medium-grained hornblende-pyroxene granite)

The Halokwan granite has been intruded along subcircular schist/gneiss contact zones in the form of a partial sill (or cone-sheet) intrusion. Schists, when exposed are rather permeated at the contact which in certain parts is sinuous. Granite outgrowths are seen to penetrate the host schists along the foliation planes (Fig. 2). Contact with granitic gneisses is never exposed and mainly covered by talus and scree fragments. Xenoliths of schists and norite are common and produce hybrid rocks of intermediate composition when absorbed by granites.

In the field the rock is very distinct for its uniform medium-grain texture, highly leucocratic character (felsic contents about 96%) and the very low content of dark minerals which are almost replaced by the opaque minerals (ilmenomagnetite?).

i. Hamlab Granite-Porphyry (hornblende-pyroxene granite-porphyry)

The Hamlab granite-porphyry forms a small arc-shaped body exposed on the surface as bouldery patches charged with small disoriented quartz veins or veinlets. The rock is coarse-to medium-grained, in some places shows weak foliation and like Thainat granite
in very rich in felsic minerals. Unlike Thainat and Tehilla granites, the Hamla granite contains approximately equal amounts of pyroxenes and hornblende and is totally devoid of biotite (Table 4). Biotite is common in Tehilla and Thainat granites which contain fair amounts of hornblende always exceeding pyroxene (Table 4). Country rock xenoliths are very abundant.

Microscopic examination has revealed later that this rock unit is largely affected by a strong fault (Fig. 2). Specimens collected from near the fault zone show variable degrees of recrystallization; the relatively fine-grained macro-components have grown big enough to allow for the appearance of plagioclase twinning. In highly advanced stages the porphyritic texture has been replaced by inequigranular mosaic pattern. Quarts is heavily strained and recrystallized so that the grain boundaries of the compound crystals are slightly diffused. Peribite and soda plagioclase crystals show slight undulatory extinction and the former have recrystallized perhaps due to heating to give less perthitic feldspar few of which display a bluish 'schiller' of the moonstone variety. In the field a small amount of the excess silica (recrystallised quarts) is seen filling tension gashes and fissures in the rock as vitreous pods or clots of fused quartz crystals.
J. Thainat Granite (hornblende-pyroxene granite)

This body forms partial discontinuous sill intrusions (or cone-sheets) surrounding the Tehilla granite-porphyry from outside, and crops out as isolated low hills or narrow bands. Granite tends to be porphyritic when it occupies narrow channels. Xenoliths and lens-shaped rafts of schists and norite are very common, and granite is observed to cut into and overlies the latter (Fig. 7). In places hybrid rocks of a mixed granite/norite composition are formed, and in only one locality a mechanic rock breccia is formed (Plate 3).

The granite of this unit appears to be similar in composition to Tehilla granite-porphyry with slight increase in felsic constituents (about 94%) and a more or less uniform gneissic texture. The rock is commonly non-foliated but narrow bodies may show crude foliation commonly emphasized by crystal alignment. The grain-size is relatively reduced towards the margins, though small veins may still exhibit coarse texture to indicate slow crystallization under relatively hot conditions.

k. Tehilla Granite-Porphyry (hornblende granite-porphyry)

It forms discontinuous outstanding ridges of horse-shoe or ovoidal shape, and encloses micrororite xenoliths and rafts which are cut and commonly overlain by the later granites (Fig. 7); in
certain places the basic rocks are excessively attacked and veined so as to produce a local intrusion broccia. The invading granite veins are relatively coarse-grained and unmilled, though they are very narrow, with cooling joints and late fractures seen to extend into the host norite and thus suggest that the norites were invaded while they were relatively hot and not completely crystallized. Granites seem to have been emplaced under a relatively feeble force, since they are seen in places to bifurcate when they are confronted with solid compact mass of norites or troctolites. In this case granites tend to swing around and can only penetrate along weak contact zones, fractures or foliation planes of the country rock schists. Therefore, the hiatus and gaps seen in Tekila granite body, especially the one to the west, are most probably due to the above mentioned cause.

The rock is coarse-to medium-grained and contains sufficient phenocrysts of alkali feldspar to use the name 'granite-porphyry'. Granite may show weak to moderate planar foliations according to mode of intrusions and width of the channels occupied; narrow bodies and marginal granite facies are relatively well-foliated. Foliation is usually marked by the parallel or subparallel alignment of perthite and quartz phenocrysts. The interstitial coloured minerals have further emphasized foliation when they were dragged parallel to the
feldspar- and quartz crystals. The trend of foliation always follows the general attitude of the intrusive body and dips steeply inwards (Fig. 2).

Narrow mills similar to Tehilla granite-porphyry in all respects are generally disposed eccentric to the main body. Most of these mills are exposed at the inside of Tehilla granite intrusion (Plate 4).

Common Field Characteristics Of The Granite Intrusions

The units when examined in the field are found to share certain properties in common: the granites are highly jointed and usually break down into loose boulders which when subjected to weathering processes commonly give well-exfoliated boulders; 'onion-skin' (Plate I.a.) and 'boiler plate' or bare slab features are always observed especially in Tehilla granite body. The outcrops are, therefore, usually covered by loose boulders and scree fragments. Joints (Plate 5) are vertical or steeply dipping (between 70° and 90°) and run approximately N-S, E-W and tangentially. They are almost open and rarely occupied by dyke material.

Xenoliths and rafts of the country rock schists and basic rocks are very common and found in all granite bodies. They are
usually aligned in accord with the general trend of the intrusive bodies, thus suggesting a rather passive mechanism of intrusion.

In places some schist rafts may show slight twisting and contortion. Many schist xenoliths are metamorphosed and converted into fine-granular hornfels which shows notable reduction in the coloured minerals and increase in felsic ones. Basic xenoliths are commonly digested by granite magma when they are relatively small in size; fragments are seen in different stages of transformation. Big rafts usually show no sign of metamorphism by granites apart from slight effects along the contacts.

Contact zones of the granite bodies, when visible, are of vein and permeated type; granites along these zones tend to bifurcate into microsills (few millimetres wide) enclosing thin slices of country rock schists which always show slight twisting – an indication of mild force of intrusion. Granites generally show no remarkable chilling against the country rocks, but slight reduction in grain-size is commonly noted. It is interesting to see even the small veinlets of granites showing a relatively coarse texture. The absence of chilling might indicate slow cooling of the granite magma which seems to have invaded the country rocks when they were relatively hot. Another notable feature of these granites is the absence of pegmatite-plutite phase, except in negligible quantities. Few
narrow veins are seen cutting into Tehilla and Thainat granite bodies. The absence of pegmatite-plagioclase phase could suggest a highly differentiated magma under relatively dry conditions (Taylor and Nesbitt, 1956).

Petrography and Mineralogy of the Granite Intrusions

The granites are generally leucocratic with felsic constituents (alkali feldspar and quartz) amounting to more than 90 per cent of the rock by volume (Table 4). Colour of the fresh rocks usually varies from white-greyish, pale buff or pale pink. Texturally the granite suite varies between coarse and medium ranges, and some members may develop crude planar foliations almost parallel to contact zones and dip steeply to the inside. Some granite bodies (Tehilla and Hanlab) contain abundant feldspar phenocrysts to be designated as granite-porphyrites. The mineralogy of the granite intrusions is very simple and consists mainly of alkali feldspar and quartz with minor amounts of coloured silicates which include green amphiboles (hastingsite) and red-brown biotite accompanied in some places by pale-green sodic pyroxene (cochinite-augite). The latter is totally absent from Tehilla granite-porphyry while biotite is hardly seen in Hanlab granite-porphyry. The coloured silicates are often in closest reaction relationship; the amphibole and biotite are usually external to the sodic pyroxene, and biotite commonly encloses the
amphibole. The coloured minerals seem to have crystallized very late since they always occur interstitial to the early felsic components. The petrography and crystallization reactions between the granite constituents suggest a slow and steady cooling of the magma. The magma appears to be viscous and has presumably been emplaced in a semicrystalline state charged with alkali feldspar crystals which are, in part crystallized prior to the intrusion.

The alkali feldspars (orthoclase microperthites) are very abundant and make up over 65 per cent of the granites modal composition. Alkali feldspars are exclusively orthoclase microperthites that form anhedral tabular plates measuring between 3 and 6.5 mm on the average. The crystals look euhedral on their general form, though in detail the surface boundary is irregular. Perthites are always turbid or cloudy, due to partial or complete alteration to kaolinite and sericite, with clear islands of sodic plagioclase lamellae. Crystals commonly exhibit simple and penetrating Carlsbad twins, and some develop a broad mantle of clear sodic plagioclase along their margins to give a rapakivi texture. The perthites have moderate to large optic angle (about 65°) as estimated from the isogyre curvature and negative sign. Crystals usually carry detached granules of quartz and sodic plagioclase and they may occasionally contain accessory mineral grains like siron, opaques, etc... The quartz
may gather along the margins or around the perthite crystals to develop a relatively coarse micropegmatite on local scale. This has developed in Tehilla granite-porphyry.

The perthite texture is mainly of the vein variety but some crystals may exhibit patchy perthites with fine lamellar twinning. The vein lamellae are apparently untwinned, but a few veins may show tiny multiple twins hardly visible. The patchy type of perthite seems to have grown later and normal to the vein variety, and when they both develop in one crystal this relation is commonly seen (Plate 6). Along contact zones perthites show less degree of unmixing thus suggesting a relatively rapid cooling. The perthitic texture can be picked easily under the microscope by difference in birefringence or the nature of alteration. The origin of these perthites is most probably attributed to the exsolution reactions at low temperature since they show remarkable uniformity in texture and mineral ratio.

The eudic plagioclase is fairly common as exsolved perthitic lamellae and as independent subhedral grains measuring up to 0.5×0.3 mm on average. These grains are counted in modal analysis with perthites as feldspars. The discrete grains commonly exhibit fine lamellar twinning sometimes accompanied by simple Carlsbad twins. In a few crystals the twin lamellae are slightly bent (observed in
Tehilla granite-porphyry) an indication of post-depositional stresses. Some plagioclase crystals are partially altered to dirty kaolin and a fine aggregate of sericite crystals. The plagioclase has a very small extinction angle (θ' ranges between 6° and 9° maximum) and lower index of refraction than Canada Bolano. These properties assign an albite-clinoclase composition which will be referred to as sodic plagioclase throughout the text. The sodic plagioclase does not need to show any regular variation in composition within the granite suite. The crystallization relations indicate that the free sodic plagioclase crystals have most probably been deposited from the late soda-rich residuum, but those gathering around the margins of some perthite crystals are probably developed by solid diffusion process, that is, separation by slow rate cooling. The free silica in perthites could be primary enclosures or exsolved from orthoclase at low temperatures.

Quartz is very abundant in all granites and varies between 24 and 30 per cent of the rock modal compositions (Table 4). The abundance of quartz is in some way related to the crystallization of the silica-poor ferromagnesian minerals such as hastingsite and biotite (Chapman and Williams, 1935). Quartz does not show any regular modal variation within the granite members. It has grown interstitial and interlocking with the perthites. Crystals are
commonly multiple and may measure collectively up to 3 mm in diameter. The grains are, therefore, allotriomorphic with rounded or subrounded form and smooth margins; they are usually dragged and twisted around the early feldspar crystals in a plane parallel to the foliation. Some quartz grains may locally intergrow with alkali feldspars to produce a micrographic pattern or micropegmatite. They may also produce microscopic aegirine when intergrown with sodic plagioclase. Quartz crystals are often fractured, heavily strained and commonly show undulatory extinction. Some crystals may exhibit diffused grain margins that indicate late-stage recrystallization (Baguin, 1968). These features suggest a late-stage granulation probably due to post-depositional stresses.

The coloured minerals are sparsely developed in small amounts that vary considerably from one rock unit to another and even within each granite body. They have crystallized later interstitial to the early felsic constituents and includes sodic pyroxene, hastingsite and biotite. Coloured minerals are commonly associated and usually occur as complex aggregate often associated and charged with accessory minerals.

The dark minerals show very interesting reaction relations; hastingsite and biotite are always seen replacing the pale green sodic pyroxene, and alteration reactions are seen in different
stages of transformation. These reaction relations could indicate that the pale green sodic pyroxene was, probably, once the most dominant dark mineral which later altered to green or bluish green hornblende (hastingsite), biotite and even to iron-oxide ores (ilmenomagnetite?). Therefore, green hornblende and biotite tend to increase from early to younger granite intrusions while the sodic pyroxene shows a marked decrease in this trend. The absence of sodic pyroxene from Tecilla granite-porphryy could be attributed to more advanced replacive reactions that give hornblende and biotite in place of the sodic pyroxene. However, the presence of sodic pyroxene was indicated from the eccentric dyke bodies which are believed to belong to Tecilla granite intrusion; this might further confirm the above presumption. The green hornblende (hastingsite) is frequently replaced by brown biotite and both are further replaced by opaques. In Halokwan granite replacive opaques dominate and constitute twice the amount of the coloured minerals (Table 4).

The hornblende (hastingsite) is the most dominant dark mineral. It is commonly green or bluish green and strongly pleochroic. Colour difference (green-blue) may be due to soda variations. The hornblende forms ragged tabular crystals or short prisms commonly of amorphous outline and small grain-size ranging from less than a millimetre in length to about 2 mm. Amounts of hornblende show
an increase towards the younger members (Table 4). Few crystals from Tahilla and Thahmat granites may show twinning on \( \sqrt{100} \) plane. Poikilitic crystals with quartz grains and accessory mineral inclusions are not uncommon. Some crystals may occasionally develop colour zoning and show olivine-green core and irregular patchy bluish green periphery. Nature of zoning may suggest that the bluish green variety has developed later probably due to the enrichment of the residual liquid in soda and iron-oxides. Inclusions of oxides and biotite within the hornblende crystals usually develop thin bluish green screen around them; iron could have been leached out of those minerals or inclusions and diffused into the enclosing host to produce the bluish green variety.

The optical properties of hornblende shown on Table 3 may assign a hastingsite composition.

The sodic pyroxene forms small elongated prisms less than a millimetre in length, pale green or pale yellowish green in colour, weakly pleochroic and highly birefringent. These criteria, coupled with the large extinction angle \( (c'z = 24^\circ - 37^\circ) \) could indicate an augite-augite variety. The augite-augite is relatively more dominant in Hamalab granite-porphyry and apparently not observed in Tahilla granite-porphyry. Few subhedral and twinned crystals are
occasionally seen in Thainat granite enclosed by perthites and are commonly surrounded by clear soda plagioclase rim. This relation might further suggest a soda-rich pyroxene. Secondary reddish brown material of iron-oxide constantly cover the cleavage planes of altered pyroxene crystals of Thainat granite.

Biotite is present as thin flakes or tabular ragged crystals ranging in length between 1 and 0.1 mm. It is commonly yellowish brown or reddish brown in colour, though green variety is in places present. Pleochroism is very strong from ⁄₁ = yellow or yellowish brown to yellowish green, ⁄₂ = dark brown or reddish brown to dark green. The common reddish brown colour may indicate high content of titanium. Inclusions of accessory minerals (zircon, apatite and opaques) are common, with pleochroic haloes around zircon. Some biotite crystals may show a gradational alteration to reddish brown isotropic iron-oxide and then to almost black iron-ore.

The accessory minerals are fairly common in all granite units. They are usually associated with the dark mineral assemblages and include, in order of abundance, opaques, sphene, zircon and apatite.

The opaques occur as irregular block grains sparsely distributed and many rimmed by sphene, though in some places they enclose small grains of zircon and apatite. Biaxialal grains are not infrequent.
The character and mutual relations of the opaque grains to other minerals may indicate a primary as well as secondary origin. The sphene/opaque association may suggest a titanium-rich magentic (ilmenomagnetite?).

**Sphene** is orange-brown, dull purple, yellowish brown or yellowish green in colour and slightly pleochroic. It forms irregular grains up to a maximum of 1 mm in diameter. Subhedral crystals of rhombohedral cross-section are occasionally observed in Thainat granite. Sphene crystals may enclose zircon and apatite grains. Some crystals are partially altered to dull brownish-blue anatase.

**Zircon** forms well-shaped crystals of rectangular, hexagonal or square forms. Crystals may measure up to 0.4 X 0.1 mm, pale purplish in colour and weakly pleochroic.

**Apatite** is less common forming well-shaped slender prisms and short six-sided crystals which may record up to 0.2 X 0.04 mm.

**Mineral Evolution and Sequence Of Crystallization**

The textural relationships of the granite-phase mineral suite may suggest the following sequence of events:

1) Early crystallization of the accessory minerals possibly in
the order: zircon, apatite, ilmenomagnetite and sphene.

ii) Crystallization of the felsic constituents with the evolution of the orthoclase microperthite first, followed intimately by quartz and sodic plagioclase. However, simultaneous crystallization of felsic components cannot be denied.

iii) Crystallization of the coloured minerals interstitial to the felsic components followed later probably in the following order: augite-augite, hastingsite and biotite. Most of the augite-augite was later partially or completely converted to hastingsite and biotite which are now fairly common and relatively more abundant. Biotite has also grown after hastingsite.

iv) The granites were subjected to post-depositional deformations as indicated by: fracturing and granulation of the mineral constituents, undulatory extinction and recrystallization of quartz grains, and by slight bending of the plagioclase lamellae. Fractures are unevenly distributed and usually filled with mineral flakes such as biotite, hastingsite, etc... Tehilla granite-porphyry seems to have suffered a relatively more intensive deformation since it shows in addition to the above effects, mild displacement along joint planes. This deformation may be due to late crystallization forces or most probably associated with the late faulting movements that
affected every part of Tehilla igneous complex.

Chemistry Of The Granite Intrusions

Chemically all granites analysed are alkalic, and tend to
plot on the central zone of the alkalic field as shown by 'Wright' (1969)
alcalinity ratio variation diagram (Fig. 5). More complete
discussion of the granites chemistry has been dealt with in
following chapters.

Summary And Conclusions

The granitic phase of Tehilla complex falls into four groups
(Tehilla granite-porphry, Theinat granite, Hadala granite-porphry
and Halokwan granite) which are rather similar in their structural
setting, general petrography, mineralogy and chemistry, though they
show minor differences in details. The four intrusive units have
been emplaced in form of multiple high-angle cone-sheet (or sills)
bodies. The essential features of the mineralogy of the Tehilla
granites may be summarized as follows:

1) The granites are highly leucocratic and very rich in felsic
constituents (orthoclase, microperthite and quartz) which make
more than 90 per cent of the rock composition by volume.

2) Feldspars are wholly orthoclase with widespread perthitic
texture of vein and patchy types.

iii) Plagioclase is usually of subordinate amounts and is never more calcic than albite oligoclase.

iv) Coloured silicates are few and rather simple; they include augite-augite, hastingsite and biotite. They show slight variation in modal proportions from one unit to another. The coloured minerals crystallized later than the felsic ones, and have evolved in the proper order of Bowen reaction series: pyroxene → amphiboles → micas.

v) Accessory minerals are fairly common and rather consistent. They include ilmenomagnetite, zircon, sphene and epidote.

vi) Foliation when common is mainly attributed to frictional drag of a flowing viscous magma and its suspended crystals against narrow walls.

Petrographic, mineralogical and chemical studies of the Tehilla granites may permit the following inferences:

i) The granitic magma was probably intruded in a semi-liquid state, that is, highly viscous and carry partly phenocrysts of orthoclase microperthite.

ii) Crystallization has proceeded slowly and steadily. This is
probably due to the fact that the country rocks were relatively hot at the time of granite invasion. Therefore, heat loss along the border zones was not sufficient to cause rapid or immediate crystallization, but merely increased the viscosity of magma so that crystallization took place slowly and steadily to give a moderately coarse-grain texture (Hess, 1950). This might also explain the absence of chilled contacts.

iii) The notable absence of pegmatite-aplite phase could suggest that the granitic magma was possibly intruded under relatively dry conditions (Taylor and Emeleus, 1956).

iv) The granitic magma was possibly intruded under relatively mild force; the weakness of planar foliation in the rock may indicate that there was little motion in the magma, that is, the magma was intruded in a semi-liquid form; schists along the marginal zones of the granite intrusions were slightly twisted; and country rock rafts and inclusions within granites show conformable attitude to the regional trend.

v) The chemical analyses show all granites to be of alkaline affinity.

vi) The granites were subjected to post-depositional stresses which are commonly marked by reorientation, fracturing and
undulatory extinction of the quartz crystals; slight bending of some plagioclase lamellae; and minor displacement along joint planes of the Tehilla granite-porphry.
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Table 4: Average model correlation (volume) of the tongue diameter and

**Table 4: Average model correlation (volume) of the tongue diameter and**

- **Volume**
- **Temperature**
- **Humidity**
- **Humidity (Temperature)**
- **Temperature (Humidity)**
- **Volume (Temperature)**
- **Volume (Humidity)**
- **Temperature (Volume)**
- **Humidity (Volume)**
- **Correlation coefficient**

**Note:**
- The table represents the correlation coefficients between different variables.
- Each column corresponds to a different variable, and each row corresponds to a different correlation coefficient.
- The values in the table indicate the strength and direction of the correlation between the variables.
2.1-3. The Younger Granite Minor Intrusive Phase

Introduction

The minor intrusives phase comprises numerous intrusions, mainly dykes, which can be grouped according to their compositions and relative ages as follows:

0. Quartz veins

1. Granitic (or acid) dykes
   ii. Local acid dykes.
   i. Regional acid dykes.

2. Acroplagiocratic adamellites
   ii. Minor adamellite intrusions (dykes).
      i. Mica-adamellite cone-shield intrusion.

3. Basic dykes (or dolerites)

The dolerite dykes are seen affecting the latest major unit of the complex, Tehilla granite-porphyry, and themselves being traversed by adamellite and granitic dykes. The latter are commonly seen cutting into the adamellite intrusions. Quartz veins have affected every rock unit in the Tehilla complex. Granitic dykes and quartz veins are seen, in places, injected into the same channel previously occupied by dolerite dykes.
1. Dolerite Dykes

Dolerite dykes are more numerous and they possibly belong to a more extensive dyke swarm. Dykes are roughly parallel, commonly trending NW-SE, some trend approximately E-W, and few may show a NE-SW orientation. In general dimensions are small usually between 0.3 and 7 metres in width and the bodies are rarely traceable for more than 30 or 45 metres. Few may measure several metres in length and one or two are exceptionally long. In the field contrast in colour from the host rocks (granite and schists) makes the dykes easily recognizable and mapable, but the opposite is true when the dykes cut into basic intrusions, since they are identical in composition and, therefore, show no contrast on weathering. Most of the dykes have narrow chilled edges and highly jointed character so they break down into small angular fragments.

Microscopic examination of dolerites reveal two rock facies, one presumed to form local dykes and the other regional ones. However, distinction between the two dykes is very difficult in the field and, therefore, they are mapped undifferentiated. Chilling seems to be totally absent from the regional dyke rock. The rock is dense block and plagioclase-phryic with few phenocrysts of glassy plagioclase laths normally between 1 and 3 mm in length. The plagioclase phenocrysts are more basic (labradorite) than the groundmass variety which is
slightly alkaline (andesine). Phenocrysts are commonly cloudy and moderately resorbed. Some crystals are zoned, and a few may show complex twinning.

The regional dykes are trachytic and composed of plagioclase laths with abundant opaque grains (titanium-rich magnetite?) and a few crystals of brown biotite. Pyroxene which appears to be bronzite has been highly replaced by opaques, chlorite and biotite. Apatite is not uncommon and replacemnt of chlorite is relatively more abundant.

The local dykes show great similarity in composition to the middle olivine-microcrorite of the basic phase, and could have possibly been extracted from the same local magma source. The rock has trachytic to subophitic texture and consists mainly of plagioclase laths with numerous opaque granules, short plates of green-brown biotite and a little brown hornblende. Apatite is relatively more abundant than in the regional dykes. In fresh specimens, olivine and pink bronzite crystals are commonly seen.

m. Anorogenic Adammellites

The anorogenic adamellites are commonly emplaced as dykes and cone-sheet bodies. Unlike the orogenic adamellites they are of rather uniform composition and totally devoid of microcline
feldspar which is very common in the orogenic variety.

i. Microadamellite Cone-sheet Intrusion

It forms distinct simple multiple intrusion of bouldery, disconnected narrow outcrops that run concentric to Tuhilla granite-porphry. It commonly bifurcates and branches into smaller bodies (Fig. 2) that occur conformable to foliation planes of the country-rock schists and show a relatively low dip to the inside (40°-65°). It can, thus, be considered a multiple sill body or cone-sheet intrusion. The width of these bodies varies from a few metres up to several metres across (maximum recorded is about 72 metres). The rocks are jointed approximately in N-S, E-W and tangential directions. Exfoliation weathering is a very common feature in outcrops of this rock. The sills (cone-sheets) contain small dark xenoliths of schists and troctolite.

The rock is grey or dark grey in colour, fine-grained and mainly composed of feldspars and quartz, interspersed with abundant dark grains of mica and hornblende. In places, the rocks may get porphyritic and develop poor foliations. Fine micropoegmatitic and myrmekitic intergrowths are frequently distinguished under the microscope. Average modal analyses on Table 5 show the microadamellite rock to consist mainly of plagioclase (aligoclase),
orthoclase microperthite and quartz with few sporadic and interstitial dark minerals of biotite and green hornblende. The accessories constitute the normal suite found in granites-opaques, sphene, apatite and zircon.

The plagioclase forms subhedral to subhedral laths (1 X 0.2 mm average size) nearly always shows normal continuous zoning with slightly calcic core and more sodic periphery. Zoning is clearly emphasized by alteration, that is, the core is almost cloudy and twinned, while the margins are clear and apparently untwinned. Oligoclase commonly exhibits Albite and Carlsbad twins which are occasionally encountered in one crystal.

**Orthoclase microperthite** is cloudy with clear vein lamellae. Perthites are always of vein-type. **Quartz** forms interlocking grains often with shadowy extinction. Small rounded grains are embraced by or enclosed in some perthites.

The dark minerals include biotite and green hornblende. They are usually associated together and frequently altered to green chlorite along their margins and fracture zones. Biotite occurs in small flakes (0.1 - 0.2 mm in diameter) with jagged ends and brown colour. It is strongly pleochroic from yellow or yellowish brown to dark brown. Orange or reddish brown variety is often observed replacing hornblende. Pleochroic haloes are occasionally seen.
Green hornblendes form ragged and short prisms, strongly pleochroic from brown-green or yellowish green to green, olive- or bluish-green and is probably a hastingsite. Secondary sericite and epidote are normally derived from feldspar decomposition, and the former may show progressive alteration to give muscovite, chlorite and finally biotite. The accessory minerals are commonly associated with or enclosed by the dark minerals. Sphene may envelop some opaque crystals, and forms pleochroic pale yellow or yellowish brown grains that measure up to 0.5 X 0.2 mm. Some crystals may develop good rhombic sections.

11. Microadamellite Dykes

They are mainly exposed on the southwestern corner of the mapped area (Fig. 2) in form of short narrow dykes (4 - 9 metres wide) or small bosses. The rocks may contain foreign fragments of schists, metabasites and probably a few fragments of Dorudeh adamellite. Quartz segregations and occasional miarolitic cavities are seen in the microadamellite rocks; the latter are indication of shallow-level intrusions.

Petrographically the dyke rocks differ from the cone-sheet microadamellite in being relatively poor in quartz (less than 15 per cent) and sodic plagioclase but rich in orthoclase microporphrites. However, chemically both rocks are intimately related, though the
dyke adamellite is slightly low in lime but relatively higher in alkalis than the cone-sheet adamellite.

The rock is more leuconocratic than the cone-sheet adamellite, medium-grained and basically made of turbid orthoclase microperthite, quartz and sodic plagioclase (albite-oligoclase) with subordinate amounts of bluish-green hornblende (hastingsite) and clinopyroxene (aegirine-augite). Accessories include opaques, muscovite, apatite and sphene. Few micropegmatites and myrmekitic intergrowths are detectable under the microscope.

The sodic plagioclase (albite-oligoclase) varies greatly in amounts from section to section and is often replaced by orthoclase to give perthite and antiperthite varieties. The relative abundance of plagioclase, therefore, depends on the degree of replacement, when intensive the rock shows low content of plagioclase. Therefore, the modal amounts given in Table 5 do not represent the precise mineral content of the rock.

The coloured minerals are generally associated together. The aegirine-augite is frequently replaced by the bluish-green hastingsite, biotite and opaques. Biotite and opaques may also grow after the hastingsite.
Granitic (or acid) Dykes

The granitic dykes are of limited extent as compared to the basic dykes. They comprise regional as well as local dykes.

1. Regional Dykes

They trend approximately E-W and outcrop mainly in the northern parts of the mapped area (Fig. 2). Dykes are sometimes traceable for a few kilometres, and they usually vary in width from about 7 to 55 metres.

The rocks are of microgranitic composition and present much more variations in texture. They include: microgranitic, aplitic, granophyric and phonolitic types in which grain-size rarely exceeds a millimetre in diameter. The variation in texture appears to be governed by extent and magnitude of the fissures occupied; the narrower dykes give a more dense and foliated rock. The dykes have a typical granitic composition and are largely composed of turbid microperthitic feldspar (mostly orthoclase), quartz and lesser proportions of sodic plagioclase as compared with the local granitic dykes. The dark minerals are markedly few including maphic flakes and needles of brown or red brown biotite, scattered opaque granules (probably magnetite) and a few crystals of siron. Biotite has possibly originated in the same way as that of the local dykes. In some rocks the dark minerals are completely
altered and indistinguishable being only represented by skeletal grains of opaques.

The spherulitic variety carries a few idiomorphic phenoocrysts of zoned plagioclase (oligoclase ?) and quartz set in a granophyric microfelsic matrix which is made up mainly of alkali feldspars and quartz. Radiating quartz and feldspar filaments normally surround the quartz and feldspar nuclei.

ii. Local Dykes (biotite microgranite)

They form narrow short bodies (few metres wide) commonly trending E-W. The rock is highly leucocratic, fine-grained and more or less foliated. It is predominantly made up of microperthite feldspars (mainly orthoclase) and quartz with few amounts of scattered needles and ragged flakes of brown biotite, opaques, silliman and occasional prisms of olive-green hornblende. One slide contains euhedral grain of garnet probably derived from the calc-silicate country rocks. Secondary minerals comprise dusty kyanite, sericite and a few grains of epidote resulting from the decomposition of feldspars. Biotite is mainly formed after the secondary sericite, though partly crystallized from the residual solutions caught within mineral interstices and their fracture zones. Plagioclase varies considerably in modal proportions and is commonly replaced by alkalifeldspars. Fill and vein types of replacement porphyrites.
0. Quartz Veins

Quartz veins represent the latest igneous event in this region. They are very common and widely distributed on a regional scale. The veins mainly trend E-W and measure from a few millimetres up to a few metres across. The vein bodies seem to have suffered extensive weathering since derived quartz pebbles are commonly seen covering most of the low plains.

The vein quartz intrusions were shortly succeeded by small amounts of fugitive expulsions mainly of green actinolite which have affected the quartz veins and the nearby outcrops. It is seen in the field as patchy green colouration staining the rocks along grain boundaries and fracture zones.
<table>
<thead>
<tr>
<th>Component</th>
<th>(i)</th>
<th>(ii)</th>
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<tbody>
<tr>
<td>Sodic plagioclase</td>
<td>33.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Orthoclase microperthite</td>
<td>29.8</td>
<td>69.8</td>
</tr>
<tr>
<td>Quartz</td>
<td>27.9</td>
<td>14.6</td>
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<tr>
<td>Anchimgite</td>
<td>1.3</td>
<td>3.2</td>
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<tr>
<td>Augite</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>Biotite</td>
<td>6.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Opaques (magnetite ?)</td>
<td>0.4</td>
<td>3.9</td>
</tr>
<tr>
<td>Other accessories</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>95.9</td>
<td>99.7</td>
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<tr>
<td><strong>Number of samples analysed</strong></td>
<td>(4)</td>
<td>(2)</td>
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</table>

**Explanation:**

(i) Coarse-coated microgabbrolite.
(ii) Lyso-rocks microgabbrolite.
V. PETROCHEMISTRY

1. INTRODUCTION

Thirty-six rock samples from the Tchilla igneous complex were analysed; of these 12 were of basic rocks, 11 amphibolites and 13 granites. Major oxides and a few trace elements (Sr, Rb, Zr) were analysed using X-ray fluorescence (XRF) methods in Department of Earth Sciences at the University of Leeds. The alkalies (Na₂O, K₂O) were determined by Flame-photometry method and ferrous oxides by wet chemistry using potassium-permanganate method.

The C.I.P.W. norms have been calculated from the chemical analyses, using an Algol computer programme written by Dr. R.H. Hay and Dr. R.W. Le Maitre of the British Museum, Department of Mineralogy, and Dr. B.C.H. Butler, University of Oxford. The details of chemical analyses and norms are presented separately for each rock group in the Appendix. (Table 7, 8 and 9). The average compositions are listed in Table 6.a. Analyses of some igneous rocks belonging to other Younger Granite massifs of northern Sudan (Jebel Qellil, Sileit-Sa-Sufur, Abu Tikir, Salala and Saboloko) are presented in Table 10.

2. CHEMICAL CHARACTERS OF INDIVIDUAL ROCK-GROUPS

(Refer to Table 6.a). It should be noted that the rock suite
of Tahilla complex comprises three major rock types: the basic rocks which include troctolites, norites and dolerite dykes; the adamellites which are subdivided into orogenic and anorogenic adamellites; and the acid rocks or granites. The anorogenic adamellites are here considered with Tahilla rocks mainly for comparison with the orogenic type which is related to the post-tectonic intrusions of Tahilla complex.

The basic rocks reveal the following chemical characteristics: the group as a whole shows a considerable content of titania and total iron, a feature reflected in their mineralogy by the occurrence of titanium-rich magnetites which may locally aggregate to form ore bodies. Norites and troctolites are relatively depleted in magnesia; this is reflected by the nature and composition of their dark minerals which include an iron-rich olivine, bronzite, biotite and hastingsite. Both rocks are also rich in soda and slightly deficient in potash.

The troctolite shows high alumina content exceeding the averages of Neckolds (1954). The increase in alumina could be attributed to the composition of the plagioclase being less calcio (an 47-55) and to the early separation of the micasilicates (olivine and bronzite) that controlled the distribution of alumina in the magma (Jaafar, 1970). The norms of troctolite show nepheline which is not noted among its mineral constituent. The absence of sodium micasilicate
in the basic rocks could be ascribed to the original composition of the parent
magnesia being relatively poor in alkalis and silica (Green and Ringwood, 1967).

The adamellites are slightly deficient in alumina and magnesia compared with similar adamellites of Rockwell (1954). The orogenic adamellites record high silica values and show an excess of soda over potash. When compared together, the two adamellite rocks show remarkable differences in chemistry justifying their subdivision into two separate groups. The anorogenic adamellites are low in silica, high in alumina, magnesium, alkalis and total iron when compared with the orogenic adamellites. Corundum appears in the norm of the latter, but is totally absent from the former type. The main variances between the two rocks imply the existence of two parental magmas.

Since orogenic adamellites were emplaced earlier and bear no relation to the present-exposed post-tectonic rocks of Tehilla complex they may be classified as older basement rocks whose evolution is connected with the tectonic movements that preceded the intrusion of Tehilla complex. The orogenic adamellites show no regular chemical variations. However, field observations indicate an extensive wall-rock zoning that may account for the chemical and mineralogical inconsistency of the orogenic adamellites.
The granites are generally low in alumina, high in total iron and alkalies. The alumina ranges between 12.07 and 12.80 per cent and, therefore, is lower than the average values recorded for alkali granites (Nockolds, 1954). The iron may vary locally with a maximum value of 5.63 per cent. Unlike adamellites, in the granites potash shows slight excess over soda, and the molecular proportions of alkalis never exceed the alumina values in either the adamellites or the granites.

The normative analyses (Table 6.e) are in good agreement with modal compositions (Table 6.b) except for the presence of corundum which appears in rocks comparatively high in alumina. Normative albite is predominant over the orthoclase. Magnetite and ilmenite are shown in significant amounts.

3. THE BEHAVIOUR OF MAJOR OXIDES AND TRACE ELEMENTS VERSUS DIFFERENTIATION INDEX (D.I.)*

Curves of continuous variations may be obtained if the weight percentages of the major oxides are plotted

* D.I. has been calculated by the same computer programme used for C.I.P.W. norms calculations.
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<tr>
<th>A</th>
<th>Core-troctolite</th>
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<tr>
<td>B</td>
<td>Olivine-norite</td>
</tr>
<tr>
<td>C</td>
<td>Olivine-microcrater</td>
</tr>
<tr>
<td>D</td>
<td>Basic dykes (dolerites)</td>
</tr>
<tr>
<td>E</td>
<td>Derudob adamellite</td>
</tr>
<tr>
<td>T.265</td>
<td>Tehilla adamellite</td>
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<tr>
<td>T.112</td>
<td>Microadamellite</td>
</tr>
<tr>
<td>F</td>
<td>Microadamellite core-sheet</td>
</tr>
<tr>
<td>G</td>
<td>Microadamellite dykes</td>
</tr>
<tr>
<td>T.75</td>
<td>Halokwan granite</td>
</tr>
<tr>
<td>H</td>
<td>Hamlab granite-porphyry</td>
</tr>
<tr>
<td>I</td>
<td>Thoinat granite</td>
</tr>
<tr>
<td>J</td>
<td>Tehilla granite-porphyry</td>
</tr>
<tr>
<td>K</td>
<td>Local acid dykes</td>
</tr>
<tr>
<td>L</td>
<td>Regional acid dykes</td>
</tr>
</tbody>
</table>

- **BASIC ROCKS**
- **OрогENIC ADAMELLITES**
- **ANOROCENoС ADAMELLITES**
- **GRENITES**
- **GRENITIC DYKES**
against Index of Differentiation (D.I.) - Fig. 3. These curves may indicate fractional differentiation of magmatic liquids (Rockolds and Allen, 1953; Simpson, 1954; Bowen, 1956; Yoder and Tilley, 1962). The points along the curves, with few exceptions, show very little scatter. It should be noted that there is a progressive increase in the amounts of silica, alkalies and decrease in amounts of lime, magnesia, total iron and alumina on passing from early basic to late acidic rock types. This trend is, more or less, in favour of magmatic differentiation.

Silica is low in basic rocks and sharply increases with increase in D.I. Soda is high in basic rocks, becomes rather constant in intermediate rocks and then shows slight increase towards acid phase. Potash steadily increases from basic to intermediate stage, and then rises gently at the acid stage. Lime sharply decreases from basic to acid rocks and the curve approaches a linear alignment. Magnesia decreases rapidly from basic to intermediate rocks and then shows progressive but gentle drop among the acid members. Total iron rises to a maximum in the middle or late-stage basic rocks and then declines steadily towards the acid rocks; the Fe/Mg ratio increases from basic to acidic members - this is a common trend in differentiated magma series (Greenwood, 1951). Alumina drops steadily but gently from basic to acid rocks.
The plot of Rb, Sr and Zr trace elements (in ppm) against D.L. (Fig. 4) shows the following relations: Rb increases steadily from basic to acidic end and is constantly parallel to $K_2O$ with more straight character. Sr shows a steady decrease from basic to acidic rocks following CaO trend. Zr first increases to maximum and then declines in acid rocks.

The plot of Sr and Rb against CaO and $K_2O$ respectively (Fig. 5 a-b) shows that Sr increases with increase in CaO and Rb gives similar relation with $K_2O$.

The general behaviour of the oxides and trace elements in rocks from Tahilla complex suggests that, although there is a slight scatter of points, yet there is a general trend which is consistent with the process of magmatic differentiation during the evolution of Tahilla complex.

4. CHEMICAL AFFINITY OF TAHILLA IGNEOUS ROCK SUITE

The plot of the average compositions of Tahilla rocks on "Wright alkali-linarity Ratio Variation Diagram" (Fig. 6) shows them to lie in the field of mild alkali to alkaline affinity. All granito samples plot in the moderate-alkaline field and give an average alkalinity ratio of 3.79 (range from 3.24 to 4.24).
FIG. 4 Variation diagram for trace elements, Tenille Complex.
Symbols as in Fig. (3)
FIG. 5 Shows the relations between a) Sr and CaO, and b) K₂O and Rb in Tehilla rock suite. Symbols as in Fig. (3)
adammellites grade from mild alkaline (earlier adamellites) to alkaline (late adamellites), while the basic rocks range from mild alkaline (early trachybasite and norite) to alkaline (late mangerite and dolerite dykes). It is of interest to note the general increase in alkalinity from early to late members of each rock group, and from early basic rocks to late acid rocks.
FIG. 6 Alkalinity ratio variation diagram for analyses from Tehilla(⊙), Qaḻū(○), Silebat-Es-Sufur(+)，Abu Tikir(□), Salala (△) and Sabalaka(△) intrusive complexes.
VI. EMPLACEMENT MECHANISM AND EVOLUTION OF TEHILLA COMPLEX

1. EMPLACEMENT MECHANISM

Petrography and field studies indicate that the intrusive bodies of Tehilla complex were mainly emplaced by repeated sills (sheet) injections from a differentiated magma reservoir probably sited at about 7 km beneath the complex. These sills may join each other on their way up or may be joined by sheet intrusions that occupied horizontal fractures which might have existed at different levels (Fig. 7). Therefore, although some bodies appear as massive intrusions, traces of sills could be detected in some parts of the outcrop as resistant ridges (Fig. 7). Roof sheets are commonly observed along valley cuts.

During injection magma could have possibly widened the occupied fissures by slight wedging and horizontal stretching of the country rock schists. Schists close to the intrusive bodies, especially along Tehilla granite-porphyry contacts, are closely packed and slightly twisted. However, it is evident in the field that this force of intrusion was generally weak since the enclosed country rock fragments have often preserved the regional trend, and the late granite intrusions seem to show no capacity to cut into the early basic rocks except along joint planes and fractures. In
addition, the weakness of the planar foliation in granite bodies may also indicate slow motion of viscous magma (Buddington, 1959).

Examination of several specimens sampled from a suite of sills

a) Tectonic sagging of the country rock schists due to cross folding \( (F_b \text{ and } F_c) \) that gave an oval-shaped (horse-shoe) basin structure (Fig. 8.a).

b) Injection of the basic phase into the sagged country rocks to produce a massive lobolith occupying the trough and two marginal discontinuous sill bodies (Fig. 8.b). Lobolith and marginal sill
A view of part of the Tolilla granite-porphyry intruding and overlying the middle norite intrusion. (looking S.).
intrusions were probably formed by welding of separate sheets placed conformable to the foliation planes of the basin-schists.

It is possible that the marginal sill-bodies have separated from the major basic phase at higher levels and not drawn independently from the magma chamber. The lopolith basic rocks are, hence, known as core- troctolite, while the two marginal sill intrusions constitute an early olivine-norite and a late middle olivine-microxenite bodies. The marginal sills are believed to be younger than the core-troctolite.

The intrusion of the basic phase might have been associated with vast amounts of volcanic products not represented at the present surface, perhaps, due to drastic removal by weathering and denudation. Volcanic activity is reported from similar Younger Granite complexes in Sudan: Sabaloka (Almond, 1971), Salala (Ehre, 1955), Jbel Geili and Sileiat-Ul-Sufur (Ahmed, 1968).

c) Production of tension fractures and weak zones due to increase of pressure in magma chamber (Billings, 1943) as a result of partial collapse of the warping crust during refolding and injection of the basic phase. Down warping may explain the contorted marble bands close to the complex, since such deformation may not be wholly attributed to this type of granite intrusion.

d) Tension fractures have consequently developed concentric and
inwardly dipping joint-planes along which the late acid phase bodies have been emplaced as multiple high-angle cone-sheets or sill injections (Fig. 8.c.). These sheets are joined upwards or connected with cross-fractures to produce massive bodies (Fig. 6). In this complex, five distinct partial high-angle cone-sheet bodies have been recognized which seem to have evolved from the outside inwards, probably in the following order: Holkham granite, Hamlah granite-porphry, Thamal granite, Tohilla granite-porphry, and anorogenic microadamellite. The first four are all of granitic composition while the latest one is of an adamellite composition.

The acid phase cone-sheet bodies seem to have evolved at relatively close intervals since they show no remarkable difference with regard to lithology, texture or chemistry, though they are topographically very distinct. Field relations, also, indicate that the acid phase has been emplaced probably before the final consolidation of the basic phase units since no chilled contacts are observed between the two rock groups.

e) The latest event in the history of Tohilla complex is the injection of minor bodies mainly in form of dykes and quartz veins. The dykes recognized show granitic, doleritic, as well as adamellitic composition and cut diagonally across all older rocks.
(a) Folded metamorphosed country rocks

(b) Emplacement of the basic phase as a lopolith and sills

(c) Injection of granites and adamellites as multiple intrusions
(d) Present erosion level of Tehilla igneous complex showing extension of cone-sheets to postulated magma chamber in depth
VII. STRUCTURES OF TEHILLA REGION

1. INTRODUCTION

It should be noted that the structural elements represented in the area mapped (Fig. 2) are identical to and consistent with the regional ones shown on Fig. 1. The structures considered here include: folding and flexures of metamorphic rocks, the structural setting of Tehilla complex, as well as faults.

2. FOLDING AND FLEXURES

Foliation trends are mainly indicated by the parallel alignment of the mineral components, especially the dark micas and amphiboles. These trends commonly follow a N-S and E-W directions (Figs. 1 and 2). However, local flexuring may produce, in places, distinctive NE and NW minor trend patterns. Near the syntectonic plutons and the Younger Granite intrusions (Fig. 1) foliations are deflected around these bodies. In few cases trends of metamorphic rocks may show complete parallelism.

The two main trends mentioned above (N-S and E-W) have been previously proposed to represent interference pattern of cross folds which, in places, developed a series of culminations and depressions that are believed to be occupied by ovoidal or rounded bodies of syntectonic granite, adamellite or Yogajur Granite.
intrusions. If this presumption is accepted, then the swing of foliations around these bodies may not be wholly attributed to the force of intrusions. Synemolitic plutons within the thesis area generally show a passive mode of injection by attacking the country rock schists along foliation planes; the undigested xenolithic fragments show conformable trend to the regional pattern. The Tehilla complex seems to have been emplaced under relatively mild forces; the Hallockian granite has developed an intricate outer contact zone by sending stringers that follow the E-W regional trend oblique to the general attitude of the complex. This behaviour might indicate that the complex units have, more or less, initiated a pre-existing regional pattern rather than being wholly responsible for making them.

3. STRUCTURAL SETTING OF TEHILLA COMPLEX

The intrusive bodies of Tehilla complex and the closely associated country rock schists show a centripetal inclination, thus, indicating a basin-shaped structure. Dips recorded for the complex intrusion against the country rocks vary between 45° and 85° inwards, but the common dip value is about 65° (Plate 7). It was previously proposed that the basin feature was a result of cross folding (F₅ and F₆) that took place prior to the evolution of the Tehilla complex. Partial collapse of the warping crust during
Plate 7

Different views showing the attitude of contact of Tshilla granite-porphyry against the country rocks.

Southwest of Tshilla station. (looking NNW).