PERTHITES IN SOME HIGH-LEVEL GRANITE PLUTONS OF WESTERN RAJASTHAN, INDIA, AND THEIR SIGNIFICANCE IN RELATION TO THEIR GEOLOGICAL SETTING*

by M. V. N. MURTHY† *and* P. K. VENKATARAMAN, *Geological Survey of India, 27 Jawaharlal Nehru Road, Calcutta 13*

(Communicated by D. N. Wadia, F.R.S., F.N.I.)

(*Received August 18, 1966*)

The paper incorporates the results of petrographic and optical studies on alkali feldspars in riebeckite/aegirine and hornblende granites (Siwana-type), supplemented by petrographic studies of biotite and hornblende-biotite granites (Jalor-type) belonging to the same epoch of igneous activity, from Barmer district, Western Rajasthan, India. These are one-feldspar granites with almost entirely alkali feldspar of intermediate composition (cf. Kali-granites of Johannsen 1962, p. 51) invariably perthitic (mesoperthites), ranging from orthoclase cryptoperthites (never microperthites) to microcline microperthites (never cryptoperthites). These high-level granites, Late Precambrian in age, are closely comparable to the suite described from Northern Nigeria by Jacobson *et al.* (1958).

Field, petrographic, modal and optical studies confirm the conclusion arrived at by theoretical considerations, viz. the perthites are formed by exsolution and not by replacement (Tuttle and Bowen 1958). The role of deformation, cooling and catalytic action of volatiles, especially water-vapour under pressure, in promoting exsolution, is examined; the last factor is considered to be the most important. The apparent anomaly of water-rich biotite granites being one-feldspar (perthite) granites is explained by taking into consideration the relation between hydrostatic pressure (as indicated by the level of the granite) and water-vapour pressure. In high-level granites, water-vapour, even when copiously available, escapes into the country rock. In deeper levels, where the escape is slow and the hydrostatic pressure high, exsolution and recrystallization are promoted by water-vapour under pressure giving rise to two-feldspar granites. Some of the characteristic features of high-level granites are noted.

INTRODUCTION

In connection with the studies on the Bentonite deposits of Barmer district, Rajasthan, Murthy and his co-workers (cf. Siddiquie and Bahl 1965) collected specimens of Siwana-type granites (La Touche 1911) from five different plutons (Jasai, Bisala, Mungeria, Taratra and Siwala) and the

---

* Published with the kind permission of the Director-General, Geological Survey of India.

† *Present address:* Geological Survey of India, Assam Circle, Eastern Region, Shillong 3.

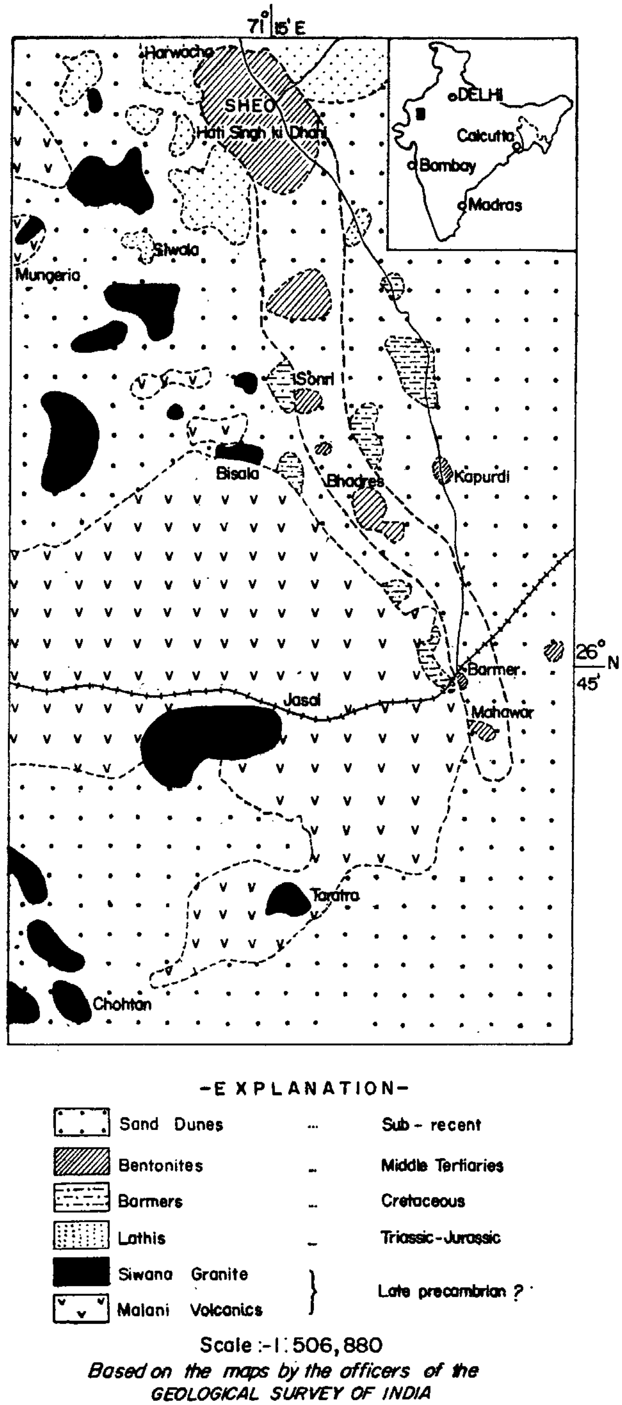


FIG. 1. Geological map of the Barmer area showing the occurrence of Siwana granites and Malani volcanics.

Malani rhyolites from the area shown in Fig. 1. These formations are considered to have belonged to the *Purāṇas* and to be intermediate in age between the Delhi and the Upper Vindhyan formations (Pascoe 1959, p. 553; Krishnan 1956, p. 201); they may be Late Precambrian in age. Recently, zircons from the Siwana granite have been dated to be 1100$\pm$50 m.y. (Vinogradov *et al.* 1964).

Siwana Granites and Equivalent Rhyolites.—The discordant intrusive character of the granite plutons was also noted by La Touche (1911, pp. 24, 56, 62, 63) at Taratra and elsewhere; they cross-cut the Malani rhyolites. According to La Touche (1911) and Coulson (1933) the granites were not separated much in time from the rhyolites and both belong to the same epoch of igneous activity, the same magma being extrusive as well as intrusive. This is confirmed by the presence of extrusive riebeckite-aegirine rhyolites and intrusive riebeckite-aegirine granites (cf. Murthy *et al.* 1961, p. 427; Murthy and Venkataraman 1964). The magmatic nature of the granites is also indicated by zircon studies (Krishnan 1961; Viswanathan 1962, *in press*).

Studies of thin sections from the type area around Siwana, 102 km east of Barmer, registered in the Geological Survey of India, establish the presence of riebeckite-aegirine granites and rhyolites. Rocks collected by La Touche (Geological Survey of India collections) from the granite masses of Chohtan, Randhana and Dandoli are also similar; the Siwana granites are not hornblende granites as originally described but contain accessory riebeckite and/or aegirine in varying amounts. The granite from Siwala is an exception; it contains accessory hornblende and neither riebeckite nor aegirine.

Jalor Granite.—Beyond the volcanic area and the associated Siwana-type riebeckite-aegirine granites, there are also plutons of biotite granites, with or without minor hornblende; these belong to the Jalor-type of La Touche (1911). They are intrusive into the Aravalli schists but in places are in contact with the lavas into which they seem to be intrusive. The Jalor and the Siwana granites belong to the same epoch of igneous activity (Pascoe 1959, p. 536).

Geological Setting of the Granites.—The close association of sub-areal rhyolites with intrusive granites of similar composition, absence of interbedded sediments, discordant intrusive contacts, etc., indicate that they belong to the epizonal volcano-tectonic association of Buddington (1959). They are disharmonious (Walton 1955) high-level granites comparable to those described from Northern Nigeria where they occur as ring-dykes (Jacobson *et al.* 1958, p. 11). The writers have not studied the type Siwana area where the outcrop pattern of the riebeckite-aegirine granite is suggestive of a ring-dyke (Murthy 1962), vividly described by Pascoe (1959, p. 537) as under: The Siwana granite bosses lie along a more or less continuous ring, 19 miles across from west to east and 16 miles from north to south. Whether this almost circular plan has any connection with the root of a volcano is not known for the disposition of the flows and ash beds, which might have afforded some indication, has been disturbed by subsequent earth movements.

Nature of the Present Studies.—The granites studied in this paper are predominantly perthite-bearing with only minor amounts (less than six per cent by volume) of discrete plagioclase crystals; they simulate one-feldspar granites. The recent work of Tuttle and Bowen (1958) indicates the importance of studies on such granites (cf. Walton 1955) in deciphering the origin of granitic rocks. According to Tuttle and Bowen (1958) the bulk of the plagioclase of granitic rocks is not formed by direct crystallization from a magma but is derived by exsolution and recrystallization of a single Na-bearing alkali feldspar phase, the process having been aided by volatiles.

In the present paper, results of the detailed microscopic study of some of the Barmer granites are presented. These include modal analyses, optical determinations of the feldspars, their inferred compositions, crystal characteristics and the nature of the perthites. These studies have been supplemented by examination of the Siwana granites from outside the Barmer area as also thin section studies of the Jalor-type of granites from Sirohi. An attempt has been made to evaluate the various factors considered important in the formation of perthites. The interrelationships of the level of granite emplacement, as indicated by the geological *milieu*, the water-vapour pressure and the formation of perthites are stressed. Some of the distinctive features of the disharmonious granites studied are also recorded.

Present Studies

Determinative Methods.—The optical determinations and the modal analyses reported in this paper were carried out by Venkataraman. A Leitz 4-axis Universal Stage was used to obtain in thin section all the optical and the crystallographic data of the perthites studied. The nature of the K-feldspar was established with the help of Nikitin's stereogram. The optic axial angle was obtained by the following three methods: (*a*) by reading off directly on the graduated drum of the k-axis, when both the optic axes emerged, and by applying necessary corrections applied with the Tröger's (1939) graphs, (*b*) by computing by the method of characteristic extinction angle (based on Biot-Fresnel Law) and (*c*) by the method of characteristic retardation (after Max Berek). The birefringences were obtained by applying the Nikitin-Boldireff method (Naidu 1958, p. 63); thus the refringences were arrived at indirectly. Much difficulty was experienced in getting the refractive indices by the immersion method (Rittmann and Grutter 1939). The cleavage fragments are rarely parallel to the principal planes of the optical ellipsoid and hence only α and γ could be obtained. The extinction angle X_a on (010) was measured by bringing X and a on the same great circle of a Wulff's net.

Modal analysis of the different granites (Table I) was carried out by the method of Chayes (1949) by traversing thin sections spaced 1 mm apart and identifying the mineral at the intersection of the cross-chairs at 0·3 mm intervals. On an average, 2,000 points were counted in each section.

TABLE I

Modal analyses of Siwana-type granites from Barmer district, Rajasthan

Constituents	8729	Bis–1	HNS–2	8992	HNS–4
Quartz	39·12	16·69	32·88	34·34	33·79
Alkali feldspar (crypto- and microperthitic)	49·53	10·87	55·21	57·63	46·42
Plagioclase (discrete grains) ..	3·18	5·31	1·79	1·41	2·80
Quartz—feldspar intergrowth ..	—	54·95	—	—	—
Riebeckite and aegirine	7·27	10·78	8·70	6·69	—
Hornblende	—	—	—	—	—
Ores and accessories (apatite, zircon, iron ore, etc.)	0·86	1·34	2·41	0·59	1·69
TOTAL	99·96	99·94	100·99	100·66	100·09

Note : 8729, Bis–1, HNS–2, 8992 and HNS–4 stand for the granites from Jasai, Bisala, Mungeria, Taratra and Siwala respectively, Barmer district, Rajasthan.

Quartz, alkali feldspar (mainly perthitic) and plagioclase were, in all cases, recorded separately as also riebeckite, aegirine, ores and other accessories. Much of the alkali feldspar is perthitic and no attempt was made to estimate the plagioclase content. Perthite is counted as alkali feldspar, even though, in places, the plagioclase lamellae are coarse enough to be recognized as such. Since the plagioclase is a result of exsolution, it is reasonable to include the whole under alkali feldspar from which it has been exsolved. Clear K-feldspar, though negligible in amount, was recorded separately; however, distinction could not be made modally between orthoclase and microcline.

The thickness of the lamellae in the cryptoperthites ranged from 1 to 5 μ and those in the microperthites were $> 5\ \mu$ (cf. Tuttle 1952*a*).

Composition of the Alkali Feldspars.—The composition of the cryptoperthites (Table II) was obtained by extrapolating the three optical properties, viz. refractive indices, extinction angle on (010), and the optic axial angle, on the diagrams prepared by Oftedāhl (1951), Tuttle (1952*b*) and Marfunin (1961). In the first case, the intersection of the mean refractive index and the extinction angle X_a gave the Or : Ab : An ratio. On Tuttle's diagram, the intersection of either the optic axial angle or of the extinction angle with the standard curves gave the composition (Fig. 2). The Or percentage, as obtained by Oftedāhl's diagram, was

TABLE II

Optical properties and the chemical composition of orthoclase cryptoperthites from Siwana granites, Western Rajasthan

Optic axial angle	Extinction angle on (010)	Mean refractive index	Composition		
			Oftedāhl (1951)	Tuttle (1952b)	Marfunin (1961)
71°	11·0°	1·5275	$Or_{52}Ab_{46}An_2$	$Or_{58}(Ab_{93}An_{07})_{42}$	$Or_{57}Ab_{43}$
73°	11·5°	1·5290	$Or_{47}Ab_{49}An_4$	$Or_{53}(Ab_{93}An_{07})_{47}$	$Or_{54}Ab_{46}$
79°	12·0°	1·5281	$Or_{49}Ab_{50}An_1$	$Or_{50}(Ab_{93}An_{07})_{50}$	$Or_{49}Ab_{51}$
81°	12·5°	1·5279	$Or_{45}Ab_{52}An_3$	$Or_{46}(Ab_{93}An_{07})_{54}$	$Or_{48}Ab_{52}$

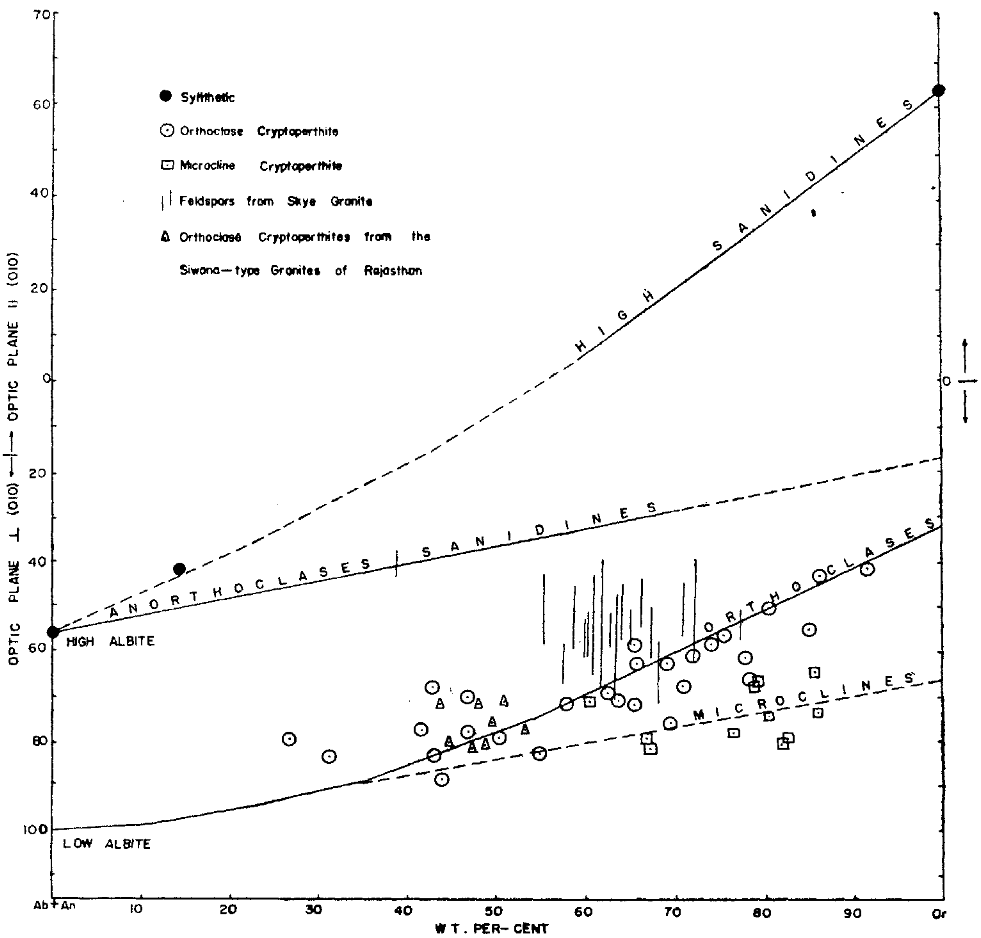


FIG. 2. Relation between optic axial angles and composition of alkali feldspars (after Tuttle 1952).

consistently low when compared to the values obtained by other methods. It should, however, be mentioned that in the diagram prepared by Marfunin (1961), no account had been taken of the presence of the anorthite molecule in the K-feldspar structure. On the basis of the composition obtained by any or all of the methods outlined above orthoclases may be termed 'mesoperthites' (Michot 1951).

Petrography.—The granites studied are hypidiomorphic, inequigranular non-porphyritic. They consist essentially of prisms of alkali feldspar (45 per cent by volume) which are mainly perthitic, variable but minor amounts of discrete plagioclase grains (one to six per cent by volume) mainly of small size, and interstitial quartz. The granite from Bisala consisted essentially of micropegmatite; patchy micropegmatite also occurred in the granites from Bandhana. The accessories included riebeckite and aegirine as long slender and ragged prisms; in some cases they were intimately intergrown with one another. Zircon and minor amounts of iron ore occur as accessories. In the granite from Siwala, although the accessory is hornblende, the alkali feldspar is perthitic as in the other granites studied. The type Siwana granite (Reg. No. 8472, G.S.I.) is similar, except that the aegirine occurs in coarse prisms, and is in places associated with minor amounts of riebeckite. Thin sections of the Jalor-type granite have been described by La Touche (1911) and Coulson (1933); they contain mainly alkali feldspars (crypto- to microperthitic) and in places minor amounts of large, discrete plagioclase, besides accessory biotite, with or without hornblende.

The granites studied here are comparable to the kaligranites of Johannsen (1962, pp. 51–58) which contain practically no plagioclase (never more than five per cent). They are characterized by perthites and by one or more of the alkali-pyroxenes and amphiboles. The excess soda found in the actual analyses is to be accounted for by the soda in the microperthite, or in the cryptoperthite.

Nature of the Perthites.—In the Barmer granites studied, two types of perthites have been recognized by optical studies, viz. orthoclase cryptoperthites and microcline microperthites (Venkataraman *et al.* 1964). The composition, expressed in weight percentage, and the optic axial angle when plotted on the diagram prepared by Tuttle (1952*b*) fall in the region of cryptoperthites (Fig. 1). The monoclinic phase of the alkali feldspar, viz. orthoclase, is always cryptoperthitic and never microperthitic; visual examination indicates that such orthoclase cryptoperthites are minor in amount; the inhomogeneity of the alkali feldspar is recognizable only under a magnification of $\times 360$.

Most of the alkali feldspar grains are triclinic microcline, which is always microperthitic; the plagioclase member is the low-temperature form. There is a wide range in the triclinicity of the alkali feldspars as can be inferred from optical properties (cf. Ansilewski 1961). Untwinned microcline grains are predominant and grains twinned on either the Albite or the Pericline laws are subordinate; those twinned on both the laws, i.e. cross-hatched types, are rare. In one of the granites, namely in that from Bisala, the K-feldspar and quartz are intimately intergrown in all shapes and sizes. The optical properties of the triclinic K-feldspar phase in the perthites are difficult to determine because they are too much intermixed with exsolved plagioclase.

Discussion

Origin of Perthites.—The plagioclase of the perthites studied here as also those in similar high-level granites (e.g. Nigeria) are highly variable in shape, size, etc.; they may be lamellar, patchy or in some sections occur as anastomosing veins, forming a braided pattern (Plate VI, Fig. 18 in Jacobson *et al.* 1958). Well-oriented string and film perthites, considered typically due to exsolution, are absent. The origin of the plagioclase by exsolution or replacement thus becomes problematic (cf. Alling 1932).

The following factors should be taken into consideration in deciphering the origin of perthites:

(*a*) *Field Evidence.*—The granites studied are of the disharmonious type. They are high-level plutons resulting from the emplacement of granitic magma. The contact with the country rock is sharp; there is apparently no chilling. No recognizable plagioclase-rich veins have been observed either within the granite body or in the country rock at the contact.

(*b*) *Microscopic Evidence.*—In the thin sections of specimens at the contact the alkali feldspar is similar to those noted elsewhere in these granites; discrete plagioclase, if any, is minor. There are no recognizable plagioclase-rich veins in thin sections also. The 'eurite' dykes described by La Touche (1911) show only one-feldspar, viz. alkali feldspar.

The replacement of the alkali feldspar, if any, is not caused by albitic solutions within the rock. There are no discrete plagioclase grains associated with quartz which is the last felsitic mineral to crystallize. Where there is graphic intergrowth (granite from Bisala), the alkali feldspar which is intergrown with quartz also shows plagioclase lamellae; the lamellae always occur within the alkali feldspar crystals. The plagioclase patches in a single crystal are in optical continuity among themselves giving the appearance of a close intergrowth between the potash and plagioclase feldspars. In places, relatively large plagioclase grains occurring along the periphery are in optical continuity with the alkali feldspars.

There are no textural indications to suggest that the formation of the plagioclase lamellae, grains, etc., was initiated along grain boundaries. The plagioclase lamellae, even in sections where they are well developed, terminate abruptly at, and are normal to, the grain boundary. Some parts of a crystal may show closely-spaced parallel lamellae, considered typical of exsolution, and others, of patchy plagioclase; there seem to be no justification to consider different modes of origin for the two. In such sections there are no intergranular plagioclase grains which may be interpreted as having been derived by replacement.

Discrete grains of plagioclase, when present, are invariably small and occur only along the contact between two-feldspar grains and not between quartz and feldspar; there are no veins of plagioclase grains in such sections. According to Tuttle and Bowen (1958, p. 141), 'the sinuous nature of the contact between the plagioclase along the periphery and the alkali feldspar is believed to indicate that the plagioclase has unmixed from the host by solid diffusion, perhaps aided by volatile fluxes, during the cooling of the Beinn and Dubhaich Granite'.

The presence of orthoclase cryptoperthites and of microcline microperthites and the range in triclinicity recognized even in the same thin section indicate that the triclinic phase microcline is derived from a higher temperature monoclinic alkali feldspar. The present studies of the nature of perthites in the Barmer granites confirm the conclusion arrived at earlier by Mackenzie (1954) and Schermerhorn (1961), that both triclinization and exsolution are related phenomena (Venkataraman 1962, pp. 64-65). The observations indicate that perthite formation is intensified with increasing degree of triclinization. Exsolution, rather than replacement, can account for the phenomena.

The anorthite content of the discrete grains of plagioclase ranges from 15 to 24 per cent, whereas the blebs of plagioclase occurring within the alkali feldspar are less calcic, the An content ranging from four to nine per cent. The plagioclase was apparently exsolved over a range of temperatures under varying conditions; hence the difference in composition between the exsolved and lamellae and the discrete grains, as also the varying composition in the discrete grains themselves. These observations along with the other features noted above support exsolution rather than replacement.

(c) *Theoretical Considerations.*—The granites described here are of the hypersolvus types (Tuttle and Bowen 1958, p. 137); they are almost entirely composed of one-feldspar, viz. alkali feldspar, and have only minor amounts of plagioclase. Optical studies indicate that the alkali feldspars are intermediate in composition between pure K and Na end-members. Experimental studies by Tuttle and Bowen (1958, p. 40) indicate that alkali feldspar of such a composition crystallizes at a relatively high temperature, viz. above 660° C. The bulk of the Na in the rock is thus held in the alkali feldspar which can be exsolved. According to Tuttle (1952*a*, p. 116), the 'probability of microcline and albite . . . crystallizing from a granitic magma is extremely remote'.

The foregoing considerations lead the authors to the conclusion that the perthites described here are actually due to exsolution. The extensive development of perthites in these high-level granitic plutons results from the high amount of Na held in the original alkali feldspar.

Cause of Exsolution—Given sufficient amount of Na in the alkali feldspar, the causes which give rise to perthites can be examined. In literature, three principal causes have been considered responsible for the separation of the sodic phase, viz. (*a*) deformation, (*b*) cooling and (*c*) fluxing action of the volatiles, especially of water-vapour.

(*a*) *Role of Deformation.*—Mäkinen (1913), who derived the albite lamellae by exsolution from the host potash feldspar, did not entirely ignore stress as a factor in perthite formation.

In the Barmer granites studied the quartz grains, as also sometimes the feldspars, show effects to intense strain. To discern the relationship, if any, between the amount of strain and the perthite formation, modal percentage of the perthites versus that of strained quartz grains was plotted (Fig. 3). The figure suggests that with increasing strain there is an apparent increase in the amount of perthites.

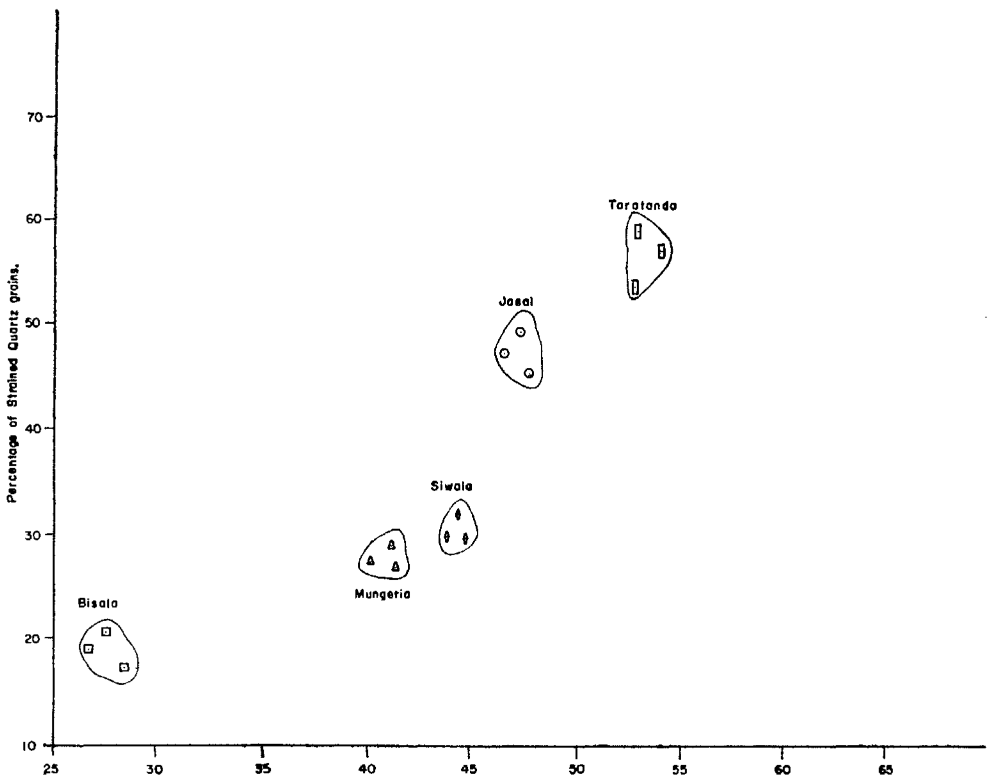


FIG. 3. Relationship between perthite percentage and strain.

(*b*) *Role of Cooling.*—Slow cooling is considered by many as an important factor in exsolution. 'Under plutonic conditions, cooling after crystallization may be slow enough to allow establishment of equilibrium by unmixing of the unstable solid solution into two or more stable solid solutions with more limited isomorphous substitution ... Perthites are potash feldspars (orthoclase or microcline) with microscopically intergrown bodies of albite plagioclase which commonly are the results of unmixing from original homogeneous potash soda feldspars' (Turner and Verhoogan 1960, pp. 68-69). Remarkably extensive development of perthites is especially common in many high-level granites, which admittedly must have cooled relatively rapidly in the 'cooler' environment of the epizone in contrast to the 'hot' environment of the mezo- or katazones.

(*c*) *Role of Volatiles including Water-vapour.*—The experimental studies of Tuttle and Bowen (1958) indicate that from a granite magma only one-feldspar crystallizes above 660° C, viz. alkali feldspar, since complete solid solution exists between $NaAlSi_3O_8$ and $KAlSi_3O_8$; below this temperature two-feldspars crystallize. They also noted that high-temperature alkali feldspars, in presence of water-vapour under pressure, exsolve into two phases. Their study indicated that in perthite-quartz granites, the amount of modal plagioclase was always low when compared to normative plagioclase; also these carried amphibole instead of biotite as the principal mafic accessory. Since amphiboles are not stable in the presence of excess water, they concluded that the presence of most of the Na in the alkali feldspars, instead of as modal plagioclase (which is either absent or poor), was due to crystallization under relatively dry conditions. They also concluded that the fine perthitic intergrowths and homogeneous alkali feldspars were retained in nature only because they had been formed in a dry environment.

Tuttle and Bowen (1958) also recorded that in contrast to the amphibole-bearing granites which have only perthitic feldspars, the mica-bearing granites carry two feldspars, viz. microcline and plagioclase, and most of the normative plagioclase is present as modal plagioclase. The presence of biotite as the principal dark mineral in two-feldspar granites results from excess of water-vapour pressure. Their statistical study of the 1,269 granite analyses showed that irrespective of the type of the accessory in the granites, the Q-Or-Ab plots occupied the central area in the trilinear diagram (Tuttle and Bowen 1958, p. 123).

In the granites studied in this paper, perthites are well developed both in the Siwana (riebeckite, aegirine, hornblende) and in the Jalor (mainly biotite with some hornblende) granites. Large prisms of primary plagioclase, although occurring in relatively larger amounts in the Jalor granites than in the Siwana granites, are still in minor amounts when compared to the alkali feldspars. In Nigeria, biotite granites genetically related to the riebeckite granites also show minor amounts of plagioclase (Jacobson *et al.* 1958, p. 18). The granites carry the bulk of the Na in the alkali feldspar; except in the case of the albite-biotite granites, considered to have been formed due to late albitization, they are not two-feldspar granites.

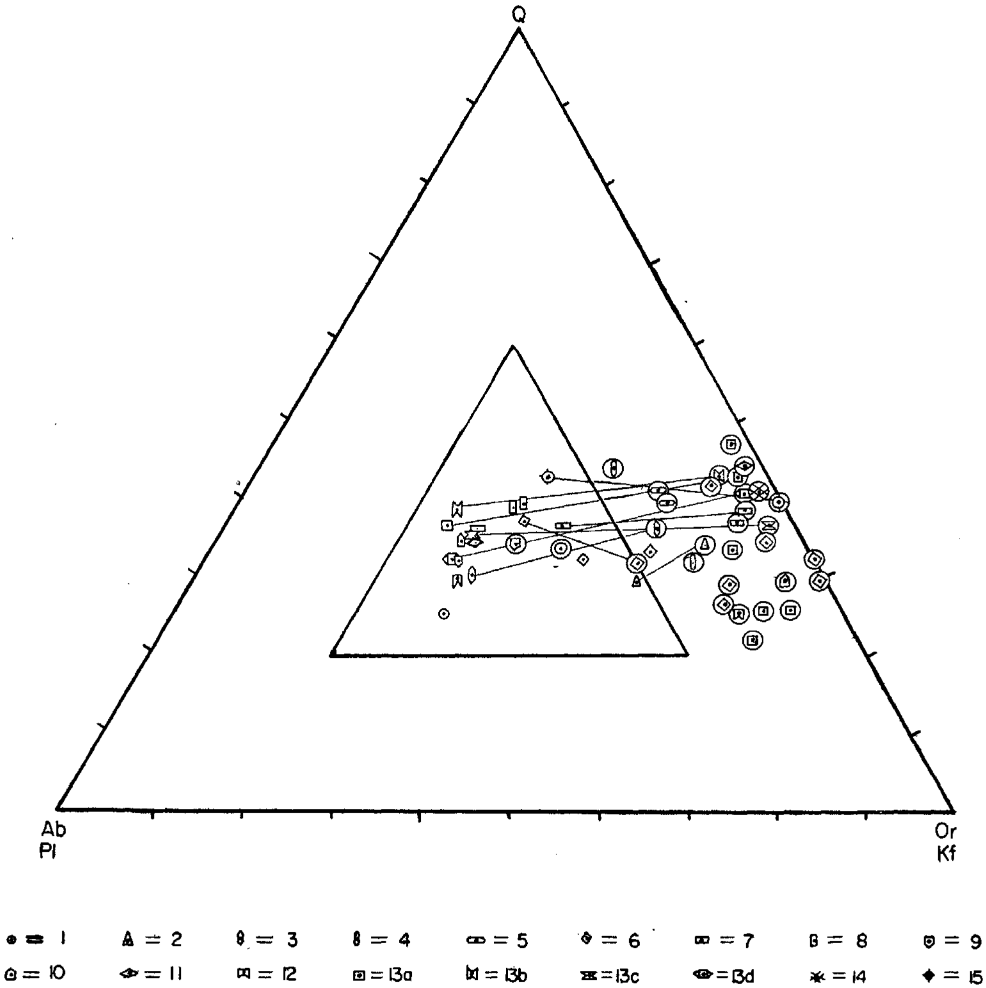
Both the riebeckite and biotite granites were apparently rich in volatiles (Jacobson *et al.* 1958), and yet they are two-feldspar granites. This apparently contradicts the conclusions of Tuttle and Bowen noted above; although these granites carry biotite as the principal dark mineral, they are perthite granites and not two-feldspar granites (Table III).

TABLE III

Normative and modal compositions of biotite granites from Nigeria

		Norm	Mode
	Biotite granite, Liruei, X 568		
Quartz	..	34·91	37·0
Orthoclase	..	26·19	54·8
Plagioclase	..	35·37	6·3
	Bargesh biotite granite, L 796		
Quartz	..	35·94	35·6
Orthoclase	..	30·02	55·9
Plagioclase	..	30·18	4·9

A preliminary study of the literature also shows that many high-level granite plutons are characterized by perthitic feldspars irrespective of whether they carry amphibole or biotite (e.g. Dartmoor, Arran, Skye, etc.). Among the granite plutons in Ontario, Canada, studied by Saha (1959) the epizonal riebeckite granite is a one-feldspar perthite-quartz granite, while deeper (mesozonal ?) biotite granite is a two-feldspar granite. The absence of equivalent volcanics suggests that this riebeckite granite is deeper in level than those of Nigeria or Barmer which belong to the volcano-tectonic setting of Buddington (1959). The observations made above suggest that, for water-poor granite magmas, depth does not appear to have any significant influence on exsolution or recrystallization, at least within the epizone. However, depth does appear to have an effect on water-rich granite magmas. At higher levels, even the biotite granites tend to be one-feldspar granites; at deeper levels, they are two-feldspar granites. This is implied in the following statement of Tuttle and Keith (1954, p. 71) where the evidence of quartz and feldspar in the Tertiary granites of Skye is discussed: 'Had this granite been emplaced at a greater depth when cooling would have been of longer duration and where higher pressure would tend to prevent escape of volatile constituents, it is probable that the feldspar and quartz would have taken on the features of the minerals of more common two-feldspar granites containing microcline and low-albite and low-temperature quartz.'



(For details *see* Table IV)

FIG. 4. Normative (Q-Ab-Or) and modal (Q-Pl-Kf) plots of some epizonal granites of the world (normative plots: uncircled, modal plots: circled).

Figure 4 is a plot showing the relative distribution of the normative and modal values of some of the epizonal granites of the world, for which data have been collected from the literature available (cf. Table IV). The plots all bear out the conclusion that irrespective of the level of the granites the normative Q-Or-Ab plots fall more or less centrally in the triangle (Tuttle and

TABLE IV

Explanatory chart for Fig. 4

Sl. No.	Place of occurrence	Source of data
1.	Granites from Cascade Range, Oregon, U.S.A.	*Am. J. Sci.* (1936), p. 428.
2.	Biotite granite from Owl's Head, N. Hampshire, U.S.A.	*Bull. geol. Soc. Am.*, **48** (1937), p. 501.
3.	Biotite granite from Percy Quadrangle, N. Hampshire, U.S.A.	*Am. Miner.*, **20** (1935).
4.	St. Austell's (biotite) granite, England.	*Q. Jl. geol. Soc. Lond.*, **79** (1923), p. 547.
5.	Dartmoor granite, England.	*Q. Jl. geol. Soc. Lond.*, **38** (1932), p. 171.
6.	Skye granite, Scotland.	*Mem. geol. Soc. Am.*, **74** (1958).
7.	Biotite granite from the Younger Granite Province, Nigeria.	*Mem. geol. Soc. Lond.*, No. 1 (1958), pp. 1–72.
8.	Riebeckite-aegirine granite from the Younger Granite, Province Nigeria.	
9.	Wollaston granite, Ontario.	*Bull. geol. Soc. Am.*, **70** (1959), p. 1293.
10.	Perthite granite from Delero, Ontario.	
11.	Riebeckite granite from Manchuria.	*Mem. Ryojun. Coll. Engg.*, Vol. XI, No. 6 (1938).
12.	Riebeckite granite from Quincy, Mass., U.S.A.	(*a*) *Proc. Am. Acad. Arts Sci.*, Vol. XLIX (1914). (*b*) *Bull. U.S.G.S.*, Vol. 704, 1921.
13.	Riebeckite-aegirine granite from: *a.* Jasai *b.* Mungeria *c.* Taratra *d.* Siwala (Barmer district, Rajasthan.)	
14.	Riebeckite granite from North Conway Quadrangle, N. Hampshire, U.S.A.	*Am. Miner.*, **20** (1935).
15.	Riebeckite-aegirine granite from Lower Cong., Angola.	Holmes, A. (1930), Petrographic Methods and Calculations.

Bowen 1958, p. 128). However, for high-level granites, such as for those from Barmer, Nigeria, etc., the modal Q-Pl-Kf plots fall mainly along the Q-Kf join; the same is true of the Skye granites (Tuttle and Bowen 1958,

p. 110). This suggests that there is an interrelationship between the level of emplacement and the type of feldspar crystallizing in any particular granite. High-level granites, irrespective of their water-content (as indicated by the type of mafic accessory, whether biotite or amphibole), carry most of the normative plagioclase in the alkali feldspar.

The presence of similar exsolution perthites in both biotite and riebeckite granites and the lack of complete unmixing in the alkali feldspars of the Nigerian biotite granites can be explained as follows: Because of the high level at which the granites were emplaced, the volatiles, including water-vapour, tend to escape from the magma and are, therefore, not available under high pressure to accelerate unmixing, recrystallization and formation of two feldspars. 'If a granite cools in the presence of a copious supply of volatile materials, unmixing will take place readily and it is expected that potassium- and sodium-feldspars will separate completely . . . On the other hand, if all the volatiles are used, or if they escape during crystallization, slow cooling will not produce complete unmixing. Unmixing will proceed to the cryptoperthite stage or perthite stage but the hypersolvus character of the granite will still be preserved' (Tuttle and Bowen 1958, p. 139). Tuttle and Bowen have emphasized in several places in their memoir the importance of water-vapour under pressure as an aid in unmixing. It is suggested here that in evaluating the importance of water-vapour and the formation of perthites, etc., the geological setting and the level of the granite must be taken into consideration. In the high-level granites, hydrostatic pressure being relatively low, the volatiles, even when present in large amounts, tend to escape, and complete unmixing does not take place; the process may be arrested at the perthite stage. It is suggested that the undoubted exsolution perthites seen in the two-feldspar granites represent part of the Na present either residually in the K-feldspar after exsolution, or the amount that was incorporated in the feldspar structure when the K- and Na-feldspars crystallized as two separate phases below 660° C. 'The sodium content of potash feldspar is a measure of the final temperature at which crystallization took place rather than the temperature of magmatic crystallization' (Tuttle and Bowen 1958, p. 129).

Characteristics of Disharmonious High-level Granites

In an important discussion on the emplacement of granites, Walton (1955, p. 16) emphasized the importance of systematic studies on the characteristics of high-level granites. 'Strongly disharmonious granites are admittedly uncommon and perhaps peculiar, but out of their study we may hope to define those features that can develop entirely out of the magmatic, endomagmatic and contact metasomatic processes, as contrasted with those that require some appreciable level of regional metamorphic energy. We then may really know what we are talking about when we use textural criteria to establish the mode of origin' (Walton 1955).

The following characteristics of the high-level granites can be summarized: (1) They tend to be one-feldspar granites or are rich in alkali feldspar, irrespective of the accessory, or of the water content of the magma. (2) The grain size is highly variable, the quartz tending to be interstitial; large plagioclase crystals when present appear to be subordinate in amount. (3) Micropegmatite and granophyric textures are developed either forming the entire groundmass or in patches. In such cases, the interstitial alkali feldspar is not a non-perthitic microcline. (4) Perthitization is extensive and variable. The same section may show orthoclase cryptoperthites and microcline microperthites (Venkataraman *et al.* 1964). The microcline does not commonly show a quadrille structure. The presence of microperthite with quadrille structure indicates that the triclinic phase is derived from monoclinic alkali feldspar; this is confirmed when such sections also show monoclinic alkali feldspar. (5) Exsolved plagioclase grains are variable in composition among themselves. (6) Many of these hypersolvus granites tend to be peralkaline in character and have Na-amphibole and/or pyroxene as characteristic accessories (Tuttle and Bowen 1958, p. 137). The development of magmas of such compositions and the crystallization of the Na-Fe minerals, which are also rare in deeper-level granites, suggest that their development is a distinctive feature of high-level granites.

In the high-level granites from Nigeria, extensive so-called late deuteric albitization in the biotites and in the riebeckite granites of Nigeria has been described. Jacobson *et al.* (1958) described extensive replacement of the earlier exsolution perthites by late stage albite, which sometimes forms a second generation of crystals. They are especially well developed in the biotite granites in which 'the perthitic textures have been masked or completely obliterated by later generations of albite . . .' (Jacobson *et al.* 1958, p. 15). It is noteworthy that there are wide variations in the degree of albitization; 'replacement' perthites are associated with the exsolution perthites ; never with non-perthitic microcline, if any.

A study of the chemical and the modal analyses of the biotite granites from Nigeria shows as much potash in their composition as in the relatively less albitized biotite granites; the $Na_2O : K_2O$ ratio is more or less the same. The modal biotite cannot account for all the potash of the rock. This indicates that most of the potash is held in the alkali feldspar in the albite-biotite granites. Replacement of the potash, if any, did not result in any removal of potash in the rock and consequently the percentage of soda has not increased; the process seems to have taken place in more or less 'closed' systems.

The above observation is explicable if we assume that the soda, now represented by albite, was originally held in the alkali feldspar, probably of an intermediate composition in these high-level, one-feldspar granites. The exsolution process was evidently aided by the volatile fluxes which were in good supply (Jacobson *et al.* 1958, pp. 48, 93), and the process of exsolution would have continued after the perthite stage; and soda would then have crystallized at a later discrete phase. Whether exsolution or 'replacement' textures are developed predominantly would depend on the availability and amount of volatiles at the time of cooling of the granite in different parts of the pluton. The albitization would undoubtedly be late but is actually an extension of the same process of exsolution, the soda being derived from the original alkali feldspar and not being residual. Depending on the quantity of volatiles available it is possible that such albite-rich solutions from one part of the rock may migrate into another part and there give rise to actual replacement. Perhaps it is significant that such replacement is often described in high-level granites; much more data are necessary before it can be concluded that the phenomenon is characteristic of only high-level granite plutons, although it is tempting to suggest that it is so.

CONCLUSIONS

(1) Intensively and extensively developed mesoperthites of the high-level granites studied are due to exsolution and not to replacement. They are characterized by the alkali feldspars with a range in triclinicity, composition and in the degree of perthitization. The exsolved plagioclase is lamellar; the individual lamella may or may not be oriented and may also be patchy.

(2) Perthites in high-level granites are developed irrespective of the nature of the type of the accessory mineral developed (biotite, hornblende, riebeckite, aegirine), i.e. irrespective of the original water content of the magma.

(3) The effectiveness of water-vapour pressure as a catalytic agent in promoting exsolution, recrystallization, etc., is related to the hydrostatic pressure, i.e. the level of the granite. High-level granites tend to be one-feldspar granites, irrespective of the original water content of the magma, because the water escapes into the country rock.

(4) Late albitization (deuteric) seems to be an extension of the same process as exsolution; the soda is not residual, but is derived from the earlier crystallized soda-rich alkali feldspar.

ACKNOWLEDGEMENTS

The authors are thankful to Shri H. N. Siddiquie of the Geological Survey of India, for having placed at their disposal the specimens for study as also other relevant field data. They are also deeply indebted to Dr. B. C. Roy, Director-General, Geological Survey of India, for encouragement given by him during the course of the present studies.

References

Alling, H. L. (1932). Perthites. *Am. Miner.*, **17**, 43–65.

Ansilewski, J. (1961). The problem of the classification of the alkali feldspars. *Archwn. miner.*, **23**, 5–59.

Buddington, A. F. (1959). Granite emplacement with special reference to North America. *Bull. geol. Soc. Am.*, **70**, 671–747.

Chayes, F. (1949). A simple point-counter for thin-section analysis. *Am. Miner.*, **34**, 1–11.

Coulson, A. L. (1933). The geology of Sirohi state, Rajputana. *Mem. geol. Surv. India*, **63** (1).

Jacobson, R. R. E., Macleod, W. N., and Black, R. (1958). Ring-complexes in the Younger granite province of Northern Nigeria. *Mem. geol. Soc. Lond.*, **1**, 72.

Johannsen, A. (1962). A Descriptive Petrography of the Igneous Rocks, Vol. II. 428 pages. Indian Edn., Published by Allied Pacific Pvt. Ltd., Bombay.

Krishnan, M. S. (1956). Geology of India and Burma, 3rd edn., 555 pages, Higginbothams (Pvt.) Ltd., Madras, India.

Krishnan, T. K. (1961). A statistical study of zircons from Jasai granite, Barmer district, Rajasthan, *Indian Miner.*, **15**, 423.

La Touche, T. H. D. (1911). Geology of Western Rajputana. *Mem. geol. Surv. India*, **35** (1).

Mackenzie, S. Wm. (1954). The orthoclase-microcline inversion. *Mineralog. Mag.*, **30**, 354.

Mäkinen, E. (1913). Die Pegmatite von Tammela in Finland und Ihre Minerale. *Bull. Commn. geol. Finl.*, **35**.

Marfunin, A. S. (1961). The relation between structure and optical orientation in potash-soda feldspars. *Curs. Confs. Inst. Lucas Mellada Invest. geol.*, 97–109.

Michot, P. (1951). Essai sur la geologie de la catazone. *Bull. Acad. r. Belg. Cl. Sci.*, **37**, 271–72.

Murthy, M. V. N. (1962). The significance of ring-pattern of Siwana granite bosses in Western Rajasthan. *Indian Miner.*, **16** (3).

Murthy, M. V. N., Siddiquie, H. N., and Venkataraman, P. K. (1961). Riebeckite-aegirine rhyolites and granites in the Malani suite of Igneous rocks, Western Rajasthan. *Indian Miner.*, **15**, 427-28.

Murthy, M. V. N., and Venkataraman, P. K. (1964). Relict Carlsbad twinning in microcline inverted from orthoclase in two granites of the Erinpura suite, Rajasthan. *Indian Mineralogist*, **5**, 17–21.

Naidu, P. R. J. (1958). Four-axes Universal State. Commercial Printing and Publishing House, Madras, India.

Oftedähl, C. (1951). Special features of Oslo igneous feldspars. *Intl. Geol. Cong.*, 1948, 18th Session, pt. II, Sec. A, **116**.

Pascoe, E. H. (1959). A Manual of the Geology of India and Burma, Vol. II. Published by the Govt. of India.

Rittmann, A., and Grutter, O. (1939). Tabellen zur bestimmung von Mineralien Min. Petr. Instt. der Universitat Gasel.

Saha, A. K. (1959). Emplacement of three granitic plutons in Southeastern Ontario, Canada. *Bull. geol. Soc. Am.*, **70**, 1293–1326.

Schermerhorn, L. J. G. (1961). Orthoclase, Microcline and Albite in granites. *Min. Pett. Mitt.*, Bd. **41**, ht. 1, s. 13.

Siddiquie, H. N., and Bahl, D. P. (1965). Bentonite deposits of Barmer district, Rajasthan. *Mem. geol. Surv. India.*

Tröger, E. (1939). Nomogramme zur reduction von Kippwinkeln am Universaldrehtish: Zentlel. *Miner.*, abt. A, s. 177–89.

Turner, A. J., and Verhoogan, F. (1960). Igneous and Metamorphic Petrology. McGraw-Hill Book Co.

Tuttle, O. F. (1952*a*). Origin of the contrasting mineralogy of extrusive and plutonic salic rocks. *J. Geol.*, **60**, 107–24.

——— (1952*b*). Optical studies on Alkali feldspars. *Am. J. Sci.*, Bowen Volume, pt. **2**, 553–67.

Tuttle, O. F., and Bowen, N. L. (1958). Origin of granite in the light of the experimental studies in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. *Mem. geol. Soc. Am.*, **74**, 153.

Tuttle, O. F., and Keith, M. L. (1954). The granite problem—Evidence from quartz and feldspar of a tertiary granite. *Geol. Mag.*, **91**, 61.

Venkataraman, P. K. (1962). Studies on perthite-formation in some high-level granites of Barmer district, Rajasthan. *Indian Miner.*, **16**, 65-66.

Venkataraman, P. K., Sen Sharma, R. N., and Xavier, J. (1964). Petrology of some peralkaline granites of Barmer district, Rajasthan. Research papers in Petrology. *Geol. Surv. Ind.*, 57–73.

Vinogradov, A., Tugarinov, A., Zhykov, N., Stapnikova, E., Bibikova, L., and Khorve, K. (1964). Geochronology of the Indian Precambrian. *XXII Intl. Geol. Cong.*, Volume of Abstracts, 64-65.

Viswanathan, T. V. (1962). Zircon studies of some high-level granites from Barmer district, Rajasthan. *Indian Miner.*, **16**, 66.

——— (*in press*). Zircons of some granites from Rajasthan. Research papers on zircons.

Walton, M. (1955). The emplacement of 'Granite'. *Am. J. Sci.*, **253**, 1–18.