CHAPTER VI

METAMORPHISM AND GRANITISATION

The rocks of Ankola-Gokarn area point out to a complex metamorphic and structural history. Considering the details of these rocks given in the preceding chapters, it becomes fairly obvious that no precise line of demarcation can be drawn between the progressive regional metamorphism and the granitisation, which followed immediately the former. It is also quite evident that the successive deformational events considerably aided the metamorphic and metasomatic (granitising) processes.

In fact, the area affords an excellent example of the various geosynclinal events, taking place during the active period of an orogenic cycle.

The amphibolitic and the granitic rocks in the different parts of the study area, have preserved numerous evidences to enable the author to build up a possible sequence of metamorphic events in this part of the Dharwarian geosyncline. However, in this work, he was considerably handicapped by the fragmentary nature of outcrops and the obliteration of various features due to repeated folding and granitisation. Thus, the author has been able to work out, only a very general pattern of the metamorphism and granitisation of the rocks of the area.

METAMORPHISM

Metamorphic characters as shown by the Ankola-Gokarn rocks, can for the most part, be considered as of regional type - comprising a series of dynamo-thermal changes, mostly of progressive nature. The rocks involved were perhaps basic rocks, which changed over to a group of hornblendic rocks (amphibolites). On account of the absence of other rock types (especially metasediments like pelites or semipelites), the study of metamorphism has been made difficult. Moreover, large scale granitisation has considerably modified the amphibolitic rocks, and this has handicapped the author in obtaining the precise details of the regional metamorphic changes.

It can be surmised that the original rock which were metamorphosed to the present amphibolitic complex, was of basic igneous nature-perhpas a mass of gabbro or a thickness of lava flows. In their present transformed and differentiated form, it is rather difficult to make any definite statement about the original rock. In the existing state, the amphibolites are gneissic and mainly consist of hornblende, plagioclase (andesine) and quartz, and show a wide variation in relative proportions of the three minerals from band to band. This variation is mostly due to differentiation during metamorphism. The assemblage nearest to the original basic rock could be represented by the massive and foliated varieties containing hornblende and plagioclase. The chemical analysis of a representative sample compares fairly well with that of a typical gabbro (Table 1).

The mineral assemblage (hornblende-plagioclase quartz ± biotite and epidote), typically indicates a medium grade of regional metamorphism, and the ACF diagram (Fig. 5) plotted from a few carefully selected chemical analyses point to the 'almandine-amphibolite facies' (Turner and Verhoogen, 1962).

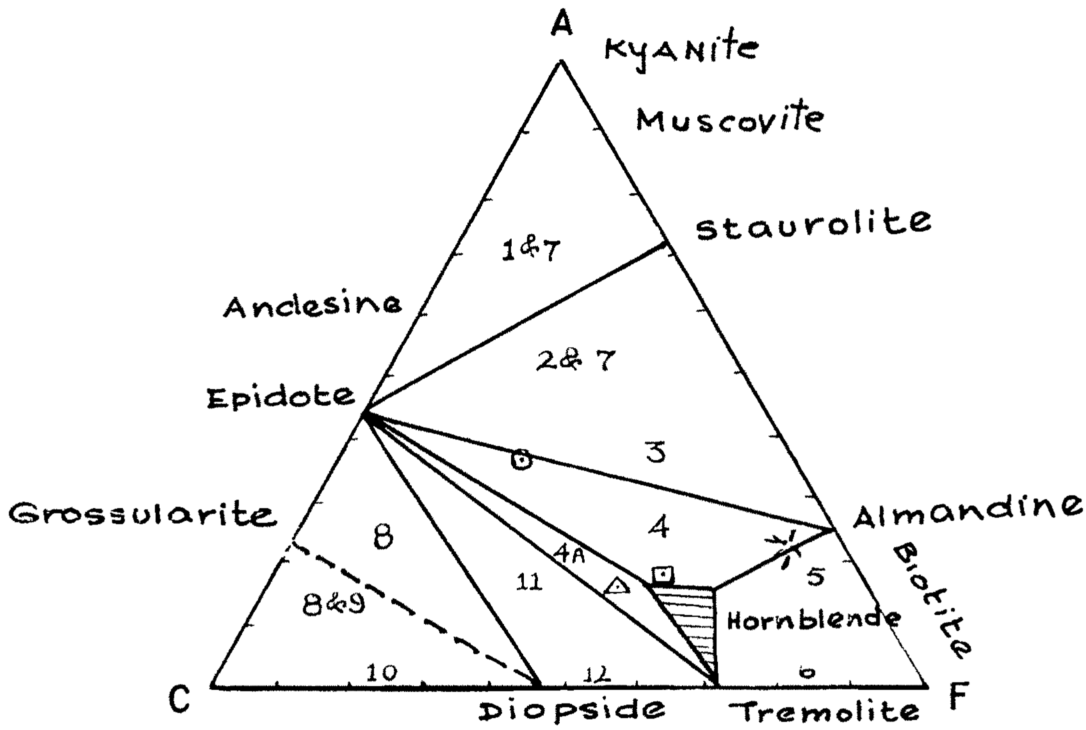
The banded nature of amphibolites and their granitisation, has made a detailed chemical study of these rocks, somewhat difficult. As already mentioned, the metamorphic differentiation has resulted into bands showing wide range of mineralogical variation containing exclusively hornblende at one end to those with plagioclase and quartz at the other. All intermediate varieties are also found. Chemical analysis of a few distinct varieties were conducted, and the variation diagram(Fig.6) showing the behaviour of various constituents, when traced from hornblendic to hornblende free (felspar-quartz) bands, is very illustrative. It is seen that the differentiation of the basic rocks is effected by the following changes:

(i) There is no appreciable change in the K_2O and Al_2O_3 content.

(ii) Broadly, CaO, FeO, MgO and Fe_2O_3 increase in hornblendic variety and decrease towards the felspathic variety.

FIG. 5

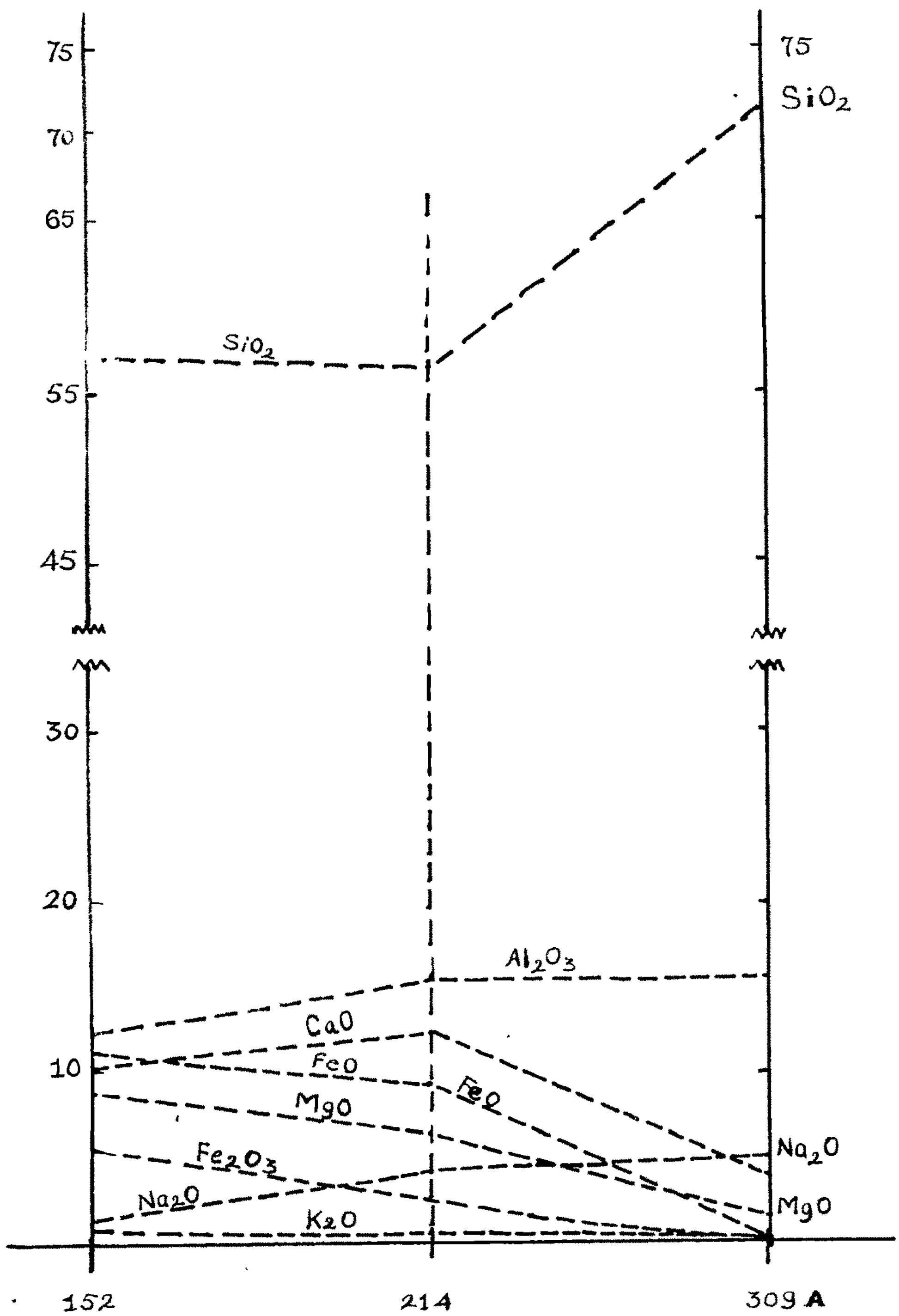
ACF DIAGRAM FOR AMPHIBOLITES



		A	C	F
Sp. 214	△	15 .300	35·200	49·500
Sp 152	⊡	17·150	27·150	55·700
Sp 222 B	✕	22·150	7 ·900	69 ·950
Sp 309 B	⊙	37·730	38 · 640	23.630

FIG.6

VARIATION DIAGRAM FOR AMPHIPOLITIC ROCKS



(iii) Na_2O shows only a slight increase from dark to light coloured varieties.

(iv) SiO_2 shows an increase in hornblende free variety. It is not however, clear if there was any addition of this constituent from outside. As there is no appreciable rise in alkalies, the rise in silica content could be partly at the cost of decreasing mafic content, though some addition is also not ruled out. Arrival of SiO_2 from outside perhaps heralded the onset of granitisation stage.

Considering the fact that these differentiated amphibolites show numerous tight folds, especially in the streaky variety, the author is inclined to suggest that the deformation that gave rise to this folding (F_1) synchronised with the metamorphism, and was to a great extent responsible for differentiation and segregation along the fold cores. Deformation of a basic rock in deep-seated conditions, at high temperatures, would facilitate metamorphic differentiation, and give rise to a banded amphibolitic complex. There is little doubt that the migration of various constituents during deformation gave rise to the banded rock with hornblende, plagioclase and quartz in varying proportions. But it is not clear if any quartzitic layers also got involved and mixed up with basic rocks. In some places, the extreme streakiness and abundance of siliceous bands (e.g. Tadri coast) do indicate the possibility of existence of some siliceous sediments. But this point needs further investigation and elucidation.

One thing that stands out very clearly is that the processes of metamorphism, gradually changed over to those responsible for the granitisation and thus the area affords an unique example of smooth transition of regional metamorphism to granitisation.

GRANITISATION

The large scale transformation of amphibolites to various granitic rocks, is seen to have been brought about in stages - each stage having left its clear imprint on the rocks. All transitions from amphibolites to a typical granite exist, and the pattern of granitisation can be worked out in fair detail on the basis of field and laboratory studies. It is interesting to observe that a close synchronisation existed between the various deformational (fold) episodes, and the successive granitising events.

In the following pages, the author has attempted to give an outline of the entire granitisation history of the rocks of the area. On account of the scattered nature of outcrops and rapid variation in mineralogy within short distances, it was found difficult for the author to obtain a very precise picture of the evolution of granitic rocks. But the following account is detailed enough to bring out the salient features of the pattern and processes of granitisation that operated in the area during the orogenic upheaval.

EVIDENCES OF GRANITISATION

The granitic rocks contain a number of evidences - field, mineralogical, textural and chemical - to point out their metasomatic origin. The various criteria taken into account to suggest granitisation, have been summarised below.

I. Field evidences

Field study ideally supports granitisation, and the following features as recorded in the area clearly point out to a slow metasomatic transformation.

(i) Extensive relicts of pre-existing structures well preserved in granites: The granitic rocks have preserved a number of relicts of the host rock, and distinctively look typical migmatites in the field. These relicts include

(a) large chunks of granitic (nebulites of Sederholm, 1907) rocks preserving undisturbed all the intricate fold patterns inherited from the pre-existing amphibolites;

(b) spindle shaped fold cores of partly digested amphibolites and

(c) bands, lenses, streaks and irregular fragments of partly granitised amphibolitic rocks.

(ii) Total absence of intrusive contacts: In the field, nowhere the granitic material is seen forming intrusive masses either in the amphibolites or in the gnessic granite itself. The only striking mode of occurrence of quartzo-felspathic veins in amphibolites is as thin conformable bodies along the foliation and these too imperceptibly merge into the metamorphically differentiated leucocratic portions of the amphibolites. They are thus, evidently products of segregation and secretion rather than intrusions from outside.

Even the massive and non-foliated granitic portions co-existing within gneissic mass, do not show sharp contacts.

They are obviously, more of the nature of 'disturbed' or 'mobilised' migmatites (Haller, 1962) affected by deformation causing widespread squeezing and obliteration of pre-existing structures. Thus, massive and gneissic granites are seen to merge into each other, and from the point of view of the origin, both the varieties are identical. The pre-existing structures (foliation, banding etc.) could have been obliterated by deformation as stated above, or on account of the mobility as a consequence of the rock attaining an appropriate granitic composition. Whether or not such mobility implies that the rock became an actual melt is now less readily recognised (King, 1965, p.227).

(iii) Differentiated leucocratic and melanocratic segregations: The numerous leucocratic lenses and veins in granites, having distinct rims of exclusively hornblendic material, indicate clearly concretionary growth of granitic constituents "filtering off" the dark minerals outward. Similar mechanism of differentiation due to metasomatism is also seen in bodies of hornblende rich rock with leucocratic rims.

(iv) Nature of the pegmatite and aplite veins: As it has already been alluded to, the granitic rocks abound in quartzo-felspathic veins and dykes. Some of these are conformable with the foliation, and form distinct streaks and elongate lenses of variable sizes. There are others which cut across the foliation trends at various angles. These have fairly sharp contacts with the enclosing rock, and some are folded while some are cutting the folds too. Characteristically, most of these 'intrusive looking' bodies, on a close scrutiny, betray a metasomatic origin. These quartzo-felspathic bodies are found to have grown along the foliation, shear planes, and joints by a process of replacement. As a rule, these veins are coarser at their outer margins and increasingly become fine grained inwards. Secondly the foliation of the enclosing rock is seen at many places preserved undisturbed in these veins. All these, together with the other evidences taken together, indicate a slow and gradual growth. Ramberg (1952, p.251) has ideally described similar veins as "replacement or non-dilation" pegmatites.

II. Mineralogical and Textural Evidences

Considering the mineralogy of the various intermediate types, with granitic (microcline granite) at one end and the amphibolites at the other, it is so obvious that the hornblendic rocks have gradually changed over to granites through a series of metasomatic changes brought about by dominantly siliceous emanations containing potash. A close study of a large number of thin sections, clearly establishes a coherent sequence of events - each event faithfully recorded in the mineralogy and texture of the rocks. Petrographic studies ideally reveal the following characteristic features suggestive of progressive granitisation:

(i) <u>Progressive increase in quartz and plagioclase content</u>: Before the actual granitisation, a differentiated amphibolitic complex comprising bands of varying mineral composition ranging from those almost exclusively hornblendic (appinitic) at one end to those free from hornblende and made up mostly of a medium plagioclase (plus a little quartz) existed. The earliest granitisation is seen in the enrichment of various bands in quartz and plagioclase. This change was accompanied by homogenisation and part-obliteration of the pre-existing mineralogical banding. This progressive quartzo-felspathic enrichment is better recognised in hornblende rich portions, which gradually tend to resemble quartz diorites and trondhjemites.

(2) Presence of microcline in varying proportions:

The granitic rocks show presence of microcline in variable proportions and thin sections ideally reveal a later potassic activity, progressively increasing in some areas only. With increased microcline content, the mineral is seen replacing the plagioclase. The earliest stage of the activity of the potash bearing solutions is heralded by the (i) appearance of interstitial microcline, and (ii) gradual change of hornblende to biotite. With increased potash enrichment, there is recorded an overall increase in the amount and size of microcline grains. The plagioclase is seen replaced by microcline and all stages of replacement are noted in thin sections. The culmination of the potassic phase is represented by the development of microcline-rich typical granites, and by the widespread development of 'ovoids' of microcline along the outer margins of the quartzo-felspathic veins in some areas.

(3) Sutured relationship: A convincing evidence in favour of replacement origin, is that of sutured relationship between (a) hornblende and quartz, (b) plagioclase and quartz and (c) plagioclase and microcline.

Frequent invasion of hornblende crystals by quartz along the former's margins, is a good indication of the activity of granitising emanations. The attack on hornblende by quartz is more of the nature of corrosion, the latter forming clusters near the borders of hornblende. Similarly, the influx of siliceous solutions is characterised by the replacement of plagioclase by quartz. The typical contact line between the two minerals, shows a fairly sutured outline and is made up of a series of curves with their convex sides facing the attacked mineral. The replacement of plagioclase by microcline has also given rise to quite complicated and sinuous junctions between the two minerals.

(4) Apparent intergrowth of plagioclase and microcline:

The progressive replacement of plagioclase by microcline, has imparted to several felspar grains - a 'perthitic' or 'antiperthitic' appearance depending on the degree of replacement. The 'perthites' suggest an advanced stage of replacement, while the 'antiperthites' indicate the early stage. In all cases, the 'intergrowth' is patchy and irregular.

(5) Myrmekitic texture: The replacement phenomenon between plagioclase and microcline has at many places, given rise to typical myrmekites. That myrmekite can be formed by replacement of plagioclase by microcline, has been suggested by a number of workers (Agarwal, 1957; Bose, 1959; Cannon, 1962; Chatterjee, 1965; Gangopadhyaya, 1959; Snook, 1965). A number of years back, Drescher-Kaden (1948, p.102) has pointed out that the solutions that form the potash felspar of the granitised rocks corrode plagioclase along 'smekal defects' and deposit silica in the form of vermicular quartz.

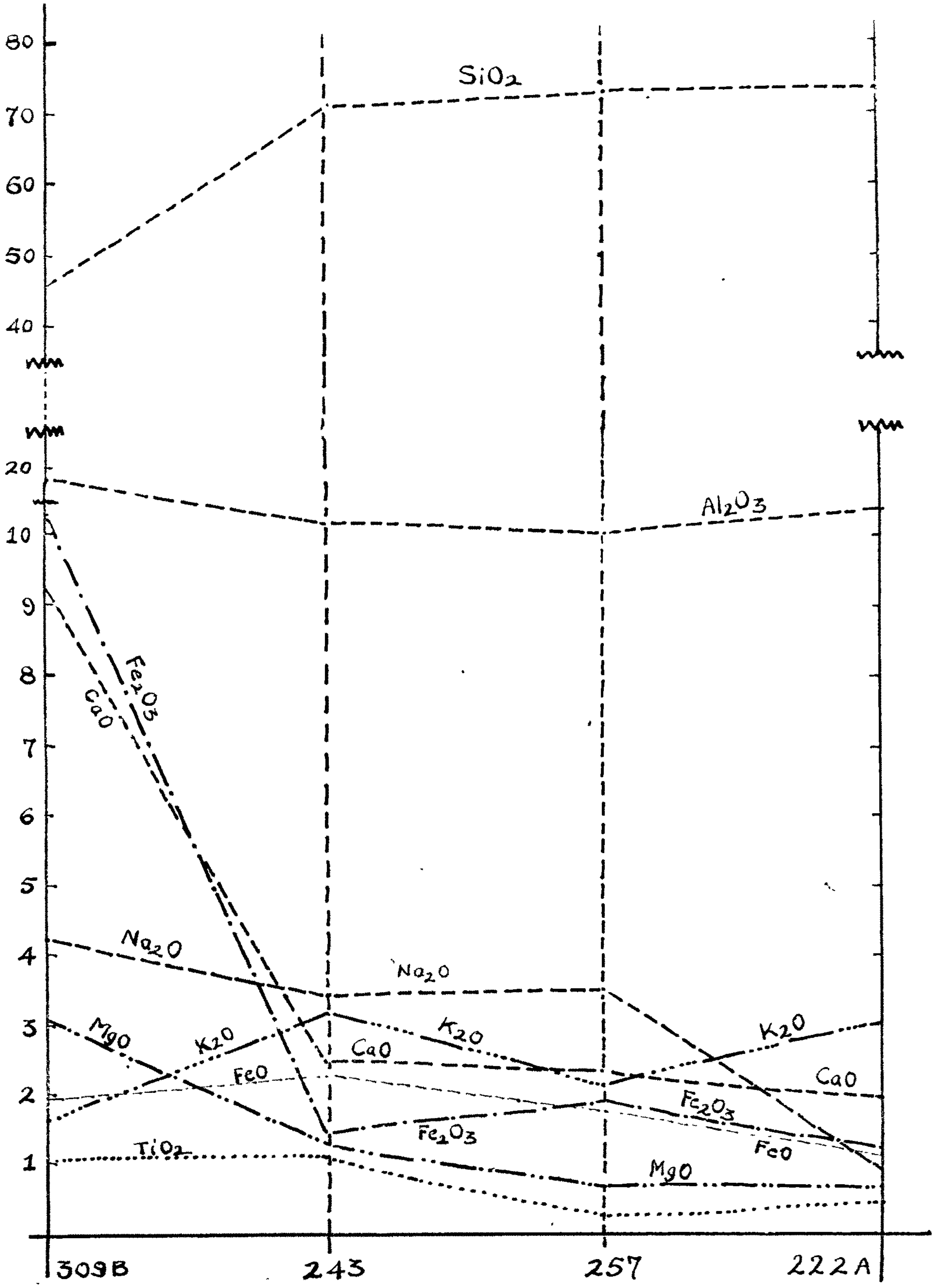
III. Chemical Evidences:

The chemistry of the granitic rocks too point out to their metasomatic origin. On account of rapid and wide variation in the mineralogy of these rocks, even within the limits of a single outcrop, it was not possible to conduct a detailed chemical study of the rocks, but the author could select carefully a few typical and representative samples taking into account their location, field characters and mineralogy, and these were chemically analysed. The analyses of rocks representing different stages of granitisation, when plotted on a number of diagrams, give a clear idea of the chemical changes undergone by the rocks during granitisation. Facts that emerge out of this chemical study fully support the various field, mineralogical and textural evidences of granitisation discussed earlier in this chapter.

(i) Variation diagrams: The trends of the percentages of SiO_2, Al_2O_3, Fe_2O_3, FeO, TiO_2, MgO, CaO, Na_2O and K_2O, in a number of samples ranging from a typical amphibolite to a light coloured potash granite (Table 2) very clearly reveal the chemical changes brought about by the granitisation. It is seen from the plotted variation diagrams (Fig. 7) that SiO_2 shows a marked increase from amphibolite to a hornblendic granite, but later on it remains more or less constant. There is no appreciable change in the Al_2O_3 while Fe_2O_3 shows the expected decline; and so behave the FeO, MgO and CaO. A slight rise in TiO_2 in biotitic granite is understandable, the biotite being of a brown colour. It is significant to note that there is negligible rise in Na_2O content; practically it remains constant till the influx of potash, with whose arrival, Na_2O shows a steady decrease, obviously at the cost of increasing K_2O. K_2O is seen to show a general rise.

FIG. 7

VARIATION DIAGRAM FOR GRANITIC ROCKS



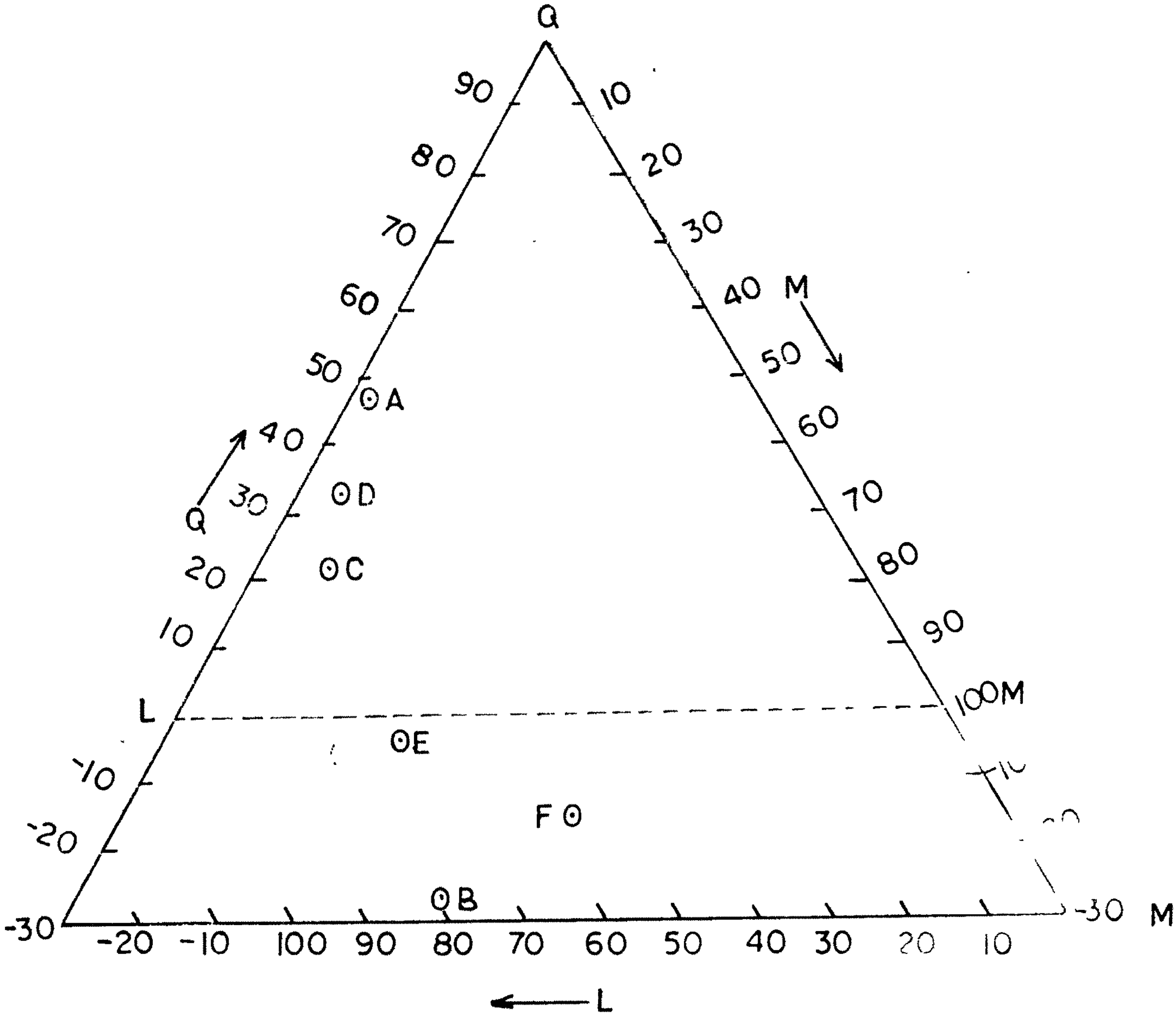
(ii) QLM Values: These values calculated from the analyses of 5 representative rocks (Table 3) when plotted on Von Wolff's diagram (Fig. 8) reveal that with increasing granitisation, the free quartz (Q) percentage shows a marked increase. The leucocratic mineral percentage (L) indicate moderate decrease, while the percentage of melanocratic constituents (M) show an appreciable decrease on increasing granitisation. The gradual and systematic changes, well illustrated by the QLM diagram, could not have been brought about except by a process of granitisation.

(iii) K_2O : Na_2O Mols: The Mol values for K_2O and Na_2O of the analyses of a few representative samples of granitic rocks (Table 4) when plotted on standard diagrams prepared by Marmo (1955), ideally show that most of them fall within the synkinematic field (Fig. 9).

(iv) Niggli Values: Niggli values of Si and Al of these granites, when plotted on standard diagrams of Marmo (1955) again confirm their synkenematic origin (Table 5, Fig. 10).

FIG. 8

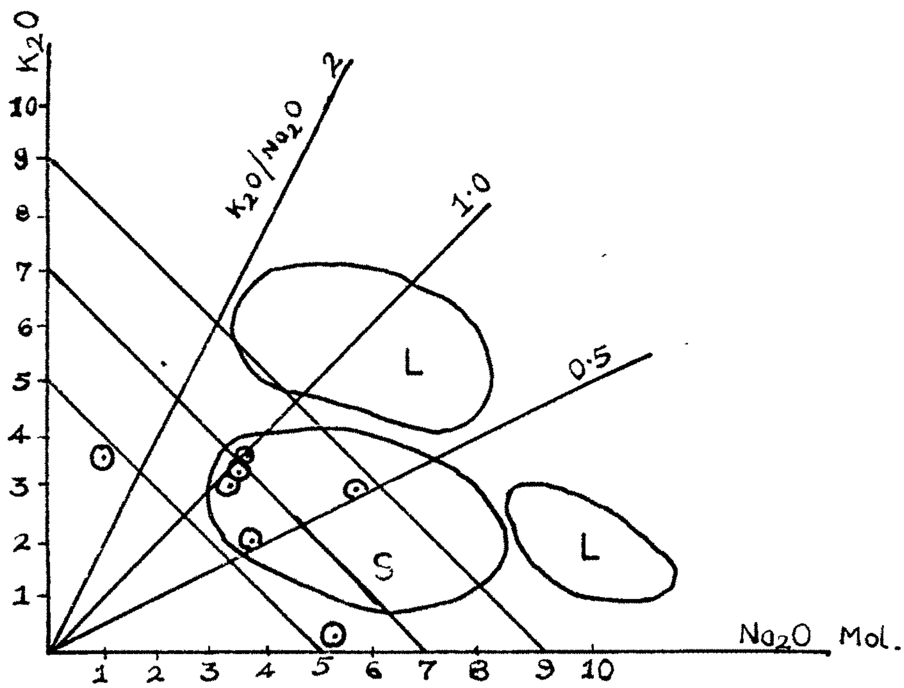
V. WOLFF'S DIAGRAM SHOWING
QLM VALUES OF GRANITIC ROCKS



A = sp. 222 A
B = sp. 222 B
C = sp. 223
D = sp. 309 A
E = sp. 309 B
F = sp. 214

FIG. 9

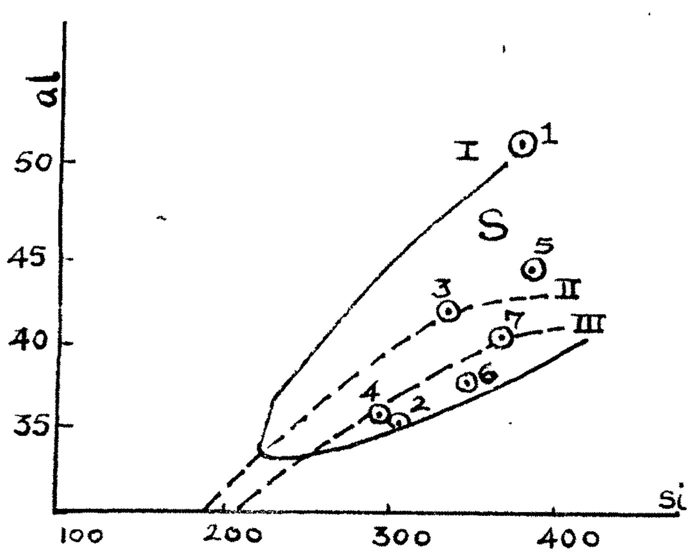
MOLECULAR DIAGRAM
(After Marmo)



S= SYNKINEMATIC FIELD
L= LATEKINEMATIC FIELD

FIG. 10

NIGGLI VALUES
(After marmo)



MECHANISM AND SEQUENCE OF GRANITISATION

The transformation of amphibolites to granitic rocks, was brought about under deep-seated conditions, and the granitising fluids gave rise to widespread mineralogical and textural changes, the result being a migmatitic complex of granitic rocks ranging in composition from diorites to quartz microcline segregations. The various deformational episodes augmented the effectiveness of the agents of metasomatism, and thus gave rise to a number of textural and structural variations, and also facilitated the formation of replacement and secretion pegmatites.

The granitisation appears to have been brought about by a progressive 'soaking' of the amphibolites by suitable emanations, the mechanism of transformation being a process of intricate diffusion of granitising fluids along the 'pore spaces', foliation, joints and shear planes. As a result, the rocks show an overall increase in quartz and felspar. The accompanying deformational stresses not only aided the above process, but also caused segregation of quartzo-felspathic material in patches, veins, schlierens knots, and dykes. This segregation was accomplished by 'metasomatic differentiation' resulting into 'filtering off' of the darker constituents either as rims or cores. This mechanism was mainly responsible for the widespread metasomatic growth of pegmatite veins and dykes along the foliation planes, joints and other fractures.

The chemical study has revealed that the transformation did not involve much increase in soda or alumina, and thus it is surmised that granitising emanations were rich in silica and potash, the latter having arrived a little later. Being a deepseated phenomenon, granitisation imperceptibly followed the regional metamorphic processes.

The study of granites thus reveals the following sequence of events:

(i) Metamorphic differentiation leading to hornblendic, dioritic and felspathic bands.

(ii) Enrichment of various bands in quartz.

(iii) Partial change of hornblende to biotite and appearance of interstitial microcline.

(iv) Large scale change of hornblende to biotite and increase of microcline content. Replacement of plagioclase by microcline. Formation of microcline 'ovoids' in pegmatites.

All parts of the area were not equally affected by the granitisation, and show considerable variation. It is obvious that the intensity of the potassic activity was not uniform. Thus, the microcline content is very variable in different parts of the granitic areas. The author would also like to emphasise that the heterogeneity in granitic rocks has been due, not only to the varying intensity of the granitisation, but is to a considerable extent, due to the segregation of light and dark-coloured constituents, brought about by a process of 'differentiation' or 'filtering off' - all throughout the duration of granitisation. As a result, a wide variation in the nature of the pegmatitic veins, cutting the granitic rocks is seen, their composition depending in turn, on that of the surrounding rocks out of which these were squeezed and secreted out.

From the preceding account, following important conclusions are arrived at:

(1) There was a smooth change over from regional metamorphic processes to those of granitisation without any significant gap.

(2) The transformation of amphibolites into various granitic rocks was brought about by the emanations rich in SiO_2 and K_2O.

(3) The entire granitisation for the most part, was synkinematic.

GRANITISATION IN RELATION TO FOLD EPISODES

Deformation, regional metamorphism and granitisation - all these formed an integral part of the orogenic activity, and a close relationship existed between them. The author has summarised below the successive events of granitisation in relation to the various fold episodes:

(1) Granitisation was initiated before the early folding (F_1):

This is clear from the abundant leucocratic bands in the partly granitised amphibolites, which show tight isoclinal folding. Also, the pegmatitic streaks and veins in granitic terrains show effects of two foldings - the early being isoclinal (F_1).

(2) Granitisation continued to be effective during the early folding (F_1):

It appears that the stresses which gave rise to the isoclinal folding (F_1) considerably aided the processes of granitisation which continued to be operative during this deformation. A number of quartzo-felspathic veins and dykes are seen to have originated along the axial plane direction of this early folding. Secondly, the occurrence of ellipsoid and lensoid masses of melanocratic rock in the granites, with distinct rims of leucocratic material, afford an excellent example of differentiation and filtering off action.

(3) <u>Granitisation continued after F_1 and synchronised with the second folding (F_2)</u>:

In the field itself, it is evident that metasomatic changes of granitisation became quite prominent after the cloase of the early folding (F_1). Prior to the late folding (F_2), a number of cracks and joint planes developed, and these afforded ideal sites for the growth of pegmatites. During F_2, all such veins and dykes were folded. At a number of places, the pre-existing structures were obliterated. It is obvious that by the time the second folding (F_2) affected the rocks, the whole mass was adequately "soaked" with granitising emanations and was in fairly plastic condition. During the deformation therefore, this migmatised or granitised mass, was considerably mobilised thus giving rise to non-foliated or massive patches of granitic rocks. As a result of F_2, the granitic terrain has taken up an 'agmatitic' appearance. In addition to the mobilisation causing folding of earlier structures and their frequent obliteration, during this folding, considerable metasomatic growth of a new generation of quartzo-felspathic veins and dykes also took place along joints and fractures.

(4) Granitisation outlasted the late folding (F_2):

The presence of numerous sharp leucocratic veins and dykes unaffected by F_2 and cutting across all pre-existing structures (related to F_1 and F_2), clearly indicate their growth after second folding F_2.

PROBABLE CAUSES OF GRANITISATION

The author believes that the ultimate causes of the granitisation are closely connected with the orogenic upheaval, and in some obscure way related with the complex process of geosynclinal folding which Ramberg (1945, p.261) has called a large scale equilibriopetal exothermic process. As Ramberg (1952, p.273) has suitably explained, "it is very likely that the whole sequence of geological processes which result in the folding and rise of folded mountain ranges is a large scale event which proceeds spontaneously, tending to create a stable situation out of the unstable state of affairs of the geosynclinal stage. In the urge of nature to achieve stable equilibrium throughout the parts of the crust (and substratum) which are occupied by the geo-syncline, displacement of matter on a small and large scale is crucial. Thus rock matter is displaced mechanically by faulting, folding and plastic creep or flow of solid rocks and flowage of molten magmas. We know also that another kind of material transport is operating viz., the diffusional migration creating metasomatism and growth of petroblastic rocks in the solid state. This latter kind of material displacement is intense and large-scale in deeper sections of folded mountains. During such lively chemical exchange of rock-making matter, it is inevitable that significant heat effects occur. Since granitisation and allied metaso-matism mean consolidation of energy-rich or activated particles "at countless points throughout the rock", it is fair to assume that the net effect will be positive. That is, granitisation and other kinds of metasomatic replacements should contribute much to the heat required to account for not only the elevated temperature in regional metamorphism but also refusion of acidic magmas.

Whether the circulation of hydrothermal solutions or long distance ionic diffusion in a stationary medium, is the main factor in granitisation, is highly problematic. Many geologists think water to be essential for the transportation of ions. Read (1948, p. 15) invoked the efficacy of hydrothermal solutions and believed that at high temperatures, molecular diffusion could bring about changes in solid rocks on a rather limited scale only. But later views favour "dry transformation" by ionic diffusion in solid state without water. Perrin (1954, p.451) considers that ions can move for long distance causing granitisation.

The rocks of the study area suggest that the granitic component introduced into the amphibolites was not of the nature of a melt, as there are few evidences to show any injection of a molten material. On the other hand, various criteria point towards a gradual metasomatic alteration of amphibolites into gneisses, the transformation having been brought about by the passage through solid rocks, of a stream of interchanging constituents. It appears that in bringing about granitisation, hydrothermal solutions played rather a subordinate role. The various textural and mineralogical features of the granites point to the possibility of metasomatism brought about by the mechanism of solid diffusion without much water.

The important controlling factors in solid diffusion are temperature and pressure. Heat results in increased diffusion. Stresses promote solid diffusion because they decrease pore space. Shearing distorts the crystal lattices and so promotes ionic migration. Reynolds (1947,pp.409-11) has suggested three possible ways in which ions may migrate through a solid (crystalline) medium:

(i) Through spaces in lattice, if the lattice is sufficiently open and the migrating ions are of appropriate size.

(ii) From one lattice point to another within the crystal mesh. This type of diffusion occurs when the atoms in a crystal are in a state of rapid thermal vibrations. At a certain temperature, these vibrations become so large that ions may break away and wander through the lattices.

(iii) Through zones of atomic disorder, lattices are composed of minute blocks which are not perfectly aligned. These mosaic structures give rise to atomic disorder at the junctions of mosaic units. Atomic disorder is also found along the boundaries of closely packed crystal grains. Orogenic stresses create pronounced atomic disorder.

Obviously, in a region of active orogeny where geosynclinal rocks have been subjected to high temperatures and different types of stresses, ideal conditions would exist for initiating such processes. Thus regional metamorphism and granitisation form a connected sequence of events closely related to the orogeny. The nature of the ultimate source of the emanations, though undoubtedly being in the deepseated parts of the geosyncline, is yet to be properly understood. Some believe that sources of granitising emanations are the palingenetic granitic magma, while others suggest a chemical "squeezing" of K, Na, Si, O at deeper levels and their subsequent upward migration. Whatever may be the source of the granitising emanations, it is almost universally agreed that the downwarping of the sialic crust forming the roots of the fold mountains, on touching the hot simatic substratum leads to the generation of these emanations.

Though the migration of quartzo-felspathic matter in a granitisation zone may extend in almost any direction, depending upon the particular conditions which control the driving free-energy gradients of the movable material, there seems little doubt that the average direction of motion of granitic matter is upward from deeper portions of the geosyncline to relatively shallower levels. Granitic minerals - quartz, alkali felspars and micas, have low densities and hence are thermodynamically most stable in the shallower zones. For this reason the above minerals or minerals containing same elements as quartz, felspar and micas (Si, Na, K, Al, O, H) will tend to disintegrate when pushed to deeper levels, and following the demands of thermodynamics, these elements must migrate upward until they get consolidated in the quartz and the alkali felspar lattices in the zone of granitisation. In words of Ramberg (1952,p.261-262), "To compensate for this upward diffusion current, the whole 'crust' sinks bodily through the swarm of slowly rising atoms, ions and molecules. In part, the calco-ferro-magnesian elements are also migrating chemically downward. In any case, the net result will be that granodioritic matter is rising and calco-ferro-magnesian matter is sinking in the evolving folded zones, thereby minimizing the thermodynamic instability which causes the orogenic evolution. In other words, we may take the view that the energy potential gradient which drives the orogeny is the same as that which drives the granitization and other kinds of large scale metasomatism. Thus it is so evident that folding, thrusting and plastic flow of the rocks, as well as their recrystallisation and metasomatism, together with their local refusion, are all visible proofs of the exhaustion of the giant energy potential gradient which stands behind the whole phenomenon of orogeny".

TABLE I: Analyses of amphibolitic rocks.

	Daly's average of 24 analyses *	Different bands in amphibolitic rocks Sp. 214	Sp. 309A	309B	152	222B
SiO_2	49.500	46.300	71.600	47.100	47.000	45.000
TiO_2	0.840	0.970	0.340	1.050	1.501	1.135
Al_2O_3	18.000	15.550	15.500	17.450	12.360	18.629
Fe_2O_3	2.800	2.582	0.460	12.948	5.130	6.478
FeO	5.800	9.934	0.215	1.890	11.210	9.014
MgO	6.620	6.720	1.810	3.137	9.370	7.242
CaO	10.640	12.311	4.061	9.464	10.660	1.960
Na_2O	2.820	4.137	5.040	4.290	1.750	7.470
K_2O	0.980	0.386	0.374	1.747	0.630	0.624
$-H_2O$	-	0.400	0.050	0.262	0.061	0.235
$+H_2O$	1.600	0.510	0.350	0.665	0.098	1.587
MnO	0.120	0.510	-	-	-	0.300
P_2O_5	0.280	-	-	-	-	-
Total	100.000	100.250	99.800	100.070	99.770	99.889

* Analyses of olivine free from gabbro (Johanson, 1951, Vol. III, p.221).

TABLE 2

Variation diagram

(Analyses)

	309(B) (i)	243 (ii)	257 (iii)	222(A) (iv)
SiO_2	47.100	71.800	72.405	71.600
TiO_2	1.050	1.120	0.340	0.503
Al_2O_3	17.450	13.114	13.865	16.801
Fe_2O_3	12.948	1.513	1.827	1.119
FeO	1.894	2.353	1.868	1.079
MgO	3.137	1.114	0.869	0.724
CaO	9.464	2.610	2.490	2.000
Na_2O	4.290	3.507	3.786	1.050
K_2O	1.747	3.243	2.185	3.507
$-H_2O$	0.262	0.045	0.011	0.634
$+H_2O$	0.665	-	0.067	0.800
MnO	-	-	-	-
Total	100.070	100.659	99.713	99.880

TABLE 3

Q L M Values

(Analyses)

	222 A	309 A	223	222 B	309 B
SiO_2	71.600	71.600	69.800	45.000	47.100
TiO_2	0.503	0.340	0.350	1.135	1.050
Al_2O_3	16.801	15.500	14.303	18.629	17.450
Fe_2O_3	1.119	0.460	1.574	6.478	12.948
FeO	1.079	0.215	0.592	9.014	1.894
MgO	0.724	1.810	1.427	7.242	3.137
CaO	2.000	4.061	2.520	1.960	9.464
Na_2O	1.050	5.040	5.750	7.470	4.290
K_2O	3.507	0.374	2.820	0.624	1.747
$-H_2O$	0.634	0.050	0.200	0.235	0.262
$+H_2O$	0.800	0.350	0.600	1.587	0.665
MnO	-	-	-	0.300	-
Total	99.880	99.800	99.930	99.889	100.070
Q	47.095	32.364	21.875	-27.785	-3.623
L	50.450	60.960	68.820	79.563	72.912
M	2.450	6.676	9.305	48.358	30.711

TABLE 4

Mol Values
(Analyses)

	223	309 A	207	242	243	257	222 A
SiO_2	69.800	71.600	69.300	72.300	71.800	72.405	71.600
TiO_2	0.350	0.340	0.200	0.500	1.120	0.340	0.503
Al_2O_3	14.303	15.500	14.608	14.225	13.114	13.865	16.801
Fe_2O_3	1.574	0.460	1.451				
FeO	0.592	0.215	1.748	1.562	2.353	1.868	1.079
MgO	1.427	1.810	1.610	0.769	1.114	0.869	0.724
CaO	2.520	4.061	3.760	2.010	2.610	2.490	2.000
Na_2O	5.750	5.040	3.775	3.591	3.507	3.786	1.050
K_2O	2.820	0.374	3.430	3.231	3.243	2.185	3.507
$-H_2O$	0.200	0.050	0.010	0.027	0.045	0.011	0.634
$+H_2O$	0.600	0.350	0.300	0.180	0.240	0.067	0.800
MnO	-	-	-	-	-	-	-
Total	99.936	99.800	100.282	100.245	100.659	99.713	99.880
			Mol values for Na_2O and K_2O				
K_2O/Na_2O	0.490	0.074	0.908	0.899	0.924	0.577	3.333
$K_2O + Na_2O$	8.570	5.414	7.205	0.822	6.750	5.971	4.557

TABLE 5

Niggli Values

	223	309 A	207	242	243	257	222 A
Si	309	329.6	296.7	380	350	366	380
Al	34.62	42.01	36.750	42.50	37.45	40.90	52.61