American Journal of Science

APRIL 1949

METASOMATIC GRANITIZATION OF BATHOLITHIC DIMENSIONS[1]

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PART I

ABSTRACT. In the Nanga Parbat area (Northwest Himalayas) a thick group of presumably pre-Cambrian argillites with thin calcareous and basic bands is overlaid by Cretaceous-Eocene volcanics, and both are bordered by extensive Eocene norite masses. These rocks have undergone regional metamorphism during Early Tertiary orogeny. Synkinematic metamorphism of the argillites progresses from slates and phyllites through micaschists, biotite-paragneisses, kyanite-schists and -paragneisses to sillimanite-paragneisses. The metamorphic zones in the argillites are matched by those in the calcareous bands.

Synkinematic granitization of the potash-predominant variety begins within the kyanite zone with microperthite-porphyroblast-schists passing to potash-rich augengneisses of granitic appearance which contain relict kyanite in their groundmass. Lit-par-lit replacement—as against mechanical injection — along active foliation planes makes banded gneisses. In the interior of the Nanga Parbat massif, granitization becomes more complete, and coarse-grained granitic gneiss forms. Here only small quantities of argillite altered to sillimanite-schist have escaped transformation into granitic rock. The calcareous bands are not granitized, and are preserved as conformable intercalations in the gneissose granite which has replaced the argillites. Metamorphism and granitization progress both along and across the strike of the altered sediments. There is complete structural continuity from the weakly metamorphosed sedimentary areas to the intensely granitized region. Also the type of tectonic deformation is the same throughout these areas, and is that characteristic of the deformation of solid rocks during orogenic metamorphism. The granitized body as mapped measures 25 by 60 miles.

The chemical nature of the granitizing agent is discussed. The metamorphic isograds (approximately vertical in this region) are shown to be independent of depth, and a function of differential introduction of heat from below. It is stressed that degree of metamorphism and granitization are systematically linked, and convection of heat by the granitizing solutions is held responsible for high grade regional metamorphisms in the upper part of the crust.

INTRODUCTION

THE idea that granitic rocks may form by metamorphic processes, is not new. It dates back to the French school

[1] Read during the April 1948 annual meeting of the Cordilleran Section of the Geological Society of America at Pasadena.

of the last century, and to the subsequent classical contributions by J. J. Sederholm (1907, 1923, 1926, 1934). However, only during the last dozen years or so has the problem of granitization received ever-increasing general attention. There is no need for giving a historical review here, since several recent publications have done so, among which the Geological Society's granite memoir is outstanding. It is significant that various geologists, working in widely separated parts of the world, have arrived at more or less similar conclusions, quite independently of each other, and often without previous knowledge of published reports of earlier students of the problem. It appears that geology has at present reached a stage in which there is inherent a tendency to re-examine fundamental conceptions and theories sacred by tradition, and to substitute new ideas where critical evaluation of the ever-increasing body of observed facts so demands.

This is especially true of the theory of the origin of granitic rocks—one of the basic problems in geology, considering the predominance of such rocks in the crust, and the role they play in the tectonic history of mobile belts. That granitic rocks can form by metamorphic transformation of pre-existing solid rocks on a comparatively small scale is today accepted by the great majority of geologists, since this process has been conclusively demonstrated by a number of authors, usually with an emphasis on small-scale features. Most geologists seem to feel that such processes are, as a whole, subordinate, and probably represent contact phenomena occurring in the marginal zones of igneous granitic batholiths. However, some of the workers in this field believe that metamorphic granitization is a process of much more fundamental and general significance. To prove this point, it has to be demonstrated that large masses of granitic rocks have as a whole, and not only marginally, formed by metamorphic transformation of solid rocks. The present paper attempts to contribute to this problem by describing some areas in which large masses of granitic rocks can be shown to have a metamorphic origin throughout.

The material presented was collected in the high mountains of Asia, but this is merely accidental; it appears to me that the areas described are not in any way extraordinary, but typical of what is found all over the world. The petrogenetic aspect of the Himalayan gneisses described below is identical with that of many gneisses ranging from pre-Cambrian to Mesozoic ages which I have seen in this country, in China and in Europe, just as the "small granodioritic blocks formed by additive metamorphism" described by G. E. Goodspeed (1937) from Northeast Oregon are duplicated in the Okanogan country in Eastern Washington, in the Indus Valley in the Northwest Himalayas, or near the Yangtse Valley in Northwest Yunnan.

The material presented below is arranged according to whether granitization was synkinematic, i. e. took place under conditions of active orogenic deformation, or whether it was postkinematic, i.e. took place under static conditions when orogeny had ceased. Then some cases are briefly described which might serve to illustrate the relationships between syn- and postkinematic granitization. At the end of each part, it is attempted to draw certain general conclusions, presuming that the material presented is typical.

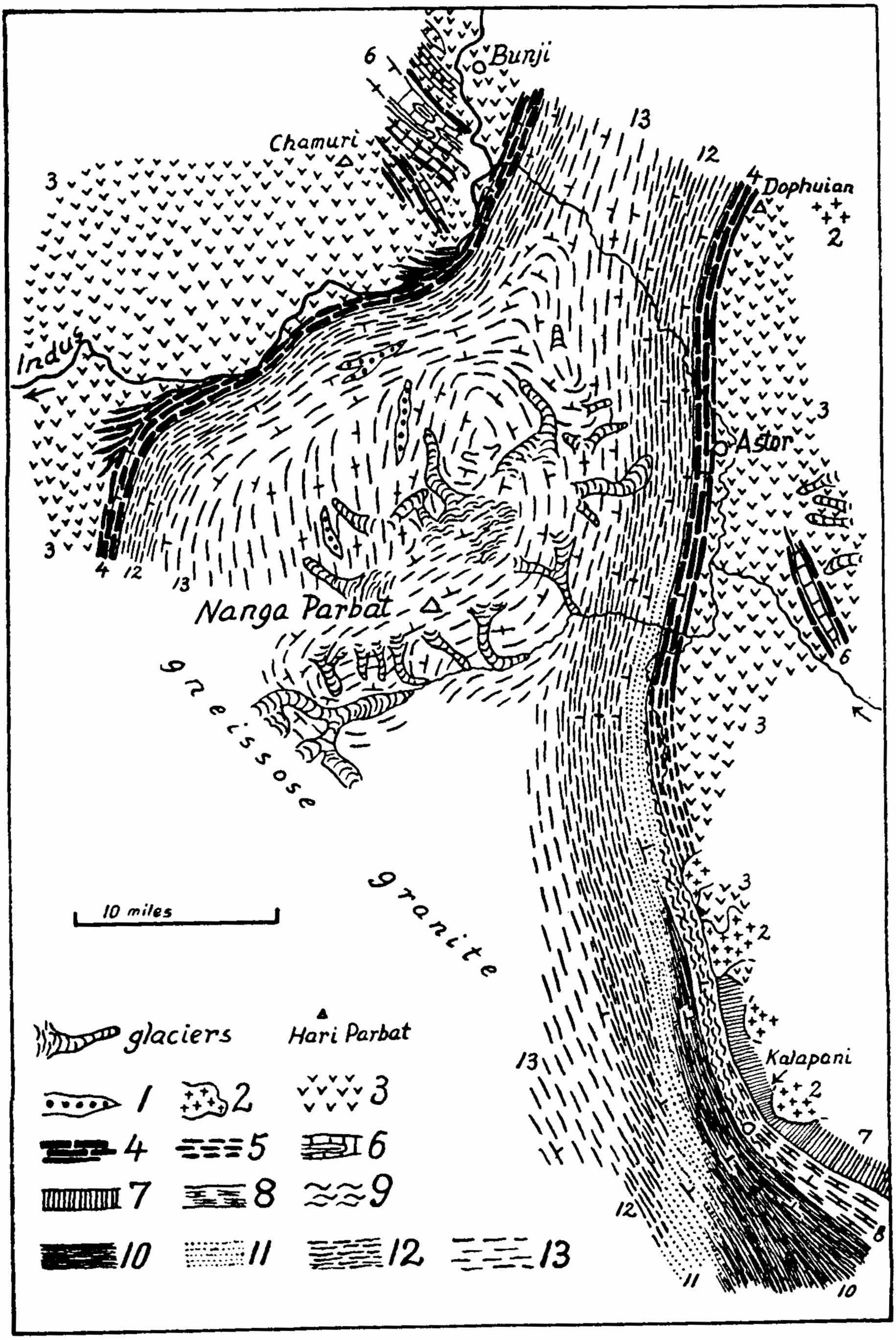
FIRST PART

Synkinematic granitization in Nanga Parbat area Northwest Himalayas

The Nanga Parbat area[2] in the crystalline inner zone of the Northwest Himalayas offers an unusually clear example of synkinematic granitization on a batholithic scale. Passages from metamorphic sediments of lowest to such of highest grades, and from chemically unaltered to intensely granitized rocks, are magnificently exposed in continuous sections for dozens of miles and over a vertical range of 23,000 feet. No structures or processes other or later than the main process of progressive alteration are superimposed, so that this process is revealed in grand simplicity.

Nanga Parbat Mountain rises north of the Great Himalayan Range, close to the upper Indus. The Nanga Parbat area shows a bending to north of the more westerly main trend of

[2] The writer did four months of field work in this area during Willy Merkl's 1934 Nanga Parbat expedition. The petrographic study has occupied a number of years since. A report on field observations has been presented (Misch, 1935) but, apart from a short abstract (Misch, 1936a), publication of the petrographic results has been delayed by emigration to China and the outbreak of the Sino-Japanese war, and the ensuing lack of adequate facilities in the interior of China.



Bunji
Chamuri
Dophuian
Indus
Astor
Nanga Parbat
gneissose
granite
10 miles
Kalapani
glaciers
Hari Parbat
1
2
3
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5
6
7
8
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12
13

the Himalayas. This area forms a part of the eastern limb of the great syntaxial loop of the Northwest Himalayas which D. N. Wadia (1931) has described in detail in the sedimentary zones farther south.

(I) MAIN ROCK UNITS OF NANGA PARBAT AREA

The least metamorphosed bedded rocks are found in the southeast of the area shown in text figure 1, and farther south. Here occurs a *group of black phyllites and slates* with subordinate thin limestone bands, and occasional thin layers of quartzite and altered greenstone. The original thickness is very great and tectonic accumulation by intense folding is added. The resulting thickness exceeds six miles in the southeastern part of the region shown in figure 1, and south of this region the phyllite-slate group forms a still much thicker section. In the southeastern part of the region, this group is succeeded on the east by variegated tuffaceous and calcareous slates which in their upper part are interbedded with tuff breccias. Still higher in the section, there appear basic and also more acidic lava flows which in their lower part are intercalated with the tuffaceous rocks. This *volcanic formation* has been shown by D. N. Wadia (1937) to be *Cretaceous-Eocene*, on the basis of fossils discovered further southeast. Wadia

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Text Fig. 1. Geologic sketch map of Nanga Parbat region, Northwest Himalayas. After P. Misch (1935), fig. 8.

1: tourmaline-granite; postorogenic
2: quartz-diorite and granodiorite; post-norite
3: norite, hypersthene-diorite, etc.; widely altered to metanorite and metadiorite; Eocene
4: mesozonal amphibolite } synorogenic-metamorphic norite etc.
5: epizonal greenschist } synorogenic-metamorphic norite etc.
6: marble and schist zones in norite, metanorite, etc.
7: basaltic and more acidic lavas } Cretaceous-Eocene volcanic formation
8: variegated tuff breccias and tuffaceous-calcareous argillites } Cretaceous-Eocene volcanic formation
9: tuffaceous argillaceous rocks (8) epizonally metamorphic
10: Salkhala group; dark slates and phyllites with subordinate thin limestone and greenstone bands
11: non-granitized schists; chiefly mesozonally metamorphic Salkhalas
12: mesozonal migmatitic gneisses (chiefly augengneisses and banded gneisses); incompletely granitized Salkhalas
13: migmatitic granitic gneiss; granitized Salkhalas
(11)-(13) contain intercalations of schists, marbles, and amphibolites; mesozonal in (11) and (12), katazonal in (13)
} (9)–(13): metamorphism and granitization synorogenic

(1932) assigns the underlying black slate group to the *pre-Cambrian Salkhala series* of the Western Himalayas. According to this author, the Salkhalas are everywhere separated by an angular unconformity from the Late Algonkian Dogra slate and all younger rocks. In the area here discussed, no angular relationship is visible in the field between the black slate group and the volcanic formation, their directions of foliation being parallel. In the tuffaceous rocks the foliation is essentially parallel to the bedding. In the black slates and phyllites, no bedding is visible in the field. Under the microscope, some of these rocks show intensely folded fine-bedding traversed by the foliation; isoclinal folds have their limbs parallel to the foliation and become drawn-out and finally obliterated by slip along the foliation planes. Any angular unconformity which may originally have existed is thus masked by the foliation.[3] The foliation is later than the volcanic formation and has originated during the late or post-Eocene main Himalayan orogeny.[4]

The black slates and phyllites and their limestone and greenstone bands pass gradually into *mesozonal crystalline schists* toward the west and north, that is, both across and along the strike. After progressive metamorphism has reached a mineral facies corresponding to the lower part of the mesozone, potash-feldspar porphyroblasts appear in the dark-colored schists[5] (chiefly biotite-paragneisses[6]) of argillaceous

[3] According to Wadia, such intense minor folding is characteristic of the Salkhalas though later structures may be superimposed.

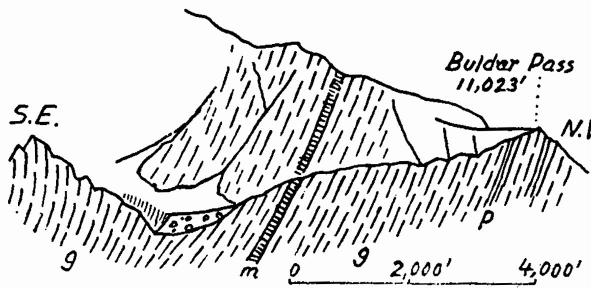
[4] The Himalayan folding is often called "Late Tertiary." However, the folding of the geosynclinal main range is Early Tertiary. Only the foldings of the successive foredeeps, marginal thrusting of the main range over the fore-deep rocks, and some local disturbances within the main range are Late Cenozoic (cf. Misch, 1936b, with references).

[5] The term *schist*, without a prefix, is here used to indicate any schistose rock derived from an argillaceous sediment, and having reached a higher metamorphic grade than phyllite. "Schist" thus includes micaschist, paragneiss and related rocks. "Crystalline schist" is a comprehensive term including all foliated metamorphic rocks. Schistose rocks differing in their composition from schists of argillaceous derivation, are indicated by a qualifying prefix or adjective, e.g. "chlorite-schist," "greenschist" (epidote-albite-chlorite-schist), "actinolite-schist," "calcareous schist," "quartzite-schist," etc.

[6] The term *paragneiss* is here used for crystalline schists having as main constituents quartz, mica and feldspar, and derived from sediment. Most paragneisses are fine-grained, rich in biotite and dark-colored. They may be thinly foliated, but are mostly somewhat more compact. They differ from micaschists in having feldspar as one of their main constituents, and mostly in being less thinly foliated.

derivation which thus grade into *mesozonal migmatitic augen-gneisses and banded gneisses*, both across and along the strike. The mesozonal rocks form a continuous belt on the eastern side of the Nanga Parbat gneiss massif, and a similar belt occurs in the northwest on the opposite side of the massif.

In the mesozonal belts, granitization remains incomplete, and material of purely sedimentary derivation is still recognizable everywhere. Toward the *interior of the gneiss massif*,



Text Fig. 2. Section and view south of Buldar Pass, northeast of Nanga Parbat.

g: coarse-grained granitic gneiss
m: white marble
p: fine-grained dark-colored biotite-schist (paragneiss)

granitization reaches a much higher degree. Most of the argillite-derived fine-grained dark-colored paragneiss becomes more coarsely recrystallized and feldspar-enriched, and thus loses its distinctive character. Here the mesozonal migmatitic gneisses grade into *coarse-grained light-colored granitic gneisses or gneissose granites.* These rocks form the bulk of the interior of the gneiss massif. Layers of dark-colored argillite-derived katazonal paragneiss, and of banded gneiss containing clearly discernible paragneiss laminae, are quantitatively very subordinate, but are intercalated throughout the interior of the massif. The granitic gneiss also contains layers of kata-amphibolites and of marbles with katazonal lime-silicates. These rocks may be associated with some paragneiss, but also occur directly intercalated in granitic gneiss. Particularly striking are a few places where pure white marble forms regular bands of small thickness but great longitudinal extent immediately in the coarse-grained gneissose granite (cf. text figure 2).

Field observations suggest, and microscopic structures confirm, that the progressive regional metamorphism is *synkinematic*. The same holds true of the process of granitization though in the interior of the gneiss massif there are indications that crystallization in general and granitization in particular continued after deformation ceased.

In addition to the black slate group (Wadia's Salkhalas), the *Cretaceous-Eocene volcanic formation* occurring in the southeast of the area, *has undergone regional metamorphism.* In the extreme southeast of the area, alteration does not go beyond the slaty stage, and disappears on the east in the upper members of the volcanic formation. Toward the north, however, the metamorphism of the volcanic formation increases along the strike. Chlorite-schists, calc-phyllites, intensely laminated tuff-breccias with chloritic matrix, etc. represent the epizone. Farther north, hornblende-garbenschiefer and calc-micaschists, often rich in epodite-clinozoisite minerals, show the facies of the uppermost mesozone. Still farther north, some normal mesozonal amphibolites probably prolong this stratigraphic unit.

Another group of rocks in the Nanga Parbat area consists of very extensive masses of *norite and hypersthene-diorite* with local dunite. These rocks border the gneiss massif both on the east and northwest. The eastern norite area is on the south in contact with the predominantly basic lavas of the Cretaceous-Eocene volcanic formation. The norite is contemporaneous with or slightly younger than the lavas. That both are genetically related has already been pointed out by D. N. Wadia (1932).

Most of the noritic rocks have been more or less metamorphosed. There are all passages to statically recrystallized metanorites and metadiorites with crystalloblastic hornblende, epidote, etc. As the borders of the gneiss massif are approached, static recrystallization gradually gives way to kinematic metamorphism,[7] and *mesozonal amphibolites* are formed. The mineral association remains the same, except for the appearance of garnet in the deformed rocks. At the borders of the gneiss massif, the norite-amphibolites are

[7] The noritic series, its relation to large areas of included metamorphic Salkhalas where alternations and gradational contacts are observed, the later metamorphism of the noritic rocks, and the relations between their static and kinematic types of metamorphism, will be dealt with in another paper.

intimately intercalated and interfolded with the paragneisses and migmatitic gneisses. Both rock units, e. g. the norite bodies and the gneiss massif, have here participated in the same process of tectonic deformation and of crystallization accompanied by some granitization. This process of synkinematic metamorphism took place during the Early Tertiary main Himalayan orogeny, not a very long time after the original norite bodies had formed. At contacts with granitized bands, the amphibolites tend to be locally biotized.

Whereas the metamorphism of the norites is generally mesozonal, it becomes epizonal (chlorite - epidote - albite - schists, etc.) along the western border of the eastern norite body, where this border approaches the epizonal southeastern portion of the Nanga Parbat area.

Directionless granitic rocks occur in several parts of the area, but remain subordinate. Small irregular patches and pockets of quartz-dioritic and granodioritic rocks showing gradational contacts and porphyroblastic textures are common in directionless or weakly schistose metanorites. Some larger bodies of granodiorite occur in the noritic rocks and the lavas of the volcanic series. Within the gneiss massif, dikes and larger bodies of postorogenic white tourmaline-granite occur at several places, but the largest attain a size of only a few miles.

The *boundaries* between the metamorphic rock series described are all steep. The *metamorphic isograds* are steeply inclined planes in the whole area. For the most part, they are nearly perpendicular, the dip being either normal or slightly overturned.

(II) PROGRESSIVE METAMORPHISM OF SEDIMENTS IN NANGA PARBAT AREA

Argillite series.—This is the problem confronting us: do the granitic gneisses which form the bulk of the Nanga Parbat massif, owe their origin to intrusion of granitic magma, or to metasomatic[8] granitization? I shall try to give evidence for the latter process, e. g. for a formation of the granitic

[8] The term "metasomatic" is here used in its widest sense, i.e. to indicate any alterations of rocks during which chemical changes are brought about by an introduction of new substances, which process may or may not involve a simultaneous removal of other substances.

gneisses by synkinematic metamorphic transformation and replacement of sediments, concurrent with certain chemical changes which chiefly consisted of the addition of alkali. This problem cannot be approached without a previous discussion of the progressive metamorphism the non-granitized sediments have undergone. Moreover, granitization should not be visualized as an isolated phenomenon, but in its integral relationship to higher-grade regional metamorphism.

Most of the sediments in the Nanga Parbat area are argillites belonging to the Salkhala group, and the sedimentary base of the granitic gneisses almost entirely consists of these rocks. Therefore, the series of progressively metamorphosed argillites is the one with which we are chiefly concerned. It shows, in a continuous succession observed both across and along the strike, *a number of "mineral facies"* (cf. P. Eskola, 1920) which can be readily assigned to the three classical *"depth" zones.* The writer does not know another area in which the zones of regional metamorphism are displayed with equal completeness and continuity and in equally magnificent exposures. The *factor controlling the spatial distribution of mineral facies and zones* in this area can be shown to be exclusively *temperature.* Confining pressure was approximately the same in places greatly differing in their degree of metamorphism. For the metamorphic zones succeed each other horizontally, with approximately vertical boundaries; in fact, most of the katazonal rocks forming the interior of the Nanga Parbat massif are exposed at higher elevations than most of the meso- and epizonal rocks of the marginal areas. Stress action was also of the same intensity in the different metamorphic zones as is shown by the structures of the rocks although, as is to be expected, crystallization has healed cataclastic mineral structures more completely in the hotter inner portions of the massif than in the marginal areas.

The series of metamorphosed argillites begins with black carbonaceous slates and ends with high-grade sillimanite-bearing rocks. The upper epizone is represented by carbonaceous *phyllitic slates* composed of sericite and quartz, often with additional chlorite. They pass into less finely textured normal *epizonal phyllites* (cf. pl. 1, fig. 1) composed of the same minerals, often with the addition of albite; the albite tends to form small porphyroblasts which frequently show helicitic structures and sometimes bear signs of having been rolled. In the albite-free low-grade rocks, some sodium is probably camouflaged in sericite (admixture of paragonite). In the *lower part of the epizone*, small porphyroblasts of supposedly manganese-rich garnet appear, still in association with chlorite.[9] At the *base of the epizone*, the phyllites become more highly crystalline and approach micaschists. The essential minerals are muscovite and quartz. Chlorite still survives as a contemporaneous (not retrogressive) constituent and assigns these rocks to the epizone although members of the biotite series occur in some of them as a predominantly fine-grained constituent resembling sericite in texture. The albite may pass into oligoclase-albite. Garnet is common. In the various epizonal Salkhala argillites described, calcite, epidote and clinozoisite are only locally found, since these argillites are usually poor in calcium. On the other hand, these minerals are common in calcareous slates and phyllites of the Cretaceous-Eocene volcanic formation. Otherwise, those rocks show the same mineral assemblages as the Salkhala argillites.

As the mesozone is entered, contemporaneous chlorite disappears. The *upper part of the mesozone* is characterized by schists composed of well-formed biotite and muscovite, and of quartz (cf. pl. 1, fig. 2). Occasionally muscovite becomes subordinate to biotite or even disappears, obviously owing to a relatively high content in iron and magnesium, and to the lack of a pronounced aluminum excess. Almandite is a common accessory and tends to form porphyroblasts; "snow-ball garnets" are common and indicate, the same as other structural features, that crystalloblastic growth and mechanical deformation were simultaneous. There is often some additional oligoclase (usually on the sodic side, owing to a low calcium content of the sediment). If the amount of oligoclase is increased, the micaschists pass into paragneisses (cf. pl. 2, fig. 1), according to the definition of the term given above. Potash-feldspar appears within the mesozone, but not at its upper boundary. None of the feldspars show porphyroblastic tendencies in these micaschists and paragneisses. The

[9] The writer cannot follow the widely used classification "chlorite zone," "biotite zone," "garnet zone," since in the rocks studied by him the ranges of stability of these minerals overlap.

amount of feldspar rarely reaches that typical of the granitic gneisses.

The *lower mesozone* is characterized by the appearance of kyanite. This mineral does not occur in all argillites metamorphosed in this zone, but only in those which have a pronounced aluminum excess, that is, in rocks derived from rather pure clays. In these rocks, kyanite often becomes one of the main constituents (cf. pl. 2, fig. 2). The other minerals are the same as in the upper part of the mesozone. However, there seems to be a tendency to somewhat reduce the amount of mica and especially of muscovite, and accordingly to increase the amount of feldspar. The crystallization of free aluminum-silicate accounts for this, most of the aluminum excess having been fixed in muscovite before the temperature had become high enough to permit formation of kyanite.[10] Accordingly, most of the kyanite rocks are paragneisses rather than micaschists, and potash-feldspar is rarely absent. Occasionally muscovite is reduced to the role of an accessory or is even absent. However, biotite-free varieties exceptionally occur; they are rocks very low in magnesium and with a moderate iron content which was fixed in the almandite present in almost all the kyanite rocks. In exceptional cases, kyanite rocks are so low in feldspar that they must be classified as micaschists, the limited amount of potash present having all been used up by the mica, and the quantity of sodium having only been sufficient to make some accessory oligoclase. Apart from kyanite rocks, the lower mesozone contains "ordinary" micaschists and paragneisses hardly distinguishable from similar rocks of the upper mesozone (cf. pl. 2, fig. 1).

In the *katazone*, *sillimanite* takes the place of kyanite (cf. pl. 3, fig. 1). All sillimanite-rich rocks collected were found to contain a considerable amount of potash feldspar usually represented by sanidine, and generally a considerably lower amount of oligoclase. At the same time, biotite considerably exceeds muscovite, and this latter may even be absent; high temperature which led to the crystallization of almost all of the aluminum excess as sillimanite, is the obvious explanation.

[10] It is of course realized that the amount of water available is another factor controlling the relative amounts of mica and feldspar. However, this factor can here be neglected since there are indications that there was no shortage of water in any of the metamorphic zones in this area.

Like the kyanite-rich rocks, those rich in sillimanite are derived from rather pure clays. Some of the sillimanite-rich rocks are practically free of quartz. Along with the high aluminum excess, this underlines the pure nature of the original clays from which this particular variety of rock was derived.

As a whole, non-granitized metamorphosed argillites occur only in very subordinate relict bands in the katazonal interior of the Nanga Parbat massif. Most of these bands do not contain sillimanite, but are "ordinary" paragneisses. Their mineral composition does not differ from that of the "ordinary" paragneisses of the mesozone, except for frequent absence of muscovite.[11] As in the mesozone, the oligoclase is usually on the sodic side. This is due to a primary low calcium content. Where katazonal paragneisses are in contact with lime-silicate bands, their plagioclase becomes at once more basic. The low calcium content of the meso- and katazonal paragneisses is also demonstrated by the presence of rutile whereas in metamorphosed calcareous shales of both zones the titanium has combined with calcium to form sphene. Like the mesozonally metamorphosed argillites, those of the katazone lack porphyroblastic development in their feldspars. In all these rocks, the carbonaceous matter characteristic of the Salkhala slates is still widely present in the form of finely scattered graphite flakes.

The textures of the meso- and katazonally metamorphosed argillites are fine-grained. Most of these rocks are dark-colored, owing to their high content in finely divided biotite. The appearance of the metamorphosed argillites is very different from that of the granitized rocks which show light colors, coarser textures, and porphyroblastic feldspars.

Lime-silicate series. — The argillite series is perfectly matched by the series of progressively metamorphosed impure calcareous rocks occurring as subordinate thin bands in the Salkhalas and, in the eastern portion of the area, in the lower part of the Cretaceous-Eocene volcanic formation. Considering the small amount of calcareous rocks in the Salkhalas, and in view of the fact that they have usually escaped granitiza-

[11] The writer cannot agree with the opinion held by many authors that muscovite is a stranger to the katazone. He thinks that muscovite, like hornblende, is "*unconditionally stable*" in the mesozone, and is "*conditionally stable*" in the katazone (meaning, stable under certain limited chemical conditions). This subject will be treated elsewhere.

tion, their metamorphism is only briefly discussed in the present paper.[12]

Upper-epizonal calcareous slates and *epizonal calc-phyllites* contain the same minerals as the non-calcareous argillites, with additional calcite (dolomite), epidote and clinozoisite. Also here, fine-grained members of the biotite series appear before chlorite becomes unstable. Calc-micaschists with either biotite or muscovite or both, are frequently rich in epidote or zoisite; they range close to the boundary of epi- and mesozone, and seem to belong to the highest mesozone. To the same mineral facies belong *calc-micaschists with hornblende porphyroblasts*; part of them are developed as *garbenschiefer*. These rocks are derived from dolomitic shales whereas the epidote-zoisite-rich micaschists represent calcareous shales. Varieties rich in magnesium and very poor in potash become para-amphibolites free of mica. In some of these rocks, the green hornblende is still associated with contemporaneous chlorite which assigns this variety to the lowest epizone.

The majority of the rocks just described belong to the Cretaceous-Eocene volcanic formation although bands of calcareous phyllites and micaschists are also found in the Salkhalas, often together with marble layers. In the *upper mesozone*, such bands are characteristically developed as *calcareous zoisite-bearing biotite-muscovite-quartz-schists*; they usually contain oligoclase and often almandite. Within the *lower mesozone*—corresponding to the kyanite-schist facies in the pure argillites—scapolite appears in the impure calcareous bands intercalated in the Salkhalas. The rocks are *scapolite-paragneisses* and, more rarely, scapolite-micaschists. Their minerals are: scapolite, zoisite, biotite, muscovite (often absent), oligoclase, potash-feldspar, calcite, quartz, almandite, and sphene. The latter mineral is common in impure calcareous rocks from epi- to katazone. Impure epi- and mesozonal marbles contain the same minerals as the schists described.

In the katazone, the association calcite + quartz becomes unstable in the impure calcareous bands in the Salkhalas. Now true lime-silicate minerals form. However, not infrequently the reaction remains incomplete, presumably owing to the CO_2 being unable to escape (cf. V. M. Goldschmidt, 1911). In the upper katazone, basic plagioclase and diopside appear

[12] This subject will be more fully discussed in another paper.

and scapolite still survives from the lower mesozone (unless it is retrogressive). Examples are: hornblende-bytownite-granulite with quartz, calcite and garnet, forming a band in biotite-paragneiss; diopside-scapolite-marble and granulite, with basic plagioclase and some potash-feldspar, occurring in a similar way.

With further increase in temperature, the *katazonal lime-silicate-granulite bands* reach their typical development and wollastonite is added as a characteristic constituent, representing the same mineral facies in which sillimanite forms in pure argillites. The wollastonite is associated with bytownite or bytownite-anorthite. This paragenesis is remarkable since, according to V. M. Goldschmidt's classical memoir on the contact metamorphism in the Oslo region (1911), this association could not be stable and the two above minerals ought to react to form grossularite. However, in the Nanga Parbat rocks wollastonite and bytownite are intergrown as contemporaneous and obviously stable partners. Since pressure would favor the reaction, and since the Nanga Parbat rocks have undoubtedly formed under considerably higher pressure than the Oslo and similar contact rocks, it must be concluded that in the interior of the Nanga Parbat massif *temperature was considerably higher than in the "inner contact zone,"* and was thus able to overcome the not inconsiderable pressure and prevent the grossularite reaction. This is confirmed by the presence, in part of the Nanga Parbat lime-silicate-granulites, of later grossularite replacing the paragenesis wollastonite + bytownite. The grossularite reaction began to take place when temperature, though still katazonal, had become somewhat lower.

The magnesium of the lime-silicate-granulite bands is fixed in diopside. Where such bands are in contact with ordinary paragneiss, a boundary zone rich in common green hornblende usually intervenes, demonstrating that hornblende, containing less Ca as well as Ca + Mg than diopside, is "conditionally stable" in the katazone (cf. above, foot-note no. 11). As the rock grades into purer argillite, biotite takes the place of hornblende. In the lime-silicate bands, biotite never occurs, and the potash is fixed in some accessory orthoclase. The lime-silicate-granulites contain either excess quartz or excess calcite, but sometimes both are present (incomplete reaction, cf. above). Bands of *lime-silicate-marble* often contain forsterite, instead of diopside (most economic use of limited silica available). If aluminum was available and there was a shortage of silica, spinel has formed in marble bands. Also, phlogopite is found in marbles of this zone.

The gradation, biotite - paragneiss, hornblende - granulite, lime-silicate-granulite, lime-silicate-marble, pure marble, is often observed within a few centimeters and even less, and close and regular interbanding is common. It is thus indicated that the primary differences in chemical composition which can be traced back to but slightly metamorphosed Salkhala sediments, have been perfectly preserved even under katazonal conditions, and that *practically no chemical migrations have taken place within the calcareous rocks.* This fact is remarkable, in view of the considerable chemical changes which have transformed most of the metamorphosed argillites into granitic gneisses (cf. below). The preservation of pure marble layers, not only next to paragneiss, but even within (migmatitic) granitic gneiss, illustrates the lack of chemical migrations in the calcareous bands.

The progressive metamorphism of argillaceous and impure calcareous rocks at Nanga Parbat is summarized in table 1. The *progressive metamorphism of basic rocks* matches that of the sediments. Basic rocks occur in the Cretaceous-Eocene volcanic formation, in the norite masses, and, as subordinate intercalations, in the Salkhalas and the gneisses formed from them. There is no need to describe in the present paper the various mineral facies displayed by the basic rocks. It may only be mentioned that in the sillimanite-gneiss and lime-silicate-granulite facies, there is no sign of an "eclogite facies" in the basic rocks, but they are developed as katazonal amphibolites; obviously, the eclogite facies is not a normal katazonal facies, but one restricted to extreme pressure, e. g. great depth.

(III) SYNKINEMATIC GRANITIZATION IN NANGA PARBAT MASSIF

(a) *Outer zones*

After metamorphism of the Salkhala argillites had reached a certain stage within the lower mesozone, their granitization began. Its intensity steadily increased toward the katazonal interior of the gneiss massif.

Both on the eastern and western side of the Nanga Parbat massif, granitization set in within the kyanite zone. First smaller and then large porphyroblasts of potash-feldspar began to form in the fine-grained schists (cf. pl. 3, fig. 2). As the number of porphyroblasts increases, the *feldspar-porphyroblast-schists* grade into *coarse-grained augengneisses* of granitic appearance (cf. pl. 4, fig. 1) and, if porphyroblasts are aligned in stringers and coalesce into bands, they grade into *banded gneisses* (cf. pl. 3, fig. 2; pl. 4, figs. 2-4). Both kinds of metamorphic migmatites are usually rich in almandite. There are all kinds of gradations, intermediate types, interlayering and interfingering of these variously granitized rocks, as well as of non-granitized metamorphic argillites.

(1) *Mesozonal migmatitic augengneisses.* — Both on the eastern and western side of the Nanga Parbat massif, there is a *continuous belt* thousands of feet wide in which massive coarse-grained augengneisses greatly predominate. These belts occupy the outermost parts of the massif of granitized Salkhalas. This augengneiss belt is absent only in the southeastern part of the area shown in figure 1.

Although having an igneous appearance (pl. 4, fig. 1), these massive augengneisses reveal their metasomatic origin in the field, by the presence of all gradations between augengneisses and argillite-derived schists and in the interlayering of both kinds of rock (cf. Misch, 1935). Microscopic examination confirms the metasomatic-migmatitic nature of the augengneisses. Their *groundmass* is, in its mineral composition and texture, identical with the biotite-schists and paragneisses described above which are altered Salkhala argillites. In this matrix, the large *potash-feldspar porphyroblasts*, usually microperthite, grew, replaced and penetrated it, and enclosed relics of its mineral grains (pl. 5, fig. 1; pl. 6, fig. 2; pl. 7, fig. 1). The irregular and crenulated borders of the porphyroblasts finally approach crystal faces, as the porphyroblasts tend to become idioblastic (pl. 6, fig. 2). Karlsbad twinning is common. The amount of porphyroblasts become very large, they exceed half of the volume of many rocks, and the original schist becomes restricted to relict stringers and winding bands between the large feldspars. Of particular interest is the presence of kyanite in the argillite-derived matrix of many of the augengneisses (pl. 5, fig. 1; pl. 7, fig. 1). Projections of growing feldspar porphyroblasts can be seen invading kyanite-rich paragneiss fabric, and absorbing it (pl. 7, fig. 1). Pure aluminum-silicate would hardly crystallize in a rock so rich in potash that more than half of it consists of potash-feldspar (not to mention the additional potash fixed in mica). In other words, the kyanite chemically represents an *unstable relic*. One chemical equilibrium was succeeded by a new and different one, and the difference was chiefly due to an introduction of potash.

The texture of the rock indicates that the potash-feldspar porphyroblasts have not been introduced as a whole, but are the product of a *reaction between the argillite-derived schist and newly introduced material* rich in potash. The introduced material was in a condition which enabled it to infiltrate and permeate the country rock, and to react with it. This means that the introduced material consisted of *hot solutions*.[13] The formation of the potash-feldspar porphyroblasts cannot be attributed to metamorphic differentiation within the country rock, both because the amount of potash in the augengneisses is higher than in the argillite-derived schists in the non-granitized areas, and because the matrix of the augengneisses possesses the original mineral composition of the argillite-derived schists and cannot therefore be a differentiate.

The *amount of material added* was not large (no exact figures can be given unless chemical analyses are made). A normal argillite is not too far from a granite in its chemical composition, and an addition of a moderate amount of alkali and usually some silica will transform it into a rock of granitic composition; whether silica is needed depends on the amount of quartzose silt admixed with clay minerals in the original argillites. In the mineral composition of these augengneisses,

[13] Several authors have recently emphasized the importance of solid diffusion in chemical migrations during metamorphism. Though it has been demonstrated that such a process is possible, the writer's observations lead him to believe that solid diffusion will, if at all, usually take place only on a very minor scale (as between adjacent minerals—albitization of basic plagioclase where invaded by newly formed hornblende, observed by the writer in metanorites), but can hardly be held responsible for major chemical transfers during regional metamorphism and granitization; the action of solutions is often shown by textural features connected with the intergranular film, and that water was present is indicated by the occurrence of hydrous silicates, as well as by general considerations (water content of sediments, especially of argillites, phyllites, micaschists, etc.).

there is no indication of an introduction of sodium at this stage. However, there is a possibility that some sodium was introduced already at an earlier stage of metamorphism, namely in those mesozonal paragneisses, which contain a considerable amount of oligoclase. Since these rocks are fine-grained and lack porphyroblastic feldspars, there is no textural indication of an introduction of sodium, and it could be ascertained only by chemical analyses. Even if there has been some addition of sodium, these fine-grained and even-textured paragneisses could not possibly be described as "granitized."

Unless an equal amount of material has been removed in solution from the country rock—of which there is no indication in the rock successions in question—the *volume* must have been somewhat increased by granitization. Such a small increase in volume would not be easy to prove even in a rock granitized under static conditions, and is much more difficult to ascertain in these rocks which have been metamorphosed and granitized during mechanical deformation. The winding shape of bands of paragneiss material between the feldspar porphyroblasts might be considered as an indication of increase of volume in the areas replaced by porphyroblasts. That the augengneisses are *synkinematic* is shown by the elongation and alignment the porphyroblasts have acquired during their crystalloblastic growth, and by cataclastic deformation the porphyroblasts have suffered at some places where movement outlasted growth, whereas in other places all cataclastic structures have been healed by crystallization.

(2) *Mesozonal migmatic banded gneisses.*—Banded gneisses occur as intercalations within the belts of massive augengneiss, but have their main development on the inner side of these belts. Here they form *zones several miles wide* on both sides of the Nanga Parbat massif. In the southeast of the area where the augengneiss belt disappears, the zone of banded gneisses grades into the area of non-granitized argillite-derived schists. The banded gneisses consist of alternating layers of dark-colored biotite-schist and paragneiss, and of white or light-colored gneiss of the appearance of an acidic orthogneiss (pl. 3, fig. 2; pl. 4, figs. 2-4).

The *biotite-schist and paragneiss bands* are, in composition and texture, identical with the rocks occurring in the non-granitized areas of metamorphic Salkhala argillites. Kyanite frequently occurs in these bands (pl. 5, fig. 2; pl. 6, fig. 1). The *light-colored bands* (pl. 7, fig. 2; pl. 8) are for the most part less fine-grained, and are leucocratic and rich in feldspar, especially potash-feldspar (frequently microcline). Muscovite is generally present in addition to potash-feldspar, oligoclase (usually sodic), and quartz. Biotite occurs in much smaller amounts than in the dark-colored bands, and is often altogether absent. Almandite and tourmaline are common accessories both in the light- and dark-colored bands. Tourmaline is also widely developed in the non-granitized areas of metamorphic argillites, and therefore can hardly be considered as a "pneumatolytic" mineral, but may have been derived from the boron originally contained in the marine argillites.

Apart from white bands with little or no biotite, there are also *bands intermediate in composition* and color between the dark-colored schists and the white bands. All gradations and all kinds of interbanding occur (pl. 4, figs. 2 and 3). The *thickness of individual bands* of dark-colored schist and light-colored gneiss is widely variable, both ranging from a few millimeters to many feet. The *proportion* of both kinds of rock in the banded gneisses is likewise extremely variable. The series begins with metamorphic argillites containing only a few thin white bands usually accompanied by individual feldspar porphyroblasts (pl. 3, fig. 2), and it ends with white acidic gneisses in which only subordinate thin layers of schist have been preserved (pl. 8). Banded gneisses showing different proportions are intercalated in numerous repetitions.

There occur *all passages between banded gneisses, augengneisses, and feldspar-porphyroblast-schists* (pl. 3, fig. 2; pl. 4, fig. 4; pl. 5, fig. 2; pl. 6, fig. 1), and subordinate layers of typical augengneisses may be intercalated in the main zone of banded gneisses. Across the strike, light-colored bands frequently grade into schists with potash-feldspar porphyroblasts (pl. 4, fig. 4). Along the strike, light-colored bands frequently die out within the schist, or are continued by layers rich in potash-feldspar porphyroblasts (pl. 4, figs. 2 and 4). Looking at such layers from the other end, their porphyroblasts may be said to coalesce finally into white bands. Also within the light-colored bands, the feldspar frequently shows a *porphyroblastic development*, often discernible in the field

PLATE 1

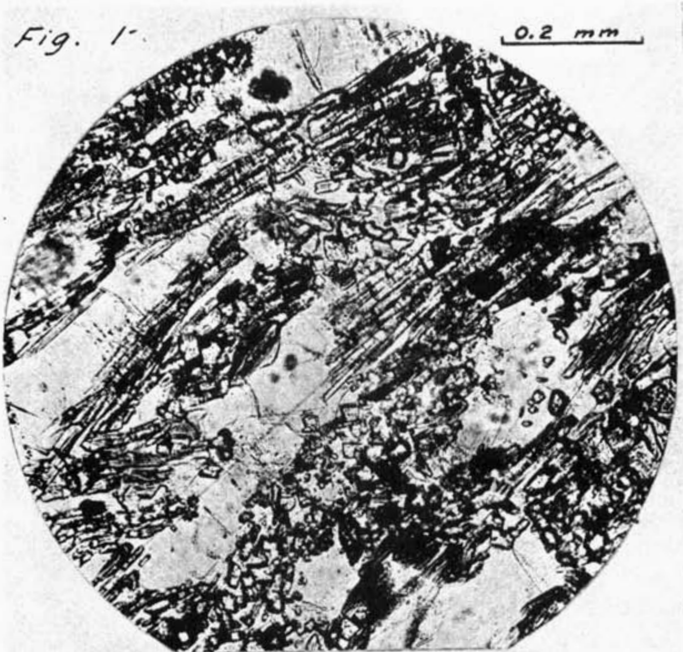
Fig. 1. Epizonally metamorphic argillite: phyllite. Sericite and quartz. Plain polarized light. North of Kalapani, southeastern part of Nanga Parbat area (specimen no. 16.8.24).

Fig. 2. Mesozonally metamorphic argillite: micaschist. Muscovite, biotite, quartz, almandite. Plain polarized light. Rampur ridge, eastern part of Nanga Parbat area (no. 19.6.25).

PLATE 2

Fig. 1. Mesozonally metamorphic argillite: biotite-paragneiss. Biotite, muscovite (less), oligoclase, quartz, almandite. Plain polarized light. Bunar Nullah, northwestern part of Nanga Parbat area (no. 24.5).

Fig. 2. "Low" - mesozonally metamorphosed argillite: kyanite - biotite-paragneiss. Kyanite, biotite, oligoclase, potash-feldspar, quartz, almandite, traces of muscovite. Plain polarized light. Ridge south of Rama Valley, eastern part of Nanga Parbat area (no. 12.6.2).



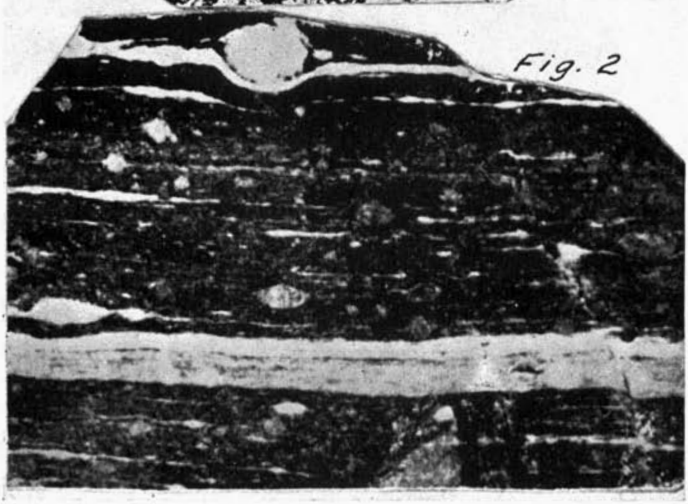


PLATE 3

Fig. 1. Katazonally metamorphic argillite: sillimanite-biotite-paragneiss. Quartz-less variety, portion rich in sillimanite. Sillimanite, biotite, orthoclase (sanidine), oligoclase (less). Plain polarized light. North face of Nanga Parbat above Ganalo Glacier, central part of Nanga Parbat gneiss massif (no. 24.7.8).

Fig. 2. Beginning of granitization in metamorphic argillite: mesozonal banded feldspar-porphyroblast-gneiss. Rock surface, nat. size. South of Mangdoyan north of Astor, eastern part of Nanga Parbat gneiss massif (no. 13.5.8a).

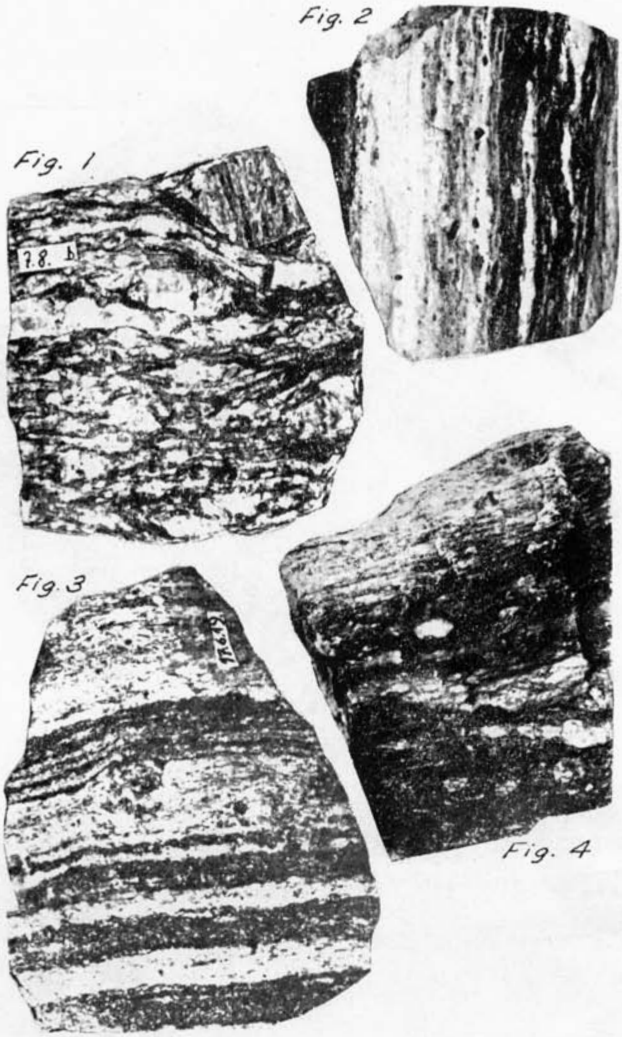


PLATE 4

Granitization in mesozonal metamorphic argillites.

Fig. 1. Augengneiss. Potash-feldspar porphyroblasts replacing fine-grained dark colored kyanite-biotite-paragneiss. Abt. ½ nat. size. South of Astor, eastern part of Nanga Parbat gneiss massif (no. 7.8b).

Fig. 2. Banded gneiss (tourmaline-bearing). Completely granitized white quartz-feldspar bands, non-replaced dark-colored biotite-paragneiss bands, and intermediate bands. Thinning of white replacement bands. Small potash-feldspar porphyroblasts. About ½ nat. size. North of Astor, eastern part of Nanga Parbat gneiss massif (no. 9.6.5).

Fig. 3. Banded gneiss. Gradations between light-colored replacement layers and dark-colored biotite-paragneiss bands. In replacement layers some porphyroblastic texture megascopically visible. About ½ nat. size. Chugam area south of Astor, eastern part of Nanga Parbat massif (no. 17.6.19).

Fig. 4. Banded gneiss showing passage to augengneiss. Potash-feldspar porphyroblasts in part coalesce into replacement bands. About ½ nat. size. Gishat Nullah, southeastern part of Nanga Parbat area (no. 17.8.8a).

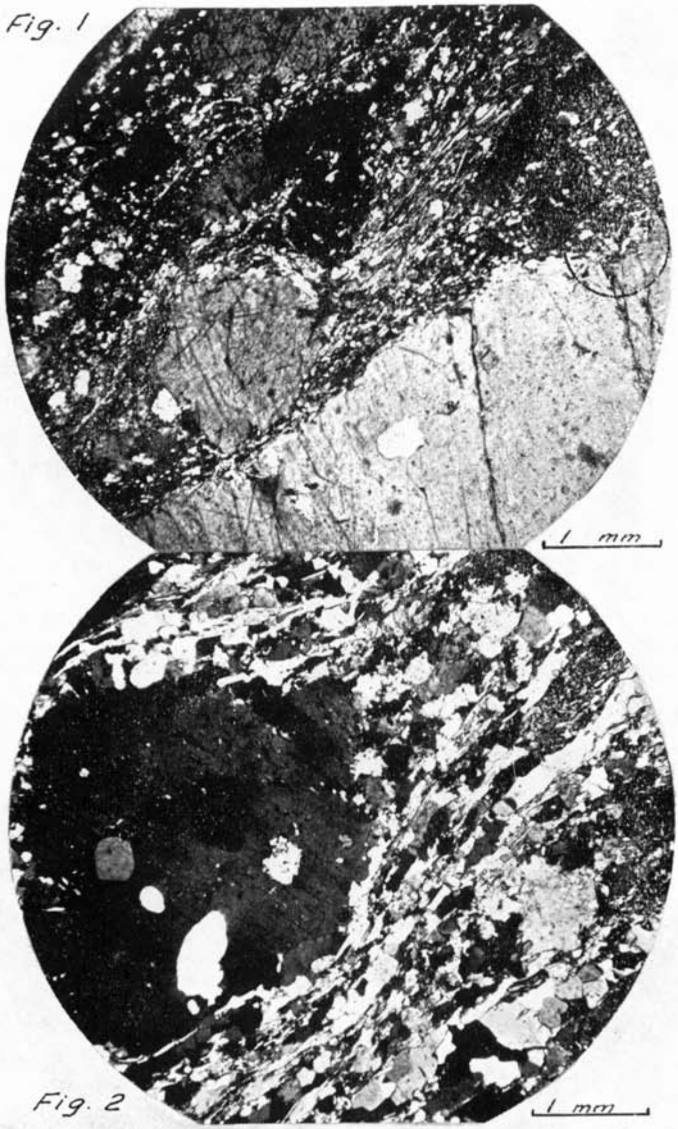


PLATE 5

Fig. 1. Mesozonal augengneiss. Microperthite porphyroblasts metasomatically replacing kyanite-biotite-paragneiss. Crossed nicols. Circle on right: area shown in plate 7, fig. 1. South of Astor, eastern part of Nanga Parbat gneiss massif (no. 10.6. augengn.-valley).

Fig. 2. Potash-feldspar porphyroblast replacing kyanite- and biotite-bearing groundmass in incompletely replaced light-colored banded gneiss of mesozone. Crossed nicols. Ridge north of Rama Valley north of Astor, eastern part of Nanga Parbat gneiss massif (no. 11.6.9).

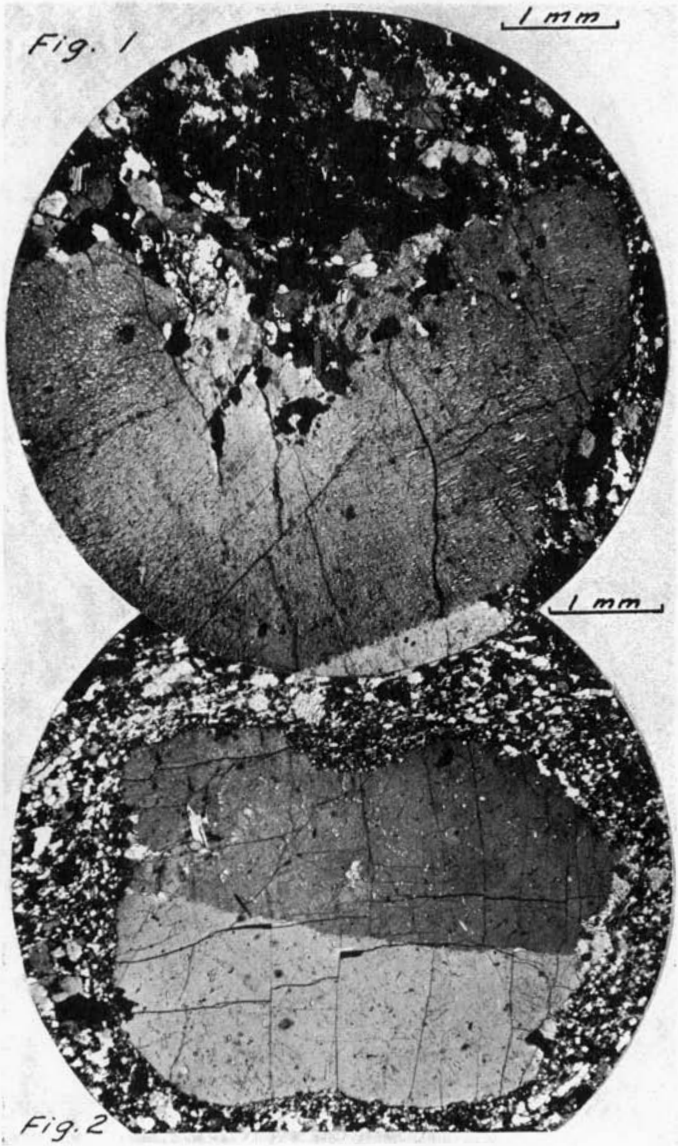


PLATE 6

Fig. 1. Part of large microperthite porphyroblast replacing fine-grained kyanite-biotite-paragneiss in porphyroblastic and partly lenticular banded gneiss of mesozone. Crossed nicols. South of Astor, eastern part of Nanga Parbat gneiss massif (no. 7.8.g).

Fig. 2. Microperthite porphyroblast replacing very fine-grained biotite-paragneiss. Mesozonal augengneiss comparatively poor in augen (passage to feldspar-porphyroblast-schist). Idioblastic tendency of porphyroblast. Crossed nicols. South of Astor, eastern part of Nanga Parbat gneiss massif (no. 7.8.d).

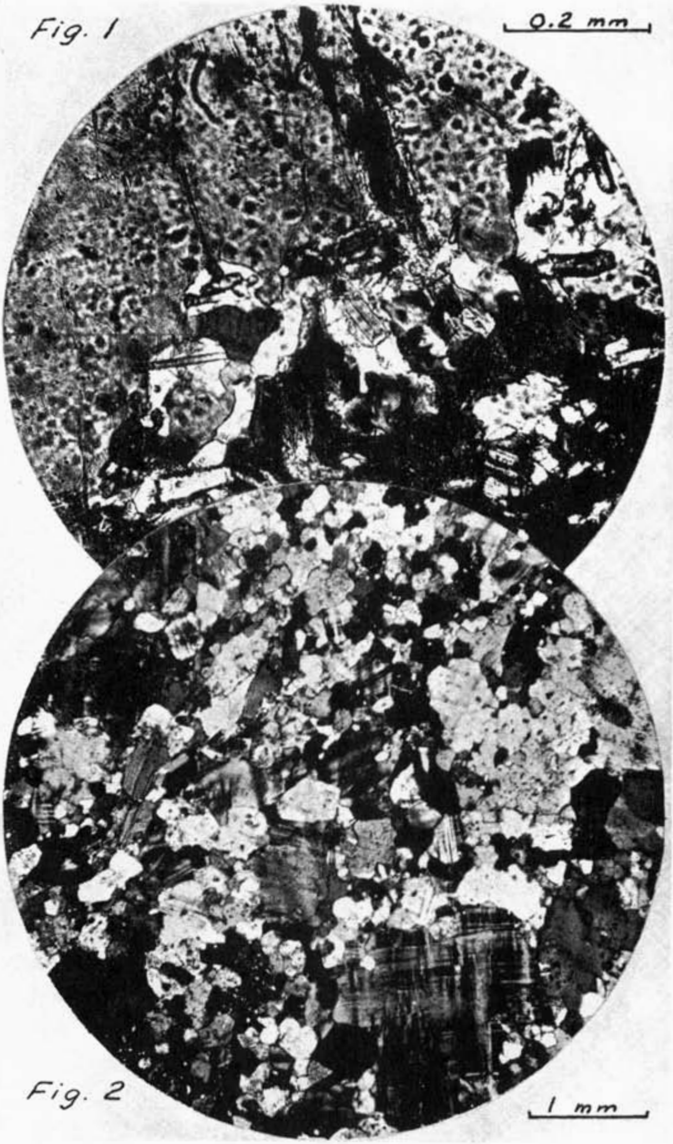
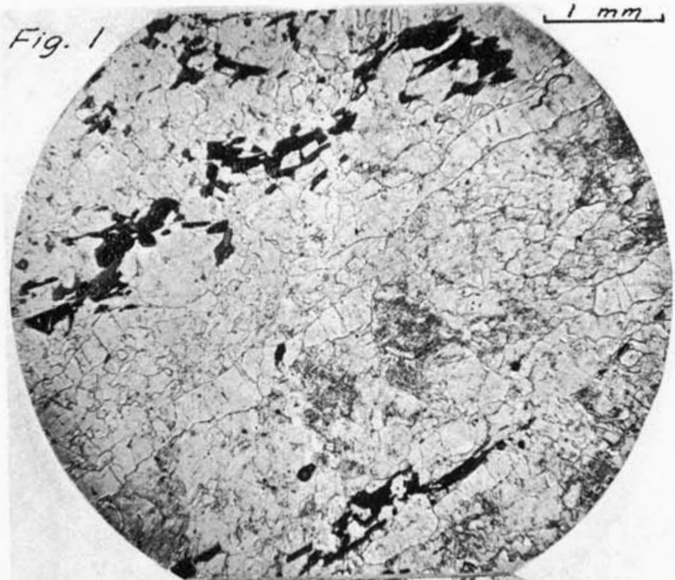


PLATE 7

Fig. 1. Border of microperthite porphyroblast replacing kyanite- and biotite-rich paragneiss matrix in mesozonal augengneiss. Detailed view of area marked by circle in pl. 5, fig. 1. Crossed nicols. South of Astor (no. 10.6. augengn.-valley).

Fig. 2. Completely granitized white band in mesozonal banded gneiss. Porphyroblastic microcline, quartz, oligoclase, very little muscovite. Granoblastic. Crossed nicols. Dichil Finger, eastern border zone of Nanga Parbat gneiss massif north of Astor (no. 3.7.37).



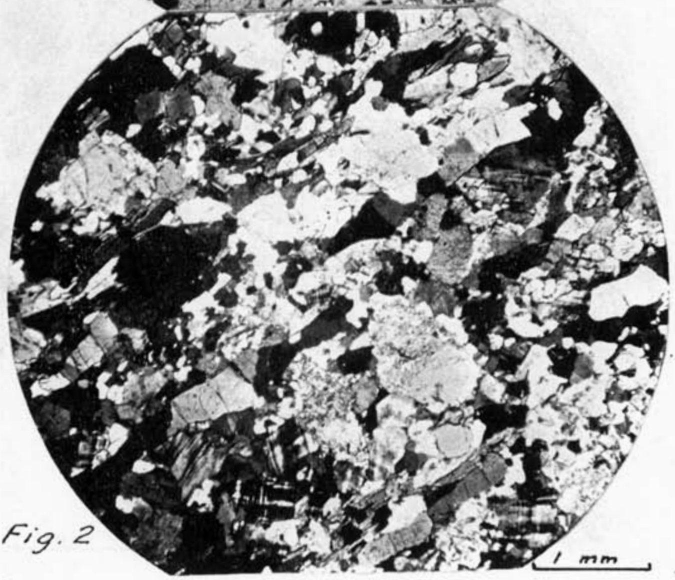


PLATE 8

Figs. 1 and 2. Mesozonal banded gneiss. Portion showing high degree of replacement. Relict bands of biotite-paragneiss being invaded and absorbed. Olive-green biotite, microcline, quartz, oligoclase, in biotitic bands accessory epidote with orthite. Figs 1 and 2 show the same area, in plain polarized light and under crossed nicols. East ridge of P. 16,000′ west of Rattu valley, eastern part of Nanga Parbat gneiss massif (no. 21.6.8).

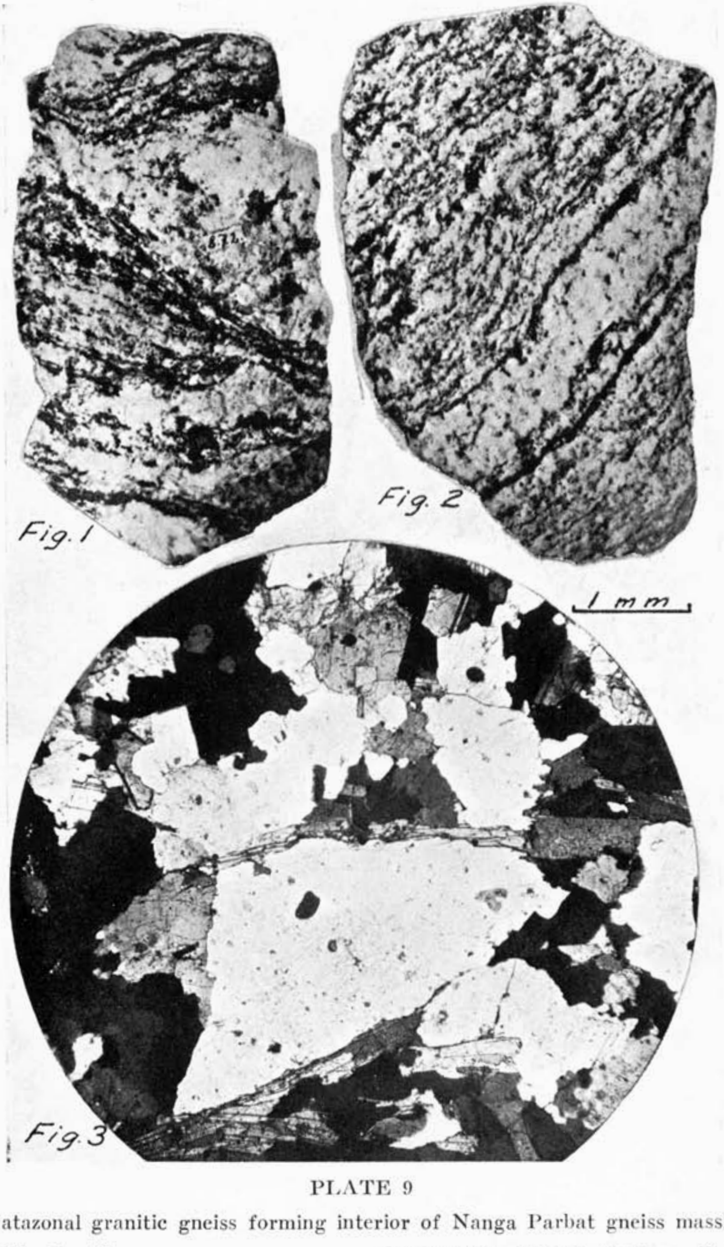


PLATE 9

Katazonal granitic gneiss forming interior of Nanga Parbat gneiss massif.

Fig. 1. Very coarse-grained biotite-flasergneiss. Uneven texture. Porphyroblastic growth of feldspar. About $\frac{1}{2}$ nat. size. Buldar ridge northeast of Panga Parbat (no. 8.7.2).

Fig. 2. Banded biotite-flasergneiss. About $\frac{2}{3}$ nat. size. North face of Nanga Parbat (no. 18.7.2c).

Fig. 3. Coarse-grained biotite-flasergneiss. Orthoclase, oligoclase, quartz, biotite, some almandite. Final stage of granitization. Granoblastic texture. Crossed nicols. North face of Nanga Parbat (no. 18.7.1).

(pl. 4, fig. 3), and more generally visible under the microscope (pl. 5, fig. 2; pl. 6, fig. 1; pl. 7, fig. 2). At the borders of light-colored bands, the feldspars can often be seen invading the schist (in a manner comparable to that observed in the augengneisses), and thereby to "dilute" the schist so that its biotite becomes more thinly spread (pl. 8). Occasionally, more coarsely recrystallized biotite becomes concentrated in extremely thin layers (almost films) along sharp borders of white bands.

The similarity in composition of the dark-colored bands and the metamorphic Salkhala argillites of non-granitized areas, and the great variability in the thickness and proportion of dark- and light-colored bands compared with the slightly variable composition of the non-granitized schists, prove that *the banding cannot be due to metamorphic differentiation* of the argillite-derived country rock, but has been brought about by an introduction of material. The transformation of the metamorphic argillites into banded gneisses has been accompanied by a *definite change in the chemical composition of the rock*, and at the end of this series of transformations occur those banded gneisses in which unaltered schist material has become very subordinate. Metamorphic differentiation has taken place only very locally and on a very minor scale, producing those thin biotite-enriched bands which have been occasionally segregated at the borders of white bands.[14] Judging from the mineral composition of the rocks, the introduced material in the banded gneisses is alkali (predominantly potash), and usually also silica. The possibility that some sodium had been introduced already at an earlier stage of metamorphism, has been discussed above (cf. chapter 1).

Which was the *mechanism of introduction* of this material? Banded gneisses of the type described are commonly considered as the result of "*lit-par-lit injection.*" There are considerable

[14] In the Nanga Parbat area, metamorphic differentiation appears to be responsible for the formation of certain banded amphibolites derived from some of the norites and related rocks. In this case, lighter and darker bands are composed of exactly the same mineral varieties, and only their relative amounts differ in different bands. There is no indication that the bulk composition of the rock has been changed. The individual bands are uniformly thin, and the proportion of lighter and darker bands does not vary greatly. I consider these features as characteristic of banding originated by metamorphic differentiation, in contrast to banding due to introduction of foreign material.

divergencies in the use of the term "injection." In this country, it is usually applied in its restricted and proper sense, e. g. for an intrusion of magma or magmatic solutions or similar mobile materials into some space created by a breaking-open or splitting-up of the solid country rock, emplacement being a mechanical process. In Europe, the term "injection" has been widely used in a looser and more comprehensive sense, comprising processes of infiltration, soaking and replacement, as well as true injection, but excluding intrusion of larger continuous bodies of magma. The term has, for instance been used in this sense by V. M. Goldschmidt in his classical study of the "injection metamorphism in the Stavanger region" in Norway (Goldschmidt, 1921), in which part of the "injection gneisses" described are shown to owe their origin to infiltration and replacement by solutions (assumed to be derived from a magmatic source). More recently, C. E. Wegmann has, in an important contribution to the analysis of migmatites (Wegmann, 1935), suggested the restriction of the term "injection" to its proper meaning. The definition given by him agrees with the usage customary in this country; with the modification that intrusion of larger continuous bodies of magma is excluded from the term "injection." In a preliminary report on the Nanga Parbat area written immediately after my return from the field (Misch, 1935), I have used the term "injection" in the broad sense which used to be customary in Europe, but I would now apply it only in its restricted sense. In that paper, I applied the term "injection gneisses" to various types of gneisses of metamorphic-migmatic origin, including the porphyroblast-gneisses and the massive augengneisses, although their replacement origin was pointed out in that paper. The banded gneisses I then considered as the result of true lit-par-lit injection by acidic-granitic material derived from a magmatic source. Subsequent petrographic study of the rock suites from Nanga Parbat has, however, convinced me that most, and probably all, of the material composing the light-colored layers in the banded gneisses owes its origin to *infiltration and replacement of the country rock, rather than to true injection.*

The following features which have been described above, are in favor of such an interpretation by "*lit-par-lit replacement*": the presence of numerous bands intermediate in composition between the original schists and the white gneiss bands, and the occurrence of gradational contacts—features which suggest different degrees of replacement of the original schist; the intimate association of banded gneiss with, and its grading into, undoubted replacement rocks, e.g. augengneiss and feldspar-porphyroblast-schist; and the porphyroblastic texture widely developed in light-colored gneiss bands, which links such bands still more closely to layers of porphyroblasts that often prolong the light-colored bands. There is also a general argument against an origin of the banded gneisses by true lit-par-lit injection. It is difficult to visualize that schists while being subjected to considerable pressure and to action of intense orogenic stress, could have been split open by magma or magmatic solutions throughout areas measuring tens of miles along the strike and a number of miles across it. On the other hand, infiltration along layers of active shearing could have taken place under such mechanical conditions. This argument seems to be even more convincing where banded gneisses do not dip steeply, but have gentle dips, as in certain parts of the Nanga Parbat area,[15] and as in some other regions I have since had an opportunity to study. If in such cases banding were the result of true injection, each injected layer of liquid would have had to uplift and carry the tremendous load of thick overlying rock masses.

The suggestion that lit-par-lit replacement has played the main part in the formation of the banded gneisses, does not preclude the possibility that there may have been some subordinate contribution of true injection material which became activated as a final result of the migmatic metamorphism. However, no structural features indicative of mass movement of granitic material were observed. On the contrary, the tectonic structure of the banded gneisses—as well as of all other migmatitic gneisses in the Nanga Parbat area—is of a type characteristic of deformation of solid rocks during orogenic metamorphism, and is identical with the type of structure seen in the non-migmatitic schist areas. This general structural aspect of the problem will be discussed below.

Lit-par-lit replacement, as against true lit-par-lit injection, implies an emphasis on *chemical processes*, as against a purely mechanical process. The introduced material infiltrated and

[15] Parts of the southeast and northeast; cf. figs. 17 and 21 in (Misch, 1935).

permeated the country rock, and reacted with it. To make banded gneiss, the *loci of infiltration and reaction* must have been thin layers in some way distinguished from neighboring layers. One might think of primary differences in the mineral composition of the schists, certain layers being more pervious or having a greater chemical affinity to the granitizing solutions.[16] However, the areas of non-migmatitic metamorphosed argillites do not show primary differences of this kind, and in the southeastern part of the Nanga Parbat region these areas of metamorphosed argillites grade into banded gneisses and augengneisses along the strike (cf. fig. 1). The explanation must then lie in some other condition that existed during the time of migmatitic metamorphism. It appears that this was the condition of active shearing movements along the foliation planes of the country rock which took place during the regional metamorphism and the migmatitization connected with it. The introduced material, consisting of solutions,[17] infiltrated the country rock *along layers distinguished as particularly active shear zones* during the differential movements which were taking place throughout the country rock. The loci of layers of feldspar porphyroblasts were determined in the same manner as those of the white bands eventually formed.

There arises the question why the result of migmatitic infiltration should have been predominantly massive augengneiss in certain marginal belts, and chiefly banded gneiss in neighboring zones. These two rock varieties cannot be considered merely as less and more advanced stages in the process of migmatitic transformation; for the banded gneisses contain layers of non-migmatitic schist whereas such are, apart from subordinate intercalations, absent in the augengneiss belts. Incipient banded gneisses are represented by schists with layers of porphyroblasts, but not by uniformly feldspathized rocks. The difference between the belts of augengneiss and the zones of banded gneiss are probably due to a more highly volatile character of the infiltrating solutions in the marginal belts predominantly transformed into augengneiss, the solutions thus being able to permeate the country rock in a more uni-

[16] The latter argument applies wherein the Nanga Parbat massif calcareous or basic intercalations have, in contrast to the enclosing metamorphic argillites, escaped granitization.

[17] As to the solutional character of the introduced material, I refer to the discussion with respect to augengneiss.

form manner. Such a disposition seems plausible at a time when the "migmatite front" (to use a term coined by Wegmann, 1935) had advanced to its maximum extent and remained more or less stationary for a period.

It has been stated above that the banded gneisses were formed when orogenic stress was active, which means under conditions of differential movement within the rock masses concerned. Foliated structure within the light-colored as well as the schist bands, general sharp parallelism of banding and foliation and of other elements such as stringers of porphyroblasts, and presence of some cataclastic mineral structures not healed, prove the *synkinematic* (synorogenic) character of the banded gneisses.

(*b*) *Migmatitic gneissose granites in the interior of the Nanga Parbat massif*

Though the augengneisses and banded gneisses in the outer zones of the Nanga Parbat gneiss massif have been shown to owe their origin to metasomatic granitization, it is still feasible that these zones, though having a width of miles and occupying an area of more than 100 square miles, could be nothing but extensive contact zones granitized along the margins of a synorogenic intrusive body occupying many hundreds of square miles in the interior of the massif. We cannot therefore speak of "metasomatic granitization of batholithic dimensions," unless it also can be demonstrated that the granitic gneiss in the interior of the massif owes its origin to granitization, and not to igneous intrusion.

The rocks forming the interior of the gneiss massif have been outlined in chapter (II), and the non-granitized metamorphic sediments occurring here briefly described in chapter (III). Whereas in the banded gneisses and augengneisses of the marginal areas large quantities of argillite-derived fine-grained paragneiss and biotite-schist material are preserved and are easily distinguished from the metasomatically replaced portions of the rocks, this distinction becomes less well marked in the interior of the massif, and typical fine-grained paragneiss material is preserved only in quantitatively very subordinate intercalations. Otherwise, the argillite-derived rocks gradually become more coarsely recrystallized and feldspar - enriched, as the interior of the massif is approached. The result is mainly flasergneisses of moderately fine to medium grain and of medium shades. Their sedimentary derivation is only shown by their grading into typical fine-grained paragneisses (cf. Misch, 1935). Toward the interior of the massif, these rocks pass into the *coarse-grained biotite-flasergneiss of granitic appearance and composition* (*or gneissose granite*) which here predominates (cf. pl. 9, figs. 1 and 2).

This gneiss is composed of orthoclase, oligoclase (varying from a little over 10 to somewhat over 20 percent anorthite), quartz, biotite, and frequently also muscovite as an equal and contemporaneous constituent. Almandite is a common accessory. Although the rock is rather uniform regionally, it is anything but homogeneous in detail, and its *texture is usually very uneven.* The gneiss is generally coarse-grained though the grain size ranges from more medium-grained to extremely coarse-grained varieties, often within very short distances. Some of the gneisses are even-granular, but an uneven grain, due to the development of large feldspars (especially orthoclase), is more common and occurs always in extremely coarse-grained varieties. The biotite content of the gneiss varies greatly, even within short distances. In single rock specimens the biotite is usually unevenly distributed, being concentrated in bands, stringers and patches (pl. 9, figs. 1 and 2). The almandite may also be enriched in certain bands. The gneisses possess crystallization-foliation (free of cataclastic mineral deformation), but the degree of their schistosity is variable and never becomes extreme. Most of the rocks show flaser structure which may pass into augen structure (cf. pl. 9, fig. 1). More typical augengneisses are subordinate. They differ in their texture from those of the marginal parts of the Nanga Parbat massif, their groundmass being more coarse-grained and their orthoclase porphyroblasts usually being less well-formed crystals. In some augengneisses, the biotite-rich groundmass exceeds the porphyroblasts. Banded structures are quite common in the gneisses, and are often found in light-colored varieties (pl. 9, fig. 2). Acidic bands are occasionally bordered by thin layers enriched in biotite (local metamorphic differentiation). The banded and augen structures described recall those typical of the marginal zones of the massif, with coarse-grained crystallization of the entire rock and more general feldspathization superimposed. Banded and augengneisses of the type of the marginal zones, characterized by the preservation of fine-grained and non-granitized schist material, are very rare in the interior of the massif; they occur only occasionally in association with the subordinate intercalations of fine-grained paragneiss found in the granitic gneiss. The microscopic texture of the granitic gneiss is crystalloblastic and usually shows the same uneven character which is megascopically visible; it can be described as granoblastic, partly with porphyroblastic tendencies. Many gneisses show a tendency to approach an almost igneous-appearing microscopic texture which many petrographers would classify as "pan-allotriomorphic granular," but the crystalloblastic character and the uneven nature of the fabric remain preserved. An advanced case is shown in plate 9, figure 3.

The character of the gneiss is strongly suggestive of a metamorphic - migmatitic rather than an intrusive origin. Among the features described, the following are especially indicative of such an origin: variability of composition, grain size and other textural features; uneven nature of texture; frequent presence of porphyroblastic features; crystalloblastic texture (though this latter does not constitute conclusive evidence since it could be superimposed). Of particular interest are the augen and banded structures described above; they suggest that these rocks had originally gone through the stage of mesozonal incomplete granitization which is now displayed in the marginal zones of the massif, and had subsequently, with further spreading of granitization, become more coarsely recrystallized and more thoroughly feldspathized, so that the paragneiss material still preserved in the mesozonal banded and augengneisses lost its distinctive character, although the banded and augen structure is preserved as a relic. In general, the biotite-rich stringers and patches in the unevenly textured granitic gneisses are rather suggestive of recrystallized relics of biotite-paragneiss. Exceptionally, sillimanite was found to occur in granitic gneiss, indicating participation of argillite-derived material.

Apart from the character of the gneiss itself, there are *other and even stronger arguments in favor of an origin by metasomatic granitization.* The first is the presence of *intercalations of undoubted metamorphic sediments* and some basic rocks which, though quantitatively subordinate, occur throughout the wide area of granitic gneiss. *These intercalations are structurally conformable with the granitic gneiss.* Most of them are thin, and many of them can be followed for long distances. It is difficult to visualize that mechanical intrusion of magma could have spared such septa and, even if it did, could have left them structurally intact without thoroughly disturbing and disrupting them. If, on the other hand, these intercalations are interpreted as relict bands which have escaped metasomatic granitization, their presence and their mode of occurrence are readily understood.

Many of these intercalations consist of katazonal fine-grained paragneiss whose contacts with the granitic gneiss are usually gradational. Some layers within such paragneiss intercalations may be partially granitized, having been transformed into feldspar-porphyroblast-schist and porphyroblastic augen-gneiss. Often paragneiss and granitic gneiss alternate in parallel layers. All these features indicate granitic replacement rather than intrusion.

Of particular interest are the *thin marble layers* with their associated lime-silicate-granulite bands, which form regular conformable intercalations in the gneiss often traceable for long distances. None of the marble layers observed exceed a thickness of 100 feet and most of them are much thinner. No intrusion could have left these bands structurally intact; moreover, it is difficult to comprehend how the marbles could have escaped fusion if temperature had been high enough to keep silicate compounds in a molten state at the existing pressure for a considerable time in large magmatic masses surrounding the marbles. There is more marble relative to metamorphic argillite in the interior of the gneiss massif than in the area of non-granitized Salkhala phyllite and of schist and paragneiss derived from it. The absolute proportion of marble, on the other hand, is nearly of the same order in the interior of the massif as in the non-granitized areas. This proves that most of the argillites which greatly predominate in the original sedimentary section, became transformed into granitic gneiss whereas most, if not all, of the marbles escaped granitization—a truly metasomatic process, and one of differential character. In this connection, it should be recalled that the non-granitized Salkhala argillites grade into the mesozonal migmatitic gneisses and then into the central granitic gneisses not only across but also along the strike. Generalizing, it may be said that the marbles extend from an area of phyllites through one of schists into one of mesozonally migmatitized schists and continue right into the granitic gneisses. The relict nature of the thin marble bands is particularly striking where they occur as conformable intercalations in coarse-grained granitic gneiss without being accompanied by any paragneiss, all of the argillite originally enclosing the marble having been transformed into granitic gneiss. Several cases of this kind have been observed (cf. fig. 2), although the majority of the marbles are still associated with some paragneiss which varies in thickness from a few inches to several hundred feet.

The reason why calcareous bands have escaped granitization is obvious. Whereas it does not take much introduced material to transform an argillite into a rock of granitic composition, the substance of a marble would have to be almost entirely replaced to achieve the same result. Apart from the different chemical affinity of marble and argillite to granite, their relative permeability to alkali-rich solutions is probably an additional factor. Whereas slate is undoubtedly less pervious to aqueous solutions than limestone, their metamorphic equivalents must be supposed to act differently under conditions of granitization. Now metamorphic argillite would be more pervious, consisting of a granular fabric of silicate minerals (and being, in case of synkinematic granitization, in a state of active differential movement); and, having an excess of aluminum, metamorphic argillite would have a strong tendency to precipitate alkali from permeating solutions rich in alkali. On the other hand, under the existing high pressure preventing escape of its CO_2, marble would be less pervious to those solutions; at the same time, it would have no tendency of precipitating alkali from solutions rich in it. Also, under pressure, marble might plastically flow and hence be less permeable than schist traversed by active shearing planes.

Basic rocks—chiefly katazonal amphibolites—intercalated in the interior of the gneiss massif, and originally forming bands in the Salkhala argillites, have likewise essentially escaped granitization. Generally, granitization of basic rocks is not uncommon, and has been described by a number of authors. In areas where I have observed this process, there is usually the following series of transformation: original basic rock (amphibolite, basic hornfels, etc.; sometimes with lime-silicate rock at the beginning of the series, other times with metabasalt, greenstone, metanorite, metagabbro, etc.); gabbroid rock; dioritic rock; quartz-dioritic and, not always, granodioritic rock (for instance: Indus Valley north of Nanga Parbat; Fish Lake, Palmer Lake and other places in Okanogan country, Eastern Washington; Northern Sierra Nevada; all these examples are postkinematic). In this series, the alkali added apart from silica etc. is sodium—in contrast to the predominant potash metasomatism in the Nanga Parbat gneiss massif—and as far as potash has at all been introduced, it has come in only near the end of the transformation. There can be no doubt that there are two chief chemical types of granitization, i.e. *predominant potash metasomatism*, and *predominant sodium metasomatism.* Both are apt to act on metamorphosed argillites, but the latter seems to be more easily able to attack basic rocks apart from argillites. The only effect of granitization of the potash metasomatism type on basic intercalations which I have observed in the Nanga Parbat gneiss massif, consists of biotitization of hornblende which has often marginally transformed hornblende-rich intercalations into almost pure schistose biotite rock.

Summing up from a structural angle, the relationships described can be said to be characterized by *structural continuity.* This applies if we proceed from the non-granitized zones through the incompletely granitized to the more fully granitized areas, and is also valid in a stratigraphic sense, insofar as individual stratigraphic units run through these three zones. Structural continuity also exists within the granitized areas between granitized rocks and non-granitized relics (regularity of mutual intercalation, conformable and gradational relations, harmonic and equal participation in the same individual folds).

The structural features listed confirm the replacement origin of the granitic gneiss, and illustrate the absence of intrusive structures. The same is demonstrated by the *type of tectonic deformation.* It is identical in the zone of phyllites, the area of non-granitized schists, the mesozonal migmatitic belts, and the katazonal region of granitic gneiss with its relict intercalations. The structure in all these zones is characterized by well-defined trends which remain constant for long distances and are clearly related to the regional structure of the northwest Himalayas, and by a regular character of the major folds. There is no sign of that structural turmoil and turbulent folding and flowage which one would expect if magma had broken into the sediments under high pressure and intense stress, and which is known to occur even in solid rocks deformed under conditions of extreme plasticity. There are, of course, as in all areas of crystalline schists, numerous intensely compressed minor folds of "mobile" character throughout the zones described, but they are, in the interior of the gneiss massif as well as in the phyllite area, all regularly aligned parallel to the prevailing local trend. Most of these minor folds are isoclinal, and their narrow arcs can often be seen to become obliterated by the foliation which is parallel to their limbs.

The type of structure described is that *typical of solid rocks deformed under conditions of regional metamorphism.* The fact that this type of deformation characterizes the granitic gneiss area as well as the phyllite zone, is the last argument I wish to offer in favor of a replacement origin of the granitic gneiss or gneissose granite, and therewith of the whole of the vast gneiss massif of Nanga Parbat.

A short discussion on the *chemical composition of the "granitizing solutions"* is necessary. The *predominant solvent* was undoubtedly water (presence of hydrous silicates in all metamorphic zones; water content of the original rocks). As to the substances carried, *material present in a solution* and *material precipitated from a solution* must be distinguished. Only the latter is *directly recorded* in the rocks. If, for instance, an aluminum-excess rock has precipitated potash from a solution and augengneiss has thus been formed, the permeating solution may have contained other substances not recorded by precipitation. However, certain *indirect conclusions* are possible. The solution from which potash was precipitated must have had an excess of alkali over aluminum, if it did at all contain more than traces of aluminum. Moreover, the solution must have contained more potash than sodium. Otherwise, the porphyroblasts of microperthite in the augengneiss would be accompanied by such of sodic plagioclase. On the other hand, the solution may have contained a large or a smaller amount of silica. Silica would not be necessarily precipitated by a rock already possessing an excess of free silica. When kyanite and mica of the original schist were replaced by feldspar porphyroblasts, some silica was consumed. Some silica was supplied by quartz of the original schist, which together with mica and kyanite was replaced by feldspar. Where the amount of quartz was not sufficient, additional silica was precipitated from the solution. Whether a small amount of silica has been added in the augengneisses, could be ascertained only by a series of chemical analyses. In the white replacement layers in the banded gneisses silica has undoubtedly been introduced in addition to alkali. For these layers are rich both in feldspar and quartz, and poor in mica, and thus more silicic than the original mica-rich schist.

Another indirect conclusion as to the composition of the granitizing solutions can be drawn from the plagioclase in the granitized rocks. The mesozonal augengneisses and banded gneisses usually contain sodic oligoclase, like the non-granitized metamorphic argillites. If the granitizing solutions had contained any considerable amounts of calcium, the plagioclase in the mesozonal granitized rocks would have become a calcic oligoclase, and possibly epidote minerals would have formed. Even the katazonal migmatitic granitic gneisses usually contain a sodic oligoclase. If the granitizing solutions had contained even a moderate amount of calcium, the plagioclase would of necessity have become more calcic under katazonal temperatures. If the solutions had had any considerable content in iron (and magnesium), the amount of biotite could not show a marked decrease in the granitized rocks compared to non-granitized schists, and the intercalated marbles would probably have been affected.

This leads to another criterion. Where granitizing solutions have acted *differentially* on rocks of different composition, further indirect conclusions as to the chemical nature of the solutions are possible. If in the same section rock A has been granitized and rock B has escaped granitization, the permeating solutions were obviously rich in those substances required to transform rock A into one of granitic composition, but deficient in those elements primarily needed to convert rock B into one of granitic composition. Solutions which were "granitizing" with regard to rock A, do not deserve this name with regard to rock B. Differential granitization therefore makes it possible to eliminate a number of substances as essential constituents of the solution.

An example is granitization of basic rocks, such as amphibolites, in comparison to that of metamorphic argillites. It has been shown above that basic rocks are mainly apt to be granitized if the permeating solutions have a high sodium content—apart from the large amount of silica which is of course required. It seems that predominant potash metasomatism does not generally affect basic rocks very much (apart from biotitization), although potash is frequently introduced at a late stage of the transformation of basic rocks, whereas the earlier stages are usually characterized by definite sodium predominance.

(IV) RELATIONS BETWEEN PROGRESSIVE REGIONAL METAMORPHISM AND SYNKINEMATIC GRANITIZATION

From a general point of view, one of the most striking features displayed in the Nanga Parbat area is the *intimate relationship and the simultaneous increase of progressive regional metamorphism and of synkinematic granitization.* Throughout the area, granitization does not begin before regional metamorphism in the argillites has reached the stage of the low-mesozonal kyanite-schist facies, and it invariably does start in this zone. It here remains rather incomplete—considerable quantities of non-replaced argillite material being preserved—and its type is that represented by banded and augengneisses. As regional metamorphism approaches the stage of the katazonal sillimanite-paragneiss and lime-silicate-granulite facies, granitization becomes more complete—argillite relics being subordinate—and develops the type represented by granitic gneiss or gneissose granite.

The succession of zones and mineral facies of regional metamorphism can in this area be shown to be exclusively *a function of increasing temperature* (cf. chapter II a). Since the degrees of regional metamorphism and of synkinematic granitization are definitely linked, this latter must likewise increase with temperature, and the same must apply to the introduction of material which is implied in metasomatic granitization. In other words, *rise of temperature and increasing infiltration by granitizing solutions go parallel.*

The rise of temperature during metamorphism and granitization in this, and many other areas, is *unrelated to geologic depth,* i. e. is not a normal geothermal rise.[18] There must, therefore, have been a *differential supply of heat* resulting in an upward curving of geisotherms—at very steep angles in this area in which the metamorphic isograds are approxi-

[18] Normal geothermal rise of temperature can, of course, also reach temperatures sufficiently high for high-grade regional metamorphism, but *only at great depths* of the crust. Here, migmatitization may take place without introduction of additional heat.

mately vertical. There are no known processes which could have created a sufficiently large amount of heat *in situ.* Heat must therefore have been *introduced* from below. Was this done by conduction or convection? The former seems unlikely in itself, considering the high angle of upward curvature of geisotherms; the systematic relation between rise of geisotherms and introduction of granitizing solutions confirms that *convection was the means of introduction of heat.* In other words, *the granitizing solutions carried both chemical substances and heat.* It is in these terms that we have to conceive the "rising of the migmatite front," to use again the phrase coined by Wegmann (1935). If no regional introduction of material were involved in granitization, it could be argued that progressive metamorphism, being itself controlled by rise of temperature, is the cause and granitization merely a consequence. However, material has undoubtedly been added "from somewhere below"; to demonstrate this fact, the chemical changes involved in the making of the migmatitic gneisses have been stressed, and it has been pointed out why these gneisses cannot have formed by processes of metamorphic differentiation of the country rock, i. e. by local transfer as against regional introduction of material.

If the analysis given above is correct, *high-grade regional metamorphism is not only necessarily linked with synkinematic granitization, but depends on it for a supply of additional heat, with the exception of great depths of the crust.* In the Nanga Parbat area, regional metamorphism without granitization did not go beyond the phyllitic (and perhaps uppermost mesozonal) stage. All zones of higher-grade metamorphism are in their spatial distribution so clearly related to the central rise of the migmatite front, that a genetic control is obvious. This applies not only to the high-grade metamorphic sediments preserved within the granitized area, but also to the zone of higher-grade rocks outside the margin of the granitized area. The rocks involved are the typically mesozonal (higher mesozone and beginning of lower mesozone) mica-schists and paragneisses which form a belt between the low-grade rocks and the mesozonal augengneisses and banded gneisses. To this belt, additional heat must have been supplied from the neighboring granitized area, and the means may have been conduction, since the rocks in question are outside the granitized area and heat could not therefore have been conveyed to them by the granitizing potash-rich solutions directly—unless this belt was, outside the area of actual granitization, reached by aqueous solutions carrying some sodium (cf. above). To generalize, *the front of synorogenic granitization is in time and space preceded by a zone of regional metamorphism of a higher grade than that achieved by orogenic metamorphism not linked with granitization.* It is obvious that *the further increase* (from low-mesozonal to katazonal) *of the metamorphic grade in the sediments preserved within the granitized area of Nanga Parbat, illustrates the control by successively increased introduction of heat, conveyed by successively more active and hotter granitizing solutions.* In the granitized rocks themselves, this progression is shown quantitatively by increasing completeness of granitization, and qualitatively by the passage to a more truly granitic type of gneiss in the interior of the massif.

The *Nanga Parbat example* of progressive metamorphism and synkinematic granitization is *typical* and, it may be said, *normal*; its only distinguishing features are unusually clear, deep and continuous exposures. The rocks and processes described are repeated all over the world. Provided the principles suggested are correct at Nanga Parbat, they will also apply elsewhere, subject, of course, to certain modifications due to varying physical and chemical conditions (cf. below). However, one qualification must be made. Synorogenic granitization and metamorphism at Nanga Parbat took place in a *geosynclinal environment.* Therefore, areas which can be properly compared are other geosynclines. Metamorphism and granitization are characteristic of orogenic transformation in the interior portions of first-order geosynclines, and they here often rise to *comparatively high levels. At extreme depths* of the crust, processes will be modified. Such cases are believed to be displayed in some Archeozoic regions, and perhaps in the roots of some exceptionally deeply eroded later geosynclinal chains. Numerous areas of Archeozoic crystalline schists do not, however, differ from such of later ages, and can frequently be shown to represent old geosynclines exposed at levels comparable to those visible in later geosynclines.

The statement made above concerning the Nanga Parbat area, that *orogenic metamorphism without granitization* is apt to achieve only low-grade mineral facies ("pure dynamometamorphism") is borne out by numerous migmatite-free regions of phyllites and basal-epizonal and upper-mesozonal micaschists, and of other low-grade schists (greenschists, etc.). Among regions I have studied, a good example is the geosyncline of West Yunnan at the southwestern border of China (cf. Misch, 1945 a and b). Here Paleozoic and Mesozoic sediments and volcanics have been dynamically metamorphosed during Mesozoic orogeny into epizonal and occasionally uppermost-mesozonal crystalline schists within an area of many thousands of square miles, without having achieved a higher grade of metamorphism anywhere. No synkinematic migmatites of Mesozoic age have been observed anywhere in this region.

The *beginning of granitization* of the potash-metasomatism type was at Nanga Parbat found to be within the lower mesozone, and granitization was shown to be preceded in space and in time by mesozonal regional metamorphism resulting from an introduction of additional heat from the area of granitization (possibly connected with some finely divided sodium-precipitation from solutions). These relations seem to be general; for in all areas of synorogenic migmatites known to me, metamorphism has achieved a mesozonal mineral facies before granitization has set in. However, there appears to be some variation as to the part of the mesozone, and therewith as to the temperature, at which granitization begins. There seem to be cases where migmatic processes start already higher within the mesozone. A good example seems to be that of the Stavanger region in Norway described by V. M. Goldschmidt (1921). Here synorogenic granitization is predominantly of the sodium - metasomatism type. It is entirely of this type in the zone of beginning replacement (albite- and oligoclase-porphyroblast-schists); this zone is upper-mesozonal, judging from the minerals described in the schists. It appears, from the rock succession recorded by Goldschmidt, that here additional potash-metasomatism came in only at a more advanced stage of progressive granitization.[19] There seem to be other

[19] The more typically granitic rocks in this region are described as intrusive, but the continuous nature of the series is so pronounced, and the general character of the rock succession so strikingly resembles that described in the present paper, that an identical genetic interpretation suggests itself.

cases which also suggest that synorogenic granitization of the sodium-metasomatism type is apt to begin at a temperature lower than that at which potash-metasomatism was found to commence at Nanga Parbat.

Finally, I wish to emphasize *the general validity of the statement that high-grade regional metamorphism and synorogenic granitization are invariably and necessarily linked.* They are expressions of one and the same process. There is not any region known to me either from study of the literature or from personal field work, where katazonal or lower-mesozonal crystalline schists occur without metamorphic migmatites or granitic rocks.

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(*To be Continued*)