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### PROGRESSIVE METAMORPHISM AND GRANITIZATION OF THE MAJOR PARAGNEISS, NORTHWEST ADIRONDACK MOUNTAINS, NEW YORK

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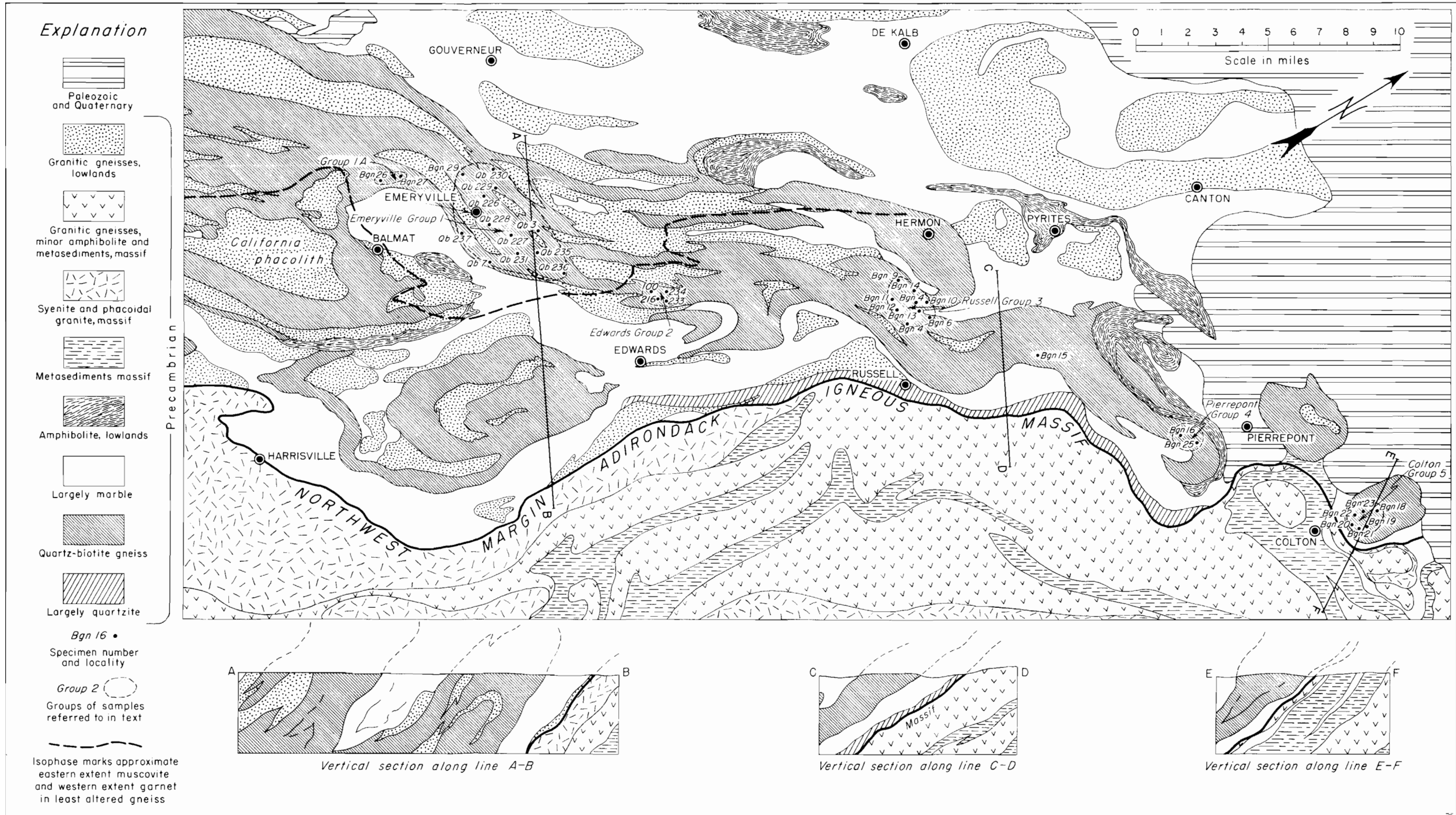
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#### Notes



GENERAL GEOLOGIC MAP AND VERTICAL SECTIONS OF THE NORTHWEST ADIRONDACK MOUNTAINS SHOWING THE FORM AND DISTRIBUTION OF THE GNEISS AND LOCATIONS OF THE SAMPLES STUDIED IN DETAIL



# PROGRESSIVE METAMORPHISM AND GRANITIZATION OF THE MAJOR PARAGNEISS, NORTHWEST ADIRONDACK MOUNTAINS, NEW YORK

## PART I: TOTAL ROCK

BY A. E. J. ENGEL AND CELESTE G. ENGEL

WITH ANALYSES OF TRACE ELEMENTS BY  
A. A. CHODOS AND ELISABETH GODIJN

### ABSTRACT

The progressive metamorphism and partial granitization of a belt of quartz-mica-feldspar-garnet paragneiss is considered in detail. This paragneiss is traced and sampled along a belt 35 miles long that extends across the Grenville Lowlands into the central massif of the Adirondack Mountains, New York. Geologic thermometers indicate temperatures of metamorphism of about 500° C. at the southwest end of the belt and about 600° C. near the perimeter of the massif.

Minimum temperatures of metamorphism in the gneiss are determined largely from solid solutions of magnesite in dolomite, FeS in sphalerite, paragonite in muscovite, and TiO<sub>2</sub> in magnetite. Maximum temperatures of metamorphism are inferred principally from the absence of wollastonite in closely associated siliceous marbles. The gradient in *T* is checked by the  $\delta O^{18}$  in quartz and coexisting magnetite in the gneiss.

The composition of the paragneiss and its constituent minerals is determined from 75 new chemical analyses, 50 partial chemical analyses, 400 analyses of trace elements, and modal analyses of approximately 400 rocks.

At the lower-temperature end of the belt the least altered gneiss is a quartz-biotite-oligoclase-muscovite gneiss averaging (weight per cent) 70.25 SiO<sub>2</sub>, 0.67 TiO<sub>2</sub>, 14.14 Al<sub>2</sub>O<sub>3</sub>, 0.55 Fe<sub>2</sub>O<sub>3</sub>, 3.83 FeO, 2.20 CaO, 1.76 MgO, 0.05 MnO, 3.43 Na<sub>2</sub>O, 2.40 K<sub>2</sub>O, and (in ppm) B, 10; Ba, 600; Co, 8; Cr, 35; Cu, 16; Ga, 11; Ni, 15; Pb, 12; Sc, 12; Sr, 300; V, 56; Y, 50; Yb, 3; Zr, 170. This is inferred to approximate the bulk composition of the parent sedimentary rock.

With increasing temperature of metamorphism of the least altered gneiss, the mineral composition changes as follows: muscovite disappears, garnet appears, plagioclase increases in abundance, and average An content and quartz decrease. Complementary changes in chemical composition include an increase in Al, Fe<sup>++</sup>, total Fe, Mg, Ca, Cr, Ga, Ni, and V. Amounts of K, Si, Fe<sup>+++</sup>, H<sub>2</sub>O, and Ba decrease.

This "degranitization" or "basification" of the gneiss appears to be a metamorphic process that begins at about 550° C. and is well defined at 600° C. The mobilized Si, K, and H<sub>2</sub>O appear to be partly liberated and partly trapped as a venitic migmatite.

Granitization of parts of the gneiss is accompanied by an increase in K feldspar and Ab content of plagioclase and by a decrease in biotite, plagioclase, and quartz. Chemical changes in major elements include an increase in K and a decrease in Ti, Fe<sup>+++</sup>, Fe<sup>++</sup>, Mg, Ca, H<sub>2</sub>O, and in Na-K ratio. Changes in the amounts of minor elements in granitized parts of the gneiss include increases in Ba and Pb and a decrease in Co, Cr, Ni, Sc, Sr, Ti, V, and Y. All granitizing substances in the gneiss in areas of lower-temperature metamorphism appear to be introduced either laterally or from below. Those in areas of highest-temperature metamorphism are partly introduced, partly derived locally from the gneiss. The implied basic front evolved during granitization of the gneiss may have been large, for the introduced granitizing substances replace one-third of the sedimentary rock throughout a zone over ½ mile thick, 75 miles wide, and more than 40 miles long.

Calculations of the chemical composition of the more even-textured gneiss, from modal analyses and mineral analyses, show about the same deviation from the actual chemical analyses as exists in the 34 analyses of G-1 and W-1 as reported by Fairbairn *et al.* (1951).

CONTENTS

TEXT	Page
Introduction	1371
Acknowledgments	1371
Scope	1371
Geological setting	1372
Choice and location of rock samples	1376
Preparation of samples	1377
Methods of rock analysis	1377
Introduction	1377
Chemical analyses, major and minor elements	1377
Spectrographic analyses, trace elements	1378
Modal analyses	1379
Calculations of chemical composition from modal analyses	1380
Temperature of metamorphism	1382
Introduction	1382
Geologic evidence of a temperature gradient	1383
Absolute temperatures	1383
Data from magnesian calcites	1383
Thermometric significance of titaniferous magnetite	1384
Temperatures from FeS in sphalerites	1384
Na content of muscovites in the gneiss	1386
Temperature limits implied by wollastonite-free siliceous marble	1386
Temperatures as indicated by the $O^{18}-O^{16}$ ratio in coexisting quartz and magnetite	1386
Presentation of rock analyses	1387
Rock metamorphism	1387
Assumptions	1387
General lithologic features	1388
Least altered gneiss	1393
Introduction	1393
Mineralogy and texture	1394
Chemical composition: major elements	1396
Chemical composition: minor elements	1399
Granitized gneiss	1403
Introduction	1403
Mineralogy and texture	1404
Chemical composition: major elements	1407
Chemical composition: minor elements	1410
Summary	1411
References cited	1412

ILLUSTRATIONS

Figure	Page
1. Generalized plan and vertical section indicating stratigraphy and structure of the Grenville-like rocks in the northwest Adirondack Mountains, New York	1373
2. Curves derived from data in the text indicating maximum, minimum, and probable temperatures of reconstitution of the gneiss complex between Emeryville, New York, and the massif	1374
3. Generalized curves showing interrelationships in the mineralogical, chemical, and textural evolution of the gneiss complex due to granitization	1389
4. Generalized curves indicating changes in mineral and major-element composition of 11 specimens of least altered gneiss	1394

Figure	Page
studied in detail as traced from Emeryville to Colton, New York	1394
5. Generalized curves indicating changes in mineral and major-element composition of least altered gneiss as traced from Emeryville to Colton, based upon 73 specimens	1398
6. Variations in mineral and chemical composition of specimens in Group 1 resulting from increasing degrees of permeation and replacement of the least altered gneiss by granite-forming substances, especially potassium	1405
7. Graphs showing compositional trends in the gneiss complex at Emeryville and Colton resulting from pervasive and complete granitization of the gneiss	1407

Plate	Facing page
1. Generalized geologic map and vertical sections of the northwest Adirondack Mountains showing the form and distribution of the gneiss and locations of the samples studied in detail	1369
2. Textures of gneiss	1388
3. Migmatite and inequigranular granitized gneiss	1389
4. Detailed geologic map of the Emeryville area showing interrelationships of the rock types within the gneiss and locations of specimens in Group 1	1414

TABLES

Table	Page
1. Duplicate chemical analyses of masked specimens of G-1 and W-1 made with analyses of gneiss and indicative of precision of analytical methods	1378
2. Precision and accuracy of alkali analyses using flame photometer	1378
3. Per cent standard deviations of replicate spectrographic analyses of trace elements	1379
4. Modal analyses of two rocks	1380
5. Data comparing precision of direct chemical analyses and use of modal analyses and physical and chemical properties of minerals in determining chemical compositions of rocks	1381
6. Delta $O^{18}-O^{16}$ ratios for coexisting quartz and magnetite in gneiss at Emeryville and Colton and in hornblende granite gneiss in the adjoining part of the massif	1387
7. Chemical and modal analyses of selected specimens of least altered gneiss between Emeryville and Colton, New York	1390
8. Average chemical and mineralogical compositions, and range in compositions of least altered gneiss in the gneiss complex between Emeryville and Colton, New York	1396
9. Chemical and modal analyses of specimens of granitized gneiss from the paragneiss complex between Emeryville and Colton, New York	1400

Table	Page	Table	Page
10. Average trace-element composition of least altered gneiss and granitic gneiss compared with that of the Littleton formation.....	1402	13. Average chemical and mineral compositions of least altered and more granitic gneiss from the Emeryville and Colton areas, New York.....	1408
11. Analyses of trace elements in the Littleton formation.....	1403	14. Average composition of least altered gneiss at Emeryville and compositions of granites in the massif that shred and are contaminated by the gneiss.....	1410
12. Modal and trace-element analyses of four typical specimens of uniformly granitized gneiss from the Colton area, New York.....	1406		

## INTRODUCTION

Many, probably most, of the changes in mineral species that occurred during metamorphism of rocks now exposed have been recorded. Unfortunately the exact or even approximate conditions of temperature, pressure, and composition ( $T$ ,  $P$ ,  $X$ ) that pertain as rocks evolve from one metamorphic grade to another remain unknown.

Equally vague is the knowledge of the changes in the physical and chemical properties of the constituent minerals or of the entire rock, as these are a function of changing  $T$ ,  $P$ , or  $X$ . With an exception or two, conclusions regarding the extent of isochemical metamorphism and those intriguing threshold conditions at which elements or ichors become mobile are based upon extrapolations from laboratory studies or essentially intuitive inferences from field relationships.

This study attempts to resolve a few more of the uncertainties and to pinpoint some major problems of progressive metamorphism of a graywackelike sedimentary rock under conditions approaching and equivalent to the highest rank of regional metamorphism and incipient magmatism.

## ACKNOWLEDGMENTS

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## SCOPE

This study complements an earlier paper (Engel and Engel, 1953b). The 1953 paper summarized our initial studies of the regional

relationships of an Adirondack paragneiss, its general geological features, and its possible origin. Most of the data were field and petrographic observations complemented by a limited number of chemical analyses of the gneiss complex in the Emeryville-Edwards areas (see southwest part of Pl. 1, this paper).

Regional study of the gneiss complex indicates that two contrasting types of metamorphic rocks are widespread. One type is reconstituted<sup>1</sup> paragneiss with no obvious important additions of substances; although loss or segregation of substances occurs in the reconstituted gneiss in areas of highest-temperature metamorphism, this rock is referred to in this paper as least altered gneiss. The reconstitution of the gneiss offers an example of progressive metamorphism of an initially monotonous belt of clastic sedimentary rock which is like many graywackes in composition. The physical and chemical changes in the least altered gneiss and each of its constituent minerals throughout a 35-mile belt from Emeryville to Colton, New York, are described and related to a gradient in temperature and to other factors in the metamorphism.

The second type of metamorphic rock is granitized<sup>2</sup> paragneiss. The granitized parts are interspersed with least altered gneiss throughout the 35-mile belt. Granitization and reconstitution of the paragneiss appear to have proceeded together. In many places the least altered gneiss grades into granitic gneiss; many other contacts between least altered gneiss and granitic gneiss, however, are sharp and well defined. At the sites of transition it is possible to trace the intermediate physical and chemical changes in the gneiss and in constit-

<sup>1</sup> Reconstituted designates what seem to be essentially equilibrium reactions of the metasedimentary constituents.

<sup>2</sup> "Granitized" is used in a purely descriptive sense to indicate the development of granitelike characteristics in the paragneiss, whether by mechanical injection or permeation replacement of metasedimentary rock by magma, fluids from magma, ions, ichors, and so on.

uent minerals induced by the granite-forming processes. Although the origin of the granitizing substances may be very different at Emeryville from that at Colton, many changes induced in the gneiss seem quite similar, despite the differences in temperature between the two places.

Temperatures of metamorphism at Emeryville and for at least 25 miles to the southwest seem to have reached 500°C., and possibly 525°C.; those at Colton 35 miles northeast seem to have reached or slightly exceeded 600°C. These absolute temperatures are based upon (1) solid-solution studies in associated carbonates, ilmenomagnetites, muscovites, and sphalerites; (2) the absence of wollastonite in siliceous marbles; and (3) geologic features and distribution of obviously igneous granite to ambiguous and metamorphic types. The gradient in temperature is substantiated by analyses of the O<sup>18</sup>-(<sup>16</sup>) ratio in magnetite and quartz in the gneiss.

Inasmuch as certain of the geothermometers employed are pressure sensitive, the depth and rock pressure during metamorphism are estimated, largely from reconstructions of the rock cover and structure extant during metamorphism. These calculations suggest the exposed rocks were metamorphosed at depths of about 8–10 km, with confining pressures of 2500–3000 atmospheres. Probably, however, the pressures were nonhydrostatic, and conceivably the metamorphism occurred at depths as great as 15 km. A more precise piezometer obviously is needed.

Sampling in the southwestern third of the 35-mile segment of gneiss—that metamorphosed under the coolest conditions—was facilitated by the authors' maps (A. E. J. Engel, *in press*), prepared at a scale of 800 feet to the inch. Information on which sampling of the other two-thirds of the segment could be based was obtained from quadrangle maps by Buddington and Leonard (*in press*) and from our own field studies. The field data together with petrographic information from about 1000 thin sections were used as a basis for choosing about 35 representative rock specimens for the following detailed studies:

(1) Chemical analyses for major, minor, and trace elements in least altered and incipiently granitized gneiss collected at intervals along the 35-mile segment.

(2) Modes of the rocks.

(3) Analytical studies of the major constituent minerals of the 35 rocks. These minerals are biotite, garnet, plagioclase, K feldspar, muscovite, and quartz. Principal analytical

work was focused upon the biotites, K feldspar, and garnet. In the biotites and garnets, chemical compositions, optical data, color, specific gravity, and crystal-structure data have been related to geological occurrence. Two K feldspars have been completely analyzed. Seven other K feldspars and seven muscovites were separated and analyzed for K, Na, and trace elements. Plagioclase compositions were determined by oil-immersion methods.

Partial wet-chemical and spectrographic analyses and optical studies have been made on approximately 200 additional rocks and minerals.

The analytical data on minerals and rocks are related to the inferred geological conditions during metamorphism. Part 1 discusses the metamorphism of the total rock. Part 2, which will follow within several months, is the study of the physical and chemical properties of the component minerals in the gneiss, as these are related to the metamorphism.

#### GEOLOGICAL SETTING

The geology of the northwest Adirondacks has been studied and discussed in recent years by numerous workers, especially Brown (1936), Brown and Engel (1956), Buddington (1939; 1948; 1952; 1957), Buddington and Leonard (*in press*), A. E. J. Engel (1949; 1956), and A. E. J. Engel and C. G. Engel (1953a; 1953b).

Most pertinent to the ensuing discussion is the paper dealing principally with some of the geological features and the origin of the major paragneiss (Engel and Engel, 1953b). The interested reader is referred to it for a more detailed discussion of the general geology and field relationships.

The paragneiss is the major clastic unit in the Grenville-like<sup>3</sup> metasedimentary sequence of the northwest Adirondack Mountains. The 35-mile segment of paragneiss from which the samples have been obtained extends from Emeryville (northwest of Balmat, New York) northeast to the vicinity of Colton, New York. Plate 1 and Figure 1 are generalized geological maps of this region. This segment of gneiss trends obliquely across the dominantly metasedimentary Grenville Lowlands to the perimeter of the Adirondack igneous massif (Buddington, 1939, p. 5–6; Engel and Engel,

<sup>3</sup> The term Grenville series is deeply entrenched in the literature of the northwest Adirondack Mountains, although the term implies a stratigraphic correlation that is by no means established (A. E. J. Engel, 1956).



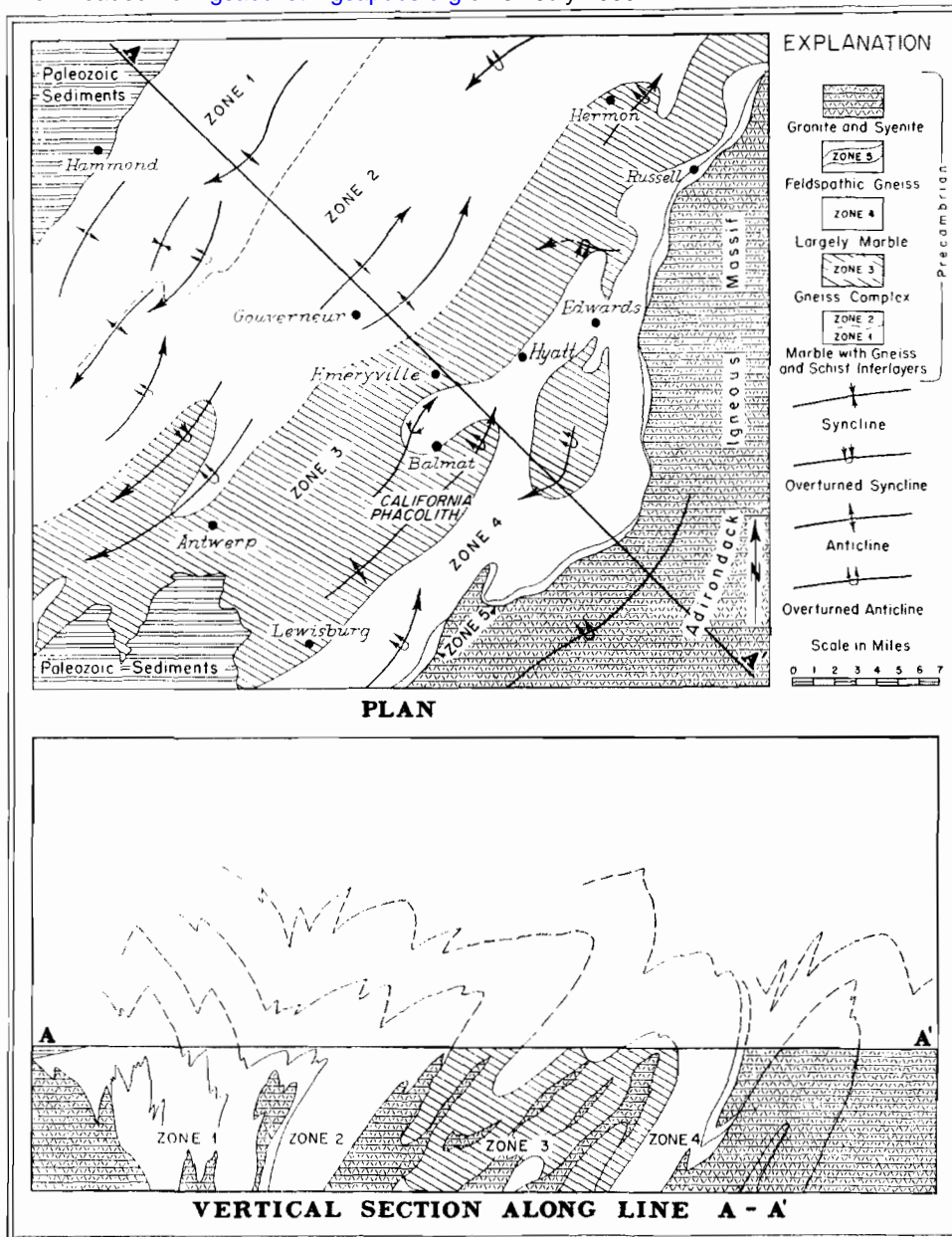


FIGURE 1.—GENERALIZED PLAN AND VERTICAL SECTION INDICATING STRATIGRAPHY AND STRUCTURE OF THE GRENVILLE-LIKE ROCKS IN THE NORTHWEST ADIRONDACK MOUNTAINS, NEW YORK

Gross structure is interpreted to be that of the center and overturned southeast flank of a bulbous anticlinorium. At and near the surface, stratigraphic zone number 5 coincides with the outer edge of the central Adirondack Massif. Note that the dip of the overturned gneiss complex (zone 3) is essentially parallel with the northwest dip of the edge of the massif.

1953b, Fig. 1 and p. 1052). Samples of gneiss discussed in this paper come from a single, originally monotonous formation at least 2000 feet thick.

The gneiss is structurally complex. Its general relationships to other units in the Grenville series and to the Adirondack igneous massif are shown in Plate 1 and Figure 1. The broad

form of the Grenville series throughout the Grenville Lowlands is interpreted to be anticlinorial. The southeastern flank of the anticlinorium is overturned between Emeryville

and Colton on the order of 5 miles. As noted earlier, however, depth of metamorphism may have been appreciably greater. At Colton the depth of metamorphism is even more

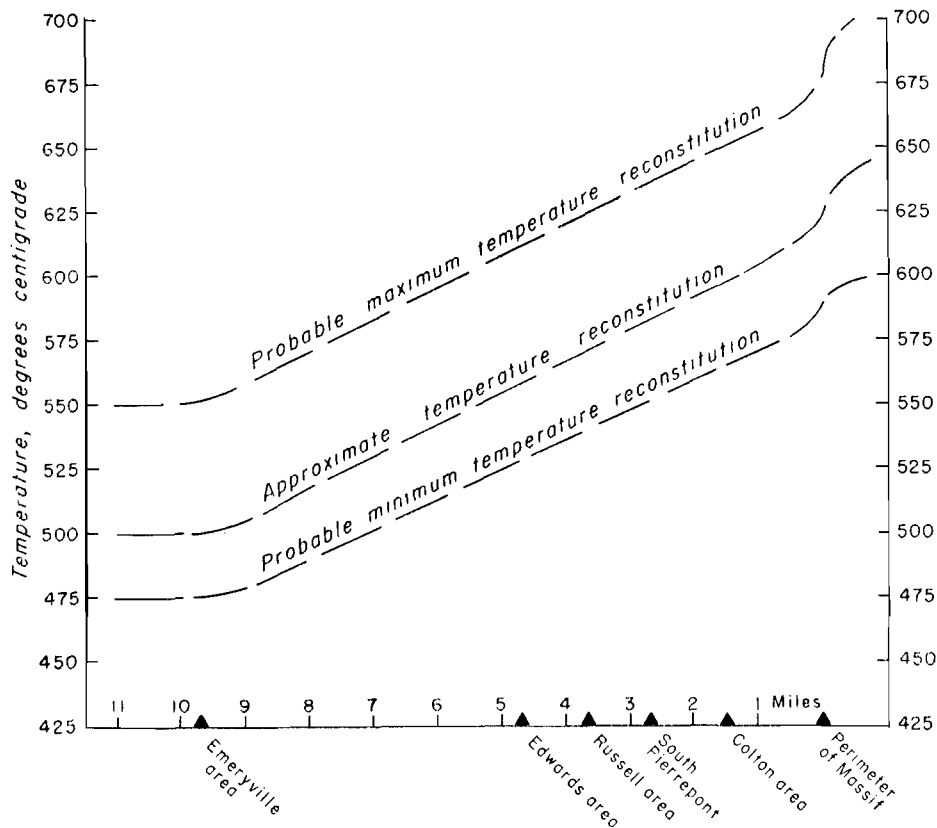


FIGURE 2.—CURVES DERIVED FROM DATA IN THE TEXT INDICATING MAXIMUM, MINIMUM, AND PROBABLE TEMPERATURES OF RECONSTITUTION OF THE GNEISS COMPLEX BETWEEN EMERYVILLE, NEW YORK, AND THE MASSIF

Distances of points from the massif are measured along horizontal lines drawn essentially normal to the trace of the massif. (See Pl. 1.)

and Colton and dips roughly  $45^\circ$  northwest. Consequently, the present northwest dip of the overturned gneiss throughout the area sampled is roughly parallel to the dip of the outer margin of the igneous massif. The subparallelism in dip of the gneiss and the perimeter of the massif requires emphasis for the following reasons: numerous lines of field evidence (A. E. J. Engel, in press) indicate that these geometrical relationships were approached or existed during final stages in the intermediate- to high-temperature metamorphism and granitization that produced the existing minerals in the gneiss. Under these conditions the geological reconstruction indicates a depth of metamor-

phism at Emeryville on the order of 5 miles. As noted earlier, however, depth of metamorphism may have been appreciably greater. At Colton the depth of metamorphism is even more difficult to obtain from regional geological considerations. In fact the data seem to conflict. Stratigraphic and structural reconstructions suggest depths no greater than those at Emeryville, but the lithologic features of the metasedimentary and igneous-looking rock types suggest greater depths of metamorphism along and within the massif. For example, both charnockitic syenites and anorthosites appear to have been emplaced as igneous rocks at the present level of erosion.

The trace of the perimeter of the massif (Pl. 1) seems to represent a line along which temperature was approximately the same during the metamorphism recorded in the gneiss. This



was first noted by Buddington almost two decades ago (1939, p. 326–333). Subsequently, detailed field studies and investigations of the rocks and mineral deposits in the region have confirmed this (Buddington, 1952; A. E. J. Engel, in press). If the depth of metamorphism along this line is assumed to be approximately 5 miles, the maximum temperatures of metamorphism there probably ranged between 600° and 625° C. and could not have exceeded 765° C. Temperatures increased from the perimeter of the massif inward toward the anorthositic core. Outward from the perimeter of the massif along lines essentially at right angles to its trend, temperatures decreased to a calculated 500° C. in the central part of the Grenville Lowlands (Fig. 2.) Field evidence (Engel and Engel, 1953b), studies of solid solution of TiO<sub>2</sub> in magnetites (Buddington *et al.*, 1955), and the data presented in Parts 1 and 2 of this study indicate that isograds of temperatures intermediate between those of the perimeter and those in the center of the lowlands can be drawn as sinuous arcs essentially parallel to the perimeter. It follows that the maximum positive temperature gradient is along a line drawn normal to the southeast overturned side of the gneiss, down to and through the upper surface of the Adirondack igneous massif.

These relationships of increasing temperatures of metamorphism inward from the gneiss to the massif are utilized in the presentation of all data and are explained in a succeeding section.

Two points are of considerable interest with regard to the metamorphic history of the gneiss. The concordance in dip to the northwest of the gneiss and the margin of the massif (Pl. 1) seems to have resulted from the overturning of the gneiss to the southeast (Engel and Engel, 1953b, p. 1054–1059 and Fig. 2, p. 1056). Consequently, the existing systematic metamorphic zonation may be superimposed upon and blot out a very different pattern of largely lower-temperature metamorphic features in the gneiss. At some earlier stage in the formation of the anticlinorium in the Grenville Lowlands, that part of the gneiss now overturned and dipping northwest, nearly parallel to the outward sloping edge of the massif (Fig. 1; Pl. 1), must have dipped in the opposite direction, southeastward toward the trough of a large syncline at the northwest boundary of the massif. This earlier stage in the development of folds in the lowlands seemingly was at the onset of the major epoch of granitic intrusion but subsequent to the emplacement of anorthosites,

gabbros, and syenites (Buddington, 1939; 1957, p. 304–305). During this period the rank of metamorphism in the gneiss segment under discussion is presumed to have been lower than that found at Emeryville today.

The line marking the perimeter of the massif (Pl. 1) actually is a zone of intense shearing and displacement. Extensive solid flow as well as discontinuous rupture of the rocks has occurred along the perimeter. Buddington (1939, p. 251–282, Figs. 24, 25; 1952) has presented many geological data that substantiate this conclusion. Our own detailed mapping of local areas indicates an irregular but crude increase in intensity of rock deformation and displacement (plastic tearing-apart) in the metasedimentary rocks as the perimeter of the massif is approached either from the core or from the Grenville Lowlands side. Minimum stratigraphic discontinuities in the metasedimentary sequence along the boundary between the lowlands and the massif probably exceed 1 or perhaps 2 miles. Precise estimates are difficult because of poor exposures of key units, many of which were largely obliterated by the emplacement of the younger granites. The displacements of the metasedimentary units seem to involve both vertical and horizontal motions. Most of the early rock movements (post-syenite, syn-early granite) seem to have involved rolling and thrusting of the metasedimentary rocks of the lowlands southeastward against and possibly over a synclinal perimeter of the massif. This is suggested especially by the subhorizontal axes in the large folds in the syenites and enveloping metasedimentary rocks in this area (Buddington, 1939; 1948, p. 25; A. E. J. Engel, in press). Later rock motions, during and in part after the emplacement of the bulk of the younger granites, seem to have been dominantly strike slip. Rocks of the lowlands were dragged northeast relative to those of the massif, and great cross folds were superimposed upon the pre-existing horizontally folded complex. The evidence for refolding, the relationships of cross folds to pre-existing subhorizontal folds, and the lateral displacement involved are discussed by Brown and Engel (1956) and by A. E. J. Engel (in press).

The intermediate- to high-temperature metamorphic assemblages and textures in the gneiss discussed in this paper evolved during lateral displacements and cross-folding motions in response to the same fundamental cause. These motions have not induced sharp discontinuities

in the pattern of progressive increase in degree of metamorphism as the massif is approached.

Although the curve of rising temperatures (and pressure?) from the Balmat-Emeryville area to Colton appears to have no marked discontinuities or abrupt changes in slope, an abrupt steepening of this temperature curve may occur at the massif (Fig. 2). This change of slope in the temperature curve needs further detailed study. Its clarification is dependent upon either pressure-independent thermometers or more accurate piezometers.

#### CHOICE AND LOCATION OF ROCK SAMPLES

The numbers and locations of specimens of gneiss chosen for the more detailed analytical studies are given in Plates 1 and 4. Compositions of the specimens are given in Tables 7 and 9. The primary objective in choice of these samples was to obtain, from intervals along the gneiss belt, specimens that were representative of (1) least altered gneiss, and (2) rocks transitional in composition between the least altered and the migmatitic and granitized gneiss. The specimens are divided into six groups, each representative of a given area and presumably therefore representative of only a very small range of temperature. These groups of specimens are used to evaluate specific chemical and physical changes induced in the gneiss and its component minerals by (1) local temperature gradients; (2) regional temperature gradients; and (3) pervasive lit-par-lit injection and "soaking" of the gneiss by alkali-silicate fluids. Groups of samples of each of the above types, obtained in five areas as shown in Plates 1 and 4, are designated as follows:

**EMERYVILLE GROUP 1:** Samples in the Emeryville area, at the southwest end of the 35-mile segment of gneiss. The center of the group is approximately 9.7 miles from the nearest margin of the massif (Pl. 1). The group consists of 12 specimens. Four of these, Qb 235M, Qb 230, Qb 228, and Qb 231 are from the cores of the larger areas of least altered gneiss. The remaining eight specimens are examples of gneiss in various stages of granitization and lit-par-lit injection.

**GROUP 1A (WEST BALMAT AREA):** Consists of only two specimens from the gneiss complex. They were taken just southwest of Group 1 (Pl. 1) between it and the California phacolith. Specimen Bgn 27 is from the core of a large lens of least altered gneiss, whereas Bgn 26 is taken from a zone of subtle transition between this gneiss and equigranular, uniformly feld-

spathized gneiss. The close proximity of specimens of Group 1 and 1A (Pl. 1) is reflected in the similar textures and compositions. In most respects these two groups may be considered as one and the total number of groups as five.

**EDWARDS GROUP 2 (EDWARDS AREA):** Consists of four specimens. The center of Group 2 is approximately 4.7 miles from the nearest perimeter of the massif and about 6.7 miles northeast of the center of Group 1; their opposed edges are about 3 miles apart (Pl. 1). Specimen Qb 234 of Group 2 is from the center of the largest body of least altered gneiss in the Edwards area, specimen Qb 100 is inequigranular augen gneiss, and specimens Qb 216 and Qb 233 are equigranular, uniformly feldspathized gneiss.

**RUSSELL GROUP 3 (RUSSELL AREA):** Nine specimens in Group 3 were studied, four in detail. The center of Group 3 is about 3.7 miles from the massif and about 9 miles northeast of the center of Group 2. The opposed perimeters of these groups are about 8 miles apart as measured along the strike. Specimen Bgn 14 is from the center of a lens of least altered gneiss. The other three specimens studied in detail are from a zone of transition between this gneiss and a faintly foliated, inequigranular granite gneiss.

**PIERREPONT GROUP 4 (SOUTH PIERREPONT AREA):** Two specimens of gneiss have been studied in detail. This group has its center about 11 miles northeast of the center of Russell Group 3 and about 2.7 miles from the perimeter of the massif. Opposed boundaries of these groups are 10 miles apart. No specimens of least altered gneiss suitable for mineral separations were obtained in the South Pierrepont area. Specimen Bgn 25 represents only incipiently feldspathized gneiss from a zone which merges into equigranular granitic gneiss. Specimen Bgn 16 represents rock intermediate between the incipiently feldspathized gneiss and the inequigranular granite gneiss.

Group 5, from the Colton area, consists of four specimens of least altered gneiss (Bgn 18, 19, 20, and 21) and two specimens of uniformly granitized gneiss (Bgn 22 and 23). The center of this group is about 1½ miles from the Adirondack Massif, and three specimens are within 1 mile of the massif (Pl. 1). The center of Group 5 is about 7 miles northeast of the center of Group 4 near Pierrepont. Time limitations prevented a thorough chemical study of more granitized gneiss from this area, although a limited number of analyses were made (Tables 12, 13, 14).

The irregular distribution of desired rock types and the complexity of the gneiss prevented the use of a more precise sampling pattern. Nevertheless, the spacing of groups and of samples within any group is reasonably uniform along the gneiss segment. There are no great differences in either appearance or composition between the specimens of least altered gneiss in any single group. Systematic differences in texture and composition of least altered gneiss do appear between groups. The maximum differences in composition of least altered gneiss between groups 1 and 5 are inferred to be metamorphic, the product of reconstitution, as amplified in a later section. Major differences in composition in any one group do appear in the specimens of variously granitized gneiss which are closely associated with gneissic granite in the field.

Additional difficulties encountered in sampling were induced by incipient but widespread alteration and cataclasis. More than three-fourths of the samples collected for analysis had to be abandoned after petrographic study because of the patchy retrograde alteration or mortar structure. Neither accurate modal analyses nor clean mineral separations were obtained on specimens with well-developed mortar structure. The retrograde alteration of the gneiss consists largely of chloritization of biotite and sericitization of plagioclase. Alteration varies slightly from specimen to specimen as may be seen from inspection of the modes in Tables 7 and 9. Because of the detailed mapping and collections in the southwest one-third of the gneiss segment, the specimens in Groups 1, 1A, and 2 probably are more wisely selected and representative of the desired rock type than specimens from Groups 3, 4, and 5.

Wherever rock exposures permitted, 15–20 pounds of the freshest possible rock was collected. Each sample included two slabs, at least 4 inches across, with flat or slightly rounded faces. The slabs were used as pestle and mortar to crush smaller chips. Far too many sample sites were on glaciated, flat or only gently arched exposures, well removed from the nearest road and air hammer. At these spots sample size was sacrificed rather than location. In several instances the maximum sample obtained was about 5 pounds. We are acutely conscious of limitations in size and quality of the rock and mineral samples, and the 3000 miles between our laboratory and more material.

#### PREPARATION OF SAMPLES

Commonly four representative rock slices were sawed for thin sections from about 400 to 1000 gms of each sample—depending upon lithologic uniformity and composition—and the remaining sample was then crushed to –100 mesh. This crushing was accomplished by disintegration of rock chips between anvil-like slabs of the same rock specimen. The resulting –100 fraction was quartered down, and about 15 gms was split off for wet-chemical and spectrochemical analyses. All splitting of samples was done with a high purity aluminum microsplitter. About 4 gms of the 15 gm sample was split off and ground to a powder in a mechanical agate mortar for the spectrographic work. Silk screens were used in all sizing operations.

The bulk of the –100-mesh rock sample—350–1000 gms—was used for the separation of the constituent minerals as noted in Part 2 of this study.

#### METHODS OF ROCK ANALYSIS

##### *Introduction*

Analyses of rocks include chemical analyses for major and minor elements, spectrochemical analyses for trace elements, and modal analyses of the volume per cent of mineral constituents in each rock. These analytical methods are discussed in the order named. Unless otherwise specified the chemical analyses of major elements are by Celeste Engel, and the spectrographic analyses of trace elements are by A. A. Chodos and Elisabeth Godijn. In a concluding part of this section the chemical analyses of major constituents in the rock are compared with chemical compositions as calculated from the modal analyses.

##### *Chemical Analyses, Major and Minor Elements*

Each sample of gneiss analyzed by C. G. Engel (Tables 7 and 9) was handled as an unknown prepared by A. E. J. Engel. At intervals during the 3 years in which these rock analyses were made, samples of G-1 and W-1 (Fairbairn *et al.*, 1951) were introduced as unknowns along with other specimens of gneiss. The results of these analyses, and the “adjusted” means of G-1 and W-1 (Fairbairn, 1953, p. 146–147) are in Table 1. These indicate reproducibility and any major bias relative to analyses from other laboratories. In the deter-



minations made by C. G. Engel,  $Al_2O_3$  appears to be consistently high by about 2 per cent of the amount determined and  $SiO_2$  slightly low. Otherwise no major systematic error is apparent from the analyses of G-1 and W-1.

TABLE 1.—DUPLICATE CHEMICAL ANALYSES OF MASKED SPECIMENS OF G-1 AND W-1 MADE WITH ANALYSES OF GNEISS AND INDICATIVE OF PRECISION OF ANALYTICAL METHODS

	G-1 $\bar{x}$	G-1*	Mean deviation	W-1 $\bar{x}$	W-1*	Mean deviation
$SiO_2$	72.86	72.65	.21	52.69	52.53	.16
$TiO_2$	.25	.25	.00	1.10	1.10	.00
$Al_2O_3$	13.94	14.16	.22	14.72	15.20	.48
$Fe_2O_3$	.93	.85	.08	1.50	1.39	.11
FeO	.99	.90	.09	8.71	8.63	.08
MnO	.027	.03	.003	.165	.16	.00
CaO	1.41	1.35	.06	10.96	11.02	.06
MgO	.39	.36	.03	6.63	6.55	.08
$Na_2O$	3.25	3.34	.09	2.00	2.04	.04
$K_2O$	5.42	5.48	.06	.63	.67	.04
$H_2O+$	.36	.33	.03	.56	.52	.04
$P_2O_5$	.09	.10	.01	.126	.12	.006
Total	99.92	99.80		99.80	99.93	

\* Celeste G. Engel, analyst.

Certain modifications of classical analytical methods were introduced in the rock analyses. These variations in techniques are taken from the methods of "rapid analysis" as formulated by Shapiro and Brannock (1952; 1956). The "main portion" ( $SiO_2$ ,  $R_2O_3$ , CaO, MgO) on all rocks was done by conventional gravimetric methods employing a 1.0000-gm sample. This sample was fused in  $Na_2CO_3$  in a platinum crucible. The fusion was dissolved in HCl, and silica, alumina, total iron, calcium, and magnesia were determined from this fusion. FeO was determined on a 0.5000-gm sample boiled gently in concentrated  $H_2SO_4$  and HF. Crucible and contents were dumped quickly into a dilute solution of phosphoric acid, boric acid, and sulfuric acid and titrated with a standard solution of potassium dichromate.

Total Fe and  $Fe_2O_3$ , and MnO,  $TiO_2$ , and  $P_2O_5$  were determined on a 0.4000-gm sample, dissolved in a platinum crucible on a steam bath in sulfuric and hydrofluoric acids. The resulting solution was increased to 200-ml volume with water. Aliquots were taken to

determine  $Fe_2O_3$ , MnO,  $TiO_2$ , and  $P_2O_5$  on the Beckman Model B spectrophotometer.<sup>4</sup> In most of the rock analyses another aliquot of this same solution was used to determine  $Na_2O$  and  $K_2O$  on the Beckman Model DU

TABLE 2.—PRECISION AND ACCURACY OF ALKALI ANALYSES USING FLAME PHOTOMETER

Sample	Date	Flame photometer*		Officially determined concentrations	
		$Na_2O$	$K_2O$	$Na_2O$	$K_2O$
G-1	1/21/55	3.31	5.48	3.25	5.42
	10/12/56	3.38	5.37	3.25	5.42
W-1	4/16/56	2.16	.67	2.00	.63
N.B.S. Feldspar #70	4/16/56	2.40	12.87	2.38	12.58

\* Celeste G. Engel, analyst.

photometer with a flame attachment. This method was used after its precision was established by replicate analyses of G-1, W-1, and of the National Bureau of Standards Feldspar #70. The replications are listed in Table 2. Distinction has been made, however, in the listing of rock analyses (Tables 7 and 9) between those determinations of  $K_2O$  and  $Na_2O$  by flame photometer and those by the J. Lawrence Smith method.

The plus water (+110° C.) was determined on a 1-gm sample, in a Penfield tube, with a flux of lead oxide. Furnace temperature prior to action of the flux was approximately 850° C.

#### Spectrographic Analyses, Trace Elements

Trace-element analyses were made emission spectrographically by essentially the same method described by Murata (*in* Gordon and Murata, 1952). Standards were made by mixing either (1) chemically analyzed minerals or (2) pure oxides of the elements into a quartz-feldspar base. Proportions of quartz to feldspar were 6:4. Concentration steps of 10,000, 4640, 2150, and so on down to 2.15 ppm were prepared by dilution with the base. The standards

<sup>4</sup> The analyses of  $Fe_2O_3$  made in this way were checked by five analyses with a silver reductor. In this method iron from the  $R_2O_3$  group, in an HCl solution, was reduced by passing the solution down a column of metallic silver.

and samples were exposed using the following equipment and methods:

Spectrograph:	Jarrell-Ash 3.4 m grating instrument, Wadsworth mount, dispersion, 5.2 Å/mm in the first order.
Excitation:	19-ampere short-circuit D. C. arc from a Jarrell-Ash Vari-source. Sample as the anode. Analytical gap, 4 mm magnified 5X and focused on the slit. Central 2 mm used with a slit width of 25 microns; 25-mg samples were burned to completion (90-120 sec.). Total energy method with no internal standardization.
Electrodes:	High purity one-quarter inch graphite rod as the anode. U.C.C. #3417. Pointed one-eighth inch cathode.
Wave-length Range:	2300-4800 Å in the first order.
Plates:	Eastman Kodak III-0.
Processing:	4 minutes in DK-50 developer at 20° C., 20 sec. short stop, 10 min. in acid fix, 20 min. wash.
Plate Calibration:	Selected iron lines after method of Dieke and Crosswhite (1943). Each plate is calibrated.
Densitometer:	Applied Research Laboratories model #2250.

The average sensitivities for the various elements are listed in all tables which include spectrographic data. The sensitivity value represents the average limit of detection and will vary from plate to plate. Each sample was exposed in duplicate; the average was regarded as one analysis. In addition masked duplicates were repeatedly prepared and inserted into the analytical sequence by A. E. J. Engel. Wherever the trace-element data indicated the possibility of a trend, the critical samples were masked and rerun on a single plate. Under these conditions reproducibility is approximately 25 per cent of the amount reported. Detailed data on analytical precision for each element were determined by statistical analyses of the differences between masked samples on the same, and on different plates. The statistical method is described fully by Snedecor (1946, p. 66-68), and the statistical data are summarized in Table 3.

#### Modal Analyses

All modal analyses of rocks were made from stained sections approximately  $\frac{3}{4}$  by 1 inch in

size. For maximum efficiency the sections were cut essentially normal to the strongest foliation, prepared as suggested by Chayes (1952) with hydrofluoric acid as an etching agent and

TABLE 3.—PER CENT STANDARD DEVIATIONS OF REPLICATE SPECTROGRAPHIC ANALYSES OF TRACE ELEMENTS

Element	Per cent standard deviation		Ppm.	
	Same plate	Different plates	Sensitivity	Mean*
B	60	80	10	12
Ba	20	31	1	800
Co	9	16	2	8
Cr	22	20	5	40
Cu	40	50	1	15
Ga	26	24	5	10
La	..	20	80	100
Mn	26	36	2	400
Mo	..	..	3	5
Nb	..	..	15	15
Ni	36	40	2	20
Pb	33	88	10	15
Sc	14	26	2	15
Sn	..	..	5	10
Sr	54	36	2	300
Ti	13	77	2	5000
V	39	20	2	60
Y	13	25	10	50
Yb	15	64	1	4
Zn	24	..	80	80
Zr	18	19	2	200

\* This mean value is shown only to indicate that many elements are near the limit of their sensitivity. It represents the mean of only those samples used for statistical analyses.

sodium cobaltic nitrate as a stain. In specimens of gneiss devoid of marked lithologic layering, where grain intercepts are less than 0.5 mm and grains average between .05 and 0.3 mm in diameter, calculations indicate that two sections proved adequate if a total of 3000 counts were made. In the coarser-grained and inequigranular layered specimens (Pl. 2, fig. 2), three to four sections were counted, yielding 4500 to 6000 counts per total specimen (Table 4). Number of sections and points counted in more homogeneous specimens was based upon Chayes' replication schedule for maintaining analytical error (Chayes, 1956, p. 79-91,

Fig. 11). Grain counting was done with a point counter (Chayes, 1949) adapted from a Bausch and Lomb mechanical stage. Distance between centers is equivalent to a horizontal traverse of about 0.3 mm. Traverses were spaced at

The successive changes in composition at intervals of 500, 1000, and 1500 points (Table 4) indicate the changes in modal analysis in a part of the gneiss devoid of other large garnet clusters.

TABLE 4.—MODAL ANALYSES OF TWO ROCKS

Recorded at counting intervals ranging from 100 to 4500 points to show fluctuations induced by coarse-grained, inequigranular, and irregularly layered gneiss.

	Specimen Bgn 25				Specimen Bgn 21				
	100	500	1000	4500	100	500	1000	1500	4500
Quartz	41.00	23.80	20.00	19.20	28.00	26.60	25.70	31.67	36.27
Plagioclase	38.00	54.30	54.30	48.07	19.00	46.80	53.10	49.63	48.90
K feldspar	4.00	3.40	5.40	10.26	.00	2.00	2.30	2.07	.73
Biotite	17.00	17.60	18.60	19.56	10.00	11.80	11.90	11.27	7.07
Garnet	..	..	.90	2.01	43.00	11.80	5.90	3.93	5.87
Sphene	..	tr	.10	.13	..	..	..	..	..
Apatite	..	tr	.10	.06	..	..	.10	.07	.05
Chlorite	..	.30	.30	.41	..	..	tr	.20	.17
Sericite	..	.40	.20	.18	..	..	.20	.30	.33
Opakes	..	.20	.10	.12	..	1.00	.60	.66	.53
Zircon	..	..	tr	tr	..	..	.20	.20	.08
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

sites randomly chosen from 10 possibilities within each millimeter. Tabulations were made with a biological counter.

In these specimens the largest analytical errors arise from inadequate areas traversed relative to band width and to the size and distribution of porphyroblasts, especially garnet. Actually the garnet porphyroblasts are not of single crystals but involve either garnet sieved by quartz or a cluster of garnet, quartz, K feldspar, and a little biotite or chlorite, commonly enveloped in a dominantly quartzose sheath. Most feldspar porphyroblasts are sieved with biotite and quartz. Individual grains of garnet and feldspar are both large and small. The presence of very small grains coupled with the polymineral nature of the cluster rules out precise traverses on large polished slabs. The problem is exemplified by modes of two garnetiferous specimens, Bgn 21 and Bgn 25, which have been tabulated in per cent at intervals of 100, 500, 1000, 1500, and 4500 counts (Table 4). In specimen 21, the first traverse crossed a garnet cluster before 100 points were recorded, resulting in an average percentage composition (at 100 points) of 43 garnet, 10 biotite, 19 plagioclase, and 28 quartz, with no K feldspar.

Specimen Bgn 25 shows a reverse relationship in which several of the last traverses went through two clusters, one of garnet, and the other of K feldspar (4500-point column, Table 4).

Very fine-grained alteration products, especially chlorite replacing biotite and sericite replacing feldspar, require high power for adequate resolution and constitute a major source of eye strain and tension if but a minor source of error. Equally fine-grained cataclastic effects compounded the difficulty of getting an unbiased result.

*Calculations of Chemical Composition From Modal Analyses*

The efforts expended in detailed modal analysis of the gneiss were prompted in part by the desire to calculate a chemical composition of the rock from the mode and to compare this composition with that obtained by conventional wet-chemical analysis. Calculation of the chemical composition of the rock from the mode was attempted on the 24 specimens from which adequate physical and chemical data were available. In each example the chemical



compositions of the total rock, and of biotite and garnet (where present), were determined by chemical analysis. The composition of component K feldspar was obtained by chemical

of all garnets were determined directly with a micropycnometer. Densities of plagioclase, biotite, K feldspar, and all accessory minerals were calculated from the compositional data.

TABLE 5.—DATA COMPARING PRECISION OF DIRECT CHEMICAL ANALYSES AND USE OF MODAL ANALYSES AND PHYSICAL AND CHEMICAL PROPERTIES OF MINERALS IN DETERMINING CHEMICAL COMPOSITIONS OF ROCKS

	Group 1 specimens			Group 5 specimens			Actual chemical analyses		Analyses of G-1 by 34 analysts		
	1	2	$\bar{x}$ 3	4	5	$\bar{x}$ 6	G-1 7	W-1 8	$\bar{x}$ 9	10	11
SiO <sub>2</sub>	.26	.65	.26	.40	.61	.10	.21	.16	72.24	.27	1.19
TiO <sub>2</sub>	.03	.05	.01	.10	.15	.04	.00	.00	.26	.034	.24
Al <sub>2</sub> O <sub>3</sub>	.26	.40	.20	.30	.51	.01	.22	.48	14.34	.27	1.62
Fe <sub>2</sub> O <sub>3</sub>	.06	.09	.01	.19	.26	.19	.08	.11	.92	.21	.74
FeO	.25	.46	.25	.27	.50	.26	.09	.08	1.01	.09	.31
MnO	.10	.28	.04	.05	.12	.04	.02	.00	.03	.007	.021
MgO	.14	.32	.13	.01	.03	.01	.03	.08	.39	.09	.37
CaO	.09	.15	.06	.22	.22	.30	.06	.06	1.40	.10	.50
Na <sub>2</sub> O	.19	.35	.09	.14	.20	.05	.09	.04	3.30	.18	.69
K <sub>2</sub> O	.05	.09	.00	.15	.23	.15	.06	.04	5.48	.22	1.63
H <sub>2</sub> O+	.01	.02	.01	.08	.11	.08	.03	.04	.39	.11	1.03
P <sub>2</sub> O <sub>5</sub>	...	...	...	...	...	...	.01	.006	...	...	...

Columns 1 and 2. Mean and maximum deviations between major-element compositions of 12 specimens in Group 1 as determined by direct analysis and by calculations from modal analyses, using physical and chemical properties of the constituent minerals (specimens are Bgn 26, 27, Qb 236, 235M, 3, 7, 230, 229, 231, 226, 227, 228).

Column 3. Mean deviation between the mean compositions of the specimens in Group 1 cited above, as determined by averaging direct analyses and averaging analyses calculated from modes using physical and chemical properties of the constituent minerals.

Columns 4, 5, and 6. Data from Group 5 analogous to those for Group 1 in columns 1, 2, and 3.

Columns 7 and 8. Mean deviations of chemical analyses of G-1 and W-1 as done by Celeste G. Engel from "adjusted" mean compositions of these rocks (see Fairbairn, 1953, Table 1).

Column 9. Average of 34 analyses of the granite G-1 by 34 different analysts working in different laboratories (see Fairbairn *et al.*, 1951).

Columns 10 and 11. Mean and maximum deviations between the 34 analysts of the granite G-1 listed in Fairbairn *et al.* (1951).

analysis in 8 specimens, and from these data, compositions of the remaining 16 were estimated. Composition of plagioclase was obtained from optical constants and checked independently from the chemical analyses of Ca in the rocks. Analyses were made for Na in seven muscovites. Compositions of accessory sericite, chlorite, and magnetite were estimated.<sup>5</sup> Densities

<sup>5</sup> Sericite is assumed to have the same composition as muscovite. An intermediate chlorite with equal proportions of antigorite, ferroantigorite, amesite, and daphnite was used (See Winchell and Winchell, 1951, p. 381); TiO<sub>2</sub> in magnetite varied from 1.5 at Emeryville to 3.0 at Colton.

The detailed mineralogical data will be presented in Part 2 of this paper.

The results of the calculations of rock composition from the modes exceeded expectations. In the 24 specimens studied, the maximum deviation of each major constituent oxide except MnO and FeO in the gneiss as determined from the mode, from the value of the oxide as determined chemically, is no greater than the maximum deviation in the same oxide in the 34 analyses of the granite W-1, as analyzed by 34 silicate analysts (Fairbairn *et al.*, 1951).

Moreover, calculations from modes of the

composition of 12 of the more equigranular specimens of gneiss (Tables 7 and 9) yield mean and maximum deviations of the major oxides, except MnO, MgO, and FeO, that are less than these deviations in the 34 analyses of W-1, as posted in Fairbairn *et al.* These data are shown in Table 5. In column 1 of Table 5 are the mean deviations of each major oxide, as computed from the modes of the 12 specimens, from the values of the oxides as determined by wet-chemical analysis. In column 2, Table 5, are the maximum deviations of each oxide, as computed from the mode and mineral analyses, from the value obtained by wet-chemical analyses of the rock. In column 3, Table 5, are the mean deviations of the arithmetic-mean composition of the 12 rocks as computed from the mode, from the arithmetic-mean composition of the 12 rocks as obtained by chemical analyses.

Data on the mean deviations of the 34 wet-chemical analyses of G-1 (Fairbairn *et al.*, 1951) are in columns 10 and 11 of Table 5, along with a computed mean of the 34 analyses (column 9, Table 5).

In columns 7 and 8 are the mean and maximum deviations between the standards G-1 and W-1 as done by C. G. Engel, from the "adjusted" mean compositions of these standard samples (Fairbairn, 1953, Table 1; Table 1, this paper).

The data suggest that, if given an analysis of biotite and garnet from the gneiss together with a careful mode of reasonably homogeneous gneiss within a radius of 2–3 miles of these minerals, the bulk composition of the gneiss can be calculated with about the same precision as the 34 analysts obtained in their work in the granite G-1 (Fairbairn *et al.*, 1951; Fairbairn, 1953). In areas of this size involving the most homogeneous parts of the gneiss where the chemical compositions of more than one biotite and one garnet are known, the precision of such calculations of the concentration of most major elements in the gneiss is greater than that achieved by the 34 analysts of G-1.

Chayes has pointed out repeatedly (*in* Fairbairn *et al.*, 1951; Chayes 1956, p. 1–31) that good modal analyses have not been made often enough, and they have not been adequately exploited by geologists. Work on the gneiss complex seems to confirm that view. For example, if only a couple of chemical analyses were possible during studies of the gneiss complex, these would have been made most profitably on biotite and garnet. In this way the chemistry of not only the parent rock,

but of the constituent garnet and biotite as well, could be indicated within or close to the precision of practicing silicate chemists. It has taken about 75 complete chemical analyses of rocks and their constituent minerals to demonstrate this fact but other economically disposed geologists may take note.

The calculations involved in preparation of Table 5 also bring out some interesting and not fully understood sources of error in this work. For example, the values of CaO, FeO, and MgO as calculated from the modal analyses are almost invariably higher than these values obtained by chemical analysis. In contrast  $Al_2O_3$  as calculated from the mode is lower, in about 70 per cent of the examples, than the  $Al_2O_3$  as determined by chemical analysis. The unsymmetrical deviations of CaO and  $Al_2O_3$  values obtained by the differing methods of analysis do not seem attributable to error in identification of plagioclase, for the deviations in  $Na_2O$  values are small and uniformly dispersed about the arithmetic means (Table 5). Possibly systematic errors are involved in both modal and chemical analyses. We hope to study this problem further.

The relatively large mean and maximum deviations in determinations of MnO via the two methods in the rocks of Group 1 seem attributable to the big variations in MnO content in specific minerals and in closely spaced specimens of rock. In Group 5 where Mn is more uniformly distributed in each of the constituent minerals, the mean deviation between MnO values obtained by the two methods is almost halved.

The similarity of chemical compositions of rocks obtained through modal analyses with rock compositions obtained by direct chemical analysis seems to justify the use of the former in this study. Accordingly, in demonstrating broad chemical trends, and in miscellaneous other calculations throughout this paper where precision and accuracy are least critical, chemical analytical data have been supplemented with rock compositions derived from modes. Each of these additions is specified. Agnostics may make appropriate allowances.

## TEMPERATURE OF METAMORPHISM

### *Introduction*

The increase in temperature of metamorphism of the gneiss from Emeryville northeast to the massif (Fig. 2) is demonstrated by numerous lines of evidence. Most data indicate

only a relative increase in temperature. Evidence of this type includes (1) systematic changes in mineralogy and texture of the gneiss and associated metasedimentary rocks; (2) an increase in the abundance of granite and syenite with igneous features as the massif is approached; (3) the crude zonation of essentially contemporary hypogene mineral deposits, from mesothermal types at Emeryville to hypothermal deposits immediately southeast of Colton.

In the search for data on absolute temperatures of metamorphism, solid solutions of one phase in another were studied. Analyses were made of solid solution of  $MgCO_3$  in calcite, paragonite in muscovite,  $TiO_2$  in magnetite, and FeS in sphalerite. The data from these studies seem to offer minimal temperatures of the metamorphism. Further bracketing of temperatures was attempted through studies of phase reactions such as the presence or absence of wollastonite in siliceous calcite marbles. Most of these attempts to calculate temperatures of metamorphism are crude because of the uncertainties in regard to the pressures of metamorphism. Consequently the suggested temperatures of metamorphism—about  $500^\circ C$ . at Emeryville and about  $600^\circ C$ . at Colton—may be in error by about  $50^\circ$ .

#### *Geologic Evidence of a Temperature Gradient*

The variations in mineral and chemical composition and in texture in the gneiss between Emeryville and Colton, as described in succeeding parts of this paper and in Part 2, are completely consistent with and support the interpretation of a temperature gradient of about  $100^\circ C$ . between Emeryville and Colton during metamorphism.

Between Emeryville and Colton the ratio of granite with igneous characteristics to metasomatic granite increases markedly. In the gneiss of the Emeryville area, only one body of granite has features indicative of magmatic origin. This is the California phacolith (Pl. 1), first recognized and described by Buddington (1929). This phacolith is an equigranular, light-pink, two feldspar-quartz granite. It is enveloped by a narrow, distinctive and markedly disharmonic sillimanite-garnet aureole bearing gneiss formed at temperatures seemingly in excess of  $575^\circ C$ . (A. E. J. Engel, in press). The remainder of the granite lenses and layers are devoid of obvious contact effects. At least half of them are demonstrably metasomatic (Engel and Engel, 1953b, p. 1060–1061; Figure 2 of Plate 3, this paper).

The relative abundance of granite and syenite of probable igneous origin in the vicinity of Colton and near by in the massif has been described and carefully documented by Buddington (1939; 1948; 1957) and by Buddington and Leonard (in press). The regional picture is therefore one of a central, hotter igneous-rich complex, bordered by metasedimentary rocks partly injected and replaced by outward-spreading, highly mobile magma or K- and Si-rich fluids. Within the massif the several igneous-looking rock types are arranged in a crude zonal pattern, including from core to perimeter, (1) anorthosite; (2) gabbroic anorthosite; (3) syenite and syenitic granite; and (4) granite (Buddington, 1939, Pl. 2). Recently Buddington *et al.* (1955) have shown that the amount of  $TiO_2$  in the magnetites of these rocks is directly correlative with their inferred temperatures of solidification from magma. The use of  $TiO_2$  in magnetite as a geological thermometer of metamorphism is discussed in following pages.

The zonation of mineral deposits also has been noted (Buddington, 1939, p. 251–303; Buddington and Leonard, in press) to be sympathetic with the previously described rock and temperature patterns. The anorthositic core of the massif contains concentrations of highly titaniferous magnetite, thought to be segregation deposits. In and near the sheathing granite-syenite complex are numerous much less titaniferous skarns and granite-gneiss magnetite ores (Buddington and Leonard, in press). West of the massif, along the gneiss complex at Edwards and Balmat, important deposits of sphalerite, pyrite, and pyrrhotite, with minor galena, have replaced the marble (Brown, 1936; 1947). In this same area and farther west on the northwest side of the gneiss are large belts of highly pyritic gneiss (Prucha, 1953).

#### *Absolute Temperatures*

*Data from magnesian calcites.*—The amount of magnesium in solid solution in calcite in the magnesian marbles adjacent to the gneiss has been determined by Graf and Goldsmith (1955) and independently by the authors. These analyses suggest the metamorphism of the gneiss in the Emeryville area reached temperatures of at least  $475^\circ$  to  $500^\circ C$ .

Limitations and potentials of this method are noted by Graf and Goldsmith (1955), Goldsmith *et al.* (1955), and Harker and Tuttle (1955). Ideally the calcite should have formed in equilibrium with coexisting dolomite, assuring an



excess of  $MgCO_3$  in the system. Even if dolomite was not a coformed phase, the magnesium in solid solution in the calcite may indicate a minimum temperature of metamorphism. The reaction is insensitive to  $PCO_2$  and to  $MgO$  concentration. Perhaps the most serious difficulty involved in using magnesian calcites as thermometers lies in either (1) finding specimens which seem to have been effectively "quenched" at or near the maximum temperature of metamorphism (2) correctly interpreting whether or not dolomite in or near the calcite has been exsolved during cooling of the marble.

The specimens of calcite analyzed by Goldsmith *et al.* (1955, Table 4, specimens 70, 71, and 75) and by the authors are more coarse crystals intergrown with dolomite in the marble about 1000 feet north of Balmat Corners. X-ray and spectrochemical studies indicate the calcites contain respectively about 5.6, 4.1, and 5.4 mol per cent  $MgCO_3$  (as corrected, Graf and Goldsmith, 1958) in solid solution in the calcite. The pressure correction (2000–3000 atmospheres) has been investigated by Goldsmith (written communication) and appears to be negligible. Consequently the indicated temperature of metamorphism was about 500° C., possibly 525° C. (Graf and Goldsmith, 1958, Fig. 1). Subsequent search of 500 thin sections of marble in the Emeryville area revealed three specimens of coarsely crystalline marble in which the calcite crystals contain tiny bleblike dolomite inclusions. In these specimens, coarse crystals of dolomite appear to have formed with the perthitelike magnesian calcites. The perthitelike calcites were carefully separated from the large crystals of dolomite. The sample selected was treated with ferric chloride and ammonium sulphite (Keller and Moore, 1937) to check for dolomite contamination. The concentrate proved to be free of all but the blebs of dolomite in the calcite. Wet-chemical analyses of the three blebby calcites indicate 5.1, 4.8, and 4.7 mol per cent  $MgCO_3$ . Both calcite and dolomite in the marble are relatively pure, containing less than 0.5  $FeO + Fe_2O_3 + MnO$ . If the dolomite blebs were exsolved from the calcite during cooling, a minimum temperature of about 500° C. is indicated for the growth of the parent magnesian calcite crystals. This was presumably during the development of the assemblage quartz, greenish biotite, muscovite, oligoclase in the gneiss near by.

The marbles at the opposite end of the gneiss segment near Colton are poorly exposed and have not been studied in detail. Consequently

studies of magnesian calcites from this area have not been attempted.

*Thermometric significance of titaniferous magnetite.*—Recently Buddington *et al.* (1955) have discussed the variations of titanium content of Adirondack magnetites, as related to the kind, origin, and temperature of formation of various host rocks. Several titanium-bearing phases, especially ilmenite and ulvöspinel, occur as intergrowths in Adirondack magnetites. The textural features and relative abundance of these intergrowths strongly suggest they are of exsolution origin. Buddington's studies show that the amount of titanium present in the exsolved ilmenite or ulvöspinel may reflect the temperature of formation of the specific host rocks—if titanium has been present in the system in excess of that fixed in the magnetite. An excess of titanium is inferred to have existed wherever  $TiO_2$  (ilmenite) is present not only as a solid solution or as exsolved ? blebs in the magnetite, but also in independent grains.

The occurrence of titaniferous magnetite and separate grains of ilmenite in the gneiss and in granitic rocks associated with it offers a possible method of estimating temperatures of growth of the magnetite. Since the magnetite has formed with the silicates under study, the temperature at which they have grown is essentially this value. The  $TiO_2$  content of five magnetites formed with independent ilmenite in rocks of the Emeryville area at the height of metamorphism is approximately 0.75 to 1.7 weight per cent. Two of these magnetites with 1.2 and 1.4 per cent  $TiO_2$  occur in the gneiss; two with 0.97 and 1.7 per cent  $TiO_2$  are in interlayered amphibolites; and one specimen having 0.75 per cent  $TiO_2$  occurs in dominantly if not wholly metasomatic granite. In contrast, five magnetites from the Colton area—three in the gneiss and two in interlayered amphibolites—contain 2.0 to 3.6 per cent  $TiO_2$ , averaging about 3.0 per cent. In the youngest granites just southeast of Colton, which were emplaced during reconstitution in the gneiss, the  $TiO_2$  content of three magnetites is slightly higher, averaging 3.9 per cent. These data, as calibrated by Buddington *et al.* (1955, Table 11 and text), suggest that the minerals under study in the gneiss near Balmat formed at about 475°–500° C., whereas those near Colton were developed at about 600° C.

*Temperatures from FeS in sphalerites.*—A possible minimum temperature of formation of the mineral assemblages in the gneiss in the Balmat-Edwards area may be indicated by the FeS content of sphalerites (Kullerud, 1953;

Barton and Kullerud, 1957). In these areas the sphalerite occurs with abundant pyrite and scattered pyrrhotite in marble and rarely in pyritic gneisses and schists (Brown and Engel, 1956). The use of the sphalerites as indicators of temperatures requires the assumption that the sulfides were emplaced as an integral phase of metamorphism, at essentially the temperature of the enclosing metamorphic rocks. If instead, the sulfides were deposited from localized hydrothermal fluids at very different temperatures, they contribute little to the present discussion.

Three features of the sulfide deposits suggest they may be indicators of the temperatures of metamorphism at the time of their deposition. These features are their (1) form, (2) distribution, and (3) paragenetic relationships to widespread metamorphic minerals. The sphalerite, pyrite, and pyrrhotite are replacement deposits that include not only veins (Brown, 1936) but also diffuse patches and grains disseminated through parts of stratigraphic zones (A. E. J. Engel, 1948). Scattered grains of sulfides occur in marble and in at least two of the metamorphosed clastic beds interlayered in the marble near the paragneiss (Brown and Engel, 1956, p. 1603 and Pls. 1 and 2). Locally, small veins and disseminated masses of pyrite and pyrrhotite occur in the paragneiss with occasional, very tiny crystals of sphalerite and galena. Many sulfide-bearing rocks appear to be devoid of obvious channelways or conduits along which hydrothermal solutions would be localized. In fact the seeming imperviousness of many host rocks has led Brown (1947) to suggest that the sulfides could not be hydrothermal deposits in the conventional sense.

The sulfide mineralization is relatively widespread, although the only known commercial deposits of sphalerite are in the Balmat and Edwards areas. Small veins and disseminated grains of sulfides occur in both marble and schists from Balmat at least to Pyrites, New York. (Pl. 1).

The paragenetic relationships of sulfides to metamorphic minerals also are consistent with an intimate relationship between the sulfide mineralization and the prevailing metamorphic processes. The assemblage diopside-dolomite-calcite-quartz evolved in the marble as the minerals quartz, biotite, plagioclase, and muscovite grew in the gneiss in the Emeryville area (A. E. J. Engel, in press). Subsequently formed retrograde metamorphic assemblages are widespread, although spotty in their development, in both gneiss and marble. The

paragenesis in the marble is as follows: diopside → tremolite → anthophyllite → serpentine → talc. The development of these minerals in parts of the marble is paralleled by the appearance of traces of clinozoisite, chlorites, sericite, and albite in parts of the gneiss.

The more iron-rich sphalerites, along with some of the pyrite and pyrrhotite, were introduced during the anthophyllite stage of retrograde metamorphism in the marble. The formation of less iron-rich sphalerites and of iron sulfides continued, however, throughout the period in which serpentine and early talc formed (Brown, 1936; A. E. J. Engel, in press). Much talc postdates all the sulfides.

All these relationships admit but certainly do not prove the possibility that the iron-rich sulfides formed at not only the same time but at the same temperatures as anthophyllite in the marble, and that these temperatures were widespread in the Emeryville area. If this is true, the temperatures recorded in the sphalerites are no higher, and possibly lower, than those at which the quartz, biotite, oligoclase, and muscovite grew in the paragneiss. In effect, temperatures of formation of the sphalerites richest in iron may offer a minimum temperature for the metamorphism of the gneiss.

Analyses of sphalerites coexisting with pyrite in the marble just northwest of Balmat (Pl. 1) have been made by both Brown and Kullerud. It is not clear, however, that these sphalerites grew with coexisting pyrrhotite, hence the values noted may be below actual temperatures of crystal growth (Barton and Kullerud, 1957). These sphalerites contain between 7 and 8.9 weight per cent FeS (Kullerud, 1953, Table 14 and p. 138). Assuming the sulfides were emplaced at approximately 2000 atmospheres, a temperature of formation of at least 350°–375° C. ± 25° C. may be inferred. Mr. Bruce Doe (personal communication) subsequently analyzed specimens of sphalerite intergrown with pyrrhotite at the Balmat number two mine, which is about 4500 feet southeast of the gneiss (*see* Brown and Engel, 1956, Pl. 2). At this writing he has found as much as 10.3 weight per cent FeS in several of the sphalerites. Assuming a pressure of about 2000 atmospheres, the analyses suggest the sphalerites were formed at temperatures of at least 430° C. FeS content of two sphalerites at Edwards (intergrown with pyrite?) analyzed by Kullerud suggests a minimum temperature of growth of 385° ± 25° C. (Kullerud, 1953, Table 14, samples 59, 87). Presumably sphalerites intergrown with pyrrhotite as well as pyrite will indicate

higher temperatures. These data appear entirely consistent with the interpretation of minimum temperatures of metamorphism of at least 450° C. Sphalerites coexisting with pyrrhotite in the gneiss have not been extracted and analyzed, largely because of the formidable problems of concentration and purification. Data from the sphalerites in the gneiss would of course be most valuable in the present context.

*Na content of muscovites in the gneiss.*—The amount of solid solution of paragonite (Na mica) in muscovite has been shown by Eugster and Yoder (1955, p. 124-125) to be primarily dependent on the temperature of formation of the mica, if the system is saturated in Na. Actually the muscovite in both gneiss and associated pegmatites at Emeryville coexists with an intermediate to calcic oligoclase rather than albite or paragonite. Accordingly the muscovites cannot be expected to contain the maximum amount of Na consistent with their temperature of formation.

Analyses of four muscovites from the gneiss and three from associated pegmatite show a range in mol per cent paragonite from 7.2 to 8.1. The highest value (8.1) indicates that the temperature of metamorphism must have exceeded 400° C. (uncorrected from  $P_{H_2O}$  and  $P_{total}$ ). This is at least 75C.° below temperatures of metamorphism indicated by the other solid-solution geothermometers.

*Temperature limits implied by wollastonite-free siliceous marble.*—Throughout the Emeryville-Colton region, siliceous calcitic marbles occur on both sides of the gneiss. Quartz-calcite beds and intergrowths in these marbles have been searched for wollastonite. None has been found. In the associated siliceous dolomite layers, diopside is the highest rank silicate present. As much of the quartz and calcite is almost surely of sedimentary origin (A. E. J. Engel, 1949; Brown and Engel, 1956) these two minerals have coexisted without reaction throughout the metamorphism of the gneiss. Assuming (1) the depth of burial of the marble and gneiss at Colton was not in excess of 5 miles and (2)  $P_{total} \geq P_{CO_2}$ , the temperature of metamorphism of gneiss and marble in the Emeryville-Colton region did not exceed 750° C. This conclusion is based upon the calculated and the experimentally determined invariant equilibrium reaction curve,  $CaCO_3 + SiO_2 \rightleftharpoons CaSiO_3 + CO_2$  (Harker and Tuttle, 1956; Danielsson, 1950; Weeks, 1956). Probably the weakest assumption involved is that the metamorphism occurred at depths less than

5 miles. If much greater depths were involved, the maximum possible temperature of the reactions would be increased. Of course many students of metamorphism assume that during the regional metamorphism  $P_{CO_2} \ll P_{total}$  (cf Barth, 1952, p. 286-287; Ramberg, 1952, p. 155-156). If this is true, the maximum temperature of metamorphism at Colton would be depressed much closer to the 600° C. indicated by the solid-solution data.

*Temperatures as indicated by the  $O^{18}-O^{16}$  ratio in coexisting quartz and magnetite.*—The isotopic compositions of coexisting mineral pairs such as quartz-calcite or quartz-magnetite which precipitate slowly under equilibrium conditions from a water-rich solution have values that depend upon (1) the isotopic composition of the water; (2) the amount of water; and (3) the temperature of growth of the minerals (Clayton and Epstein, 1958). Analyses by Clayton and Epstein of numerous specimens of coexisting quartz and magnetite from suites of metamorphic and igneous rocks indicate isotopic equilibrium commonly is closely approached during mineral formation. These workers show that the  $\delta(O^{18}-O^{16})$  ratios for quartz minus  $\delta(O^{18}-O^{16})$  values for magnetite indicate a consistent relative temperature of formation of these minerals which is in excellent agreement with geologic data on their origin. The smaller the  $\delta$  quartz minus magnetite value, the higher the temperature of mineral growth.

During the course of this study Clayton kindly undertook analyses of coexisting quartz and magnetite from the gneiss at Emeryville and at Colton. In addition, analyses were made of coexisting quartz and magnetite from the gneissic hornblende granite just southeast of Colton along the outer margins of the Adirondack Massif. This granite, interpreted to be magmatic in origin, is discussed in a succeeding section of this paper.

The analytical data are listed in Table 6. The decreases in  $\delta$  quartz minus  $\delta$  magnetite from 11.1 to 8.2 in the gneiss between Emeryville and Colton is indicative of appreciably higher temperatures of metamorphism at Colton. In general Clayton and Epstein find that  $\delta$  quartz minus magnetite values of 8 to 8.5 are characteristic of these minerals in plutonic, igneous granites. Values of  $\delta$  7 to 8 are recorded for igneous granodiorite and rhyolites.

Although these data are not yet calibrated to a precise temperature scale, they are of special interest for the following reasons: (1) processes of oxygen-isotope fractionation of the



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type recorded are strongly temperature dependent but are nearly independent of pressure. In this respect they are superior to some other thermometers used in this study and are good evidence of the temperature gradient between

TABLE 6.—DELTA O<sup>18</sup>-O<sup>16</sup> RATIOS FOR COEXISTING QUARTZ AND MAGNETITE IN GNEISS AT EMERYVILLE AND COLTON AND IN HORNBLENDE GRANITE GNEISS IN THE ADJOINING PART OF THE MASSIF

Specimen and Locality	Quartz ‰	Magnetite ‰	Quartz-Magnetite ‰
Paragneiss, Emeryville (Qb 67)	14.8	3.7	11.1
Paragneiss, Colton (Bgn 18)	12.3	4.1	8.2
Hornblende microcline granite gneiss (outer part massif)	11.9	3.3	8.6

Emeryville and Colton; (2) the oxygen-isotope data confirm much geologic evidence (noted in succeeding pages) that the gneiss at Colton was metamorphosed under essentially ultrametamorphic or near-magmatic conditions of *T* and *P*; (3) an absolute calibration of the oxygen-isotope data is possible using experimental methods.

#### PRESENTATION OF ROCK ANALYSES

A standard method of presentation is used to aid rapid comparisons between the analytical data on various figures and tables. Inherent in the method is the conclusion that a positive temperature gradient existed in the gneiss between Emeryville and Colton during metamorphism. The relative temperature of formation of any specimen in this study may be indicated (1) by the relative distance measured along the strike of the gneiss from Colton southwest to the specimen or (2) by the distance of the specimen or group of specimens from the edge of the massif, as measured along a line on the earth's surface drawn normal to the trace of the massif. The last-named measurement is used as a scale (horizontal co-ordinate) and calibrated against an approximation of the temperature of crystal growth (reconstitution) in Figure 2. This scale seems justified by the fact that the outer surface of the massif and the southeast, overturned side of the gneiss are subparallel and dip at moderate angles northwest (Pl. 1). In all tables and figures, therefore,

the horizontal co-ordinate is used as a measure of the shortest horizontal distance of the center of each group of specimens from the massif. The vertical co-ordinate represents the property of the rock or mineral being compared as a function of distance and, consequently, relative temperature of formation. The specimens of Group 1 (Emeryville area) are rather uniformly distributed around a point 9.7 miles from the perimeter of the massif, as measured along a line on the map (drawn essentially normal to the perimeter (Pl. 1)). Specimens in Groups 2, 3, 4, and 5 are distributed around points respectively 4.7, 3.7, 2.7, and 1.5 miles from the perimeter of the massif (Pl. 1). Comparisons are confined for the most part to statistical values of each group rather than those of individual specimens. Consequently, group values for given properties of rocks or minerals in the Emeryville area (Group 1) are plotted at a point on the horizontal co-ordinate 9.7 miles from the right-hand side of graph (perimeter of the massif). Group values for rocks or minerals in the Edwards area (Group 2) are plotted at a point 4.7 miles from the right side (massif), and so on. Considering the complexity of the geology, comparisons of properties of individual rocks or component minerals within any single group simply as a function of slight differences in distance from the massif do not seem justifiable. Hence the relative position of a specimen within the group is not to be regarded as highly significant, although for simplicity the sequence of specimen numbers is kept constant throughout the illustrations.

#### ROCK METAMORPHISM

##### *Assumptions*

Assumptions and errors involved in estimating the temperatures, depth, and pressures of metamorphism have been noted; other critical factors, seemingly impossible to evaluate rigorously, are the extent to which the composition of the gneiss varied from place to place before and during metamorphism and the kind and chemical potential of fluids in the gneiss during its metamorphism. Much geological evidence noted in following passages suggests that the sedimentary parent to the gneiss was compositionally uniform between Emeryville and Colton, and it would be pleasant to assume that the changes recorded in the least altered gneiss are induced largely by temperature. But it would be absurd to argue that the pre-metamorphic composition of the

gneiss was everywhere identical, or that even the small variations were unimportant (*see* Yoder, 1952, p. 615-617).

The data presented on succeeding pages, (see especially Table 13) indicate large volumes of water were expelled from the gneiss and from associated metasedimentary rocks during the metamorphism described. Maximum expulsion of water occurred in areas of most complete granitization. For example the mean H<sub>2</sub>O (110° C.+) content of least altered gneiss found at Emeryville is 0.72 weight per cent. In intimately associated gneiss replaced by granite, the water content decreases to 0.32. In the Colton area the least altered gneiss is less hydrous than that at Emeryville, averaging only 0.4 water. Moreover, most granite replacing this gneiss has less than 0.2 per cent water, and numerous bodies of metasomatic (?) granite contain only 0.1 per cent water (Table 13, column 7). Assuming 2-3 per cent water in the gneiss during incipient stages of its metamorphism, it is clear that appreciable water streamed through and out of this metasedimentary rock as metamorphism proceeded.

An enormous volume of CO<sub>2</sub> accompanied the water. The metasedimentary rocks on either side of the gneiss are siliceous magnesian carbonate rocks (Engel and Engel, 1953b, Table 1, p. 1055). The metasedimentary section, including the gneiss, is at least 12,000 feet thick (after metamorphism). Two-thirds of this section is siliceous marble. During the stages of high-rank metamorphism in these siliceous dolomitic marbles, over half the original sedimentary silica reacted with dolomite to produce calcium magnesium silicates, especially diopside. Calculations based upon detailed mapping and analyses indicate CO<sub>2</sub> comprising at least 10 per cent by volume of the early metamorphic marbles was expelled from them (A. E. J. Engel, in press). Much of this CO<sub>2</sub> must have streamed through the gneiss, or at least through more permeable parts of it, as the gneiss was reconstituted and granitized.

If the metamorphism of the gneiss is considered as an isolated problem, there appears

to be no way to evaluate the effects of (small ?) variations in composition, or of the chemical potential of CO<sub>2</sub> or H<sub>2</sub>O, upon temperatures of metamorphism. At least a crude appraisal of these effects seems possible, however, if studies analogous to this one can be expanded to other terranes. For example, studies could be undertaken of paragneisses most nearly approaching the Adirondack gneiss in "residual" composition. Almost surely, certain conditions of metamorphism—*P* or *T* or the kinds and amounts of volatiles—as recorded in the residual system will have been different. An evaluation of temperatures of metamorphism and types of mineral assemblages, together with the properties of constituent minerals, as attempted in succeeding pages and in Part 2, should indicate far more clearly the range of conditions in which a given assemblage may form.

#### *General Lithologic Features*

The gneiss has evolved from a monotonous, clastic, sedimentary rock into a complex of least altered and variously granitized gneiss. Few exposures of the paragneiss more than 15 or 20 feet thick are devoid of at least thin granitic seams or pegmatitic lenses. In much of the rock described as least altered, these seams do not exceed a foot or two in width or 10 per cent by volume of the gneiss. If the pegmatitic seams are avoided total K feldspar is commonly less than 5 per cent by volume, and the K<sub>2</sub>O-Na<sub>2</sub>O ratio is commonly about 1.3 or more. Exposures of this least altered gneiss in part blend, in part merge abruptly along and across the strike into extensively migmatized or uniformly feldspathized granite gneiss.

The gross interrelationships of form, composition, and texture in the gneiss complex in the Emeryville-Edwards areas are illustrated in Plates 2, 3, and 4 and in Figure 3. Figure 3 is modified from Figure 7 in the paragneiss paper (Engel and Engel, 1953b). Around Emeryville the least altered gneiss is a faintly foliated, equigranular, sodic rock composed of quartz,

#### PLATE 2.—TEXTURES OF GNEISS

FIGURE 1.—Least altered gneiss near Emeryville (Group 1) with minor pegmatite. The dark massive rock in the lower two-thirds of the photo is the quartz-oligoclase-biotite gneiss with accessory muscovite and K feldspar, inferred to be little changed in bulk composition from its early or pre-metamorphic parent. The lenses of pegmatite are quartz, microcline, and oligoclase, with a little muscovite.

FIGURE 2.—Least altered gneiss near Colton (Group 5). The dark spots are garnet sieved chiefly by quartz. The lighter-colored finer-grained matrix is a quartz-andesine-biotite rock with accessory K feldspar. Grain size of the matrix rock is several times coarser than that in the least altered gneiss at Emeryville (Figure 1).

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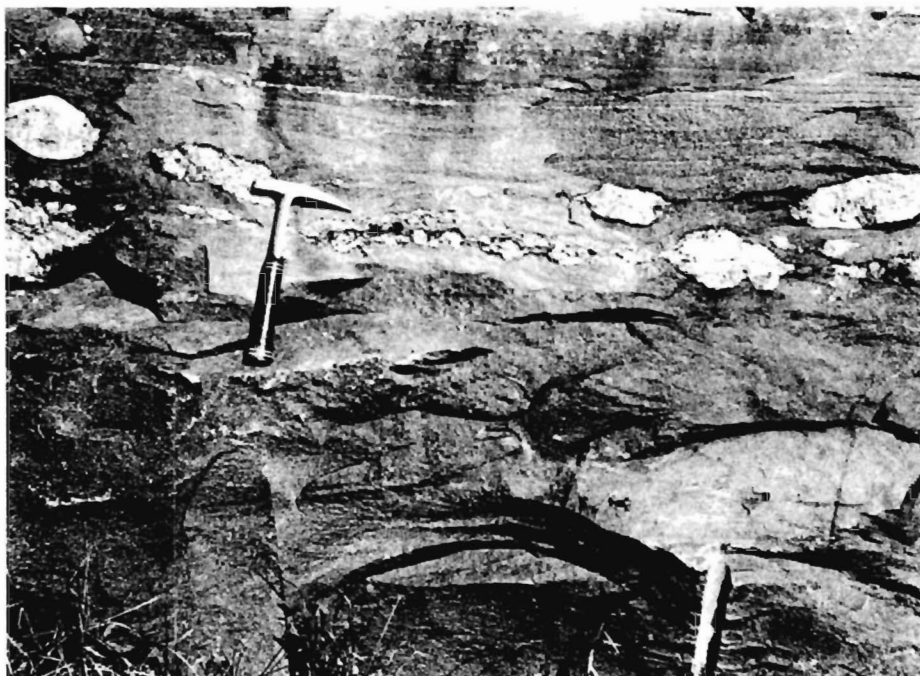


FIGURE 1



FIGURE 2

TEXTURES OF GNEISS





FIGURE 1

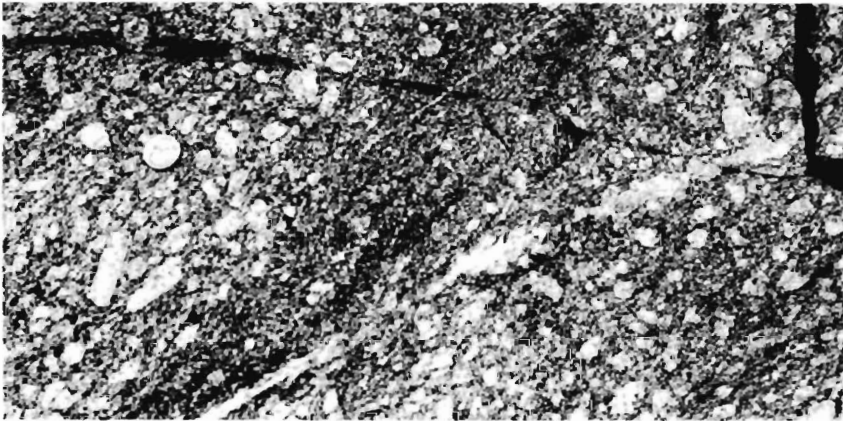


FIGURE 2

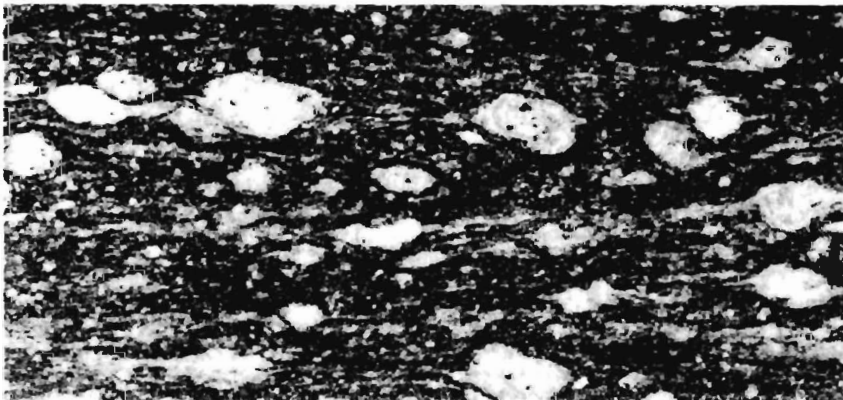


FIGURE 3

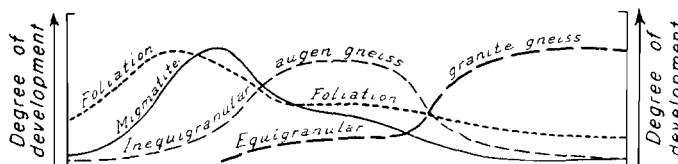
MIGMATITE AND INEQUIGRANULAR GRANITIZED GNEISS



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Least altered gneiss    Migmatite    Inequigranular granite gneiss    Alaskitic granite gneiss

Trends in texture



Trends in mineral composition

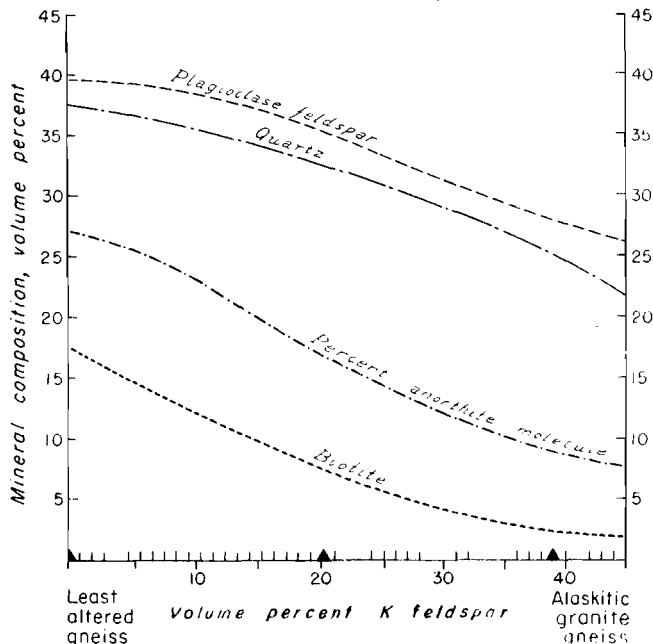


FIGURE 3.—GENERALIZED CURVES SHOWING INTERRELATIONSHIPS IN THE MINERALOGICAL, CHEMICAL, AND TEXTURAL EVOLUTION OF THE GNEISS COMPLEX DUE TO GRANITIZATION

Curves are based upon specimens whose modal analyses are published in Engel and Engel, 1953b, Figures 5, 6, and 7. Each tick on the horizontal co-ordinate indicates a modal analysis. These analyses are arranged from left to right in order of increasing K feldspar content. This order is inferred from field relationships to represent increasing degree of injection and replacement by granite-forming substances. Gaps in the sequence of ticks indicate no specimen of requisite K feldspar composition is available. The darts mark composite specimens analyzed chemically. These chemical analyses appear in columns 1, 3, and 4, Table 13.

PLATE 3.—MIGMATITE AND INEQUIGRANULAR GRANITIZED GNEISS

FIGURE 1.—Crenulated migmatite. The light-colored pegmatitic layers are composed largely of quartz, K feldspar, and oligoclase with scattered muscovite, biotite, and garnet. The darker gneiss has undergone slight to marked feldspathization (K feldspar) and shows a range in composition equivalent to that of specimens in Table 9. The crenulated pegmatite in part follows, and in part cuts across the dominant foliation. About  $\frac{3}{4}$  mile south of Balmat, New York. Note the hammer for scale.

FIGURE 2.—Inequigranular granitic gneiss. The large (up to 2 inches long) anhedral to almost euhedral porphyroblasts are pink microclines, some of which cut or abut against the dominant foliation. They clearly formed by replacement of the groundmass (paragneiss) which now has about the composition of the rock in column 3, Table 13. Note the quarter dollar for scale.

FIGURE 3.—Inequigranular granitic gneiss (augen gneiss). This is the dominant granitic gneiss in the complex. It commonly grades into least altered gneiss and is intermediate in composition between it and more granitic gneiss. The differences between the microcline "eyes" in this rock and the euhedrons in Figure 2 are largely of form, induced by shearing motions during and slightly after the growth of the "eyes" The scale is 6 inches long.

TABLE 7.—CHEMICAL AND MODAL ANALYSES OF SELECTED SPECIMENS OF LEAST ALTERED GNEISS BETWEEN EMERYVILLE AND COLTON, NEW YORK  
In chemical analyses, oxides given in weight per cent

	West Balmat Group 1A	Emeryville Group 1					Edwards Group 2	Russell Group 3	Colton Group 5				
	Bgn 27	Qb 235M	Qb 230	Qb 231	Qb 228	$\bar{x}$	Qb 234*	Bgn 14	Bgn 18†	Bgn 20	Bgn 21†	Bgn 19†	$\bar{x}$
SiO <sub>2</sub>	67.92	68.24	68.65	70.91	68.12	68.77	68.04	68.85	61.27	65.37	68.63	63.87	64.79
TiO <sub>2</sub>	.70	.67	.65	.66	.87	.71	.80	1.02	.78	.67	.52	.57	.64
Al <sub>2</sub> O <sub>3</sub>	15.53	14.82	15.19	13.88	14.44	14.77	14.80	14.90	17.94	17.83	16.06	17.84	17.42
Fe <sub>2</sub> O <sub>3</sub>	.77	1.08	.51	.54	.33	.65	.23	.36	.67	.53	1.02	.56	.70
FeO	3.51	3.81	3.90	3.88	4.89	4.00	5.04	4.26	6.81	3.47	.86	6.03	5.04
MnO	.05	.06	.08	.07	.04	.06	.07	n.d.	.05	.04	.05	.09	.06
MgO	2.04	1.88	1.86	1.42	2.17	1.87	1.73	2.37	3.01	1.81	1.71	2.63	2.29
CaO	2.22	3.04	2.42	2.24	2.32	2.45	2.76	2.17	3.29	4.35	3.61	3.45	3.68
Na <sub>2</sub> O	3.90	3.11	3.84	3.34	3.30	3.50	3.42	3.58	3.51	3.89	3.34	3.53	3.57
K <sub>2</sub> O	2.67	2.59	2.09	2.40	2.46	2.44	2.37	1.82	1.93	1.57	1.02	1.04	1.39
H <sub>2</sub> O+	.72	.72	.74	.59	.87	.73	.61	.81	.56	.49	.36	.37	.45
P <sub>2</sub> O <sub>5</sub>	.11	.09	.10	.07	.09	.09	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	..
F	.07	.07	.07	.08	.08	.07	.09	.06	.04	.05	.03	.04	.04
Total	100.21	100.18	100.10	100.08	99.98		99.96	100.20	99.86	100.07	100.21	100.02	

Modes													
Volume per cent													
Quartz	32.33	34.67	33.89	38.96	32.35	34.44	33.60	34.04	22.58	26.55	36.27	28.40	28.45
Plagioclase	44.37	40.98	45.17	38.92	46.35	43.16	42.63	43.84	46.83	55.05	48.90	49.25	50.00
K feldspar	1.71	4.60	.75	3.71	.67	2.29	4.67	1.20	3.08	3.40	.73	.93	2.04
Biotite	19.97	17.46	18.32	16.05	19.85	18.33	16.81	19.47	15.66	10.08	7.07	7.45	10.06
Garnet			.13		.10	.05	1.94	1.00	9.70	4.40	5.87	12.78	8.19
Chlorite	.47	.72	.27	.96	.17	.52		.33	.76	.13	.17	.40	.37
Muscovite	.80	.47	1.18	1.10	.01	.71							
Opauques**	.07	.37	.17	.23	.07	.18	.10	tr	.08	.20	.53	.10	.23
Zircon	.06	.07	tr	.07	.07	.05	tr	tr	tr	tr	.08	.05	.03
Apatite	.16	.12	.12	tr	tr	.08	tr	tr	tr	tr	.05	.11	.04
Sericite	.06	.41	tr	tr	.36	.16	.25	.12	.51	.19	.33	.53	.39
Other		.13 <sup>c</sup>				.03			.80				.20
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Composition of plagioclase	Ab 75	Ab 64	Ab 72	Ab 72	Ab 72	Ab 71	Ab 69	Ab 72	Ab 64	Ab 60	Ab 65	Ab 64	Ab 63
Number of sections	2	2	2	3	2		2	2	3	3	3	3	3
Number of counts	3000	3000	3000	4500	3000		4500	3000	4500	4500	4500	4500	

\* Analyses calculated from mode.

† Alkali determinations by J. L. Smith method.

\*\* Chiefly magnetite with hematite, ilmenite and pyrite.

tr Less than .05.

<sup>c</sup> Calcite.



TABLE 7—Concluded

Trace Elements  
(Parts per million)

Element	Sensitivity	West Balmat Group 1A	Emeryville Group 1					Edwards Group 2	Russell Group 3	Colton Group 5				
		Bgn 27	Qb 235M	Qb 230	Qb 231	Qb 223	$\bar{x}$	Qb 234*	Bgn 14	Bgn 18†	Bgn 20	Bgn 21‡	Bgn 19‡	$\bar{x}$
B	10	8	6	10	9	7	8	<10	15	18	12	10	14	
Ba	20	1100	620	650	220	375	593	1400	600	400	360	380	435	
Co	2	7	7	9	5	8	7	9	9	7	8	12	9	
Cr	5	28	32	40	28	38	33	38	45	40	38	60	46	
Cu	1	12	18	11	8	40	18	25	3	16	9	12	10	
Ga	5	11	12	10	11	8	10	10	20	12	10	15	14	
La	80	pt	pt	pt	120	90	pt	pt	125	88	70	90	93	
Mn	2	550	350	500	200	135	347	350	140	200	300	550	298	
Mo	3	..	..	pt	..	5	..	..	..	..	..	..	..	
Nb	15	<10	<10	12	16	pt	pt	<10	10	pt	pt	pt	pt	
Ni	2	16	16	20	12	18	16	23	30	15	18	25	22	
Pb	10	8	14	9	8	15	11	10	18	6	10	25	15	
Sc	2	13	12	14	14	14	13	15	15	22	16	28	20	
Sn	5	..	pt	..	7	..	..	..	..	..	pt	pt	..	
Sr	2	360	330	340	250	275	311	710	425	350	250	350	344	
Ti	2	2500	2000	2400	2200	2600	2340	1350	3500	2800	2500	3300	3025	
V	2	65	60	64	50	55	59	62	78	65	42	75	65	
Y	10	44	44	35	75	55	51	35	55	35	65	85	60	
Yb	1	5	4	3	6	4	4	5	2	2	4	6	3	
Zr	2	170	130	175	210	200	177	240	200	180	100	140	155	
Number of analyses		4	3	3	2	2	14	2	3	3	3	2	11	

pt Approximately at level of sensitivity.

greenish-brown biotite, calcic oligoclase, and a little muscovite. Figure 1 of Plate 2 is a photograph of this gneiss veined by pegmatite. Granite and pegmatite intertongued with and transitional into gneiss include both inequigranular and equigranular varieties, the latter being generally less biotitic, more massive, and highly potassic. Plate 3 illustrates three types of more granitic migmatite and inequigranular granitic gneiss. In the Emeryville-Edwards areas a mappable textural break commonly occurs at or near the mineralogical composition: plagioclase 38 (Ab78), quartz 35, K feldspar 15, and biotite 10 (Fig. 3). This common textural discontinuity is used in field mapping to delineate incipient migmatite and least altered gneiss from more granitized gneiss (called highly granitized gneiss on Pl. 4). Along perhaps three-fourths of the "contacts" of these lithologic types, a slight to obvious compositional discontinuity coincides with the textural break. Along the remaining "contacts" no clearly defined compositional break exists; at many of these localities abrupt variations in textures also disappear. Some of the least altered gneiss and migmatite grade into granite gneiss. Examples of this compositional and textural transition between gneiss and granite gneiss are indicated on Plate 4 by the stippled pattern labeled migmatite and highly granitized gneiss.

As the least altered segments of the gneiss complex are traced northeastward toward Colton (and the massif), grain size increases appreciably (Pl. 2, compare Fig. 1 with Fig. 2). Gross interrelationships of least altered gneiss and incipient migmatite to granite gneiss remain quite similar. The amount and per cent of least altered gneiss may decrease slightly from Emeryville to Colton. Important changes occur in its composition. Granite gneiss also undergoes changes in composition and texture as it increases in abundance and in igneous characteristics toward the massif. These features of least altered gneiss and associated granite gneiss are discussed in the succeeding sections.

#### *Least Altered Gneiss*

*Introduction.*—The properties of 11 specimens of least altered gneiss have been studied in detail. These include five specimens from the Emeryville area—Groups 1 and 1A—as follows: Bgn 27, Qb 235M, Qb 230, Qb 231, Qb 228; one specimen from the Edwards area—Group 2—Qb 234; one specimen from the

Russell area—Group 3—Bgn 14; and four specimens from the Colton area—Group 5—Bgn 18, Bgn 20, Bgn 21, Bgn 19. The chemical and mineral compositions of these specimens are listed in Table 7, together with average compositions in the Emeryville and Colton groups. The localities from which the samples came are shown on Plates 1 and 4. The distinction between least altered and incipiently granitized or otherwise altered gneiss is necessarily somewhat arbitrary. The compositions of several other specimens of gneiss that from field and petrographic studies are clearly only slightly altered (granitized) have been listed with the granitized types of gneiss in Table 9. These very slightly granitized specimens are: in the Emeryville area (Group 1), Bgn 29, Qb 236, Qb 7, Qb 229; in the Edwards area (Group 2), Qb 100; in the Russell area, Bgn 9; and in the South Pierrepoint area (Group 4), Bgn 29.

Modal analyses of 1500 to 4500 counts each have been made on 62 additional specimens of least altered gneiss. Of these 62 rocks, 19 are in Group 1, 18 in Group 2, 15 in Group 3, and 10 in Group 5. The mineral and chemical compositions of these 62 specimens, together with the compositions of the 11 previously cited specimens are summarized in Table 8 as the mean and the range of compositions of least altered gneiss in Groups 1, 2, 3, and 5. The chemical compositions of the 62 specimens not listed in Table 7 are calculated from the modes by using the mean composition of constituent minerals as determined by the various methods of analysis cited in the introduction. The justification for computing these analyses from the modes has been given in the section on modal analysis of rocks.

Arguments have been presented (Engel and Engel, 1953b, p. 1078–1083) why the chemical composition of least altered gneiss of the Emeryville-Edwards region is thought to approximate the early or pre-metamorphic sedimentary rock. The designation least altered gneiss was made during field mapping. Its composition as determined by either modal or chemical analyses has proved to be as distinctive as its texture or field relationships (Table 7; Table 8, column 1; Fig. 4).

The associated pegmatite and granite gneiss (Fig. 3; Fig. 7) appear to be introduced into the more granitic gneiss of the Emeryville area, rather than partly sweated out of the least granitic parts (Engel and Engel, 1953b, p. 1078–1081).

Least altered gneiss of the Colton area also

seems to be essentially devoid of introduced substances; but either K, Si, and H<sub>2</sub>O have been removed from this least altered gneiss, or its sedimentary parent was a more mafic rock.

tion”<sup>6</sup> of the least altered gneiss are many interesting changes in texture and mineral composition. These are discussed with the aid of Tables 7 and 8 and Figure 5, which sum-

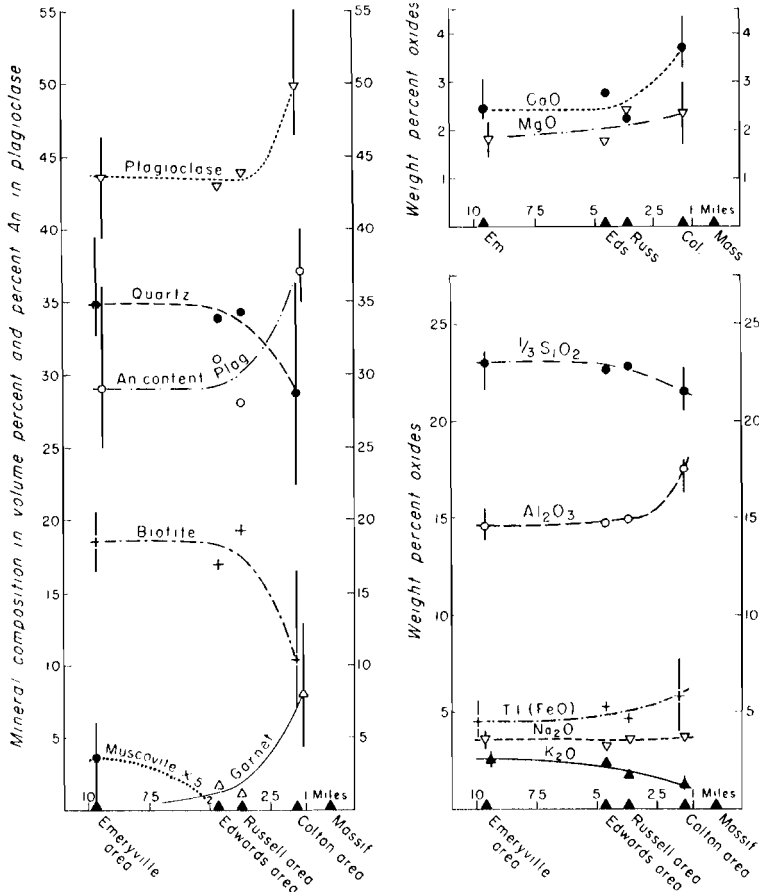


FIGURE 4.—GENERALIZED CURVES INDICATING CHANGES IN MINERAL AND MAJOR-ELEMENT COMPOSITION OF 11 SPECIMENS OF LEAST ALTERED GNEISS STUDIED IN DETAIL (TABLE 7) AS TRACED FROM EMERYVILLE TO COLTON, NEW YORK

Points indicate the mean composition of least altered gneiss in each area or group. The vertical lines through points at Emeryville and Colton indicate the maximum range or dispersion of values from the mean. Distances between areas on the horizontal co-ordinate are measured along horizontal lines drawn normal to the trace of the perimeter of the massif to the center of each area or group (see Pl. 1).

This is clearly shown in Figures 4 and 5, prepared from, respectively, the modal and chemical analyses of least altered gneiss in Tables 7 and 8. Conceivably K and Si were mobilized from the gneiss at Colton and segregated to form some of the more granitic lenses and leaves there, as well as mobile constituents of the “granite” injecting and granitizing the gneiss in the Emeryville area. Complementary to the possible “degranitization” or “basifica-

marize the compositional data on specimens of least altered gneiss between Emeryville and Colton.

*Mineralogy and Texture.*—The assemblage quartz, greenish-brown biotite, oligoclase, and muscovite in least altered gneiss at Emeryville

<sup>6</sup> Terms used by respectively Rosenquist (1952, p. 75) and Ramberg (1951, p. 33) to express the loss of alkali (s) and silica from rocks during extreme metamorphism.



represents the lowest-rank regional metamorphic conditions<sup>7</sup> in the Adirondack orogen. In conventional terms this is presumably upper-middle rank, the highest temperature part of the amphibolite facies of Eskola (1920).

As the least altered parts of the gneiss are traced northeastward to Colton, the following general changes occur: muscovite disappears approximately 10 miles northeast of Emeryville in the Edwards area (Pl. 1; Fig. 4; Fig. 5), and almandite garnet and K feldspar appear consistently through the least altered gneiss. Southwest of Edwards, garnets are confined principally to contacts of pegmatite and gneiss (Engel and Engel, 1953b, p. 1072–1075). As the massif is approached, garnet becomes a major constituent in the least altered gneiss. Sympathetically, the mean plagioclase becomes more calcic. Plagioclase at Emeryville averages Ab 73; that at Colton averages about Ab 67 (Table 8). Biotite changes from greenish brown through successive shades of brown and reddish brown to deep red brown. The quartz content of the gneiss decreases from a mean of about 38 per cent at Emeryville to less than 30 per cent near Colton. Statistical analyses of the data using the “Student’s” *t* test (Mood, 1950, Ch. 9) indicate all the cited differences are real. The probability of the differences of the means being due to chance is less than 0.05 in every instance. The changes in the physical and chemical properties of the minerals are discussed in Part 2.

Texturally, most of the least altered gneiss in the Emeryville area is massive, medium-grained (*see* Engel and Engel, 1953b, especially Table 10), and granoblastic. In volume it totals about one-third the gneiss complex. More or less migmatitic and granitized gneiss makes up the other two-thirds. Northeastward, the grain size of the less deformed parts increases several times, and the per cent of least altered gneiss may decrease slightly. The changes noted in least altered gneiss between Emeryville and Colton are accompanied by the appearance of lithologic (segregational?) banding northeast of Russell. The appearance of bands or layers is a most subtle effect, but their existence is striking if gneiss from opposite ends of the belt is compared directly (Pl. 2, Figs. 1 and 2). The gneissic layers in the Colton area range up to several inches in thickness and are defined by alternations of more or less biotitic

and garnetiferous rock. In some of the banded gneiss, grain size varies systematically across the bands from coarse to fine, simulating graded bedding. A good approximation of the bulk composition of the most distinctly layered gneiss requires a sample cut across a foot or more of the rock, normal to the layers. The restriction of these layers to the area of highest-temperature metamorphism, and the fact that individual bands make a most improbable sediment suggest they are due to metamorphic differentiation. Such differentiation is most compatible with the evidence that more felsic constituents are separated from the least altered gneiss.

The detailed patterns of distribution of garnet and muscovite are of interest, in so far as they may reflect the occurrence of an isograd or merely an isoblast or isophase.<sup>8</sup> It is to be recalled that in going northeast garnet first appears throughout the entire gneiss complex in the Edwards area. Southwest of Edwards, in the Emeryville area, garnet is confined largely to contacts of pegmatite and gneiss and is rare or absent in many parts of least altered gneiss (Engel and Engel, 1953b, p. 1072–1076). Muscovite occurs throughout the gneiss complex in the Emeryville area and disappears abruptly from all parts of the gneiss in the Edwards area. The isophase line indicating the disappearance of muscovite is therefore relatively undeflected at contacts of more or less granitic and pegmatite gneiss; but the isophase drawn at the first appearance of garnet is extremely irregular.

The distribution of garnet may be explained in one of several ways. Conceivably garnet was a stable phase in the least altered gneiss around Emeryville and Balmat (that is southwest of Edwards), but the reaction permitting its formation was infinitely slow. The possibilities of sluggish reaction rates in displacing an isophase have been emphasized by Yoder (1952), from his studies of artificial systems. If this interpretation is the correct one, the presence of garnet in the pegmatitic seams may be due to an increased mobility of the reaction in those parts of the gneiss soaked by granitizing and pegmatite-forming fluids.

An obvious alternative is that garnet was not a stable phase in the least altered gneiss

<sup>7</sup> Omitting, of course, the relatively small scale, patchy, retrograde alteration of chlorite, sericite, albite, and so on.

<sup>8</sup> Yoder (1952, p. 621–623) has pointed out possible differences between an isograd and an “isoblast”—a line indicating the appearance of a new phase with increasing metamorphism. The word isophase is used in this paper as synonymous with isoblast.

but was stable at sites of pegmatites because of differences between these different rock systems in temperature, pressure, composition, or chemical potential of a vapor phase. Contrasting possibilities may be imagined, of pegmatites forming along zones of shear in which vapor pressure of volatiles was either relatively high or low. Garnet may have formed along the pegmatites if this site was relatively anhydrous compared to the body of the least altered gneiss. Certainly a marked compositional gradient existed between areas of pegmatization and the cores of least altered gneiss, as is clear from inspection of Figures 3 and 7. Garnet exists principally at sharp contacts of pegmatite and gneiss or in gneissic inclusions and schlieren in the pegmatites. The well-defined pegmatites and granitic layers more devoid of mafic con-

stituents contain no garnets. This is expectable, for wherever the granitic- and pegmatite-forming processes have gone well toward completion, an alaskitic leucogranite gneiss is formed (see right-hand side of Fig. 7). In this granitic system garnet is not an equilibrium phase.

*Chemical composition: major elements.*—The major changes in chemical composition in the least altered gneiss between Emeryville and Colton that complement the mineralogical changes are plotted in Tables 7 and 8 and in Figures 4 and 5, alongside the data on mineral composition. Si, K, Fe<sup>+++</sup>, and H<sub>2</sub>O decrease as the massif is approached, whereas total Fe, Al, Mg, and Ca increase. These changes first became apparent in plotting the data from the nine specimens of least altered gneiss studied in detail (Fig. 4; Table 7). From statistical

TABLE 8.—AVERAGE CHEMICAL AND MINERALOGICAL COMPOSITIONS, AND RANGE IN COMPOSITIONS OF LEAST ALTERED GNEISS IN THE GNEISS COMPLEX BETWEEN EMERYVILLE AND COLTON, NEW YORK

Data include the analyses of least altered gneiss in Table 7, plus data from 62 additional specimens added to improve the sampling and clarify trends in composition. In chemical analyses, oxides given in weight per cent.

	Emeryville Area Group 1			Edwards Area Group 2	Russell Area Group 3	Colton Area Group 5		
	1	2	3	4	5	6	7	8
SiO <sub>2</sub>	70.25	72.01	66.71	69.61	69.16	65.97	69.92	60.84
TiO <sub>2</sub>	.67	.88	.59	.74	.70	.64	.81	.50
Al <sub>2</sub> O <sub>3</sub>	14.14	16.74	12.01	14.39	15.09	16.83	18.01	15.48
Fe <sub>2</sub> O <sub>3</sub>	.55	1.51	.33	.47	.33	.36	1.11	.20
FeO	3.83	4.89	2.87	4.35	4.24	4.92	6.81	3.38
MnO	.05	.03	.09	.06	.05	.07	.11	.03
MgO	1.76	2.58	1.26	1.75	1.74	2.25	3.16	1.68
CaO	2.20	3.22	1.55	2.56	2.85	3.41	4.51	2.49
Na <sub>2</sub> O	3.43	3.90	2.93	3.45	3.62	3.70	3.96	2.67
K <sub>2</sub> O	2.40	2.91	1.84	2.06	1.70	1.46	2.46	1.02
H <sub>2</sub> O+	.72	.97	.21	.56	.52	.39	.60	.30
Total	100.00			100.00	100.00	100.00		
Number of specimens	24†			19	16	14*		

Modes  
Volume per cent

Quartz	37.86	45.60	30.96	36.50	34.99	29.28	36.27	22.58
Plagioclase	39.86	47.30	32.01	42.00	44.75	48.92	55.10	41.90
K feldspar	3.19	4.60	.23	3.70	2.91	3.17	4.30	.73
Biotite**	17.60	21.96	13.00	14.98	13.85	10.68	16.46	7.07
Garnet	.03	3.00	.00	2.21	3.10	7.38	14.10	.08
Muscovite	.86	1.84	.01	tr	..	..	..	..
Others††	.60	1.63	.37	.61	.40	.57	1.27	.22
Total	100.00			100.00	100.00	100.00		
Composition of plagioclase	Ab 73	Ab 78	Ab 50	Ab 71		Ab 67	Ab 55	Ab 74
Number of specimens	24†	..	..	19	16	14*	..	..

TABLE 8.—*Concluded*

Trace Elements  
 (Parts per million)

Element	Sensitivity	Emeryville Area Group 1			Edwards Area Group 2	Russell Area Group 3	Colton Area Group 5		
		1	2	3	4	5	6	7	8
B	10	10	15	<6	10	10	12	18	<10
Ba	1	612	1200	375	600	650	492	700	280
Co	2	8	12	5	10	8	7	12	4
Cr	5	35	45	25	25	40	56	65	35
Cu	1	16	40	6	12	15	12	20	3
Ga	5	11	15	8	12	12	14	20	10
Mn	2	356	575	135	340	350	341	600	140
Nb	15	pt	16	<10	<10	<10	pt	15	<10
Ni	2	15	20	12	10	12	21	30	15
Pb	10	12	15	<8	10	12	15	25	6
Se	2	12	16	11	15	15	17	30	8
Sr	2	310	490	225	550	500	304	580	230
Ti	2	2800	3000	2000	3000	2200	3000	3500	2000
V	2	56	65	50	50	65	81	90	42
Y	10	46	75	35	55	40	58	85	25
Yb	1	3	5	2	3	4	3	6	2
Zr	2	171	200	130	180	220	176	200	100
Number of specimens		9†	...	...	4	6	8*	...	...

\* Modes and major-element composition based upon 14 specimens, whereas trace-element data are from only 8 of these specimens

† Modes and major element composition based upon 24 specimens, whereas trace-element data are from only 9 of these specimens.

\*\* Includes minor chlorite which replaces biotite.

†† Chiefly apatite, zircon, magnetite, and pyrite.

Description of samples:

Columns 1, 2, and 3 are mean, maximum, and minimum values respectively for 24 specimens of least altered gneiss in the Emeryville area, including the five specimens in Table 7. Composition of major elements in 19 specimens not shown in Table 7 are calculated from modes and chemical analyses of minerals.

Column 4 is the mean of 19 specimens of least altered gneiss in the Edwards area. One of these specimens (Qb 234) is listed in Table 7. Composition of other specimens calculated from the modal data.

Column 5 is the mean of 16 specimens of least altered gneiss in the Russell area. One of these specimens (Bgn 14) is listed in Table 7. Compositions of other specimens calculated from the modal data.

Columns 6, 7, and 8 are mean, maximum, and minimum values respectively for 14 specimens of least altered gneiss from the Colton area, including the four samples in Table 7. Compositions of 10 specimens not shown in Table 7 are calculated from modes and chemical analyses of minerals.

studies using the "Student's" *t* test it was obvious, however, that these trends, based upon only 11 specimens, might be due to chance. Accordingly the additional 62 specimens incorporated in Figure 5 and Table 8 were chosen on the basis of their systematic distribution in the least altered gneiss. All the trends indicated by the limited sampling exist in the larger sample (Fig. 5). The probability that the differences in means of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO, CaO, and H<sub>2</sub>O are due to chance is less than 0.05. With the larger sample, definite evidence of "basification" of the gneiss appears about three-fourths of the way from Emeryville to Colton, that is, about 10 miles from the massif (measured along the strike of the gneiss). If the temperature calibration is

approximately correct, and the changes are of metamorphic origin, the temperature of incipient degranitization at this point was about 550° C. ± 50° C.

Several questions arise: (1) Is the change in composition of the least altered gneiss metamorphic in origin? (2) Are at least some of the granitic and migmatitic parts of the gneiss complex in the Colton area frozen-in relicts of degranitization-differential anatexis? (Eskola, 1933) (3) Is the potassic injection material that invades the gneiss at Emeryville in part or wholly derived from lateral extensions or underlying parts of the gneiss undergoing ultra-metamorphism and degranitization? There appear to be no data definitely opposed to these possibilities. Yet none can be established



definitely. The fact that the changes in composition of the least altered gneiss between Emeryville and Colton coincide with increased temperatures of metamorphism is certainly

The least altered parts of the gneiss complex appear, nevertheless, to be compositionally similar to those present at Emeryville. The least altered gneiss seems, therefore, nearly

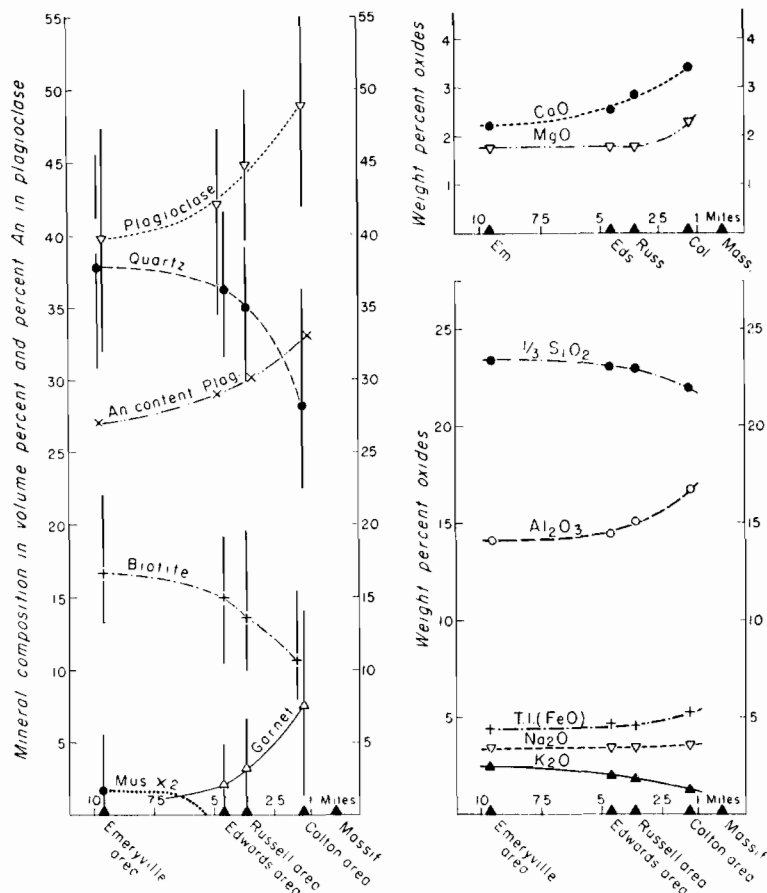


FIGURE 5.—GENERALIZED CURVES INDICATING CHANGES IN MINERAL AND MAJOR-ELEMENT COMPOSITION OF LEAST ALTERED GNEISS AS TRACED FROM EMERYVILLE TO COLTON, BASED UPON 73 SPECIMENS

(See Fig. 4 and Table 8.) Chemical compositions of 62 of the specimens are calculated from modal analyses and from chemical analyses of the constituent minerals in the gneiss.

suggestive of a metamorphic origin. Southwest of Emeryville the gneiss complex can be traced about 20 miles to a point beyond Antwerp and Philadelphia, New York. There it passes beneath the lower Paleozoic sedimentary formations. Throughout this southwesterly segment of the gneiss (not described in this paper) the conditions of metamorphism were essentially those of Emeryville. In the Philadelphia and Antwerp, New York, areas, however, granitized gneiss is more abundant, and least altered gneiss rarer than at Emeryville.

uniform in composition throughout a distance of about 30 miles, from a point southwest of Antwerp to Edwards. Viewed on this regional scale, the systematic change in composition of the gneiss with increased temperature (and rank) of metamorphism strongly suggests the cause is metamorphic.

As noted earlier, the interpretation of a metamorphic origin for the basification of the gneiss in the Colton area seems susceptible to proof. Several metasedimentary units in the Grenville subprovince (A. E. J. Engel, 1956,

p. 77, 81–84) and elsewhere in the world are of about the same composition as the least altered gneiss at Emeryville. Segments of some of these gneiss belts appear to have undergone progressive metamorphism, at about the temperatures recorded in the Adirondack paragneiss. If investigations indicate they also undergo a basification coincident with extremely high-grade metamorphism, a metamorphic origin for the compositional change would seem established.

Propos of this problem, the work and observations of Ramberg (1951), Shaw (1954), and Lapadu-Hargues (1949) are of considerable interest. Ramberg has studied paragneisses in Greenland that have a bulk composition very similar to the Adirondack gneiss. Ramberg concludes from the samples studied that

“The main gneiss of the granulite facies is distinctly more basic than the main gneiss of the amphibolite facies area. The former is relatively rich in Mg, Fe<sup>++</sup>, Fe<sup>+++</sup>, Ca, Ti and Mn; the latter in Si, Na, K, O, H<sub>2</sub>O.”

He suggests that the cause of the change is metamorphic. An obvious question is whether Ramberg's sampling and field data are adequate to demonstrate his conclusion.

In contrast Shaw's handling of analyses of the Littleton formation (New Hampshire) indicates no change in the composition of this rock with increased rank of metamorphism, other than minor addition of CaO and Na<sub>2</sub>O and loss of H<sub>2</sub>O (1956, p. 919–934). Shaw comments (p. 920):

“It is commonly believed by many petrologists that argillaceous sediments generally do not change in composition during metamorphism (except by loss of volatiles) although exceptions have been recognized in some areas.”

As Shaw notes (1956, p. 920), however, there has been essentially no careful work to justify this belief. His studies certainly suggest that only volatiles have been lost during the metamorphism of the Littleton formation. He then concludes:

“The view that pelitic rocks usually undergo a far-reaching change in composition during regional metamorphism can therefore not be accepted.” (1956, p. 931).

Obviously critical differences in metamorphism from region to region may determine whether it is crudely isochemical or not. Presumably temperature is a critical factor. In the paragneisses of Greenland and the Adirondack

Mountains, isochemical metamorphism appears to occur up to temperatures of about 550° C. Inasmuch as most regional metamorphism in exposed rocks seems to be at lower temperatures, very approximate isochemical metamorphism may prove to be the rule.

Shaw's concluding comments were taken out of a context in which he reviewed the work of Lapadu-Hargues (1949). In this widely cited work Lapadu-Hargues assembled analyses of metamorphic rocks which seem to indicate a progressive change in composition of clastic metasedimentary rocks with increasing rank of metamorphism. Unfortunately the analyses are of rocks from widely diverse terranes and of very different, commonly not well understood origins. Accordingly their arrangement and interpretation by Lapadu-Hargues is liable to considerable question and error.

There seems to be no great quarrel about the eclectic concept of mobilization and upward migration of silicon, alkalis, and water from deep-seated rocks undergoing extreme metamorphism. The sialic nature of continental masses seems to prove that the process can occur. And if the process occurs, it can be interrupted, leaving a granitic extract in various states of birth and migration. The difficulty is in distinguishing the venitic from the arteritic<sup>9</sup> migmatites (Engel and Engel, 1953b, p. 1079–1080).

Both the data and theoretical considerations are consistent with the idea of degranitization and venitic migmatization of the gneiss at Colton, in contrast to arteritic migmatization and injection of granitic substances in the Emeryville area. These interpretations do not conflict with Buddington's interpretation (1939; 1948; 1957) that much of the granitic rock in the Colton area is of a deeper-seated magmatic origin and is injected into and shredding the gneiss. This magma presumably was frozen in its ascent from deeper, even hotter sources in the orogen.

*Chemical composition: minor elements.*—The trace-element compositions of the least altered gneiss in the Emeryville-Colton region are shown in Tables 7 and 8. It should be noted that two separate averages are given for gneiss in both the Emeryville and Colton areas. The averages in Table 7 are of the composition of specimens of least altered gneiss given there. The specimens are, for Group 1: Bgn 27, Qb 235M, Qb 230, Qb 231, and Qb 228, and for

<sup>9</sup> Terms suggested by respectively Holmquist (1921) and Sederholm (1923).

TABLE 9.—CHEMICAL AND MODAL ANALYSIS OF SPECIMENS OF GRANITIZED GNEISS FROM THE PARAGNEISS COMPLEX BETWEEN EMERYVILLE AND COLTON, NEW YORK

In chemical analyses, oxides given in weight per cent

	West Balmat Group 1A	Emeryville Group 1								Edwards Group 2			Russell Group 3			South Pierrepont Group 4		Colton Group 5	
	Bgn 261	Bgn 29*	Qb 236	Qb 237*	Qb 3†	Qb 7†	Qb 229	Qb 226	Qb 227	Qb 233*	Qb 100	Qb 216	Bgn 9	Bgn 4†	Bgn 6	Bgn 25	Bgn 16*	Bgn 22*	Bgn 23*
SiO <sub>2</sub>	69.63	68.67	67.83	67.58	70.12	68.75	65.02	69.40	69.51	64.30	61.96	68.89	69.32	67.37	67.12	61.28	66.61	68.89	69.96
TiO <sub>2</sub>	.66	.61	.81	.70	.62	.62	.73	.57	.62	.98	1.01	.68	.51	.56	.68	.76	.72	.45	.63
Al <sub>2</sub> O <sub>3</sub>	14.41	15.25	13.92	14.89	13.79	15.53	16.12	15.22	14.45	14.74	17.23	13.90	15.66	16.89	16.05	18.28	15.56	15.13	14.85
Fe <sub>2</sub> O <sub>3</sub>	.87	.43	.62	.56	.60	.47	.48	.56	.92	.79	.56	.31	.34	.21	.50	.60	.61	.41	.35
FeO	3.78	3.26	4.49	3.88	3.65	3.89	5.08	2.61	3.35	6.52	5.15	4.55	3.27	2.52	3.01	4.79	4.57	4.10	2.53
MnO	.03	.01	.07	.01	.06	.07	.04	.06	.07	.10	.07	.04	.05	n.d.	n.d.	n.d.	.03	.06	.02
MgO	1.49	1.72	2.79	2.05	1.81	1.62	2.31	1.73	1.61	2.76	2.01	1.94	1.55	1.87	1.46	2.84	2.44	1.65	1.45
CaO	2.38	2.46	1.75	1.95	1.73	2.16	2.33	2.09	1.69	.88	3.81	1.66	2.39	1.43	2.12	2.96	2.35	1.67	1.57
Na <sub>2</sub> O	2.76	3.82	2.84	3.29	3.05	3.23	3.54	2.66	3.56	1.74	3.66	2.64	3.63	4.02	3.37	4.23	3.32	3.08	3.17
K <sub>2</sub> O	3.32	3.11	3.95	4.27	3.73	3.04	3.36	4.17	3.47	6.39	3.39	4.41	2.71	4.67	5.13	3.45	3.28	4.40	5.29
H <sub>2</sub> O+	.59	.61	.84	.76	.78	.71	.91	.70	.73	.78	.79	.68	.48	.58	.59	.74	.59	.23	.33
P <sub>2</sub> O <sub>5</sub>	.05	n.d.	n.d.	n.d.	.08	.07	.08	.07	.10	n.d.	.07	.07	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
F	n.d.	.05	.08	.06	.04	.06	.10	.05	.06	.08	.13	.10	.04	n.d.	n.d.	n.d.	.06	n.d.	n.d.
Total	99.97	100.00	99.99	100.00	10.06	100.22	100.10	99.89	100.14	100.06	99.84	99.87	99.95	100.12	100.03	99.93	100.05	100.07	100.15

Modes, Volume per cent

Quartz	35.58	30.26	34.23	29.69	35.64	34.75	28.28	33.91	33.37	27.57	17.25	34.14	32.43	21.25	24.90	19.20	30.38	29.29	28.65
Plagioclase	34.65	42.84	31.83	34.68	32.02	36.10	41.29	33.01	35.93	13.71	44.64	28.03	44.50	20.10	31.47	48.07	37.62	29.99	28.97
K feldspar	11.24	9.43	9.69	16.39	13.86	8.85	6.94	15.22	12.30	31.37	10.73	18.13	8.87	24.70	29.40	10.26	12.15	26.77	30.65
Biotite	16.65	15.61	23.13	18.92	17.01	17.60	21.87	16.09	16.83	21.10	21.54	17.97	10.10	10.35	13.20	19.56	15.03	17.09	9.50
Garnet	..	..	..	..	..	.50	.45	.20	..	5.59	.20	1.22	3.31	.40	.42	2.01	3.92	6.40	1.80
Chlorite	.49	.61	.34	tr	.47	.39	.44	.11	.13	.30	.27	.11	.31	.37	.23	.41	.20	.16	.16
Muscovite	.73	.22	.32	.17	.70	1.30	.44	1.19	.74	..	..	.17	..	..	..	..	..	..	..
Opakes**	.53	.20	tr	tr	tr	tr	tr	.10	.08	.09	.36	tr	.07	.17	.15	.12	.31	.18	.10
Zircon	tr	tr	tr	.07	.04	.07	.09	.05	tr	.08	.07	.11	.05	.07	tr	..	tr	tr	tr
Apatite	tr	tr	.09	.08	.06	.08	.08	.05	.15	.03	.43	tr	tr	.32	tr	.06	tr	tr	tr
Sericite	.13	.71	.37	tr	.20	.36	tr	.07	.40	.16	.73	.12	.26	1.95	.23	.18	.39	.12	.17
Other	tr	.09	tr <sup>a, c</sup>	.13 <sup>c</sup>	.10 <sup>c</sup>	tr <sup>a</sup>	.12	tr <sup>t, s</sup>	.07	..	3.78 <sup>b, c, a</sup>	..	.10 <sup>c</sup>	.32 <sup>c</sup>	..	.13 <sup>a</sup>	..	..	..
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Composition of plagioclase	Ab 68	Ab 73	Ab 73	Ab 74	Ab 74	Ab 70	Ab 72	Ab 68	Ab 77	Ab 74	Ab 68	Ab 72	Ab 72	Ab 76	Ab 75	Ab 68	Ab 70	Ab 76	Ab 76
Number of sections	2	2	2	2	2	2	3	2	2	3	3	2	3	2	2	3	3	3	3
Number of counts	3000	3000	3000	3000	3000	3000	4500	3000	3000	4500	4500	3000	4500	3000	3000	4500	4500	4500	4500

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Trace Elements  
(Parts per million)

Element	Sensitivity																			
B	10	40	40	24	16	12	15	pt	32	8	6	12	...	...	...	20	<10	<10	<10	<10
Ba	20	125	600	1200	830	750	540	650	2600	1000	980	700	...	400	1000	560	2100	1100	1200	1315
Co	2	8	7	7	8	8	7	6	3	6	10	10	...	5	5	6	10	10	8	4
Cr	5	34	28	34	31	40	30	19	30	28	35	15	...	20	20	25	22	46	21	19
Cu	1	7	44	2	1	7	4	35	3	2	20	7	...	7	10	80	6	47	8	12
Ga	5	7	12	9	9	9	8	12	12	11	17	13	...	15	15	13	25	14	17	14
La	80	...	pt	...	...	...	...	pt	75	pt	...	70	...	70	...	...	...	pt	pt	pt
Mn	2	800	350	380	350	350	650	365	300	370	250	320	...	200	80	240	300	840	520	700
Mo	2	...	...	...	...	pt	...	...	...	...	...	...	...	...	...	pt	...	...	...	...
Nb	15	...	<10	...	...	pt	...	pt	15	10	...	...	...	10	15	...	>10	<10	10	11
Ni	2	18	14	12	16	22	20	12	7	13	18	7	...	10	20	23	16	27	15	11
Pb	10	10	15	7	12	4	2	15	10	18	20	7	...	100	10	13	13	16	15	27
Sc	2	16	15	11	12	13	15	18	15	14	15	15	...	9	8	11	32	18	16	12
Sn	5	pt	...	...	...	...	...	pt	15	...	pt	...	...	...	...	11	...	...	...	...
Sr	2	180	550	500	430	300	310	185	220	470	470	700	...	100	1500	270	250	510	320	390
Ti	2	2700	2000	2500	2500	2500	2600	2300	2800	2600	2600	3400	...	2000	3000	2200	3000	3000	2800	3200
V	2	51	50	45	57	56	41	50	52	48	71	53	...	50	60	50	75	76	50	43
Y	10	61	50	32	44	45	45	65	45	50	54	57	...	40	20	60	58	47	48	52
Yb	1	3	4	2	3	3	3	4	3	3	4	3	...	3	1	4	7	5	5	5
Zr	2	160	160	150	150	170	175	140	200	180	180	200	...	200	200	215	134	175	200	240
Number of analyses		2	4	3	3	3	1	3	1	3	1	1		1	1	1	1	1	1	1

\* Analyses calculated from mode.  
 † Alkali determinations by J. L. Smith method.  
 \*\* Chiefly magnetite with hematite, ilmenite, and pyrite.  
 tr less than .05.  
 ° calcite.  
 ¢ sphene.  
 ¢ allanite.  
 ¢ hornblende.  
 ¢ tourmaline.  
 pt approximately at level of sensitivity.



Group 5: Bgn 18, 19, 20, and 21. Inspection of the average values for the elements in these two groups indicates they are very similar. The elements Ba, Co, Mn, Nb, Sc, Sr, Ti, Y, larger group of specimens (nine from Emeryville and eight from Colton) are given in columns 1 and 6 of Table 8. Application of the "Student's" *t* test to these larger samples

TABLE 10.—AVERAGE TRACE-ELEMENT COMPOSITION OF LEAST ALTERED GNEISS AND GRANITIC GNEISS COMPARED WITH THAT OF THE LITTLETON FORMATION  
 (See Shaw, 1954, pt. 1, Table 15.)

Element	Sensitivity*	Middle-Grade Metamorphism			High-Grade Metamorphism		
		Littleton formation (Shaw 1954) 1	Least altered gneiss Group 1 2	Granitic gneiss Group 1 3	Littleton formation (Shaw, 1954) 4	Least altered gneiss Group 5 5	Incipiently granitized gneiss Group 5 6
Co	2	19	8	4	18	7	5
Cr	5	113	35	4	109	56	18
Cu	1	23	16	19	13	12	18
Ga	5	16	11	12	20	14	12
Ni	2	64	15	4	57	21	8
Pb	10	16	12	38	27	15	32
Sc	2	11	12	6	16	17	8
Sr	2	524	310	270	760	304	225
V	2	125	56	24	120	81	30
Y	10	39	46	35	52	58	30
Zr	2	191	171	150	203	176	160
Number of specimens		20	9	3	30	8	4

\* Sensitivity reported by Chodos and Godijn.

Column 1, average composition of the Littleton formation at middle-grade metamorphism (Shaw, 1954, Table 15).

Column 2, average composition of least altered gneiss in the Emeryville area (from Table 8, col. 1).

Column 3, average composition of more granitic gneiss, Emeryville area (from Table 3, col. 3).

Column 4, average composition of the Littleton formation, at high-grade metamorphism (Shaw, 1954, Table 15).

Column 5, average composition of least altered gneiss in the Colton area (from Table 8, col. 6).

Column 6, average composition of incipiently granitized gneiss in the Colton area (Table 13, col. 6).

Yb, and Zr all lie within two standard deviations. The "Student's" *t* test shows that for these elements the probability of the means being due to chance is somewhat greater than 0.10. The elements B, Cr, Ga, Ni, Sc, V, and Y may, however, be enriched, and Cu and Ba ? may be depleted in the gneiss at Colton. This is indicated by the fact that there is about 0.10 or less probability that the differences are due to chance.

In an effort to clarify whether real differences in trace-element composition do exist, four additional specimens of least altered gneiss from each area were analyzed. The average trace-element compositions of this

of least altered gneiss in the two areas suggests that there are probably real although relatively small increases in Cr, Ga, and V in the gneiss at Colton and possibly small increases in Ni and Y. An increase in these elements at Colton is consistent with the increase in the major elements Fe, Mg, Ca, and Al noted previously. The decrease in Ba and Cu in the gneiss at Colton also appears to be probable. The loss of Ba, sympathetic with the loss of K, is expectable. Almost surely many other changes in trace-element composition could be noted with adequate sampling and highly refined analytical methods. Mn and Pb, for example, probably decrease in the least altered gneiss between

Emeryville and Colton, although present data certainly are not precise enough to demonstrate this.

In Table 10, the average trace-element compositions of least altered gneiss are compared with the trace-element composition of the Littleton formation that has been studied in some detail by Shaw (1954, Part I). In columns 1 and 4 of Table 10 are the average composition of respectively medium- and high-grade paragneisses of the Littleton formation. The average compositions of least altered gneiss from the Emeryville and Colton areas (Groups 1 and 5) are given in columns 2 and 5. A direct comparison is justifiable for most elements, as is indicated by the good reproducibility of analyses between the analysts involved (Table 11). Exceptions should be noted for Sc, Zr, and possibly Sr and V. Shaw's values for Zr are consistently about 30 per cent higher than the values obtained by Chodos and Godijn. His values for Sc are consistently about 50 per cent lower, and his values for V may be lower in most instances. The numbers Shaw reports for Sr are roughly three times higher in two of the three samples run.

The trace-element compositions of the two formations are similar in many respects (Table 10). This is especially true for Zr, Y, Sc, Pb, Ga, and Cu, in which respective concentrations are within or close to the analytical errors between the laboratories. The Littleton formation seems to be richer in Co, Cr, Ni, and V than the gneiss. This is despite the fact that both formations contain approximately the same amounts of Ti, Fe<sup>++</sup>, and Mg (*see* Shaw, 1956, Part III, p. 924). The principal differences in major-element composition are in Al, Ca, Na, K, and Fe<sup>+++</sup>. The Littleton is richer in Al, Fe<sup>+++</sup>, and K and much poorer in Ca and Na than the gneiss. The Na<sub>2</sub>O-K<sub>2</sub>O ratio in the Littleton is only 0.22; in the least altered gneiss at Emeryville this ratio is about 1.4, and near Colton it increases to more than 2. In terms of the ratio of Na to K the Littleton formation is typical of metasedimentary rocks derived from kaolinitic and illitic sandstones, whereas the gneiss seems to have evolved from a sodic tuff or graywacke-like rock rich in chlorites, montmorillonites, or zeolites (Engel and Engel, 1953b).

#### Granitized Gneiss

*Introduction.*—Four general types of more granitic gneiss are distinguished. They are (1) incipient migmatite; (2) migmatite; (3) augen

TABLE 11.—ANALYSES OF TRACE ELEMENTS IN THE LITTLETON FORMATION

Analyses by Shaw (1954, pt. 1, Table 15) and by Chodos and Godijn are compared to indicate precision between the two laboratories. The analyses L1C-G, L2C-G, and L3C-G were made on the same plates with analyses of gneiss reported in Tables 7, 8, and 9.

Element	L1S 1	L1C-G 2	L2S 3	L2C-G 4	L3S 5	L3C-G 6
Co	11	10	21	15	10	6
Cr	86	96	160	121	93	102
Cu	24	23	59	40	6	14
Ga	31	20	35	19	16	18
Ni	64	65	110	69	46	43
Pb	33	31	1	10	13	10
Sc	11	23	14	25	10	24
Sr	110	130	400	130	350	120
V	68	127	150	115	81	121
Y	36	37	52	40	41	42
Zr	180	140	190	145	260	200

Column 1, trace-element composition of "low grade slate L1" as reported by Shaw (1954, pt. 1, Table 7).

Column 2, trace-element composition of masked sample of L1 by Chodos and Godijn.

Column 3, trace-element composition of "low grade slate" L2 as reported by Shaw (1954, pt. 1, Table 7).

Column 4, trace-element composition of masked sample of L2 as determined by Chodos and Godijn.

Column 5, trace-element composition of "low grade slate" L3 as reported by Shaw (1954, pt. 1, Table 7).

Column 6, trace-element composition of masked sample of L3 as determined by Chodos and Godijn.

gneiss; and (4) equigranular uniformly granitized gneiss. Examples of types 2 and 3 are shown in Plate 3. Most of the specimens in Table 9 belong to the equigranular, uniformly granitized type of gneiss. The specimens of granitized gneiss studied in greatest detail were largely of this type because of its greater textural uniformity, which in turn enhances the possibility that component minerals have formed in equilibrium and permits more accurate modal and chemical analyses.

Specimens of uniformly granitized gneiss in Table 9 include: Group 1A, Bgn 26; Group 1, Bgn 29, Qb 236, 237, 3, 7, 229, 227; Group 2, Qb 233, 216; Group 3, Bgn 9, 4, 6; Group 4, Bgn 25, 16; Group 5, Bgn 22, 23. Modal

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analyses and trace-element composition of four typical specimens of uniformly granitized gneiss from Group 5 are listed in Table 12.

*Mineralogy and texture.*—The separation between least altered and uniformly granitized gneiss is made on the basis of total K feldspar present. Those specimens of gneiss with less than 5 per cent K feldspar are referred to as least altered gneiss. Those with more than 5 per cent K feldspar are called incipient migmatite. This type of separation is employed purely because of convenience and utility. It is liable to criticism in that (1) some least altered gneiss may be more potassic (2) K feldspar may have formed in the least altered gneiss as a product of the decomposition of muscovite, or at higher temperatures of metamorphism through the transformation of biotite to garnet.

Careful cross check of these possibilities, through studies of the field relationships of the more or less K-rich gneiss and modal analyses indicates that more than about 5 per cent K feldspar is not common in those bodies of gneiss which have not undergone obvious permeation or replacement by granitic material. This is certainly true in the Emeryville-Edwards area, where muscovite and biotite are stable. Farther northeast, in the parts of the gneiss metamorphosed at higher temperatures where K feldspar might normally form, the biotite breaks down very slowly (Fig. 5). With the slow decomposition of biotite, potassium is either abstracted from the least altered gneiss or is largely segregated in the granitic and pegmatitic bands. Finally, as shown below, the use of other compositional indices for granitization such as an increase in total K, or  $K + Na$  in the obviously granitized rock, or an increase in the ratio of K to Ca, or of  $K + Na$  to  $Fe + Mg + Ca$ , and so on also seems to justify essentially the same separations between the least altered and more granitic gneiss.

Marked differences in texture do appear between the several types of more granitic gneiss. The differences in textural types of granitic gneiss are diagrammed in Figure 3, photographed in Plate 3, and described in following pages. The smoothed curves in Figure 3, indicating the changes induced by granitization of the gneiss, are derived largely from modal analyses of the more uniform-textured specimens in the Emeryville area. Each tick on the horizontal co-ordinate of the diagram represents the modal analysis of a specific rock. The three solid darts represent position of rocks whose mineral and chemical compositions are given

in columns 1, 3, and 4 of Table 13. The specimens are plotted from left to right in order of increased content of K feldspar. Gaps in the occurrence of ticks indicate no specimens of requisite K feldspar content were available (The modal data from which these curves are obtained are given in Engel and Engel, 1953b, Figs. 5, 6.) The curves indicate the kind of continuous variation in mineral composition between the least altered gneiss and equigranular granitic gneiss, that is, where the most subtle transitions of rock type and texture occur. They also reflect, however, the kinds of mineralogical changes that appear in the transitional contacts between least altered gneiss and any of the more granitic types in the Emeryville area. At the more abrupt contacts of gneiss and granite gneiss, it is obvious that sharp deflections would appear in the curves. The most common and marked deflections coincide with those in the textural curves, at roughly one-third and two-thirds of the distance from left to right. These are the contacts between gneiss and augen gneiss and between augen gneiss and equigranular more alaskitic granite gneiss as mapped (Pl. 4).

Type 1 (incipient migmatite) is especially common southwest of Edwards, where least altered gneiss is relatively most abundant. It consists of lenses and layers of quartz-microcline and quartz-perthite pegmatite and aplite ranging from a fraction of an inch to tens of feet thick, separated by several, up to as much as 30 feet, of least altered gneiss.

Most of the granitic seams contain quartz, microcline, oligoclase, biotite, and scattered muscovite. Southwest of Edwards, almandine garnet borders these seams, but it is not found in the uninjected parts of the gneiss. Many granitic seams are partly crushed, but others are essentially undeformed and appear to postdate all severe cataclasis. Most incipient migmatite in the Emeryville-Edwards areas has about the bulk composition and texture indicated in Figure 3 by the vertical zone just to the right of least altered gneiss and to the left of the area designated migmatite.

Type 2 (migmatite) is common throughout the 35-mile segment of gneiss. Migmatite is a more uniformly and completely "injected" gneiss than Type 1, with lit-par-lit alternations of more granitic and more gneissic layers, each being from a fraction of an inch to several inches or a foot in width. Figure 1 of Plate 3 shows an outcropping of migmatite that has flowed extensively in the solid or semisolid state. Most exposures exhibit very little

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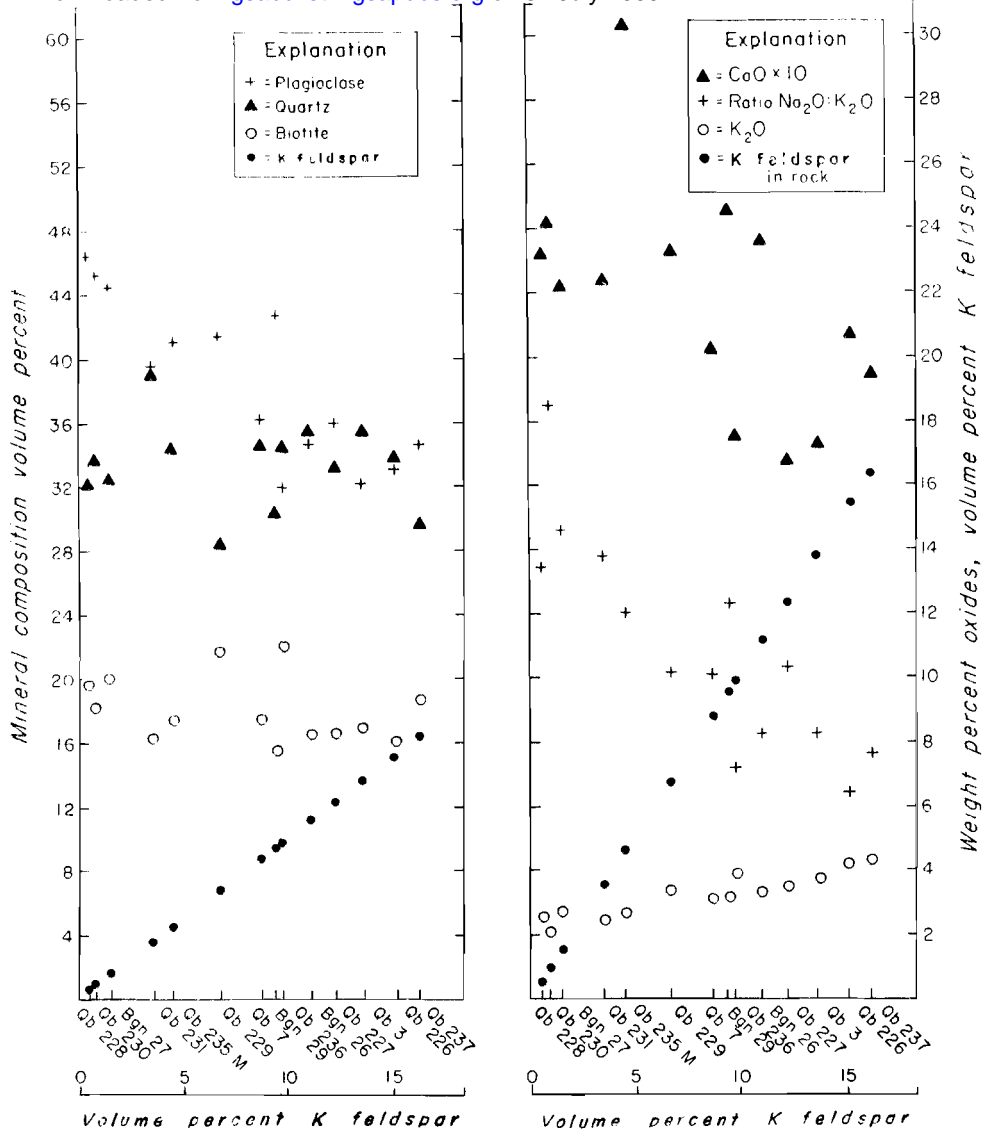


FIGURE 6.—VARIATIONS IN MINERAL AND CHEMICAL COMPOSITION OF SPECIMENS IN GROUP 1 RESULTING FROM INCREASING DEGREES OF PERMEATION AND REPLACEMENT OF THE LEAST ALTERED GNEISS BY GRANITE-FORMING SUBSTANCES, ESPECIALLY POTASSIUM

(See Table 9.) Positions of specimens are indicated by ticks on the horizontal co-ordinate. These are plotted from left to right in order of increasing K feldspar content, which is essentially the same order as increasing K, or decreasing Na<sub>2</sub>O-K<sub>2</sub>O ratio, CaO, MgO, or FeO. The graph on the left shows the variations in mineralogy, and that on the right shows changes in chemical composition resulting from increasing granitization.

ptygmatic folding, and many appear almost unfolded. Typical bulk compositions and textural features of migmatite in the Emeryville-Edwards areas are shown in the left hand one-third of Figure 3, except that in the more granitic seams the plagioclase may be more sodic than is indicated by the curve.

Type 3 (augen gneiss) consists of inequigranular augen gneiss and porphyroblastic granitic gneiss, in which large crystals and clusters of perthitic microcline, and locally oligoclase, have grown in a more or less pervasively feldspathized groundmass of gneiss. It occurs throughout the gneiss complex as the



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commonest type of granite gneiss and is described as the Hermon granite gneiss (Buddington, 1939; Buddington and Leonard in press). Plate 3, Figures 2 and 3 are examples of this type of feldspathization. In the specimen in Figure 2 of Plate 3 the microcline porphyroblasts are remarkably euhedral. This type porphyroblastic gneiss is subordinate to the augen gneiss shown in Figure 3 of Plate 3. Typical textural and compositional features of the augen gneiss in the Emeryville-Edwards areas are shown in the central third of Figure 3.

Type 4 (equigranular granitic gneiss) is essentially equigranular, pervasively feldspathized gneiss in which uniformly disseminated, fine- to medium-grained microcline has replaced to varying degrees the plagioclase and biotite of the least altered gneiss. The resulting rock is a faintly to distinctly foliated feldspathic gneiss or granite gneiss (granodiorite to quartz monzonite gneiss). Buddington has published some excellent photographs of this uniformly granitized gneiss (1957, Pl. 1).

The gneiss complex in the Russell-Colton areas has not been mapped in sufficient detail to justify a specific interrelationship of texture and mineral composition between least altered and more granitic gneiss. Approximately the same textural relationships hold, and in a gross way the change in mineralogy is similar. In the northeast segment of the gneiss, of course, the biotite curve (Fig. 3) would be accompanied by a subparallel garnet curve. Sillimanite also appears, commonly in variously granitized parts of the gneiss as Buddington notes (1957, Pl. 1 and p. 297-299). It is only rarely, however, the product of regional metamorphism without granitization. Instead, it appears to be a by-product of complex interaction of potassium-rich fluids with gneiss (Buddington 1948, p. 36-39; Buddington and Leonard, in press) and is outside the scope of this study.

Additional differences exist in the compositional types of granitic rock associated with the gneiss at and near Colton. The varieties of granitic gneiss described thus far are generally agreed to be in large part, possibly wholly, of metasomatic origin (Buddington, 1957; Gilguly, written communication; Brown, oral communication; Engel and Engel, 1953b, p. 1076-1078). The present authors would add that although this granitic gneiss in the Emeryville area is largely the result of the introduction of granitic constituents, part of the granitic gneiss at Colton may be sweated out of the immediately associated least altered gneiss.

TABLE 12.—MODAL AND TRACE-ELEMENT ANALYSES OF FOUR TYPICAL SPECIMENS OF MORE UNIFORMLY GRANITIZED GNEISS FROM THE COLTON AREA, NEW YORK

Minerals in modal analysis given in volume per cent.

	Bgn 6A	Bgn 1A	Bgn 4A	Bgn 2	Mean
Quartz	30.70	24.60	23.60	24.70	25.90
Plagioclase	26.20	25.10	23.30	22.30	24.23
K feldspar	17.80	35.00	33.10	40.60	31.63
Biotite	9.60	14.00	18.80	11.30	13.42
Garnet	6.50	1.10	.20	.60	2.10
Sillimanite	9.00				2.25
Others*	.20	.20	1.00	.50	.47
Total	100.00	100.00	100.00	100.00	100.00

Trace Elements  
(Parts per million)

Element	Sensitivity	Bgn 6A	Bgn 1A	Bgn 4A	Bgn 2	Mean
B	10	15	<10	<10	<10	6?
Ba	1	900	1000	1200	2000	1275
Co	2	9	2	5	5	5
Cr	5	20	12	25	17	18
Cu	1	15	25	17	16	18
Ga	5	16	10	12	11	12
Mn	2	360	130	120	110	180
Nb	15	pt	pt	pt	pt	15?
Ni	2	14	4	6	7	8
Pb	10	23	28	41	37	32
Sc	2	12	6	4	10	8
Sr	2	225	245	190	240	225
Ti	2	700	1200	1700	400	1000
V	2	20	35	25	40	30
Y	10	32	25	51	14	30
Yb	1	3	3	3	2	3
Zr	2	100	150	190	200	160

\* Chiefly apatite, magnetite, pyrite, zircon, sphene, chlorite.

pt = approximately at the limit of sensitivity.

Looked for but not found: Ag, As, Au, Bi, Cd, Ge, In, La, Mo, Pt, Sb, Sn, Ta, Th, U, Zn.

Two additional types of granite and granitic gneiss occur intimately associated with the gneiss near Colton and along the perimeter of the massif. These are (1) hornblende-microporthite granite and gneiss equivalents and (2) microporthite alaskite granite and gneiss equivalents. Both these granitic rocks, where least deformed, show numerous igneous characteristics, as has been shown by Buddington

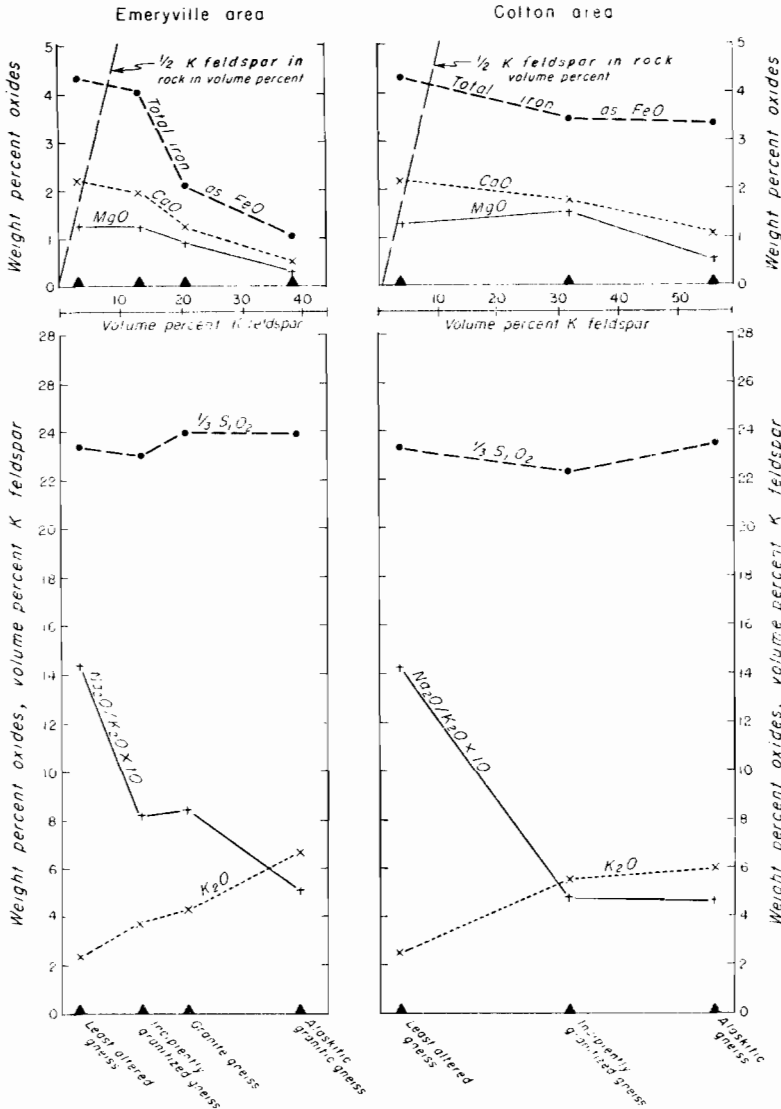


FIGURE 7.—GRAPHS SHOWING COMPOSITIONAL TRENDS IN THE GNEISS COMPLEX AT EMERYVILLE (LEFT) AND COLTON (RIGHT) RESULTING FROM PERVASIVE AND COMPLETE GRANITIZATION OF THE GNEISS

Changes of these types are characteristic of transitional contacts between gneiss and granite. The ticks on the horizontal co-ordinates represent the positions of composite specimens whose detailed compositions are posted in Table 13. Note that the analyses are plotted from left to right in order of increasing content of K feldspar, which is essentially equivalent to plots in order of increasing  $K_2O$ , or decreasing  $Na_2O-K_2O$  ratio,  $MgO$ ,  $CaO$ , or  $FeO$ .

(1939; 1948; 1957) and by Buddington and Leonard (in press).

The hornblende-micropertthite granite forms great batholithic masses within the massif where it occupies two-thirds of the area of younger granitic rocks (Buddington 1957, p. 292). It is rare in the Grenville Lowlands. The micropertthite alaskite occurs both within the massif and in the Grenville Lowlands, where

it forms phacoliths (Buddington 1929; 1957) in the metasedimentary rocks. It is the granite of the California phacolith, west of Balmat, the only obviously igneous granite in or near the Emeryville area.

*Chemical composition: major elements.*—The continuous to semicontinuous changes in composition between least altered and granitized gneiss are plotted in Figures 6 and 7 and

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TABLE 13.—AVERAGE CHEMICAL AND MINERAL COMPOSITIONS OF LEAST ALTERED AND MORE GRANITIC GNEISS FROM THE EMERYVILLE AND COLTON AREAS, NEW YORK

In chemical analyses oxides given in weight per cent.

	Emeryville Area Group 1				Colton Area Group 5		
	1	2	3	4	5	6	7
SiO <sub>2</sub>	70.25	69.25	72.31	71.89	65.97	66.93	70.99
TiO <sub>2</sub>	.67	.63	.31	.14	.64	.85	.20
Al <sub>2</sub> O <sub>3</sub>	14.14	14.63	14.76	15.45	16.83	16.32	14.28
Fe <sub>2</sub> O <sub>3</sub>	.55	.70	.33	.26	.36	.45	1.19
FeO	3.83	3.45	1.76	.85	4.92	3.15	2.30
MnO	.05	.05	.02	.04	.07	.04	n.d.
MgO	1.76	1.74	.79	.36	2.25	1.56	.53
CaO	2.20	1.97	1.40	.58	3.41	1.76	1.12
Na <sub>2</sub> O	3.43	3.06	3.57	3.40	3.70	2.67	2.80
K <sub>2</sub> O	2.40	3.79	4.27	6.69	1.46	5.57	5.97
H <sub>2</sub> O+	.72	.71	.44	.32	.39	.52	.08
P <sub>2</sub> O <sub>5</sub>	.07	.05	.03	.04	n.d.	n.d.	.09
Total	100.07	100.03	100.00	100.02	100.00	99.82	99.55

## Modes

(Volume per cent)

Quartz	37.86	33.62	32.68	25.37	29.28	25.90	24.0
Plagioclase	39.86	34.06	35.50	37.89	48.92	24.23	10.1
K feldspar	3.19	13.80	20.78	38.92	3.17	31.63	56.6
Biotite	17.60	17.10	7.73	2.46	10.68	13.42	..
Garnet	.03	tr	..	..	7.38	2.10	..
Muscovite	.86	.69	1.30	1.73	..	..	..
Sillimanite	..	..	..	..	..	2.25	..
Otherst	.60	.73	2.10	2.53	.57	.47	7.8
Plagioclase composition	Ab 73	Ab 72	Ab 81	Ab 91	Ab 67	Ab 74	Ab 90

## Trace Elements\*

(Parts per million)

Element	Sensitivity							
B	10	10	22	12	6?	12	6?	..
Ba	1	612	750	910	1100	492	1275	..
Co	2	8	7	4	<2	7	5	..
Cr	5	35	16	4	<1	56	18	..
Cu	1	16	4	19	12	12	18	..
Ga	5	11	10	12	16	14	12	..
Mn	2	356	434	260	118	341	180	..
Nb	15	pt	pt	..	<10	pt	15	..
Ni	2	15	12	4	<2	21	8	..
Pb	10	12	21	38	46	15	32	..
Sc	2	12	10	6	<2	17	8	..
Sn	5	7?	7?	..	12	<5	<5	..
Sr	2	310	320	270	96	304	225	..
Ti	2	2800	1800	750	430	3000	1000	..
V	2	56	53	24	10	81	30	..
Y	10	46	49	35	26	58	30	..
Yb	1	3	3	3	4	3	3	..
Zr	2	171	172	150	185	176	160	..
Number of specimens		9	5	3	3	8	4	..

\* Looked for but not found: Ag, As, Au, Bi, Cd, Ge, In, La, Mo, Pt, Sb, Ta, Th, U, Zn.

† Chiefly apatite, zircon, sericite, magnetite, chlorite, and pyrite.

## Description of specimens:

1. Least altered gneiss. Modal analysis is mean of analyses of 24 specimens. Trace-element values are the mean of analyses of 9 of the 24 specimens composing the average mode.

2. Incipiently granitized gneiss. Modal analysis and chemical compositions are averages of analyses of Bgn 26, Qb 3, Qb 226, Qb 227, (Table 7).

(Continued at foot of page 1409)

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 in Tables 12, 13, and 14. The data are specifically for the changes in composition found at transitional contacts between least altered gneiss and equigranular to inequigranular granitic gneiss at (1) Emeryville and (2) Colton. Some variations in composition of the specimens listed in Table 9 are graphed in Figure 6. More comprehensive trends of granitization near Emeryville, as shown by chemical analyses, are listed in columns 1, 2, 3, and 4 of Table 13, and are graphed on the left-hand side of Figure 7. Analyses of rocks from the Colton area are listed in columns 5, 6, and 7 of Table 13 and are graphed on the right-hand side of Figure 7. In Figures 6 and 7, the positions of the analyses on the horizontal co-ordinate are determined by the content of K feldspar in the rock. This ranges from essentially nil to 50 per cent by volume. It is apparent, however, that about the same trends in composition result if the positions of specimens are determined by total iron, Mg, Ca, or K and so on.

Granitization of least altered gneiss as shown in the tables and figures noted involves increases in K and decreases in Fe, Mg, Ca, and in the ratio of Na to K. The specimens of granitized gneiss listed in Table 9, graphed in Figure 6, and studied in detail, represent only incipient stages in the granitization process. The intermediate and end stages of granitization are represented by the right-hand sides of both graphs in Figure 7.

Evaluation of the several possible mechanisms of granitization is beyond the scope of this work, but several implications may be noted briefly. If the gneiss in the Edwards-Emeryville areas and to the southwest is in large part replaced by more granitic rock, and if these granitic (K-rich) constituents are introduced into the gneiss, Fe, Ca, Mg, OH and chemically coherent trace elements are expelled from the gneiss. The segment of gneiss that has undergone this depletion is at least 30 miles long from Edwards southwest to the Paleozoic overlap, southwest of Antwerp and Philadelphia, New York, and appears to have had an early metamorphic thickness of

at least 2500 feet. In the Emeryville area detailed mapping suggests that one-fourth to one-third of the gneiss is replaced by granitic gneiss as felsic as, or more felsic than that listed in column 3, Table 13. Reconnaissance of the gneiss southwest of Emeryville, beyond Antwerp and Philadelphia, New York, suggests even greater metasomatism throughout this part of the gneiss. Obviously a very large basic front could be involved. The approximate volume of any such front would be, of course, conditional upon volume changes and upon the amount of gneiss actually replaced. Quantifying these figures will be no mean task for the future.

The significance of the trends in the Colton area is complicated by the fact that some of the granitizing substances seem to have had their origin in the gneiss itself. In indicating trends imparted by granitization near Colton, the composition of least altered gneiss plotted in Figure 7 is that found at Emeryville, not that now found near Colton. This is because the early or pre-metamorphic parent of the least altered gneiss at Colton is assumed to have had about the same composition as that now found at Emeryville. Basification of the least altered gneiss at Colton occurred during this metamorphic differentiation and the development of the intertonguing more granitic gneiss. But in addition to this metamorphic differentiation, granitic magma and K-rich fluids rising from even deeper sources seem to have permeated, shredded, and partly replaced parts of the gneiss at Colton. The extent of metasomatism involved in this last-named granitization in the Russell-Colton region would presumably indicate the volume of mafic constituents expelled there. Data necessary for even a crude estimate are not at hand.

Apropos to the expulsion of iron from the gneiss complex at Colton, Buddington has stressed the fact that much of the magmatic ? granite that has shredded and variously replaced the gneiss along and within the massif is remarkably high in total iron (1957, p. 303, Table 6; Buddington and Leonard, in press). Most of the iron is in the ferric state, largely as magnetite

3. Granitic gneiss. Modal analysis is mean of analyses of three specimens. Chemical analyses are of a mix of equal parts of the powders of the three specimens.

4. Alaskitic granite gneiss. Modal analysis is mean of analyses of three specimens. Chemical analyses are of a mix of equal parts of the powders of the three specimens.

5. Least altered gneiss. Modal analysis is mean of analyses of 14 specimens (Table 8). Trace-element values are the mean of analyses of 8 of the 14 specimens, composing the average mode.

6. Incipiently granitized gneiss. Modal analyses and trace-element compositions are average of analyses of specimens Bgn 2, Bgn 6A, Bgn 1A, and Bgn 4A listed in Table 12. The chemical analysis of major constituents is of a mix of equal parts of the powders of these specimens.

7. Granitic gneiss. Garnet alaskite contaminated with gneiss, Horseshoe Lake, Tupper Lake Quadrangle (with Adirondack Massif). Analyst Lee C. Peck. Quoted from Buddington 1957, p. 298.



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and hematite. In much of this granite contaminated by the gneiss, the total iron content may be one-half to three-fourths of that present in least altered gneiss. These possible relationships are indicated by the data in Table 13. Column 1 shows the composition of the least altered gneiss at Emeryville. In columns 6 and 7 are analyses of respectively sillimanite-quartz-microcline granite contaminated with gneiss, and garnet alaskite, also a product of reaction with the gneiss. Both these granites are emplaced within the gneiss near the margin of the massif. In some of these highly granitic rocks which are volumetrically abundant (e.g. the garnet alaskite), a mechanism existed for the formation or retention of relatively large amounts of ferric iron. Whether this iron is in part or wholly from the gneiss at the present level of erosion, or from deeper levels, or of more cryptic magmatic source is not indicated to us by any of our data. Buddington and Leonard (in press) conclude that the bulk of this iron and that in the skarns and iron ores associated with the granites is largely of deep-seated magmatic origin.

The granitization of parts of the gneiss is essentially a potassium metasomatism, not too unlike that known in many terranes in the world (Billings, 1938; Eskola, 1948; and so on). This type granitization of metasedimentary rocks is an interesting contrast to those instances where Na rather than K is the principal element introduced. The migmatites of Sutherland, as described by Read (1931) and Cheng (1943) are a curious case in point. The initial sediments in Sutherland appear to have been rich in potassium and low in Na. With migmatization and granitization the ratio of Na<sub>2</sub>O to K<sub>2</sub>O is reported to increase greatly. Mineralogically the migmatization is said to be accompanied by an increase in plagioclase and a decrease in muscovite, K feldspar, biotite, garnet, and quartz (Cheng, 1943).

The enormous scale of the K-Si metasomatism in the Adirondack Mountains and its contemporaneity with emplacement of large granitic batholiths seems clearly established. The detailed mechanisms of both processes remain unknown. They represent the final pulse in the evolution of the Adirondack orogen, at approximately 1 billion years ago. All pre-existing rock units are invaded and partly replaced by both granite magma and K and Si ions, atoms, or fluids, producing K feldspar, quartz, and finally sericite. Pre-existing anorthosites, gabbros, syenites, amphibolites, and clastic sediments such as the paragneiss are especially

shredded, altered, and injected; but even the orthoquartzites and marbles are enriched in K and Al. Just east of Emeryville more than a cubic mile of marble is replaced by potassic

TABLE 14.—AVERAGE COMPOSITION OF LEAST ALTERED GNEISS AT EMERYVILLE AND COMPOSITIONS OF GRANITES IN THE MASSIF THAT SHRED AND ARE CONTAMINATED BY THE GNEISS

Oxides given in weight per cent.

	Average least altered gneiss 1	Garnet alaskite gneiss 2	Sillimanite-quartz microcline gneiss 3
SiO <sub>2</sub>	68.77	70.99	71.44
TiO <sub>2</sub>	.71	.26	.65
Al <sub>2</sub> O <sub>3</sub>	14.77	14.28	14.89
Fe <sub>2</sub> O <sub>3</sub>	.65	1.19	2.40
FeO	4.00	2.30	1.38
MnO	.06	.09	.03
MgO	1.87	.53	.30
CaO	2.45	1.12	.50
Na <sub>2</sub> O	3.50	2.80	1.36
K <sub>2</sub> O	2.44	5.97	5.99
H <sub>2</sub> O+	.73	.30	.52
P <sub>2</sub> O <sub>5</sub>	.09	.20	.22
Total	100.04	100.03	99.68

1. Least altered gneiss from Group 1, mean of five chemical analyses from Table 7. Analyst, C. G. Engel.

2. Garnetiferous, inequigranular granitic gneiss 1 mile west of Bear Pond, Tupper Lake quadrangle (from Buddington and Leonard, in press). Analyst, Lee C. Peck.

3. Microcline-rich granitic gneiss, Oswegatchie quadrangle (from Buddington, 1957, Table 4, column 6). Analyst, Lee C. Peck.

granite gneiss and pegmatite contemporaneous with the granitic gneiss in the gneiss complex.

This composite wave of K-rich alteration and magmatic injection is by no means confined to the Adirondack segment of the so-called Grenville subprovince (Engel and Engel 1953a; A. E. J. Engel, 1956) of the Canadian Shield. Similar injection and replacement of metasedimentary and older igneous-looking rocks occurs throughout the entire southwest part of the subprovince in southeastern Ontario and southwestern Quebec, a region of about 300,000 square miles (Engel and Engel, 1953a, Fig. 1).

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*Chemical composition: minor elements.*— Trace-element compositions of incipiently granitized gneiss studied in detail between Emeryville and Colton are listed in Table 9 with modal and other chemical data. Concentrations of elements in more completely granitized gneiss, as well as the mean composition of least altered gneiss from Emeryville and Colton, are listed in Tables 12, 13, and 14. An obvious limitation in the data is the small number of specimens analyzed. Despite this limitation certain trends coincident with granitization appear quite real. Specifically Ba and Pb almost surely increase in the more granitic gneiss. Application of the "Student's" *t* test to the data indicates the probability of the differences being due to chance is less than 0.01 for each of these elements.

The apparent decreases in Co, Cr, Mn, Ni, Sc, Sr, Ti, V, and Y in the more granitic gneiss also seem to be real. Trends of the type observed are consistent with empirical data from other rocks and with theoretical conceptions of coherence between minor and major elements.

#### SUMMARY

The major Adirondack paragneiss extends across the Grenville Lowlands from a point southwest of Antwerp to the perimeter of the central Adirondack igneous mass at Colton, New York. Detailed field and analytical studies have been made of the northeasterly 35-mile segment of the gneiss between Emeryville and Colton. The gneiss seems to have evolved from a monotonous tuff or graywackelike rock into a complex of little altered and variously granitized parts. Two types of metamorphism of gneiss are considered. One is the progressive metamorphism of least altered gneiss, that is, the rock seemingly little altered in bulk composition from the parent sedimentary rock. The second type is the granitization of widely distributed parts of the least altered gneiss.

Geologic thermometers indicate temperatures of both types of metamorphism of the gneiss of about 500° to 525° C. at the southwest end of the belt and about 600° C. near the perimeter of the massif. These data are based upon an assumed depth of metamorphism of about 5 miles, which may be in error by 50 per cent or more. Minimum temperatures of metamorphism are obtained largely from studies of the solid solubility of magnesite in dolomite, FeS in sphalerite, paragonite in muscovite, and TiO<sub>2</sub> in magnetite. These studies indicate temperatures of metamorphism

at Emeryville exceeded 475° C. and at Colton exceeded 550° C.

Maximum temperatures of metamorphism are inferred principally from the absence of wollastonite in closely associated siliceous marbles. Assuming a depth of 5 miles, temperatures of metamorphism at Colton did not exceed 750° C. and probably were less than 650° C.

The indicated increases in temperatures of metamorphism between Emeryville and Colton are confirmed by independent lines of evidence, namely (1) the increase in metamorphic rank and grain size in all mineral assemblages, (2) the increase in contemporary granite having igneous characteristics, and (3) the marked decrease in  $\delta O^{18}$  values in quartz minus magnetite that occur as mineral pairs in the gneiss.

At Emeryville the least altered gneiss is a monotonous-appearing, distinctly foliated, medium-grained, quartz-greenish biotite-oligoclase rock with about 1 per cent muscovite. The bulk chemical composition is that of an average graywacke or dacitic tuff with NaO-K<sub>2</sub>O ratio of  $\sim 1.3$ . This least altered gneiss forms about one-third of the complex at Emeryville and is cut by and transitional into the more granitized parts.

As the least altered gneiss is traced from Emeryville to Colton, muscovite disappears at  $\sim 525^\circ$  C., and almandine garnet appears throughout the rock. Sympathetically the average plagioclase becomes more calcic, biotite changes from greenish brown through successive shades of brown, reddish brown, to deep red brown, quartz content decreases, grain size increases, and segregational banding appears in the gneiss.

The changes in texture and mineralogy in least altered gneiss are accompanied by systematic changes in its bulk chemical composition. With increasing temperature of metamorphism the least altered gneiss is enriched in Al, Fe<sup>++</sup>, total Fe, Mg, Ca, Cr, Ga, Ni, and V. The concentrations of K, Si, Fe<sup>+++</sup>, H<sub>2</sub>O, and Ba decrease. These changes in chemical composition of least altered gneiss are detectable at temperatures of metamorphism of about 550° C. and are well defined at Colton ( $\sim 600^\circ$  C.). The cause of the change is interpreted as a metamorphic "degranitization" or "basification" in which Si, K, and H<sub>2</sub>O are mobilized and partly liberated but partly frozen into the rock as venitic migmatite.

Granitization of the gneiss may involve several processes, especially mechanical injection of magma, permeation, and replacement of

the gneiss by magma, by fluids from magma, or by ichors and ions. Granitic rock clearly of igneous origin is not common in or associated with the gneiss complex at Emeryville but is abundant in the Colton area and immediately southeast.

Throughout the gneiss complex the granitic parts include (1) lit-par-lit injection gneiss (migmatite); (2) augen gneiss rich in porphyroblasts (and locally phenocrysts?) of K feldspar; and (3) even-grained uniformly feldspathized gneiss. All these types of granitization of the gneiss are accompanied by an increase in K feldspar and in Ab content of plagioclase and by a decrease in biotite, plagioclase, and quartz. During granitization, K increased and Ti, Fe<sup>+++</sup>, Fe<sup>++</sup>, Mg, Ca, H<sub>2</sub>O, and Na-K ratio decreased. Changes in the amounts of minor elements in granitized parts of the gneiss include increases in Ba, Pb, and possibly Sn, and decreases in Co, Cr, Mn, Ni, Sc, Sr, Ti, V, and Y.

All granitizing substances in the gneiss in areas of lowest-temperature metamorphism (less than 550° C.) appear to be introduced either laterally or from below. Their source may include ultrametamorphosed parts of the gneiss as well as other parts of the crust or upper mantle.

In the areas of highest temperature of metamorphism studied, the granite-forming constituents appear to be partly introduced and partly sweated out of the associated "basified" gneiss.

Granitization of the gneiss has resulted in the expulsion of large quantities of H<sub>2</sub>O, Fe, Mg, and Ca. At least one-third of the gneiss in a zone more than 2500 feet thick, 75 miles wide, and 30 miles long is partly to completely replaced by more anhydrous granitic rock. Exact volume changes are unknown, however, and although there are numerous mafic metamorphic rocks in the region, none can be proved to represent a basic front.

Calculations of the chemical analyses of more even-textured rock in the gneiss complex, from data of modal and mineral analyses, show about the same deviation from actual chemical analyses as exists in the 34 analyses of the standard rocks G-1 and W-1.

#### REFERENCES CITED

- Barth, Tom, F. W., 1952, *Theoretical petrology*: N.Y., John Wiley and Sons, Inc., 387 p.
- Barton, Paul B., and Kullerud, Gunnar, 1957, Preliminary report on the system FeS-ZnS-S, and implications regarding the use of the sphalerite geothermometer: *Geol. Soc. America Bull.*, v. 68, p. 1699
- Billings, M. P., 1938, Introduction of potash during regional metamorphism in western New Hampshire: *Geol. Soc. America Bull.*, v. 49, p. 289-302
- Brown, J. S., 1936, Structure and primary mineralization of the zinc mine at Balmat, New York: *Econ. Geology*, v. 31, p. 233-258
- 1947, Porosity and ore deposition at Edwards and Balmat, New York: *Geol. Soc. America Bull.*, v. 58, p. 505-545
- Brown, J. S., and Engel, A. E. J., 1956, Revision of Grenville stratigraphy and structure in the Balmat-Edwards district, northwest Adirondacks, New York: *Geol. Soc. America Bull.*, v. 67, p. 1599-1622
- Buddington, A. F., 1929, Granite phacoliths and their contact zones in the northwest Adirondacks: *N. Y. State Museum Bull.* 296, 251 p.
- 1939, Adirondack igneous rocks and their metamorphism: *Geol. Soc. America Mem.* 7, 354 p.
- 1948, Origin of granite rocks of the northwest Adirondacks, p. 21-43 in Cillully, James, *Chairman*, Origin of granite: *Geol. Soc. America Mem.* 28, 139 p.
- 1952, Chemical petrology of some metamorphosed Adirondack gabbroic, syenitic and quartz syenitic rocks: *Am. Jour. Sci.*, Bowen Volume, p. 37-84
- 1957, *Interrelated Precambrian granitic rocks*, northwest Adirondacks, New York: *Geol. Soc. America Bull.*, v. 68, p. 291-305
- Buddington, A. F., and Leonard, B. F., Jr., (in press), Precambrian magnetite deposits of St. Lawrence County, New York: *U. S. Geol. Survey Prof. Paper*
- Buddington, A. F., Fahey, Joseph, and Vlisidis, Angelina, 1955, Thermometric and petrogenetic significance of titaniferous magnetite: *Am. Jour. Sci.*, v. 253, p. 497-523
- Chayes, Felix, 1949, A single point counter for thin section analysis: *Am. Mineralogist* v. 34, p. 1-11
- 1952, Notes on the staining of potash feldspar with sodium cobaltinitrite in thin sections: *Am. Mineralogist*, v. 37, p. 337-340
- 1956, *Petrographic modal analysis*: N. Y., John Wiley and Sons Inc., 113 p.
- Cheng, Yu-Chi, 1943, The migmatite area around Bettyhill, Sutherland: *Geol. Soc. London Quart. Jour.*, v. 99, Parts 3 and 4, p. 107-154
- Clayton, R. N., and Epstein, S., 1958, The relationship between O<sup>18</sup>-O<sup>16</sup> ratios in coexisting quartz, carbonate, and iron oxides from various geological deposits: *Jour. Geology*, v. 66, p. 352-373
- Danielsson, A., 1950, Das Calcit-Wollastonitgleichgewicht: *Geochim. et Cosmochim. Acta*, v. 1, p. 55-69
- Dieke, G. H., and Crosswhite, H. M., 1943, The use of iron lines as intensity standards: *Jour. Opt. Soc. America*, v. 33, p. 425-434
- Engel, A. E. J., 1948, Diamond drilling in the West Branch area, Gouverneur district, New York: *U. S. Geol. Survey prelim. Rept.*, p. 3-222
- 1949, Studies of cleavage in the metasedimentary rocks of the northwest Adirondack Mountains, New York: *Am. Geophys. Union Trans.*, v. 30, p. 767-784

- Downloaded from [gsabulletin.gsapubs.org](https://gsabulletin.gsapubs.org) on 31 July 2009
- 1956, Apropos the Grenville, p. 74-98 in Thonson, J. E., *Editor*, The Grenville problem: Royal Soc. Canada, Special Pub. No. 1, 285 p.
- in press, The Precambrian geology and talc deposits of the Balmat-Edwards district, New York: U. S. Geol. Survey Prof. Paper
- Engel, A. E. J., and Engel, Celeste G., 1953a, Grenville series in the northwest Adirondack Mountains, New York, Part I, General features of the Grenville series: *Geol. Soc. America Bull.*, v. 64, p. 1013-1047
- 1953b, Grenville series in the northwest Adirondack Mountains, New York, Part II, Origin and metamorphism of the major paragneiss: *Geol. Soc. America Bull.*, v. 64, p. 1049-1097
- Eskola, Pentti, 1920, The mineral facies of rocks: *Norsk geol. tidsskr.*, v. 6 p. 143-194
- 1933, On the differential anatexis of rocks: *Comm. géol. Finlande Bull.*, v. 17, no. 103
- 1950, The nature of metasomatism in the processes of granitization: 18th Internat. Geol. Cong., Great Britain, Rept. pt. 3, p. 5-13
- Eugster, H. P., and Yoder, H. S., 1955, Micas, p. 124-126 in Abelson, P. H., Annual Report of the Director, Geophysical Laboratory (1954-1955): Carnegie Inst. Wash. Year Book. 54, 311 p.
- Fairbairn, H. W., 1953, Precision and accuracy of chemical analyses of silicate rocks: *Geochim. et Cosmochim. Acta*, v. 4, p. 143-156
- Fairbairn, H. W., *et al.*, 1951, A cooperative investigation of precision and accuracy in chemical, spectrochemical and modal analysis of silicate rocks: U. S. Geol. Survey Bull. 980, 71 p.
- Goldsmith, Julian R., Graf, Donald L., and Joensuu, Oiva, I., 1955, The occurrence of magnesian calcites in nature: *Geochim. et Cosmochim. Acta*, v. 7, no. 5, p. 212-230
- Gordon, M., and Murata, K. J., 1952, Trace elements in Arkansas bauxite: *Econ. Geology*, v. 47, p. 169-179
- Graf, Donald L., and Goldsmith, Julian R., 1955, Dolomite-magnesian calcite relations at elevated temperatures and CO<sub>2</sub> pressures: *Geochim. et Cosmochim. Acta*, v. 7, nos. 3 and 4, p. 109-128
- 1958, The solid solubility of MgCO<sub>3</sub> in CaCO<sub>3</sub>, a revision: *Geochim. et Cosmochim. Acta*, p. 218-219
- Harker, R. I., and Tuttle, O. F., 1955, Studies in the system CaO-MgO-CO<sub>2</sub>, Part 2, Limits of solid solution along the binary join CaCO<sub>3</sub>-MgCO<sub>3</sub>: *Am. Jour. Sci.*, v. 253, p. 274-282
- 1956, Experimental data on the P<sub>CO<sub>2</sub></sub>-T curve for the univariant reaction: calcite + quartz wollastonite + carbon dioxide: *Am. Jour. Sci.*, v. 254, p. 234-256
- Holmquist, P. J., 1921, Typen and nomenklatur der Adergesteine: *Geol. Fören. i Stockholm Förh.*, v. 43, p. 612-631
- Keller, W. D., and Moore George, E., 1937, Staining drill cuttings for calcite-dolomite differentiation: *Am. Assoc. Petroleum Geologists Bull.* v. 7, p. 949-951
- Kullerud, Gunnar, 1953, The FeS-ZnS system, a geological thermometer: *Norsk geol. tidsskr.*, bd. 32, h. 2-3, p. 61-147
- Lapadu-Hargues, P., 1949, Contribution aux problèmes de l'apport dans le métamorphisme: *Soc. Géol. France Bull.*, ser. 5, tome 19, p. 89-109
- Mood, A. M., 1950, Introduction to the theory of statistics: N.Y., McGraw-Hill Book Co., 325 p.
- Prucha, John, 1953, The pyrite deposits of Jefferson and St. Lawrence counties, New York: N. Y. State Sci. Service Rept., Inv. No. 8, 66 p.
- Ramberg, Hans, 1951, Remarks on the average chemical composition of granulite facies and amphibolites-to-epidote amphibolite facies in West Greenland: *Dansk Geol. Foren. Meddel.*, bd. 12, p. 27-34
- 1952, The origin of metamorphic and metasomatic rocks: Chicago, Univ. Chicago Press, 317 p.
- Read, H. H., 1931, The geology of central Sutherland: *Geol. Survey of Scotland Memoir*
- Rosenquist, I. T., 1952, The metamorphic facies and the feldspar minerals: *Bergens Mus. Årbok, Nat. rekke no. 4*, 116 p.
- Sederholm, J. J., 1923, On migmatites and associated Precambrian rocks of southwest Finland: *Comm. géol. Finlande Bull.* no. 58, part 1
- Shapiro, Leonard, and Brannock, W., 1952, Rapid analysis of silicate rocks: U. S. Geol. Survey Circ. 165, 17 p.
- 1956, Rapid analysis of silicate rocks: U. S. Geol. Survey Bull. 1036-C, 56 p.
- Shaw, Dennis M., 1954, Trace elements in pelitic rocks, Part I, Variations during metamorphism: *Geol. Soc. America Bull.*, v. 66, p. 1151-1166
- 1956, Geochemistry of pelitic rocks, Part III, Major elements and general geochemistry: *Geol. Soc. America Bull.*, v. 67, p. 911-934
- Snedecor, G. W., 1946, *Statistical methods*: Ames, Iowa, Iowa State College Press, 351 p.
- Weeks, W. F., 1956, A thermochemical study of equilibrium relations during metamorphism of siliceous carbonate rocks: *Jour. Geology*, v. 64, p. 245-270
- Winchell, A. N., and Winchell, Horace, 1951, *Elements of optical mineralogy*: N.Y., John Wiley and Sons, Inc., 347 p.
- Yoder, H. S. Jr., 1952, The MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O system and the related metamorphic facies: *Am. Jour. Sci.*, Bowen Volume, p. 569-627
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