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Geology of Precambrian Rocks, Granite Falls-Montevideo Area, Southwestern Minnesota

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GEOLOGY OF PRECAMBRIAN ROCKS, GRANITE FALLS-MONTEVIDEO AREA, SOUTHWESTERN MINNESOTA

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ABSTRACT

Precambrian rocks exposed in the Granite Falls-Montevideo area, within the Minnesota River valley, consist of interlayered metamorphic rocks that are intruded by mafic dikes and a small adamellite body. Lithologically the metamorphic rocks are granitic gneiss, hornblende-pyroxene gneiss, garnet-biotite gneiss, and a heterogeneous sequence of interlayered gneisses containing variable proportions of biotite, hornblende, pyroxene, feldspar, and quartz. The mafic dikes are tholeiitic diabase, hornblende andesite, and olivine diabase.

Dynamothermal metamorphism approximately 2500-2700m.y. ago produced an inclined, cylindrical fold system that plunges approximately 15° N. 85 W. Most mineral assemblages resulting from the metamorphism belong to the granulite facies. Mineral assemblages characteristic of the amphibolite facies are interlayered with those of the granulite facies, and there is no indication of metamorphic zoning. Coexisting mineral assemblages indicate that there was an approach to chemical equilibrium and that there were no significant variations in physical conditions during metamorphism.

Common retrograde metamorphic textures are "serpentine" veins in orthopyroxene, rims of cummingtonite on orthopyroxene, and rims of sea-green actinolite-hornblende on clinopyroxene and hornblende.

Intrusion of tholeiitic diabase dikes along a northeast-trending fracture system occurred after the metamorphism and folding. A minimum age for the tholeiitic diabase is 2080 m.y.

Cataclastic deformation, represented by narrow northwest-trending shear zones and by granulation, took place after intrusion of the tholeiitic diabase but before intrusion of the 1700-1800 m.y. old hornblende andesite dikes. The 1800 m.y. event is also represented by intrusion of a small adamellite body that was contemporaneous with a thermal event that resulted in the resetting of the biotite ages in the metamorphic rocks.

INTRODUCTION

Scattered outcrops of Precambrian igneous and metamorphic rocks in the Minnesota River valley (pl. 1) represent the farthest southwesterly exposures of the Precambrian Canadian shield in Minnesota except for the Sioux Quartzite. The rocks in the Minnesota River valley provide an isolated window into the Precambrian, and cannot yet be correlated closely with Precambrian rocks in other parts of Minnesota. Isotopic dating (Goldich and others, 1961) shows that the metamorphic rocks in the Minnesota River valley were metamorphosed during the Algoman orogeny (2400-2750 m.y. ago) – an event that also is represented in northern Minnesota. In addition, the metamorphic rocks of the Granite Falls-Montevideo area give potassium-argon biotite ages of approximately 1800 m.y., which is the approximate time of the Penokean orogeny in central Minnesota and in northern Wisconsin and Michigan (Goldich and others, 1961).

Although the timing of major events in the Minnesota River valley, as indicated by isotopic dating, is in many ways similar to that in other parts of the state, meaningful correlations of the geologic events in the separate areas cannot be made without detailed field investigations of the structure and petrology in each of the separate areas. The Granite Falls-Montevideo area (pl.1) was chosen as the first area in the Minnesota River valley for detailed studies of the structure and petrology for the following reasons: 1) diverse rock types are present, (2 outcrop density is good, 3) at least two metamorphic events, as indicated by isotopic dating, are known, and 4) a large fold was mapped by Lund (1956).

Previous Work

The Minnesota River valley was visited by several early explorers who referred to the nature of the rocks exposed in the area (see Hall, 1899). Geologic reports on the crystalline rocks of the Minnesota River valley published prior to 1900 include those of J. Hall (1869), Winchell (1873), Winchell and Upham (1884, 1888), and C.W. Hall (1899). Several specimens from the Granite Falls area were included in an early U.S. Geological Survey educational series of rock specimens (Diller, 1898). Structural and ornamental stones quarried in the Minnesota River valley have been described by Bowles (1918) and Thiel and Dutton (1935).

More recent investigations of the Granite Falls-Montevideo area include the geologic mapping and description of the igneous and metamorphic rocks by Lund (1956), and isotopic age determinations by Goldich and others (1961), Goldich and Hedge (1962), Catanzaro (1963), Stern (1964), and Hanson and Himmelberg (1967).

Scope and Methods of Investigation

Geologic mapping was conducted for a period of 5 months during the summers of 1962 and 1963; the mapping was done on areal photographs having an approximate scale of 1:20,000. The final geologic maps (pl.1) were prepared by transferring the data on the areal photographs onto standard 7½-minute topographic maps.

Approximately 250 thin sections of samples collected during the geologic mapping were studied in detail with the polarizing microscope to determine the minerals present and their textural relationships. Modal analyses were made by counting 1000 points per thin section.

Partial chemical compositions of one or more minerals from 46 samples were determined with the use of a Materials Analysis Company Model 400 electron microprobe. The mineral analyses and a discussion of the methods used are presented in a separate report (Himmelberg and Phinney, 1967).

Acknowledgments

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PRECAMBRIAN ROCK UNITS

The Precambrian rocks exposed in the Minnesota River valley in the Granite Falls-Montevideo area consist of interlayered metamorphic gneisses and amphibolites that are intruded by numerous mafic dikes and a small adamellite body. To clarify the interpretation of the petrology and structure of the area, the metamorphic rocks were mapped and are described in this report in terms of lithology without formal designation.

The metamorphic rock units are granitic gneiss, hornblende-pyroxene gneiss, garnet-biotite gneiss, and interlayered gneiss. These units are grossly equivalent to those of Lund (1956), who mapped the area previously (tbl. 1). The major differences between the units distinguished in this report and the earlier mapping by Lund are as follows: 1) rocks mapped by Lund as Montevideo granite gneiss southeast of Granite Falls (secs. 10, 11, and 12, T. 115 N., R. 39 W.; pl. 1) are not included in the granitic gneiss of this report but instead are mapped as interlayered gneiss; 2) a part of the rocks mapped by Lund as Montevideo granite gneiss in secs. 28 and 33, T. 116 N., R. 39 W. (pl. 1) are designated hornblende-pyroxene gneiss in this report; and 3) the northern and southern edges (approximately 500 feet) of Lund's Granite Falls quartz diorite gneiss that occurs southeast of Granite Falls are distinguished on Plate 1 of this report as hornblende-pyroxene gneiss.

Table 1 – Names for metamorphic rock units of this report compared with those used by Lund (1956)

Lund (1956)	This Report
Montevideo granite gneiss	Granitic gneiss
Gabbro gneiss	Hornblende-pyroxene gneiss
Granite Falls garnetiferous quartz diorite gneiss	Garnet-biotite gneiss
	Interlayered gneiss

Metamorphic Rocks

Granitic Gneiss

The granitic gneiss is a leucocratic, pink to red, medium-grained, generally equigranular, wholly crystalloblastic rock that consists primarily of quartz, feldspar, and biotite and has local disseminated garnet (fig. 1). Compositional banding imparted by biotite-rich bands alternating with quartzo-feldspathic bands generally is present. The quartzo-feldspathic bands range in thickness from less than one inch to approximately 50 feet. Mineral foliation, nearly always parallel to the compositional banding, is given by preferred orientation of biotite and local flat quartz grains.

Quartz-feldspar-biotite pegmatities and bluish quartz lenses are parallel to and crosscut the foliation of the gneiss. The pegmatites are generally less than six inches thick, but the quartz lenses are as much as one foot thick. Minor folding, warping, and incipient boudinage are present commonly in the gneiss, but the degree of such deformation varies from place to place. Numerous hornblende-pyroxene gneiss layers and lenses of variable thickness are present in the granitic gneiss. The exposed contacts between the hornblende-pyroxene gneiss and the granitic gneiss are sharp and conformable although locally slightly scalloped.

The principal minerals of the granitic gneiss are quartz, microcline, plagioclase, and biotite; apatite, zircon, rutile, hematite, and garnet are minor constituents. Secondary minerals include chlorite, sericite, epidote, hematite, leucoxene, and sphene. Approximate modes of representative samples are given in Table 2.

Quartz, plagioclase, and microcline occur in all samples of granitic gneiss, but the percentages of individual minerals vary. The plagioclase ranges in composition, as determined by the Rittmann zone method (Emmons, 1943, p. 115), from An_{15} to An_{20}. Both polysynthetic twinned and untwinned plagioclase grains are present. Rectangular-shaped microantiperthite blebs are present in many samples, but are never abundant. Microcline is commonly microperthitic and has fair to excellent grid twinning. All the feldspars are sericitized to some degree, and commonly are clouded by opaque oxide. Some samples of feldspar from the Montevideo area show extreme "exsolution" of hematite, and this probably accounts for the pronounced red color of the granitic gneiss in the Montevideo area as compared to the generally pink granitic gneiss near Granite Falls.

Biotite is the only mafic mineral in the granitic gneiss. It rarely makes up more than 10 percent of the rock and in many samples makes up less than one percent; it is absent in some quartzo-feldspathic bands. The biotite is pleochroic, ranging from dark brown to straw yellow, and commonly has exsolved hematite and leucoxene. Most commonly the biotite is partly altered to green chlorite; locally it is partly altered to an opaque oxide and sphene. Primary hematite with intergrown rutile is sparse.

Figure 1 – Crystalloblastic texture of granitic gneiss. The rock is composed of quartz, plagioclase, microcline, and biotite. Sample M8115, (x 65, crossed nicols).

Table 2 – Modes, in volume percent, of granitic gneiss (Tr, trace; -, not found)

Sample Number	M8115	M8116	M8162	M8278
Quartz	25.0	33.1	33.6	29.5
Plagioclase	54.0	26.1	51.6	35.0
Microcline	15.9	39.5	12.1	31.2
Biotite	5.0	0.9	1.2	3.5
Garnet	–	Tr.	–	–
Hematite	0.1	0.4	0.5	0.6
Apatite	Tr.	–	Tr.	Tr.
Zircon	Tr.	Tr.	Tr.	0.1
Rutile	–	–	–	Tr.
Chlorite	–	–	Tr.	–
Sericite	Tr.	Tr.	1.0	0.1
Leucoxene	–	–	Tr.	–
An content of plagioclase	18	15	18	18

M8115 Great Northern railroad cut, NW¼, sec. 28, T. 116 N., R. 39 W.
M8116 Southwest edge of outcrop area, NW¼, sec. 28, T. 116 N., R. 39 W.
M8162 Small rock quarry at Great Northern Crushing Plant, SE¼, sec. 29, T. 116 N., R. 39 W.
M8278 U.S. Highway 212 roadcut, SE¼, sec. 20, T. 117 N., R. 40 W.

Hornblende-Pyroxene Gneiss

The hornblende-pyroxene gneiss is a gray to black, medium-grained, generally equigranular rock that has a wholly crystalloblastic texture (fig. 2) ranging from granoblastic to nematoblastic. The mineralogy of the gneiss is variable, particularly with respect to the quantities of individual minerals, but the rock always is characterized by hornblende and/or pyroxene. Approximate modes of various mineralogic types of least retrograded hornblende-pyroxene gneiss are given in Table 3.

The hornblende-pyroxene gneiss varies structurally from a uniform amphibolite to a conspicuously banded gneiss (fig. 3). Because the two rock types have both lithologic and structural similarities the amphibolite and the gneiss were mapped as a single rock unit.

The amphibolite variety of the hornblende-pyroxene gneiss unit is dark and uniform and locally has a crude gniessic structure resulting from rodding of hornblende-pyroxene aggregates. Amphibolite occurs most commonly as layers and lenses of variable thickness in the granitic gneiss, ranging from less than one foot to approximately 250 feet thick, and where possible these bodies were mapped. It also occurs as discrete layers (maximum thickness approximately 25 feet) within the hornblende-pyroxene gneiss that occurs around the nose of the anticline northwest of Granite Falls (secs. 28 and 33, T. 116 N., R. 39 W.; pl. 1). Contacts between amphibolite and the lighter gneisses in the unit are sharp and conformable, and the long axis of amphibolite lenses are parallel to the trend of the foliation.

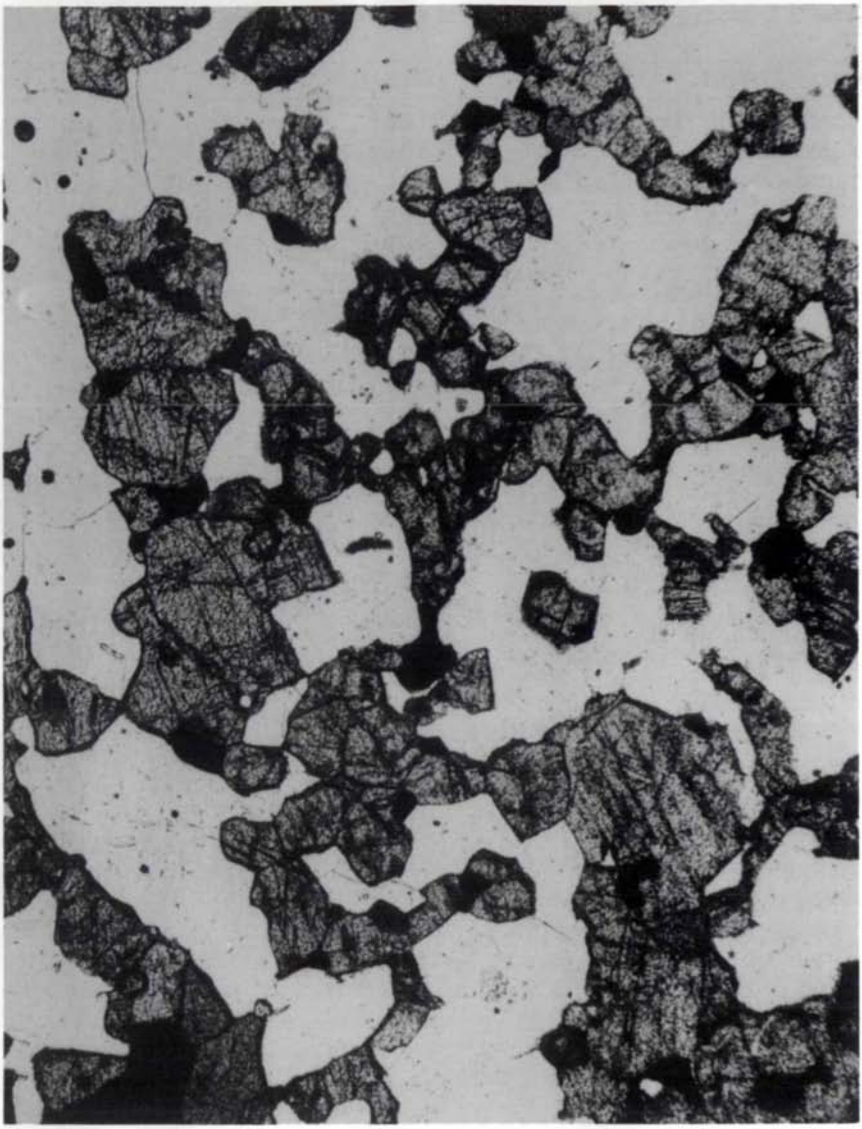

Figure 2 – Crystalloblastic texture of hornblende-pyroxene gneiss. Pyroxene and plagioclase are present in section. Sample M8110, (x 25, plane light).

Figure 3 – **Compositional banding in hornblende-pyroxene gneiss. Dark bands consisting primarily of hornblende, pyroxene, and plagioclase alternate with light bands consisting primarily of pyroxene, plagioclase, and quartz. SE¼, SW¼, sec. 28, T. 116 N., R. 39 W.**

The extensive hornblende-pyroxene gneiss exposed immediately south of Granite Falls (secs. 3 and 4, T. 115 N., R. 39 W.; pl. 1) is a uniformly gray rock that has a crude gneissic structure and locally a faint compositional banding. Approximately the southern one-quarter of this unit is characterized by excellent compositional banding of variable thickness, which most commonly results from differences in the percentage of individual minerals within respective layers rather than in the kind of minerals present.

The hornblende-pyroxene gneiss exposed around the nose of the anticline northwest of Granite Falls (secs. 28 and 33, T. 116 N., R. 39 W.; pl. 1) consists of a heterogeneous sequence of interlayered mafic and felsic gneisses. The mafic layers consist of gneisses and amphibolites composed of abundant hornblende and pyroxene and only minor quartz; the felsic layers contain abundant quartz and plagioclase with subordinate pyroxene and hornblende. In some felsic layers, pyroxene is the only mafic mineral present. Rocks intermediate in composition between the mafic and felsic varieties as well as garnetiferous and magnetite-rich units are present. Thin layers (maximum thickness about 20 feet) of pegmatitic-granitic gneiss are interlayered with the hornblende-pyroxene gneiss in this area.

Hornblende-pyroxene gneiss is not common in the Montevideo area (pl. 1), and the few exposures that are present are generally amphibolite layers and lenses in the granitic gneiss. The small outcrop exposed in Section 34, T. 117 N.,

Table 3 – Modes, in volume percent, of hornblende-pyroxene gneiss (Tr, trace; -, not found)

Sample Number	M8079	M8098	M8140	M8141	M8165
Quartz	1.2	0.6	–	–	Tr.
Plagioclase	65.4	59.4	41.1	30.1	49.5
Hornblende	0.5	2.4	36.4	68.1	17.3
Orthopyroxene	6.6	20.5	12.9	–	23.7
Clinopyroxene	6.2	9.4	9.2	Tr.	8.5
Biotite	Tr.	6.8	Tr.	0.2	0.6
Magnetite-ilmenite	7.7	0.9	Tr.	1.2	0.4
Garnet	12.0	–	–	–	–
Potassium feldspar	–	–	–	–	–
Apatite	0.4	Tr.	0.2	Tr.	–
Zircon	–	Tr.	Tr.	Tr.	–
Hematite	–	–	Tr.	Tr.	–
Sericite	Tr.	Tr.	Tr.	0.4	Tr.
Calcite	–	–	Tr.	Tr.	–
Cummingtonite	–	–	Tr.	–	–
Actinolite	–	–	0.2	–	–
Epidote	–	–	–	–	–
Pyrite	Tr.	–	–	–	–
An content of plagioclase	34	48	52	45	49

Sample Number	M8168	M8169	M8182	M8185	M8205
Quartz	14.6	–	34.2	4.0	22.5
Plagioclase	69.8	32.9	50.4	66.6	59.8
Hornblende	1.7	46.7	5.0	15.9	1.2
Orthopyroxene	9.9	8.4	–	10.6	3.5
Clinopyroxene	2.2	10.0	2.4	2.5	0.1
Biotite	Tr.	–	Tr.	0.1	11.9
Magnetite-ilmenite	0.9	0.8	6.5	0.1	6.7
Garnet	–	–	0.2	–	–
Potassium feldspar	0.6	–	1.1	–	0.2
Apatite	0.3	0.1	0.2	Tr.	0.1
Zircon	Tr.	–	Tr.	0.1	Tr.
Hematite	Tr.	Tr.	Tr.	–	–
Sericite	–	Tr.	Tr.	Tr.	Tr.
Calcite	–	–	–	–	–
Cummingtonite	–	–	–	0.1	–
Actinolite	–	1.1	–	–	–
Epidote	–	–	Tr.	–	–
Pyrite	–	Tr.	–	–	–
An content of plagioclase	33	42	32	65	45

M8079 Granite Falls Memorial Park, NW¼, sec. 3. T. 115 N., R. 39 W.
M8098 Minn. Highway 67 roadcut at Granite Falls Memorial Park, NW¼, sec. 3, T. 115 N., R. 39 W.
M8140 Small amphibolite lens, SE¼, NW¼, sec. 32, T. 116 N., R. 39 W.
M8141 Small amphibolite lens, NW¼, sec. 32, T. 116 N., R. 39 W.
M8165 Roadcut about 500 feet south of road intersection, SW¼, sec. 28, T. 116 N., R. 39 W.
M8168 Ridge top, SE¼, SW¼, sec. 28, T. 116 N., R. 39 W.
M8169 Ridge top, SW¼, SW¼, sec. 28, T. 116 N., R. 39 W.
M8182 Ridge top, nose of anticline, center sec. 33, T. 116 N., R. 39 W.
M8185 NW¼, NW¼, sec. 4, T. 115 N., R. 39 W.
M8205 South of highway, center sec. 4, T. 115 N., R. 39 W.

R. 40 W. is a garnetiferous hornblende-pyroxene gneiss lithologically similar to a 50-foot-thick layer of garnetiferous hornblende-pyroxene gneiss that occurs near the garnet-biotite gneiss contact southeast of Granite Falls (secs. 3 and 4, T. 115 N., R. 39 W.; pl. 1).

Quartz lenses and veins as much as 10 feet long and one foot wide are parallel to and crosscut the foliation of the hornblende-pyroxene gneiss. Other common characteristics are pockets of coarse-grained pyroxene and plagioclase and small (1/8 inch) healed fractures. Structures such as minor folding, warping, and boudinage are rare in the hornblende-pyroxene gneiss.

The principal minerals in most of the hornblende-pyroxene gneiss are plagioclase, hornblende, clinopyroxene, and orthopyroxene; quartz, biotite, opaque oxides, and apatite are minor minerals, and sphene is rare (samples M8140, M8165, M8169, and M8185, tbl. 3). Individual minerals vary in amount, and some amphibolites consist essentially of plagioclase and hornblende (sample M8141, tbl. 3). In those rocks that contain only one pyroxene, the pyroxene commonly is the Ca-rich variety.

Hornblende-pyroxene gneiss with uncommonly abundant quartz and plagioclase and hornblende-pyroxene gneiss with an appreciable biotite content (samples, M8098, M8168, M8182, M8205, tbl. 3) occur in sequences that are compositionally banded. Untwinned potassium feldspar is present in minor amount in some quartz-rich hornblende-pyroxene gneiss. Garnet-bearing hornblende-pyroxene gneiss (samples M8079 and M8182) is not common but does occur interlayered (maximum thickness approximately 50 feet) with the other types; generally it is magnetite-rich. Three exposures of amphibolite lenses are unique in that they contain large plagioclase porphyroblasts that range in length from a quarter of an inch to approximately three inches, most of them exceeding one inch.

Plagioclase is an abundant constituent in the hornblende-pyroxene gneiss; it is generally clear but slightly sericitic. Polysynthetic twinning is common and microantiperthite texture is present in some samples. The anorthite content of plagioclase from 28 samples, determined by use of the electron microprobe, ranges from An_{32} to An_{89} (Himmelberg and Phinney, 1967, p. 332). No systematic zoning was observed although some plagioclase grains show a broad undulatory extinction.

Hornblende, clinopyroxene, and orthopyroxene form discrete polygonal grains that are intimately intergrown with sharp curvilinear grain boundaries. The hornblende and to a lesser extent the pyroxene are commonly prismatic and impart a nematoblastic texture to many samples. Hornblende, clinopyroxene, and orthopyroxene may be equigranular or inequigranular; where inequigranular, the hornblende is coarser grained than the pyroxene.

Analyses of hornblende with the electron microprobe show significant variations in Al_2O_3, FeO, and MgO (Himmelberg and Phinney, 1967, p. 332). Orthopyroxene displays pleochroism in shades of pink (X) and pale green (Z). Clinopyroxene is generally pale green and non-pleochroic. The mole ratio of MgO/MgO+FeO in the hornblende ranges from 0.24 to 0.58; in the orthopyroxene it ranges from 0.27 to 0.58; and in the clinopyroxene it ranges from 0.31 to 0.76.

Some orthopyroxene and less commonly the clinopyroxene have a fine lamellar structure (about one micron in width) under crossed nicols that does not appear to be produced by exsolution. Henry (1942, p. 187) suggested that this type of lamellar structure in orthopyroxene is a result of translation in (001) in the direction [100] accompanied by bending of the lamellae. Naidu (1954, p. 236) and Subramaniam (1962, p. 27) attribute such lamellae in clinopyroxene to twinning.

Primary biotite is generally present only in trace amounts, but in some samples it attains a maximum of approximately 20 percent of the rock. It is generally dark brown or reddish brown and shows a preferred orientation where abundant. Opaque oxides are common and locally abundant (e.g., sample M8182), and generally consist of individual grains and intergrowths of magnetite and ilmenite. Hematite is present in some layers. Potassium feldspar is rare and always untwinned. Garnet, which is rich in the almandine component and contains between 7 and 8 percent by weight CaO (Himmelberg and Phinney, 1967, p. 332), is present in some layers.

Textures involving replacement of primary hornblende, orthopyroxene, and clinopyroxene are common, and the amount of replacement is variable and locally extreme. The most commonly observed secondary minerals are cummingtonite and a sea-green (bluish tint) amphibole.

Cummingtonite occurs as parital or complete rims around orthopyroxene and as fibrous or blade-like aggregates with relict orthopyroxene granules, or in some cases without relict primary minerals. The boundary between cummingtonite and the primary mineral is always sharp and commonly marked by small opaque oxide granules that are distributed along the contact. Considerable amounts of opaque oxide, at least a part of which is hematite, are commonly associated with cummingtonite aggregates. Wide rims and aggregates of cummingtonite commonly have green hornblende margins. Cummingtonite that formed from orthopyroxene at hornblende-orthopyroxene grain boundaries crystallized homoaxially on the hornblende. Where the cummingtonite rims are partial and narrow they occur only at hornblende-orthopyroxene grain boundaries, but wider rims completely enclose the orthopyroxene. Apparently the hornblende acted as a nucleus for the formation of cummingtonite because of the similarities in the crystal structures of the two amphiboles.

Sea-green (bluish tint) amphibole occurs as rims around hornblende (fig. 4) and clinopyroxene and as granular aggregates. Narrow rims are generally homogeneous and continuous, but wider ones commonly consist of granular aggregates. Several samples were observed where primary hornblende is mantled by actinolite; the actinolite may have a sharp border of bluish green hornblende. Samples showing replacement of hornblende by coexisting cummingtonite, actinolite, and epidote are present but not common.

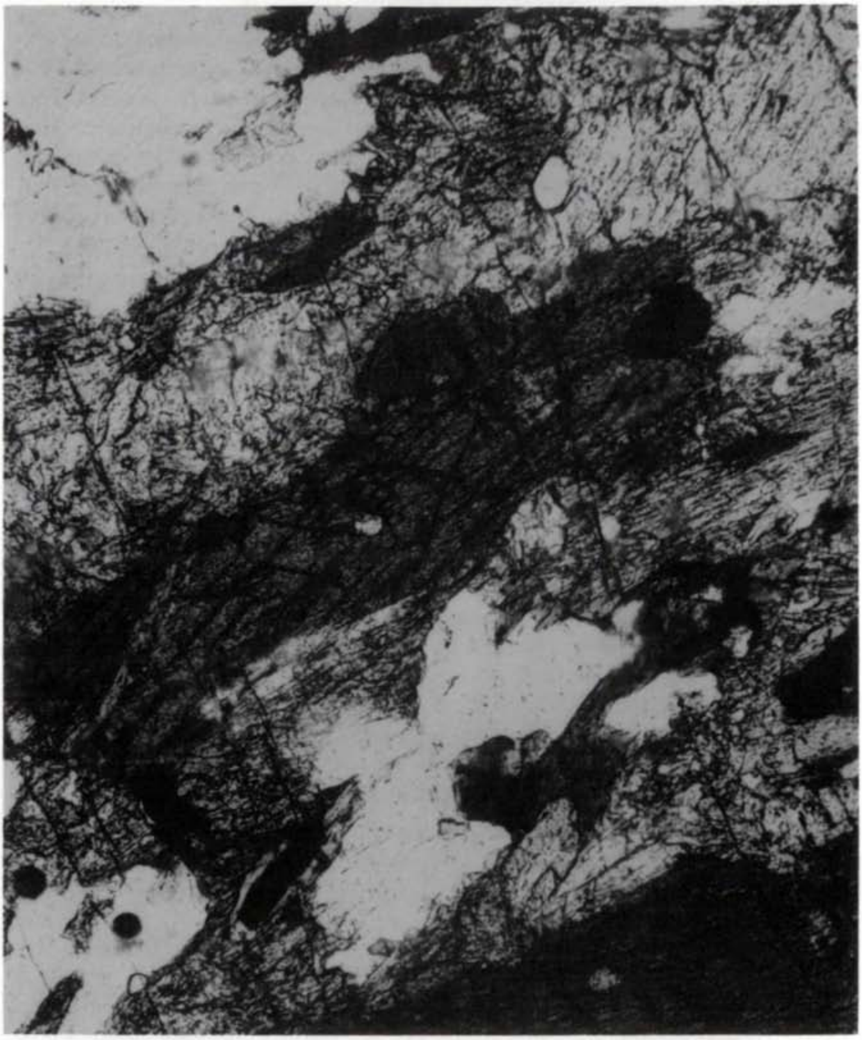

Figure 4 – Mantle of green amphibole around primary brown hornblende, hornblende-pyroxene gneiss. Sample M8198 (Plane light; x 65).

One other common replacement texture involving orthopyroxene is the occurrence of a yellow-brown or green fibrous to platy mineral along fractures in orthopyroxene. This secondary mineral has nearly parallel extinction and $2V_X$ of approximately 24°, and was identified as a serpentine-type mineral. The degree of replacement is variable and in some samples it is complete. The serpentine replacement of orthopyroxene does not occur instead of cummingtonite; commonly the orthopyroxene is mantled by cummingtonite and has serpentine along fractures that do not continue into the cummingtonite (Fig. 5).

A common replacement texture is the occurrence of biotite around the periphery of magnetite; rarely magnetite may have a sphene around its periphery.

The replacement textures discussed above occur in samples that generally show no evidence of shearing or cataclasis. Where cataclastic textures and shearing are present, the alteration of the mafic minerals is generally extreme, producing epidote, chlorite, calcite, and secondary opaque oxides; also, the plagioclase commonly is saussuritized.

Garnet-Biotite Gneiss

The garnet-biotite gneiss is one of two types – a dark gray, medium-grained, well foliated gneiss (samples M8086, M8096, M8219, M8239, tbl. 4), and a light gray, coarse, granular gneiss (samples M8211, and M8048, tbl. 4). The coarse granular gneiss is common but not abundant and occurs as bands (maximum thickness about four feet) in the well foliated garnet-biotite gneiss. The garnet-biotite gneiss is generally equigranular and has a wholly crystalloblastic texture produced by interlocking grains with sharp curvilinear contacts. Quartz and feldspar are generally granular, and the foliation is produced by preferred orientation of biotite and prismatic orthopyroxene.

Southeast of Granite Falls, both the north and south margins of the garnet-biotite gneiss contacts are in contact with hornblende-pyroxene gneiss. The northern contact is well exposed in the Minnesota Highway 67 road cut at the Granite Falls Memorial Park (NW¼, sec. 3, T. 115 N., R. 39 W.; pl. 1), where it is conformable and marked essentially by the first appearance of garnet. The southern contact is not directly exposed, and it is possible that it is a fault contact. The contact of the garnet-biotite gneiss with hornblende-pyroxene gneiss northwest of Granite Falls is not exposed.

The principal minerals of the garnet-biotite gneiss are plagioclase, quartz, biotite, and garnet; lesser minerals are potassium feldspar, opaque oxides, apatite, zircon, and sericite. In addition, the well foliated gneiss generally contains orthopyroxene as a principal mineral.

Quartz and plagioclase are abundant. Plagioclase is generally clear, slightly sericitized, and has polysynthetic twinning and microantiperthite texture. Plagioclase compositions determined from 13 samples range from An_{29} to An_{40}. Potassium feldspar is not abundant, generally constituting one percent or less, and is not present in all samples. It is untwinned, rarely microperthitic, and has a $2V_X$ of 60° -63°, indicating it is an orthoclase of approximate composition Or_{70}.

Biotite is dark reddish brown to straw yellow. Orthopyroxene is pleochroic in pale pink (X) and faint green (Z), and is in the compositional range of

Figure 5 — Hornblende-pyroxene gneiss. Orthopyroxene is partly replaced by serpentine along fractures, and is mantled by cummingtonite. Note that serpentine does not extend into cummingtonite. Sample M8274 (Plane light; x 25).

Table 4 – Modes, in volume percent, of garnet-biotite gneiss (Tr, trace; -, not found)

Sample Number	M8048	M8086	M8096	M8211	M8219	M8239
Quartz	30.7	29.5	25.3	32.5	21.4	23.6
Plagioclase	60.7	44.5	50.3	55.5	42.6	50.7
Potassium feldspar	1.9	–	0.3	0.8	0.6	1.1
Biotite	3.5	19.7	14.7	10.7	22.5	17.8
Orthopyroxene	–	–	9.3	–	7.5	Tr.
Garnet	2.4	6.3	–	Tr.	4.5	6.8
Magnetite-ilmenite	0.1	Tr.	0.1	Tr.	0.9	Tr.
Apatite	–	Tr.	Tr.	Tr.	Tr.	Tr.
Zircon	0.2	–	Tr.	Tr.	Tr.	Tr.
Chlorite	0.1	Tr.	–	–	–	–
Cummingtonite	–	Tr.	–	–	–	–
Sericite	0.4	Tr.	Tr.	0.5	Tr.	Tr.
Pyrite	–	–	–	–	Tr.	–
An content of plagioclase	29	29	32	31	34	32

M8048 At Minnesota River, NE¼, SE¼, sec. 2, T. 115 N., R. 39 W.
M8086 NW¼, NW¼, sec. 10, T. 115 N., R. 39 W.
M8096 At contact, Minn. Highway 67 roadcut at Granite Falls Memorial Park, sec. 3, T. 115 N., R. 39 W.
M8211 SW¼, NE¼, sec. 4, T. 115 N., R. 39 W.
M8219 Roadcut at curve of Minn. Highway 67, Granite Falls Memorial Park, sec. 3, T. 115 N., R. 39 W.
M8239 NW¼, SE¼, sec. 11, T. 115 N., R. 39 W.

hypersthene. Orthopyroxene that has rims of cummingtonite and is serpentinized along fractures is present locally.

Pink, medium-grained, almandine garnet is generally present. Its CaO content is considerably lower (1.5 to 2.5 percent by weight) than for the garnet in the hornblende-pyroxene gneiss. In the granular gneiss, garnet occurs in disseminated coarse-grained clusters and accordingly an individual thin section may not contain it. Blebs of quartz and to a lesser extent biotite and opaque oxides are present in the garnet. The opaque oxides are mainly magnetite and ilmenite.

Interlayered Gneiss

The interlayered gneiss occurs on the ridge south of the Minnesota River in sections 10, 11, and 12, T. 115 N., R. 39 W. (pl. 1). It is a heterogeneous, generally well-foliated, layered rock sequence consisting of several rock types – leucocratic granitic gneiss, hornblende-pyroxene gneiss (amphibolite), biotite-quartz-plagioclase-hornblende gneiss, and granitic hornblende gneiss. Approximate modes of the last two rock types are given in Table 5.

The leucocratic granitic gneiss is an equigranular, essentially granoblastic rock having a preferred orientation of biotite. Principal minerals are quartz, plagioclase, and microcline, with minor amounts of biotite, chlorite, epidote, apatite, zircon, and sericite. Plagioclase is sericitized, microantiperthitic, and commonly has polysynthetic twinning. Microcline has grid twinning, is microperthitic, and is relatively unaltered. Biotite is generally altered to a green chlorite with anomalous interference colors.

The hornblende-pyroxene amphibolite is similar in mineralogy and texture to that described in the section on hornblende-pyroxene gneiss except that it is commonly extremely altered.

Biotite-quartz-plagioclase-hornblende gneiss is generally equigranular, and has a preferred orientation of biotite, prismatic hornblende, and elongate quartz grains. Granulation is common, particularly around grain boundaries. Principal minerals are biotite, plagioclase, quartz, and generally hornblende, all of which vary moderately in amount. Accessory and secondary minerals include apatite, zircon, opaque oxide, chlorite, eqidote, and sericite. Some layers contain a pink medium-grained garnet. Minor amounts of grid-twinned microcline are present in some samples. One sample contains fibrous cummingtonite aggregates with borders of green amphibole. The cummingtonite is probably secondary after orthopyroxene. Plagioclase is slightly sericitized; twinned and untwinned grains are equally common, and microantiperthitic texture is present in some samples. Biotite is dark brown and commonly altered to a green chlorite with anomalous interference colors. Hornblende is green with a brownish hue or bluish tint.

Table 5 – Modes, in volume percent, of interlayered gneiss (Tr, trace; -, not found)

Sample Number	M8245	M8256	M8253
Quartz	21.3	26.2	32.3
Plagioclase	53.3	38.8	50.5
Microcline	0.4	0.6	9.1
Biotite	13.5	31.2	Tr.
Hornblende	2.3	3.1	5.5
Cummingtonite	7.4	–	1.5
Magnetite-ilmenite	0.3	Tr.	1.1
Apatite	0.2	Tr.	Tr.
Zircon	Tr.	–	Tr.
Sericite	Tr.	Tr.	Tr.
Epidote	–	Tr.	–
Chlorite	1.3	0.1	–

M8245 NW¼, SE¼, sec. 11, T. 115 N., R. 39 W.
M8256 NE¼, SW¼, sec. 11, T. 115 N., R. 39 W.
M8253 SE¼, NE¼, sec. 11, T. 115 N., R. 39 W.

Granitic hornblende gneiss is pink, medium-grained with coarse-grained microcline porphyroblasts, and has a crystalloblastic texture. Foliation is produced by a crude preferred orientation of prismatic hornblende and elongate quartz grains. Principal minerals are quartz, microcline, plagioclase, and hornblende, with minor amounts of opaque oxide, biotite, cummingtonite, apatite, zircon, and sericite. Microcline occurs in the groundmass and as porphyroblasts approximately ½ cm in size. It is microperthitic, sericitized. and has a fair grid twinning. Plagioclase is sericitized, commonly microantiperthitic, and generally shows polysynthetic twinning. Mafic minerals consist of green hornblende with a brownish hue and reddish-brown biotite that occurs most commonly around the periphery of opaque oxide grains. Individual isolated biotite grains are also present. Cummingtonite that commonly has a border of bluish green hornblende is present as fibrous aggregates.

Igneous Rocks

Igneous rocks in the Granite Falls-Montevideo area consist primarily of mafic dikes, which can be subdivided into tholeiitic diabase, hornblende andesite, and olivine diabase. A small adamellite intrusive body is exposed along the gravel road and the Chicago, Milwaukee, St. Paul, and Pacific Railroad in the NW¼, sec. 28, T. 116 N., R. 39 W. (pl. 1). This adamellite body is equivalent to Lund's late granite (Lund, 1956). Small granitic dikes (less than 1-foot thick) occur rarely in the Granite Falls area. They vary in texture from aphanitic with quartz phenocrysts (NW¼, SE¼, sec. 11, T. 115 N., R. 39 W.) to aplitic (SE¼, NE¼, sec. 11, T. 115 N., R. 39 W.,). A one-foot, red, medium-grained leucocratic granite dike occurs just south of the pond in section 11, T. 115 N., R. 39 W.

Tholeiitic Diabase

Most of the mappable mafic dikes (maximum thickness approximately 75 feet) are tholeiitic diabase. These dikes are dark gray, medium-grained, and have fine-grained borders. Small quartz lenses (several inches) and small healed fractures (about 1/8 inch) are locally present.

Principal minerals of the least altered diabase are unoriented laths of cloudy, zoned, twinned plagioclase (approximately An_{50}), intergranular augite, and opaque oxide. Biotite is present in minor amounts and occurs exlusively with skeletal opaque oxide. Minor amounts of apatite and quartz are present and, locally, secondary epidote. Commonly, semi-fibrous green hornblende mantles augite. In some samples the replacement of augite by hornblende is complete, so that the rock consists of plagioclase and granular green hornblende aggregates that have a diabasic texture. The percentage of biotite decreases as the replacement hornblende increases, indicating that the biotite also is replaced by hornblende.

Hornblende Andesite

Hornblende andesite dikes are abundant in the area, but are commonly too small to be mapped at a scale of 1:20,000. They are generally gray to black, aphanitic, commonly porphyritic rocks that are variable in texture and modal composition. The phenocrysts are generally plagioclase and/or anhedral quartz. One type of dike is characterized by phenocrysts of granular green hornblende pseudomorphic after clinopyroxene; relict clinopyroxene phenocrysts are present rarely. Some of these dikes have a conspicuous flow structure.

Principal matrix minerals of the hornblende andesites are plagioclase, hornblende, and biotite. Minor amounts of opaque oxide, apatite, and interstitial quartz and potassium feldspar are common. Secondary chlorite, epidote, calcite, and sericite is present in many samples. The hornblende is generally brown or green and prismatic; however, one dike contains intergranular hornblende. Plagioclase is lath shaped, commonly zoned, and has polysynthetic twinning. The plagioclase composition ranges from approximately An_{40} to An_{60}. One dike in this group is pinkish gray hornblende-biotite andesite containing microcline.

Olivine Diabase

Olivine diabase, a black aphanitic rock, was observed as dikes at two localities (secs. 2, 10, and 11, T. 115 N., R. 39 W.; and sec. 19, T. 116 N., R. 39 W.; pl. 1). The dikes consist of olivine, plagioclase, and augite microphenocrysts in a matrix of unoriented plagioclase microlites, granular pyroxene, and sparse opaque oxide. Olivine contains fine powdery opaque oxide and has opaque oxide along fractures. Plagioclase phenocrysts lack zoning and have a composition of An_{65-70}. Coronas consisting of concentric rims of colorless amphibole and green amphibole occur around the olivine in some samples. Some coronas contain green spinel and orthopyroxene.

Adamellite

The adamellite is generally a pink, medium-grained, hypidiomorphic granular rock, but where it contains abundant mafic dike xenoliths it is gray. Principal minerals and their estimated percentages are plagioclase (35%), microcline (30%), quartz (25%), and biotite (10%); in addition, there are minor amounts (total 1%) of opaque oxide, apatite, zircon, chlorite, epidote, and sericite. The plagioclase is euhedral to subhedral with marked zoning and polysynthetic twinning. Lund (1956, p. 1486) reports the plagioclase composition as An_{20}. Alteration of plagioclase to sericite and epidote is common. Microcline is anhedral, relatively unaltered, slightly microperthetic, and has grid twinning. Myrmekite is present but not abundant. Biotite is dark brown to yellowish brown and commonly altered to green chlorite with anomalous purple interference colors.

STRUCTURE

General Statement

The major structural feature in the Granite Falls-Montevideo area is a gentle eastward-plunging fold system. Foliations and lineations within the metamorphic rocks statistically define the plunge of the folds as N. 85 E., 15° and indicate that the existing internal structures probably formed during one generation. Cataclastic deformation, represented by narrow shear zones and granulation in the metamorphic rocks as well as igneous intrusion took place after the period of folding.

Structures in the Metamorphic Rocks

Foliation

The Precambrian metamorphic rocks in the Granite Falls-Montevideo area characteristically have a fair to excellent foliation defined by compositional banding, preferred orientation of planar minerals, and subparallel flat quartz lenses and hornblende segregations. Compositional banding and mineral foliation are almost always parallel. The compositional banding results from slight to marked differences in mineralogical composition, commonly accompanied by textural differences, and individual bands range in thickness from less than one inch to several feet. The planar structure is of metamorphic origin; some of the compositional banding, however, probably represents a primary compositional layering.

The degree to which the foliation in the metamorphic rocks is developed differs among the various lithologic units and also within a single lithologic unit. The granitic gneiss generally has a well-developed foliation resulting from biotite-rich bands alternating with quartzo-feldspathic bands. The moderately abundant biotite content of the garnet-biotite gneiss imparts an excellent mineral foliation that is parallel to compositional and textural banding. Because of the general absence of tabular minerals in the hornblende-pyroxene gneiss, the rock lacks a good planar structure; however, it commonly has a crude to excellent compositional banding.

Foliation data obtained from surface exposures in the Granite Falls-Montevideo area are summarized in Figure 6. The diagram was constructed by plotting the poles of approximately 800 foliation measurements on the lower hemisphere of a Schmidt equal area net, and contouring by the Schmidt or grid method (Turner and Weiss, 1963, p. 61). Poles of the foliation planes form a great circle girdle with the β ($=\pi$) axis trending N. 85 E. and plunging approximately 15 degrees.

Lineation

Cloos (1946, p. 1) defines lineation as ". . . a descriptive and nongenetic term for any kind of linear structure within or on a rock." Lineations measured on surface exposures in the Granite Falls-Montevideo area consist of parallel elongate minerals and mineral aggregates, axes of small warps and folds, crenulations on foliation planes, and boudinage structure. Slickenside striae, present but not common in the area, are not included in the lineation analysis. All lineations measured in the area were plotted on the lower hemisphere of Schmidt equal-area nets and were contoured. The Granite Falls-Montevideo area was arbitrarily divided into three smaller areas: lineations measured in the Montevideo area (pl. 1) are shown in Figure 7; lineations measured in the Granite Falls area north of the township line (T. 115 N. -T. 116 N., pl. 1) are shown in Figure 8; and lineations south of the Township line are shown in Figure 9. The three diagrams represent a total of approximately 800 points.

The measured linear elements are referred to directional coordinates similar to the methods adopted by Moench, Harrison, and Sims (1962, p. 40). In this system B refers to major fold axes and to linear elements essentially parallel to them, and A refers to linear elements that are nearly at right angles to axes of major folds. This usage is geometric and completely free from kinematic and dynamic implications.

Lineations in B are the most abundant in the Granite Falls-Montevideo area, and are represented by strong maxima (15% or greater) in all three diagrams. The range in bearing of the B maxima is from N. 70 E. to S. 82 E., with a resultant plunge of approximately 15 degrees. The range of individual observations in the field is greater than this, however, and is indicated by the contours on the lineation diagrams. B lineations plunging westward at a low angle occur locally throughout the entire area, but they are most common south of the Minnesota River in section 11, T. 115 N., R. 39 W. (pl. 1). Axes of minor warps and folds and mineral lineations are the most abundant types of B lineations. Boudinage structure in B is rare. All the various types of linear elements are essentially parallel. Locally where the bearing or plunge of one type of linear element

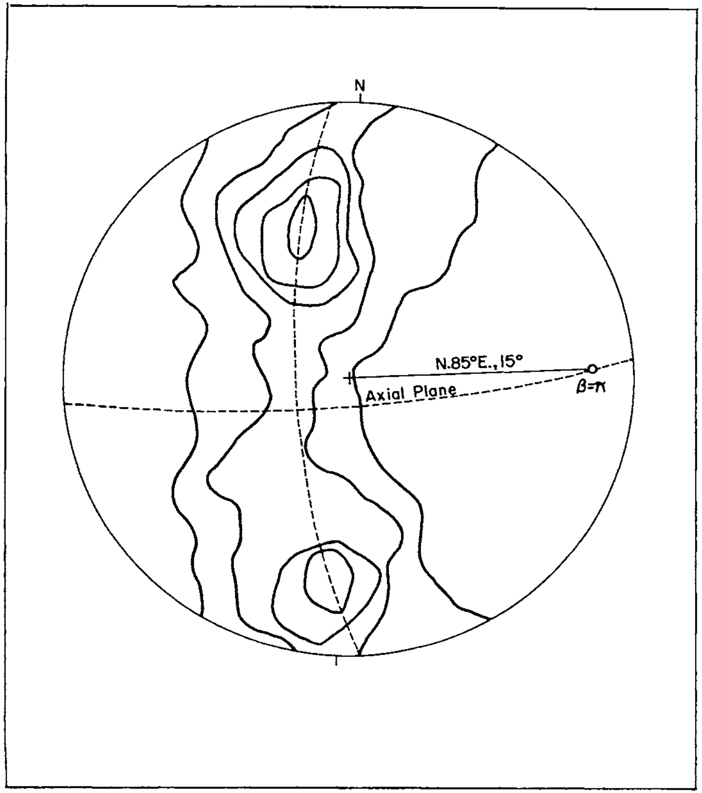

Figure 6 — Schmidt net foliation diagram of Granite Falls-Montevideo area. Contours 15%, 6%, 3%, 1%, .14% per 1% area. (Total points = 800)

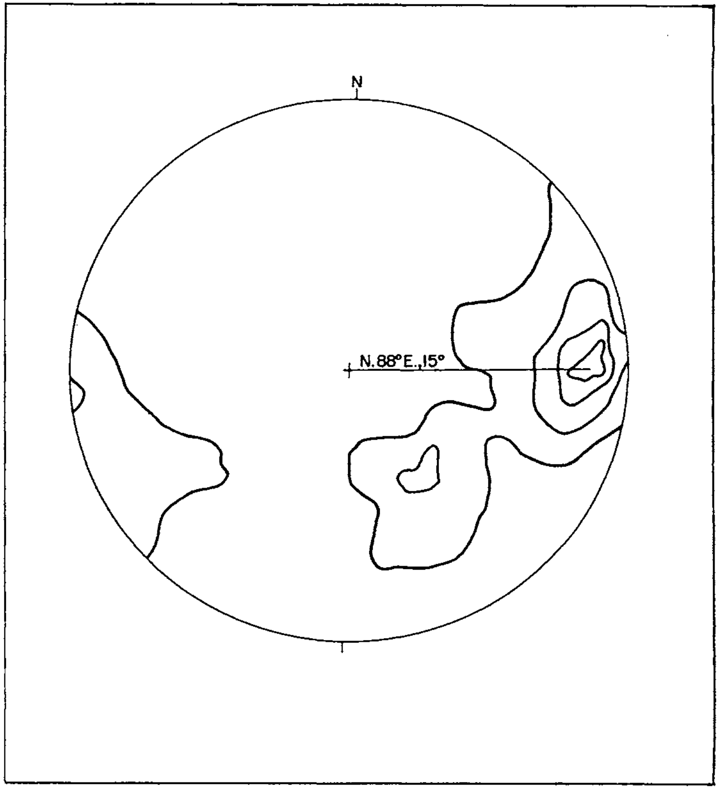

Figure 7 — Schmidt net lineation diagram of Montevideo area. Contours 25%, 15%, 5%, 1% per 1% area. (Total points = 135)

changes significantly the other types vary sympathetically.

Lineations in A are not abundant in the Granite Falls-Montevideo area, and are nearly restricted to minor warping and folding and boudinage structures. Boudinage in the A lineation direction is most commonly observed in the granitic gneiss, where granular quartzo-felspathic bands form the competent unit of the boudinage structure. Boudins in A are also expressed by competent granular bands in the garnet-biotite gneiss. The amphibolite lenses that are common in the granitic gneiss may represent boudinage-type structures. The amphibolite lenses are generally elongate parallel to the trend of foliation and where contacts with granitic gneiss are exposed the foliation of the gneiss wraps around the amphibolite in a boudin-like manner.

The absence of strong maxima on the lineation diagrams corresponding to A lineations reflects the rarity of these structures.

Major Folds

The most conspicuous structural feature in the Granite Falls-Montevideo area – an eastward-plunging anticline – is outlined around the nose by interlayered granitic gneiss and hornblende-pyroxene gneiss which is exposed immediately northwest of Granite Falls (sec. 33, T. 116 N., R. 39 W.; pl. 1). The fold is also marked by foliation attitudes in the metamorphic rocks. Granitic gneiss and intercalated lenses and layers of hornblende-pyroxene gneiss (amphibolite) form the exposed core of the anticline, and are flanked outward by hornblende-pyroxene gneiss and garnet-biotite gneiss. No outcrops exist between the map areas shown in Plate 1, but the distribution of rock types and structure on either side of the covered area indicate that it is occupied by a syncline.

The geometric and geographic orientation of the fold system in the Granite Falls-Montevideo area was analyzed statistically by use of foliation and lineation diagrams (figs. 6-9). The foliation diagram has at least a monoclinic symmetry (one symmetry plane corresponding to the great circle girdle and an axis normal to this plane), with the two maxima corresponding to the limbs of the fold system. Inspection of the foliation diagram shows that the fold system is inclined with the axial surface (plane) dipping steeply to the south. It was not determined if the fold system is symmetrical or asymmetrical (i.e., whether or not the axial plane coincides with the bisecting surface). The axial plane was constructed in Figure 6 by assuming that the fold system is symmetrical; if this is actually the case then the symmetry is orthorhombic.

The greater density of poles of south-dipping foliation planes is a result of two exposed south-dipping fold limbs – one southeast of Montevideo and one southeast of Granite Falls (pl. 1) – and only one exposed north-dipping limb. The range in attitude of the two separate south-dipping fold limbs causes the poles to overlap so that two distinct maxima were not present and poles to the two limbs were contoured together.

The presence of only one β (=π) axis for the foliation diagram (fig. 6) implies that the measured surfaces are of only one kind and of one generation (Turner and Weiss, 1963, p. 154).

Lineation diagrams (figs. 7-9) from the three arbitrary subareas of the Granite Falls-Montevideo area give the statistical bearing and plunge (=B) of the fold system as approximately N. 88 E. 15°. The attitude of the β axis of the

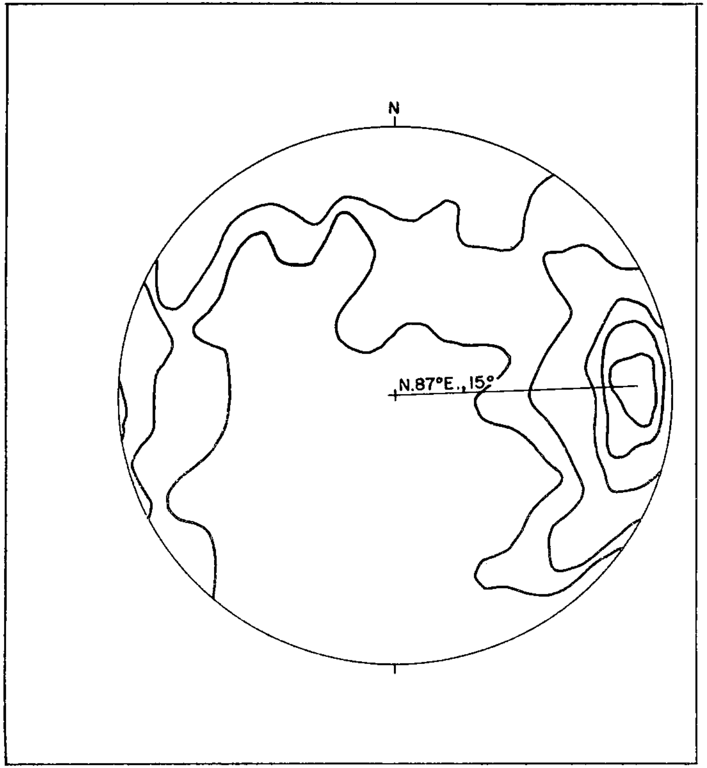

Figure 8 – Schmidt net lineation diagram of northwest Granite Falls area. Contours 15%, 10%, 5%, 1%, .26% per 1% area. (Total points = 381)

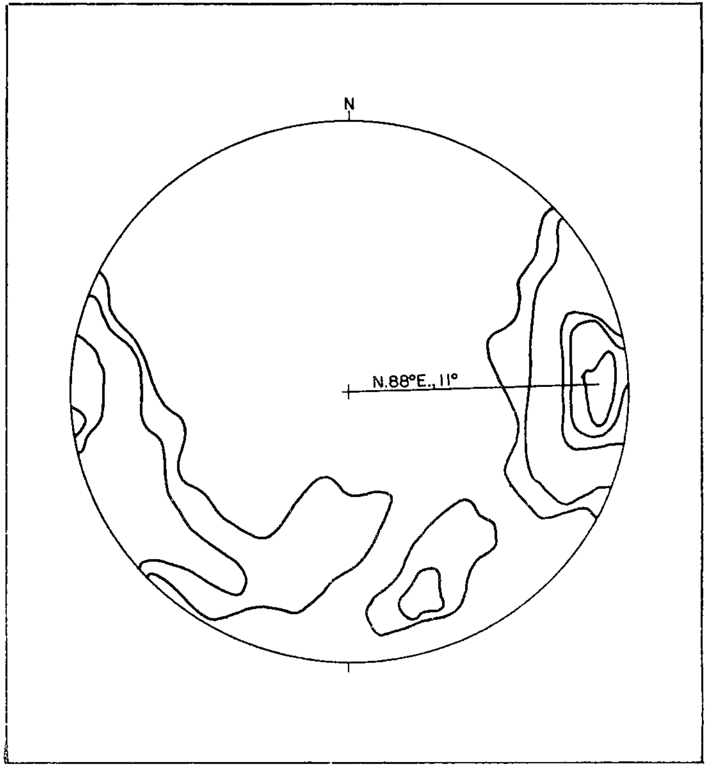

Figure 9 – Schmidt net lineation diagram of southeast Granite Falls area. Contours 15%, 10%, 5%, 1%, .38% per 1% area. (Total points = 263)

foliation diagram (fig. 7) is approximately N. 85 E., 15° and is therefore equivalent to B – the axis of folding. The equivalence of β and B as well as the equivalence of B determined independently from the three lineation diagrams determines the geometric nature of the folding as cylindrical (Turner and Weiss, 1963, p. 155), and also indicates that the fold system is homogeneous with respect to all measured fabric elements. A cylindrical fold is defined as a fold surface that can be described by a straight line that moves parallel to itself, and a cylindrical fold system is one in which all the folds of the system share the same fold axis (Turner and Weiss, 1963, p. 117).

In summary, the structure in the Granite Falls-Montevideo area can be classified according to geometry, geographic orientation, and symmetry (Turner and Weiss, 1963, p. 110, 119, 123) as a gently plunging, inclined, cylindrical fold system having at least monoclinic symmetry.

Whether the folding is flexural or passive (Donath and Parker, 1964) is not known, but the form of the fold suggests that it must lie in the symmetry plane of the fabric and probably normal to the axial plane. Presence of boudinage and minor folds as lineations in the A direction may be manifestations of alternate shortening and elongation parallel to the major fold axis, and B might be either the greatest or intermediate strain axis of the regional strain ellipsoid.

Probably the reversal in the dip of foliation that occurs between the garnet-biotite gneiss and the interlayered gneiss southeast of Granite Falls (secs. 10, 11, and 12, T. 115 N., R. 39 W.; pl. 1) does not indicate the presence of a syncline. This interpretation is based on the fact that neither the garnet-biotite gneiss nor the interlayered gneiss are repeated. Probably the reversal in dip is due either to a fault contact or to the interlayered gneiss being structurally above the garnet-biotite gneiss and overturned.

Other Structures

Shear Zones

Narrow shear zones, consisting of a mesh of closely spaced fractures (fig. 10), occur throughout the Granite Falls-Montevideo area and are well exposed in NE¼ SE¼ sec. 30, T. 116 N., R. 39 W. (pl. 1). The shear zones are generally less than one foot wide but some are as much as four feet wide; they are locally marked by mylonite, and some have stringers and lenses of granitic pegmatite. Where the shear zones are oriented obliquely to the foliation of the granitic gneiss, the foliation is warped adjacent to the shear zones as a result of movement along the zones. The rocks in the shear zones and the drag folds adjacent to them have extreme cataclastic textures (figs. 11 and 12).

The trend of the shear zones ranges from N. 35° -60° W., with an average of N. 47° W. A few shear zones also trend approximately N. 45° E. Dips of most shear zones are nearly vertical. Offset of a small mafic dike (SE¼ sec. 20, T. 116 N., R. 39 W.; pl. 1) and drag of the foliation in the granitic gneiss (e.g., NE¼ SE¼ sec. 30, T. 116 N., R. 39 W.) indicate a left-lateral displacement along the northwest-trending shear zones.

Left-lateral displacement along northwest trending shears requires that the greatest principal stress axis was oriented approximately east-west or that the movement along the shear zones was a result of a horizontal couple. Such an orientation of dynamic forces differs from that necessary to produce the existing fold system (i.e., probably oriented nearly north-south and horizontal), and indicates that the shearing probably resulted from a deformation that was later than the folding. The presence of tholeiitic diabase dikes that crosscut the foliation of the metamorphic rocks but in turn are cut by the shear zones also indicates that the shears were produced later than the folding.

The mortar textures and granulation observed in many thin sections probably resulted from the same cataclastic deformation that produced the fractures.

Faults

A fault of possible major significance is inferred but not definitely determined between the garnet-biotite gneiss and the interlayered amphibolites and gneisses southeast of Granite Falls (pl. 1). The basis for interpreting a possible fault is the extreme change in attitude of foliation of the metamorphic rocks in this area and the presence of a bleached fracture zone. The fracture zone is marked by cataclasized but not mylonitized rocks, and trends approximately N. 60° E.; it dips approximately 70° SE. The fracture zone has a maximum exposed thickness of 50 feet and occurs between the garnet-biotite gneiss and the hornblende-pyroxene gneiss in the NE¼ sec. 11, T. 115 N., R. 39 W. An alternative explanation for the extreme change in attitude of the foliation in this area is that the lithologic units that structurally overlie the garnet-biotite gneiss are overturned.

Structural Relationships of the Igneous Rocks

All the mafic dikes cut across the foliation of the metamorphic rocks. They were intruded preferentially along a nearly vertical fracture system that trends approximately N. 55° E. A few dikes trend nearly east-west, and therefore occupy other fracture sets.

At several localities older tholeiitic diabase dikes are crosscut by different varieties of hornblende andesite dikes that commonly have chilled margins against the older dikes. Further, the shear zones (described above) were formed between the two periods of dike-formation, for the older tholeiitic diabase dikes are cut by them but the hornblende andesite dikes cut across them. The relationships between the shear zones and the two ages of dikes can be observed in the large outcrop area in the SE¼ sec. 20, T. 116 N., R. 39 W. Age relations between the olivine diabase dikes and other mafic dikes were not observed in the field.

The adamellite exposed in sec. 28, T. 116 N., R. 39 W. (pl. 1) intrudes a hornblende andesite dike; and a small granite dike (approximately one-foot thick) exposed just south of the pond in sec. 11, T. 115 N., R. 39 W. cuts across a tholeiitic diabase dike as well as the metamorphic rocks.

METAMORPHIC PETROLOGY

General Statement

The metamorphic rocks of the Granite Falls-Montevideo area were metamorphosed under conditions of the granulite facies and subsequently underwent retrograde metamorphism. A detailed study of the phase equilibria and retrograde reactions of these rocks has been presented by Himmelberg and Phinney (1967), and only the major aspects are summarized in this report.

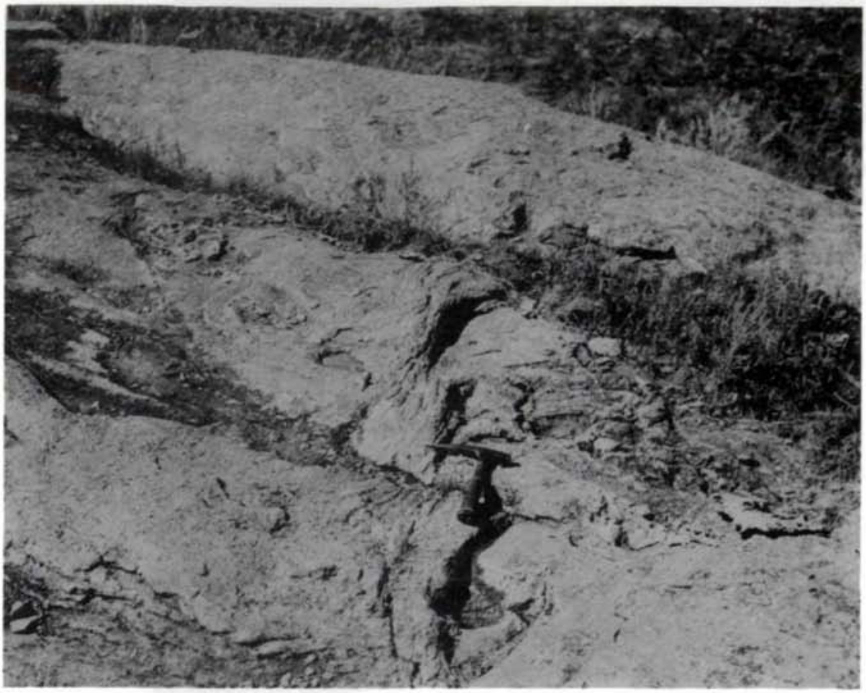

Figure 10 – Northwest-trending shear zone in granitic gneiss. NE¼, SE¼, sec. 30, T. 116 N., R. 39 W.

Mineral Assemblages

Assemblages of coexisting minerals in metamorphic rocks provide the principal evidence of the metamorphic conditions under which they formed. Listed below are those mineral assemblages from the Granite Falls-Montevideo area that are believed to represent equilibrium mineral assemblages obtained during the peak of the granulite facies metamorphism. In listing the mineral assemblages there is no regard for percentages of minerals. Minor accessory minerals are not listed and minerals listed in parentheses are generally subsidary in amount and may or may not be present in any given specimen. For convenience, and to emphasize bulk compositional controls, the assemblages are divided and listed under the three major lithologic units.

Hornblende-Pyroxene Gneiss

Quartz and plagioclase-bearing assemblages (quartz is commonly a minor mineral);

1. hornblende-orthopyroxene-clinopyroxene-magnetite-ilmenite-(biotite)
2. hornblende-orthopyroxene-clinopyroxene-biotite-magnetite-ilmenite-(potassium feldspar)
3. hornblende-orthopyroxene-magnetite-ilmenite-(garnet-biotite)
4. hornblende-clinopyroxene-garnet-magnetite-ilmenite-(potassium feldspar)
5. hornblende-sphene-hematite
6. orthopyroxene-clinopyroxene-garnet-magnetite-ilmenite-(hornblende)

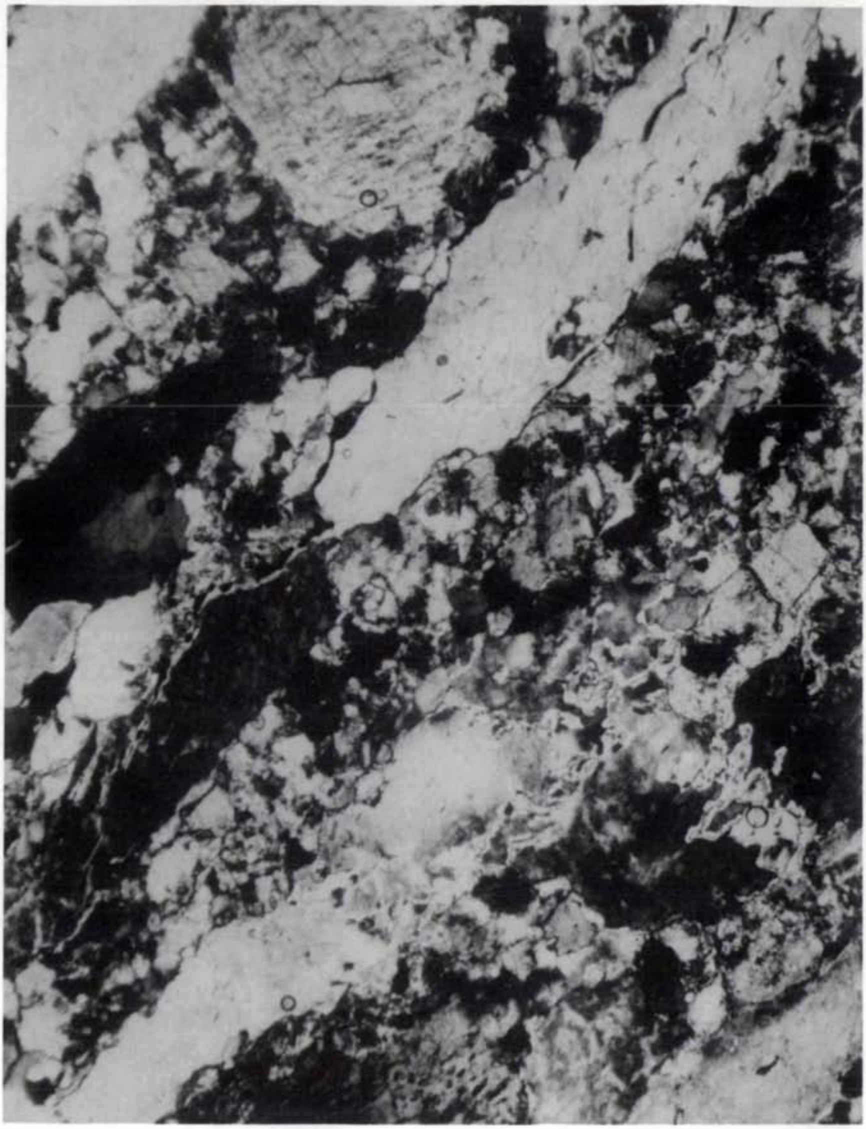

Figure 11 – Cataclastic texture in granitic gneiss resulting from shearing. Sample M8294, (25x crossed nicols).

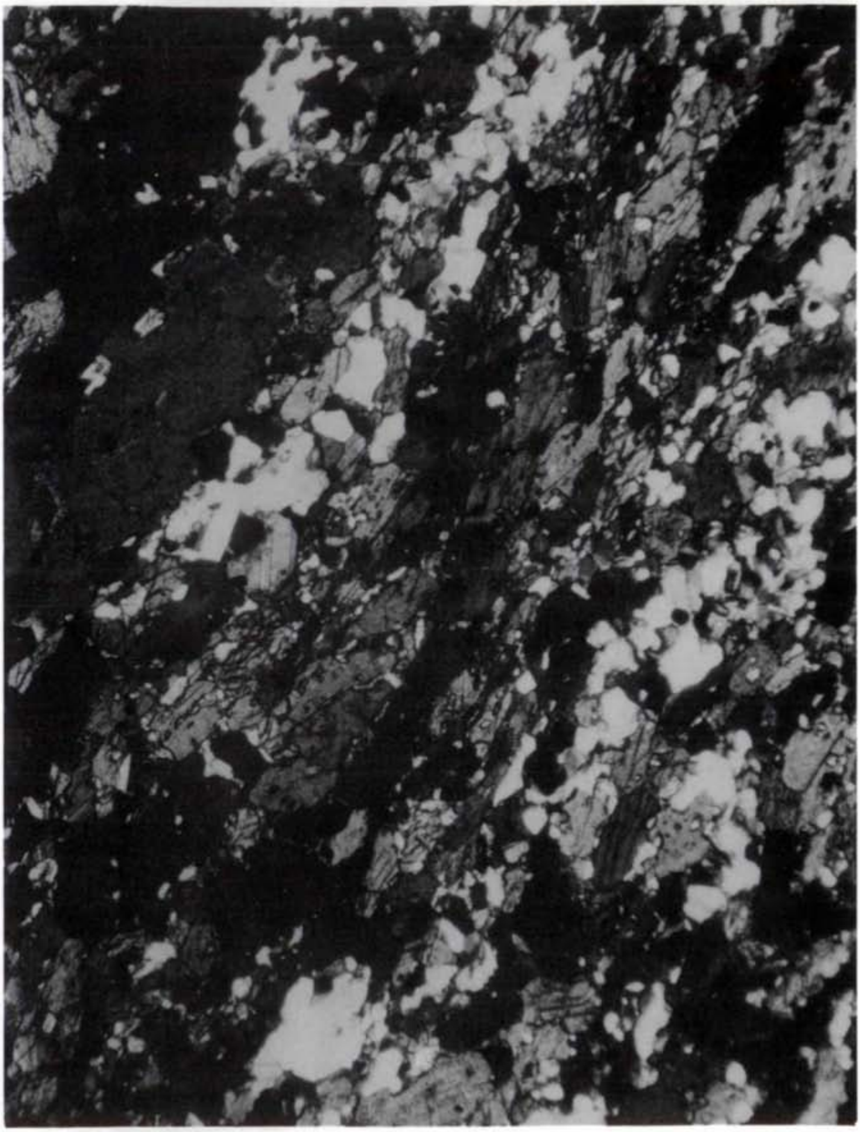

Figure 12 — Cataclastic texture in hornblende-pyroxene gneiss resulting from shearing. Sample M8289, (x25 crossed nicols).

7. orthopyroxene-clinopyroxene-magnetite-ilmenite-(biotite)
8. orthopyroxene-biotite-magnetite-ilmenite
9. orthopyroxene-magnetite-ilmenite-(potassium feldspar)
10. biotite-magnetite-ilmenite-(potassium feldspar)

Quartz-free, plagioclase-bearing assemblages:

11. hornblende-orthopyroxene-clinopyroxene-magnetite-ilmenite-(biotite)
12. hornblende-orthopyroxene-clinopyroxene-(biotite-hematite)
13. hornblende-clinopyroxene-magnetite-ilmenite-(biotite)
14. hornblende-magnetite-ilmenite
15. orthopyroxene-clinopyroxene-magnetite-ilmenite

Assemblages 1 and 11 are most common. Assemblages 1 and 2 are treated separately because 2 contains abundant biotite and generally contains minor amounts of potassium feldspar. Assemblage 10 was noted only as a narrow band occurring with assemblage 2. In assemblage 3 garnet and biotite were not observed together in association with the other minerals. The structural variety of the potassium feldspar in the above assemblages was not determined.

Garnet-Biotite Gneiss

Quartz and plagioclase-bearing assemblages:

16. biotite-orthopyroxene-garnet- (orthoclase)
17. biotite-orthopyroxene- (orthoclase)
18. biotite-garnet- (orthoclase)

In addition, all samples studied contain a trace of magnetite-ilmenite. Assemblages 16 and 18 are most common. The garnet in assemblage 18 is commonly disseminated so that the sub-assemblage quartz-plagioclase-biotite-(orthoclase) might also be considered.

Granitic Gneiss

19. quartz-plagioclase-microcline- (garnet-hematite)
20. quartz-plagioclase-microcline-biotite- (garnet-hematite-rutile)
21. quartz-microcline

Assemblages 19 and 20 are equally common; assemblage 21 is rare.

Analysis of the granulite facies mineral assemblages indicates that these rocks attained a close approach to chemical equilibrium during metamorphism (Himmelberg and Phinney, 1967). No empirically determined incompatible phases were observed; the assemblages obey the Gibb's Phase Rule (excluding retrograde minerals); there is a regular distribution of Fe and Mg between coexisting hornblende, orthopyroxene, and clinopyroxene; and there is only minor compositional variation in mineral grains and for a given mineral in a given specimen.

Both H_2O and O_2 may be treated as perfectly mobile components without violating the Gibb's Phase Rule; an exception to this is assemblage 2, in which case one of the above components must be considered inert. However, plots of coexisting biotite, garnet, and orthopyroxene in an A-F-M projection result in crossing tie lines that are most adequately explained by considering that H_2O and/or O_2 did not actually behave as perfectly mobile components. This interpretation also is supported by the presence of interlayered hornblende assemblages and pyroxene assemblages as well as by variations of the iron oxide phase in essentially the same mineral assemblage (Himmelberg and Phinney, 1967).

Metamorphic Facies

Eskola (1939, p. 360) defined the granulite facies to include those regionally metamorphosed rocks in which biotite and hornblende are unstable and are replaced by the minerals almandine, orthopyroxene, and clinopyroxene. He (1939, p. 360, 362) did not recognize amphibole, mica, and cordierite as characteristic of granulite facies proper, although he did recognize the close association of these minerals with "true" granulites, possibly defining a subfacies. Because of this close association Fyfe, Turner, and Verhoogen (1958, p. 232) established two subfacies within the granulite facies:

1. The pyroxene granulite subfacies, lacking hornblende and biotite and therefore conforming to the granulite facies as defined by Eskola (1939).
2. The hornblende granulite subfacies, in which hornblende and/or biotite are present in the garnetiferous and pyroxenic assemblages.

A review of the mineral assemblages observed in the Granite Falls-Montevideo area shows that some assemblages belong to the pyroxene granulite subfacies (e.g., assemblage 15), others to the hornblende granulite subfacies (e.g. assemblage 1), and still others to the amphibolite facies (e.g., assemblage 13 or 14).

Fyfe, Turner and Verhoogen (1958, p. 233) note the common close association of pyroxene granulites, hornblende granulites, and amphibolites, and state that this intermingling in the field might be a result of polymetamorphism, or alternatively it might reflect that existence of local gradients in temperature and water pressure during a single episode of metamorphism.

In the Granite Falls-Montevideo area the various assemblages show no distribution indicative of metamorphic zoning; further, no mineralogical isograds can be drawn. The occurrence of pyroxene or the absence of hornblende at any given locality appears to be a result of either bulk composition or chemical potential of H_2O and not a result of fluctuations or gradients in temperature or pressure. This is well illustrated by a sample (M8110) which consists of pyroxene-bearing assemblages (assemblage 15) interlayered on a scale of millimeters with hornblende-bearing assemblages (assemblage 14). Although interlayering on this scale is not common in the area, it does illustrate that the occurrence of hydrous and anhydrous assemblages in the same area is not necessarily a result of differences in temperature.

Because of the intermingling of anhydrous and hydrous assemblages it is not feasible to assign the series of assemblages to either the hornblende granulite subfacies or the pyroxene granulite subfacies, but instead it seems more appropriate to place the metamorphic rocks of the Granite Falls-Montevideo area in the overall granulite facies. It should be noted, however, that the temperature was sufficiently low to allow crystallization of hydrous phases and that the anhydrous assemblages of similar bulk composition probably represent an impoverishment in H_2O.

Retrograde Metamorphism

Turner and Verhoogen (1960, p. 452) define retrograde metamorphism as the process whereby "A high temperature metamorphic mineral assemblage is converted to an assemblage (usually more hydrous) stable at lower temperature." Such a definition implies nothing about the origin of the lower temperature assemblages; the assemblages could result from cooling that followed the main high-temperature phase of metamorphism or from a second metamorphism of lower grade than the first.

Retrograde textures involving replacement of orthopyroxene, clinopyroxene, and primary hornblende are common in samples of hornblende-pyroxene gneiss. Commonly the orthopyroxene has fractures filled with a serpentine-type mineral and is mantled by cummingtonite with no continuation of the "serpentine" into the cummingtonite. Clinopyroxene and hornblende are commonly mantled by a sea green actinolite-hornblende. In some samples the primary hornblende is replaced by actinolite, which in turn has a border of blue-green hornblende.

Textural and chemical relationships between orthopyroxene-"serpentine"-cummingtonite and brown hornblende-actinolite-blue-green hornblende suggest that there may have been a temperature decrease (forming "serpentine" and actinolite) after the main metamorphism, followed by a temperature increase that formed cummingtonite and blue green hornblende (Himmelberg and Phinney, 1967). If this is the case, it indicates that there was a second metamorphism that was younger and of lower grade than that which produced the granulite facies mineral assemblages.

AGE OF DEFORMATION, METAMORPHISM AND IGNEOUS ACTIVITY

Reconstruction of the geologic events that are represented in the Precambrian rocks in the Granite Falls-Montevideo area indicate that there were several episodes of deformation, metamorphism, and igneous activity. The available extensive radiometric dating of rocks in the Minnesota River valley permits limits to be placed on these events.

Potassium-argon and rubidium-strontium age determinations for biotite from samples of granitic gneiss and garnet-biotite gneiss give ages ranging from 1700 to 1900 m.y. with an average of approximately 1800 m.y. (Goldich and others, 1961). Rubidium-strontium age determinations for potassium feldspar from the granitic gneiss give an age of 2500 m.y. (Goldich and Hedge, 1962), and a potassium-argon age for hornblende from the hornblende-pyroxene gneiss gives an age of 2740 m.y. (Hanson and Himmelberg, 1967). The 2500 to 2740 m.y. ages from the Granite Falls area are consistent with those determined on mica, feldspar, and hornblende (Goldich and others, 1961; Goldich and Hedge, 1962; Thomas, 1963) from the Morton quartz monzonite gneiss approximately 30 miles southeast of Granite Falls.

Uranium-lead ages for zircon from one sample of granitic gneiss at Granite Falls and two samples of Morton quartz monzonite gneiss at Morton, Minnesota are discordant and give an age of 3550 m.y., with episodic lead loss at approximately 1850 m.y. (Catanzaro, 1963). Discordant U-Pb zircon ages from five other samples of Morton quartz monzonite gneiss indicate an age of 3600 m.y. (Stern, 1964). Three zircon size-fractions from the garnet-biotite gneiss at Granite Falls give practically concordant uranium-lead ages of 2650 m.y. (Stern, 1964).

Hornblende from one sample of tholeiitic diabase near Granite Falls give a potassium-argon age of 2080 m.y., and four samples of hornblende andesite give concordant hornblende and biotite potassium-argon ages of 1700 to 1800 m.y. (Hanson and Himmelberg, 1967). The adamellite near Granite Falls gives potassium-argon and rubidium-strontium ages between 1600 and 1700 m.y. for mica, feldspar, and whole rock samples (Goldich and others, 1961; Goldich and Hedge, 1962). Zircon from the adamellite indicates an age of approximately 1800 m.y. (Catanzaro, 1963).

The 2500 to 2740 m.y. ages are interpreted as the time of regional metamorphism and folding, with the 1800 m.y. event representing a period of igneous activity (intrusion of hornblende andesite dikes and adamellite) and thermal metamorphism of sufficient intensity to reset the biotite ages in the metamorphic rocks of the Granite Falls-Montevideo area. The 1800 m.y. thermal event is not reflected in the structure or megascopic character of the metamorphic rocks in the area; however, the replacement of orthopyroxene and serpentine by cummingtonite and the border of blue green hornblende around actinolite could possibly be related to the 1800 m.y. thermal event (Himmelberg and Phinney, 1967).

It is not clear whether the 2080 m.y. K-Ar age for hornblende from the tholeiitic diabase dike represents the time of emplacment or is a result of partial loss of argon from the hornblende 1800 m.y. ago. A hornblende concenctrate from the metamorphic hornblende-pyroxene gneiss gives an age of 2740 m.y. indicating that it did not lose argon 1800 m.y. ago. The interpretation is further complicated by the fact that the hornblende in the tholeiitic diabase dike is secondary, and its mode of origin is not definitely known.

The shear zones that cut the metamorphic rocks and the tholeiitic diabase dikes are cut by hornblende andesite dikes. If the 2080 m.y. age represents the time of intrusion of the tholeiitic diabase, the shearing occurred between 2080 and 1800 m.y. ago. If, however, the 2080 m.y. age is a result of partial loss of argon from hornblende, the intrusion of the tholeiitic diabase and the shearing could have occurred between 2500 and 1800 m.y. ago.

The 3550 m.y. U-Pb age of zircon from the granitic gneiss most probably is inherited from the pre-metamorphic rock.

Lund (1956, p. 1489-1490) interpreted the granitic gneiss as intrusive into previously metamorphosed igneous rocks (i.e., hornblende-pyroxene gneiss and garnet-biotite gneiss), and he attributed the foliation and granulation in the granitic gneiss to a later deformation. Goldich and others (1961, p. 142-143) followed Lund's interpretation and argued as follows:

> "The garnetiferous quartz diorite gneiss south of Granite Falls is a metamorphic rock. If the assumption is made that an orginal sequence of sedimentary rocks was metamorphosed at considerable depth to produce the Montevideo granite gneiss and the garnetiferous quartz diorite gneiss at the same time, it is hard to understand why garnet was not developed also in the dioritic and gabbroic gneisses which are similar in composition to the garnetiferous quartz diorite gneiss and are found as inclusions in the Montevideo granite gneiss."

The results presented in this report demonstrate that the existing structures and mineral assemblages in all the metamorphic rock units are a result of the same dynamothermal metamorphism, and there is no evidence that the garnet-biotite gneiss or hornblende pyroxene gneiss was involved in an older metamorphism. It is possible, of course, that such evidence was destroyed by the 2500 to 2740 m.y. metamorphism. Garnet is not restricted to the garnet-biotite gneiss (garnetiferous quartz diorite gneiss of Goldich and others, 1961) but is ubiquitous in the granitic gneiss and, where bulk composition is appropriate, occurs in layers of hornblende-pyroxene gneiss.

The metamorphic rocks were wholly recrystallized by the dynamothermal metamorphism, and it is therefore not possible to definitely determine the pre-metamorphic nature of the gneisses. The presence of lithologic units that are continuous along strike of the foliation and are interlayered in a regular stratigraphic sequence, however, argues for a pre-metamorphic layered succession of rocks rather than for large igneous bodies intrusive into one another as implied by Lund (1956). An additional argument that supports a metamorphosed stratigraphic sequence of rocks is that reconnaissance along the Minnesota River valley northwest to Odessa and southeast to Redwood Falls, as well as the detailed mapping to the southeast (J.A. Grant, 1965, oral communication) indicate that it is possible to map successions of lithologic units similar to those found at Granite Falls.

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