THESIS

PETROLOGY AND STRUCTURE OF PRECAMBRIAN CRYSTALLINE AND TERTIARY IGNEOUS ROCKS, MANHATTAN DISTRICT, LARIMER COUNTY, COLORADO

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DONALD ROBERT SAMUELSON ENTITLED PETROLOGY AND STRUCTURE OF PRECAMBRIAN CRYSTALLINE AND TERTIARY IGNEOUS ROCKS, MANHATTAN DISTRICT, LARIMER COUNTY, COLORADO BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

PETROLOGY AND STRUCTURE OF PRECAMBRIAN CRYSTALLINE AND TERTIARY IGNEOUS ROCKS, MANHATTAN DISTRICT, LARIMER COUNTY, COLORADO

The Manhattan district is located in the northwest quarter of the Rustic quadrangle about 30 miles northwest of Fort Collins, Colorado, and includes approximately five square miles of primarily Precambrian terrane. Biotite gneiss, hornblende gneiss, and amphibolite, the oldest rocks in the area, have been metamorphosed to the sillimanite-almandine-orthoclase subfacies of the amphibolite facies. The metamorphic rocks have been intruded by Log Cabin granite which comprises the majority of the rock in the area. Granite shows evidence of forceful, but not very disruptive, intrusion. Inhomogeneity in the granite suggests that it may not have been completely molten when intruded or that the magma may have been locally altered by assimilation. Pegmatite and foliated granite are considered to be phases of the Log Cabin granite.

A period of cataclasis in late Precambrian produced several shear zones in the granite. Degree of cataclasis varies and shear zone rocks range from cataclasite to mylonite. More intensely sheared zones have been rehealed with quartz and epidote. Brecciated structure in shear zones suggests at least two periods of shearing.

Uplift of the area during formation of the Ancestral Rockies or during the Laramide orogeny may have reactivated the shear zones.

An episode of mineralization, probably in early Tertiary time, produced minor uranium mineralization in a few shear zones and along minor faults in the general area. In mid-Tertiary time numerous porphyritic dikes of rhyolite, rhyodacite, and hornblende rhyodacite were emplaced primarily along joint planes in granite. Variations in chemistry and mineralogy suggest that the intrusives were formed either from a differentiating magma, from slightly different magmas, or from different fractions of the same magma modified by assimilation. Ore solutions probably associated with Tertiary magma produced pyrite, chalcopyrite, minor gold, silver, and copper mineralization in the Manhattan district. Formation of a Tertiary erosion surface apparently was accompanied by the secondary enrichment of gold on the surface above low grade primary gold ore deposits.

Near the end of Tertiary time a period of rapid downcutting was inaugurated. Although the relatively flat erosion surface is still present in the northern third of the Manhattan district, the southern portion of the area has been well dissected. Granite joints, although fairly well developed, have had little influence on development of the general topography.

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INTRODUCTION

In 1886 gold was discovered in Manhattan Creek, a small tributary of Elkhorn Creek north of Poudre Canyon in northern Colorado. Within a year several thousand people had converged on the area and established the tent city of Manhattan. Today, numerous prospect pits and old mine workings indicate the extent of past mining activity, but little commercial grade ore was discovered in the district. This investigation was stimulated by the previous mining activity and by the fact that little detailed mapping had been done in the area.

Geologically, the Manhattan district is located near the southwest edge of the Log Cabin batholith near the transition zone between older metamorphic rocks and granite. The majority of outcrops are granitic, but biotite gneiss, hornblende gneiss, and amphibolite occur as widely distributed xenoliths. The granite, referred to by many workers (e.g., Eggler, 1968, p. 1549; Peterman, Hedge, and Braddock, 1968, p. 2289) as "granite of the Log Cabin batholith", is considered to be a variety of the Silver Plume granite. The term Log Cabin granite will be used throughout this paper to indicate Silver Plume type granite of the Log Cabin batholith. A few small pods and veins of pegmatite which occur in the granite and metamorphic rocks probably represent late stage crystallates of the Log Cabin magma.

Several small shear zones consisting of variably sheared rocks ranging from cataclasite to submylonite and mylonite occur in the granite. The Precambrian crystalline rocks are cut by a series of Tertiary dikes of rhyolite, rhyodacite, and hornblende rhyodacite.

Bedrock is well exposed in the southern two-thirds of the area which is characterized by strong relief. In the north, where relief is low and heavy forest cover is common, soil is well developed and bedrock exposures are generally small and widely scattered.

LOCATION OF AREA

The Manhattan district is located in Larimer County, Colorado, near the town of Rustic, approximately 30 miles northwest of Fort Collins (Figure 1). It is in Township 9 North, Range 73 West in the Rustic 7.5 minute quadrangle and consists of approximately five square miles of Precambrian terrane.

The southern portion of the area is dissected by Sevenmile Creek, which flows to the southeast and joins the Cache la Poudre River at Rustic, about three-quarters of a mile from the southeast corner of the study area. The topography along Sevenmile Creek and to the south is quite rugged, whereas the northern portion of the study area is relatively flat. The elevation ranges from 7360 feet in the southeast corner of the area (section 32) to 9100 feet on Prohibition Mountain near the northern border.

Colorado 14, which parallels the Cache la Poudre River, provides primary access to the Rustic quadrangle. Access to the Manhattan district is provided by U.S. Forest Service roads, by jeep trails, and by numerous old mining and logging roads.

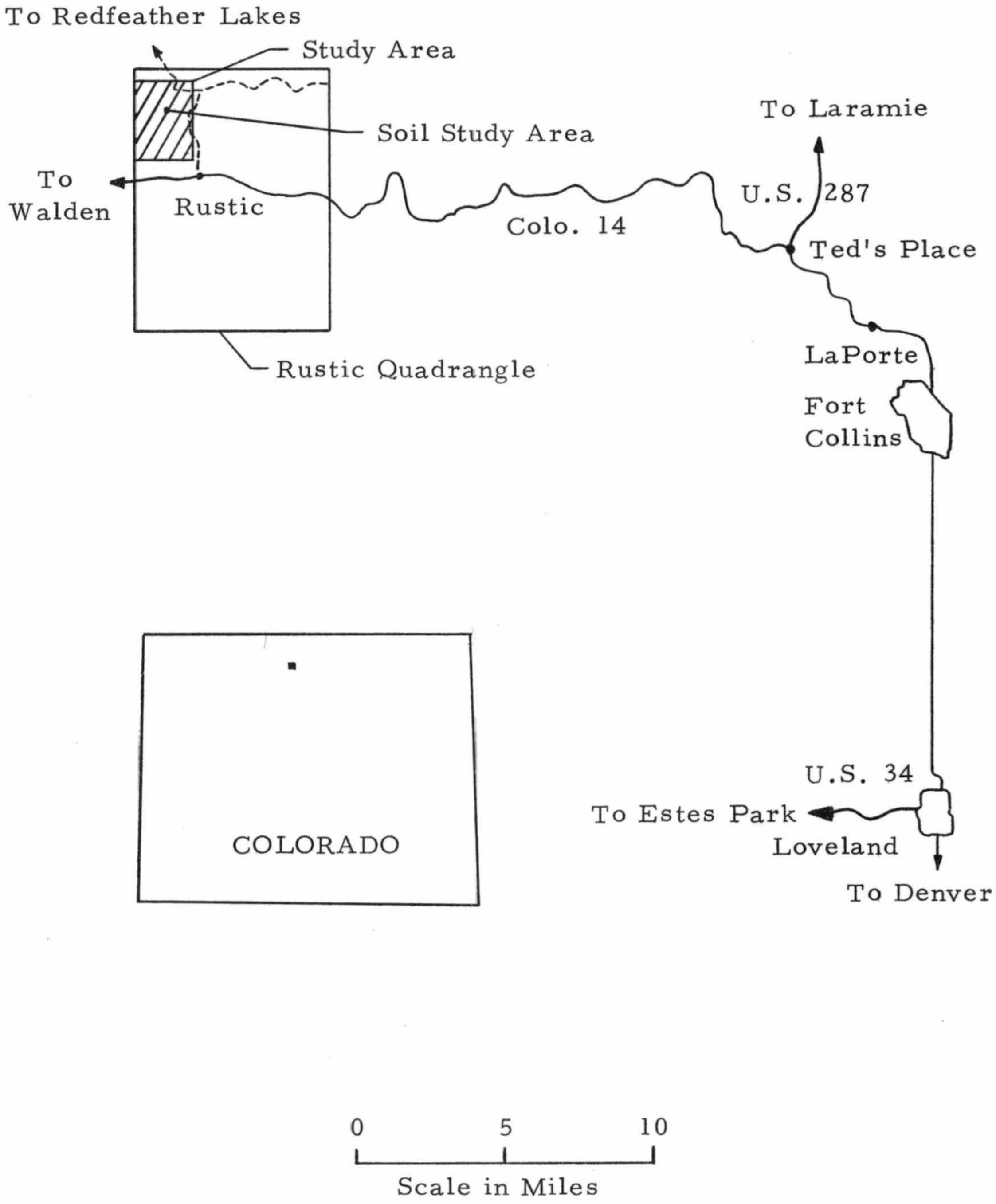


Figure 1. Index map of the study area.

METHODS OF INVESTIGATION

Field work was conducted during the summers of 1969 and 1970. Mapping was done on a portion of the U.S.G.S. Rustic quadrangle (1:24,000) enlarged to a scale of 1:12,000. U.S.G.S. aerial photographs (1:24,000) were also used as an aid in mapping.

Petrographic studies were made on thin sections prepared from 56 rock samples. Plagioclase compositions were determined by the Michel-Lévy method as described in Kerr (1959, p. 257-260). Feldspar staining techniques (Bailey and Stevens, 1960, p. 1020) were used to distinguish potash feldspar from plagioclase in rock slabs. Photomicrographs of thin sections were made with a Leitz Aristophot microscope attachment using Polaroid film.

Kittleman's (1963, p. 1405-1410) glass bead method was used to classify several Tertiary intrusives. Whole-rock analyses were obtained from samples of four intrusives and C.I.P.W. norms and rock names were determined by computer program.

Soil samples over a prospected shear zone were analyzed for five elements by atomic absorption spectrometer and trend surface analysis computer program was used to compute and plot isopleth maps.

Rock samples from numerous prospect areas were checked for radioactivity with a Precision Radiation Instruments Model 111 scintillometer.

PREVIOUS INVESTIGATIONS

Previous mapping in the Manhattan district has been minimal. Lovering and Goddard (1950) in their discussion of Front Range geology and ore deposits, noted the mining district of Manhattan and described the quality of some of the gold ore taken from the district. Miller and Laval (1958) made a preliminary study of the Tertiary intrusives of the Manhattan district in an effort to relate them to mineralization. Reconnaissance mapping of the western portion of the area was done by E. M. Warner and R. K. Corbett as part of an N.S.F. undergraduate research participation program under the direction of M. E. McCallum of Colorado State University (1967, Department of Geology, C.S.U., open files).

Several theses have been done in the area around the Manhattan district by students from the State University of New York at Buffalo and Colorado State University. Kirst (1966) and Wolfe (1967) mapped the southern half and northwest-north central portions of the Rustic quadrangle respectively. Wolfe's work includes the eastern portion of the Manhattan district. The northeast quarter of the Rustic quadrangle was described by Beverly (1969). The northeast quarter of the Kinikinik quadrangle, which borders the western edge of the Manhattan district, was investigated by Walko (1969). M. E.

McCallum is presently involved in reconnaissance work in the areas immediately south and northeast of the Manhattan district.

PRECAMBRIAN ROCKS

General Statement

Biotite gneiss, hornblende gneiss, and amphibolite comprise the Precambrian crystalline metamorphic rocks in the Manhattan district. Biotite gneiss forms the largest metamorphic outcrops (up to about three-quarters of a mile in length) and is the most abundant metamorphic rock type in the area. Amphibolite and hornblende gneiss occur throughout the area, but outcrops are relatively small (generally only a few hundred feet in longest dimension) compared to those of biotite gneiss.

Absence of structual and textural evidence makes it impossible to determine parent rock types of the metamorphics. Metamorphism of the parent rocks attained the sillimanite-almandine-orthoclase subfacies of the amphibolite facies.

The Manhattan area is near the southwest edge of the Precambrian Log Cabin batholith and interfingering of granite with metamorphic rocks is common. This interfingering relationship is much more pronounced to the south, in the area mapped by Kirst (1966), whereas granite predominates in the Manhattan district. Intrusions of pegmatite, apparently a late phase of the granite, are widespread, but usually consist of small veins and dikes up to 10 feet wide and a few hundred feet long. Small pod- and lens-shaped pegmatites also occur.

Several areas of shear zone tectonites occur in the granite. These tectonites vary in degree of shearing from cataclasite to mylonite. Many of the shear zones have been rehealed with quartz and epidote.

Biotite Gneiss

General Description

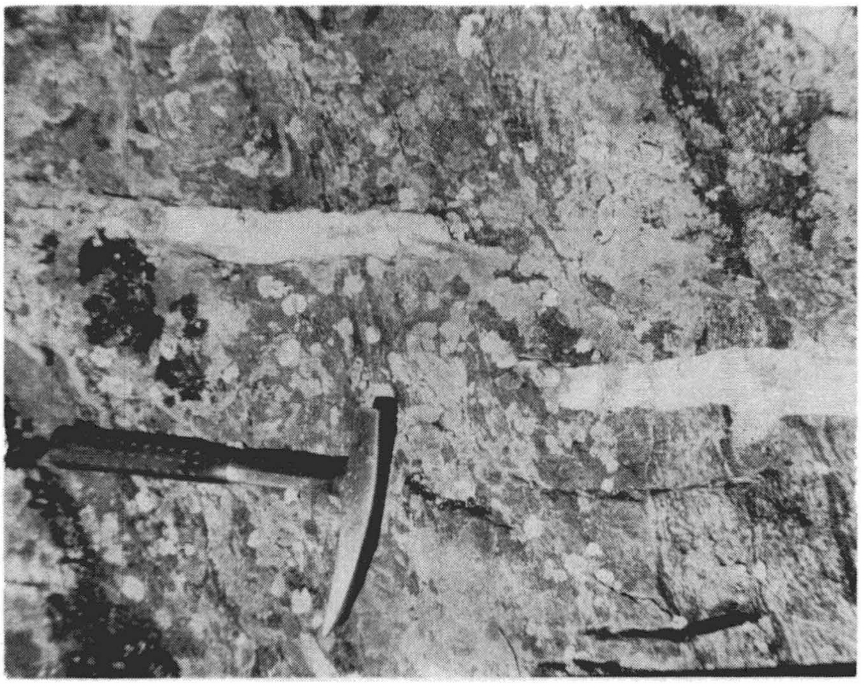
Biotite Gneiss is the most abundant metamorphic unit in the area. Xenoliths of the gneiss vary in size from small inclusions (including many skialiths) of a few inches in length up to large masses nearly three-quarters of a mile long. Outcrops typically are elongate parallel to foliation direction. Concordant and discordant veins of granite and pegmatite up to several inches in width are common in the biotite gneiss (Plate 2, Fig. 1).

The biotite gneiss is a well foliated rock composed principally of quartz, feldspar, biotite, and muscovite. Foliation is expressed by parallel alignment of biotite rich layers alternating with quartzo-feldspathic layers. The quartzo-feldspathic layers are fine- to medium-grained with the average grain size being about 1 mm. Biotite rich layers are more coarsely crystalline with many of the biotite plates reaching several millimeters in length. Rock color varies from buff to dark brown depending on the abundance of biotite.

Plate 2. Outcrops of biotite gneiss.

Fig. 1. Offset vein of granite discordantly cutting biotite gneiss.

Fig. 2. Small scale folds in biotite gneiss.



Very little mineral lineation was observed in the biotite gneiss and fold axes comprise most of the recorded lineations. Most outcrops have relatively flat foliation planes with little bending or folding. However, where folds are present they are usually fairly tight, the amplitudes and wavelengths commonly less than one foot (Plate 2, Fig. 2).

Throughout the Manhattan area biotite gneiss is a relatively homogeneous unit, although on a local scale it is sometimes very schistose and does not show the typical gneissic structure. There are also minor occurrences where the biotite content drops to only a few percent and the gneissic structure is virtually absent.

Petrography

The biotite gneiss exhibits a lepidoblastic texture defined by the subparallel orientation of biotite crystals. The major minerals in descending order of abundance are quartz, plagioclase (An_{26}-An_{33}), potash feldspar, biotite, and muscovite (Table 1). Most of the quartz grains are highly strained and exhibit very undulose extinction. Muscovite and greenish-brown biotite are commonly intergrown and usually have a subparallel orientation, but some of the muscovite is relatively young and crosscuts adjacent biotite flakes. In some samples cleavage traces of both muscovite and biotite are quite contorted. Some muscovite displays a symplectic intergrowth with

Table 1. Modal analyses (volume percent) for biotite gneiss.

	Sample			
	S-3	S-26	S-44	S-125
Quartz	31.2	36.1	36.2	39.1
Plagioclase	27.4 An_{26}	29.9 An_{27}	25.9 An_{33}	40.1 An_{32}
Potash Feldspar	4.0	12.8	31.6	5.6
Biotite	31.4	14.0	5.2	12.2
Muscovite	5.3	6.9	1.1	2.4
Epidote	0.6	tr	tr	tr
Chlorite	tr	tr	tr	tr
Magnetite	tr	tr	tr	tr
Hematite	tr	tr	-	tr
Sphene	tr	-	tr	tr
Zircon	tr	tr	-	-
Apatite	tr	-	-	-
Sillimanite	-	tr	-	-
Saussurite	tr	tr	tr	tr
Sericite	tr	tr	tr	tr

quartz (Plate 3, Fig. 1). Perthitic structure and gridiron twinning are common in the microcline.

Accessory minerals consist of epidote, hematite, chlorite, apatite, magnetite, sphene, zircon, and sillimanite. Hematite and magnetite are usually associated with the biotite rich bands and very often have developed in the biotite as long, thin stringers parallel to cleavage. Small zircons with poorly developed metamict halos (Plate 3, Fig. 2) occur in several of the biotite crystals and a few minute sillimanite needles are present in association with muscovite. Plagioclase shows a fairly high degree of alteration to saussurite, but potash feldspar is only slightly sericitized. Some of the biotite shows minor chloritization.

Hornblende Gneiss

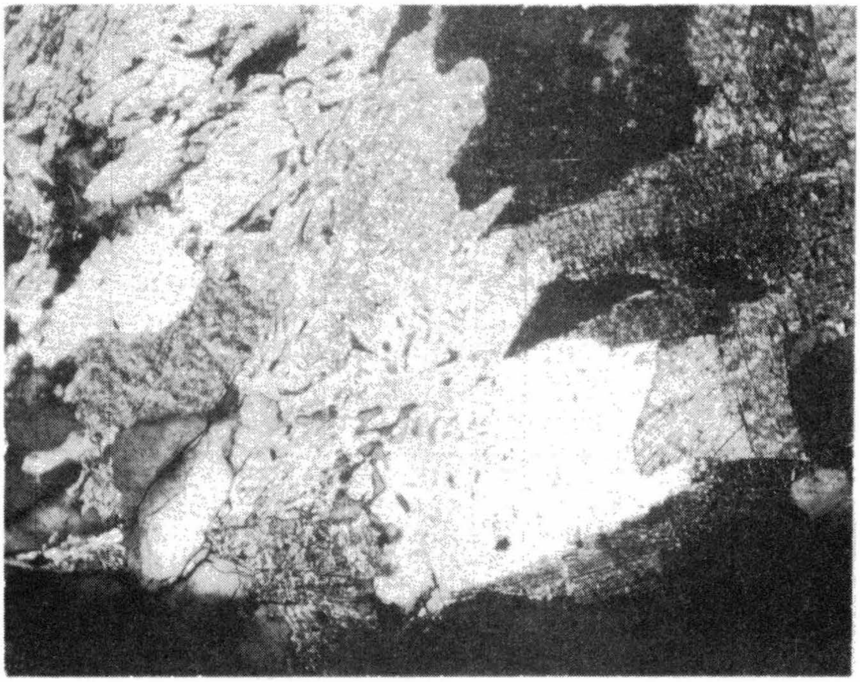
General Description

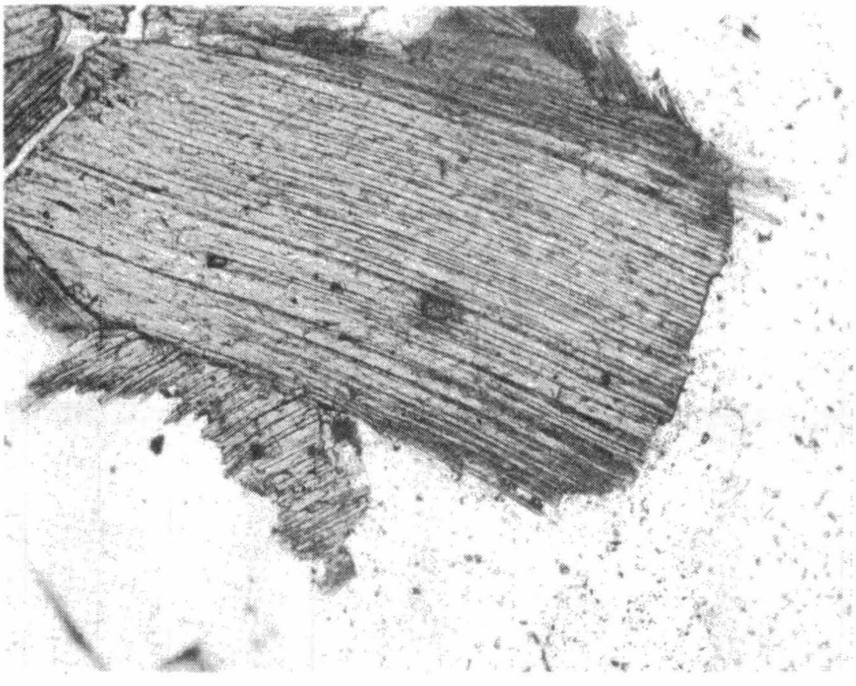
Hornblende gneiss is much less abundant than biotite gneiss. Maximum outcrop length is approximately 700-800 feet. Outcrops are scattered throughout the area, but the most prominent exposures are concentrated in the eastern portion of the Sevenmile Creek valley. Granitic veins up to several inches wide cut the hornblende gneiss concordantly and discrodantly. Scattered veins of secondary epidote (generally concordant and usually only a few millimeters thick) also occur.

Plate 3. Photomicrographs of biotite gneiss.

Fig. 1. Symplectic intergrowth of quartz (dark irregular patches) and muscovite (crossed nicols; 80X; sample S-26).

Fig. 2. Zircon crystal with metamict halo in biotite (plane-polarized light; 80X; sample S-26).





Foliation is prominent and is defined by mineral segregation in which dark green to black hornblende rich layers alternate with lighter colored quartzo-feldspathic layers. The grain size is usually less than 1 mm., but some amphibole crystals are over 5 mm. in length.

Small ptygmatic folds occur locally, but folding is relatively uncommon. Lineations are also quite rare, however, preferred orientation of hornblende crystals sometimes produces a fairly well defined lineation.

Petrography

The hornblende gneiss displays a nematoblastic texture. The major mineral constituents are hornblende (pleochroism: X = pale brown, Y = green, Z = dark green) and plagioclase ($An_{36?}$-An_{52}), but quartz and epidote may be abundant locally (Table 2). Hornblende crystals are generally xenoblastic and all appear to be products of the same metamorphic episode. Many of the hornblende crystals are poikiloblastic (Plate 4, Fig. 1), containing small, rounded quartz grains with minor amounts of potash feldspar, biotite, and sphene. Some plagioclase grains also contain abundant inclusions of rounded quartz. Irregular grains of quartz showing undulose extinction occur interstitially. Incipient alteration of plagioclase to saussurite is common. Some plagioclase grains are almost completely altered and the An content cannot be determined with good statistical accuracy.

Table 2. Modal analyses (volume percent) for hornblende gneiss.

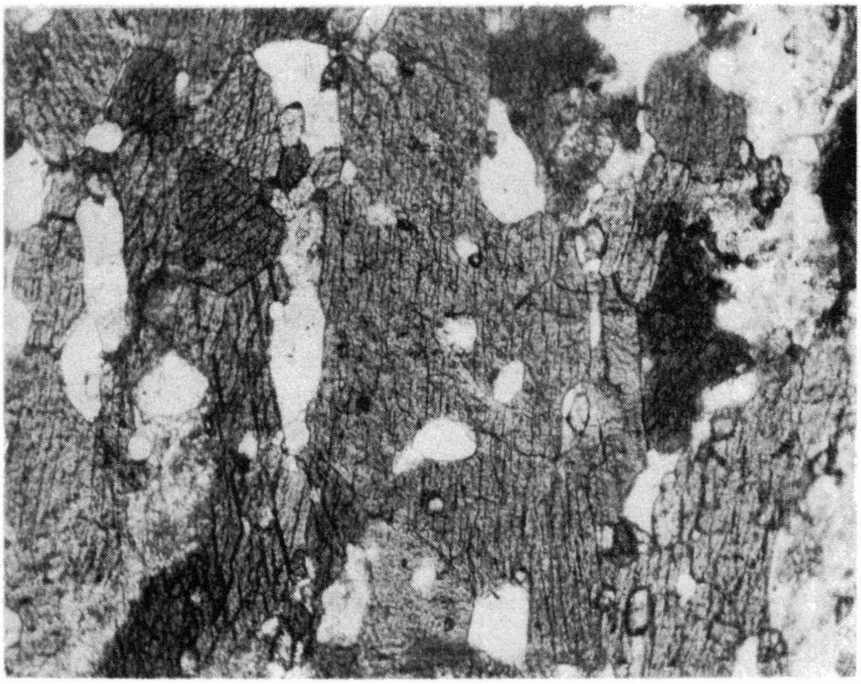
	Sample					
	S-18	S-75	S-136	S-155	S-159	S-162[1]
Hornblende	54.4	59.3	49.0	9.9	24.7	25.7
Plagioclase	7.7 An_{40}	25.6 An_{41}	21.6 $An_{36?}$	53.3 An_{40}	17.6 An_{50}	28.0 An_{52}
Quartz	6.5	5.0	tr	9.9	36.7	14.7
Epidote	27.3	1.3	23.4	19.4	14.5	tr
Sphene	3.3	5.8	3.2	2.8	4.9	1.0
Apatite	0.7	3.0	tr	1.1	1.5	1.0
Tremolite	-	-	2.2	-	-	-
Biotite	-	-	-	2.1	-	29.4
Clinozoisite	tr	-	tr	-	-	-
Hematite	tr	tr	tr	tr	tr	tr
Ilmenite	-	-	-	tr	-	-
Magnetite	-	-	tr	1.5	-	tr
Zircon	-	-	-	-	-	tr
Chlorite	-	-	-	tr	tr	tr
Saussurite	tr	tr	tr	tr	tr	tr

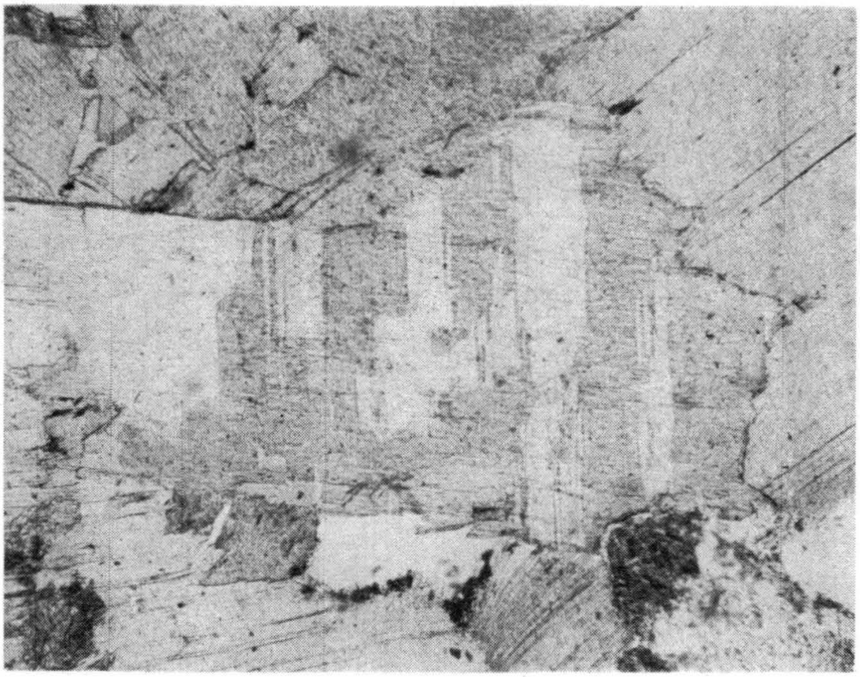
[1] Biotite-hornblende gneiss

Plate 4. Photomicrographs of hornblende gneiss and amphibolite.

Fig. 1. Poikiloblastic hornblende containing inclusions of rounded quartz and small sphene grains (plane-polarized light; 80X; sample S-75).

Fig. 2. Amphibole crystal showing development of tremolite (light) in hornblende (dark) (plane-polarized light; 80X; sample SD-30).





Accessory minerals include biotite, magnetite, ilmenite, sphene, hematite, zircon, clinozoisite, tremolite, and apatite. Brown to yellow-brown biotite commonly shows contorted cleavage traces and may be slightly chloritized. Numerous small grains of magnetite sometimes show a weak concentration in layers (2-3 mm. thick) parallel to the foliation. Sphene is fairly abundant and occurs as both small diamond shaped crystals (commonly about 0.1 mm. in longest dimension) and as larger aggregates (up to about 0.8 mm.).

Amphibolite

General Description

Xenoliths of amphibolite are scattered throughout the study area, but most of the larger, mappable units are concentrated in the eastern half. Outcrops range from about 20 to 300 feet in length and from a few feet to nearly 200 feet in width. Most of the xenoliths are elongate in outline, but do not show the pronounced elongation characteristic of the biotite gneiss. Outcrops commonly form slight topographic highs. Small veins of quartz and granite intrude the amphibolite locally.

The amphibolite is typically dark green to black, but sometimes feldspar and quartz are sufficiently abundant to produce a white and dark green mottled appearance. The grain size ranges from medium to coarse and the texture is usually equigranular.

Foliation is absent in the amphibolite. Lineations are rare, although hornblende crystals sometimes show a weak parallel alignment.

Petrography

Amphibolite shows a nematoblastic texture. The principal mineral constituents are hornblende (pleochroism: X = pale green, Y = green, Z = dark green), plagioclase ($An_{36?}$-An_{51}), quartz, and epidote (Table 3). Mineralogy of amphibolite is nearly the same as that of hornblende gneiss. The main difference is greater abundance of hornblende in amphibolite and greater abundance of quartz, epidote, sphene, and apatite in hornblende gneiss. Several of the amphibolites are characterized by lack of plagioclase. This may possibly be due to mineral or chemical variations in the parent rock. Tremolite comprises nearly 34 percent of one sample (SD-30). It occurs as patches and streaks (usually with indistinct borders) in hornblende crystals (Plate 4, Fig. 2) and may be the result of retrogressive metamorphism. Sieve structure is common in many of the hornblende crystals and in a few of the plagioclase grains. Inclusions consist mainly of rounded quartz with minor amounts of plagioclase, hematite, magnetite, muscovite, and sphene. Most of the plagioclase shows only incipient alteration to saussurite, but a few grains are so highly altered that twinning is almost completely obliterated.

Table 3. Modal analyses (volume percent) for amphibolite.

	Sample					
	S-6	S-24	S-31	S-49	S-54	SD-30
Hornblende	55.2	62.9	86.9	92.3	87.3	46.1
Plagioclase	21.9 $An_{36?}$	25.8 An_{44}	-	tr $An_{?}$	8.1 An_{51}	-
Epidote	17.7	tr	3.9	-	1.2	-
Quartz	tr	10.0	0.7	tr	3.1	tr
Tremolite	-	-	-	-	-	33.9
Biotite	tr	tr	tr	-	-	18.4
Apatite	0.5	-	-	-	-	-
Sphene	tr	-	-	7.7	tr	-
Potash Feldspar	tr	-	-	-	-	-
Chlorite	2.8	tr	3.2	-	-	-
Ilmenite	tr	tr	-	-	-	-
Leucoxene	tr	tr	-	-	-	-
Magnetite	-	tr	tr	-	-	1.4
Hematite	tr	tr	tr	tr	tr	tr
Muscovite	-	-	5.0	-	-	-
Saussurite	tr	tr	-	tr	tr	-

Apatite, biotite, sphene, potash feldspar, chlorite, magnetite, hematite, ilmenite, muscovite, and leucoxene are all generally present as accessory minerals, although biotite may compose up to 18 percent of some amphibolites. Magnetite and minor ilmenite are present along cleavage planes in some hornblende crystals and in a few biotite grains. Iron staining is common along grain boundaries and cleavage traces of hornblende. Sphene occurs as small isolated crystals (commonly about 0.2 mm. long) and larger aggregates (over 1 mm.) and as rims around small grains of ilmenite. Some ilmenite is partially altered to leucoxene.

Log Cabin Granite

General Description

Log Cabin granite is the most abundant rock type in the Manhattan district and outcrops are numerous throughout the area. It contains abundant xenoliths of biotite gneiss, hornblende gneiss, and amphibolite, and contacts with these metamorphic rocks are generally quite sharp.

The Log Cabin granite is comprised primarily of granite and quartz monzonite, although there are a few occurrences of trondhjemite. The color varies from buff to pink and microcline is usually the dominant constituent. The rock is generally medium-grained, but varies from fine (less than 1 mm. grains) to coarse (greater than 5 mm. grains) on a local scale. Equigranular texture predominates, but some samples are strongly porphyritic and display potash feldspar phenocrysts (2-3 cm.) in a finer grained matrix. These large feldspar crystals sometimes show a preferred orientation and define a weak foliation.

A few small outcrops of foliated granite occur in the eastern and northern parts of the Manhattan district. These exposures are not distinguished from nonfoliate granite phases on the map since most occurrences are quite small. The foliated granite appears to be completely gradational with nonfoliate phases. A noticeable alignment of quartz, feldspar, and biotite imparts a weak gneissic structure to the rock. On the basis of petrographic observations, the foliated granite appears to be a product of moderate to intermediate cataclasis of nonfoliate phases.

Coarse-grained pegmatite, apparently a late phase crystallate of the granitic magma, occurs sporadically throughout the area and is found as small veins in the metamorphic rocks and as veins, pods, and lenses in the granite. The veins may reach dike-like proportions of nearly ten feet wide, but generally are less than three feet in width. The pods and lenses are rarely more than about 60 feet long. The majority of the pegmatite bodies in the area are not of mappable proportions. Pegmatite generally shows moderately gradational contacts with the granite. Quartz and feldspar crystals in the pegmatite often exceed one inch in length and plates of biotite and muscovite may be 3 to 4 inches across.

Exfoliation and spheroidal weathering are fairly common in the granites of the Manhattan area due to the presence of well developed joint sets. However, the joints appear to have had little control over the development of the general topography. A few potholes up to approximately two feet in diameter and several inches deep are present on some of the outcrop surfaces (Figure 2) where the action of wind and standing water have apparently been very effective in breaking down the rock. A thin mantle of grus is fairly well developed over many of the flat or low lying areas in the northern part of the district.

Petrography

The Log Cabin granite usually displays a hypidiomorphic granular texture. However, the texture is porphyritic locally. The principal constituents are potash feldspar, quartz, and plagioclase (An_2-An_{12}) (Table 4). Microcline is the dominant constituent in normal granite, whereas plagioclase may predominate slightly in quartz monzonite. Trondhjemite contains abundant quartz and plagioclase (approximately 40 percent of each) with relatively minor microcline (about 15 percent). Weak to moderate shearing and/or crushing has affected most of the granites. Quartz grains are nearly always fractured and show undulose extinction, and many grains have

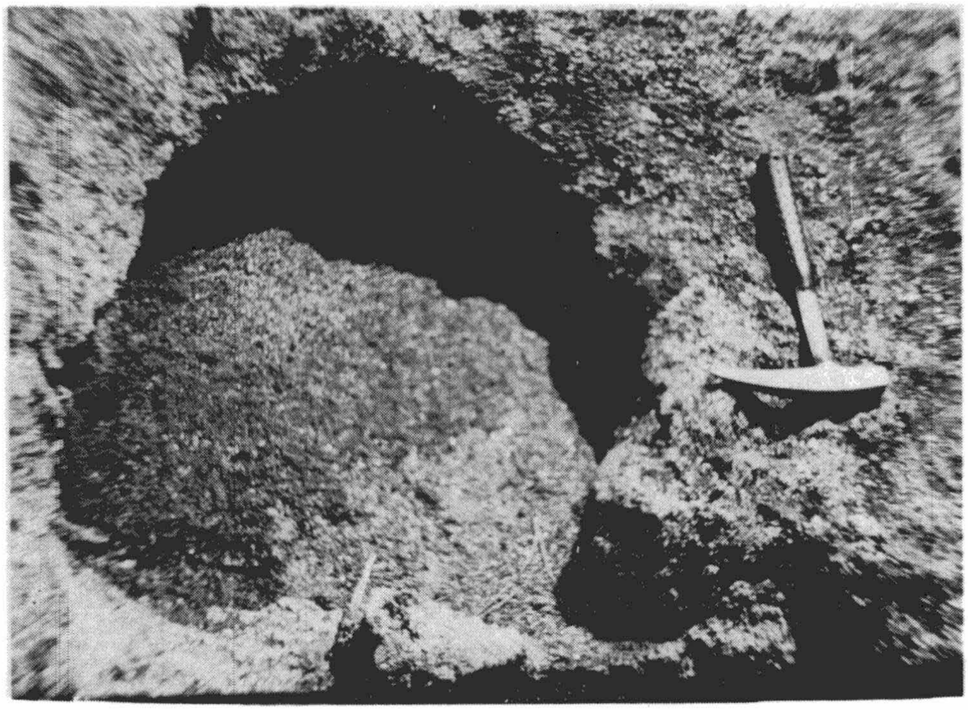


Figure 2. Pothole developed in granite.

Table 4. Modal analyses (volume percent) for Log Cabin granite.

	Sample								
	S-7	S-9	S-37[1]	S-60	S-104	S-106[2]	S-114	S-118[3]	S-166[4]
Potash Feldspar	60.5	73.1	14.8	54.2	81.9	27.7	67.9	29.1	39.8
Quartz	34.3	3.7	42.7	41.2	13.7	29.6	21.7	32.4	32.7
Plagioclase	4.6 An_{10}	21.1 An_6	41.9 An_9	3.8 An_6	4.0 An_4	28.8 An_2	9.7 An_4	33.0 An_{10}	23.3 An_{12}
Muscovite	0.6	tr	tr	0.5	tr	0.6	0.7	1.1	0.5
Biotite	-	-	tr	-	-	tr	-	3.2	2.6
Epidote	-	tr	-	-	-	8.6	-	tr	1.1
Allanite	-	-	-	-	-	tr	-	-	tr
Apatite	tr	-	-	-	-	-	-	-	-
Chlorite	-	-	tr	-	-	4.6	-	-	-
Zircon	-	-	-	-	-	-	-	tr	tr
Sphene	-	-	tr	tr	-	tr	-	-	-
Hematite	tr	1.7	-	tr	tr	tr	tr	tr	tr
Magnetite	-	-	-	tr	-	tr	-	0.9	tr
Saussurite	tr	tr	tr	tr	tr	tr	tr	tr	tr

[1] Trondhjemite

[2] Sheared quartz monzonite

[3] Quartz monzonite

[4] Quartz monzonite

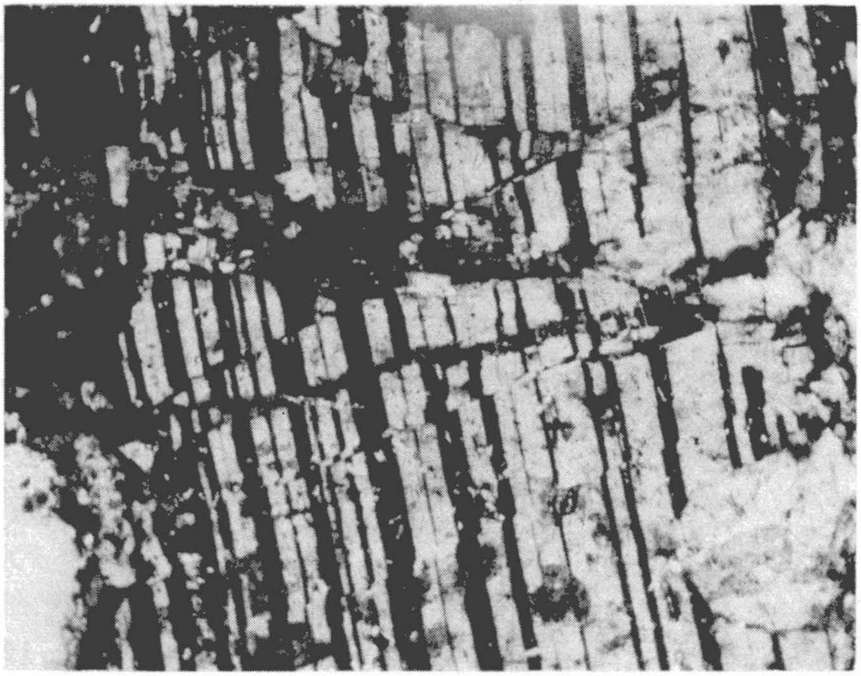
apparently recrystallized and show sutured contacts. Quartz may occur in symplectic intergrowths with muscovite. Microcline surrounds several large, rounded plagioclase crystals (Plate 5, Fig. 1) and has apparently replaced some of the plagioclase. Sericitization is very minor in the potash feldspar. Plagioclase grains sometimes have highly fractured edges with offset twin lamellae (Plate 5, Fig. 2). Secondary rims of untwinned plagioclase may occur on a few grains, but are generally quite rare. The granite appears to be mineralogically inhomogeneous as indicated in particular by the low plagioclase content (down to about 4 percent of the total) of some samples. Most of the plagioclase grains have been highly saussuritized.

The cataclastically foliated granite characteristically shows moderate to intermediate crushing. Quartz grains are highly fractured with very undulatory extinction. Many quartz grains are elongate and show a preferred optical orientation. Apparently these grains recrystallized and were aligned parallel to the direction of shearing. Plagioclase and potash feldspar grains are also highly fractured. Biotite and muscovite crystals are commonly bent or broken. Foliated granite contains numerous micro shear zones (a few millimeters thick) in which small highly crushed fragments of quartz, plagioclase, and potash feldspar have been healed by epidote. The main mineralogical difference between the foliated granite and

Plate 5. Photomicrographs of Log Cabin granite.

Fig. 1. Perthitic microcline surrounding rounded plagioclase grains (crossed nicols; 80X; sample S-7).

Fig. 2. Fractured plagioclase crystal cut by small epidote vein (near center) (crossed nicols; 80X; sample S-106).



nonfoliate phases is this secondary epidote. Also, most of the original biotite of the foliated granite has been chloritized.

Pegmatite has a hypidiomorphic granular texture and a composition similar to the surrounding granite. The principal constituents are potash feldspar (perthitic microcline), quartz, and plagioclase (An_8-An_{12}). The effects of slight crushing and shearing are indicated by undulatory extinction of quartz and by grain fracturing. The potash feldspar shows little secondary alteration, whereas plagioclase is considerably altered.

Accessory minerals in the granite and its various phases include muscovite, biotite, epidote, apatite, chlorite, sphene, hematite, magnetite, zircon, and allanite. Biotite and muscovite are commonly intergrown and the biotite is often slightly chloritized. Magnetite and hematite are commonly associated with biotite and may occur along cleavage planes of biotite. Hematite also occurs as small patches and as stains along fractures and grain boundaries. Zircon crystals are very small (commonly about 0.02 mm.) and normally can be identified only by the presence of metamict halos in biotite.

Shear Zone Tectonites

General Description

The shear zones of the Manhattan district range from approximately 10 to 200 feet in width and up to 2000 feet in length. They consist primarily of submylonite and mylonite and most contain cataclastic granite as border phases. The more intensely sheared zones have been highly epidotized and silicified. Although some shear zones in the general area are not totally rehealed (e.g., Beverly, 1969, p. 50, describes a very large unhealed fault zone about three miles southeast of the Manhattan district) all the fault zones in the Manhattan area have been rehealed with quartz and epidote.

The mylonite and submylonite are fairly coherent and often show a brecciated structure in which fine-grained fragments of mylonite are set in a coarser grained matrix of cataclasite to submylonite. This occurrence of a brecciated structure with mylonite fragments in a coarser grained phase indicates that there were probably at least two episodes of deformation which produced the shear zones in the Manhattan district. Small veinlets of quartz commonly cut through both the mylonite fragments and the coarser matrix. Streaks of quartz and epidote, apparently parallel to the direction of shear, are common in many of the coarser grained phases. Fracture surfaces are often stained with hematite. Due to the high epidote content and the hematite staining these rocks are typically pale green or greenish-brown in color.

Near the edges of shear zones there is abundant cataclasized granite which typically has numerous veins of epidote and quartz. Most of the veins are less than 1 mm. wide, but a few reach 2 to 3 cm. in width. Granulation in the cataclasized granite is not extreme and even though small veins of epidote are abundant the rock generally retains the buff to pink color of the adjacent granite.

Petrography

The shear zone rocks display a fairly wide range of textures. Degree of cataclasis varies from moderate in the cataclasized granite to extreme in fine-grained mylonite. The mineral fragments of cataclasized granite are highly fractured and have very irregular, jagged borders. The original quartz shows very undulose extinction. Some of the introduced quartz in the small veins also shows slightly undulose extinction indicating that there may have been a small amount of shearing or crushing after the introduction of quartz in veinlets. Quartz grains are sometimes elongated and show a preferred optical orientation parallel to the direction of elongation. This is apparently due to recrystallization and growth in the direction of shear. Plagioclase and potash feldspar are less abundant than in non-sheared granite because of the introduction of epidote and secondary quartz. Epidote may comprise up to 22 percent of some cataclasized granites.

Submylonite contains fragments ranging in size from fairly large porphyroclasts (2-3 mm.) of quartz to a finely crushed mixture of quartz, epidote, and feldspar. Microcline and plagioclase show a greater degree of crushing than quartz, but most fragments are still large enough to be easily recognized. Large amounts of quartz and epidote have been introduced making these the principal constituents. Epidote may comprise nearly 40 percent of the submylonite and quartz may be present in excess of 70 percent.

Fragments of mylonite sometimes show a very weakly laminated fabric defined by orientation of small, angular quartz porphyroclasts. Exact composition is nearly impossible to determine because of fine grain size, but most mylonite fragments appear to consist primarily of microcrystalline quartz and epidote.

Accessory minerals of the cataclasized granite and the submylonite include magnetite, chlorite, apatite, muscovite, hematite, sphene, biotite, pyrite, and chalcopyrite. The only recognizable accessories in mylonite are hematite, magnetite, and chlorite. Pyrite and chalcopyrite are found in some shear zones that have been affected by mineralizing solutions. These occurrences will be discussed more thoroughly in the chapter on mineralization. Sericite and saussurite are also common as alteration products of potash feldspar and plagioclase.

TERTIARY INTRUSIVES

General Description

The Tertiary intrusives in the Manhattan district typically occur as reasonably continuous dikes approximately 5 to 20 feet wide and ranging in length from about 50 feet to over 4000 feet. At some localities (e.g., the northeast quarter of section 29 and the northwest quarter of section 32) sets of two or more closely spaced dikes parallel one another (some separated by as little as 20 to 30 feet). All intrusives in the area are strongly porphyritic. Large white feldspar crystals (up to 3 cm.) account for the majority of phenocrysts, although one fairly rare type of intrusive contains abundant hornblende. Preferential weathering of phenocrysts imparts a pitted appearance to most outcrops. Red-brown hematite staining, possibly from the weathering of mafic phenocrysts, is common along fracture planes and on weathered surfaces. Liesegang rings may be present on smooth joint surfaces.

The Tertiary intrusives have been grouped into three general field categories on the basis of phenocryst type and abundance. Two of the groups are distinguished on the basis of quartz content; one group has about 10 to 15 percent quartz phenocrysts, whereas the other group has only minor quartz (usually less than 3 percent). Both of these groups have abundant feldspar phenocrysts (up to 40 percent) and little or no hornblende. The third group contains abundant hornblende phenocrysts (15 to 20 percent) accompanied by 4 to 8 percent feldspar and up to 3 percent quartz. The intrusives with abundant hornblende are usually slightly to considerably darker than the other dike rocks. The group with abundant feldspar and minor quartz is the most abundant Tertiary unit in the study area. Plagioclase comprises most of the feldspar phenocrysts. Potash feldspar phenocrysts do not show a tendency for any particular grouping and were not distinguished from plagioclase in the field classification.

In an attempt to classify the Tertiary intrusives Beverly (1969, p. 56) experimented with x-ray diffraction analysis to determine the relative amounts of quartz, potash feldspar, and plagioclase, but poor results were obtained because diffraction peaks were apparently masked by glass in the matrix. The glass bead method employed by Kittleman (1963, p. 1405-1410) was used with apparent success by Beverly (1969, p. 54) and is the method used in this study. This approach involves grinding rock samples to about a 325 mesh powder, fusing the powder into a glass bead, crushing the bead, and determining the refractive index of the glass fragments by oil immersion methods. Silica content can then be determined from the refractive index by using a curve based on values obtained from chemically analyzed samples.

The curve used to determine the silica content of the Manhattan area intrusives (Figure 3) was developed by Kittleman (1963, p. 1407) for a suite of volcanics from the Owyhee Plateau, Oregon. As Kittleman (1963, p. 1408) indicates, the curves of percent silica versus refractive index for volcanic suites in western North America show relatively little variation, and composite curve (Kittleman, 1963, p. 1407) including data from several different area is very similar to that established by Kittleman.

Table 5 and Figure 3 show the percent silica as determined from refractive indices for several intrusives in the Manhattan area. Silica percentages range from 62.2 to 73.3. Using Turner and Verhoogen's (1960, p. 275-276) classification for the rocks of the San Juan volcanic province of Colorado, the intrusives of the Manhattan district may be classified as either rhyolites (SiO_2 = 68 to 77 percent) or rhyodacites (rhyolitic quartz latite of Turner and Verhoogen, 1960, p. 275) (SiO_2 = 62 to 67 percent), although the hornblendic intrusives (hornblende rhyodacites) closely appraoch the andesite-latite category (SiO_2 = 58 to 61 percent). The hornblende rhyodacites have the lowest silica percentages (62.2 to 62.9) of all the intrusives in the area, and, according to Williams, Turner, and Gilbert's (1954, p. 27) acid-basic type of classification, these rocks would be classified as intermediate (52 to 66 percent silica). All other intrusives would fall into the acid category (greater than 66 percent silica).

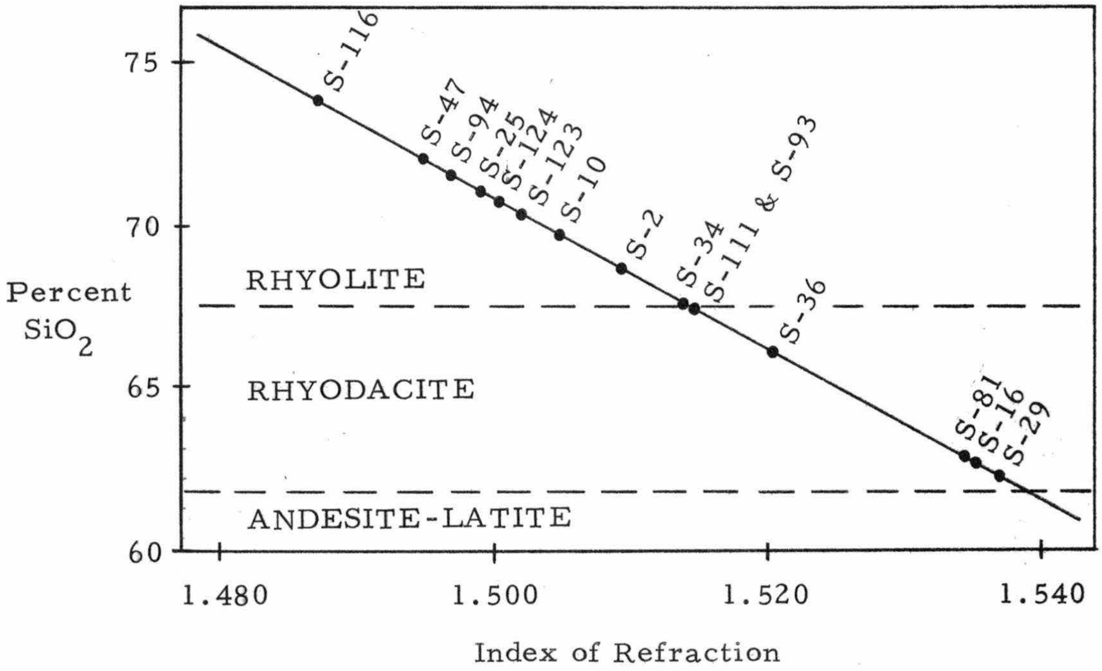


Figure 3. Percent SiO_2 versus index of refraction for Manhattan area intrusives. The regression line was developed by Kittleman (1963, p. 1407). Rhyolite and rhyodacite are distinguished on the basis of Turner and Verhoogen's (1960, p. 275-276) classification of rocks from the San Juan volcanic province of Colorado.

Table 5. Estimated SiO_2 percentages of Manhattan area intrusives determined from refractive indices of glass beads. Percentages are based on Kittleman's (1963, p. 1407) curve for volcanics of the Owyhee Plateau, Oregon (standard deviation from the regression line is approximately 2 percent). Rhyolite and rhyodacite (rhyolitic quartz latite) are distinguished on the basis of Turner and Verhoogen's (1960, p. 275-276) classification of the rocks of the San Juan volcanic province of Colorado (rhyolite = 68 to 77 percent SiO_2 and rhyodacite = 62 to 67 percent SiO_2).

Sample	Index of Refraction	Percent SiO_2
RHYOLITE		
S-116	1.489	73.3
S-47	1.495	71.9
S-94	1.497	71.4
S-124	1.500	70.7
S-123	1.501	70.5
S-10	1.504	69.8
S-2	1.509	68.7
RHYODACITE		
S-34	1.513	67.7
S-93	1.514	67.5
S-111	1.514	67.5
S-36	1.519	66.4
S-81	1.534	62.9
S-16	1.535	62.7
S-29	1.537	62.2

Whole-rock analyses were performed on four of the intrusives from the study area (Table 6) and silica values agree favorably with those determined by the glass bead tests. In three of the four samples silica percentages determined with glass beads vary only one percent or less from the results established by chemical analysis. One of the glass bead tests (for sample S-36) indicates a silica estimate 2.6 percent below the value determined in the whole-rock analysis, but this is not an extreme variation. For his data, Kittleman (1963, p. 1406) calculated the standard deviation about the regression line to be about two, so that with a very large number of samples about 68 percent would be expected to fall within two percent of the estimated regression line.

Both general field observations and glass bead tests of the intrusives show a clear separation of hornblende rhyodacite. Field distinction of the other two types of dike rocks was based on the presence or absence of abundant quartz phenocrysts. The glass bead tests, however, do not reflect this preference for separate groups. Apparently the presence of abundant quartz phenocrysts in these intrusives is not a good indication of high silica content.

In addition to the glass bead tests, a C.I.P.W. normative mineral computer program (W. Weiss and J. Puckett, C.S.U. Department of Geology, open files) was also used to classify the four chemically analyzed intrusives (Table 7). The Turner and Verhoogen

Table 6. Whole-rock analyses of four intrusives from the Manhattan area. (Analyst: Oiva Joensuu).

	Sample			
Percent	S-36	S-81	S-94	S-123
SiO_2	69.0	63.0	71.2	71.5
TiO_2	.25	.42	.15	.15
Al_2O_3	16.5	15.5	15.7	15.9
Fe_2O_3	2.35	3.75	1.22	1.12
FeO	0.72	2.40	0.44	0.62
CaO	2.80	3.50	.35	2.65
MgO	.60	1.95	.25	.42
Na_2O	3.8	3.90	5.6	4.6
K_2O	3.2	3.1	3.7	2.8
MnO	.090	.19	.010	.028
H_2O^-	.48	.34	.53	.24
P_2O_5	.09	.23	.08	.07
<u>ppm</u>				
B	<3	<3	<3	<3
Ba	1100	820	820	1100
Be	2.5	2.5	2.0	2.0
Co	<3	<3	<3	<3
Cu	<5	14	5	5
Cr	<5	14	<5	<5
Ga	18	18	18	18
La	32	40	<10	10
Ni	<5	<5	<5	<5
Pb	30	25	30	25
Rb	64	76	88	36
Sc	<3	12	<3	<3
Sr	1200	1020	660	1060
V	42	70	22	17
Y	22	35	10	8
Zn	35	110	30	70
Zr	120	140	95	70

Table 7. Computer determined normative mineral concentrations (weight percent) of four chemically analyzed intrusives from the Manhattan area (computer program by C. Weiss and J. Puckett, C.S.U. Department of Geology).

	Sample			
Mineral	S-36	S-81	S-94	S-123
Quartz	28.01	18.30	23.57	27.91
Corundum	1.91	-	2.04	0.65
Orthoclase	18.91	18.32	21.87	16.55
Albite	32.15	33.00	47.39	38.92
Anorthite	13.30	15.64	1.21	12.69
Diopside	-	0.18	-	-
Hypersthene	1.49	5.74	0.62	1.06
Magnetite	1.89	5.44	1.02	1.62
Hematite	1.05	-	0.52	-
Ilmenite	0.47	0.80	0.28	0.28
Apatite	0.21	0.53	0.19	0.16

Rock Names

Sample	Based on Percent SiO_2	From Computer Analysis
S-36	Rhyodacite	Rhyodacite
S-81	Rhyodacite	Rhyodacite
S-94	Rhyolite	Quartz Keratophyre
S-123	Rhyolite	Rhyodacite

(1960, p. 275-276) classification used in conjunction with the glass bead method involves only five rock names (from rhyolite to basalt) and is based only on silica percentages. The computer program employs 24 rock names and considers additional data (such as feldspar ratios and abundances of other normative minerals) in the classification. Consequently, rock names established by the silica percentage method may differ appreciably from those determined by computer analysis. Samples S-36 and S-81 were classified as rhyodacites by both methods. On the basis of the silica content sample S-94 was classified as a rhyolite, whereas the computer designated normative mineral classification is quartz keratophyre (due in part to the high computed Ab content of 47.39 percent). Sample S-123 was called a rhyolite on the basis of silica content, but was classified as rhyodacite by the computer (due to the calculated abundance of plagioclase over potash feldspar).

Petrography

The rhyolites and rhyodacites have a porphyritic texture. Plagioclase phenocrysts (An_{25}-An_{38}) may comprise over 40 percent of these rocks (Table 8). Zoning is evident in many of the plagioclase crystals. One of the more conspicuously zoned crystals shows a core composition of An_{32} and a border composition of An_{25}. Abundance of potash feldspar usually ranges from trace amounts up to 6 percent, but rarely it may account for nearly 20 percent of the rock. As noted in the general field classification there are a few intrusives which contain abundant quartz phenocrysts (about 10 to 15 percent), but these dike rocks fall in both rhyolite and rhyodacite categories. There is no apparent difference in mineralogy between rocks classified as rhyolite and rhyodacite on the basis of silica content. This is probably because most of the silica occurs in glass in the matrix.

Hornblende, magnetite, muscovite, biotite, ilmenite, leucoxene, epidote, hematite, apatite, chlorite, and monazite are all generally present as accessory minerals. Rims of plagioclase phenocrysts are commonly highly saussuritized and potash feldspar usually shows incipient alteration to sericite.

The hornblende rhyodacites display a porphyritic texture and consist of approximately 20 to 30 percent phenocrysts in a microcrystalline matrix. The phenocrysts are mainly hornblende (15 to 20 percent; pleochroism: X = pale green, Y = green, Z = dark green) with minor amounts of quartz, potash feldspar, plagioclase, and magnetite (commonly about 2-3 percent of each). Hornblende crystals average about 5 mm. in length and sometimes show a preferred orientation. Because plagioclase is not abundant and is moderately to highly saussuritized, the composition is difficult to accurately determine. The most calcic plagioclase measured in the hornblende rhyodacites is An_{51}. Several of the plagioclase crystals are zoned. One of the phenocrysts which showed a fairly pronounced zonation has a core composition of An_{44} and a border composition of An_{39}.

Accessory minerals in hornblende rhyodacite are muscovite, biotite, ilmenite, epidote, hematite, and apatite. Hornblende crystals often show incipient chloritization.

Table 8. Modal analyses (volume percent) for Tertiary intrusives.

	Sample							
	S-2	S-10	S-16	S-36	S-81	S-93	S-94	S-123
Matrix	59.6	68.8	67.5	71.1	78.3	58.5	78.0	43.7
Plagioclase	33.5	tr	2.6	24.3	tr	16.7	20.8*	41.1
	An_{38}	$An_{?}$	An_{51}	An_{32}	$An_{?}$	An_{29}	$An_{31?}$	An_{28}
Potash Feldspar	3.3	19.7	5.9	tr	3.6	tr	tr	tr
Quartz	tr	9.5	2.4	tr	tr	9.5	1.1	13.8
Hornblende	tr	-	19.2	-	15.7	tr	-	1.1
Magnetite	1.5	-	2.4	tr	2.0	1.4	tr	tr
Muscovite	1.1	1.5	tr	tr	-	tr	tr	-
Biotite	tr	-	-	tr	tr	-	tr	tr
Ilmenite	tr	tr	-	tr	tr	-	-	-
Leucoxene	tr	tr	-	-	-	-	-	-
Epidote	-	-	tr	2.3	tr	-	-	-
Hematite	tr	-	tr	0.7	tr	13.8	tr	tr
Apatite	-	-	-	-	tr	tr	-	tr

Table 8. (Continued)

	Sample							
	S-2	S-10	S-16	S-36	S-81	S-93	S-94	S-123
Chlorite	-	-	tr	1.4	tr	-	-	tr
Monazite	-	-	-	tr	-	-	-	tr
Saussurite	tr	tr	tr	tr	tr	tr	*	tr
Sericite	tr	tr	tr	tr	tr	tr	tr	tr

*Plagioclase phenocrysts are almost completely saussuritized.

STRUCTURE

General Statement

The structure of the northeastern Front Range has evolved through a fairly complex geologic history including several episodes of deformation, intrusion, and metamorphism. Bulk compositions of the metamorphic rocks indicate that the parent rocks were primarily sedimentary in origin. According to Peterman, Hedge, and Braddock (1968, p. 2279, 2294) the first period of deformation was accompanied by low grade metamorphism and occurred at or before 1800 m.y. ago producing large east-west isoclinal folds in the metasediments with axial planes dipping 60 to 90 degrees southward.

The second orogenic episode, dated at 1700-1800 m.y., involved medium to high grade regional metamorphism, refolding, and the intrusion of Boulder Creek granite (Peterman, Hedge, and Braddock, 1968, p. 2277, 2279, 2294). At 1390-1450 m.y. ago the Sherman granite (immediately north of the Log Cabin batholith) and the Silver Plume granite (composed of several batholiths, including the Log Cabin batholith, and smaller plutons along the northern Front Range of Colorado) were intruded into the metasediments in an episode which apparently involved only weak tectonic movements (Peterman, Hedge, and Braddock, 1968, p. 2277). After the large scale intrusions of the Sherman and Silver Plume granites there was a period of faulting and cataclasis which Peterman, Hedge, and Braddock (1968, p. 2277) estimate may have occurred about 1300 m.y. ago. Several shear zones in the Manhattan area probably reflect this tectonic period.

Uplift of the Ancestral Rockies and the Laramide orogeny were probably effective in producing new joints in the granite and widening pre-existing joints along which numerous porphyritic dikes were emplaced. The porphyritic dikes of the Manhattan area are presumed to be of Tertiary age because of proximity to petrologically similar intrusives of known Tertiary age in the Cameron Pass area (about 20 miles southwest). A potassium-argon age date by Corbett (1964, p. 106) indicates an age of 28 m.y. (Oligocene-Miocene boundary) for one of the quartz latites near Cameron Pass.

The Tertiary intrusives of the Manhattan area appear to be predominantly joint controlled. Emplacement of a few minor intrusives may have been controlled by faults or shear zones, but good evidence is lacking.

Foliations

Foliation is very well developed in biotite gneiss and hornblende gneiss and is produced by parallel alignment of biotite and by segregation of light and dark minerals. In some cataclasized granites weak foliation may result from recrystallization of quartz parallel to the shear direction.

Figure 4 is a pole-plot diagram of all the recorded foliations in the metamorphic rocks of the Manhattan area. Contouring was done by the Schmidt or grid method as described by Turner and Weiss (1963, p. 61-62). The dips of the foliations are predominantly near vertical throughout the area and a statistical fold axis trend is approximately N65W. This trend agrees fairly well with the east-west, isoclinal type of folding which Peterman, Hedge, and Braddock (1968, p. 2279) describe as having occurred during the first period of deformation. The strike of the major fold axis is reasonably close to east-west and the concentration of foliation pole-plots in the northern part of the petrofabric diagram suggests that the axial plane (if it exists) may be steeply dipping southward (presuming that the general trend of the foliation planes parallels the axial plane; this presumption is reasonably valid in the case of isoclinal folding since most of the length of the fold limb is essentially parallel to the axial plane of the fold).

Folds and Lineations

Axes of small, tight folds (usually less than one foot in amplitude and wavelength) comprise all of the recorded lineations in the gneissic rocks. Most of the folds occur in biotite gneiss. Only a few were observed in hornblende gneiss. These lineations, plotted as dots in Figure 4, are fairly well scattered, but appear to show a slight concentration in the west-northwest portion of the petrofabric

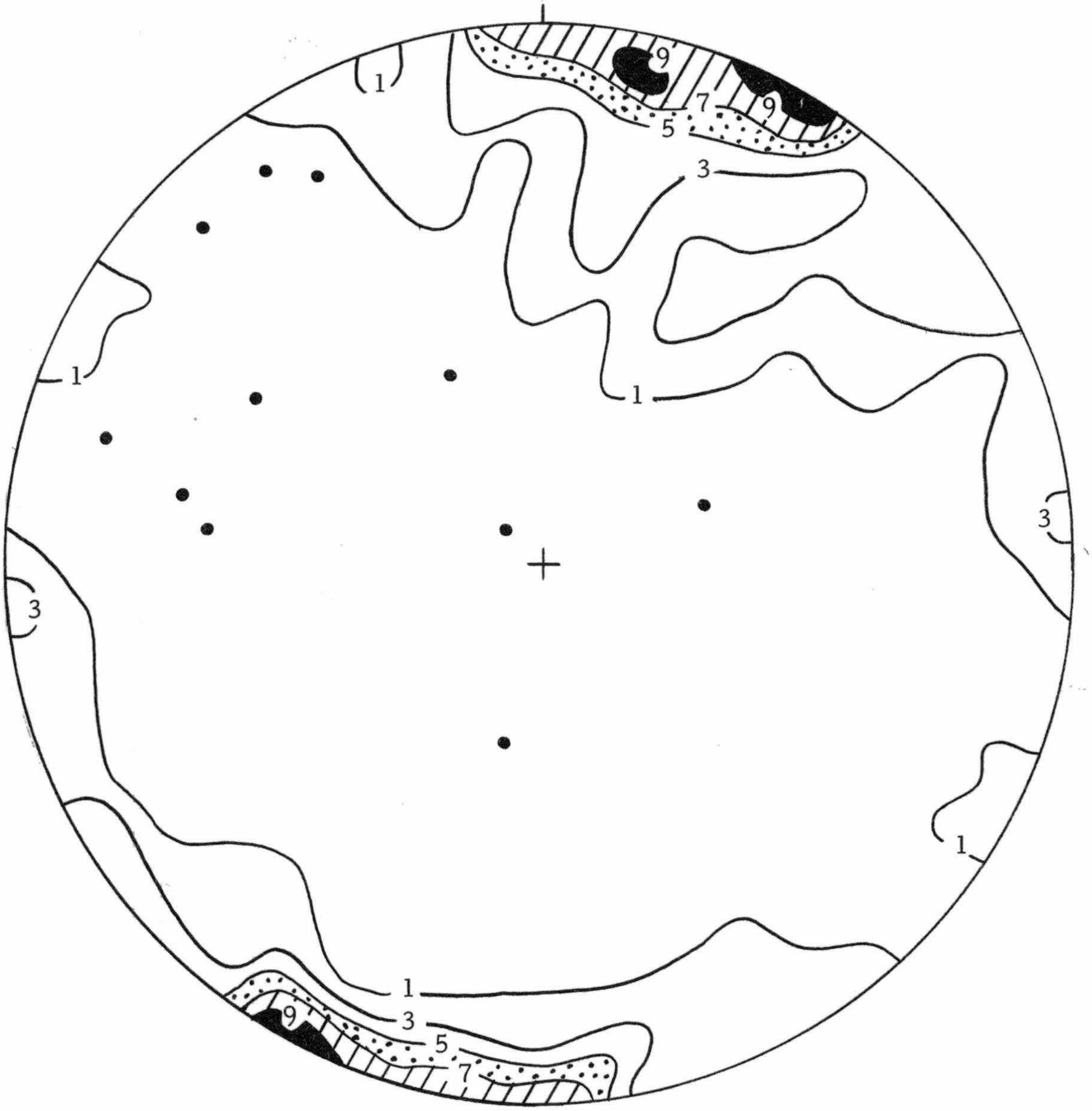


Figure 4. Contoured pole-plot diagram (% per 1% area) of 123 foliation measurements in the metamorphic rocks of the Manhattan area. Lineations are indicated by dots. Tick mark is north.

diagram suggesting a plunge of roughly 20 to 30 degrees for the major fold axis (if present).

In addition to the manually prepared pole-plot diagram (Figure 4), a computer analysis of foliation data (developed by Kelley, 1966) was also used to determine bearing and plunge of the major fold axis, if present. Results of this analysis suggest a strike of 237 degrees (S57E) and a plunge of 42 degrees for the fold axis. The computer program is designed to calculate a single "best fit" direction for the strike of the axis, and although the 237 degree direction was chosen as best fit for the data, an analysis of the intermediate steps in the computer calculation shows that a direction of about 80 degrees (N80W) for the strike of the axis fits the data almost as well. Another factor that should be considered is that the study area is quite small (about five square miles) as compared to the size of the folds being evaluated. Peterman, Hedge, and Braddock (1968, p. 2279) estimate that many of the folds in the northeastern Front Range are several thousands of meters in amplitude with wavelengths up to 6 km. Foliations in the Manhattan area may represent a single limb of a large fold, thus may not provide anough information to accurately determine a fold axis plunge. If more foliation data were available from a larger area, fold axis analyses would probably have been much more reliable. In addition to the problem of scale, several of the metamorphic xenoliths may be partially foundered blocks, thereby complicating the analysis.

Joints

Joints are well developed in the Log Cabin granite of the Manhattan district and have contributed to exfoliation and rounded outcrops. In most exposures of granite, joints of a particular set are several feet apart, but in some outcrops they may be separated by only a few inches.

Figure 5 shows the joint pattern in the Log Cabin granite of the Manhattan area. There is an array of joints from about N40E to N70W which includes the most prominent joint set in the area (N50E). Less prominent joint sets strike approximately N30W, N50W, and N80W. The pole-plot diagram of granite joints (Figure 6) shows the joint planes to be fairly steeply dipping. Wolfe (1967, p. 37) and Beverly (1969, p. 77) describe a fairly prominent joint set striking north-south in the north-central and northeast portions of the Rustic quadrangle respectively, and Beverly (1969, p. 77) also describes a very prominent east-west joint set. However, neither of these sets appears to be very well developed in the Manhattan district. Aerial photographs of both the above areas show the striking influence of joints (particularly the N50E set) on topography, but aerial photographs of the Manhattan area show only minor topographic control by joints.

According to Compton (1962, p. 291) early-formed tension fractures in a cooling pluton may commonly be filled with pegmatite.

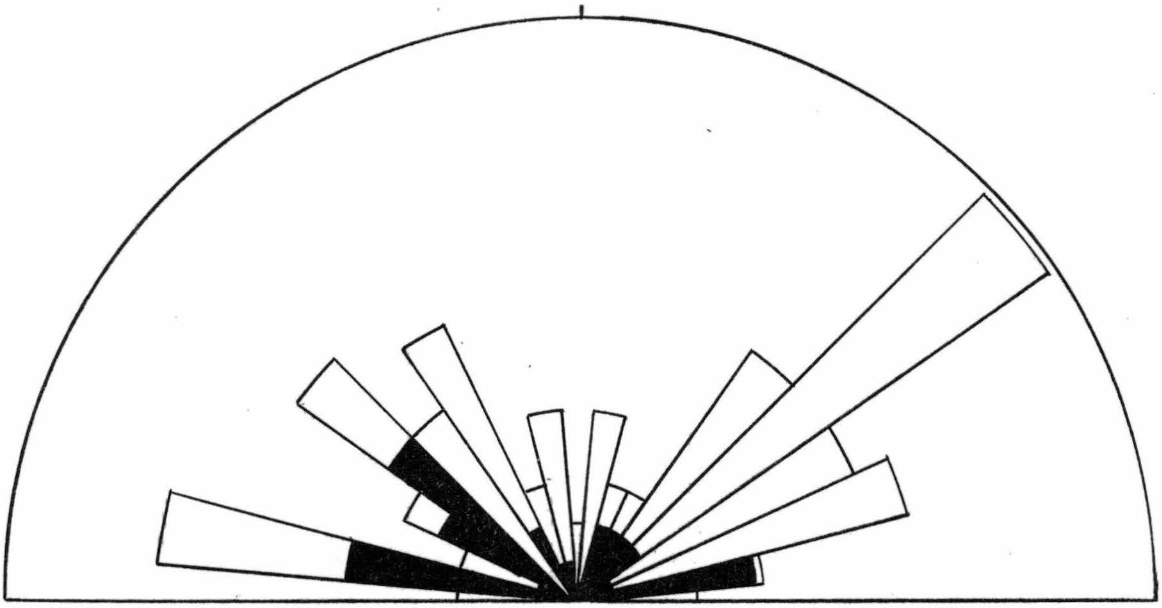


Figure 5. Rose diagram showing the frequency of 114 joint trends (open areas) and trends of Tertiary intrusives (shaded) in the Manhattan area. One inch equals five measurements. Tick mark is north.

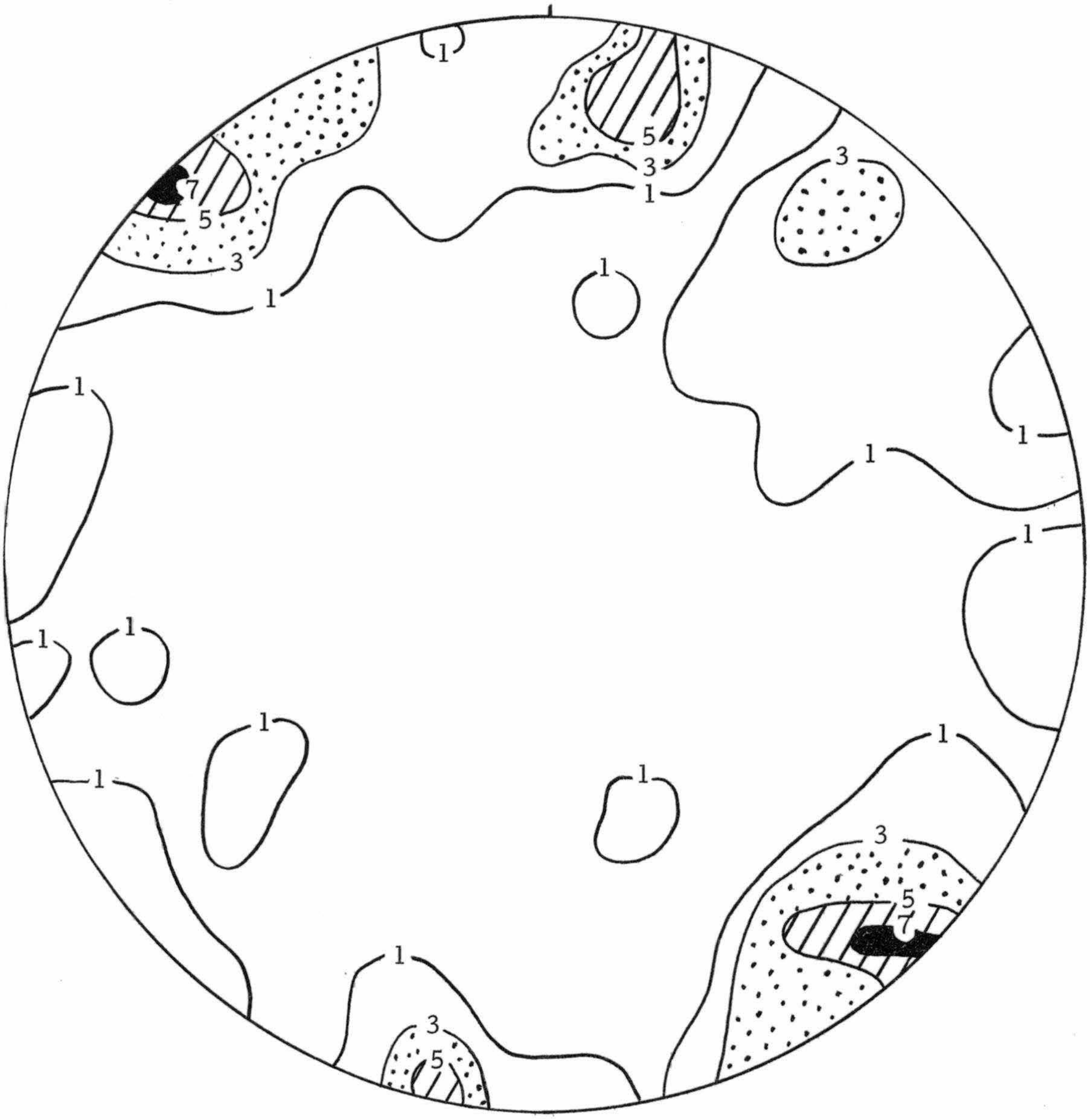


Figure 6. Contoured pole-plot diagram (% per 1% area) of 114 joint measurements in the Log Cabin granite of the Manhattan area. Tick mark is north.

Although most of the pegmatites in the Manhattan area are pod- or lens-shaped several do show thin, tabular structure (up to 10 feet wide and 300 feet long) that might be expected from such a tension fracture filling.

Most of the fractures or joints in the Log Cabin granite probably formed shortly after solidification of the magma. They are usually clean and show little sign of alteration along surfaces. The final period of faulting and cataclasis in the Precambrian (probably about 1300 m.y. ago), the uplift of the Ancestral Rockies, and the uplift during the Laramide orogeny were probably effective in producing additional joints in rocks of the area. In several granite outcrops horizontal or nearly horizontal joint planes are poorly developed. These may have been caused by erosional unloading after the Laramide uplift.

Granite joints appear to have played a dominant role in controlling emplacement of Tertiary magma. Nearly all the intrusions are relatively straight, suggesting influence of a long, linear feature such as a joint plane. Also, some of the intrusions occur in sets, that is, two or more dikes closely paralleling one another (separated by as little as 20 or 30 feet) and sometimes extending for several hundred feet. A comparison of strikes of intrusives and strikes of granite joints shows a tendency for many intrusions to closely parallel one of the major joint sets of the area (Figure 5).

Shear Zone Tectonites

The period of faulting and cataclasis which Peterman, Hedge, and Braddock (1968, p. 2277) estimate to have occurred about 1300 m.y. ago is evidenced in the Manhattan area by numerous small shear zones. Shear zones occur in granite and consist of mylonites and submylonites with border phases of cataclasized granite. Most of the sheared rocks have been highly epidotized and silicified. Some shear zones consist of small areas (generally less than 200 feet in longest dimension) which do not show a distinct linear trend. However, most of them are markedly linear. Several of the major shear zones which exhibit a pronounced linear trend closely parallel one of the major joint sets of the area, but the number of shear zones is not large enough to provide good evidence for joint control.

PETROGENESIS OF METAMORPHIC ROCKS

Metamorphic Facies

As indicated by the mineral assemblages, metamorphic rocks of the Manhattan area have been metamorphosed to the rank of sillimanite-almandine-orthoclase subfacies of the amphibolite facies. Metamorphism to the rank of the amphibolite facies involves temperatures of approximately 450-700°C. and pressures of about 2,000-10,000 bars (Turner, 1968, p. 366). High water pressures during metamorphism are indicated by the abundance of hornblende and biotite (Turner and Verhoogen, 1960, p. 552). Retrogressive metamorphism has occurred in some shear zones as indicated by abundant chlorite after hornblende.

Figure 7 shows the ACKF diagram for the sillimanite-almandine-orthoclase subfacies of the amphibolite facies. The numbers on the diagram refer to the following mineral assemblages of the metamorphic rocks in the Manhattan area:

(1) Biotite Gneiss: quartz-potash feldspar-plagioclase (An_{26}-An_{33})-biotite.

(2) Hornblende Gneiss: hornblende-plagioclase (An_{36}-An_{52})-epidote-quartz.

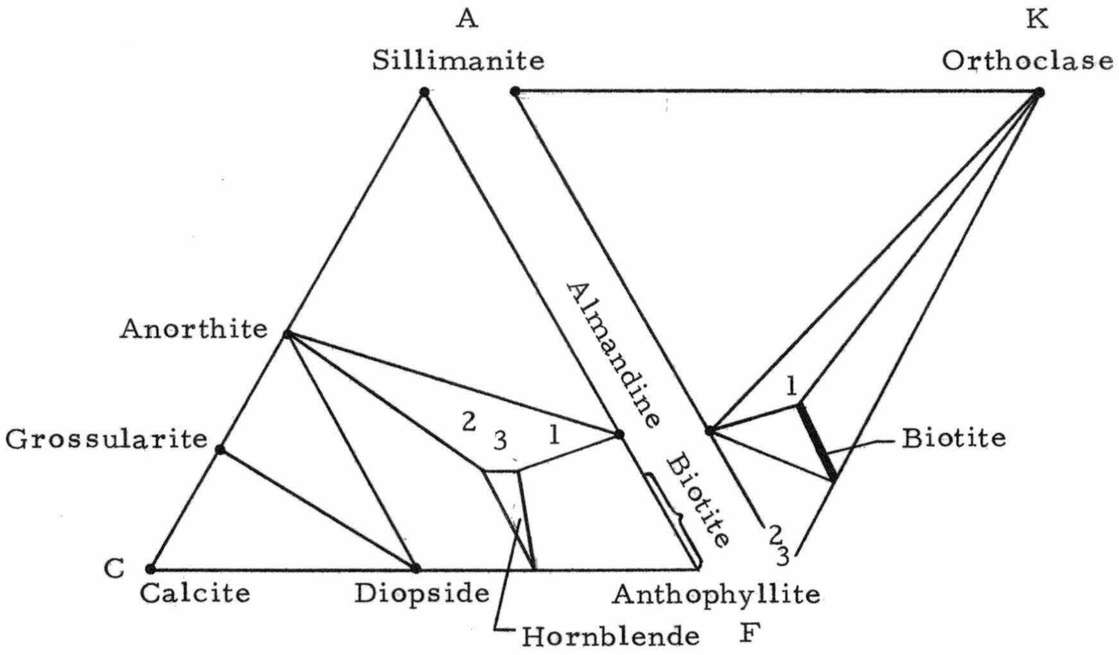


Figure 7. Sillimanite-almandine-orthoclase subfacies of the amphibolite facies; ACKF diagram for rocks with excess SiO_2, K_2O, and Al_2O_3. Quartz, potash feldspar, and plagioclase are possible additional phases. Numbers refer to mineral assemblages in the text. (After Turner and Verhoogen, 1960, p. 549-550).

(3) Amphibolite: hornblende-plagioclase (An_{36}-An_{51})-epidote-quartz (distinguished from hornblende gneiss by relative abundance of component minerals).

General Petrogenetic Evidence

On the basis of mineral assemblages and structural evidence, metamorphic rocks of the Front Range are considered to have a sedimentary parentage (Hedge, Peterman, and Braddock, 1967, p. 551). The original sequence of sediments appears to have been composed of sandstones, shales, and conglomerates that may have totaled more than 13,700 meters in thickness (Peterman, Hedge, and Braddock, 1968, p. 2277). Minor basalts or calcareous sediments may also have been present in the parent rocks.

In the Manhattan area there are no textures or structures which would indicate either a sedimentary or igneous origin for the metamorphic rocks. Probably the best indication of origin is the chemistry, although this can be very misleading, especially if material has been added or removed from the parent rocks.

Biotite Gneiss

An estimate of the chemical composition of some biotite gneiss samples was made from modal analyses (as described by Wahlstrom, 1947, p. 237-239). This approach consists of calculating weight percents from volume percents determined by modal analysis, and dividing each of the minerals into its component oxides to determine the total of each oxide in the sample. It should be emphasized that this method is not extremely accurate since specific gravities used in calculating the weight percents may vary for individual minerals. The chemical compositions of several of the minerals (such as hornblende and epidote) are also variable and general compositions must be used. However, even though this method is not extremely precise, it does provide a reasonably good estimate of the chemical composition.

In the following calculations of chemical composition from modal analyses all trace minerals have been ignored:

Sample	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
S-3	65.9	15.1	0.8	0.9	8.5	1.5	2.3	4.3
S-26	71.5	14.8	0.3	0.4	3.9	1.6	2.5	4.3

These compositions for biotite gneiss are shown plotted on Figure 8, a ternary diagram used by Mason (1966, p. 154) to indicate the chemical compositions of common sediments. In terms of the given oxides, biotite gneiss has a chemical composition similar to sandstones (probably argillaceous and very impure). For a rough comparison, a mixture of one-half sandstone and one-half shale (average compositions from Pettijohn, 1957, p. 106) would yield the following approximate composition:

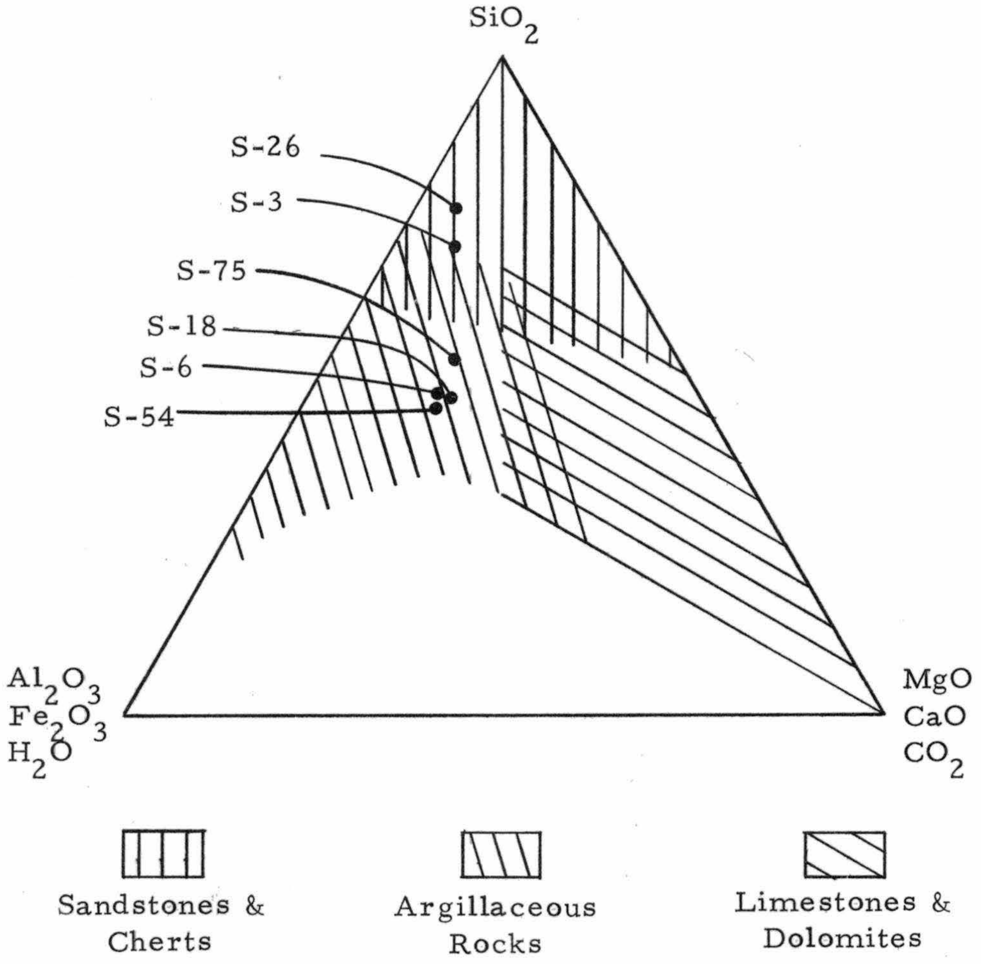


Figure 8. Comparison of the chemical compositions of common sediments (modified after Mason, 1966, p. 154) and the compositions of several Manhattan area metamorphic rocks. S-3 and S-26 are biotite gneisses, S-18 and S-75 are hornblende gneisses, and S-6 and S-54 are amphibolites.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
68.2	10.1	2.5	1.4	1.8	4.3	0.9	2.3

This composition is somewhat deficient in Al_2O_3, Na_2O, and K_2O, very deficient in MgO, and slightly high in iron oxides and CaO compared to biotite gneiss. Changing the ratio of shale to sandstone from 1:1 to 3:1 would yield the following approximate composition:

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
63.2	12.8	3.3	1.9	2.1	3.7	1.1	2.8

This is closer to biotite gneiss with respect to Al_2O_3, but is still deficient in MgO and Na_2O, and high in CaO and iron oxides. Addition of more shale would increase the MgO and Na_2O, and decrease the CaO contents very slightly, but would also increase the iron oxide contents which are already too high. Addition of limestone would increase the MgO content and decrease the amount of iron oxides, but would substantially increase the already too high CaO content.

A possible igneous parent rock would be calc-alkali granite with an average composition (Nockolds, 1954, p. 1012) of

SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
72.18	13.86	0.86	1.67	0.06	0.52	1.33	3.08	5.46

This composition is very deficient in MgO and slightly high in FeO and Na_2O compared to biotite gneiss. On the basis of chemical composition granite appears to be a slightly better candidate for a parent rock than mixtures of common sediments. However, it is possible that argillaceous sandstone could have been the parent rock with several elements added or removed during metamorphism, or that a very impure sandstone with a composition roughly approximating the biotite gneiss could have been the parent material. The absence of relict textures or structures and the probability of metasomatism make it nearly impossible to determine the parent rock with any degree of certainty.

Amphibolite and Hornblende Gneiss

The following chemical compositions for amphibolite and hornblende gneiss were calculated from modal analysis data:

Hornblende Gneiss

Sample	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	P_2O_5	TiO_2
S-18	41.5	14.3	12.7	12.2	4.6	11.9	0.5	0.3	1.5
S-75	42.9	12.8	10.5	13.8	5.2	9.1	1.5	1.3	2.7

Amphibolite

Sample	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	P_2O_5	TiO_2
S-6	41.2	15.8	12.5	13.5	5.1	9.9	1.4	0.2	-
S-54	39.8	11.6	14.9	19.7	7.4	6.2	0.4	-	-

The compositions for these two rock types are very similar and it is probable that they both were formed from the same or very similar parent rocks. The above compositions, plotted on Figure 8, indicate a chemistry similar to that of argillaceous rocks. A possible sedimentary parent rock for hornblende gneiss and amphibolite would be a calcareous shale. For a rough estimate of chemical composition for calcareous shale, 25 percent of an average limestone and 75 percent of an average shale (average compositions from Pettijohn, 1957, p. 106) were combined to give the following chemical composition:

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2
44.8	11.7	3.2	1.8	3.8	13.2	1.0	2.5	0.5

There is a large deficiency of iron oxides, a slight deficiency of MgO, and a small excess of CaO and K_2O compared to amphibolite and hornblende gneiss.

A possible igneous parent rock would be basalt. Nockolds (1954, p. 1021) gives the composition for an average tholeiitic olivine basalt as

SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TiO_2
47.90	11.84	2.32	9.80	0.15	14.07	9.29	1.66	0.54	0.19	1.65

This is deficient in iron oxides and slightly high in MgO and K_2O compared to amphibolite and hornblende gneiss, but seems to fit slightly better (particularly in terms of total iron oxides) than calcareous shale. Peterman, Hedge, and Braddock (1968, p. 2277) state that the mode of occurrence and chemical composition of amphibolites of the northeastern Front Range suggest that they are primarily metabasalts. Kirst (1966, p. 31) describes an occurrence of hornblende gneiss in the southern portion of the Rustic quadrangle which, from structural evidence, is apparently a metamorphosed basic dike, indicating the possible presence of basalt in the general area. Lack of good evidence, however, precludes identification of the Manhattan amphibolitic rocks as para- or orthoamphibolites.

PETROGENESIS OF IGNEOUS ROCKS

Log Cabin Granite

Marvine (1873) originally described the Front Range granites as having formed in place through the melting of pre-existing rocks by intense metamorphism. However, nearly all investigators since Marvine have ascribed a forceful intrusion to the origin of the several Front Range granites, including the Log Cabin batholith.

Figure 9 shows the modal compositions of several Manhattan area granite samples in terms of quartz, plagioclase, and potash feldspar. According to Turner and Verhoogen (1960, p. 350) most granitic rocks fall within the outlined area (a "low temperature trough" described by Tuttle and Bowen, 1958), indicating equilibrium between a liquid silicate melt and crystalline phases. The wide scattering of points agrees with a similar plot made by Wolfe (1967, p. 33) and suggests that the magma may not have originated by fractional crystallization and may not have been completely molten. However, wide variation in composition might also be caused by local assimilation.

The Log Cabin granite of the Manhattan area displays a relationship with older rocks which indicates a forceful, although not very disruptive, intrusion. Sharp contacts between granite and metamorphic rocks are common, and veins of granite discordantly cutting the

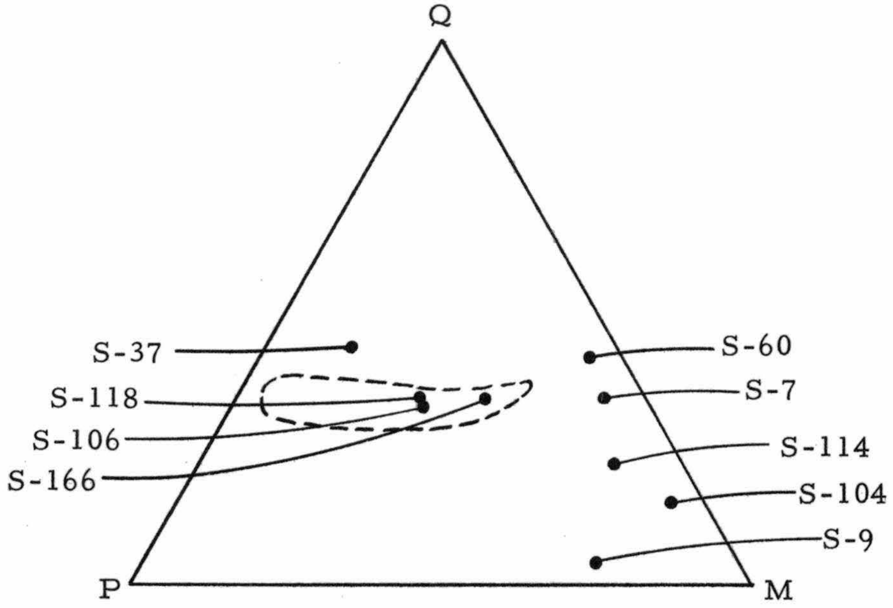


Figure 9. Modal composition diagram for several Manhattan area granite samples. Dashed line shows the area in which most granitic rocks fall (Turner and Verhoogen, 1960, p. 350). Q = quartz, P = plagioclase, and M = microcline.

older rocks are also numerous. Most of the foliations in the xenoliths retain a sub-parallel orientation which suggests that intrusion of the granite did not disrupt the previous structural pattern of the area to any great extent (the sub-parallel orientation of foliations presumably represents pre-granite structure; it seems unlikely that this orientation could be strictly a function of flow alignment since even highly irregular xenoliths, not readily susceptible to orientation by flow, have foliations aligned nearly parallel to the general trend).

Tertiary Intrusives

The study of glass beads made from powdered samples of intrusive rocks shows a moderate range of silica content in the rhyolites, rhyodacites, and hornblende rhyodacites of the Manhattan area. This is also reflected in the color of the matrices. In general, the higher the silica content of the intrusive the lighter the matrix, and the lower the silica content the darker the matrix. Intrusives with the highest measured silica contents (e.g., S-116, S-47) have very light, ivory colored matrices. Intrusives with the lower silica contents usually have a dark gray matrix (e.g., S-36, S-93, and all hornblende rhyodacite). Hornblende rhyodacite is chemically and mineralogically different from the other intrusives (Table 6). These variations suggest that the rhyolites, rhyodacites, and hornblende rhyodacites may have been intruded over a period of time from a differentiating magma, from slightly different magmas, or possibly from different fractions of the same magma that have been chemically modified by assimilation. No crosscutting relationships were observed in the Manhattan area that might indicate relative ages of the different types of intrusives. However, Corbett (1964, p. 89) states that the Tertiary rocks in the nearby Cameron Pass area (to which the Manhattan intrusives are presumably related) show a regular variation from early mafics to later felsic types and probably originated from a single differentiating magma.

MINERALIZATION

Soon after gold was discovered on Manhattan Creek in 1886 nearly 10,000 people converged on the area and formed the tent city of Manhattan (anonymous, 1968). Extensive prospecting was done as indicated by the abundance of diggings in the area. Most of the prospects are concentrated north of Sevenmile Creek valley and consist primarily of shallow pits a few feet deep. There are several fairly deep shafts in the northern third of the study area, but extent of underground workings is unknown.

The prospects are located in granite, in metamorphic xenoliths, along contacts between Tertiary intrusives and granite, and in highly epidotized and oxidized shear zones. Most of the prospects in the granite apparently were established in zones which showed evidence of shearing and oxidation. Sheared granite in these prospects is commonly very porous and may contain small hematite coated quartz crystals growing into solution cavities. Films and layers of hematite (and minor limonite) up to 1 cm. thick are present along most shear planes. Some of the sheared granites also contain locally abundant pyrite. Pyrite may occur in layers up to about 5 mm. thick along fracture planes or it may be found as small crystals disseminated throughout the host rock.

Prospects in highly epidotized shear zones rarely show evidence of any significant mineralization. Prospects along the borders of metamorphic xenoliths and at Tertiary intrusive-granite contacts were probably dug in search of mineralization by contact metasomatism. Pyrite and chalcopyrite are present along some of the fractures in metamorphic rocks, but no mineralization is apparent along any of the Tertiary intrusive-granite contacts.

Minor amounts of copper mineralization were observed in the Manhattan area during the course of this study. In addition to small amounts of chalcopyrite associated with the pyrite, thin layers of malachite are present along the fractures in a slightly sheared granite in the northeast quarter of section 29. Wolfe (1966, p. 23) reported a radioactive pegmatite in the northwest quarter of section 13 and there have been other reports of radioactive zones in the Manhattan area (e.g., Miller and Laval, 1960, p. 21). Samples from many of the prospect pits in the Manhattan district were tested with a scintillometer, but no radioactivity was detected.

According to Lovering and Goddard (1950, p. 286) the ore in the Manhattan district occurred primarily in veins (up to 2 feet wide) of coarse-grained quartz which contained disseminated pyrite and minor chalcopyrite. The ore was commonly much richer near the surface than at depth. Assays from ore of the Cache vein (just outside the study area near the center of section 31) indicated up to 15 ounces of gold per ton at the surface of the outcropping vein, about 4 ounces per ton at a depth of approximately 30 feet, and about 0.30 ounce per ton at approximately 70 feet below the surface (Lovering and Goddard, 1950, p. 286). Lovering and Goddard (1950, p. 286) concluded that the gold ore of the Manhattan district was concentrated by secondary enrichment of low grade pyritic ores and that this enrichment was closely related to the development of the Tertiary erosion surface in this region (evident in the northern third of the map area). According to Park and MacDiarmid (1964, p. 421) gold may be dissolved and reprecipitated ahead of mechanical erosion causing an enrichment of gold near the surface. Au may be oxidized to Au^{+3} in the presence of acidic solutions and a strong oxidizing agent, combine with chlorine ions to form the $AuCl_4^-$ complex, and be transported short distances. However, most of the gold near the surface was probably residual and resulted from oxidation and leaching of sulfides.

Lovering and Goddard (1950, p. 43) correlated the Tertiary intrusives of the Manhattan district with those of the Colorado mineral belt which extends southwest from Boulder to Breckenridge. Mineralization in the Colorado mineral belt is closely associated with the Tertiary intrusives of the area (Lovering and Goddard, 1950, p. 90). Because of similarities in types of intrusives and in types of mineralization (e.g., pyrite, chalcopyrite, gold, minor copper and silver) it is postulated that the gold, copper, and silver ores of the Manhattan district were also derived from mineralizing solutions which invaded the rocks shortly after emplacement of the Tertiary intrusives. However, age determinations made on minerals from the Copper King uranium mine about 10 miles northeast of Manhattan indicate a period of sulfide mineralization (pyrite, chalcopyrite, pyrrhotite, sphalerite, galena) in late Precambrian (Sims, Phair, and Moench, 1958, p. 192).

Minor occurrences of uranium mineralization reported in the general Manhattan area may have been formed slightly before emplacement of the Tertiary rocks. A lead-uranium age determination on pitchblende from the Copper King uranium mine gives an age of 55 to 76 m.y., or early Tertiary (Sims, Phair, and Moench, 1958, p. 213).

The only known production figures for the Manhattan district, reported by Miller and Laval (1960, p. 20; original source unknown), indicate that between 1932 and 1941 16 tons of ore were shipped yielding 27 ounces of gold and 9 ounces of silver.

GEOCHEMICAL SOILS ANALYSIS OVER A PROSPECTED SHEAR ZONE

General Statement

A geochemical soils analysis was made in a relatively flat area over a prospected shear zone in the west-central portion of section 20. The purpose of the study was to see if the shear zone could be delineated through the well developed soil cover which is common in the northern third of the Manhattan district.

The northeast boundary of the shear zone trends approximately N65W and can be mapped fairly accurately because there are several outcrops of unsheared granite a few feet northeast of this boundary. Several prospect pits located in sheared rock near the boundary are also helpful in mapping this part of the shear zone. The rock in these prospects has been highly sheared and epidotized and contains minor hematite coating along fractured surfaces. In the southeast corner of the sample area the shear zone becomes very rich in quartz and there is little epidote or hematite. Southwest and west of the prospects there are no good bedrock exposures and the only method of locating the shear zone is by observing abundance of epidote in the soil. Small pieces of epidote are very abundant in the soil throughout most of the sample area and on this basis it appears that most of the underlying bedrock has been highly epidotized (except in the northeast portion of the area, the southeast corner, and the extreme southwest corner). However, it does appear that the most highly sheared and epidotized portion of the shear zone is along the northeast boundary (Plate 1).

Methods of Analysis

A north-south grid was established over the shear zone and soil samples were taken from a depth of 6 to 10 inches at 60 foot intervals. A total of 66 samples was taken and only material passing through a #35 mesh sieve was used for the analysis.

Perchloric and nitric acids were used to digest five grams of each sample. The solutions were then analyzed by atomic absorption spectrometer for Fe, Ca, Mg, Mn, Zn, and Cu. Results for Cu were rejected as being unreliable because of a malfunctioning spectrometer tube.

A trend surface analysis computer program was used to compute and plot isopleth maps for each element. The computer program utilizes a least squares approach and tends to smooth some of the more highly erratic contour lines which sometimes occur in manual contouring. This smoothing technique may also bring out trends which are not readily apparent in manual contouring.

Results and Conclusions

Computer plotted isopleth maps showing concentrations (in parts per million) of Fe, Ca, Mg, Mn, and Zn are shown in Figures

10 through 14. From these maps it is apparent that neither Ca nor Fe from the heavily epidotized rocks in and around the prospects is causing an anomaly in the soil. The area of low concentration near the southeast corner of all the maps is probably due to the abundance of quartz in this portion of the sample area.

There is an area of very high concentration for all elements except Ca in the extreme southwest corner. Just outside the sample area, near the southwest corner, is a prospect pit (shown by an "x") which penetrates a shear zone trending about N50W. This shear zone contains very little epidote, but has abundant pyrite, some hematite, and minor chalcopyrite. The trend of the contour lines in this area very closely parallels the N50W direction of shearing and it is very likely that enrichment of elements in the soil is coming from this shear zone. The most prominent trend within the sample area extends about N50-60E from a high near the western boundary. This could be another shear zone with the same type of mineralization that occurs in the one near the southwest corner. It is also possible that this trend could reflect mineralization along joint planes, since the N50-60E direction closely parallels the most prominent joint set in the Manhattan area.

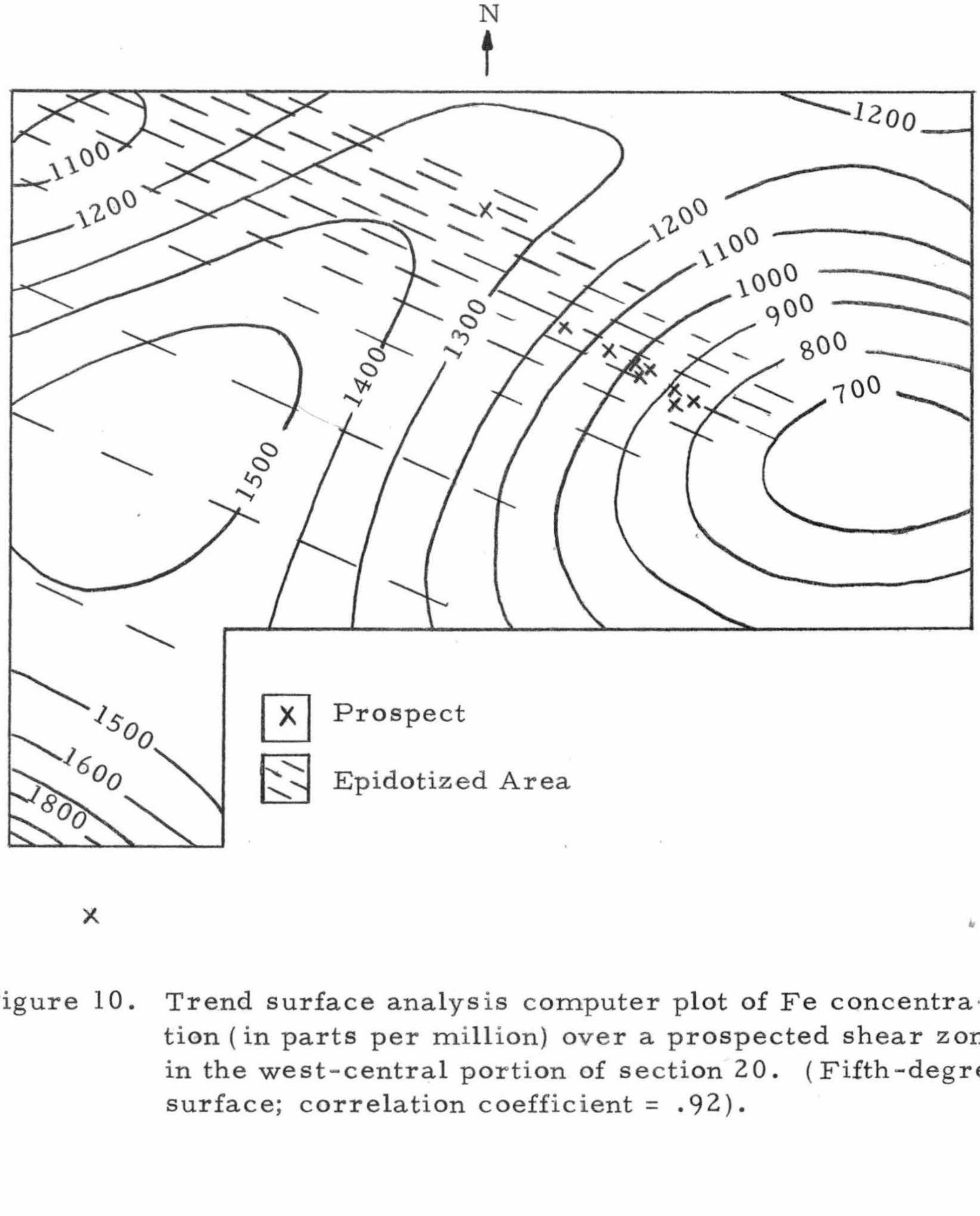


Figure 10. Trend surface analysis computer plot of Fe concentration (in parts per million) over a prospected shear zone in the west-central portion of section 20. (Fifth-degree surface; correlation coefficient = .92).

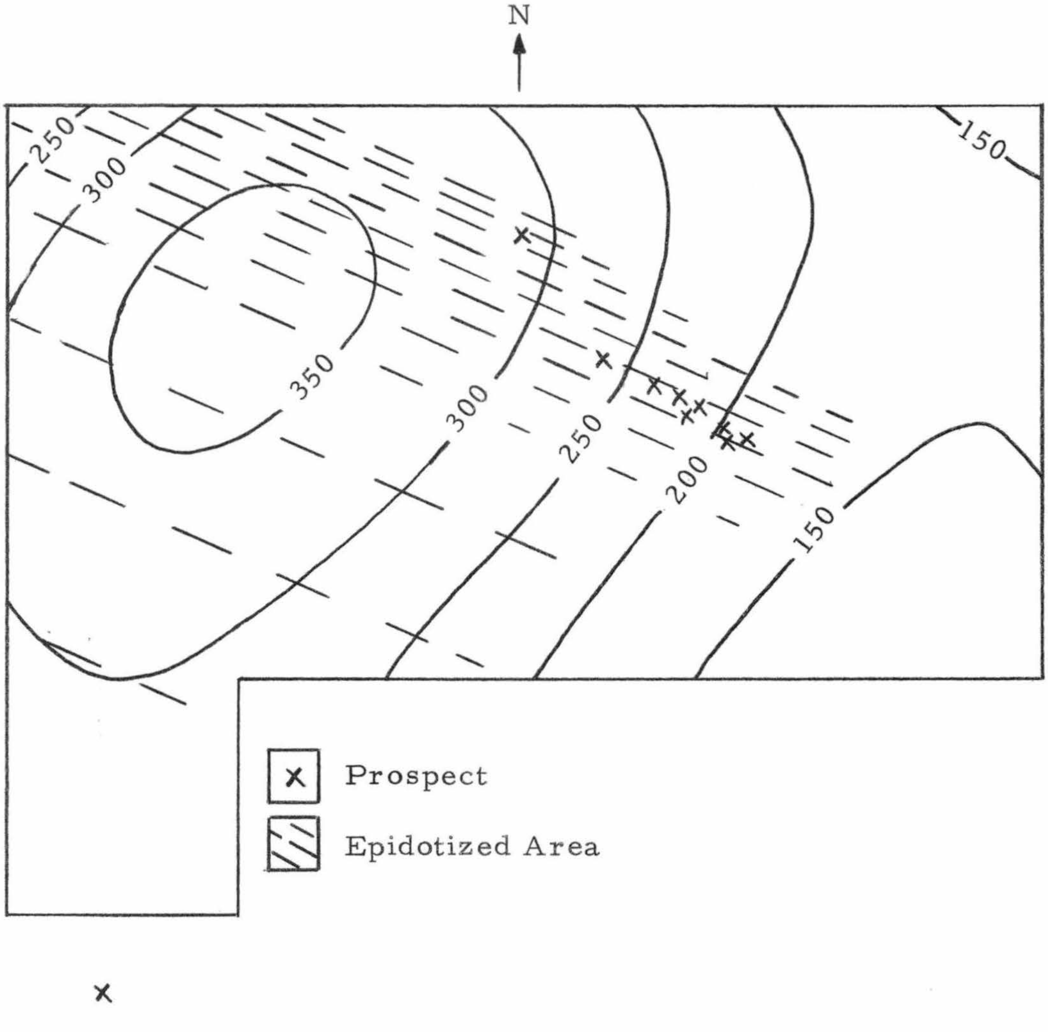


Figure 11. Trend surface analysis computer plot of Ca concentration (in parts per million) over a prospected shear zone in the west-central portion of section 20. (Third-degree surface; correlation coefficient = .67).

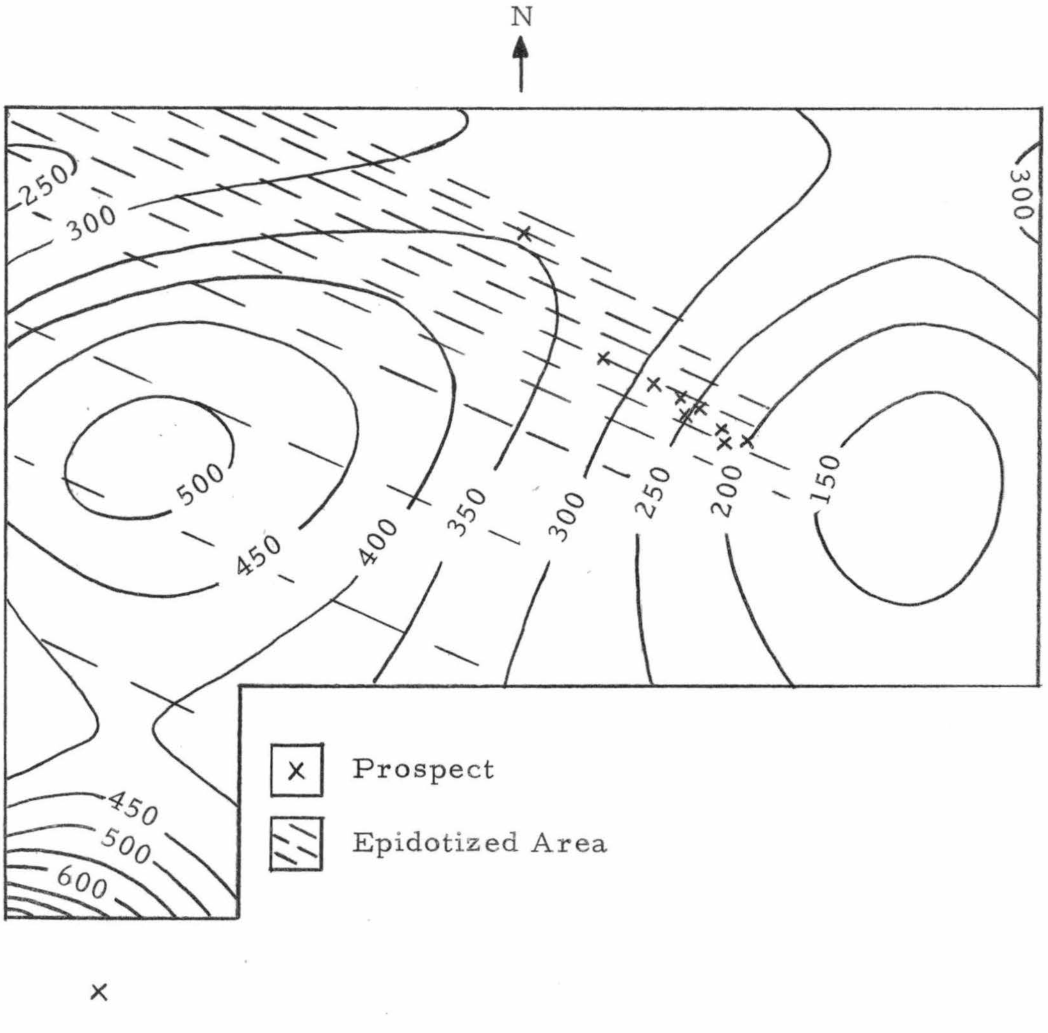


Figure 12. Trend surface analysis computer plot of Mg concentration (in parts per million) over a prospected shear zone in the west-central portion of section 20. (Fifth-degree surface; correlation coefficient = .91).

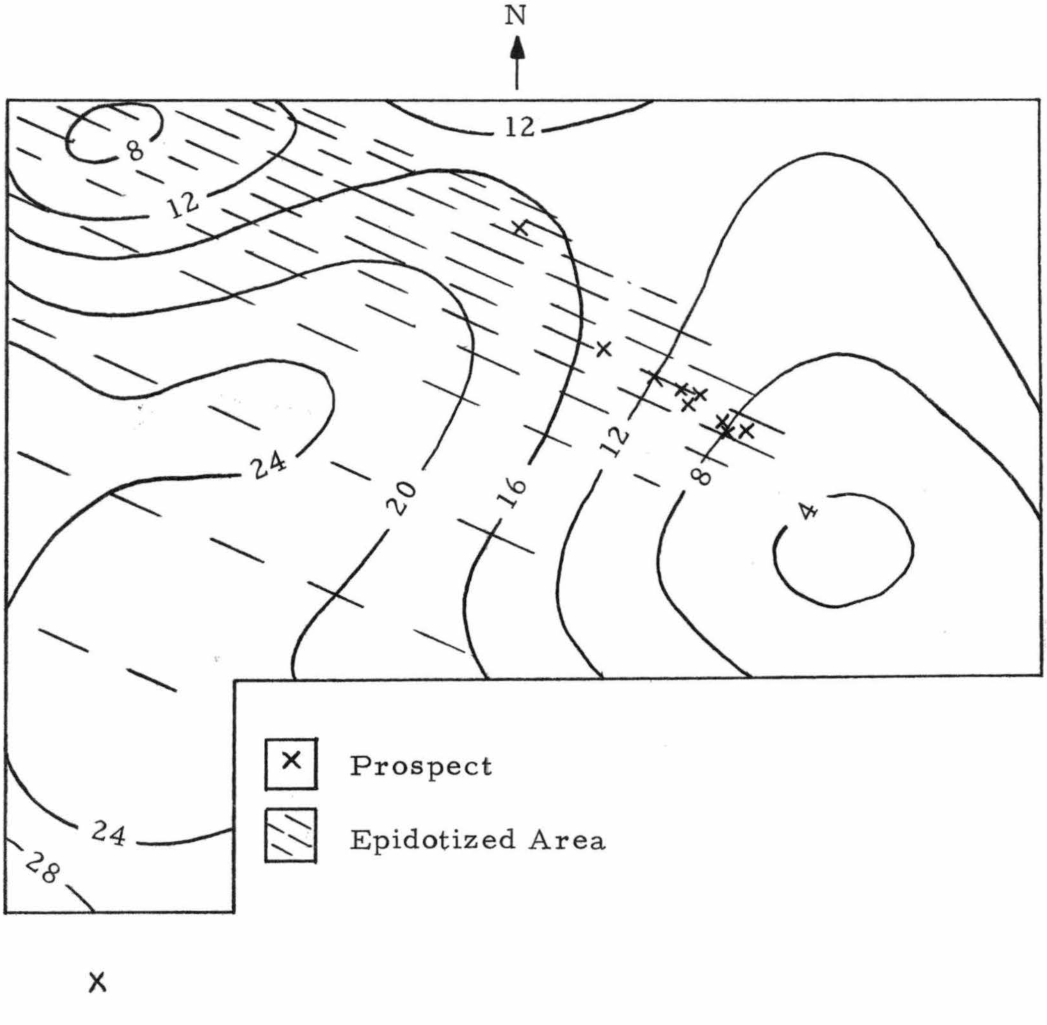


Figure 13. Trend surface analysis computer plot of Mn concentration (in parts per million) over a prospected shear zone in the west-central portion of section 20. (Fifth-degree surface; correlation coefficient = .89).

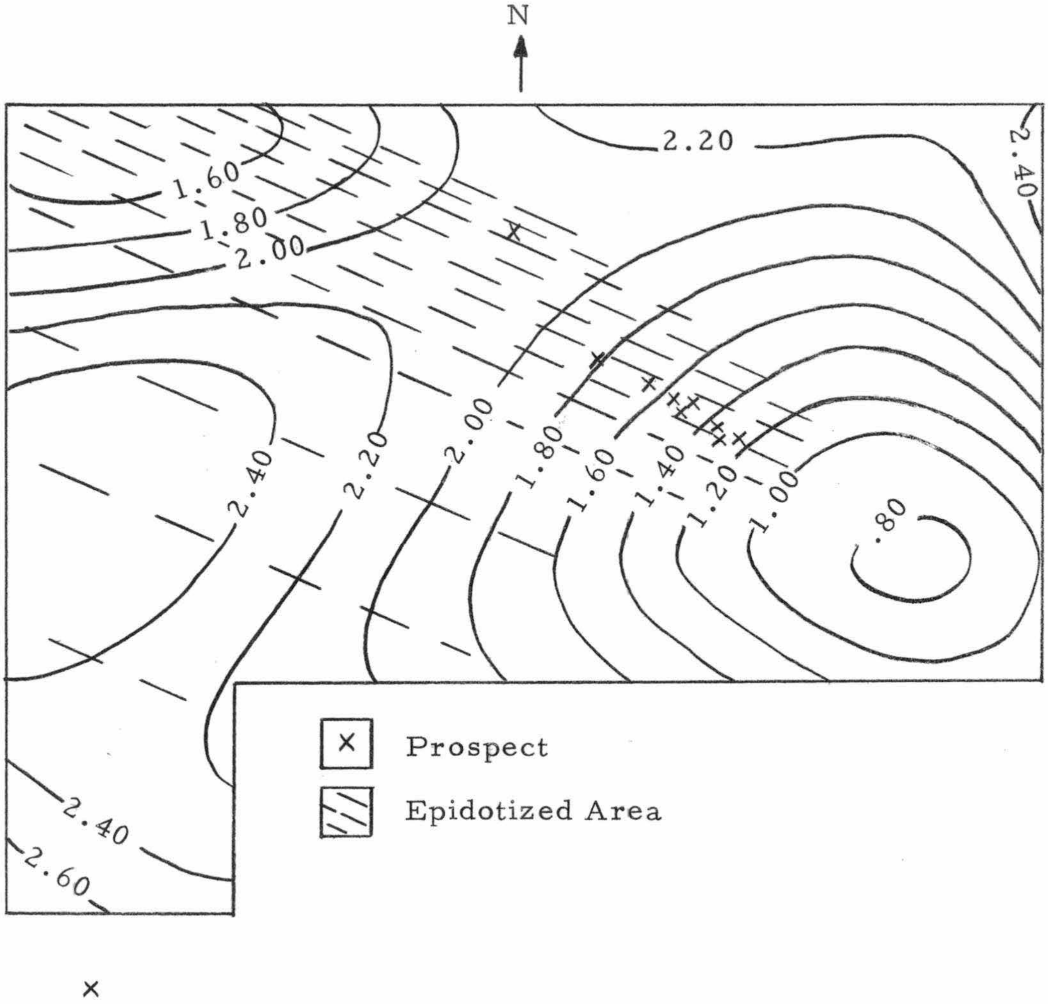


Figure 14. Trend surface analysis computer plot of Zn concentration (in parts per million) over a prospected shear zone in the west-central portion of section 20. (Fifth-degree surface; correlation coefficient = .93).

SUMMARY AND CONCLUSIONS

The geologic history of the Manhattan area is relatively complex. The following is a summary of the postulated sequence of events leading to the present geologic framework:

1. A thick layer of sediments, including impure sandstones, shales, and impure limestones, was deposited more than 1800 m.y. ago. A few basaltic dikes and/or sills may have intruded the sedimentary sequence.

2. At or slightly before 1800 m.y. ago the sediments were metamorphosed to a low rank (possibly greenschist facies) and were deformed into large isoclinal folds trending approximately east-west.

3. Between 1700 and 1800 m.y. ago the sequence was refolded and remetamorphosed to the rank of amphibolite facies.

4. The Log Cabin batholith was emplaced 1390 to 1450 m.y. ago. Intrusion of the Log Cabin granite in the Manhattan area involved little deformation of pre-existing structure as evidenced by subparallel orientation of foliations in the metamorphic rocks.

5. A period of cataclasis, possibly about 1300 m.y. ago, produced several shear zones in the area.

6. Uplift of the Ancestral Rockies and the Laramide orogeny probably produced additional joints and reactivated some shear zones, producing fault breccias.

7. Early Tertiary (55-76 m.y. ago) ore fluids produced very minor uranium mineralization in a few shear zones and along minor faults.

8. In mid-Tertiary (Oligocene-Miocene boundary) rhyolite, rhyodacite, and hornblende rhyodacite intrusives were emplaced (primarily along joint planes in Log Cabin granite). Ore fluids, probably associated with the Tertiary magma, but intruding the rocks after emplacement of the Tertiary intrusives, produced minor deposits of gold, copper, and silver.

9. Formation of a relatively flat erosion surface during Late Tertiary time produced a secondary enrichment of primary gold ore near the surface.

10. Later erosion, possibly near the end of the Tertiary, caused dissection of the southern portion of the Manhattan district.

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