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Paleoproterozoic Intrusive Igneous Rocks of Southeastern Stearns County, Central Minnesota

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Cover photograph: *Quarry-wall exposure of diabase dike that intrudes the Rockville Granite. Vertical lines in center of dike are drill marks related to quarrying. Hammer handle is 50 cm long.*

UNIVERSITY OF MINNESOTA

Minnesota Geological Survey
Saint Paul, Minnesota

Paleoproterozoic Intrusive Igneous Rocks of Southeastern Stearns County, Central Minnesota

by T.J. Boerboom and D.K. Holm

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Minnesota Geological Survey
2642 University Avenue West
Saint Paul, Minnesota 55114-1057

Telephone: 612-627-4780
Fax: 612-627-4778
E-mail address: mgs@tc.umn.edu
Web site: http://www.geo.umn.edu/mgs

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PALEOPROTEROZOIC INTRUSIVE IGNEOUS ROCKS OF SOUTHEASTERN STEARNS COUNTY, CENTRAL MINNESOTA

T.J. Boerboom[1] and D.K. Holm[2]

ABSTRACT

Granitoid rocks in the St. Cloud area, southeastern Stearns County are late- to post-orogenic intrusions within the internal zone of the western Paleoproterozoic Penokean Orogen. In the St. Cloud area these intrusions include the Reformatory granodiorite, the charnockitic Richmond granite, the Rockville Granite, and the St. Cloud Granite, as well as porphyritic microgranite and diabase dikes. These rocks are locally well exposed in the St. Cloud area, and in places quarrying operations provide excellent, fresh, three-dimensional views of the intrusive rocks. Remapping of the available bedrock exposures has led to some reinterpretation of the timing and style of emplacement of the intrusions. Newly acquired and compiled geochemical data, and the acquisition of new Ar/Ar ages for diabasic dikes, all indicate that regional tectonic interpretations need to be reassessed. High-resolution aeromagnetic data have also improved our ability to interpret the Proterozoic and Archean bedrock geology in areas of little or no outcrop, and have allowed the size and shape of the various plutons to be delineated.

Field mapping shows that the St. Cloud Granite intruded the Reformatory granodiorite as a series of variably thick dikes and sills, possibly focused along the preexisting contact between the Reformatory granodiorite and Rockville Granite to the west. The Richmond granite clearly displays a magmatic fabric texturally similar to that of the Rockville Granite. Despite the absence of outcrop evidence for intrusive relations of the Richmond granite, its textural similarity to the Rockville granite is used to interpret it as a late-orogenic Paleoproterozoic intrusion. At least two generations of diabase dikes, as well as a series of porphyritic granite dikes, together form the youngest intrusions. The latter granitic dikes show complex intrusive relations with the early set of diabase dikes, and the two are probably the product of bimodal magma generation.

Mafic enclaves within the Reformatory granodiorite, the Richmond granite, and the Rockville Granite were formerly considered to be xenoliths of country rock, but are reinterpreted here to mostly represent mafic magma cogenetic with the host granites. True crustal xenoliths of high metamorphic grade are present locally in the St. Cloud Granite, the Reformatory granodiorite, and the Richmond granite; these are texturally and mineralogically distinct from the mafic enclaves. The mafic enclaves probably formed when felsic melts generated at the base of the crust mingled with, and were contaminated by, mantle-derived mafic magma introduced during a crustal underplating event. The underplating process is probably associated with mantle lithospheric delamination that took place during late-Penokean crustal collapse.

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[1] Minnesota Geological Survey, 2642 University Ave., W, St. Paul, MN 55114; boerb001@tc.umn.edu

[2] Dept. of Geology, Kent State University, Kent, OH 44242; dholm@kent.edu

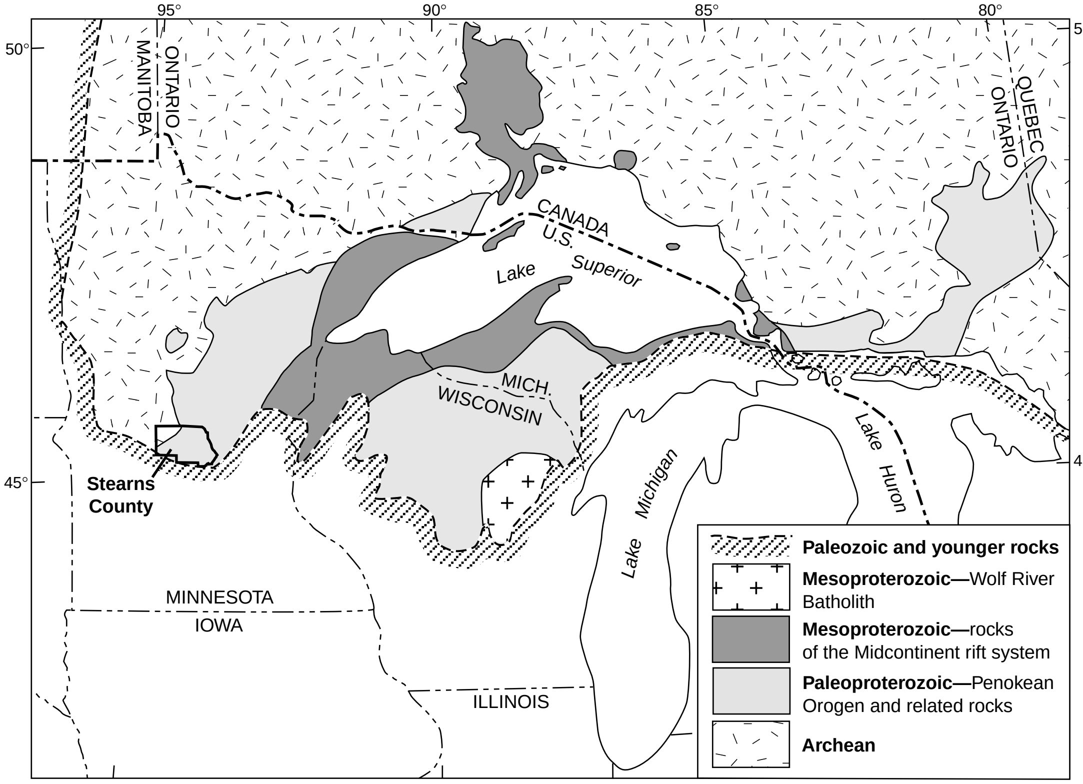

Figure 1. The extent of the Penokean Orogen in the Upper Midwest, and the location of Stearns County.

INTRODUCTION

The Precambrian bedrock of Stearns County is mostly covered by Cretaceous strata and Quaternary glacial and interglacial sediments. However, in the vicinity of St. Cloud numerous natural outcrops and quarry exposures are present, which combined with geophysical data show that Stearns County is underlain by a nearly continuous mass of mafic to felsic, late- to post-orogenic Paleoproterozoic intrusive rocks. These were emplaced into the internal zone of the Penokean Orogen (Southwick and others, 1988), which includes both Archean high-grade and Paleoproterozoic medium-grade amphibolite facies metamorphic rocks (Figs. 1 and 2). Both the Archean and Paleoproterozoic country rocks were metamorphosed and deformed during Paleoproterozoic Penokean Orogenesis (Southwick and others, 1988). Intrusions exposed in the area between St. Cloud and Richmond (Fig. 2) are the focus of this report, and include the Reformatory granodiorite, the Rockville Granite, the charnockitic Richmond granite and possibly related gabbroic and anorthositic rocks, the St. Cloud Granite, an unnamed porphyritic granite, dikes of porphyritic microgranite, and diabase dikes (Fig. 2 and Plate 1). Mafic enclaves are abundant within the Reformatory granodiorite, Rockville Granite and Richmond granite, and are interpreted to be derived from mafic melts comagmatic with the granitic rocks. Scattered xenoliths of granulite- and amphibolite-facies metamorphic country rock are recognized in the Reformatory granodiorite and St. Cloud Granite. Formal nomenclature for the St. Cloud and Rockville Granites follows Morey (1978); Reformatory granodiorite is a newly introduced informal name for Morey's Reformatory Granite; Richmond granite is a newly introduced informal name for the Richmond Gneiss of Morey (1978).

The Paleoproterozoic granitoid rocks of the St. Cloud area of Stearns County have long been quarried for both dimension stone and crushed aggregate (e.g. Thiel and Dutton, 1935). Active and inactive quarries, as well as natural outcrops are relatively abundant in parts of southeastern Stearns County (Fig. 3). These bedrock exposures were mapped in detail for the Stearns County Geologic Atlas (Boerboom and others, 1995). Elsewhere in the county, bedrock exposures are poor to nonexistent. Intrusive rocks are inferred from geophysical and drill hole data to underlie much of east-central Minnesota, including Stearns County (Fig. 2). Prior to publication of the Stearns County Geologic Atlas (Boerboom and others, 1995), the most recent mapping was completed at a reconnaissance level in the 1970's (Morey and others, 1981).

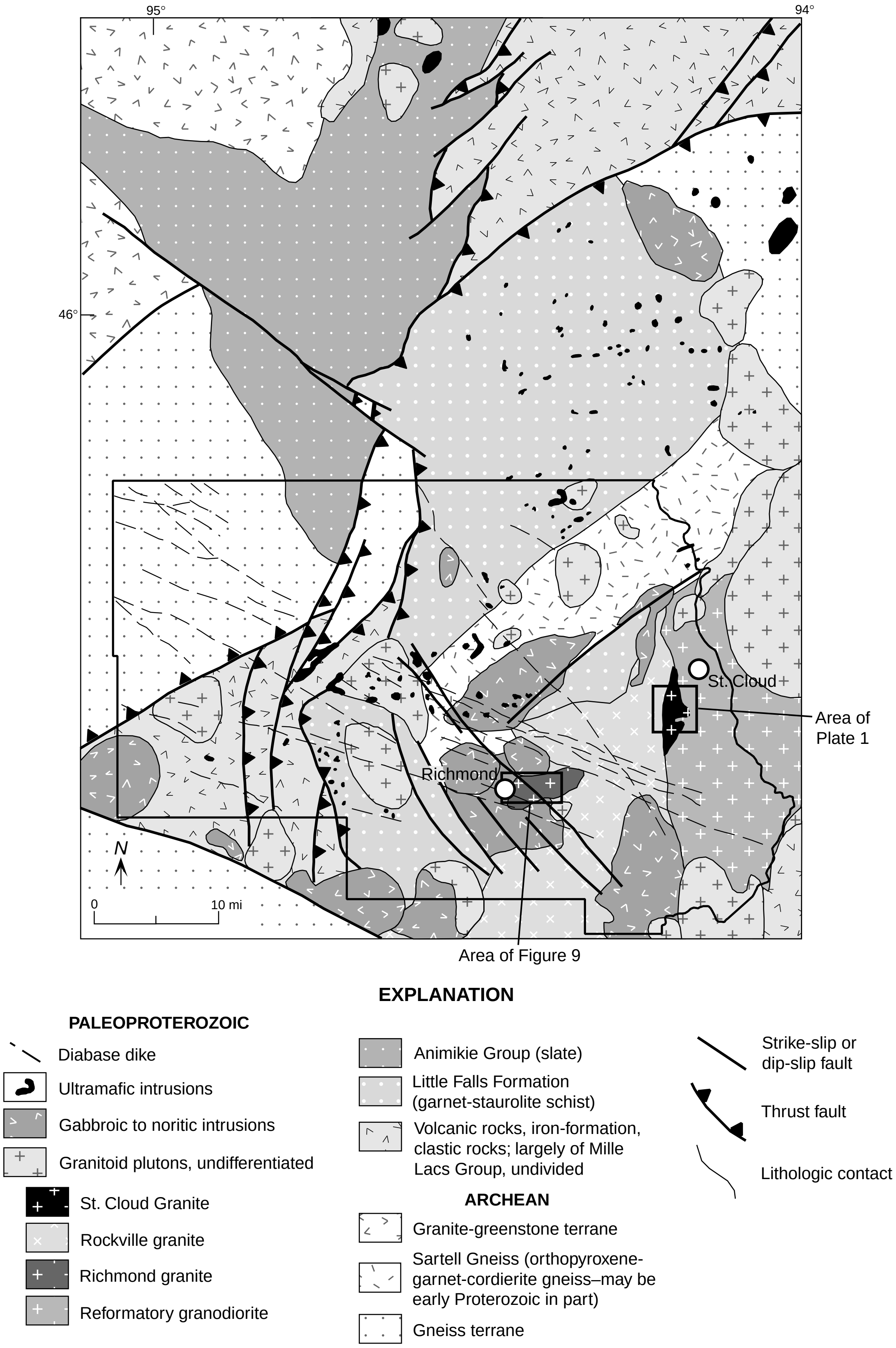

Figure 2. Generalized geologic map showing Archean and Paleoproterozoic rocks in Stearns County and vicinity, modified from Boerboom and others (1995), and Boerboom (1996) and references therein. Northeast-trending porphyritic microgranite dikes and diabase dikes not shown at this scale. Stearns County is outlined.

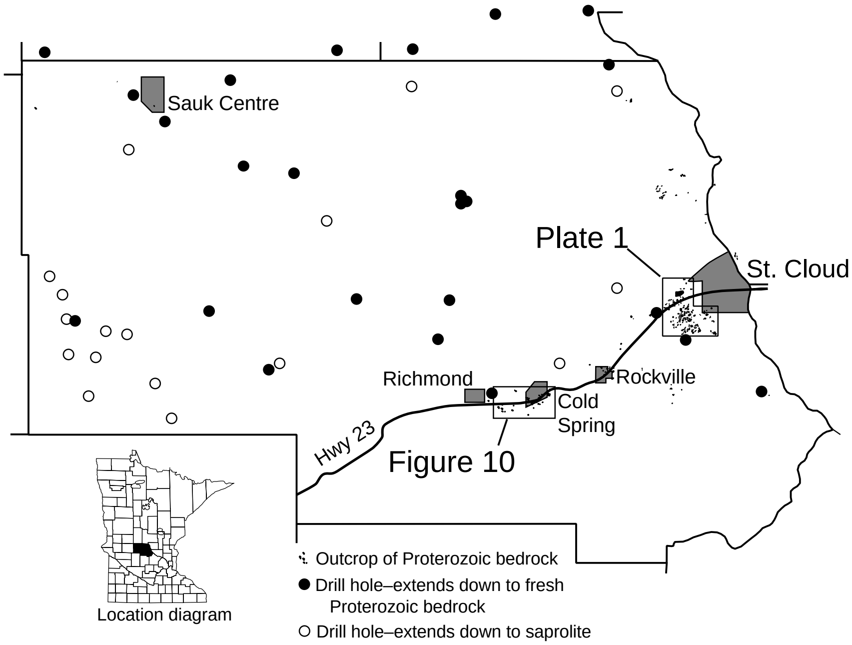

Figure 3. Stearns County area, showing location of selected drill holes and outcrops of Proterozoic bedrock.

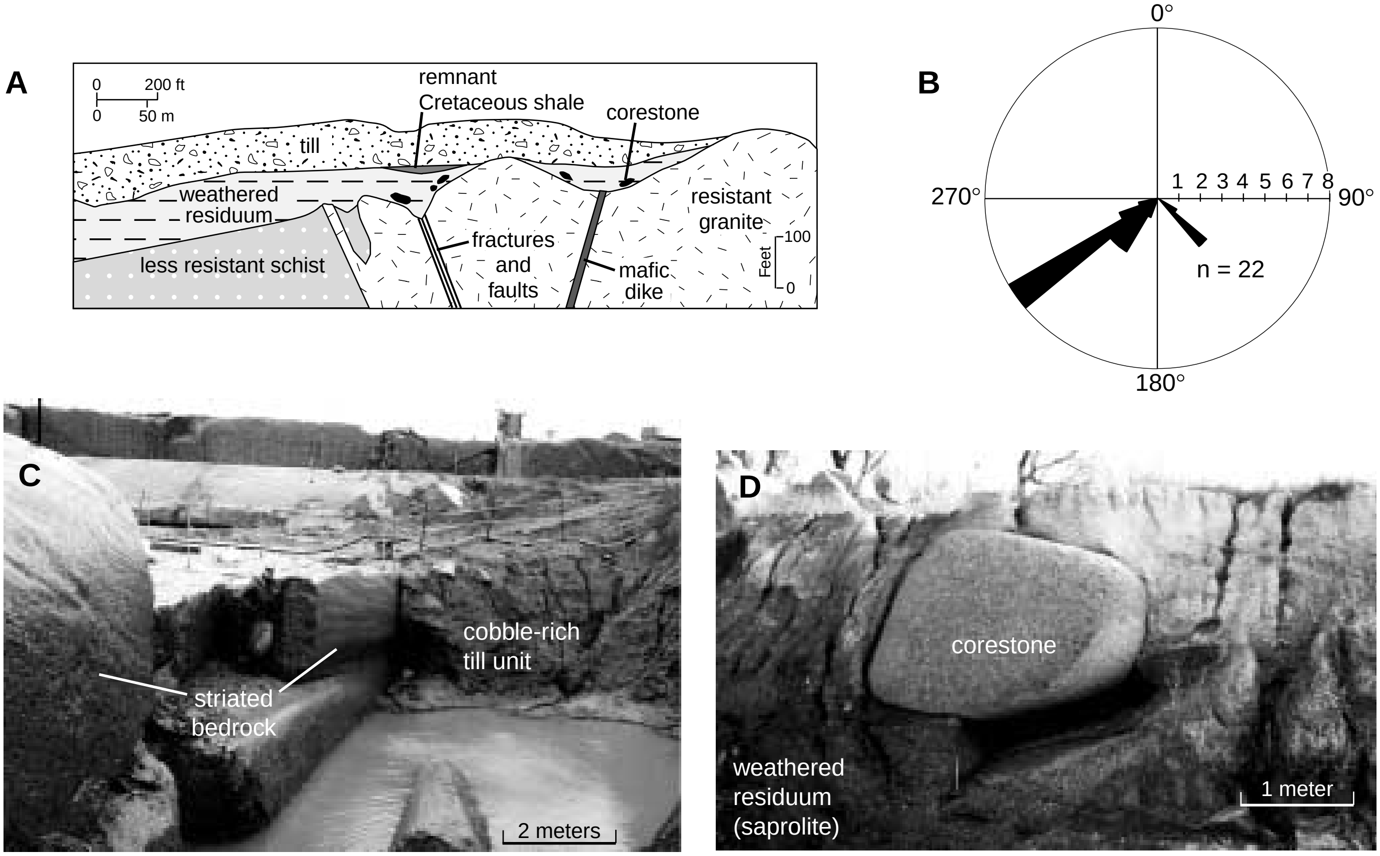

Figure 4. Characteristics of glacially sculpted bedrock exposures and 'subcrop'. **A.** Schematic cross section illustrating the typical range of features that affect the exposure of bedrock units in eastern Stearns County. **B.** Rose diagram showing strike of glacial striations measured at outcrops in Stearns County. Measurements are grouped in 10° increments, and indicate direction of ice movement (mostly northeast to southwest). **C.** Glacially scoured and striated Rockville Granite adjacent to a cobble-rich till unit in Rockville Granite quarry, located 1/4 mile south of Rockville; person standing for scale. **D.** Rockville Granite quarry, Rockville; corestone of Rockville Granite preserved within weathered residuum; hammer below corestone for scale.

In this report we summarize details of the intrusive relations between the igneous rock units, as well as the textural and chemical characteristics of the granitic and diabasic rocks and the mafic enclaves within them. The geologic map (Plate 1) provides both geological and geographical detail (the outcrops are plotted on a standard U.S. Geological Survey 7.5' quadrangle base) that will allow the reader to easily locate an outcrop of interest. The relative abundance of plutonic igneous rocks, as well as the medium to high metamorphic grade of the country rocks, indicates that Paleoproterozoic rocks of east-central Minnesota represent one of the deepest exposed levels of the Penokean Orogen.

The staurolite-bearing Paleoproterozoic metasedimentary country rocks were metamorphosed to amphibolite or higher metamorphic facies at depths of 20–22 km during the Penokean Orogeny (Holm and Selverstone, 1990). Reconstruction of P-T-t histories indicate that the country rocks remained at or near similar depths until well after the Penokean Orogeny, and that they underwent rapid exhumation at ~1770–1760 Ma, during a period of granitoid emplacement (Holm and others, 1998) associated with orogenic collapse, crustal thinning and extension. Exposures in Stearns County provide excellent opportunities to investigate the magmatic and metamorphic processes operating in the low- and mid-crust during and immediately after the collapse of a compressional orogenic belt, such as the Penokean Orogen.

OUTCROP DISTRIBUTION

Most of the outcrops in the St. Cloud area (Plate 1) are elongate in a northeast-southwest direction. This elongation results from glacial accentuation of bedrock features such as the orientation and abundance of fractures, and variations in rock type. Glacial striations are best documented near quarry margins, where glacial material has been removed to expose fresh bedrock. The striations are mostly parallel to the direction of outcrop elongation. Linear zones of little or no outcrop probably correspond to areas of concentrated fractures, diabase dikes, minor faults, or any combination of these features (Fig. 4).

Saprolite (clay-rich weathered bedrock residuum) is locally exposed in quarry walls and in some natural outcrops (Fig. 4). Where exposed, the saprolite mantles bedrock and typically contains abundant corestones (remnant, rounded boulder-sized zones of fresh rock) that undoubtedly contributed greatly to the population of glacial boulders in the overlying Pleistocene deposits (Patterson and Boerboom, 1999).

GEOCHRONOLOGY OF IGNEOUS ROCKS

All the intrusive rocks described in this report are inferred to be Paleoproterozoic. Reported U-Pb ages of 1,770 Ma for the St. Cloud Granite, and 1,812 ± 9 Ma for both the Reformatory granodiorite and Rockville Granite (Goldich, written commun. in Horan and others, 1987) are consistent with field observations, as is a K-Ar whole-rock age of 1,570 Ma for the northeast-trending diabase dikes (Hanson, 1968). The latter is a minimum age, as some of the dikes yield Pb isotope data consistent with an age of approximately 1800 Ma (Horan and others, 1987). Although the Richmond granite is not dated by the U-Pb method, Nd and Pb isotope and trace element data for it are consistent with a Paleoproterozoic age (Spencer, 1987). Scattered medium to high-grade gneissic inclusions in the Reformatory granodiorite (SE¹/₄ sec. 30, and NW¹/₄ sec. 29, T. 124 N., R. 28 W., Plate 1), and an inclusion of gray tonalitic gneiss in the Richmond granite (Fig. 10) may be either Archean or Paleoproterozoic.

We report here (Table 1, Fig. 5) the results of Ar/Ar dating of two whole-rock samples of the northeast-trending diabase dikes which crosscut 1770-Ma St. Cloud Granite (SE¹/₄ and SW¹/₄ sec. 19, T. 124 N., R. 28 W., Plate 1). The ages determined for these dikes are 1164±12 and 1190±9 Ma. The methodology used for the Ar/Ar dating is described in Holm and others (1998). These two dikes were sampled because they are only slightly altered, although both do show features typical of low-grade metamorphic alteration, such as albitization and sericitization of plagioclase, and replacement of mafic minerals by actinolite and chlorite. Neither analysis provides a true plateau age (Fig. 5), and therefore the whole-rock total gas ages of 1150–1200 Ma should only be viewed as approximations. However, the spectra are considerably less disturbed than those determined for whole-rock samples from diabase dikes in the Minnesota River Valley (Holm and Lux, 1997). The total gas ages for the northeast-trending diabase dikes of the St. Cloud area are substantially younger (by ~3 my) than those determined for the Minnesota River valley dikes. The new Ar/Ar whole-rock dike ages are also significantly younger than the three K/Ar whole-rock ages of 1280 Ma, 1460 Ma, and 1570 Ma obtained for mafic dikes in the St. Cloud area by Hanson (1968). However, Hanson (1968) considers the three K/Ar ages to be minimum ages that have been partially reset by Ar loss. Horan and others (1987) report that Pb isotope data is consistent with an age of ~1,800 Ma for the diabase dikes. Further radiometric and isotopic studies are needed to better constrain the sequence of intrusive events.

Table 1. Argon isotopic data for whole-rock diabase dike samples

[data obtained by D.K. Holm at the Ar/Ar laboratory at the University of Maine using incremental step-heating techniques]

Temp. (˚C)	^{40}Ar / ^{39}Ar	^{37}Ar / ^{39}Ar	^{36}Ar / ^{39}Ar	^{39}Ar moles*	^{39}Ar % of total	^{40}Ar$_{rad}$ %	K/Ca	†AGE(Ma)
MN-2-95 ([§]J = 0.007586): Diabase dike, SE¼ sec. 19, T. 124 N., R. 28 W.								
770	130.04	1.427	0.0850	158.0	9.6	80.8	0.343	1057.9±12.3
860	132.87	1.930	0.0669	165.3	10.1	85.2	0.254	1119.8±9.9
945	132.73	2.036	0.0476	172.0	10.5	89.5	0.240	1160.4±13.8
1035	130.05	2.412	0.0320	223.3	13.6	92.9	0.203	1174.7±12.7
1105	131.04	4.799	0.0199	256.2	15.6	95.8	0.102	1209.8±10.0
1180	128.71	6.028	0.0211	212.3	13.0	95.5	0.081	1192.3±10.3
1250	124.55	6.256	0.0257	171.4	10.5	94.3	0.078	1153.0±9.7
1310	126.29	6.968	0.0300	119.0	7.3	93.4	0.070	1157.1±10.4
FUSE	135.42	11.613	0.0409	159.8	9.8	91.8	0.042	1205.0±15.8
TOTAL				**1637.2**	**100.0**			**1163.6±11.6**
MN-37A ([§]J = 0.007497): Diabase dike, NW¼ sec. 19, T. 124 N., R. 28 W.								
770	129.91	0.663	0.0400	320.3	7.8	90.9	0.739	1144.5±8.8
860	129.64	0.783	0.0199	397.7	9.7	95.5	0.625	1185.1±9.2
945	129.97	0.748	0.0121	449.0	11.0	97.3	0.655	1203.4±9.3
1035	129.43	0.965	0.0077	617.3	15.1	98.3	0.508	1208.8±9.0
1105	128.46	1.618	0.0093	630.7	15.4	97.9	0.302	1199.6±9.0
1180	126.71	1.841	0.0069	583.2	14.2	98.5	0.266	1192.7±9.7
1250	125.49	1.962	0.0086	442.9	10.8	98.1	0.249	1180.7±9.0
1310	125.34	2.231	0.0091	337.9	8.2	98.0	0.219	1178.8±9.1
FUSE	128.04	3.950	0.0147	318.4	7.8	96.8	0.124	1188.2±9.1
TOTAL				**4097.4**	**100.0**			**1190.1±9.1**

* moles of ^{39}Ar released at each step x 10^{-14}

† Age is calculated for each incremental step. Uncertainties are reported at the 2s -level, and include the uncertainty in the flux measurement (J value).

[§] J value is the flux measurement

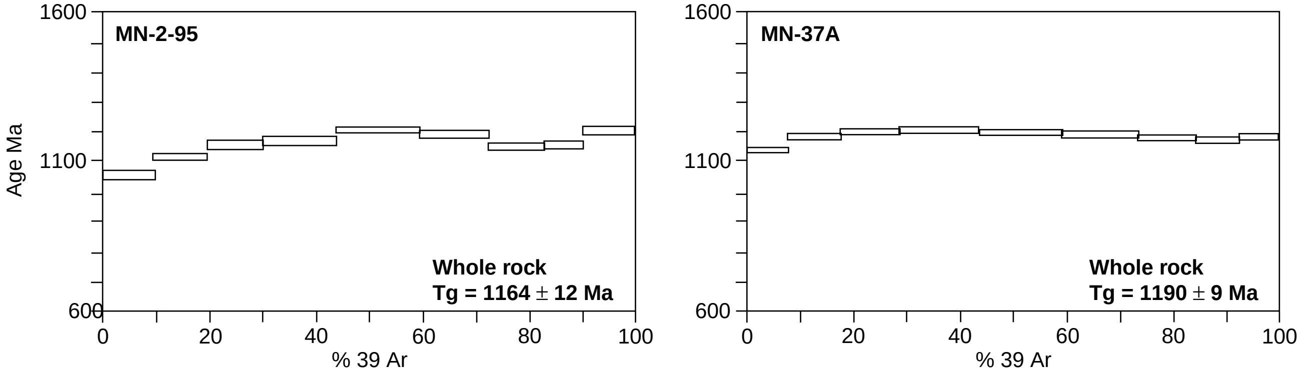

Figure 5. Ar/Ar release spectra diagrams for whole rock samples MN-2-95 and MN-37A. Tg is total gas age.

The two new Ar/Ar ages reported here (1164±12 and 1190±9; Table 1 and Fig. 5) indicate that at least some of the northeast-trending diabase dikes in the St. Cloud district might be Mesoproterozoic in age. Indeed, Chandler (1993) inferred that the Mesoproterozoic central Wisconsin dike swarm may correlate in part with the northeast-trending dike swarm of central and southwestern Minnesota based on the similarity in trend and magnetic signature. However, all of the diabase dikes documented in the Stearns County region, including the two dated here, are affected by low- to mid-greenschist facies metamorphism, in contrast to Mesoproterozoic dikes of central Wisconsin and elsewhere in the Lake Superior region, which generally retain a nearly pristine primary igneous texture. In addition, Mesoproterozoic dikes elsewhere in the Lake Superior region show up as prominent aeromagnetic anomalies, compared to the northeast-trending dikes in the St. Cloud district, which lack aeromagnetic expression. Thus the two new Ar/Ar ages reported here either record (1) the resetting of intrusive ages as a result of post-Penokean metamorphism or alteration of Paleoproterozoic dikes, or (2) true intrusive ages for the dikes, which either record very late Paleoproterozoic or early Mesoproterozoic magmatism, associated with the onset of Mesoproterozoic orogenic activity to the east.

CLASSIFICATION OF IGNEOUS ROCKS OF SOUTHEASTERN STEARNS COUNTY

Representative modal analyses were determined for all the coarse-grained igneous rocks using standard petrographic techniques and the classification system of Streckeisen (1976), and are compiled from the various sources listed in Table 2. Accurate modal analyses of the Rockville Granite, Richmond granite, and to some extent the St. Cloud Granite are difficult to obtain using standard petrographic techniques because of the coarse grain size of these granites, but the primary constituent minerals are easily identified in hand sample. The granites, especially the St. Cloud Granite, contain perthite with a relatively high proportion of exsolved albite; this is classified as alkali feldspar in the calculation of modal analyses. In the case of the diabase and porphyritic microgranite dikes, the fine grain size and/or effects of low-grade metamorphism make accurate modal analyses difficult to obtain. Normative compositions provide a useful alternative to modal analyses, especially in fine-grained rocks (Streckeisen and Le Maitre, 1979). Normative compositions calculated for igneous rocks of the St. Cloud district result in approximately the same classification breakdown as the modal analyses (Fig. 6).

A variety of standard chemical classification systems (Fig. 7) can be used to characterize the granitoid rocks as calc-alkaline rocks of subalkaline to alkaline composition. The St. Cloud Granite and the Rockville Granite (Fig. 7a) plot as alkaline on the basis of the dividing line of Miyashiro (1978), but as subalkaline on the basis of the dividing line of Irvine and Baragar (1971). Their slightly alkalic nature reflects the perthite-dominated mineralogy of the St. Cloud Granite. Despite their peraluminous nature, the granitoids are I-type, based on the classification Chappell and White, 1974; this is consistent with the abundance of biotite and hornblende, and the lack of muscovite. One of the Richmond granite samples (CS-1-111, Appendix Table AP-1) plots far into the corundum-normative field. The most likely explanation for this is that the core sampled for this analysis is a moderately weathered granite. Weathering results in the loss of elements such as calcium, and the relative enrichment in aluminum. The sample plots far to the right in the peraluminous field (Fig. 7) for this reason.

Rockville Granite

The Rockville Granite is presently extracted from three separate quarries and is marketed under the trade names of Diamond Pink, Rockville Gray, and Rockville White. It is a very coarse-grained, pinkish-white to grayish-white, weakly rapakivi-textured granite characterized by 1–3-cm microcline phenocrysts as well as smaller oligoclase (Johnson, 1978) phenocrysts in a groundmass of coarse quartz, feldspar, biotite, and hornblende, with accessory zircon, apatite, titanite, epidote, and allanite. Poikilitic yellow garnet is present in one sample from a quarry located at the northeast corner of sec. 26, T. 124 N., R. 29 W. (west of the area covered by Plate 1). Locally the Rockville Granite has a weak north-striking and west-dipping trachytoid fabric, defined by aligned feldspar phenocrysts (Fig. 8). Semi-brittle shear bands with quartz ribbons are present in large boulders of Rockville Granite in the Sauk River Valley just north of Rockville. These shear bands have a similar texture to those documented in the Richmond granite.

The Rockville Granite contains scattered mafic enclaves that vary from coarse-grained black diorite to fine-grained, gray quartz monzonite, both of which contain abundant hornblende and biotite. The diorite commonly contains microcline megacrysts (Fig. 9a),

Table 2. Representative modal analyses of granitic rocks in the St. Cloud area.
[numbers given are percentages, derived from source texts; tr = trace amount; - = not present;
en = mafic enclave; leu = leucogranite; ap = aplite]

Sample* number	Data source[†]	Quartz	K-feldspar	Plagioclase	Pyroxene	Hornblende	Biotite	Opaques	Apatite	Sericite	Chlorite	Epidote	Zircon	Actinolite	Titanite	Leucoxene	Clays	Fluorite	Other
Saint Cloud Granite																			
SC.046.A	1	22	61	10	2	4	tr	tr	tr	-	-	-	tr	-	-	-	tr	-	-
SC.062.C	1	13	49	26	-	6	5	6	tr	-	-	-	tr	-	tr	-	-	-	-
SCG[§] mean	2	29	52	10	tr	3	4	tr	tr	-	-	-	tr	-	-	-	-	tr	-
SCG[§]	3	18	65	14	-	1	3	-	-	-	-	-	-	-	-	-	-	-	-
SCG[§] Granite	4	30	50	10	tr	tr	10	tr	tr	-	-	-	tr	-	tr	-	-	tr	-
Reformatory granodiorite																			
Rgd[¶] mean	2	16	12	45	3	12	7	tr	tr	-	-	-	tr	-	tr	-	-	-	-
SC.062.B	1	19	24	37	2	5	13	tr	tr	-	-	0.8	-	0.6	-	tr	-	-	-
SC.079.D	1	14	13	47	-	7	16	2	tr	-	-	-	-	-	tr	-	tr	-	-
SC.031.A [en]	1	2	-	56	14	6	13	tr	tr	-	-	-	-	8	-	-	-	-	-
Rockville Granite																			
SC.057.C	1	21	23	41	-	3	12	tr	tr	-	-	-	-	-	-	-	-	-	tr *
SC.069	1	24	26	31	-	6	11	tr	tr	-	1	tr	-	tr	-	-	-	-	-
SC.058.A [en]	1	20	36	31	-	tr	12	tr	tr	-	tr	-	-	-	-	-	-	-	-
SC.058.B [en]	1	5	38	38	-	9	7	tr	tr	-	-	tr	-	-	tr	-	-	-	-
Richmond granite																			
SC.148.C [leu]	1	29	33	33	-	1	1	tr	tr	-	-	-	tr	1	-	-	-	-	-
SC.009.B [leu]	1	30	43	26	-	-	1	tr	tr	-	-	-	-	-	-	-	-	-	-
SC.015.B [ap]	1	39	36	20	-	-	4	tr	tr	-	1	tr	-	-	-	-	-	-	-
SC.059	1	15	23	44	3[@]	10	4	1	1	-	tr	-	-	2	-	-	-	-	-
SC.008	1	4	15	55	15[@]	6	2	2	1	-	-	-	-	-	-	-	-	-	-

* Sample number as designated by original author

[†] Data sources are: 1. This study; 2. Keighin and others, 1972; 3. Johnson, 1978; 4. Woyski, 1949

[§] SCG is the St. Cloud Granite

[¶] Rgd is the Reformatory granodiorite

[@] Hypersthene is variably metamorphosed to a nearly colorless pale green fibrous amphibole (?) with secondary opaque iron-oxide granules

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Figure 7 (on page 9). Chemical variation diagrams for granitoid rocks of the St. Cloud area. Data are from Appendix Tables AP-2 through AP-6. Symbols are as for Figure 6. **A.** Alkali-silica classification ($Na_2O + K_2O$ vs. SiO_2); the dividing lines between the 'alkaline' and 'subalkaline' fields are: solid line (Miyashiro, 1978) and dashed line (Irvine and Baragar, 1971). The basic, intermediate and acid fields are from Cox and others (1979). **B.** AFM classification (MgO vs. FeO (t) vs. $Na_2O + K_2O$) of Irvine and Baragar (1971). Solid line shows division between tholeiitic and calc-alkaline differentiation trends. **C.** Metaluminous vs. peraluminous classification of Chappell and White (1974) [(Al/(Na+K) vs. Al/(Ca +Na+K)]. **D.** I- and S-type classification (Chappell and White, 1974); classification is based on wt. percent of normative diopside (Di) or carborundum (C) vs. molar proportions of Al/(Ca+Na+K). Lines show divisions between I- and S-type fields.

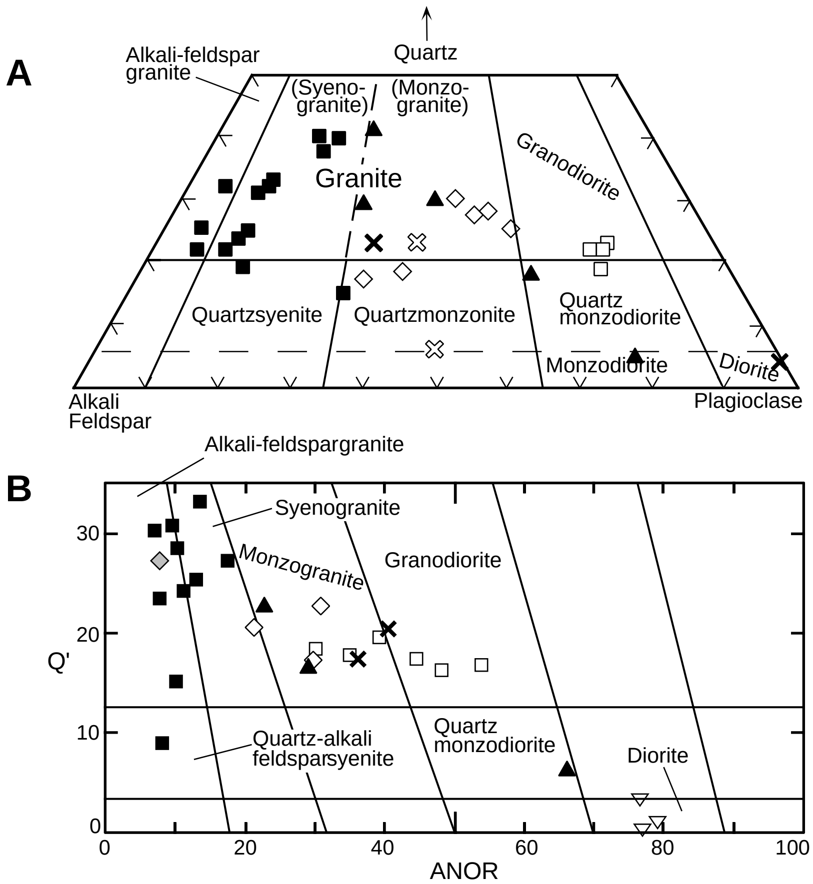


Figure 6. Composition of granitoid rocks and diabase dikes from the St. Cloud area. **A.** Quartz–Alkali Feldspar–Plagioclase plot. This plot shows modal data presented in Table 2 together with additional representative analyses. **B.** Quartz (Q') vs. Anorthite (ANOR) plot. This plot is based on normative compositions calculated from whole-rock chemical analyses presented in Appendix Tables AP-2 through AP-6. Calculation of Quartz and Anorthite is from Streckeisen and Lemaitre (1979); Q' = 100*Q/(Q+Ab+An+Or). ANOR = 100*An/(An+Or)(normative).

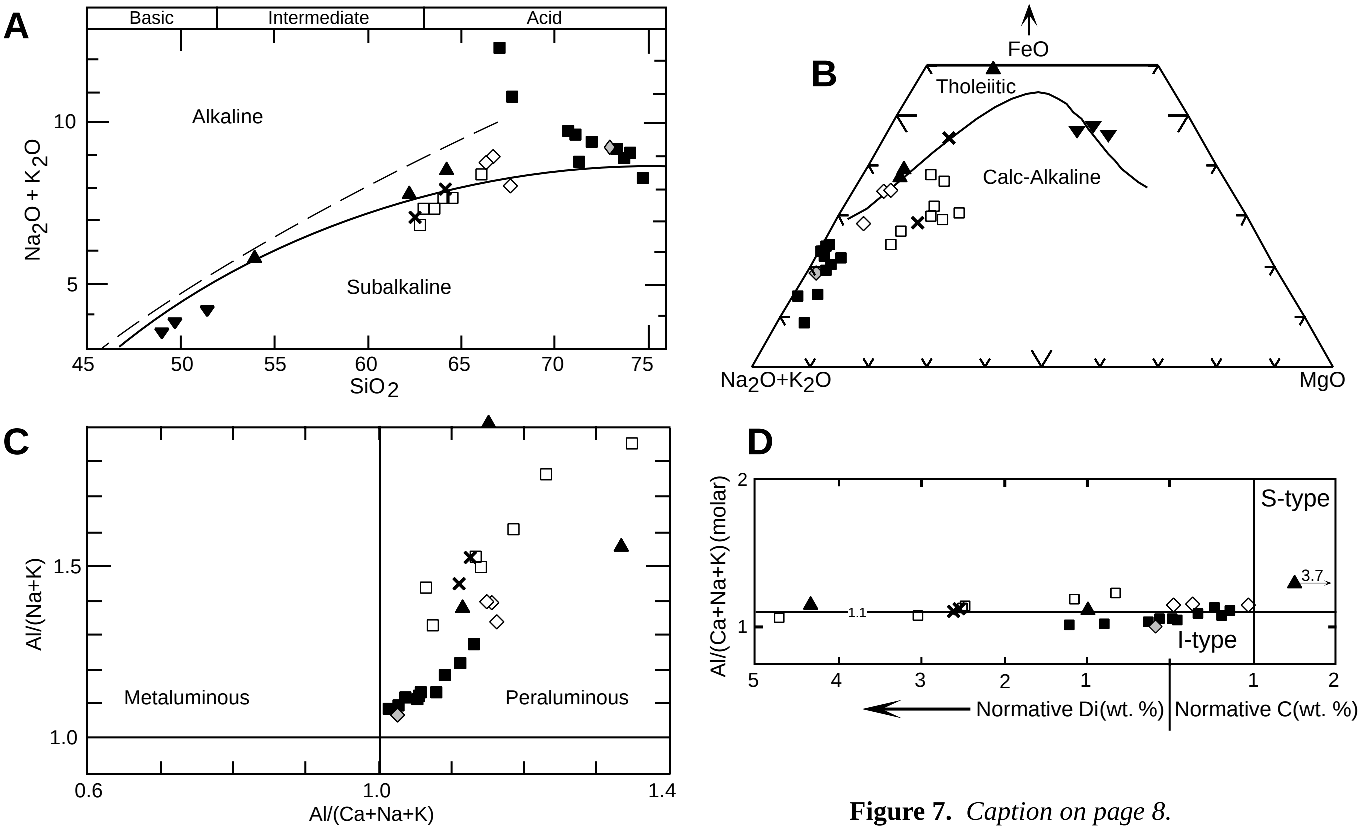


Figure 7. *Caption on page 8.*

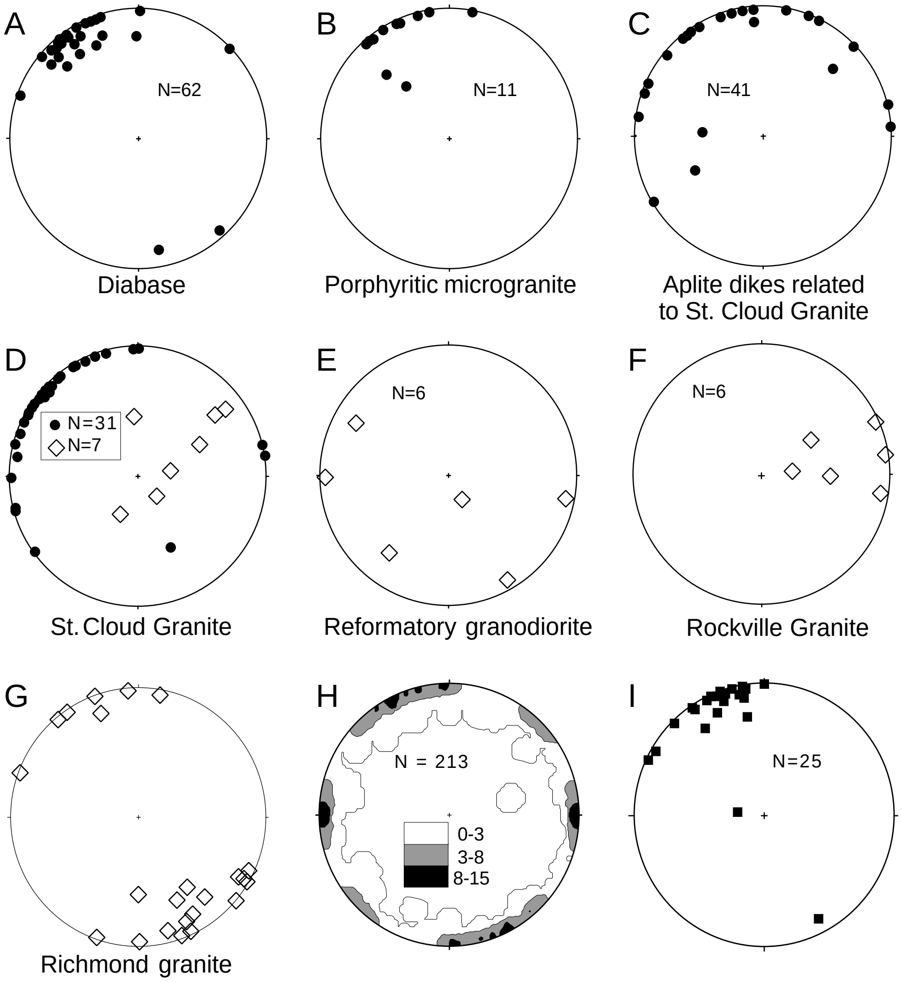


Figure 8. Stereographic projections, showing measured orientations of dikes and sills (**A–D**, black circles), trachytoid fabrics (**D–G**, diamonds), brittle fractures (**H**, data is contoured; contour intervals are (Ragan, 1973) percentage per 1 percent area), and semi-brittle shear zones (**I**, squares). All data are projected into the lower hemisphere as poles to planes.

whereas the monzonite contains scattered plagioclase phenocrysts. Both have a pristine trachytoid igneous matrix of microcline, quartz, biotite, and hornblende. Diorite enclaves in a quarry just south of the town of Rockville (Fig. 9a) are round and range from 3 to 15 cm in diameter. In contrast, a 5- to 30-cm-thick dike with a dioritic composition, and a texture similar to that of the dioritic enclaves, cuts the Rockville Granite in a quarry in section 26 (just west of the area covered by Plate 1). This dike has indistinct margins, and contains xenoliths of a white, equigranular granite that is compositionally and texturally similar to the Rockville Granite.

Commingling of mafic and felsic magmas during magma ascent and emplacement is indicated by the presence of coarse-grained diorite both as enclaves and as a dike in the Rockville Granite, as well as the presence of microcline megacrysts in the coarse-grained enclaves, pristine trachytoid igneous textures of the finer-grained enclaves, and the rapakivi texture of the Rockville Granite.

Richmond granite

The Richmond granite is a hypersthene-bearing hornblende-biotite granite of charnockitic affinity that is well exposed between the towns of Richmond and Cold Spring (Fig. 10). A small amount of this granite, marketed as Opalescent Gray, was quarried in the town of Cold Spring, but it has not been significantly exploited as a dimension stone. It is generally dark greenish-pink, although locally it is dark green where it has not been oxidized along tight fractures. This granite contains mantled potassium-feldspar phenocrysts, ranging from 2 to 6 cm in length, that define a rapakivi texture (Fig. 9c). The Richmond granite displays a consistent east-to-northeast-trending trachytoid magmatic fabric defined by aligned phenocrysts (Fig. 8). Quartz is present as more-or-less equant, anhedral-interstitial monocrystalline clots as much as 1 cm across. Locally the quartz has been flattened into elongate ribbons that define localized

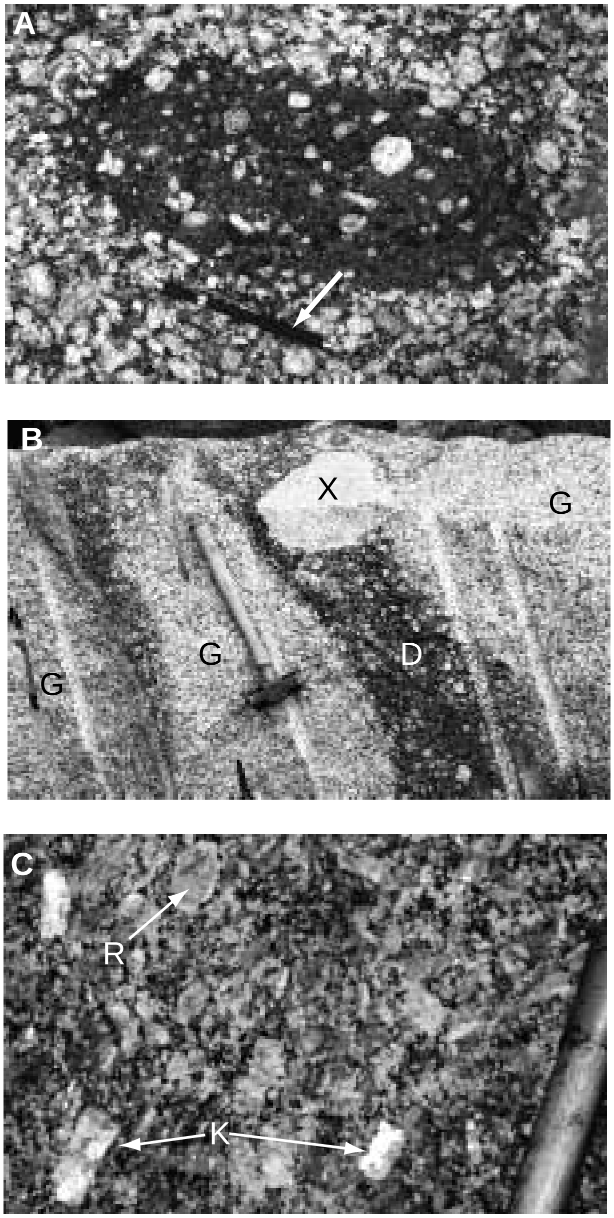


Figure 9. **A.** Rockville Granite; outcrop surface shows mafic enclave that includes K-feldspar and plagioclase phenocrysts; the pencil (arrowed) is 15 cm long. **B.** Rockville Granite; outcrop surface shows granite (G, labeled) cut by biotite-hornblende quartz diorite dike (D, arrowed); note the feldspar phenocrysts or xenocrysts, and the rounded xenolith (X, arrowed) of non-porphyritic granite within the diorite dike; the hammer handle is 40 cm long. **C.** Richmond granite; outcrop surface shows euhedral, carlsbad-twinned K-Feldspar phenocrysts (K), rapakivi texture (R), and trachytoid alignment of grains (subparallel to hammer handle). Hammer handle is approximately 3 cm wide.

meter-scale shear bands which parallel the primary trachytoid fabric. We interpret these shear bands to have formed by syn-intrusive deformation resulting from continued upward movement of an almost completely crystallized, semi-plastic magma, perhaps in tandem with structural disruption during the final stage of emplacement. A prominent northeast-trending shear zone of unknown age cuts the Richmond granite on a small island outcrop in Knaus Lake (Fig. 10). The granite here contains rolled feldspar phenocrysts in a fine-grained recrystallized matrix. The unsheared charnockite adjacent to the shear zone is a hypersthene-rich monzodioritic variant of the Richmond granite (Table 2, sample SC.008).

The dominant mafic minerals in the Richmond granite are reddish-brown biotite and dark green to brown hornblende. The biotite commonly forms symplectic intergrowths with quartz, and the hornblende is typically present as subpoikilitic grains rimming early-formed pyroxene. Hypersthene is abundant locally, especially in the dark-green, quartz-poor phases, where typically it is partially replaced either by fine-grained actinolite intergrown with secondary opaque oxide minerals, or more rarely by iddingsite. Apatite, ilmenite, and zircon are abundant as accessory phases, and are generally associated with the late-formed pyroxene and hornblende. Rare amounts of yellow garnet are present. Myrmekitic plagioclase-quartz intergrowths are common at the margins of the microcline phenocrysts. A volumetrically small part of the Richmond granite is comprised of pink, quartz-rich, feldspar-phyric, leucocratic granite associated with aplitic differentiates.

The western-most outcrops of the Richmond granite (Fig. 10) are dark gray, medium-grained, weakly porphyritic and trachytic, apatitic hornblende-biotite-quartz ferromonzodiorite (or jotunite in the charnockite terminology of Streckeisen, 1974). This rock type is interpreted to be a chilled border phase at the western margin of the intrusion. Enclaves of similar jotunite are also present near the center of the granite body. This jotunitic phase contains locally abundant orthopyroxene and clinopyroxene, and relatively abundant K-feldspar. A meter-scale xenolith of gray tonalitic gneiss is present within the Richmond granite (SW$^{1}/_{4}$ sec. 22, T. 123 N., R. 38 W., Fig. 10).

The Richmond granite was formerly considered to be an Archean gneiss (Morey, 1978). Dacre and others (1984, p. 6) recognized that the Richmond granite contained igneous textures, and concluded that it did not predate regional metamorphism (i.e. it was emplaced during peak metamorphism of the country rocks). They still considered it to be Archean, and inferred that the granite was a syntectonic intrusion

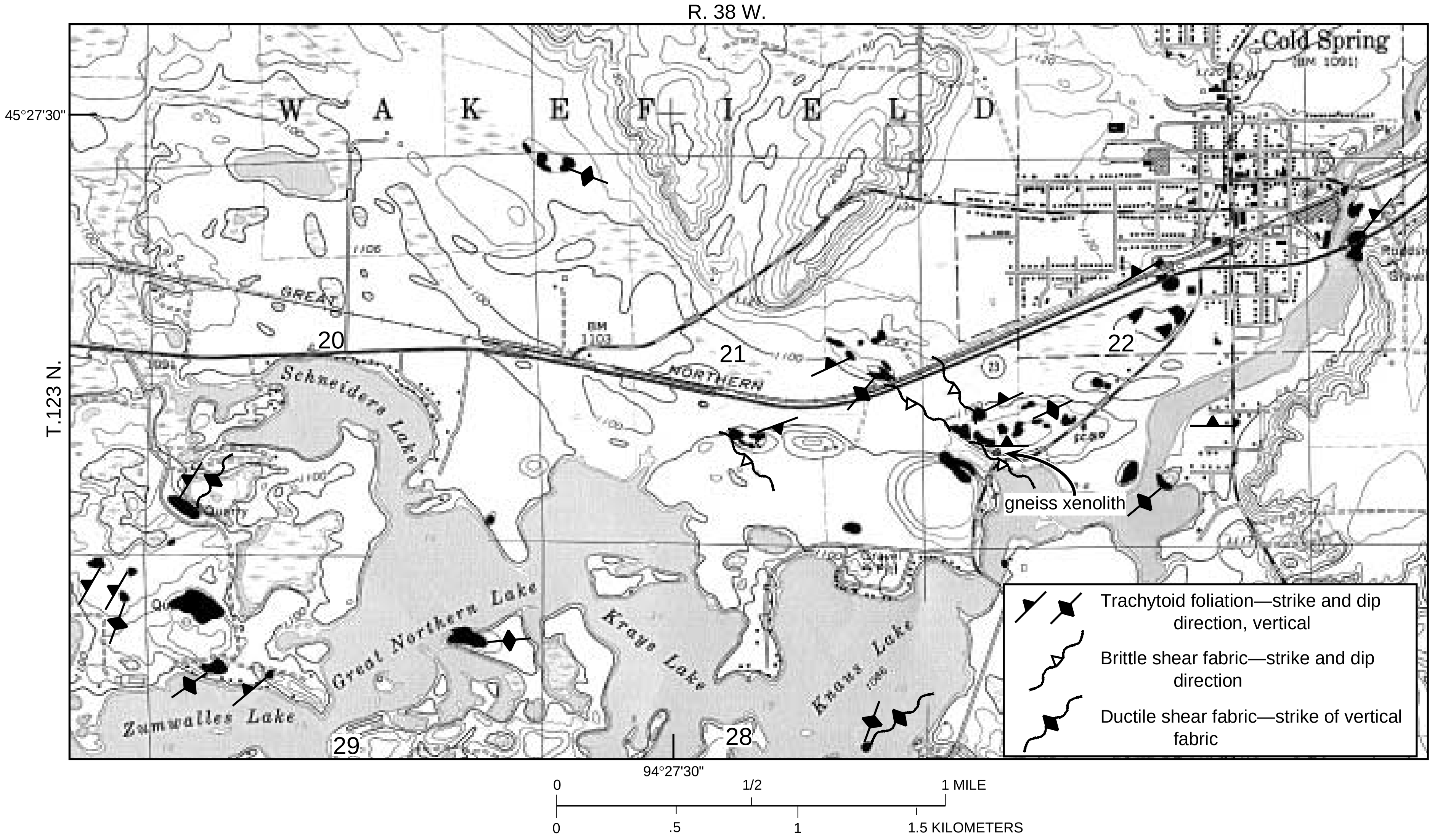


Figure 10. Central part of the Cold Spring 7.5' quadrangle showing outcrops of Richmond granite (solid black) and one outcrop of a gray granodioritic gneiss xenolith of Archean or Paleoproterozoic age (arrowed, gneiss xenolith). Structural symbols are positioned so that the end of the symbol touches the area of outcrop from which the measurement was taken. See Figure 2 for location.

that crystallized from a magma under granulite-grade regional metamorphic conditions. In contrast, the relatively pristine igneous textures documented in this study show that the Richmond granite post-dates Paleoproterozoic metamorphism of the country rock, and indicate that the Richmond granite was emplaced after the peak of Paleoproterozoic Penokean orogenesis. The presence of orthopyroxene implies that the granite cooled from a relatively dry magma generated in the lower crust; the similarity in texture to the Rockville Granite implies that it was also emplaced at a depth of 20–22 km (Boerboom and others, 1998). Dacre and others (1984) reported that the Richmond granite is cut by the Rockville Granite on a road cut on State Highway 23, just east of the town of Cold Spring (Figs. 3 and 10), but examination of this road cut and other outcrops during this study provides no evidence for these intrusive relations.

Hornblende ferrogabbronorite that contains inclusions of noritic anorthosite is present in outcrops less than a mile to the west of the western-most outcrops of Richmond granite. These mafic rocks can be interpreted as charnockitic. Geophysical evidence (Fig. 11) indicates that the Richmond granite is part of a large intrusion, composed mainly of gabbroic to noritic intrusive rocks.

Coarse-grained ~1000 Ma porphyritic intrusive charnockites from the Prince Charles Mountains, East Antarctica (Zhao and others, 1997) form several plutons ranging from 1 to 110 km^2. They are dominated by simply-twinned phenocrysts of K-feldspar as much as 7 cm long, and contain plagioclase, orthopyroxene, clinopyroxene, biotite and quartz, with apatite, ilmenite, and magnetite as relatively abundant accessory minerals. The Prince Charles Mountain charnockites were emplaced into high-grade metamorphic rocks immediately after the peak of granulite-grade metamorphism. They are characterized by high concentrations of TiO_2, P_2O_5, K_2O, Zr, Ba, and Ce, and lower MgO, and CaO concentrations, as well as low Mg# relative to typical I-type granites. Comparison with the Richmond granite shows that the Richmond granite has chemical and mineralogical traits similar to the charnockites of the Prince Charles Mountains, and may have formed in a similar manner.

Reformatory Granodiorite

The Reformatory granodiorite is presently extracted from only one quarry, just south of the city of St. Cloud, but there are numerous inactive pits from which this rock was once quarried. Its trade name is Charcoal Gray. The Reformatory granodiorite is a dark gray to pinkish gray, medium-grained, weakly porphyritic biotite-hornblende granodiorite. It is characterized by small gray tabular oligoclase to andesine phenocrysts (Johnson, 1978) as much as 5 mm long, in a groundmass of plagioclase, microcline, hornblende, and biotite, with accessory pyroxene, titanite, opaque Fe-Ti oxides, and apatite. Weak, generally subhorizontal trachytoid fabric can be observed locally in the granodiorite (Fig. 8e). Ovoid dark-gray enclaves ranging from 1 cm to 3 m in diameter are present in varied proportions throughout the Reformatory granodiorite. These enclaves were previously interpreted as inclusions of amphibolitic country rock, but their mineralogy and pristine trachytoid igneous fabric are inconsistent with such an origin. We interpret the enclaves to represent mafic magma incorporated within granitic melts as a result of magma mingling processes similar to those interpreted for the Rockville Granite.

Metamorphic country-rock xenoliths in the Reformatory granodiorite are rare, and appear to range in size from less than 50 cm to as much as several meters (sections 29 and 30, T. 124 N., R. 28 W., Plate 1). The Xenoliths consist mostly of granitic gneiss of high metamorphic grade, and contain abundant cordierite and variable amounts of garnet, sillimanite, and magnetite.

St. Cloud Granite

The St. Cloud Granite was once quarried extensively, and hence can be readily observed in abandoned quarries such as those in the SW¹/₄ of section 20, and the SE¹/₄ of section 19 (T. 124 N., R. 28 W., Plate 1). Production started in the early 1900's, peaked around 1940, and ceased in the mid-1960's. The St. Cloud Granite is a coarse-grained, dusky red-colored hornblende granite, with a distinctive mottled pink and black color. The main minerals are microcline, plagioclase (albite to oligoclase; Johnson, 1978), quartz, hornblende, and biotite, with accessory Fe-Ti oxides, apatite, zircon, titanite, and epidote. A weak porphyritic texture is defined by pink microcline phenocrysts that are only slightly larger than the other minerals. A vague trachytoid fabric defined by aligned feldspar and hornblende crystals is common and is parallel to the margins of the dikes and sills of the St. Cloud Granite (Fig. 8d). The St. Cloud Granite includes a small proportion of pink aplitic granite (NE¹/₄ sec. 19, T. 124 N., R. 28 W., Inset A, Plate 1) that is inferred to be a late differentiate. Coarse pegmatite is exceedingly rare. The St. Cloud Granite typically contains abundant angular xenoliths of

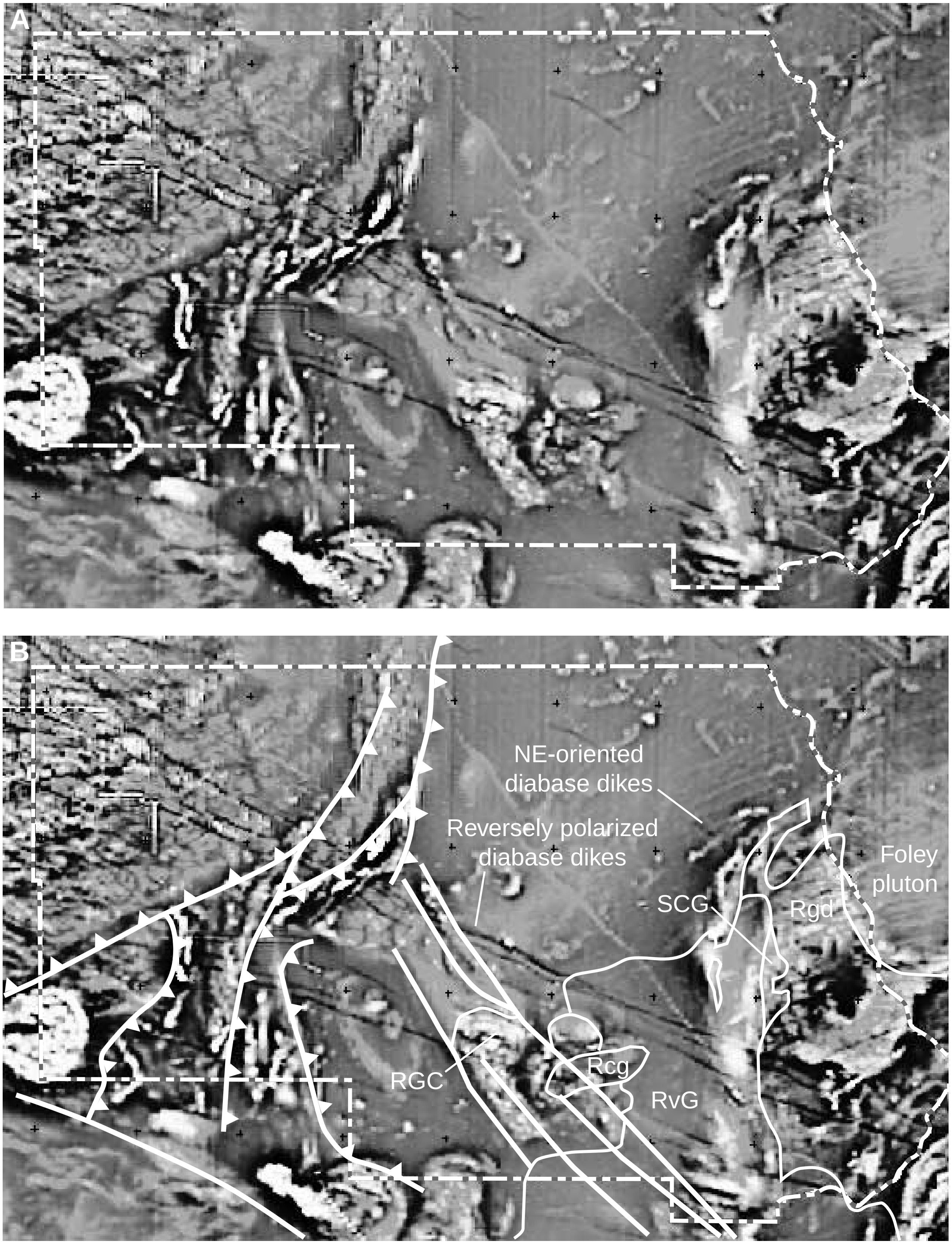


Figure 11. A. Aeromagnetic anomaly map (first vertical derivative, reduced-to-pole) of Stearns County. Boundaries of Stearns County shown by white dashed line. **B**. Same as A; annotated to show the interpreted geologic contacts and rock types. Rgd = Reformatory granodiorite; Rcg = Richmond granite; RvG = Rockville Granite; SCG = St. Cloud Granite; RGC = granitic, gabbroic and noritic intrusive rocks that form the large intrusive complex which includes the Richmond granite.

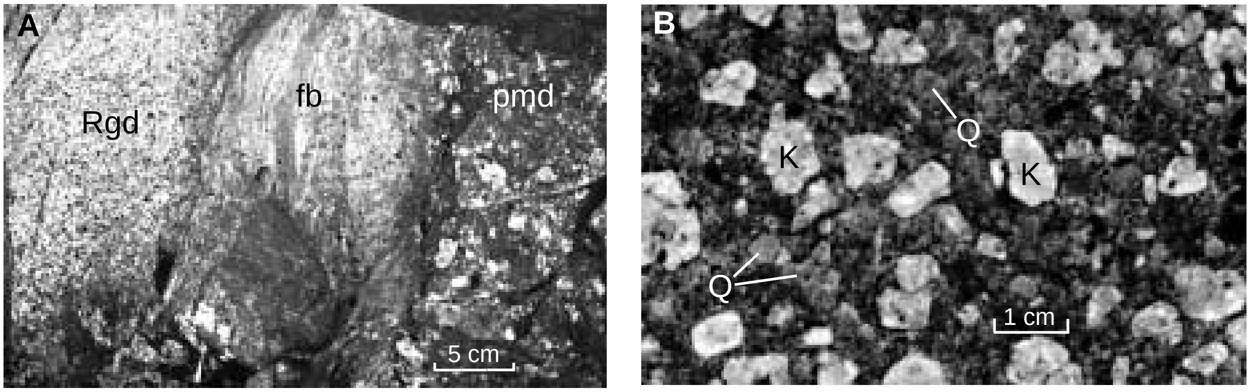


Figure 12. A. A porphyritic microgranite dike (pmd) displays a distinctly flow-banded margin (fb), and cuts the Reformatory granodiorite (Rgd). The aphanitic and aphyric flow-banded margin grades abruptly into coarsely porphyritic microgranite that contains as much as 25 percent K-feldspar phenocrysts and 15 percent quartz phenocrysts in a very fine-grained siliceous groundmass. This outcrop is located near the center of section 28 (Plate 1). **B.** Porphyritic microgranite; cut surface shown at actual size. K-feldspar phenocrysts (K) and quartz phenocrysts (Q) are arrowed, although quartz phenocrysts are difficult to distinguish in this photograph due to lack of contrast between them and the grey-pink matrix.

Reformatory granodiorite; rare garnet amphibolite country-rock xenoliths are also present.

The St. Cloud Granite was formerly considered to be contiguous with a larger mass of similar pink granite northeast of St. Cloud in Benton County (Morey and others, 1981), but on the basis of this study it is interpreted instead to be a separate, albeit possibly related, smaller body that was emplaced along the contact between the Rockville Granite and Reformatory granodiorite. On the basis of geophysical data (Fig. 11), the large granite body northeast of St. Cloud is now recognized as a separate intrusion, informally termed the Foley pluton (Jirsa and others, 1995).

Unnamed Porphyritic Granite

An unnamed porphyritic hornblende-biotite granite is exposed in a road cut in the SE$^1/_4$ of sec. 18, T. 124 N., R. 28 W (Plate 1). This porphyritic granite is present in minor proportions, and is cut by a granite that is compositionally and texturally similar to, and probably related to the St. Cloud Granite. The porphyritic granite contains small, roundish, rapakivi-textured feldspar phenocrysts in a fine-grained streaky gray matrix. In thin section, perthite phenocrysts ranging from 1 to 3 cm long are present in a groundmass of quartz, K-feldspar, plagioclase, biotite, and hornblende. The hornblende typically has cores of secondary biotite and opaque oxides. A minor amount of very coarse pegmatite is made up of gray K-feldspar and white quartz, and is found only in proximity to this porphyritic granite. The pegmatite is probably a late differentiate associated with St. Cloud Granite. Unequivocal evidence that would rule out an association between the unnamed porphyritic granite and the nearby St. Cloud Granite was not found. However, the presence of rapakivi-textured feldspar within the porphyritic granite indicates that it is may be a chilled marginal phase of the Rockville Granite.

Porphyritic Microgranite Dikes

Thin northeast-trending dikes (Fig. 12) of porphyritic microgranite cut the St. Cloud Granite, Reformatory granodiorite, and Rockville Granite. None of these dikes are documented in the Richmond granite. Most of the microgranite dikes range from 2 to 4 m wide, but one is at least 30 m wide. Another dike, at least 100 m wide, outside of the area covered by Plate 1, may also be part of this set; it is quarried at the intermittently active Crystal Gray quarry, located west of St. Cloud, just southwest of the intersection of Interstate 94 and the Sauk River. The affiliation of the porphyritic granite quarried at the Crystal Gray quarry is somewhat enigmatic, although the shape of, and zoning within the phenocrysts suggest that it is a coarse-grained version of the porphyritic microgranite dikes. On the north wall of the Meridian Aggregates quarry, a microgranite dike clearly intrudes and occupies the center of a diabase dike.

The porphyritic microgranite dikes have strongly chilled, locally flow-banded margins, and are texturally similar to volcanic rhyolite (Fig. 12). Microperthite phenocrysts that are as large as 10 mm across form between 3 and 20 percent of the dike, and quartz phenocrysts that are as much as 4 mm in diameter form between 3 and 15 percent of the dike. The microperthite phenocrysts are euhedral, and the quartz phenocrysts retain a primary euhedral shape that is modified only slightly by resorption. The fine-grained groundmass varies from anhedral-granular to spherulitic. In addition to quartz and feldspar, the groundmass contains variable amounts of fine-grained biotite, hornblende, actinolite, and chlorite, along with accessory fluorite, apatite, Fe-Ti oxides, epidote, titanite, zircon, and allanite.

Diabase Dikes

There are two main groups of diabase dikes in southeastern Stearns County. These are: (1) an early, northeast-trending set, and (2) a later northwest-trending set. The diabase dikes are interpreted to be the youngest Precambrian rocks in Stearns County. Many of the old, water-filled quarries in the Waite Park area have straight walls defined by diabase dikes, due to the natural break in the rock at the diabase/granite contacts (Fig. 13).

Northeast-Trending Dikes

The northeast-trending dikes generally lack geophysical expression, but are exposed in several outcrops and old quarries throughout the area. They are mostly 1–3 m thick, although some are as wide as 8 m. Dike margins are sharply chilled against the neighboring granitic rocks. These dikes are generally vertical to steeply south-dipping (Figs. 8 and 13). They follow preexisting northeast-trending fractures in the granites that they intrude. Small, sharp jogs along the length of the dikes are common, where they follow more north-south oriented fractures. In places (e.g. Inset B, Plate 1), these dikes fork and rejoin along their length. Where these dikes are more than 3 m thick, they have cooling fractures perpendicular to their margins that are filled with fine-grained, white, saccharoidal quartz and feldspar, that are interpreted to be remobilized partial melts of the adjacent granitic rocks. In the diabase, mafic minerals (probably pyroxenes) are replaced by actinolite and chlorite, but relict fine-grained plagioclase is present.

Sliver-shaped xenoliths of the granitic wall rocks are only rarely present along the diabase dikes margins. Some of the northeast-trending dikes, however, contain abundant xenocrysts of clear quartz and turbid feldspar, as well as small xenoliths of granitic rock fragments. These xenocrystic dikes are generally less than 50 cm wide. The xenocrysts in these dikes show a great deal of absorption and are typically concentrated by flow segregation mechanisms into the dike centers. We have not determined whether these xenocrystic dikes are related to the main swarm of northeast-trending diabase dikes or whether they represent a separate intrusive unit.

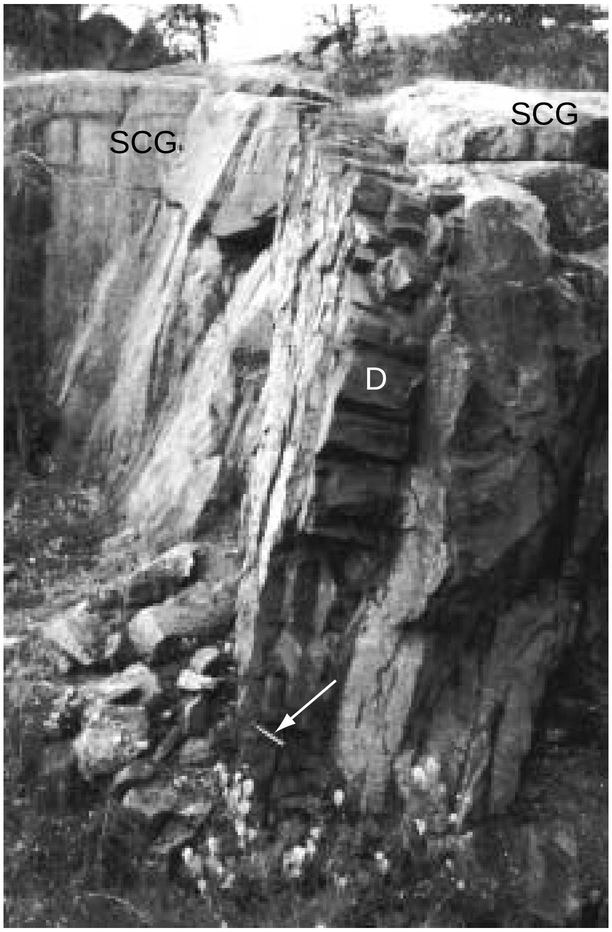


Figure 13. Typical diabase dike (D) exposed by quarrying operations in the SE$^1/_4$ sec. 19, T. 124 N., R. 28 W. Sample MN-2-95 was collected from this dike for Ar/Ar dating and isotopic analysis (Fig. 5 and Table 1). View is to the west-southwest. Dike strikes roughly N50E, dips steeply south, and here intrudes the St. Cloud Granite (SCG). The hammer (arrowed) shown near the lower part of the photograph has a 40–cm-long handle.

A northeast-trending diabase dike is in contact with a subparallel dike of porphyritic microgranite (SW$^1/_4$ sec. 19, T. 124 N., R. 28 W., Plate 1). This diabase dike is sharply chilled against Rockville Granite on one margin, but retains felty-textured plagioclase against the contact with the porphyritic microgranite on the other margin; this indicates that the microgranite was still hot when the diabase was emplaced. Adjacent to the contact with the microgranite the diabase contains abundant xenocrysts of quartz and feldspar derived from the porphyritic microgranite. These features indicate that the diabase may be comagmatic with the microgranite, or that the diabase post-dates the microgranite only slightly.

Another northeast-trending diabase dike may represent a separate generation of northeast-trending diabase dikes. This dike is exposed in the north wall of the Meridian Aggregates quarry (SW$^1/_4$ sec. 18, T. 124 N., R. 28 W., Plate 1). It is an ophitic, trachytoid diabase with small phenocrysts of plagioclase, chromite, and altered euhedral olivine, in which much of the pyroxene has been replaced by secondary fibrous amphibole. It is chilled against the mixed St. Cloud Granite/Reformatory granodiorite wall rocks, but is itself clearly intruded by a dike of porphyritic microgranite. We do not know how this diabase dike relates to the main set of northeast-trending diabase dikes, but both groups of northeast-trending dikes may have close temporal relations with the porphyritic microgranite dikes.

Northwest-Trending Diabase Dikes

Northwest-trending diabase dikes are inferred from geophysical data to be as much as 100 m wide; they can be traced across Stearns County on aeromagnetic images on the basis of their distinctive, generally reversely polarized aeromagnetic signature (Fig. 11). In the vicinity of Waite Park, only two dikes that may be part of this set are exposed. A 5 meter-thick northwest-trending diabase dike in an abandoned quarry in the SW$^1/_4$ sec. 20, T. 124 N., R. 28 W. truncates, and is chilled against a northeast-trending diabase dike (Plate 1). The other dike in this set trends west to northwest, and is exposed in the SE$^1/_4$ sec. 24, T. 124 N., R. 29 W. (Plate 1). Both these dikes have chilled margins, and when compared to the northeast-trending dikes are less altered and less metamorphosed, more strongly magnetic (they contain magnetite and pyrrhotite), and contain substantially more fresh clinopyroxene. A study of the remnant magnetism of the northwest-trending dike in section 20 shows that it is normally polarized, thus it may not be representative of the reversely polarized northwest-trending diabase dikes inferred from the aeromagnetic images.

Another northwest-trending diabase dike is exposed in the town of Sauk Centre (Fig. 3), and similar rock has been retrieved from a nearby drill core located in sec. 8, T. 126 N., R. 34 W. The outcrop and drill core are both located over the same linear, reverse aeromagnetic anomaly, one of several similar anomalies in this part of the county (Fig. 11). The rock in the outcrop displays a weak trachytoid fabric that strikes N 60° W, which is consistent with the trend of the dike as inferred from aeromagnetic data.

The Sauk Centre outcrop and drill core samples are both dark green, medium-grained apatitic quartz-hornblende ferrodiorites that are deuterically altered, and contain both magmatic hornblende and fibrous uralitic amphibole that has replaced pyroxene. Plagioclase forms tabular sub- to euhedral grains that are moderately saussuritized and partially replaced by chlorite. Quartz is present in minor proportions as small anhedral-interstitial, monocrystalline grains. Opaque oxides are abundant, and include titanomagnetite in which the ilmenite has been variably replaced by fine-grained titanite and/or leucoxene that encloses skeletal (111) magnetite lamellae. The well-preserved igneous texture of the Sauk Centre ferrodiorite indicates that it has only been affected by deuteric alteration.

The relatively coarse grain size and deuteric alteration assemblages imply that the ferrodiorite at Sauk Centre forms the center of a dike of substantial width, consistent with the width of 100 m estimated from aeromagnetic data. Although the margins of the dike are not exposed, it most likely is chilled against the country rocks. Thus, even though the texture and mineralogy of the exposed portion of the dike at Sauk Center differs from that of the northwest-trending dikes exposed at Waite Park, the two occurrences may or may not be part of the same dike set. The dike at Sauk Center may simply be much thicker than those at Waite Park, hence the coarser grain size. Given these uncertain correlations, we regard the Sauk Centre samples as more representative of the northwest-trending diabase dikes than those at Waite Park. The latter may represent a second northwest-trending set of normally polarized diabase dikes that lack geophysical expression.

INTRUSIVE RELATIONS

Based on field relations, geochronology, and textural evidence, the sequence of intrusive events for the igneous rocks in southeastern Stearns County is:

1. Reformatory granodiorite, Rockville Granite, and Richmond granite

2. St. Cloud Granite

3. Porphyritic microgranite dikes and northeast-trending diabase dikes

4. Northwest-trending diabase dikes

Intrusive relations between the Rockville Granite and the other granitoid rocks are not documented in the field due to lack of key outcrops. Available U-Pb geochronological data indicate that the Rockville Granite is generally synchronous with the Reformatory granodiorite. However, a poor outcrop of Rockville Granite west of the area shown in Plate 1 (NE$^{1}/_{4}$, sec. 27, T. 124 N., R. 29 W.) contains inclusions of igneous rock that are texturally and mineralogically similar to the Reformatory granodiorite. Geophysical data suggest that the Rockville Granite forms an east-thinning wedge that overlies the Reformatory granodiorite. The positive aeromagnetic anomaly characteristic of the Reformatory granodiorite continues westward, in a subdued fashion, beneath the documented surface extent of Rockville Granite (Fig. 11). The Richmond and Rockville granites are inferred to be broadly synchronous, based on their similar porphyritic and trachytoid textures.

The St. Cloud Granite is clearly intrusive into, and postdates the Reformatory granodiorite, as already established by earlier workers (Morey, 1978 and references therein). The St. Cloud Granite is present mostly as dikes and sills that have intruded the Reformatory granodiorite (Fig. 14), and display complex intrusive relations not readily portrayed at the map scale. The dike-like masses of St. Cloud Granite predominantly strike to the northeast, but in places have a more northerly strike (Plate 1; Fig. 8d).

Small dikes and pods of pink aplite associated with the St. Cloud Granite generally trend northeast and form offshoots into the Reformatory granodiorite (Plate 1) . Similar pink aplite bodies are present within both the Rockville Granite and the Richmond granite, where they probably formed as late differentiates of those units.

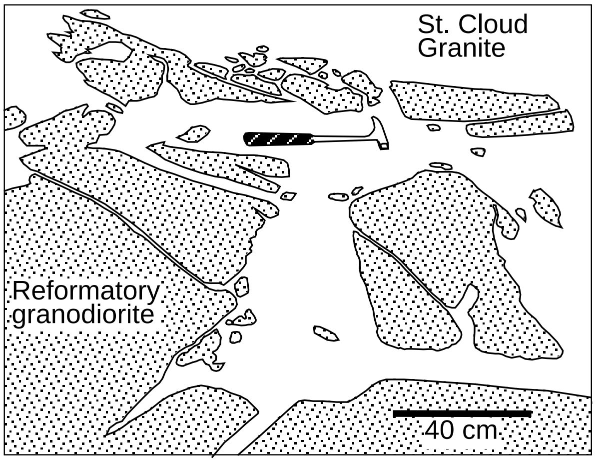


Figure 14. Outcrop sketch from SW$^{1}/_{4}$ sec. 20, T. 124 N., R. 28 W., Plate 1, shows angular inclusions of Reformatory granodiorite in St. Cloud Granite.

The porphyritic microgranite dikes are inferred to be nearly synchronous with the northeast-trending diabase dikes, based on intrusive relations. The microgranite dikes typically intrude adjacent to northeast-trending diabase dikes (e.g., Plate 1), which implies that both utilized the same fracture weaknesses during emplacement. The northwest-trending diabase dike exposed in the quarry in section 20 (T. 124 N., R. 28 W., Plate 1) in Waite Park, unequivocally cuts and is chilled against a thin northeast-trending diabase dike. If this northwest-trending dike is representative of the aeromagnetically-defined, reversely polarized northwest-trending dikes, this set of diabase dikes represents the youngest intrusive rock recognized to date in Stearns County.

STRUCTURAL GEOLOGY

The county-wide aspects of the structural geology have been discussed in a text supplement to the Stearns County Geologic Atlas (Boerboom, 1996). This poorly-understood structural history includes an episode of thrust faulting and metamorphism of the supracrustal rocks, which took place prior to emplacement of the late- to post-Penokean granites, which are the focus of this paper. Evidence for structural disruption associated with, and subsequent to intrusion of the granitoid rocks exposed in Stearns County includes abundant fractures, quartz- and epidote-filled shear zones, and one documented fault, all of which are brittle features.

Fractures are present in all the rock units. Some fracture surfaces are coated with chloritic slickenside surfaces; movement along each individual plane appears to have been minimal. Most of these fractures now dip steeply, and strike 000°, N60E, or N40W (Fig. 8H). These fractures both predate and postdate emplacement of the porphyritic microgranite and diabase dikes.

Quartz- and epidote-filled shear zones with minor offset are documented within most of the larger granitoid intrusions, but are absent from the diabase and porphyritic microgranite dikes. Most of the shear zones within the granitic intrusions strike N70E and dip steeply (Fig. 8i), and they range from 1–4 cm to as much as 10 cm wide. The shear zones are tightly annealed, and probably formed when the intrusions had cooled sufficiently to deform in a brittle fashion, but were still warm enough to supply the heat and fluids to form the veins. The shear zones probably formed as a result of crustal extension during and shortly after the time of pluton emplacement (Holm and others, 1998). This is consistent with their northeast orientation, perpendicular to the direction of maximum compressional stress related to the Penokean Orogeny. Darrah (1996) and Holm and others (1998) conclude that these quartz- and epidote-filled shear zones initially formed as semi-ductile features above 300°C and continued to form below that temperature within the brittle deformational regime during rapid regional extension and crustal thinning. They also document that the diabase dikes postdate and partly occupy these quartz- and epidote-filled shear zones.

The only fault documented in the field is in the south wall of the Meridian Aggregates quarry, at the southern edge of sec. 18, T. 124 N., R. 28 W., where the St. Cloud Granite, Reformatory granodiorite, and a northeast-striking diabase dike are all cut by a fault that strikes northwest and dips approximately 35° to the northeast. The fault zone is as wide as 1 m. It is not shown on Plate 1 because of the difficulty in portraying its exact position within the quarry. The fault is marked by a clay-rich gouge that probably originally consisted of extensively brecciated rock that was subsequently altered to clay by meteoric water channeled along the more permeable fault zone. Slight offset of the diabase dike intersected by this fault indicates a normal sense of movement. Although similar faults are not documented anywhere else, they may be present. Elsewhere in Stearns County, north- to northeast-striking thrust faults are related to Penokean orogenesis. Northwest-striking strike-slip faults are inferred from geophysical data to postdate the thrust faults (Figs. 2 and 11).

MAFIC ENCLAVES: EVIDENCE FOR MAGMA MINGLING

The textural and mineralogical attributes of mafic microgranular enclaves in the Rockville Granite and Reformatory granodiorite are similar to features attributed elsewhere to the commingling of mafic and felsic magmas (Didier and Barbarin, 1991). The rapakivi texture of the Rockville and Richmond granites may also result from magma commingling.

The textures, occurrence, geochemistry, and possible origins of mafic microgranular enclaves have been studied extensively worldwide (Didier and Barbarin, 1991). Typical mafic microgranular enclaves consist of lath-shaped plagioclase crystals that are aligned by magmatic flow, and have zoning and quench textures indicative of undercooling of the mafic magma against the relatively cool granitic host. In contrast, quartz and K-feldspar in the enclaves crystallize later at a lower temperature and nucleation rate, and hence form a poikilitic groundmass (Vernon, 1991). Mafic microgranular enclaves have igneous textures that are distinct from the typical foliated or granoblastic-polygonal grain habits of metamorphic country-rock xenoliths. K-feldspar megacrysts are common in mafic microgranular enclaves, and are attributed to the passage of preexisting feldspar phenocrysts from the felsic magma into the more mafic melts that form the enclaves (Barbarin and Didier, 1991). Rapakivi textures (the mantling of K-feldspar by plagioclase) can also be attributed to magma mixing (Hibbard, 1981; 1991).

The mafic enclaves in the Reformatory granodiorite and Rockville Granite are ovoid in shape, with quenched, trachytoid plagioclase and clinopyroxene crystals set in a groundmass of poikilitic quartz and K-feldspar. Other enclaves in the Richmond Granite and Reformatory granodiorite may be xenoliths of chilled marginal phases or other intrusive rocks, although textural evidence clearly shows that most of the mafic enclaves coexisted as a melt with the host granite magma.

ORIGIN OF MAFIC AND FELSIC MAGMAS

The mingling of mafic and felsic magmas is most likely in regions where crustal melts are generated by underplating of continental crust by mafic, mantle-derived magma (Cruden and others, 1995, and references therein). Crustal melts generated by the underlying mafic magma will accumulate at the base of the crust, and if sufficient quantities are generated, the melt may become fully mobilized, ascend rapidly, and entrain some of the underlying mafic magma as it rises. Mafic magma underplating may take place in a variety of tectonic settings (e.g. Holm, 1999; Cruden and others, 1995; Turner and others, 1992). During underplating, the increased thermal input at the base of the crust produces a granitic melt that commingles, in various proportions, with the underlying mafic, mantle-derived magma. The degree of mixing and interaction between the two magmas is dependent upon several factors. These factors include relative differences in viscosity, density, thickness, temperature, and composition, as well as degree of crystallization within the mafic underplate, the ponded felsic melt, and the overlying crust. The rate of magma ascent also affects the extent of interaction between the two magma types (Cruden and others, 1995). Several lines of evidence indicate that at least some of the Paleoproterozoic granites of the St. Cloud district may have formed as a result of crustal underplating by high-temperature mantle material.

1. Based on zircon and apatite saturation thermometry techniques, the granite melts are inferred by Spencer (1987) to have formed at high temperatures (800-1000°C). Spencer (1987) also suggests that the high-temperature conditions, as well as isotopic similarities between the diabasic dikes and granitic intrusions indicates the interaction of mantle and crustal sources.

2. The presence of mafic microgranular enclaves and rapakivi textures; these features have been attributed elsewhere to magma mingling processes (Didier and Barbarin, 1991) that occur as a result of mafic underplating.

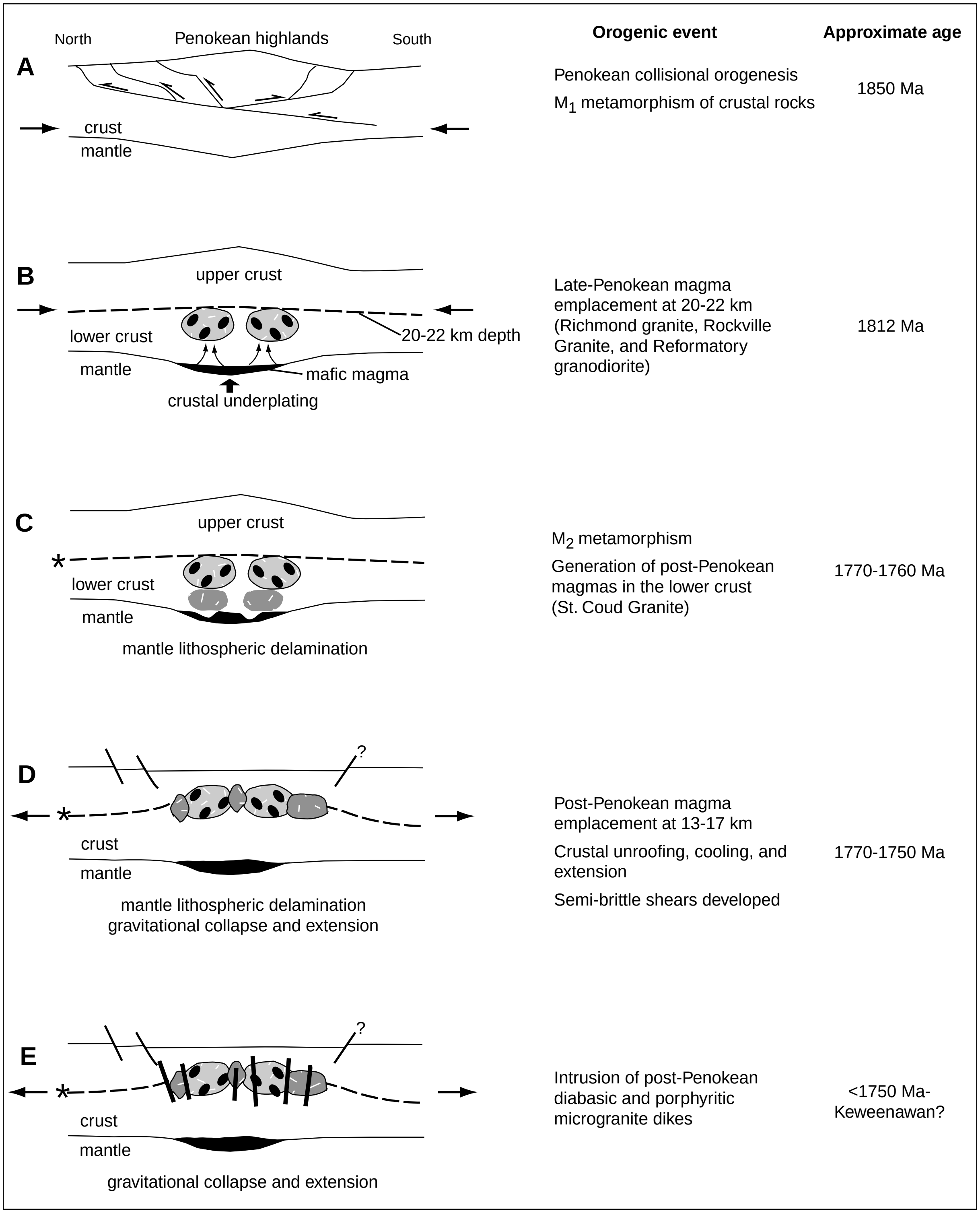
3. The close and probable cogenetic association of the porphyritic microgranite dikes with diabase dikes. This may reflect bimodal magma generation, a common feature of post-orogenic magmatic suites attributed to extension associated with mantle lithospheric thinning (Turner and others, 1992).

PALEOPROTEROZOIC TECTONOMAGMATIC MODEL

Field observations and analytical data show that granitoids within the internal zone of the Penokean Orogen can be divided into two groups, which we interpret to reflect two distinct intrusive intervals. The characteristics highlighted in Table 3 reflect two different tectonomagmatic settings—one associated with the end of constructive orogenesis (late Penokean), and the other associated with collapse of the orogenic belt some 40–50 million years later (post Penokean). A schematic summary or model for generation and emplacement of the granitic plutons following peak compression of the Penokean Orogeny is shown in Figure 15. In this model, the Richmond, Rockville, and Reformatory granites ("gray granites" of approximately 1812 Ma age, Table 3) represent melts intruded into the midcrust during the waning stages of Penokean compressional orogenesis (Fig. 15b). The abundance of mafic enclaves provides evidence for magma mingling, and implies that crustal underplating must have played an important role in the generation of these magmas. The melts were unable to penetrate into the upper crust of the Penokean Orogen, and instead formed relatively large and irregularly-shaped plutons emplaced at approximately 20–22 km depth (Darrah, 1996).

After a period of tectonic quiescence that lasted some 40 million years, melting of the lower crust (Fig. 15c) and heating of the midcrust to temperatures above 500°C (M2 metamorphism) may have been caused by mantle-lithospheric delamination at around 1770 Ma. This mantle-induced thermal heating would have softened the overthickened crust, causing it to gravitationally collapse and thin or extend (Fig. 15d). Melts generated during crustal collapse are represented by the approximately 1770 Ma "red granites" (Table 3), which intruded into the extending crust (that included the "gray granites") at depths of 17–13 km. The effects of M2 metamorphism on the earlier "gray granites" is minimal. However, the thermochronologic data of Holm and Lux (1996) and Holm and others (1998) indicate a widespread thermal resetting event associated with the collapse of the orogen at ca. 1760 Ma. As the crust extended, the mid-crustal rocks were uplifted, and cooled during crustal collapse. They acquired a brittle rheology, and the semi-brittle shears formed (Fig. 15d). Emplacement of the northeast-trending diabasic and porphyritic microgranite dikes took place slightly after development of the semi-brittle shears, because the dikes postdate them (Fig. 15e).

The data on which this model is based indicate that the orogenic history of the region began with construction of the Penokean Orogen, which resulted from crustal thickening associated with collisional orogenesis, and included M1 metamorphism, and syn- to late-tectonic plutonism (Fig. 15a, b). M2 metamorphism, post-tectonic plutonism, crustal thinning, cooling and widespread extension associated with crustal collapse (Fig. 15c, d, e) mark the end of Penokean orogenesis. Similar characteristics have also been observed in other Paleoproterozoic orogenic belts (i.e. Trans-Hudson Orogen; Holm, 1999).



	Orogenic event	Approximate age
A	Penokean collisional orogenesis M_1 metamorphism of crustal rocks	1850 Ma
B	Late-Penokean magma emplacement at 20-22 km (Richmond granite, Rockville Granite, and Reformatory granodiorite)	1812 Ma
C	M_2 metamorphism Generation of post-Penokean magmas in the lower crust (St. Coud Granite)	1770-1760 Ma
D	Post-Penokean magma emplacement at 13-17 km Crustal unroofing, cooling, and extension Semi-brittle shears developed	1770-1750 Ma
E	Intrusion of post-Penokean diabasic and porphyritic microgranite dikes	<1750 Ma-Keweenawan?

Figure 15. Model for generation of late- and post-orogenic plutons in the internal zone of the Paleoproterozoic Penokean Orogen, central Minnesota. Heavy arrows indicate compression in A and B, and extension in D and E. The heavy dashed line in B represents 20–22 km depth. The relative position of this horizon during and after crustal collapse and extension is shown by asterisk in C, D, and E.

Table 3. Characteristics and orogenic context of late- and post-Penokean igneous rocks of Stearns County, southeastern Minnesota

	Late Penokean (~1812 Ma)	**Post Penokean (~1770–1760 Ma)**
Igneous rock name or type	Richmond granite Rockville Granite Reformatory granodiorite	St. Cloud Granite Diabase dikes Porphyritic microgranite dikes
Composition and color	Granodiorite to granite; Typically gray	Granite (alkali-feldspar granite to syenogranite) Granite is typically red
Mafic Enclaves	Contains mafic enclaves	Only contains very rare mafic enclaves
Country Rock Xenoliths	May contain country-rock xenoliths	Very rarely contains country-rock xenoliths
Magmatic fabric	Moderately developed trachytoid fabric Northeast striking; typically flat	Very weak to absent trachytoid fabric
Pluton shape	Broad and irregular	Dikes and sills, large plutons Diabase dikes and sills and St. Cloud Granite are typically northeast-striking A younger set of diabase dikes strikes northwest
Geophysical characteristics	Subdued to busy magnetic signature Generally positive gravity signature	Granites typically non-magnetic (except near contacts) Generally negative gravity signature Dikes all associated with weak to moderate, positive or negative, linear magnetic anomalies
Depth of emplacement	20–22 km (5-6 kb)	13–17 km (3.5–4.5 kb)
Associated metamorphism	M1—medium to high-grade (garnet zone)	M2—medium to high grade (staurolite grade)
Structural features and fabrics	cut by semi-brittle shears	cut by semi-brittle shears

Regardless of their origin, we suggest that post-orogenic magmatism probably played a key role in the stabilization of crust following orogenesis (Holm and others, 1999).

SUMMARY

The exposed igneous rocks in southeastern Stearns County are late- to post-orogenic Paleoproterozoic intrusions. Scattered xenoliths of amphibolite and higher grade schist and gneiss are the only exceptions. Field evidence for syn- and post-intrusive structural disruption is limited to semi-brittle quartz-epidote shear zones, and rare late brittle faults. Late fractures are prominent in most exposed igneous rocks, although the spacing and orientation of these fractures varies, and their age is uncertain.

The relative emplacement order of the Richmond granite, the Rockville Granite, and the Reformatory granodiorite cannot be resolved from outcrop mapping. This is due to the lack of key outcrops in which intrusive relations can be observed. The St. Cloud Granite intrudes the Reformatory granodiorite as a complicated series of mostly northeast-trending dikes, and less-well defined sills, and is areally restricted to the western part of the Reformatory Granodiorite. Northeast-trending porphyritic microgranite dikes are in part cogenetic with the similarly oriented diabase dikes. Together they represent an episode of bimodal magma generation that postdates the St. Cloud Granite. Poorly exposed, northwest-trending diabase dikes that cut the northeast-trending set of diabase dikes are the youngest intrusive rocks recognized in southeastern Stearns County.

The granitic rocks in Stearns County can preliminarily be divided into two major groups—an earlier suite of ~1812 Ma granitic rocks that generally contain mafic enclaves and a trachytoid fabric, and a later suite of ~1770 Ma granites that lack mafic enclaves, and clearly intrude the earlier granites. The earlier suite (represented in Stearns County by the Rockville Granite, Richmond granite, and Reformatory granodiorite), was emplaced into the midcrust, at a depth of 20–22 km, late in the development of the Penokean Orogen. The later suite (represented in Stearns County by the St. Cloud Granite and nearby Foley pluton), were emplaced at depths of 13–17 km during post-orogenic collapse and extension of the overthickened Penokean crust.

Magma mingling and mixing processes may have played an important role in the evolution of the older granitic magmas. Mafic microgranular enclaves in the Reformatory granodiorite and Rockville Granite are similar to enclaves ascribed elsewhere to magma commingling and mixing processes. The rapakivi textures of the Richmond and Rockville granites are also characteristic of intrusive bodies associated with magma commingling and mixing processes. Xenoliths of metamorphosed country rock are present locally within the Reformatory granodiorite, and rarely within the St. Cloud and Richmond granites.

New geochronological data could be used to better constrain the history of orogenesis. The porphyritic microgranite dikes would provide a particularly useful date, because intrusive relations show that these dikes postdate all of the granites. The northwest-trending diabase dikes are the youngest known intrusions, and baddelyite or zircon ages from these dikes may provide new insights into regional geologic interpretations. The Richmond and Rockville granites contain abundant zircon, isotopic data from which would help constrain the duration of late- to post-orogenic magmatism, and hence help to better understand the processes that ultimately stabilized the Paleoproterozoic crust in central Minnesota.

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APPENDIX

INTRODUCTION

Tables presented in this appendix provide representative geochemical data for rock units discussed in the text. The 28 geochemical anayses were obtained from three main sources as well as some analyses acquired specifically for this project. Details of the analytical methods used, the locations of the laboratories and the names of the original analysts are outlined below., The number preceding each laboratory corresponds to the number entered under "analyst" in each of the appendix tables AP-2 through AP-10.

Each of the 28 samples is briefly described and its location given in Appendix Table AP-1. Sample locations are given in the TRS/ABCD system, which is routinely used by the Minnesota Geological Survey for locating data points of all types throughout the state. The system is a variant of the familiar Public Land Survey System (which uses the township-range-section method of locating a point). The TRS/ABCD system starts with the largest quarter section and works down to the smallest. Quarter sections are identified as follows: NE 1/4 = A; NW 1/4 = B; SW 1/4 = C; and SE 1/4 = D. Thus the SE 1/4 of the NW 1/4 of the NE 1/4 of the NE 1/4 of section 18, T. 124 N., R. 28 W. is given here as 124-28-18 AABD.

Appendix tables AP-2 through AP-6 list the major elements as weight-percent oxides in standard format; H_2O, CO_2, and loss on ignition (LOI) are listed as reported in the original analyses. The concentration of minor or trace elements (Rb, Sr, Ba, Zr and Mn) is given in parts per million (ppm) by weight. The normative composition for each sample is calculated from whole-rock analyses using IGPET software (Terrasoft Inc., Somerset, New Jersey). Minor element compositions for the 28 samples listed in appendix tables AP-2 through AP-6 are presented in Appendix Tables AP-7 through AP-10. Minor element concentrations are given in parts per million (ppm).

ANALYSTS AND ANALYTICAL METHODS

(1) **XRAL Laboratories, Don Mills, Ontario, Canada** (analyses from Setterholm and others, 1989)
Major elements: X-ray fluorescence spectrometry (XRF); wet chemistry for FeO, H2O, CO2
Minor and trace elements: Inductively coupled plasma spectrometry (ICP); direct current plasma spectrometry (DCP); induced nuclear neutron activation (INNA), as appropriate to the element and the technology available at the date of analysis
Rare earth elements: ICP, INNA

(2) **R. Knurr, Geochemistry Laboratory, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota, USA** (analysis of Sample SC.152.B).
Major elements: Direct current argon plasma/optical emission spectrometry (DCAP/OES), wet chemistry
Minor and trace elements: DCAP/OES
Rare earth elements: DCAP/OES

(3) **Lamont-Doherty Geological Observatory in the Laboratory of C.H. Langmuir; SUNY-StonyBrook** (analyses from Spencer, 1987)
Major elements, Sr, Rb, Ba, Zr, P, Ni, Cr, and Zn concentrations determined by direct current plasma emission spectroscopy on Beckman Instruments Spectrascan model 1 11B at Lamont-Doherty. All data reported on an anhydrous basis. Reproducibility of 1-2% for major elements, within 5% for Sr and Ba, and within 10% for other trace elements.
Rare earth element concentrations determined by isotope dilution mass spectrometry at SUNY-StonyBrook. Analytical uncertainty 1-2% or less.

(4) **XRAL Laboratories, Don Mills, Ontario, Canada** (analyses from Natural Resources Research Institute, Hauck and Heine, 1991).
Methods unknown, but probably the same as (1).

Table AP-1. Location and description of samples analyzed

Sample number*	Analyst's number[†]	Sample description	Sample location[§]	Source / Author
1	CS-1-111	Coarse-grained grayish-pink porphyritic chlorite-biotite granite with rapakivi texture. Chlorite is pseudomorphic after hornblende and/or pyroxene due surficial weathering.	Cold Spring quadrangle, 123-30-19 ACB drill hole CS-1	Setterholm and others, 1989
2	EM-2-81	Coarse-grained, dark green, porphyritic orthopyroxene-bearing biotite-hornblende charnockitic granite with rapakivi texture. Trachytoid foliation strike N50E, near vertical.	Cold Spring quadrangle 123-30-29 BB	Spencer, 1987
3	SC.152.B	Medium-grained, weakly porphyritic, apatitic ferrodiorite or jotunite, contains oxide minerals, clinopyroxene, orthopyroxene, and amphibole, 11% K-feldspar and 61% plagioclase. Trachytoid foliation strike N30E, 75°W.	Cold Spring quadrangle 130-30-30 AAABB	Rick Knurr University of Minnesota
4	EM 17A-81	Light gray, coarse-grained porphyritic biotite granite with rapakivi texture. Quarry just north of State Highway 23 on east edge of Rockville. Marketed as ‘Rockville Beige’ by Cold Spring Granite Company.	Rockville quadrangle 123-29-9 CDA	Spencer, 1987
5	EM 16D-81	Pinkish-gray, coarse-grained porphyritic hornblende-biotite granite with rapakivi texture. Marketed as ‘Diamond Pink’ by Cold Spring Granite Company.	St. Joseph quadrangle 124-29-26 AA	Spencer, 1987
6	SJ-1-156	Pinkish-green, coarse-grained, porphyritic hornblende-biotite granite. Greenish color due to slight surficial weathering.	St. Joseph quadrangle 124-29-24 CDB drill hole SJ-1	Setterholm and others, 1989
7	B90037	Gray, medium-grained horblende-biotite granodiorite.	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DAA	Hauck and Heine, 1991
8	B90043	Gray, medium-grained horblende-biotite granodiorite	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DAA	Hauck and Heine, 1991
9	EM 5A-81	Pinkish-gray, medium-grained hornblende-biotite granodiorite.	Cable quadrangle 35-30-6 CD	Spencer, 1987
10	EM 5B-81	Gray, medium-grained hornblende biotite granodiorite	Cable quadrangle 35-30-6 CD	Spencer, 1987
11	EM 6A-81	Gray, medium-grained hornblende-biotite granodiorite	St. Cloud quadrangle 35-31-34 BC	Spencer, 1987
12	SA-1-119	Pink and black, medium-grained, equigranular hornblende biotite granite.	St. Augusta quadrangle 123-27-19 CBA drill hole SA-1, 119 ft depth	Setterholm and others, 1989
13	B90035	Gray, fine-grained dioritic mafic enclave in Reformatory granodiorite	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DAA	Hauck and Heine, 1991
14	B90039	Gray medium-grained dioritic enclave in Reformatory granodiorite	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DAA	Hauck and Heine, 1991
15	B90034	Pegmatitic St. Cloud Granite	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DAA	Hauck and Heine, 1991

***** sample number assigned for use in this publication (see Appendix tables AP-2 through AP-10)

[†] numbers assigned to samples by original collectors / analysts; see reference indicated for original data

[§] sample locations are given in the TRS/ABCD system; see introduction to Appendix for description

Table AP-1 continued...

Sample number*	Analyst's number†	Sample description	Sample location§	Source / Author
16	B90038	Pink and black, medium-coarse-grained biotite-hornblende granite	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DAA	Hauck and Heine, 1991
17	B90042	Pink and black, medium-coarse-grained biotite-hornblende granite	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DAA	Hauck and Heine, 1991
18	EM 20A-81	Pink, medium-grained weakly porphyritic biotite-hornblende granite	St. Cloud quadrangle 124-28-19 DD	Spencer, 1987
19	EM 20B-81	Pink, medium-grained biotite granite from 15-cm wide microcline-rich dike that cuts Reformatory granodiorite.	St. Cloud quadrangle 124-28-19 DD	Spencer, 1987
20	EM 7B-81	Pink, coarse-grained biotite-hornblende granite	St. Cloud quadrangle 124-28-29 ADB	Spencer, 1987
21	EM 8A-81	Purplish-pink granite dike that cuts Reformatory granodiorite	St. Cloud quadrangle 124-28-32 BB	Spencer, 1987
22	EM 8B-81	Pink coarse-grained biotite-hornblende granite with blocky microcline crystals	St. Cloud quadrangle 124-28-32 BB	Spencer, 1987
23	EM 4A-81	Pink, medium-grained biotite granite from dike that cuts Reformatory granodiorite	Cable quadrangle 35-30-6 CD and DC	Spencer, 1987
24	EM 4B-81	Pink, coarse-grained biotite-hornblende granite with blocky K-feldspar crystals up to 1 cm in length	Cable quadrangle 35-30-6 CD and DC	Spencer, 1987
25	B90036	Quartz- and orthoclase-porphyritic microgranite from a dike coeval with a diabasic mafic dike	north wall, Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DAB	Hauck and Heine, 1991
26	B90040	Dark gray, fine-grained diabase, northeast-trending dike	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DDB	Hauck and Heine, 1991
27	B90041	Dark gray, fine-grained diabase, northeast-trending dike	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DA	Hauck and Heine, 1991
28	B90049	Dark gray, fine-grained diabase, northeast-trending dike	Meridian Aggregates quarry St. Cloud quadrangle 124-28-18 DA	Hauck and Heine, 1991

***** sample number assigned for use in this publication (see Appendix tables AP-2 through AP-10)

† numbers assigned to samples by original collectors / analysts; see reference indicated for original data

§ sample locations are given in the TRS/ABCD system; see introduction to Appendix for description

Table AP-2. Major element and normative compositions of Richmond granite samples

[major elements in weight percent oxides; minor elements in parts per million; -, no data; bolded numbers are those reported; normative compositions calculated from whole rock analyses using IGPET by Terrasoft Inc.]

Sample	**1**	**2**	**3**
Analyst	1	3	2
SiO_2	62.3	64.4	54.13
TiO_2	1.04	0.85	2.1
Al_2O_3	16.3	15.66	16.69
CaO	1.98	3.02	6.73
MgO	1.03	1.05	2.56
Na_2O	3.58	3.69	3.88
K_2O	4.2	4.83	1.92
*Fe_2O_3	2.29	-	13.36
FeO	3.6	5.87	-
MnO	-	0.08	0.18
P_2O_5	0.38	0.28	0.84
LOI	2.39	-	-
H_2O+	2.2	-	-
CO_2	0.36	-	-
Total	99.8	99.7	102.4
§FeO(t)	-	**5.87**	-
¶Fe_2O_3(t)	**6.29**	-	**13.36**
Rb	102	89	19.1
Sr	299	285	433.87
Ba	1800	1935	1550
Zr	473	571	615
Mn	380		
Normative compositions			
An	18.6	26.4	39.2
Q	20.4	14.8	4.6
or	26.4	28.8	11.4
ab	34.2	33.5	35.1
an	7.8	12.0	22.6
C	3.7		
di		1.0	4.4
hy	3.0	5.6	13.4
wo			
ol			
mt	0.9	2.5	3.8
il	1.5	1.2	2.9
hem	1.3		
ti			
ap	0.8	0.6	1.8
Q’	23.0	16.6	6.3
ANOR	22.8	29.4	66.4

* Fe_2O_3 calculated from Fe_2O_3 (t) and FeO on basis of stoichiometry; where FeO is not reported this is Fe_2O_3(t)

§ Total measured iron reported as FeO

¶ Total measured iron reported as Fe_2O_3

Table AP-3. Major-elemment and normative compositions of Rockville Granite samples

[major elements in weight percent oxides; minor elements in parts per million; -, no data; bolded numbers are those reported; normative compositions calculated from whole rock analyses using IGPET by Terrasoft Inc.]

Sample	**4**	**5**	**6**
Analyst	3	3	1
SiO_2	67.7	66.3	66.7
TiO_2	0.57	0.63	0.54
Al_2O_3	15.14	16.2	15.7
CaO	2.48	2.72	1.9
MgO	0.81	0.85	0.69
Na_2O	3.82	3.83	3.71
K_2O	4.22	4.93	5.25
*Fe_2O_3	-	-	1.43
FeO	4.71	5.09	2.5
MnO	0.06	0.07	-
P_2O_5	0.18	0.17	0.15
LOI	-	-	1.08
H_2O+	-	-	0.9
CO_2	-	-	0.28
Total	99.7	100.8	100.3
§FeO(t)	**4.71**	**5.09**	-
¶Fe_2O_3(t)	-	-	**4.21**
Rb	141	133	156
Sr	212	257	275
Ba	1192	1857	2230
Zr	379	415	384
Mn			480
Normative compositions			
An	24.5	26.5	20.2
Q	20.7	15.8	19.4
or	25.2	29.1	32.0
ab	34.7	34.3	34.3
an	11.3	12.4	8.7
C	0.2	0.0	0.9
di	-	-	-
hy	4.6	5.0	2.0
wo	-	-	-
ol	-	-	-
mt	2.2	2.2	0.4
il	0.8	0.9	0.8
hem	-	-	1.2
ti	-	-	-
ap	0.4	0.4	0.3
Q’	22.5	17.3	20.6
ANOR	30.9	29.8	21.4

* Fe_2O_3 calculated from Fe_2O_3 (t) and FeO on basis of stoichiometry; where FeO is not reported this is Fe_2O_3(t)

§ Total measured iron reported as FeO

¶ Total measured iron reported as Fe_2O_3

Table AP-4. Major-element and normative compositions of Reformatory granodiorite and mafic enclaves

[major elements in weight percent oxides; minor elements in parts per million; -, no data; bolded numbers are those reported; normative compositions calculated from whole rock analyses using IGPET by Terrasoft Inc.]

	Reformatory granodiorite						mafic enclaves	
Sample	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Analyst	4	4	3	3	3	1	4	4
SiO$_2$	64.6	66.1	63.6	62.8	64.1	63.0	62.6	64.2
TiO$_2$	0.53	0.45	0.75	0.73	0.59	0.61	0.88	0.58
Al$_2$O$_3$	16.6	15.3	16.16	16.88	14.97	15.1	14.5	15.6
CaO	3.8	3	3.94	4.57	4	3.77	3.66	3.5
MgO	1.56	1.57	1.76	2.11	2.26	2.17	1.84	2.05
Na$_2$O	4.94	4.34	3.81	3.9	3.78	3.57	3.57	4
K$_2$O	2.74	4.04	3.5	2.9	3.88	3.72	3.38	3.92
*Fe$_2$O$_3$	0.68	0.87	-	-	-	1.48	1.59	1.33
FeO	2.8	2.4	5.56	5.19	4.62	2.7	5.9	2.8
MnO	0.06	0.06	0.08	0.08	0.07	0.09	0.12	0.07
P$_2$O$_5$	0.12	0.13	0.22	0.28	0.25	0.24	0.24	0.18
LOI	0.77	0.62	-	-	-	3.23	1.16	0.77
H$_2$O+	0.4	0.4	-	-	-	1.1	0.9	0.5
CO$_2$	0.04	0.06	-	-	-	1.9	0.19	0.03
Total	99.7	99.4	99.38	99.44	98.52	100.2	100.3	99.6
[§]FeO(t)	-	-	**5.56**	**5.19**	**4.62**	-	-	-
[¶]Fe2O3(t)	**3.79**	**3.54**	-	-	-	**4.48**	**8.15**	**4.44**
Rb	118	142	142	129	156	129	124	139
Sr	642	609	557	628	652	761	260	743
Ba	991	1000	1010	654	963	991	876	1040
Zr	196	199	262	127	219	194	220	223
Normative compositions								
An	25.3	21.0	32.7	36.3	26.8	30.7	29.7	26.6
Q	14.9	16.8	15.3	14.7	15.2	17.5	17.4	15.8
or	16.4	24.4	20.9	17.3	23.3	23.1	20.8	23.8
ab	45.0	39.8	34.6	35.3	34.5	33.7	33.4	36.9
an	15.2	10.6	16.8	20.1	12.6	14.9	14.1	13.4
C	-	-	-	-	-	-	-	-
di	2.5	3.0	1.2	0.7	4.7	2.5	2.5	2.6
hy	3.1	2.9	7.3	8.0	6.1	5.1	7.3	4.5
wo	-	-	-	-	-	-	-	-
ol	-	-	-	-	-	-	-	-
mt	1.3	0.7	2.4	2.3	2.2	0.8	2.6	1.1
il	0.7	0.6	1.1	1.0	0.8	0.9	1.3	0.8
hem	0.6	0.9	-	-	-	1.0	-	0.7
ti	-	-	-	-	-	-	-	-
ap	0.3	0.3	0.5	0.6	0.5	0.5	0.5	0.4
Q'	16.3	18.4	17.4	16.8	17.8	19.6	20.2	17.5
ANOR	48.1	30.2	44.6	53.9	35.1	39.2	40.4	36.0

* Fe$_2$O$_3$ calculated from Fe$_2$O$_3$ (t) and FeO on basis of stoichiometry; where FeO is not reported this is Fe$_2$O$_3$(t)

[§] Total measured iron reported as FeO

[¶] Total measured iron reported as Fe$_2$O$_3$

Table AP-5. Major-element and normative compositions of St. Cloud Granite samples

[major elements in weight percent oxides; minor elements in parts per million; -, no data; bolded numbers are those reported; normative compositions calculated from whole rock analyses using IGPET by Terrasoft Inc.]

Sample	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Analyst	4	4	4	3	3	3	3	3	3	3
SiO_2	72.0	70.8	67.8	73.8	67.08	73.4	74.8	71.2	71.3	74.2
TiO_2	0.08	0.28	0.23	0.24	0.18	0.26	0.23	0.3	0.37	0.24
Al_2O_3	14.7	13.8	15.6	12.72	17.81	13.3	12.8	14.11	14.33	12.67
CaO	1.27	1	1.22	0.77	0.87	0.85	1.01	1.03	1.58	0.77
MgO	0.53	0.22	0.55	0.17	0.14	0.09	0.35	0.1	0.56	0.09
Na_2O	3.33	3.75	4.04	3.18	4.25	3.33	3.3	3.52	3.12	3.42
K_2O	6.08	6.01	6.74	5.69	8.06	5.86	4.98	6.11	5.65	5.62
*Fe_2O_3	0.15	0.32	0.56	-	-	-	-	-	-	-
FeO	0.8	2.5	1.4	2.87	2.02	2.75	2.06	3.07	2.55	2.69
MnO	0.02	0.04	-	0.04	0.02	0.04	0.03	0.05	0.03	0.05
P_2O_5	0.13	0.03	0.06	0.04	0.02	0.03	0.06	0.04	0.11	0.03
LOI	0.62	0.54	0.62	-	-	-	-	-	-	-
H_2O+	0.3	0.5	0.4	-	-	-	-	-	-	-
CO_2	0.05	0.05	0.05	-	-	-	-	-	-	-
Total	99.9	99.8	99.4	99.52	100.5	99.92	99.62	99.53	99.6	99.78
§FeO(t)	-	-	-	**2.87**	**2.02**	**2.75**	**2.06**	**3.07**	**2.55**	**2.69**
¶Fe_2O_3(t)	**1.04**	**3.10**	**2.12**	-	-	-	-	-	-	-
Rb	127	144	180	153	229	134	135	116	176	122
Sr	265	95	224	79	230	134	135	116	176	122
Ba	688	1170	2100	363	1734	744	893	1207	1298	335
Zr	60	514	644	329	333	347	147	468	222	396
Mn	-	-	27	-	-	-	-	-	-	-
Normative compositions										
An	15.4	8.4	11.1	11.1	9.9	11.9	13.5	12.8	20.3	7.9
Q	24.6	22.7	14.6	29.7	8.7	27.7	32.0	23.3	25.9	29.3
or	36.4	36.2	40.5	34.3	46.9	35.1	29.9	36.6	33.8	33.7
ab	30.3	34.4	36.9	29.1	37.6	30.3	30.1	32.0	28.4	31.2
an	5.5	3.1	4.6	3.6	4.1	4.1	4.7	4.7	7.2	2.7
C	0.7	-	-	0.0	0.6	0.0	0.3	-	0.5	-
di	-	1.2	0.3	-	-	-	-	0.2	-	0.8
hy	1.5	-	1.4	1.0	0.4	0.5	1.0	0.9	1.6	0.1
wo	-	0.1	-	-	-	-	-	-	-	-
ol	-	-	-	-	-	-	-	-	-	-
mt	-	1.6	-	1.9	0.8	1.9	0.8	1.9	1.3	1.8
il	0.0	0.4	-	0.3	0.2	0.4	0.3	0.4	0.5	0.3
hem	0.6	0.2	1.1	-	0.6	-	0.7	-	0.4	-
ti	-	-	0.5	-	-	-	-	-	-	-
ap	0.3	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.2	0.1
Q'	25.4	23.5	15.1	30.7	8.9	28.6	33.1	24.1	27.2	30.3
ANOR	13.2	8.0	10.2	9.6	8.1	10.4	13.6	11.4	17.6	7.3

* Fe_2O_3 calculated from Fe_2O_3 (t) and FeO on basis of stoichiometry; where FeO is not reported this is Fe_2O_3(t)

§ Total measured iron reported as FeO

¶ Total measured iron reported as Fe_2O_3

Table AP-6. Major-element and mormative compositions of porphyritic microgranite dike and diabase dike samples

[major elements in weight percent oxides; minor elements in parts per million; -, no data; bolded numbers are those reported; normative compositions calculated from whole rock analyses using IGPET by Terrasoft Inc.]

	porphyritic microgranite	diabase		
Sample	**25**	**26**	**27**	**28**
Analyst	4	4	4	4
SiO_2	73.0	49.7	49.0	51.4
TiO_2	0.21	1.19	0.83	1.22
Al_2O_3	13.2	15.6	15.3	15.8
CaO	0.73	7.82	8.03	7.74
MgO	0.29	7.32	8.33	6.48
Na_2O	3.99	2.56	1.98	2.76
K_2O	5.26	1.19	1.44	1.41
$^*Fe_2O_3$	1	2.42	2.66	2.18
FeO	1.3	7.9	7.5	7.3
MnO	0.04	0.19	0.17	0.16
P_2O_5	0.03	0.36	0.18	0.36
LOI	0.85	2.39	2.39	1.54
H_2O+	0.4	1.4	1.4	1.4
CO_2	0.07	0.02	0.1	0.01
Total	100.2	99.7	99.7	99.3
§FeO(t)	-	-	-	-
¶Fe_2O_3(t)	**2.44**	**11.20**	**11.00**	**10.29**
Rb	179	53	96	29
Sr	69	415	245	494
Ba	643	558	348	560
Zr	303	158	100	162
Normative compositions				
An	6.7	56.0	63.1	53.2
Q	26.5	0.6	-	2.3
or	31.8	7.3	8.9	8.6
ab	36.7	22.5	17.6	24.1
an	2.6	28.6	30.0	27.4
C	-	-	-	-
di	0.2	7.5	8.6	8.0
hy	0.7	26.6	29.0	23.0
wo	-	-	-	-
ol	-	-	0.4	-
mt	-	3.6	3.5	3.3
il	0.1	2.3	1.7	2.4
hem	1.0	-	-	-
ti	0.4	-	-	-
ap	0.1	0.9	0.4	0.9
Q’	27.1	1.0	-	3.7
ANOR	7.6	79.7	77.1	76.1

* Fe_2O_3 calculated from Fe_2O_3 (t) and FeO on basis of stoichiometry; where FeO is not reported this is Fe_2O_3(t)

§ Total measured iron reported as FeO

¶ Total measured iron reported as Fe_2O_3

Table AP-7. Minor-element composition of Richmond and Rockville Granite samples

[minor elements in parts per million; -, no data]

	Richmond			Rockville		
Sample	**1**	**2**	**3**	**4**	**5**	**6**
Analyst	1	3	2	3	3	1
Nb	38	-	-	-	-	23
U	1.1	-	0.618	-	-	3.7
Th	2	-	1.19	-	-	7
Pb	10	-	10.94	-	-	10
Zr	473	571	615	379	415	384
Hf	13	-	13.19	-	-	11
Ga	27	-	24.94	-	-	20
Y	48	38	48.13	34	30	23
Cs	<1	-	0.043	-	-	4
La	56	-	81.23	-	-	53
Ce	127	245	196.52	194.6	109.7	103
Pr	-	-	23.15	-	-	-
Nd	71.7	90.6	94.81	71	49.8	43.3
Sm	12.5	13.1	15.99	10.9	8.52	7.2
Eu	2	2.26	3.53	1.56	1.82	1.7
Gd	9.9	8.48	14.44	7.21	6.01	5.4
Dy	8.4	6.53	10	5.91	5.07	4.3
Ho	-	-	1.94	-	-	-
Er	4.2	3.36	5.35	3.19	2.77	2.4
Tm	-	-	0.71	-	-	-
Yb	-	2.79	4.47	2.78	2.51	
Lu	0.4	-	0.67	-	-	0.3
Co	-	-	25.5	-	-	-
Cr	12	22	7.03	50	27	18
Cu	28	-	67.1	-	-	10
Ni	11	7	10.11	11	14	16
Be	-	-	1.36	-	-	-
Sc	-	11	-	9	11	-
Tb	-	-	-	-	-	-
V	50	52	168	43	45	40
Zn	79	98	191.3	82	96	79

Table AP-8. Minor-element composition of Reformatory granodiorite samples

[minor elements in parts per million; -, no data]

Sample	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Analyst	4	4	3	3	3	1	4	4
Nb	25	22	-	-	-	13	15	23
U	4.3	7.9	-	-	-	3.6	5.1	8.5
Th	12	14	-	-	-	15	10	19
Pb	3	22	-	-	-	16	10	2
Zr	196	199	262	127	219	194	220	223
Hf	6	5	-	-	-	5	7	8
Ga	-	-	-	-	-	20	-	-
Y	15	21	26.5	28	21.5	11	34	29
Cs	3	4	-	-	-	2	4	4
La	41.2	59.1	-	-	-	58	48.8	62.6
Ce	74	107	110.5	108	113	113	92	111
Pr	-	-	-	-	-	-	-	-
Nd	33	39	46.5	47.2	48.4	47.5	40	45
Sm	6.3	6.1	7.81	8	8.25	7	7.6	7.9
Eu	1.3	1.3	1.75	1.6	1.75	1.7	1.7	1.3
Gd	-	-	5.31	5.48	5.34	5.4	-	-
Dy	-	-	4.12	4.11	3.63	3.2	-	-
Ho	-	-	-	-	-	-	-	-
Er	-	-	2.31	2.1	1.7	1.5	-	-
Tm	-	-	-	-	-	-	-	-
Yb	2.4	1.7	-	-	-	-	-	-
Lu	0.31	0.19	-	-	-	0.2	0.35	0.23
Co	9	10	-	-	-	-	22	13
Cr	180	150	43	35	64.5	40	140	190
Cu	4.9	14.9	-	-	-	10	19	11.4
Ni	2	6	18	22	21	16	<1	5
Be	3	4	-	-	-	-	4	4
Sc	8.6	7.3	11	11	9.5	-	21.4	9
Tb	0.6	0.9	-	-	-	-	0.9	0.7
V	65	67	77	89	80	80	123	76
Zn	71.3	78.4	94	92	74	91	104	66.8

Table AP-9. Minor-element composition of St. Cloud Granite samples

[minor elements in parts per million; -, no data]

Sample	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Analyst	4	4	4	3	3	3	3	3	3	3
Nb	-	11	15	-	-	-	-	-	-	-
U	9.2	3.7	5	-	-	-	-	-	-	-
Th	5	12	19	-	-	-	-	-	-	-
Pb	13	7	22	-	-	-	-	-	-	-
Zr	60	514	644	329	333	347	147	468	222	396
Hf	2	13	16	-	-	-	-	-	-	-
Ga	-	-	-	-	-	-	-	-	-	-
Y	21	14	47	-	-	-	-	18.5	-	-
Cs	4	2	3	-	-	-	-	-	-	-
La	14.7	95.7	146	-	-	-	-	-	-	-
Ce	25	164	249	311	104.4	245	102.6	182	-	221
Pr	-	-	-	-	-	-	-	-		-
Nd	10	57	84	106	33.25	95	37.9	68.2	52.2	89.7
Sm	1.5	8.7	11.9	12.26	4.04	12.67	5.87	9.05	7.35	13.62
Eu	1.1	1.7	1.5	0.98	1.63	1.12	1.07	1.51	1.08	0.69
Gd	-	-	-	6.15	2.17	7.32	3.8	5.44	4.29	8.37
Dy	-	-	-	3.81	1.49	5.02	2.82	3.81	-	5.98
Ho	-	-	-	-	-	-	-	-	-	-
Er	-	-	-	1.92	0.91	2.59	1.43	2.06	-	3.05
Tm	-	-	-	-	-	-	-	-	-	-
Yb	0.4	2.6	3	1.79	1.01	2.4	1.34	2.05	1.29	2.81
Lu	<0.05	0.39	0.43	-	-	-	-	-	-	-
Co	3	3	2	-	-	-	-	-	-	-
Cr	80	88	65	-	-	-	-	6	-	-
Cu	3	1.4	3.4	-	-	-	-	-	-	-
Ni	3	<1	<1	-	-	-	-	5	-	-
Be	5	3	2	-	-	-	-	-	-	-
Sc	1.6	6	8.8	-	-	-	-	6	-	-
Tb	<0.5	0.8	1.1	-	-	-	-	-	-	-
V	12	14	20	-	-	-	-	17	-	-
Zn	20	83.9	58.6	-	-	-	-	81	-	-

Table AP-10. Minor-element composition of porphyritic microgranite and diabase dike samples

[minor elements in parts per million; -, no data]

	porphyritic microgranite	diabase		
Sample	**25**	**26**	**27**	**28**
Analyst	4	4	4	4
Nb	24	26	17	25
U	7.7	-	1.6	2.1
Th	23	4	2	4
Pb	8	-	-	-
Zr	303	158	100	162
Hf	9	4	3	4
Ga	-	-	-	-
Y	42	20	19	27
Cs	1	4	7	2
La	101	34.8	15.7	38.5
Ce	179	59	29	68
Pr	-	-	-	-
Nd	68	26	13	29
Sm	11.5	4.5	2.4	4.9
Eu	0.9	1.6	1.1	2.1
Gd	-	-	-	-
Dy	-	-	-	-
Ho	-	-	-	-
Er	-	-	-	-
Tm	-	-	-	-
Yb	3.7	1.8	2.1	1.8
Lu	0.56	0.31	0.33	0.32
Co	2	41	47	42
Cr	91	360	500	230
Cu	4.5	28.3	49.5	34.6
Ni	<1	92	139	75
Be	5	4	4	4
Sc	2.6	29.2	32	27.7
Tb	1.2	-	-	-
V	12	189	185	220
Zn	60.9	127	113	102