

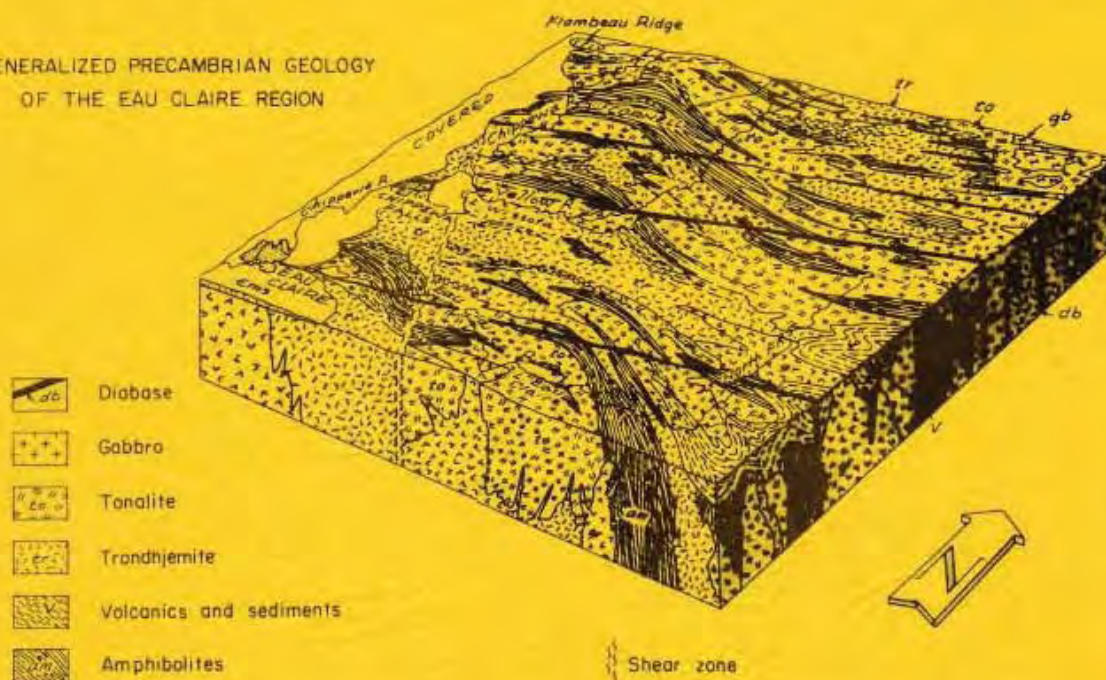
26th Annual
Institute on Lake Superior Geology



FIELD TRIP 3

Petrology, Geochemistry, and Contact
Relations of the Wausau and
Stettin Syenite Plutons, Central Wisconsin

GENERALIZED PRECAMBRIAN GEOLOGY
OF THE EAU CLAIRE REGION



May 10, 1980

University of Wisconsin-Eau Claire

26TH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY

FIELD TRIP #3

THE PETROLOGY, GEOCHEMISTRY AND CONTACT RELATIONS
OF THE STETTIN AND WAUSAU SYENITE PLUTONS
CENTRAL WISCONSIN

by

Mohan K. Sood
Department of Earth Sciences
Northeastern Illinois University
Chicago, Illinois 60625

Paul E. Myers
Department of Geology
University of Wisconsin
Eau Claire, Wisconsin 54701

Louis A. Berlin
Department of Earth Sciences
Northeastern Illinois University
Chicago, Illinois 60625

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INTRODUCTION

Alkaline igneous rocks are characterized by the presence of alkali feldspars, sodic pyroxenes, amphiboles, and feldspathoids or quartz. Generally, a high content of volatiles (Cl, F, H₂O, S, CO₂), rare elements (Nb, Ti, Zr, REE, Ta, Bi, and Be), and the presence of unusual volatile bearing minerals (sodalite, eudialite, aenigmatite, astrophyllite, villaumite, etc.) impart alkaline rocks a character of extreme chemical and mineralogical heterogeneity (Sorenson, 1974)--thus representing an interesting physiochemical system of magmatic crystallization.

Alkaline rocks commonly occur in the following tectonic settings:

- a. Tectonically stable regions of the crust--continental platforms and Precambrian shield areas of North America
- b. Rift zones--East African Rift, Rhine-Oslo Graben, Montserrat Province
- c. The intersection of fault zones--Greenland (Sorenson, 1970, 1974)

GEOLOGY AND GEOCHRONOLOGY OF CENTRAL WISCONSIN

The work of Weidman (1907) is the first effort to systematically describe the geology of north central Wisconsin. Recent re-examination of the area has been by LaBerge (1969, 1971), LaBerge and Myers (1972, 1973) and Myers (1973) in refinement of geological mapping and interpretation, Medaris et al. (1973) on the geology of the Wolf River Batholith, Van Schmus (1973), Van Schmus et al. (1980) in geochronological investigations of the region. Koellner (1974) on mineral chemistry, Berlin and Sood (1979) on geochemistry and petrogenetic models.

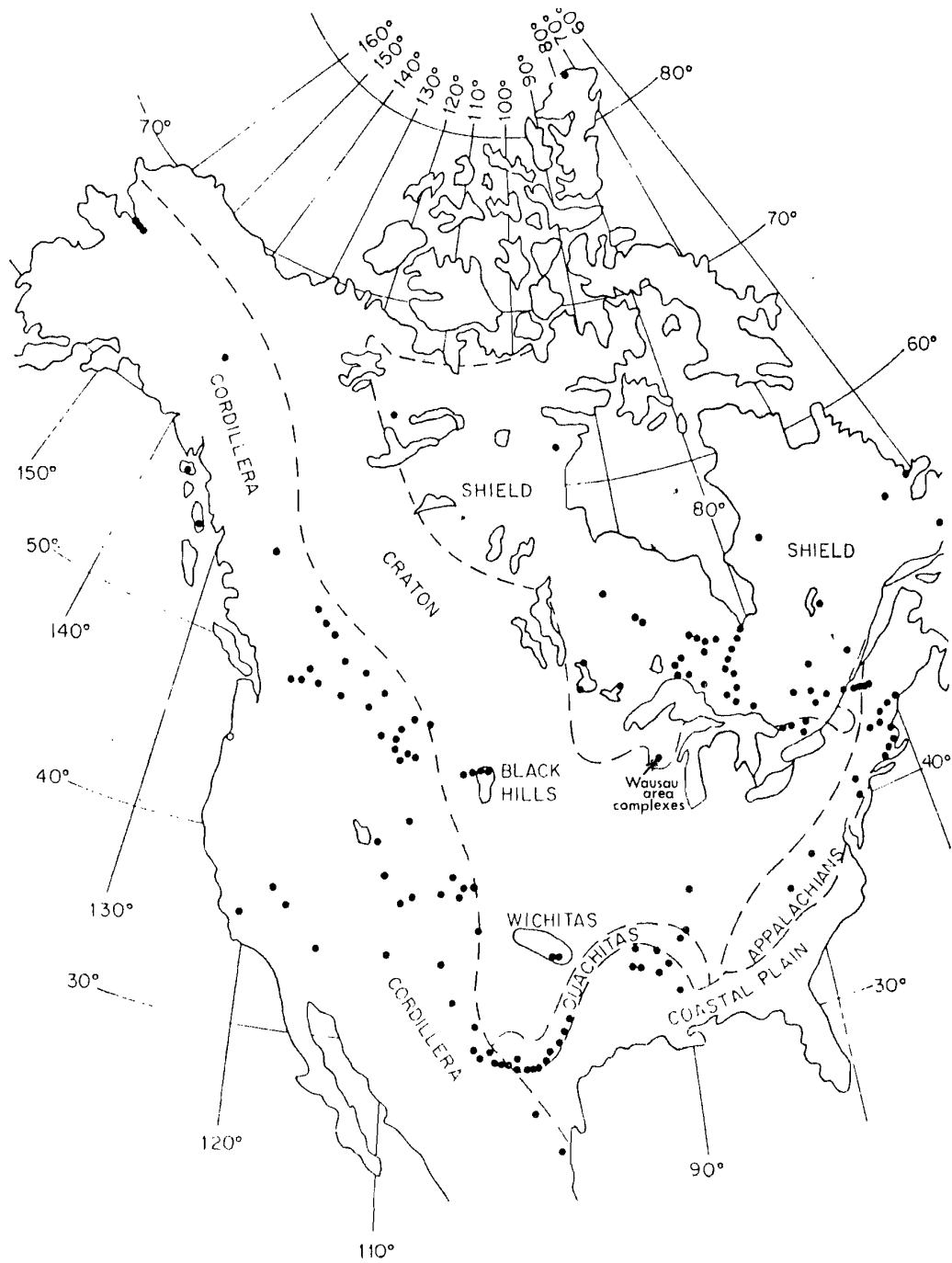


FIGURE 1

Occurrences of Alkaline Rocks of North America.
The tectonic boundaries are generalized. (From Barbee, 1976)

The oldest rocks of the region are basement gneisses, schists, amphibolites, and migmatites which are exposed in the Wisconsin Rapids-Stevens Point area (Figure 6b). However, the Central Wisconsin Complex (1800-1900 m.y.) composed of metamorphosed basalts, rhyolites and trachytes (Weidman, 1907, LaBerge and Myers, 1973) and associated granitic rocks (Dutton and Bradley, 1970) form the dominant exposures. (Not if you include rhyolite and granite in southeast Wisconsin, Smith, 1978).

Intruding the Central Wisconsin Complex are the 1500 m.y. old an-orogenic Wolf River Batholith and the two Wausau Syenite plutons (Van Schmus et al., L. Medaris, Jr., et al., 1975). The Wolf River Batholith is dominantly quartz(?) monzonitic with local phases of syenites, granite, and porphyries. Isolated masses of anorthosite occur within the batholith, but their relationship to the main body is not well understood.

The Wausau Syenite Complex comprises a silica-rich phase of granitic quartz syenite-pyroxene amphibole syenite associated at Wausau and a nearly contiguous silica-poor (nepheline bearing) phase at Stettin. Both of the plutons have somewhat elliptical concentric zonal structures. (LaBerge and Myers, 1973). The geochronological stratigraphy is given in Table I. Regional geology is shown in Figure 2, Marathon County, Figure 3. Generalized geology of the two plutons is shown in Figure 4.

TABLE I
GEOCHRONOLOGICAL RELATIONS OF
THE PRECAMBRIAN ROCKS OF CENTRAL WISCONSIN

<u>Unit</u>	<u>Major Rock Types</u>	<u>Age (m.y.)</u>
Wausau Syenite Complex		
1. Stettin body	pyroxene syenite, amphibole syenite, tabular syenite, nepheline syenite	1,520*
2. Wausau body	granite, quartz syenite, pyroxene- amphibole syenite	1,520* +25
Wolf River Batholith	quartz monzonite, syenite, granite	1,500 +25
Central Wisconsin Complex	basalt-rhyolite, trachyte, quartz monzonite, granite	1,000-1,900**
Basement Complex	gneiss, migmatite, schist, granite	uncertain, 1,900*

* Van Schmus, 1980, Chronology of igneous rocks associated with the Penokean orogeny of central Wisconsin, Geol. Society of America, Spec. Pap. 182 in press.

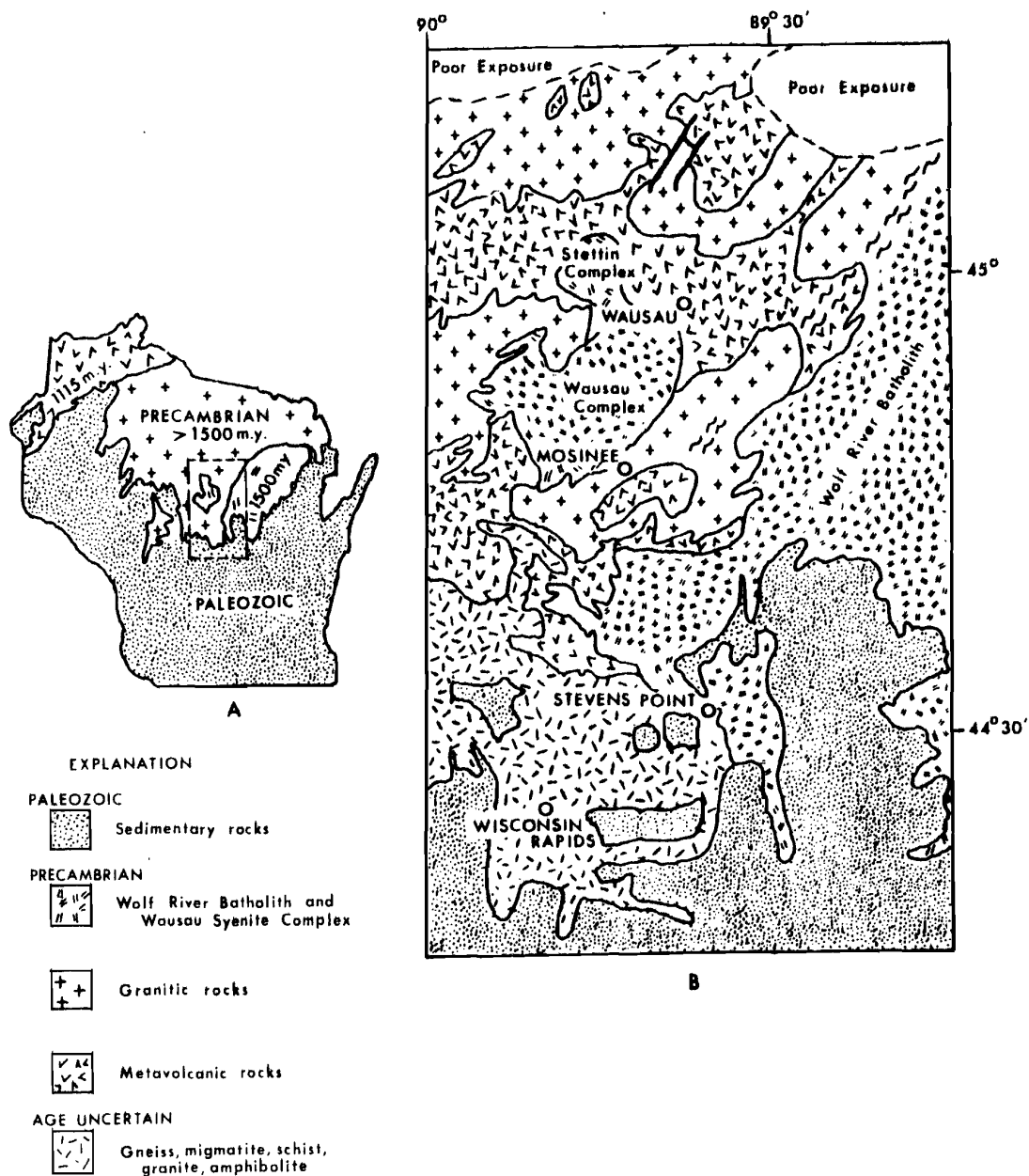


FIGURE 2

2A--Generalized geochronologic map of Wisconsin showing the location of the Wolf River Batholith and related Wausau Syenite Complex (after Van Schmus et al., 1975a)

2B--Inset of Figure 2A. Generalized geologic map of part of central Wisconsin (after Van Schmus et al., 1975b).

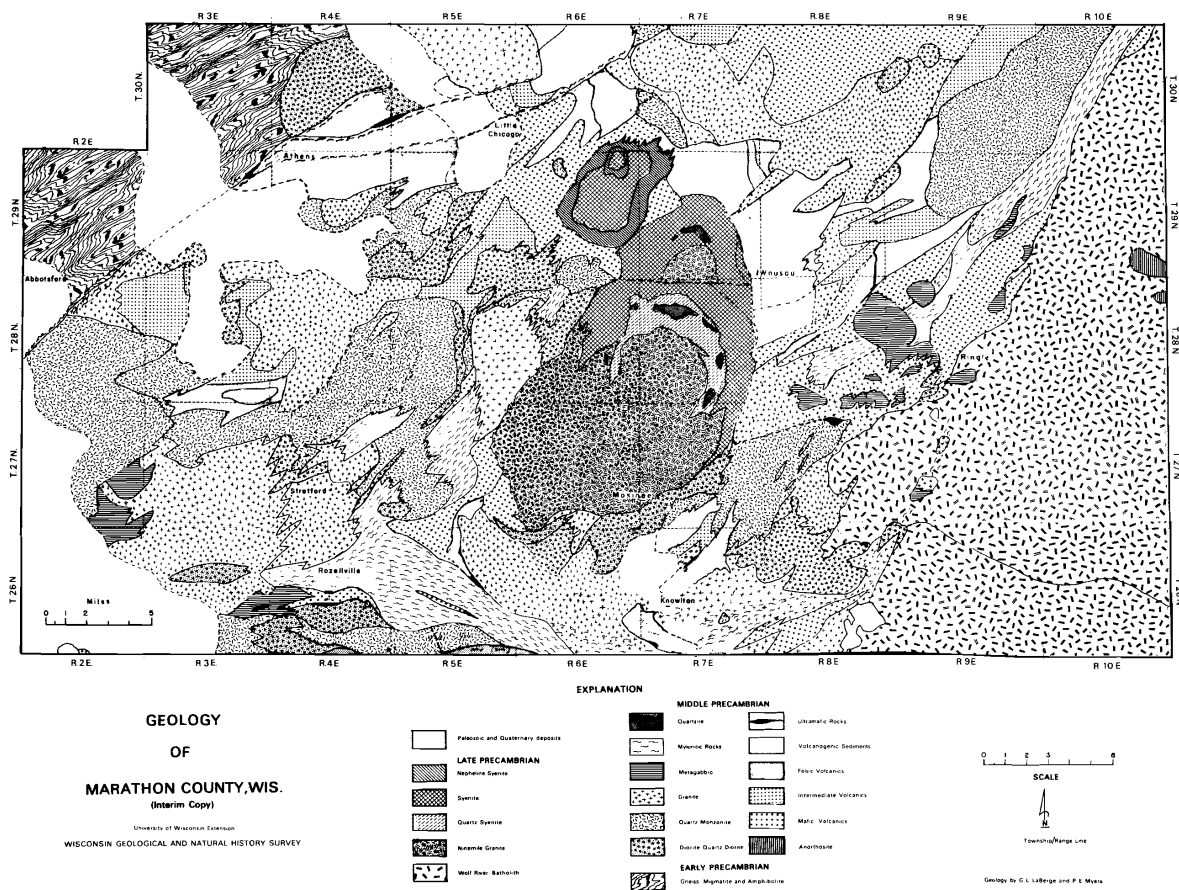


Figure 3 -- Geologic map of Marathon County by LaBerge and Myers, 1979 Wisconsin Geological and Natural History Survey, Interim Copy.

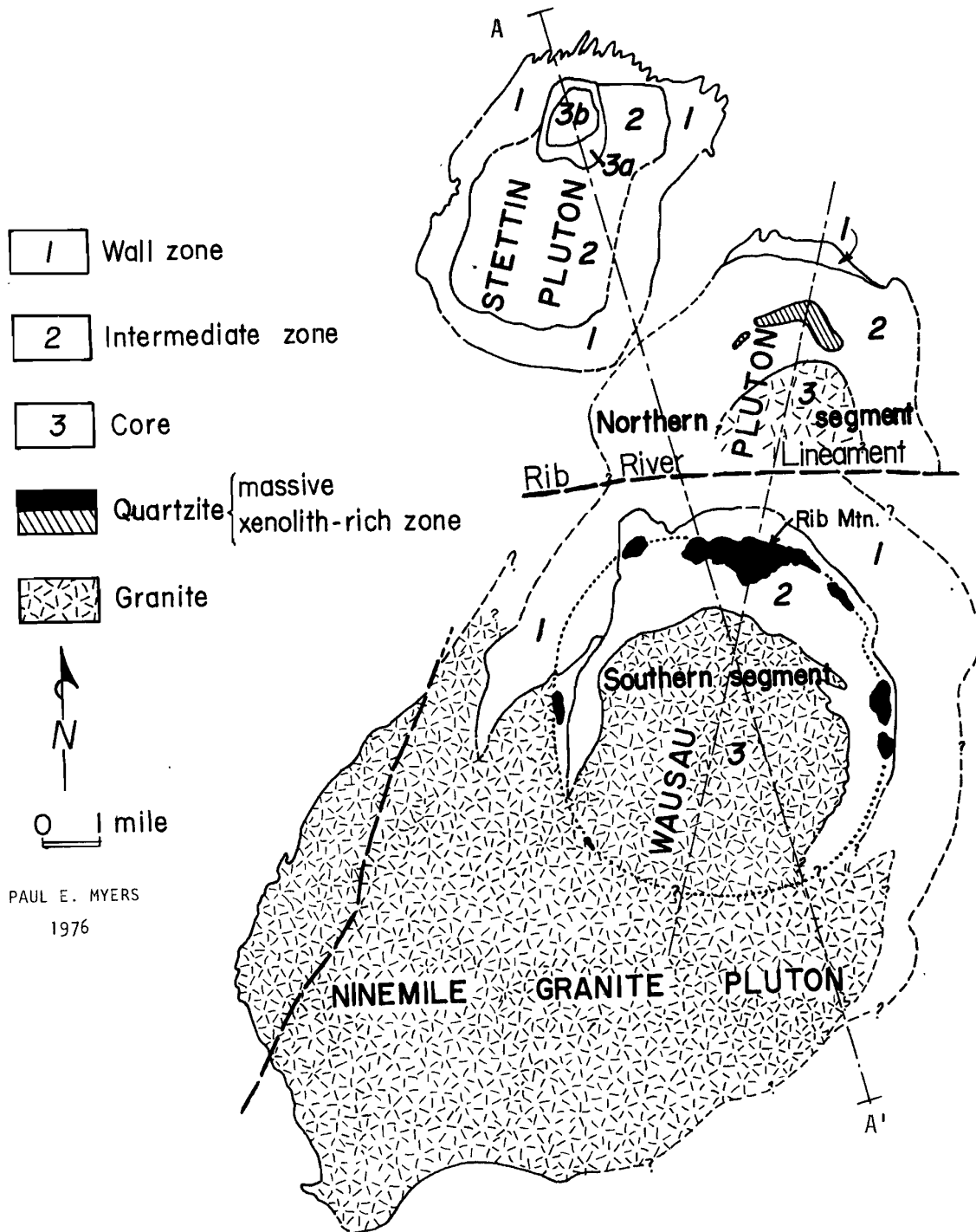


Figure 4 -- Generalized geologic map of the Wausau and Stettin syenite bodies and the Ninemile granite pluton which intrudes the Wausau syenite. Section A-A' is shown in Figure

STOP DESCRIPTIONS

NO.	TITLE	AUTHOR(S)	PAGE
1	Rib Mountain Summit Overlook	Myers	10
2	Large quartzite and biotite schist xenoliths in the core rim, Wausau syenite pluton	Myers	12
3	Flow structure of the wall zone, Wausau syenite pluton	Myers	15
4	Lensoidal quartz syenite, Employers' Mutual Insurance Company	Myers & Sood	19
5	Contact relations and minerals in the wall zone, Stettin syenite pluton	Myers & Sood	25
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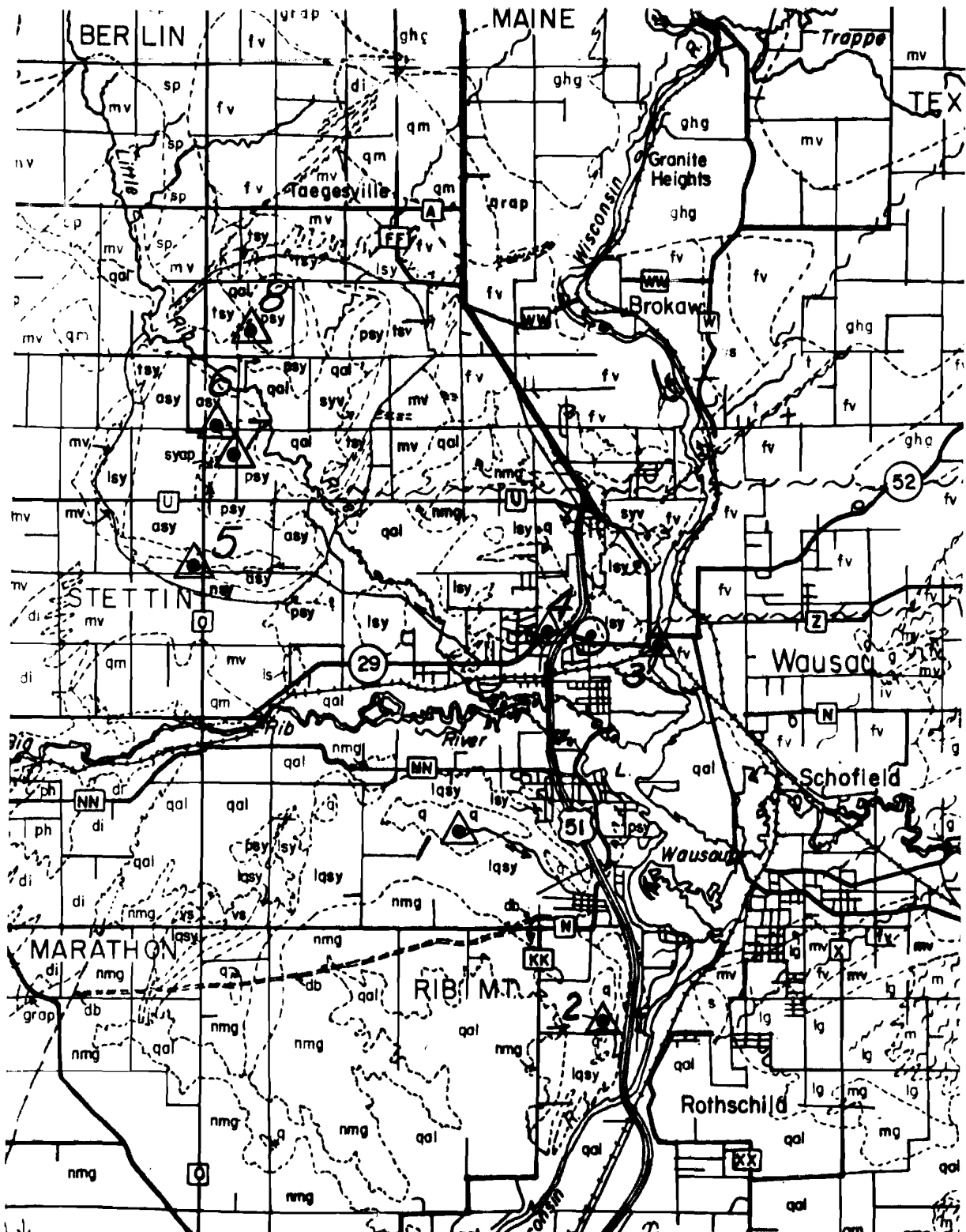


Figure 5 -- Field trip #3 route map. Geological base map by LaBerge and Myers (1979).

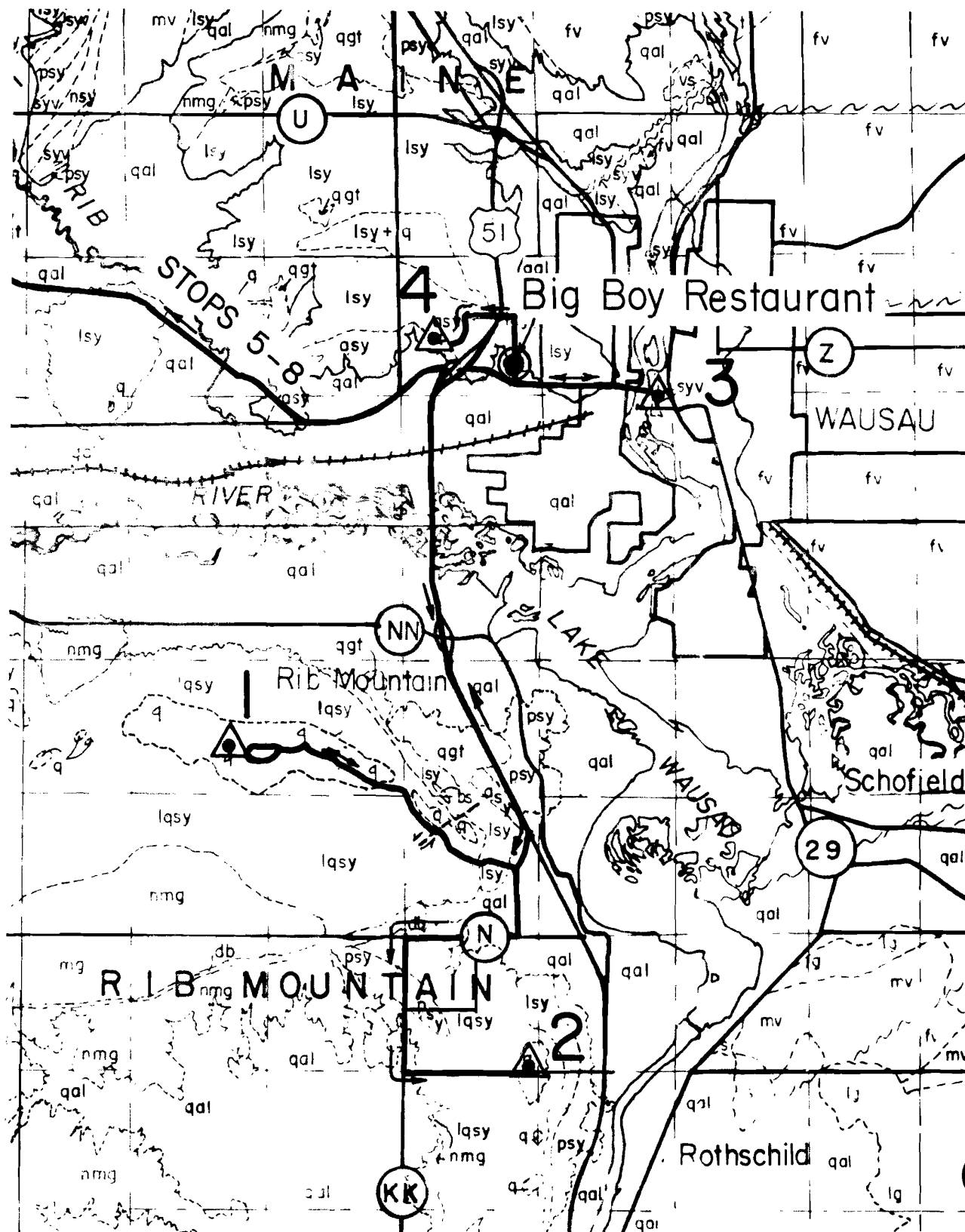
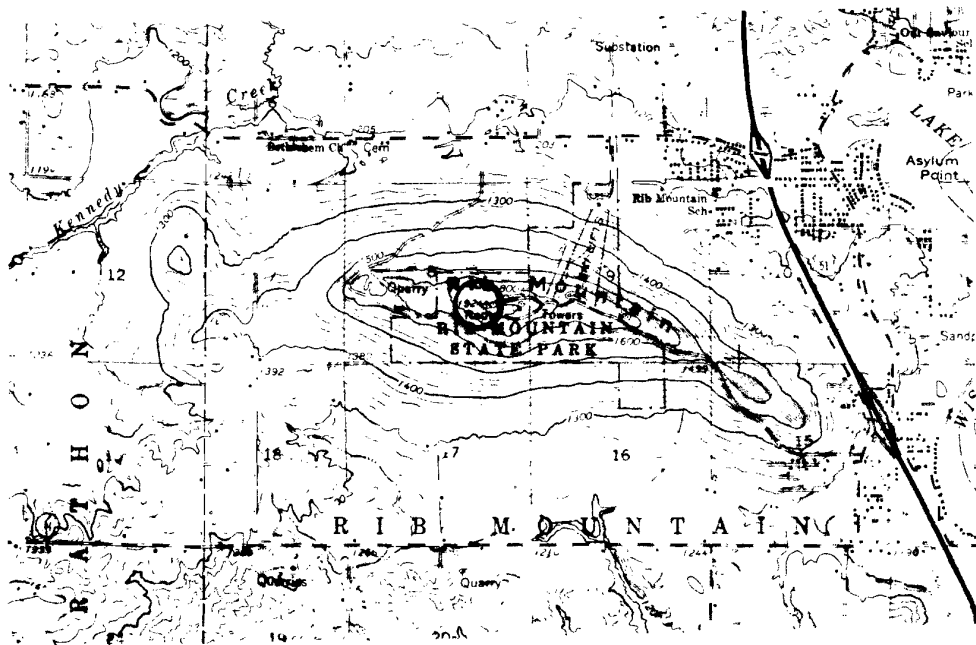


Figure 6-- Route map for stops 1 - 4 in the Wausau syenite pluton.

STOP #1

TITLE: RIB MOUNTAIN SUMMIT OVERLOOK

LOCATION: Rib Mountain State Park observation platform, SE $\frac{1}{4}$ Section 8,
T28N, R.7E., Wausau 15' quadrangle, Wausau west 7 $\frac{1}{2}$ ' quadrangle



AUTHOR: Paul E. Myers

DATE: February, 1980

SUMMARY OF FEATURES:

The Wausau syenite-quartz syenite pluton in two segments (Figure 3) and the more alkalic Stettin syenite pluton are exposed west of the Wisconsin River near Wausau in central Wisconsin. These Middle Precambrian (1520±15 m.y., Van Schmus, 1980) plutons are concentrically zoned and show a distinct north-northeasterly elongation. Each pluton has a contact metamorphic zone of syenitized wall rocks, an alkalic laminated, xenolith-rich wall zone, an intermediate zone and a core. Silica content increases inward in each pluton.

DESCRIPTION:

From this vantage point a good panorama of the region is available. Rib Mountain is the resistant remnant of a large, keel-shaped quartzite xenolith that forms a ring of xenolith five miles in diameter. To the south-east Mosinee Hill and to the southwest, Hardwood Hill are similar xenoliths of this ring structure. The flat, swampy area to the south is underlain by

the younger Ninemile pluton which intruded the southern part of the Wausau pluton. Parts of the quartz syenite rim and xenolithic masses are embedded in the Ninemile pluton.

The southern segment of the Wausau pluton is circular in plan with a diameter of eight miles. Although the core and south half of this caldera-like structure were intruded by quartz monzonite of the Ninemile pluton, its structure is preserved as a discontinuous ring of large xenoliths five miles in diameter. The largest of these xenoliths--Rib Mountain quartzite is over two miles long. Bedding in the xenolith dips steeply southward toward the core. The top of the xenolith has been eroded leaving a keel-shaped mass, slightly convex northward, and surrounded at depth by quartz syenite of the crescentic intermediate zone. Quartzite xenoliths near intrusive contacts are typically veined and impregnated by K-feldspar. Pyroxene and amphibole syenite, commonly containing volcanic xenoliths, form a discontinuous outer rim (wall zone) of the southern segment.

The northern segment of the Wausau pluton is semicircular in plan with its truncated southern edge along the Rib River. The Stettin pluton is contiguous with it on the northwest. Although its size and internal structure are similar to that of the southern segment, its intermediate zone consists of coarse gray syenite, and volcanic xenoliths predominate. The older northern segment probably represents a caldera structure, which was partially destroyed by intrusion of the southern segment.

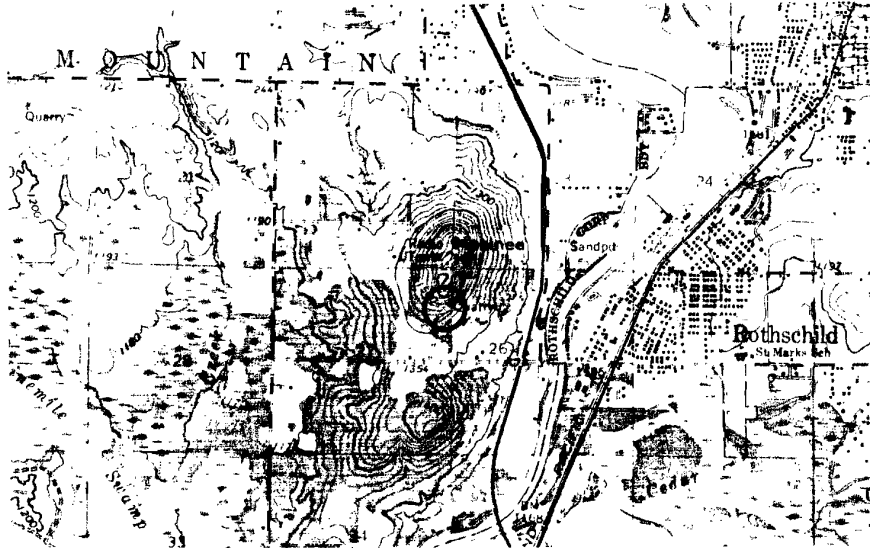
The more alkaline Stettin pluton, northwest of here, is oval in plan with dimensions of 5.0 x 3.5 miles. Three major zones distinguished in mapping where: (1) a wall zone comprising aplitic biotite syenite, nepheline syenite gneiss, and "tabular syenite", (2) an intermediate zone consisting of coarse grained amphibole and pyroxene syenite with swirled flow lineation, and (3) a circular core zone one mile in diameter comprising a rim of magnetite-rich nepheline-hedenbergite-fayalite syenite, and an inner core of pyroxene syenite.

Both the Wausau and Stettin plutons possess strongly metasomatized, but unassimilated xenolith-rich wall zones. Concentric cataclastic lamination was developed by high-angle displacements accompanying their forceful emplacement. Subsequent, more passive intrusion of the Ninemile granite caused a partial foundering of at least the southern part of the Wausau pluton.

STOP # 2

TITLE: Large Quartzite and Biotite Schist Xenoliths in the Core Rim, Wausau Syenite Pluton

LOCATION: South end of Mosinee Hill, NE $\frac{1}{4}$, NE $\frac{1}{4}$ Sec.27, T28N, R7E
Wausau 15' and Wausau West 7.5' quadrangles



AUTHOR: Paul E. Myers, University of Wisconsin-Eau Claire

DATE: February, 1980

SUMMARY OF FEATURES:

This abandoned 3-M quarry exposes the south end of a large quartzite xenolith and a much smaller xenolith of biotite schist (Figure 1). The lensoidal shape of the large xenoliths is extrapolated from shapes of smaller ones throughout the intermediate zone. Near its contact with quartz syenite the quartzite is impregnated with very fine-grained, interstitial pink microcline which selectively replaced certain layers in the quartzite. The abundance of interstitial K-feldspar diminishes toward the center of the quartzite xenolith. Smaller quartzite xenoliths have been thoroughly granitized. The question of whether these xenoliths were carried up or down along the cylindrical wall of the Wausau syenite pluton is still not answered.

The only significant bedrock occurrence of quartzite and biotite schist in this area is as xenoliths in the Wausau syenite pluton. The xenoliths have the following important characteristics:

1. They show concentric, zonal distribution and orientation around the quartz monzonitic core--the Ninemile pluton.

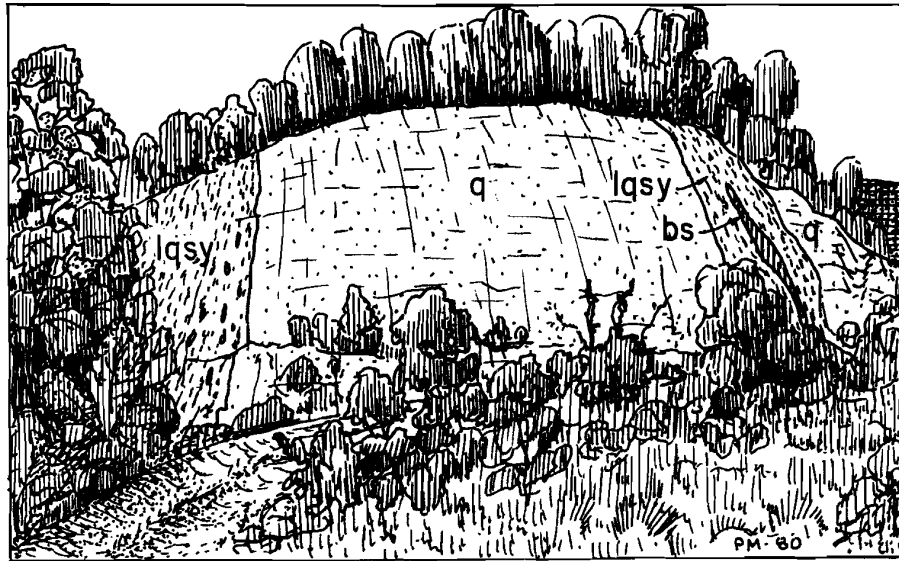


FIGURE 7. Profile of the south end of Mosinee Hill

2. The largest xenoliths occur one mile outside the core.
3. The quartzite xenoliths are the largest because of their lower susceptibility to fragmentation and assimilation.
4. Flow structure in quartz syenite and feldspar lenticulation indicate intrusion of the quartz syenite as a viscous crystal mush.
5. Mafic xenoliths were biotitized, and quartzite xenoliths were granitized through the metasomatic addition of K_2O and Al_2O_3 with selective replacement of quartzite by fine-grained microcline along bedding planes.
6. Xenoliths north of the Rib River are dominantly metavolcanic rocks, whereas the xenoliths south of Rib River are dominantly quartzite, biotite schist and very subordinate non-foliated metadiabase.
7. Quartz grains in the quartz syenite and the outer part of the Ninemile pluton are granular, subangular, coarse grained and strained.

THE NINEMILE PLUTON:

The Ninemile pluton has a granite rim containing xenocrystic quartz. Samples taken at one-mile intervals across the pluton from north to south and from west to east show a decreasing percentage of xenocrystic quartz and an increasing amount of plagioclase toward the center of the pluton. The contact at the Ninemile pluton is locally discordant, as at Black Creek 1.7 miles northwest of here. Mirolitic cavities, some filled with large quartz crystals are common along the west side of the Ninemile pluton. They indicate shallow conditions of crystallization.

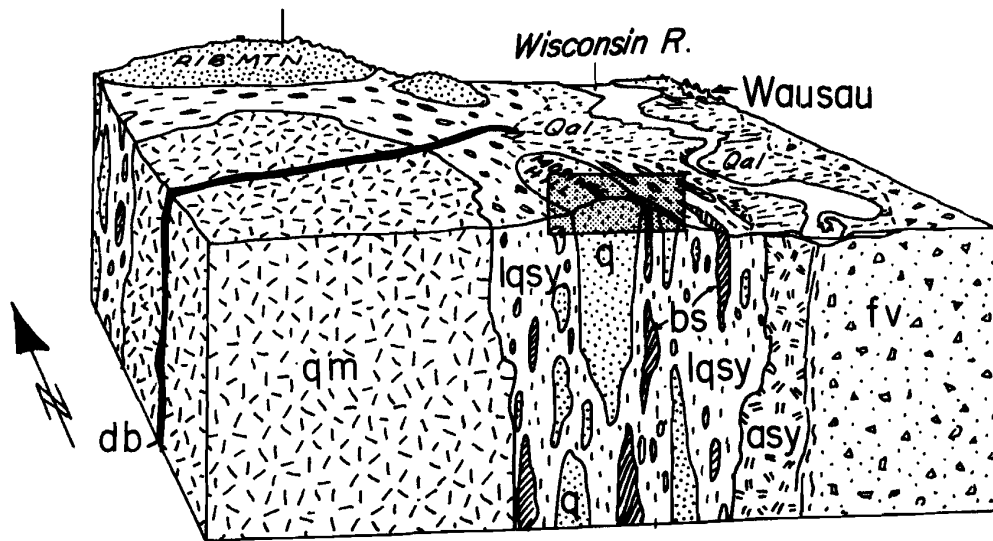
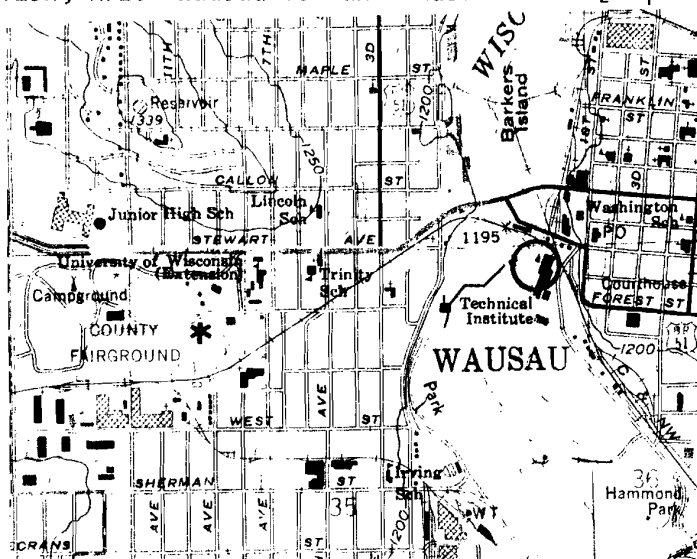


Figure 8--Block diagram of the northeastern corner of the southern segment of the Wausau syenite pluton at Mosinee Hill showing abundant, well-oriented quartzite (q) and biotite schist (bs) xenoliths in a flow-laminated, lensoidal quartz syenite (lqsy). The Ninemile quartz monzonite pluton (qm) intruded the quartz syenite with only a local discordance. The lensoidal syenite is bounded on the east by a thin wall of amphibole syenite (asy) which is itself in fault contact eastward with felsic volcanics. These rocks are cut with sharp discordance by a prominent diabase (db) dike which is characterized by a strong reverse polarity. The Qal is Wisconsin River alluvium. The shaded rectangle shows the location of the profile in Figure 1.

STOP #3

TITLE: Flow Structure of the Wall Zone, Wausau Syenite Pluton

LOCATION: Old Technical Institute, Power Dam, Wausau. NE $\frac{1}{4}$, NE $\frac{1}{4}$, Sec.35, T29N, R7E. Wausau 15' and Wausau West 7 $\frac{1}{2}$ ' quadrangles.



AUTHOR: Paul E. Myers, Department of Geology, UW-Eau Claire

DATE: February, 1980

SUMMARY OF FEATURES:

An early, medium-grained pyroxene-amphibole quartz syenite containing NW-oriented quartzite, schist, and volcanic xenoliths is cut by coarser-grained, flow-lineated quartz syenite of similar composition (Figure 9). Average xenolith orientation here is structurally continuous with the concentric lamination of the Wausau syenite pluton whose granite core is in Ninemile Swamp 5 miles southwest of here. "Rootless", lenticular pegmatite with walls of coarse K-feldspar and cores of quartz were probably differentiated from the nearly crystallized syenite at places of greatest quartzite assimilation. Thin screens of biotite schist and quartzite were rafted up or dropped down and brecciated in the viscous syenite magma (Figure 10).

DESCRIPTION:

According to Weidman (1907, p. 203-208) the "Wausau-type" quartz syenite is composed of alkali feldspars (orthoclase, microcline, albite, and microperthite), barkevitte, hedenbergite, fayalite, biotite and quartz. Accessories include fluorite, apatite, magnetite, zircon and allanite(?).

Structures and cross-cutting relations of the syenite phases exposed here typify those seen throughout the crescentic northern rim of the Wausau syenite pluton. They are listed and described below in order of decreasing age.

1. The oldest rocks here are xenoliths in the syenite. They include thoroughly recrystallized, schistose, amphibolitic metavolcanics, quartzite, and virtually unaltered felsic tuff. Note that long dimensions of xenoliths tend to be parallel to lamination and/or foliation and that, despite lithologic disparity, their mutual alignment imparts a distinct structural "grain" to the enclosing syenite--a factor believed to be of considerable significance in working out an emplacement mechanism for this pluton.
2. An early, fine-grained, flow-laminated lensoidal quartz syenite may represent a chilled phase.
3. Coarse-grained, flow-lineated pyroxene-amphibole quartz syenite cuts the fine-grained phase with sharp discordance. This unit contains irregular, lensoidal and tabular inclusions of amphibolite, schist, and quartzite most of which show little assimilation. Although most of these inclusions show northwesterly elongation, the enclosing quartz syenite displays highly discordant flow-lineation with swirls and eddies suggesting considerable turbulence and viscosity in the quartz syenite magma. After gaining access to the xenolith along its banding or schistosity, the magma pulled loose segments from its surface. With increasing magma/xenolith ratio the xenoliths became plastic and were strongly deformed in the flowing magma. Quartzite xenoliths appear to have been more readily plasticized presumably because of lower melting point. A screen of schistose metadiabase(?) crosses the south end of the outcrop. Its thin western end shows plastic deformation and "pull-outs", whereas its more brittle eastern end is segmented into many angular fragments (Figure).
4. Late-stage, lenticular granite pegmatite veins with quartz cores probably represent residual liquid segregations along incipient contraction fractures in the already crystallized syenite. They appear to be "rootless" and of local derivation--perhaps from zones of abnormally high quartzite assimilation.
5. Coarse, sodic amphibole crystallized along joint surfaces.

It is suggested that many of the structures in the syenites and quartz syenites of the Wausau pluton indicate forceful, subvolcanic injection of dry, viscous syenite magma. Detailed structural analysis may in time reveal the mechanisms of magma flow and xenolith mixing within the magma. Do the xenoliths, for instance, represent fragments from a fault breccia formed initially during caldera collapse and later invaded by upwelling syenite magmas?



Figure 9--Amphibolite (a) xenolith with swirled lineation and thin seams of syenite is cut by coarse pyroxene syenite (psy). Lenticular veins with walls of K-feldspar (Kf) and cores of quartz (q) show mutually crosscutting relations with an intervening offset along a small fault. Joint coatings are of coarse, sodic amphibole.

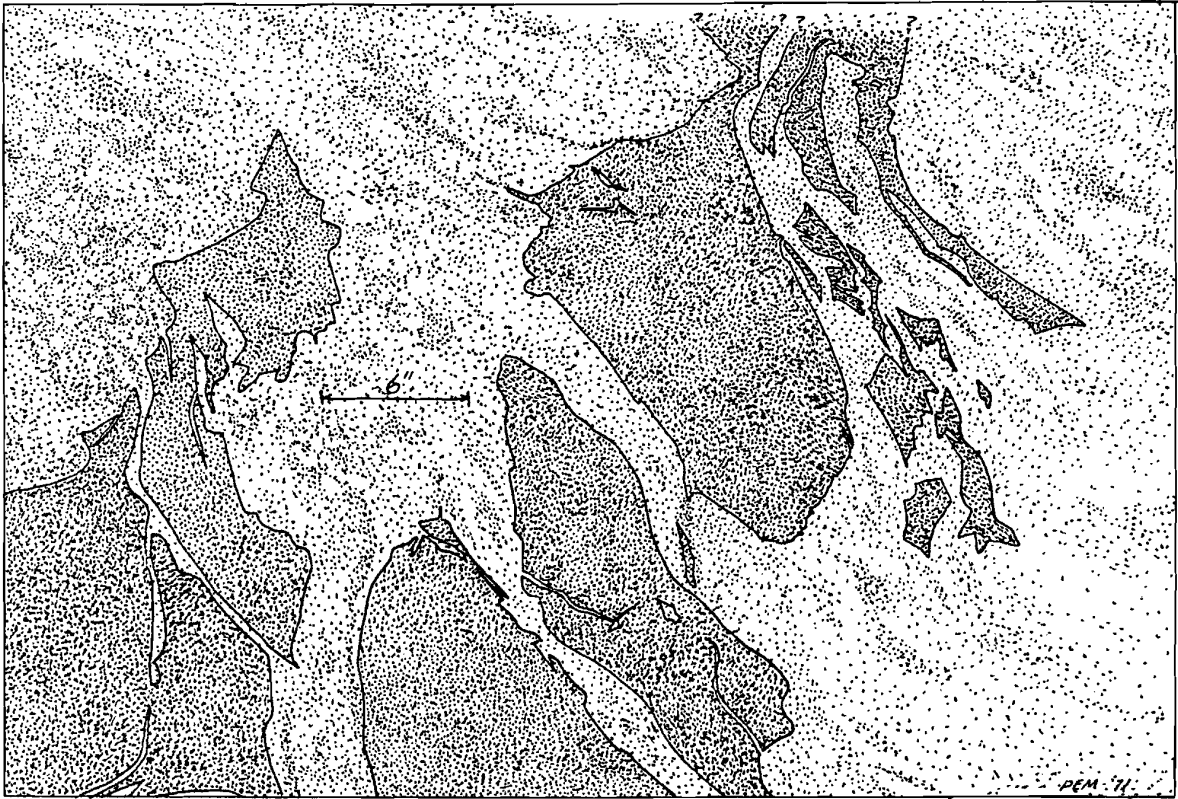
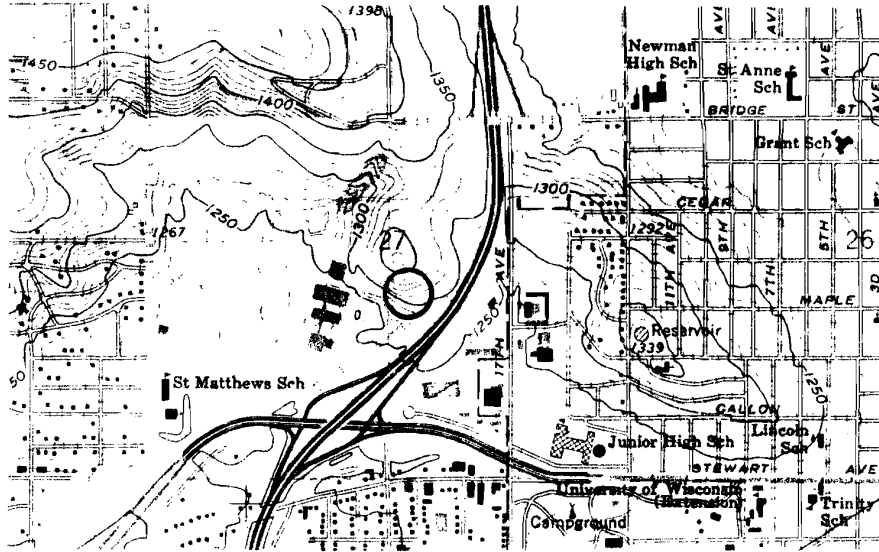


Figure 10--Segmented metadiabase screen in flow-banded lensoidal pyroxene syenite.

TITLE: Lensoidal Quartz Syenite, Employers' Mutual Insurance Company

LOCATION: NW $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 27, T 29 N, R 7 E, Wausau West 7.5' Quadrangle



AUTHOR: Paul E. Myers, and Manmohan Sood

DATE: March, 1980

SUMMARY OF FEATURES:

Coarse-grained, pink and brownish gray quartz syenite containing up to 60 percent volcanic xenoliths (best seen on horizontal surfaces) is exposed in an old quarry behind the offices of Employers' Mutual Insurance Company. This rock exemplifies contaminated quartz syenite of the "intermediate zone" of the Wausau syenite pluton (Figure 3). Associated quartz syenite elsewhere in this zone contains large, metasomatized quartzite and/or mica schist xenoliths, the most spectacular of which is exposed on the summit of Rib Mountain. The Rib River "lineament" separates the two crescentic segments of the Wausau syenite body.

DESCRIPTION:

The quartz syenite at this location is composed of coarse perthite (80%), quartz (10%), and sodic pyroxene partially replaced by mixtures of dark green amphibole, carbonate, and magnetite (10%). Quartz is interstitial. Large magnetite segregations can be observed along the road on the east side of this outcrop. Four facies of quartz syenite were recognized and analyzed chemically (See Table 2). The pink syenite contains up to 60% trachyte or rhyolite (?) xenoliths which are lensoidal with blunt, broken east ends and rounded (assimilated?) west ends. Their orientation is consistently N 70-75° W, vertical in this area (Figure 10), and they are seen best on horizontal surfaces. Large quartzite xenoliths occur in the quartz syenite along the ridge crest north of here. The crescentic form of this part of the Wausau syenite body also shows as a conspicuous magnetic anomaly owing to the high concentration of magnetite as sheets and lenses in these rocks. The xenoliths

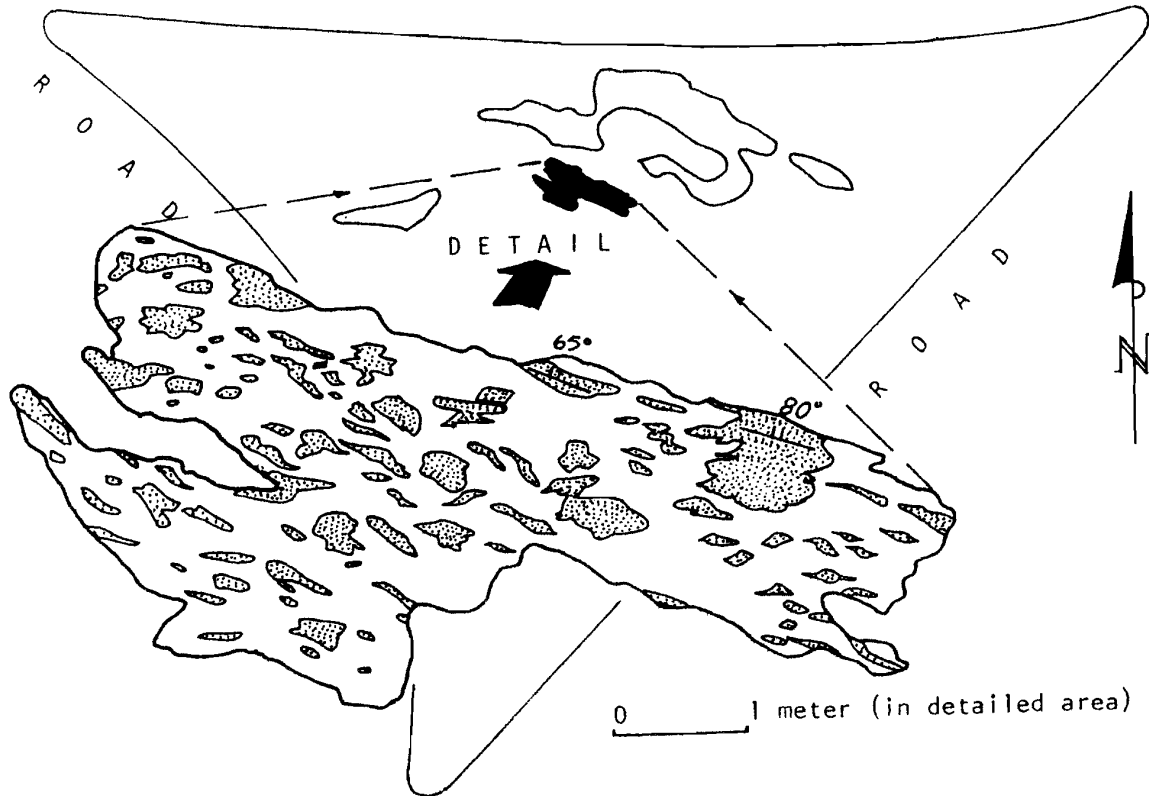


Figure 11-- Volcanic xenoliths (dotted) in flow-lineated amphibole quartz syenite (white). Outcrops in grassed area between three roads behind Employers' Mutual Insurance Company.

show up on fresh surfaces mainly as slightly finer grained, darker colored masses. In addition to the angular volcanic xenoliths, the quartz syenite here contains mafic schlieren and clots showing irregular shape and orientation as well as gradational boundaries, a factor suggesting their more distant derivation and more thorough assimilation.

Xenoliths of highly disparate lithology, and metamorphic grade occur side by side in these plutons. Their lenticular shape suggests mechanical segmentation before or during syenite intrusion. Convolute flow lineation in amphibole syenite (as at the Old Technical Institute in Wausau) indicates viscous flow, probably due to water-deficiency of the magma. At many locations it is very difficult to distinguish the intrusive phase: indeed, one is hard-pressed to find an uncontaminated syenite exhibiting the features of a true intrusive rock. Sillimanite-bearing quartzite occurs as a tabular xenolith in fine-grained hornblende syenite 2.5 km west-northwest of here. The sillimanite suggest considerable upward transport of the xenolith from a high-grade metamorphic basement. The mica schist and metagabbro(?) xenoliths at Mosinee Hill and along the east side of the Wausau syenite body also suggest a deep-seated source. The close-spaced juxtaposition of xenoliths of disparate lithology indicates considerable vertical movement of wallrock fragments. To what degree did collapse modify these intrusive relationships? Does the quartz syenite represent a syenite magma which was contaminated by xenolithic quartzite? To what degree was the syenite able to assimilate xenoliths? Textural relations seen throughout the pluton suggest little assimilation but considerable dilation owing at least in part to explosive eruption.

TABLE 2

Bulk chemical compositions of the four principal quartz syenite facies from Employers' Mutual Insurance Company Quarry.

	EW-3 (WEST)	EW-5 (EAST)	NSI (SOUTH)	SEI (NORTH)
Description →	Brownish-gray	Coarse, dark gray	Pink syenite, with volcanic xenoliths	Medium-grained syenite
SiO ₂	63.05	63.55	63.90	64.10
TiO ₂	0.78	0.54	0.47	0.48
Al ₂ O ₃	12.60	15.16	14.14	15.17
Fe ₂ O ₃	1.91	1.25	5.42	4.58
FeO	7.72	3.48	1.32	1.44
MnO	0.34	0.16	0.14	0.12
MgO	0.41	0.16	0.45	0.09
CaO	2.66	1.72	1.35	1.50
Na ₂ O	4.80	5.52	6.32	5.17
K ₂ O	4.22	5.67	6.34	5.57
H ₂ O	0.76	0.42	0.56	0.26
P ₂ O ₅	0.22	0.06	0.05	0.06
CO ₂	0.28	1.92	0.62	0.09
BaO	0.094	0.066	0.024	0.036
ZrO ₂	0.222	0.114	0.062	0.071
Rb	154	118	80	80
Sr ppm	78	83	67	42

In comparison with Nockolds' (1954) average syenite composition (see Table 2), these quartz syenites are richer in SiO₂ and total iron and poor in alkalis and lime. Their Rb and Sr contents are also low compared to other similar rocks.

THE STETTIN SYENITE PLUTON

Although Weidman (1907) mapped the geology of north-central Wisconsin and paid special attention to the mineralogy of the syenites near Wausau, Emmons and Snyder (1944) hypothesized formation of the Stettin syenite body by metasomatism of feldspathic rocks along shear zones with alkali-rich solutions derived from a subjacent granite batholith. Turner (1948) studied the heavy accessory minerals and radioactivity of the Stettin pluton, and Geisse (1951) described the petrography of this pluton. Petrographic and geochemical investigation of the mafic minerals and nepheline of the Stettin pluton initiated analytical studies which have been extended by the work of Sood and Berlin.

The concentrically zoned Stettin pluton (Figure 12) is oval in plan, elongated northeasterly, with a length of 5.5 miles and a width of 4.0 miles. Older volcanic rocks enclosing the pluton have been extensively syenitized. The eastern and southern margin of the pluton is a complexly laminated series of altered volcanic screens and pendants and various, contaminated intrusive phases of the syenite including nepheline syenite. The wall zone comprises a discontinuous outer rim of gneissic nepheline syenite, and an inner layer of tabular syenite (Stop #5). The intermediate zone (Stops #6 and #7) is composed of amphibole and pyroxene syenite showing considerable variation in composition and texture. The amphibole syenite is commonly quartz-bearing. The core zone (Stop #8) is one mile in diameter and is located asymmetrically near the north end of the pluton. The core zone comprises a well-defined, cylindrical rim of indistinctly banded nepheline syenite surrounding a core of pyroxene syenite. Field relations indicate the following intrusion sequence: (1) pyroxene syenite, (2) nepheline syenite, (3) tabular syenite, (4) amphibole syenite. Numbers 3 and 4 could be reversed. This evidence is based wholly on field relations (Myers). It should also be emphasized that the intrusion sequence may not be the same as the crystallization sequence. Analytical work (Sood and Berlin, this guidebook) suggests a very late age for the nepheline syenite. (See discussion of petrochemistry beginning on page 46).

A summary tabulation of paragenetic relations of minerals in each zone of the Stettin syenite pluton is presented with modification from Koellner (1974) in Table 3.

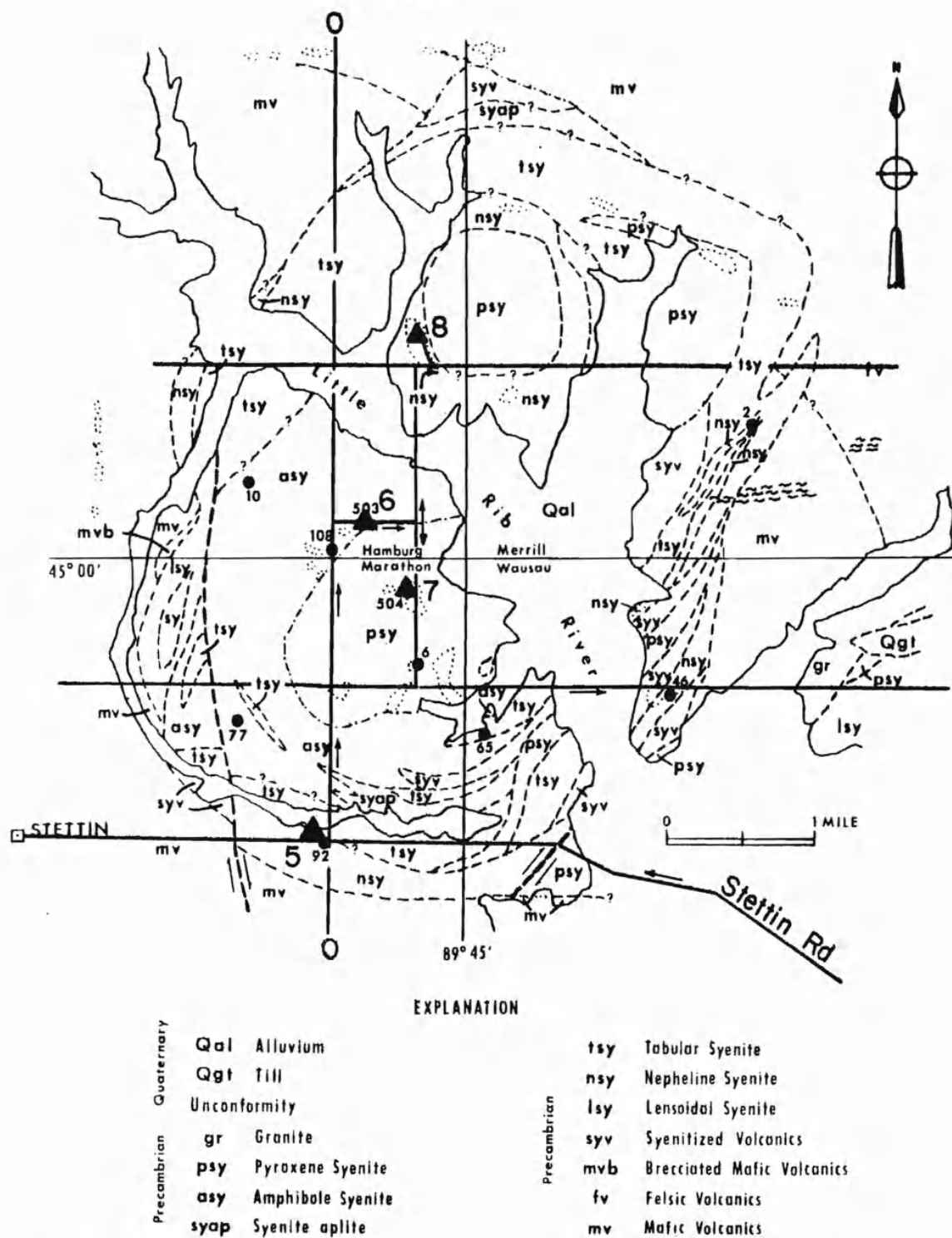


Figure 12 -- Geologic map of the Stettin complex (after Myers, 1973) including localities of samples and field trip stops.

TABLE 3

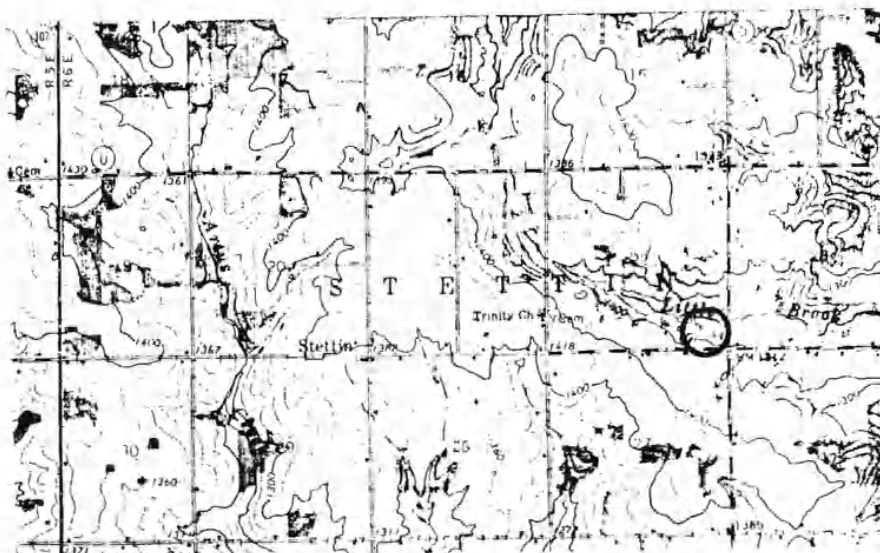
PARAGENETIC RELATIONS OF MINERALS IN EACH ZONE OF THE STETTIN PLUTON

ZONE	ROCK TYPE	PARAGENETIC RELATIONS
WALL ZONE CORE ZONE INTERMEDIATE ZONE	Tabular Syenite (Myers, 1973)	— zircon — └── pyroxene ─┘ └── alkali feldspar ─┘ └── opaques ─┘ └── green amphibole ─┘ └── biotite ─┘
	Nepheline Syenite (Koellner, 1974, p. 12)	— nepheline — └── alkali feldspar ─┘ └── olivine ─┘ └── pyroxene ─┘ └── opaques ─┘ └── green amphibole ─┘ └── biotite ─┘
	Pyroxene Syenite	└── alkali feldspar ─┘ └── apatite ─┘ └── opaques ─┘ └── olivine ─┘ └── pyroxene ─┘ └── green amphibole ─┘ └── biotite ─┘ └── carbonate ─┘ └── blue amphibole ─┘
	Amphibole Syenite (Koellner, 1974, p.33)	└── alkali feldspar ─┘ └── apatite ─┘ └── opaques ─┘ └── pyroxene ─┘ └── green amphibole ─┘ └── biotite ─┘ └── blue amphibole ─┘

STOP #5

TITLE: Contact relations and minerals in the Wall Zone, Stettin syenite pluton

LOCATION: County Highway 0 at 10146 Stettin Road, Paul Knopp property, SE $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 22, T29N, R6E, Marathon 15' quadrangle, (Sample Location 92)



AUTHORS: P.E. Myers and M.K. Söod

DATE: February 1973, February 1980

SUMMARY OF FEATURES:

The outermost rim of the Stettin pluton is gneissic nepheline syenite composed mainly of alkali feldspar, perthite, nepheline, aegirine, sodic amphibole and biotite. It is in sharp contact with, and veined by, tabular syenite composed of coarse, well-oriented laths of perthite, sodic amphibole, pyroxene, and lensoidal mafic inclusions composed essentially of the same minerals but in different proportions and of finer grain size. The mafic inclusions are well-oriented parallel to the tabular fabric of the enclosing syenite and to the wall of the pluton. They contain large perthite porphyroblasts of similar composition and size as those in the enclosing syenite. Zircons were mined at this site in the 1950's. Zircons from this site have given a U/Pb age of 1520 ± 20 m.y. by W.R. Van Schmus (oral communication).

The chief questions to be answered at this site are: (1) how were the nepheline syenite and tabular syenite emplaced, and (2) to what extent is the present mineral assemblage a result of metasomatic replacement?

The abundance of zircon and hastingsite amphibole, biotite and carbonate indicates a miaskitic trend for the nepheline and pyroxene syenites. The compositions of the nepheline and pyroxene syenites are very similar (Table). According to Koellner (1974, p. 144) the amphibole syenite is agpatic and could contain a carbonatite body.

DESCRIPTION:

The nepheline syenite (Figure 13, Tables 4 and 5) is a gray, banded rock composed here of perthitic feldspar nepheline, olivine, pyroxene, magnetite, amphibole, and biotite. Contorted aplitic and pegmatitic bands lie roughly parallel to the wall of the pluton about 1500 feet south of here. The nepheline occurs as blocky, pinkish grains which weather much more readily than the associated minerals, giving the rock a characteristic pitted appearance. Nepheline is partially altered to cancrinite and iron oxides. Banding, and mafic content of the nepheline syenite increase outward toward its contact with syenitized mafic volcanics which trend west-northwesterly. In addition to the essential minerals listed above, common accessory minerals include zircon and sphene of unusually large size and abundance, apatite, fluorite, allanite, sodalite, pyrochlore and thorgummite(?). U/Pb dating of the zircons from this site by S. Goldich (oral communication) gave a minimum age of 1400 m.y. More recent analyses of these zircons by W.R. Van Schmus yielded a U/Pb age of 1520 ± 10 m.y. Thus, the Stettin syenite is about 20 million years older than the Wolf River Batholith (oral communication).

The gneissosity and isoclinal folding exhibited by the gneissic nepheline syenite of the wall zone on the south side of the Stettin pluton suggest considerable differential movement of material along its outer wall. The extent to which metasomatism was involved during and after emplacement is not known. However, metasomatism was extensive, and that the nepheline syenite may consist in large part of metasomatized wall rocks.

Zircon from this locality is deep red-brown, doubly terminated euhedral prisms up to 14 mm in length. Some crystals display geniculate twinning similar to that of rutile. Chemical analyses of three zircons from a nearby site (NW $\frac{1}{4}$ of Sec. 22) by F.B. Hall (in Weidman, 1907, p. 313) indicates an Al_2O_3 content of between 4.28 and 7.80 percent and an Fe_2O_3 content between 1.21 and 4.47 percent. Ca, Ti, Th and rare earths were sought but not detected.

Brown pyrochlore octahedra up to 2 mm in diameter were found at this location by Weidman (1907, p. 308-309).

Allanite is confined mainly to pegmatitic portions in the nepheline syenite.

Apatite and sphene of unusually large size show affinity for clusters of mafic minerals in the nepheline syenite. Large sphene crystals up to 7 mm in length can be collected from nepheline syenite lenses and masses near its contact with tabular syenite.

The tabular syenite (Figure 14, Tables 4 & 5) is composed dominantly of coarse laths of microperthite. Vein and patch type perthites predominate. Poikilitic amphibole (hastingsite) rims pyroxene (intermediate between acmite and hedenbergite according to Koellner (1974, p. 65). The tabular fabric (Figure 15) is characterized by a random orientation of perthitic feldspar tablets in a plane parallel to the outer wall of the pluton and parallel to the long dimensions of mafic inclusions. Perthitic feldspar tablets within mafic inclusions and across their contacts are identical to those in the enclosing tabular syenite. The inescapable conclusion is that the perthitic feldspar is at least partly of metasomatic origin. Veins of tabular syenite locally cut the nepheline syenite gneiss in the old quarry face at this location. Mafic inclusions comprise from 5 to 80 percent of the tabular syenite. As the volume of mafic inclusions increases, the mafic minerals, mainly sodic amphibole, become coarsely poikilitic. Individual amphibole grains up to 12 centimeters long were observed in a small roadside excavation 1.5 miles east-southeast of here. Although the mafic inclusions contain a much higher percentage of pyroxene and olivine than the enclosing tabular syenite, they are of about the same chemical composition.

The tabular syenite forms the outermost layer on the north and west sides of the Stettin pluton where the nepheline syenite is absent. The abundance of mafic inclusions increases outward in the tabular syenite, suggesting considerable contamination by the basaltic wallrock. A unit mapped as lensoidal syenite and a closely associated syenite aplite (Myers, 1973) are found locally where the nepheline syenite is absent. The lensoidal syenite is an aplitic, gneissose rock consisting of mafic inclusions rich in biotite enclosed in an aplitic syenite. The syenite aplite is similar in texture and mineral composition but relatively free of mafic inclusions.

TABLE 4

MODAL COMPOSITIONS OF THE STETTIN ROCKS

ROCK TYPE	INTERMEDIATE ZONE				CORE ZONE	WALL ZONE			
	Amphibole Syenite				Pyroxene Syenite	Tabular Syenite	Nepheline Syenite		
SAMPLE NUMBERS*	10	77	503	108	6 and 504	65	46	2	92
Quartz	7.1	6.6	2.9	1.4					
Nepheline							26.4	17.6	6.6
Perthite	80.7	83.5	90.3	83.0	87.4	80.2	63.6	75.7	61.4
Albite	0.5		0.2						
Amphibole	11.2	8.6	5.1	13.6	5.5	19.1	8.4	4.6	29.5
Pyroxene				0.6	4.1				
Biotite	0.2				0.5	0.2	0.6	0.4	0.4
Biotite (alter.)		0.6	0.3	0.5					
Zircon		0.2	0.2	0.1	0.7				
Apatite					0.1				
Fluorite	0.2		0.5						
Calcite				0.3	0.1				
Sphene									1.1
Opaque minerals	0.1	0.1	0.3	0.2	1.3	0.1	1.0		0.5
Alteration		0.4	0.2	0.3	0.3	0.4			0.5

*Sample numbers shown on Figure 12

TABLE 5
CHEMICAL COMPOSITIONS OF THE STETTIN ROCKS*

ROCK TYPE	INTERMEDIATE ZONE				CORE ZONE	WALL ZONE			
	Amphibole Syenite				Pyroxene Syenite	Tabular Syenite	Nepheline Syenite		
Sample #	10	70	503	108	6+504	65	46	2	92
SiO ₂	66.10	65.20	64.70	61.95	59.75	61.50**	57.45	56.95	54.10
Al ₂ O ₃	13.24	15.59	15.86	16.04	16.23	16.62	16.93	21.02	16.32
Fe ₂ O ₃	2.61	2.36	2.45	3.13	2.55	5.20	2.58	2.93	3.41
FeO	4.12	2.22	2.10	2.70	5.66	1.68	5.98	2.12	7.08
MgO	0.43	0.01	0.02	0.08	0.14	0.24	0.21	0.07	1.22
CaO	0.70	0.50	0.95	1.10	2.15	1.43	2.64	0.51	4.03
Na ₂ O	5.92	6.92	7.07	6.51	5.97	6.49	6.71	7.81	5.81
K ₂ O	4.31	5.11	5.19	5.51	5.67	5.15	5.02	5.99	4.84
H ₂ O	0.73	0.83	0.70	1.95	0.51	0.63	0.98	1.43	0.77
CO ₂	0.38	0.35	0.36	0.40	0.22	0.17	0.18	0.40	0.09
TiO ₂	0.72	0.42	0.27	0.32	0.75	0.31	0.59	0.38	1.32
P ₂ O ₅	0.11	0.04	0.06	0.07	0.13	0.07	0.13	0.50	0.49
MnO	0.23	0.12	0.15	0.18	0.26	0.22	0.30	0.07	0.29
S	0.010	0.004	0.003	0.008	0.034	0.009	0.023	0.000	0.044
ZrO ₂ }	0.102	0.165	0.260	0.171	0.11	0.100	0.140	0.001	0.079
		0.215		0.143			0.241		0.105
Cl	0.03	0.013	0.024	0.010	0.010	0.345	0.02	0.025	0.02
BaO		0.071		0.150	0.160	0.103	0.086		0.208
Rb(ppm)		199.		152.	66.	133.	115.		102.
Sr(ppm)		44		105.	174.	109.	57.		345.

* Analyst-K. Ramlal, University of Manitoba

**Tabular Syenite

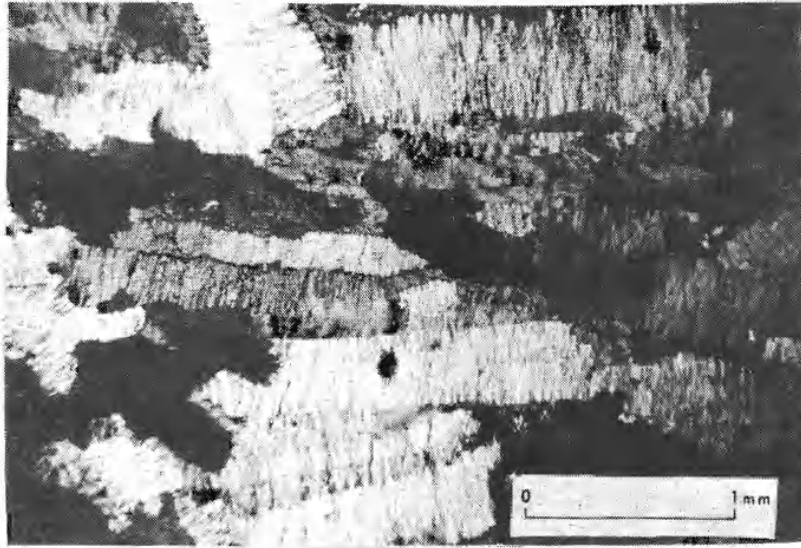


Figure 13--Photomicrograph of nepheline syenite showing euhedral nepheline grains surrounded by a matrix of discrete albite crystals and amphibole. Crossed nicols.

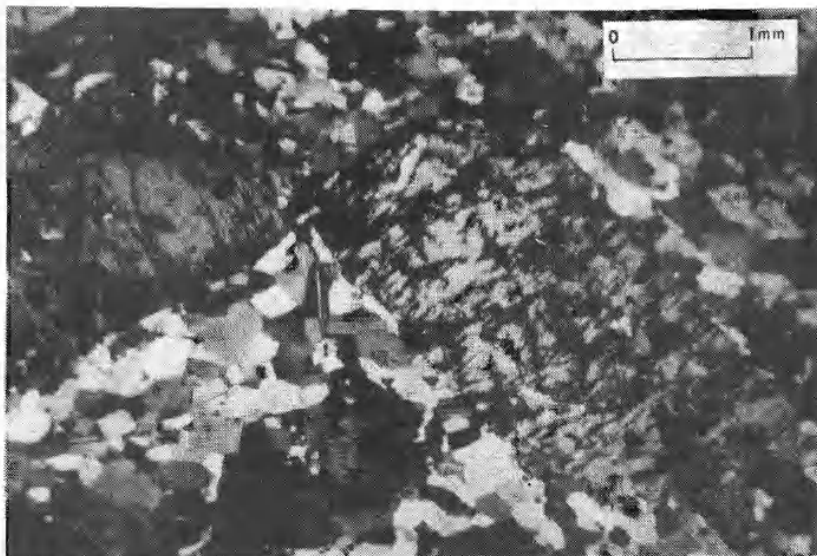


Figure 14--Photomicrograph of tabular syenite showing parallel alignment of feldspar crystals. Crossed nicols.

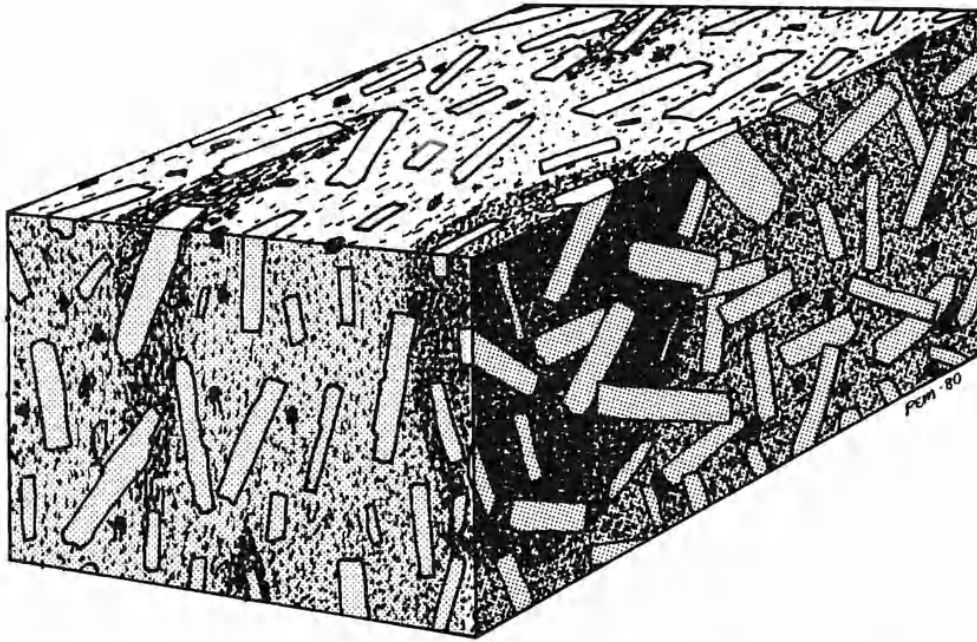
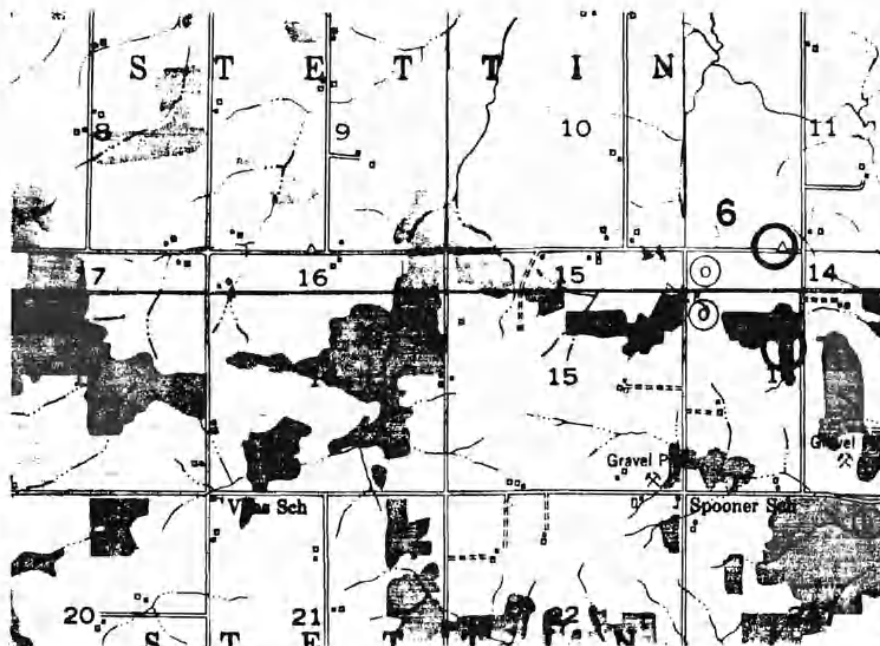


Figure 15-- Typical fabric of tabular syenite showing coarse tablets of microperthite in random orientation parallel to the wall of the pluton. Microperthite laths in the lensoidal mafic inclusions tend to have a preferred orientation parallel to those in the enclosing syenite. Some of the laths crystallized across the edges of inclusions, thus indicating a metasomatic origin of at least part of the microperthite.

STOPS #6 and #7

TITLE: Amphibole and Pyroxene Syenites of the Intermediate Zone

LOCATION: Stop #6: NW $\frac{1}{4}$, Sec. 14, T29N, R6E, Hamburg 15' quadrangle
Stop #7: NW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 14, T29N, R6E, Marathon 15' quadrangle



AUTHORS: M.K. Sood and P.E. Myers

DATE: February, 1980

SUMMARY OF FEATURES:

Massive and flow-lineated, gray to pinkish-orange amphibole syenite (Stop #6) and pyroxene syenite (Stop #7) of the intermediate zone are composed dominantly of alkali feldspar and up to 35% poikilitic arfvedsonite amphibole which encloses nuclei of pyroxene. The amphibole syenite shows considerable variation in composition and texture from pegmatitic clots of quartz-bearing aplitic phases in single outcrops. Clots of coarse feldspar and poikilitic amphibole (up to 12 cm. long) are common. Most outcrops display swirled flow lineation similar to that seen in amphibole quartz syenite at Stop #3 (Old Technical Institute, Wausau). The amphibole syenite contains a relatively large percentage of blue (riebeckitic) amphibole. Although the dominant mafic mineral in the pyroxene syenite is amphibole, pyroxene occurs in discreet grains not rimmed by amphibole. At a stone quarry 0.2 mile east of here, the pyroxene syenite shows spectacular schiller structure of the feldspar (moonstone).

DESCRIPTION:

Whereas the amphibole is characteristically pink in outcrop, the pyroxene syenite is a moderate-to-light olive gray with islands of coarse mafics enclosed in coarse tablets of randomly oriented feldspar. The amphibole syenite shows considerably greater textural variation, even at mesoscopic scale. Although vein-like and irregular masses of zoned pegmatite and aplite are common in all outcrops, the dominant rock type is medium-grained amphibole syenite with a faint to conspicuous lamination, with or without lineation created by alignment of feldspar tablets and lensoidal clots of mafic minerals--mainly amphibole and subordinate pyroxene. Pegmatitic phases of the amphibole syenite contain up to 12% quartz as coarse segregations commonly rimmed by blue (riebeckitic) amphibole.

In thin section, mafics are clustered in acicular or radiating fibers. This zone to the southwest contains small sill-like masses of tabular syenite.

The major mineral is micro-to mega-perthitic feldspar surrounding the mafic minerals which seemingly are later than the feldspars. The principal mafic mineral is bluish-green arfvedsonite-riebeckite amphibole (Table 8), sometimes mantling minor Fe-augite pyroxene. However, pyroxene is absent in some samples of this zone. Alteration of amphiboles to brown-red biotite is common in patches and along borders. The interesting feature of the amphibole grains is containment of a dark blue riebeckitic phase which is most common only in this unit. Some amphiboles poikilitically enclose euhedral feldspars (Figure 17).

Accessories include zircon which is commonly zoned, quartz (up to 12%), fluorite, calcite, FeTi-oxides, apatite and allanite.

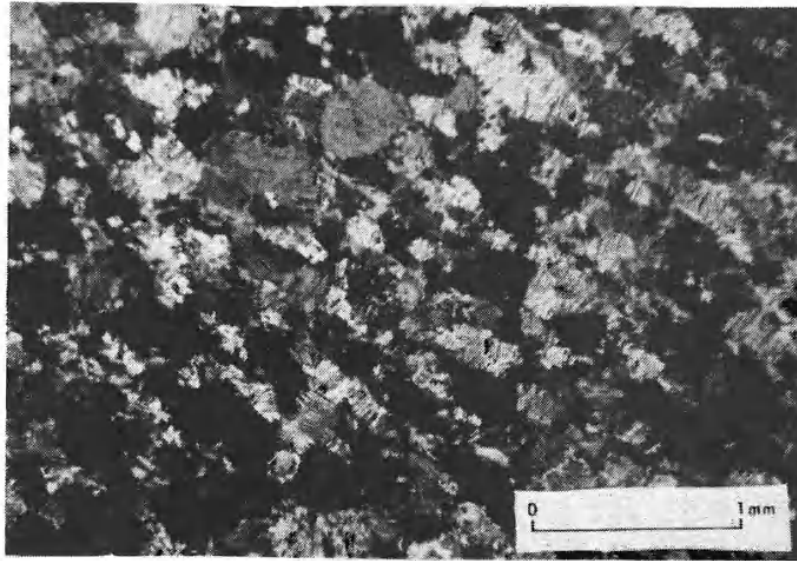


Figure 16--Photomicrograph of aplitic syenite showing a fine-grained mass of anhedral perthitic feldspar. Crossed nichols.

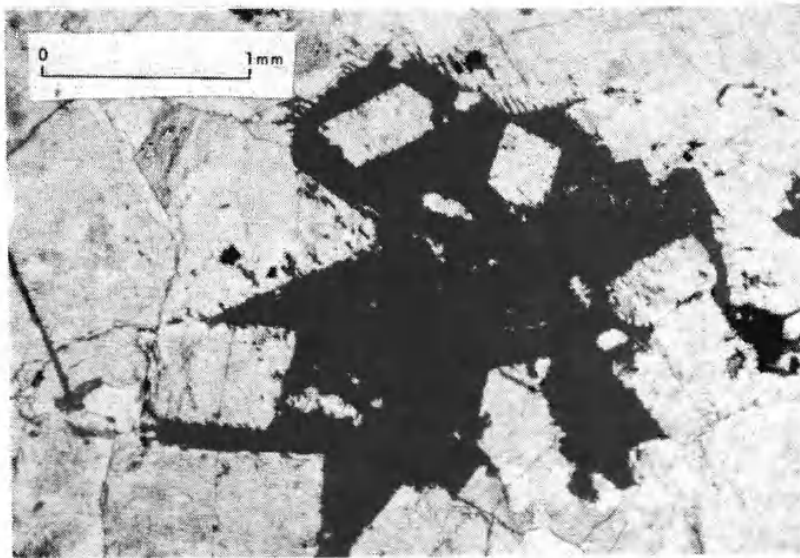


Figure 17--Photomicrograph of amphibole syenite showing poikilitic texture. Note the euhedral outlines of the feldspar crystals enclosed in the amphibole grain.

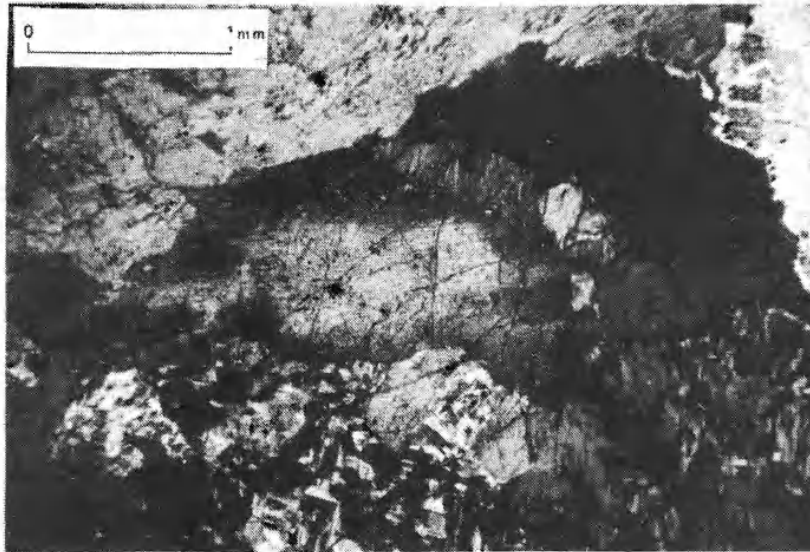


Figure 18--Photomicrograph of pyroxene syenite showing zoned grain of aegirine-augite mantled by arfvedsonite. Crossed nichols.

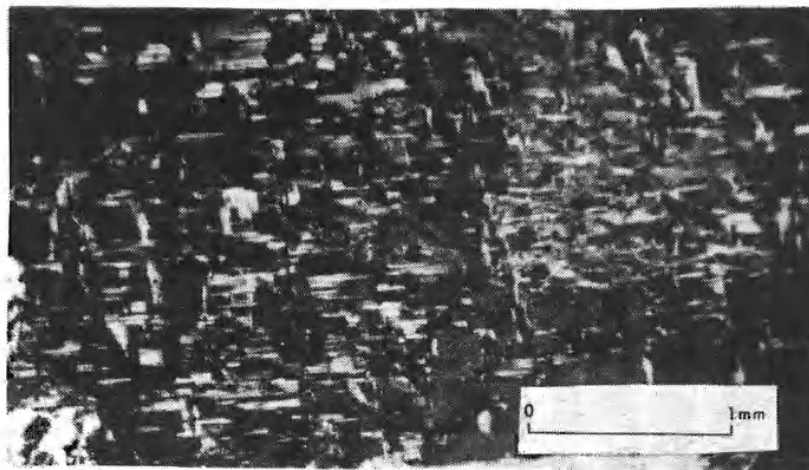
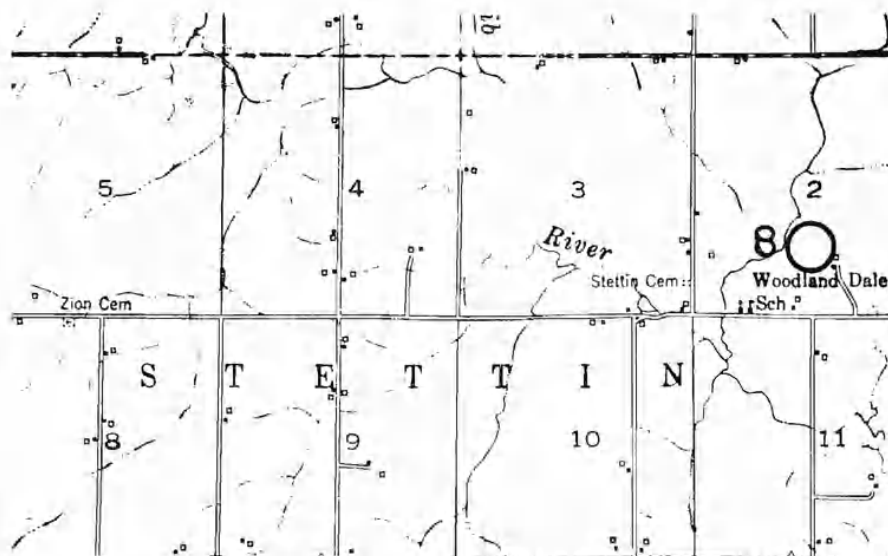


Figure 19--Photomicrograph of pyroxene syenite. Patch perthite showing albite twinning. Crossed nichols.

STOP #8

TITLE: The Core Zone of the Stettin Syenite Pluton

LOCATION: SW 1/4, SE 1/4 Sec. 2, T29N, R6E; Hamburg 15' quadrangle



AUTHORS: Paul E. Myers and M. K. Sood

DATE: February, 1980

SUMMARY OF FEATURES:

The core of the Stettin syenite pluton comprises two distinct parts: (1) a cylindrical core margin of indistinctly banded or lineated, medium-grained nepheline syenite and (2) an inner core of pyroxene syenite. Bent and crushed feldspar grains and a crude southeast-dipping layering were formed during or after emplacement of the core margin. The nepheline syenite core margin produced a pronounced donut-shaped magnetic anomaly about one mile in diameter. Drilling by Bear Creek Mining Company in the southeast corner of the inner core retrieved about 250 feet of core classified by company geologists as larvikite. No carbonatite has been found, although the agpaitic trend of the rocks here suggests that such a carbonatite is possible (Koellner, 1974, p. 144).

DESCRIPTION:

The nepheline syenite of the core margin here is indistinctly banded or lineated. The weathered surface is pale yellowish gray with pitting due to differential weathering of the nepheline. The fresh nepheline is pale greenish brown and occurs as well-oriented, subhedral to euhedral grains enclosed by tablets of feldspar up to 2 cm long. The feldspars, nepheline, and islands of mafic minerals are elongated in a plane dipping southeast at between 60 and 70°. This lamination is not parallel to the outer edge of the core margin at this location. Bent and broken feldspar and nepheline grains and lenticulation of mafic mineral clusters suggest shearing during or after intrusion.

The dominant mineral is tabular microperthite (60% orthoclase with 40% oligoclase ribbons). An additional 25% of the rock is subhedral to euhedral nepheline, which is partially altered to cancrinite. Mg-rich pyroxene and pleochroic, olive brown amphibole are of about equal abundance and make up about 20-30% of the rock. Accessory (2-5%) Mg-rich olivine and dark brown biotite accompany the other mafic minerals in lenticular clusters and islands occurring interstitially in the nepheline syenite. The biotite partially rims the amphibole and was probably formed at a late stage of crystallization.

This unit produced a pronounced, donut-shaped magnetic anomaly about one mile in diameter. Wiedman (1907, p. 251) reports unusually large and abundant magnetite octahedra from streams northwest of here. The magnetite is apparently associated most closely with the olivine.

MINERALOGY AND MINERAL CHEMISTRY

(STOP NO's 5, 6, 7 and 8)

by M. K. Sood and L. A. Berlin

The principal mineral phases in Stettin Complex are perthitic feldspars, nepheline, sodic and calcic pyroxenes, and sodic amphiboles whose representative chemistry is given in Table 4 and characteristics described below:

Feldspars

The major phase of feldspar is a microperthite in uniform veins showing parallel, subparallel, or wavy lamellar intergrowths, or as patches of one feldspar in the host (see plate 1). Both perthite and antiperthite are present, although perthite is more common than antiperthite. Frequently the tabular feldspar grains exhibit Carlsbad twinning and less commonly Mannebach twinning. The perthitic feldspar constitutes 80 to 90 percent of the syenites and 60 to 75 percent of the nepheline syenites (Table 4).

Distinct grains of albite have an average extinction angle of 15° , but are not common in any of the syenites.

Microcline, also present as distinct grains, show its characteristic spindle-shaped polysynthetic twinning and wavy extinction, but is less abundant than albite as individual grains.

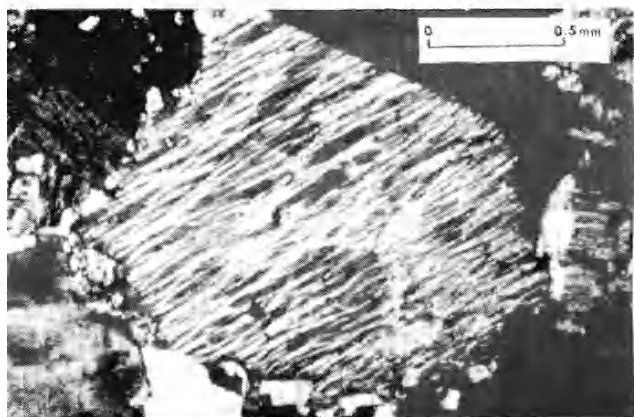
The bulk compositions of the perthitic alkali feldspars were determined for nine samples of three major zones of the Stettin complex. The samples were homogenized to a sanidine phase at 1050° in a muffle furnace for 48 hours; then $\Delta 2\theta = 201$ feldspar - 101 KBrO_3 $\text{CuK}\alpha$ was measured and the molecular percent orthoclase was determined using the homogenized natural microcline-low albite x-ray determinative curve of Jones et al. (1969) The compositions are given below in Table 6.

Table 6

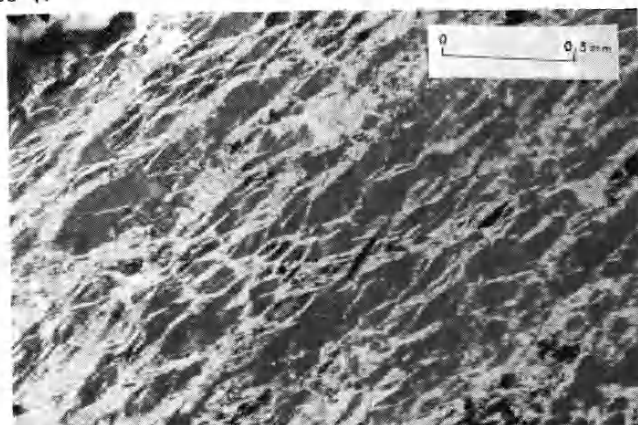
THE MOLECULAR PERCENT ORTHOCLASE OF HOMOGENIZED PERTHITIC ALKALI FELDSPARS OF THE STETTIN ROCKS

Sample	$\Delta 2\theta \text{ CuK}\alpha$	Mol % Or
<u>Core Zone</u>		
pyroxene syenite	1.40°	39
<u>Intermediate Zone</u>		
amphibole syenite	1.45	35
3 amphibole syenites	1.40	39
<u>Rim Zone</u>		
tabular syenite	1.43	37
nepheline syenite	1.35	44
nepheline syenite	1.39	41

Plate 1.



A. Enlarged section patch perthite of Plate 3B.
Crossed nicols



B. Photomicrograph of vein perthite in amphibole
syenite. Crossed nicols.



C. Enlarged section showing braided perthite.
Crossed nicols.

TYPES OF PERTHITIC FELDSPARS
IN ROCKS OF STETTIN COMPLEX:

- (a) PATCH PERTHITE
- (b) VEIN PERTHITE
- (c) BRAIDED PERTHITE

The molecular percent orthoclase ranges from 35 to 44%; however, Or% is above 40% for the nepheline syenites and is less than 40% for the nepheline-free syenites.

The intensity ratios of the $\bar{2}01$ peaks of microcline and albite were determined for the perthitic feldspars by scanning in both directions between 20° and $230-20^\circ$ $\text{CuK}\alpha$ at $1/8^\circ$ - 2θ per minute using 200 counts per full chart scale, a time constant of 5 seconds and a chart speed of 15 inches per hour. The angular positions were averaged from three scans. Then the goniometer was exactly centered on one peak at a time and the intensity was measured using a fixed time of ten seconds with a 2 second time constant. The background intensity was measured at the midpoint between the two peaks.

Then: A = number of counts on microcline $\bar{2}01/10$ s
B = number of counts on low albite $\bar{2}01/10$ s
C = number of counts on the background/10 s

The intensity ratio $I_o/I_a = (A - C)/(B - C)$.

The intensity ratio and the value of the bulk composition of Or%/Ab% for each of the perthitic feldspars studied were plotted on the graph of Kuellmer (1959)(Figure 20).

From this diagram, implications can be made as to the temperature-structural state of the feldspars. From the plots a broadening ratio (B) is obtained.

The broadening ratio is a measure of the distortion or structural mistakes in the two phases of perthite. The broadening ratio will decrease with slower crystallization and lower temperature since these conditions are favorable for the attainment of an ordered arrangement of Si and Al ions in the tetrahedral sites of the feldspar structure (Smith, 1974).

The broadening ratios for the perthitic alkali feldspars of the Stettin rocks range from low ($B = 0.30$) to intermediate values ($B = 0.9$). This is an indication of the low temperature-structural state of these perthites, corresponding to the maximum to intermediate microcline-low albite series determined from the positions of the $\bar{2}04$ and 060 reflections.

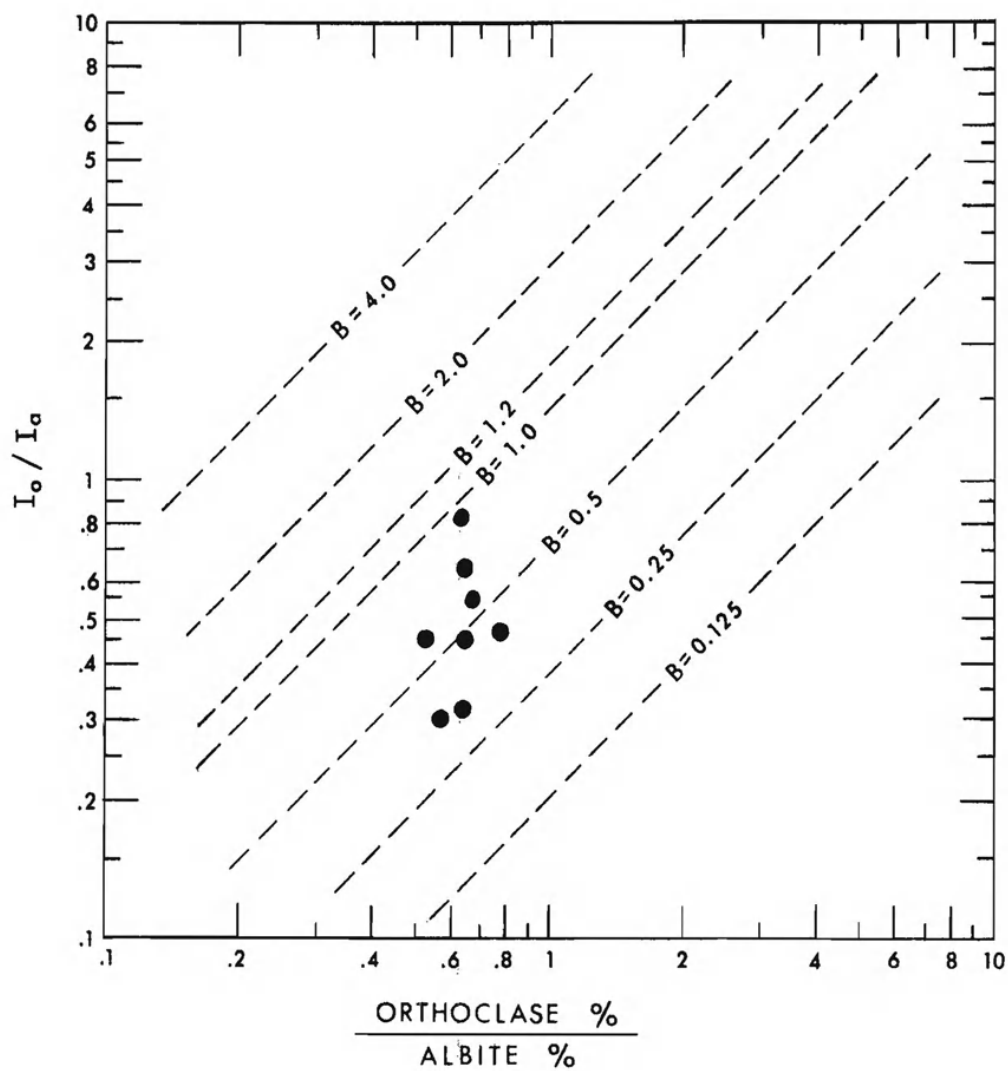


Figure 20 -- Plot of the bulk composition Or%/Ab% versus I_o/I_a for the 201 reflections of the two feldspar phases in the Stettin perthite samples for determination of their broadening ratio B (diagram after Kuellmer, 1959).

TABLE 7

ELECTRON MICROPROBE CHEMICAL ANALYSES OF MAJOR MINERALS OF STETTIN COMPLEX

	Feldspar		Amphiboles		nsy	Pyroxene*		tsy	Nepheline*	Fe-Ti Oxides
	67.42	68.23	40.45	39.90	48.1	psy 50.1		50.8	46.5	0.44
SiO ₂	67.42	68.23	40.45	39.90	48.1	50.1		50.8	46.5	0.44
Al ₂ O ₃	19.23	19.72	8.70	9.28	1.0	0.59		1.34	33.1	0.25
TiO ₂	--	--	3.17	1.31	0.1	0.26		0.30	--	7.57
FeO	--	--	29.1	34.22	26.8	23.70		26.40	0.18	90.40
MnO	--	--	0.81	1.00	1.52	0.89		0.71	--	1.19
MgO	--	--	2.28	0.73	0.62	4.41		0.99	--	--
CaO	0.44	0.25	10.3	8.89	17.8	20.30		11.00	0.13	--
Na ₂ O	7.40	11.23	2.14	3.30	2.40	0.57		6.80	15.20	--
K ₂ O	6.39	0.27	1.57	1.75	--	N.D.		N.D.	5.46	--

ATOMIC PROPORTIONS

	Feldspars Based on 8 oxygens		Amphiboles Based on 23 oxygens		Pyroxene* Based on 6 oxygens			Nepheline* Based on 32 oxygens	Fe-Ti Oxides Based on 24 oxygens
Si	2.987	2.988	6.73	6.43	2.001	1.990	2.074	8.76	0.119
Al	1.004	1.018	1.52	1.76	--	0.010	--	7.352	0.079
Al	0	0	0.118	0	0.42	0.017	0.064	--	1.530
Ti	--	--	0.372	0.147	0.004	0.008	0.010	--	20.310
Fe	--	--	3.89	4.61	0.930	0.786	0.902	0.29	0.272
Mg	--	--	0.515	0.172	0.38	0.261	0.060	--	--
Ca	0.021	0.012	1.765	1.536	0.797	0.862	0.480	0.27	--
Na	0.635	0.954	0.690	1.031	0.194	0.044	0.538	5.52	--
K	0.361	0.015	0.323	0.361	--	--	--	1.315	--
Ae					16.0	3.9	47.3		
Di					3.5	25.2	5.3		
Hd					75.1	60.8	42.8		

* From Koeilner (1974)

Nepheline

Nepheline is characterized by its euhedral rectangular form and parallel extinction in thin section. In hand specimen, crystals may reach 4 or 5 cm. in length and appear gray with a greasy luster. Nepheline grains show alteration along borders and cracks to a colorless mica, possibly paragonite (Deer et al., 1963). According to Koellner (1974) nephelines are enriched in Si by 15% and deficient in alkalis by about 13% (also see Smith and Sahama, 1954).

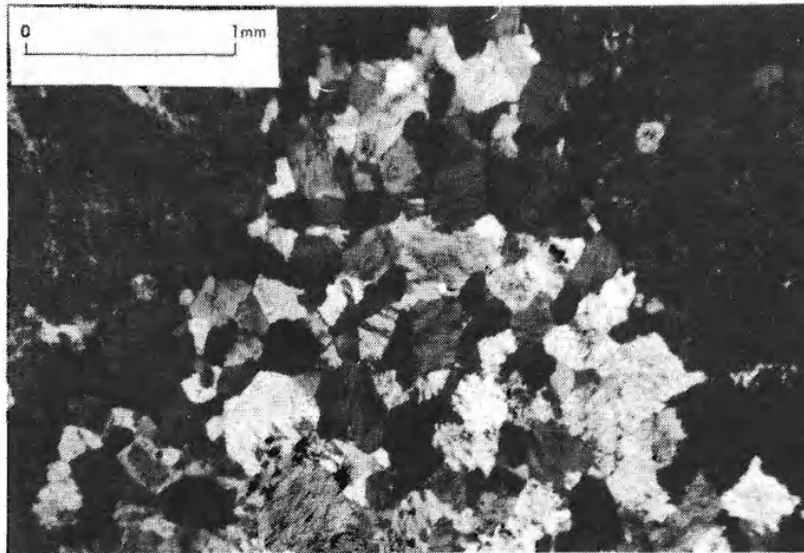


Figure 21

Photomicrograph of nepheline syenite showing nepheline grains (at left and right edges) in aplitic matrix of perthitic feldspar. Crossed nicols.

Pyroxenes

Both sodic and calcic clinopyroxenes occur in the various rocks of the Stettin Complex. Representative chemical compositions are given in Table 8. Sodic pyroxenes, aegirine and aegirine-augite, occur as distinct grains as well as crystals rimmed with bluish-green amphibole. Some grains show color zoning with pale cores and bright green rims. The average extinction angle ($X:C$) of the cores is 28° , whereas that of the rims is $13-24^\circ$, implying outward increase of the aegirine content. Calcic pyroxenes (diopside-hedenbergite) are iron-rich with aegirine content of up to 10% (Koellner, 1974).

In general, $Na+Fe^{+3}$ content of the pyroxenes is highest in the rocks of the wall zone.

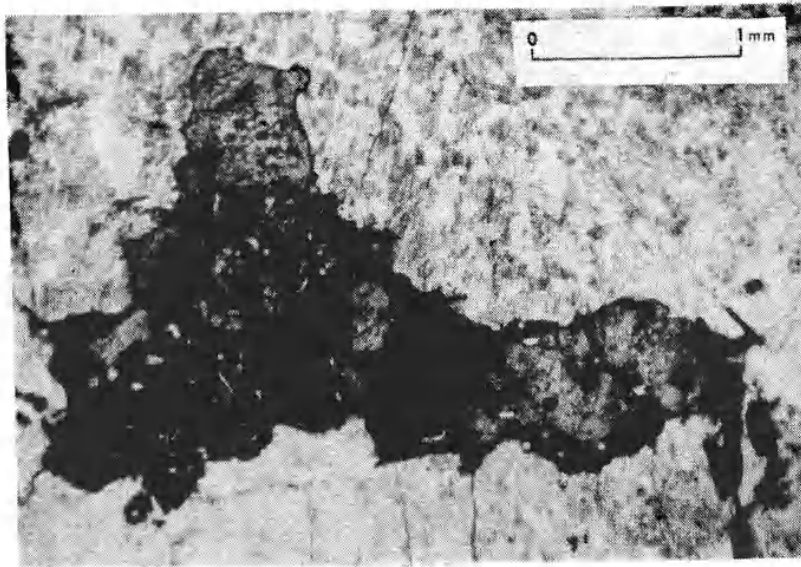


Figure 22

Photomicrograph of pyroxene syenite. Zircon crystals (left of center) surrounded by arfvedsonite (dark) and aegirine-augite. Note biotite near the center of the photograph. Small colorless apatite crystals occur as inclusions in the mafic minerals. Stained alkali feldspar surrounds the cluster. Plane polarized light.

Amphiboles

The dominant mafic mineral is a bluish green sodic amphibole. The absorption scheme of this mineral closely agrees with arfvedsonite: X = bluish green or greenish blue, Z = greenish brown or light brown. The amphibole grains have an average extinction angle (X:C) of 16° ; this corresponds to a composition of 26 Mg: (Mg + Fe^{+2} + Fe^{+3} + Mn) in the eckermannite-arfvedsonite series (Deer et al., 1963). However, the extinction angles vary from 0° to 29° . Some amphibole grains exhibit an optical character more closely resembling riebeckite and have an absorption scheme X = deep blue, Z = light blue. The extinction angle of these grains is approximately 1° .

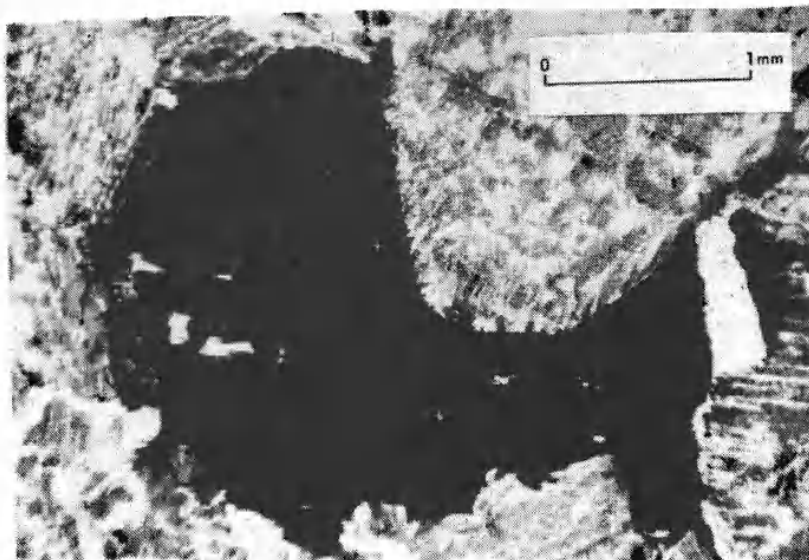


Figure 23

Photomicrograph of bluish green arfvedsonite in amphibole syenite no. 108. Quartz at right edge. Plane Polarized light.

X-ray diffraction powder patterns of the riebeckitic amphiboles show a d-spacing of 8.42°A for the 110 reflection, compared to 8.50°A for arfvedsonite. The lower d-spacing is in close agreement with other riebeckite analyses. Both sodic and calcic amphiboles are Fe-rich. Their composition probably reflects differentiation.

Biotite

It occurs in small amounts in two distinct varieties. Both have strong pleochroism but exhibit different absorption schemes. One is reddish brown to dark brown, and the other is light brown to dark green. This may suggest possibly reflecting different Ti, Fe⁺², Fe⁺³, and Mg contents (Hyama, 1959; Deer, et al., 1963).

Accessory Minerals

The only zirconium mineral so far found is zircon which occurs as zones prismatic crystals along clusters of mafic minerals especially in rocks of the Core Zone, e.g., pyroxene syenite. Other accessory minerals are sphene, fluorapatite, fluorite, calcite, Fe-Ti oxides.

PETROCHEMISTRY

Chemical compositions of the Stettin rocks are presented in Table 8. Table 9 compares average compositions of the Stettin rocks to those of Nockold's (1954). The average of the Stettin nepheline syenites show distinct differences from Nockold's average syenite. These Stettin samples, while only slightly higher in silica, are lower in Al₂O₃ and Na₂O and higher in FeO, CaO and P₂O₅. The amphibole and pyroxene syenites, also slightly higher in silica than Nockold's average syenite, are lower in Al₂O₃, MgO, CaO and K₂O, while higher in FeO, Na₂O and MnO. The differentiation indices (DI = normative quartz + orthoclase + albite + nepheline + leucite + kalsilite) (Thornton and Tuttle, 1960) for these Stettin rocks are given in Table 10. The average DI for these rocks is 84.7, which represents a high degree of differentiation. However, nepheline syenites have the highest DI of 88.9 and 93.9 respectively, indicating the greatest extent of differentiation among these rocks.

The agpaitic indices of the Stettin samples are shown in Figure 24-A. Rocks of lower SiO₂ content, the nepheline bearing rocks, have lower agpaitic indices than the more silica rich rocks. This is a reflection of the higher alumina content, due to the presence of nepheline, in the nepheline syenites. The ratio Na₂O/K₂O versus SiO₂ (Figure 24C) increases with increasing SiO₂. This diagram shows two trends suggesting that the Stettin rocks belong to two series. Amphibole and pyroxene syenites appear to follow a continuous differentiation sequence. (Figures 24A-F). C.I.P.W. normative compositions are presented in Table 10. The normative compositions of the analyzed Stettin rocks were calculated in terms of NaAlSiO₄, KAlSiO₄ and SiO₂ and are plotted in the systems NaAlSiO₄ - KAlSiO₄ - SiO₂ at 1000 bars P_{H₂O} (Figure 25). All of the rocks fall within the low temperature trough.

TABLE 8

CHEMICAL COMPOSITIONS OF THE STETTIN ROCKS*

		INTERMEDIATE ZONE			CORE ZONE		RIM ZONE		
SiO ₂	66.10	65.20	64.70	61.95	59.75	61.50**	57.45	56.95	54.10
Al ₂ O ₃	13.24	15.59	15.86	16.04	16.23	16.62	16.93	21.02	16.32
Fe ₂ O ₃	2.61	2.36	2.45	3.13	2.55	5.20	2.58	2.93	3.41
FeO	4.12	2.22	2.10	2.70	5.66	1.68	5.98	2.12	7.08
MgO	0.43	0.01	0.02	0.08	0.14	0.24	0.21	0.07	1.22
CaO	0.70	0.50	0.95	1.10	2.15	1.43	2.64	0.51	4.03
Na ₂ O	5.92	6.92	7.07	6.51	5.97	6.49	6.71	7.81	5.81
K ₂ O	4.31	5.11	5.19	5.51	5.67	5.15	5.02	5.99	4.84
H ₂ O	0.73	0.83	0.70	1.95	0.51	0.63	0.98	1.43	0.77
CO ₂	0.38	0.35	0.36	0.40	0.22	0.17	0.18	0.40	0.09
TiO ₂	0.72	0.42	0.27	0.32	0.75	0.31	0.59	0.38	1.32
P ₂ O ₅	0.11	0.04	0.06	0.07	0.13	0.07	0.13	0.50	0.49
MnO	0.23	0.12	0.15	0.18	0.26	0.22	0.30	0.07	0.29
S	0.010	0.004	0.003	0.008	0.034	0.009	0.023	0.000	0.044
ZrO ₂	0.102	0.165	0.260	0.171	0.11	0.100	0.140	0.001	0.079
		0.215		0.143			0.241		0.105
Cl	0.03	0.013	0.024	0.010	0.010	0.345	0.02	0.025	0.02
BaO		0.071		0.150	0.160	0.103	0.086		0.208
Rb(ppm)		199.		152.	66.	133.	115.		102.
Sr(ppm)		44.		105.	174.	109.	57.		345.

* Analyst-K. Ramlal, University of Manitoba

** Tabular Syenite

TABLE 9

COMPARISON OF CHEMICAL COMPOSITIONS OF STETTIN WITH NOCKOLDS (1954) AVERAGES

	Average Stettin Nepheline Syenite	Average Nepheline Syenite (Nockolds, 1954)	Average Stettin Syenite	Average Syenite (Nockolds, 1954)
SiO ₂	56.17	55.38	63.54	61.86
Al ₂ O ₃	18.09	21.30	15.39	16.91
Fe ₂ O ₃	2.97	2.42	2.62	2.32
FeO	5.06	2.00	3.36	2.63
MgO	0.50	0.57	0.14	0.96
CaO	2.39	1.98	1.08	2.54
Na ₂ O	6.78	8.84	6.49	5.46
K ₂ O	5.28	5.34	5.16	5.91
H ₂ O	1.06	0.96	0.94	0.53*
TiO ₂	0.76	0.66	0.50	0.58
P ₂ O ₅	0.37	0.19	0.08	0.19
MnO	0.22	0.19	0.19	0.11

* includes only H₂O

TABLE 10
C.I.P.W. NORMATIVE COMPOSITIONS OF THE STETTIN ROCKS

ROCK TYPE	INTERMEDIATE ZONE				CORE ZONE	WALL ZONE			
	Amphibole Syenite				Pyroxene Syenite	Tabular Syenite	Nepheline Syenite		
Sample Numbers*	10	77	503	100	6 and 504	65	46	2	92
Q	12.44%	4.86%	2.80%	1.79%		1.80%			
Or	25.61	30.06	30.62	32.28	33.40%	30.62	29.50%	35.62%	28.39%
Ab	44.05	51.92	52.97	51.92	47.72	52.44	56.48	38.39	34.16
An					0.88	2.22	1.47	2.11	4.26
Ne					1.28		7.93	14.86	8.10
Ol					3.41		3.00	0.96	4.67
Hy	7.22	2.36	1.36	1.65					
Ac	5.31	5.91	5.89	2.70					
Di		1.89	3.88	2.70	6.66		9.82		10.65
Mt	1.04	0.51	0.54	3.28	3.70	5.06	3.70	4.17	4.86
Il	1.36	0.76	0.46	0.61	1.36	0.61	1.06	0.76	2.43
Pr	0.12	0.01	0.01	0.01	0.06	0.02	0.06		0.06
Ru	0.02								
Hm						1.62			
C								0.91	
Ap	0.34	0.10	0.13	0.17	0.34	0.17	0.34	0.13	1.01
Z	0.18	0.18	0.37	0.18	0.02	0.15	0.18	0.001	0.11
H1	0.06	0.02	0.04	0.02	0.02	0.58	0.03	0.06	0.04
Tn	1.70								
CC				0.90	0.50				0.20
DI	82.1	86.8	86.4	86.0	82.4	84.9	93.9	88.9	70.6

*Tabular Syenite

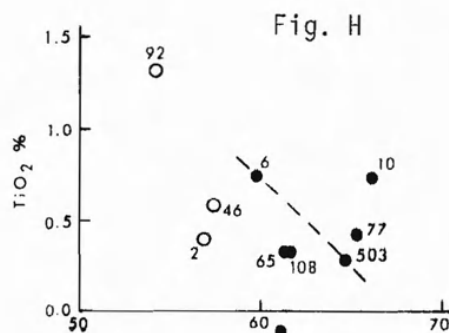
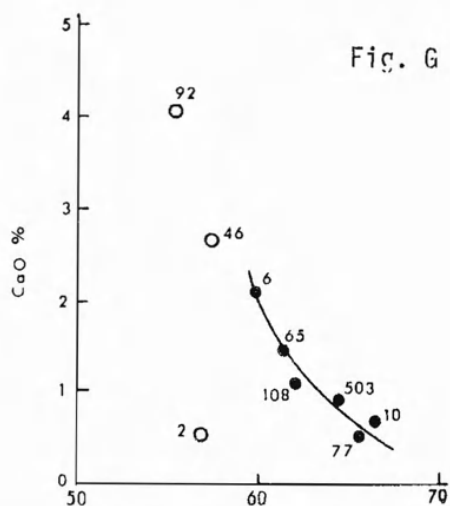
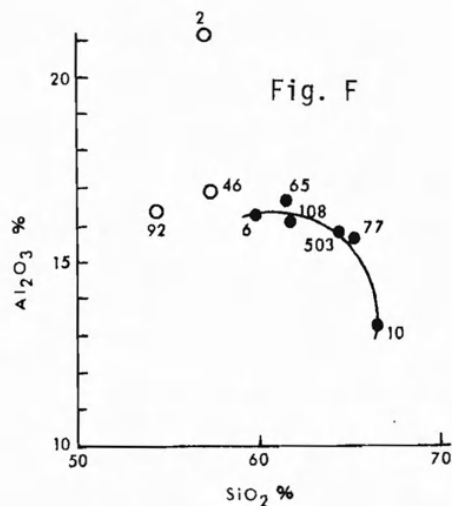
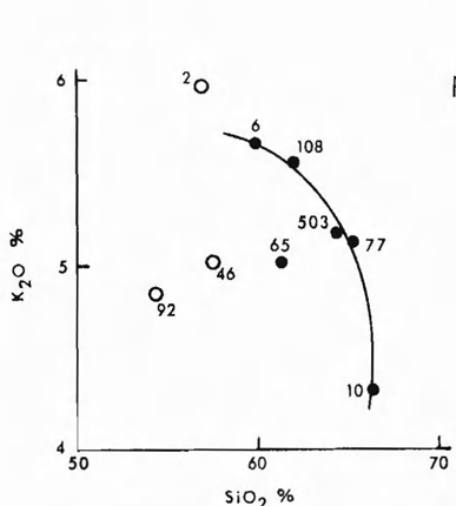
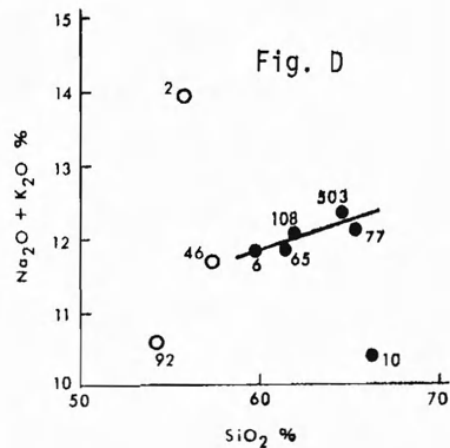
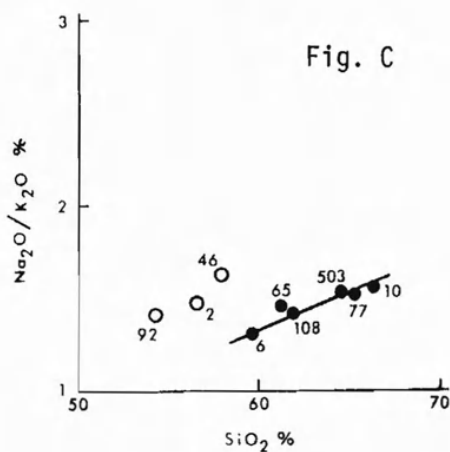
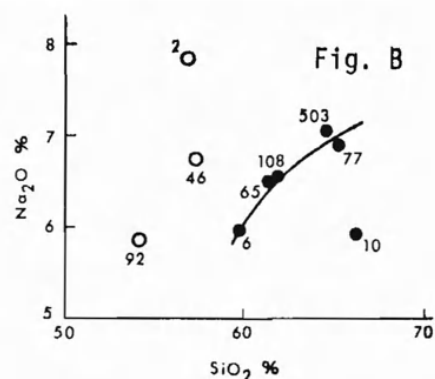
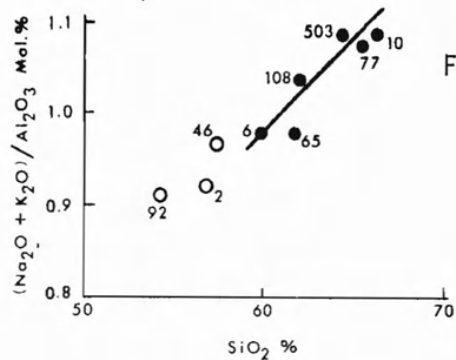


Figure 24, A-H

DISCUSSION

Due to chemical and mineralogical heterogeneity, the origin of alkaline igneous rocks is, in many cases, very complex and may be the result of several processes. Experimental studies of chemically equivalent synthetic silicate systems (Bailey and Schairer, 1966; Hamilton and Mackenzie, 1965; Schairer, 1967; Sood and Edgar, 1972; Sood, Platt and Edgar, 1970; Tuttle and Bowen, 1958) have provided a physicochemical framework to explain the crystallization behavior of alkali magmas.

Any petrogenetic model for the formation of alkaline rocks of the Wausau area must take into account:

- 1) the zoned nature of the complex
- 2) the presence of quartz-bearing aplitic and pegmatitic stages in the intermediate ring of amphibole syenite;
- 3) the fenitized zone surrounding the pluton;
- 4) the presence of volatile bearing minerals (fluorite, calcite, apatite) in most syenites, and in the quartz monzonite "core" (?) of the Wausau pluton;
- 5) major and trace element geochemistry of the syenites.

Consideration with Respect to the System Nepheline-Kalsilite-Silica

In Figure 25 normative composition of the Stettin rocks is plotted in the system Nepheline-kalsilite-silica at 1Kb P_{H_2O} along with the composition of the rocks from Kangerdlugssuaq intrusion, H_2O East Greenland (Wager, 1965). These analyses may be interpreted to show a trend of silica depletion away from the SiO_2 apex.

Rocks of the Intermediate Zone of amphibole syenite plot in the alkali feldspar-quartz region, near the alkali feldspar join, while pyroxene syenites of the Core Zone plot just below the alkali feldspar join. The positions of these syenites in the field show a silica depletion trend toward the center of the complex.

From Figure 25, it appears that the trend of these amphibole and pyroxene syenites is up the alkali feldspar surface and "over" the thermal barrier, which is similar to the interpretation by Wager (1965) for the nordmarkites, pulaskites, and foyaites of the alkaline Kangerdlugssuaq intrusion.

(In the nepheline-kalsilite-silica system at 5 Kb P_{H_2O} , these rock webs plot close to the feldspar cotectic or nepheline-feldspar H_2O cotectic. This is in agreement with mineral paragenetic and textural relations.) Further interpretations await the accumulation of additional data, especially on the Wausau pluton.

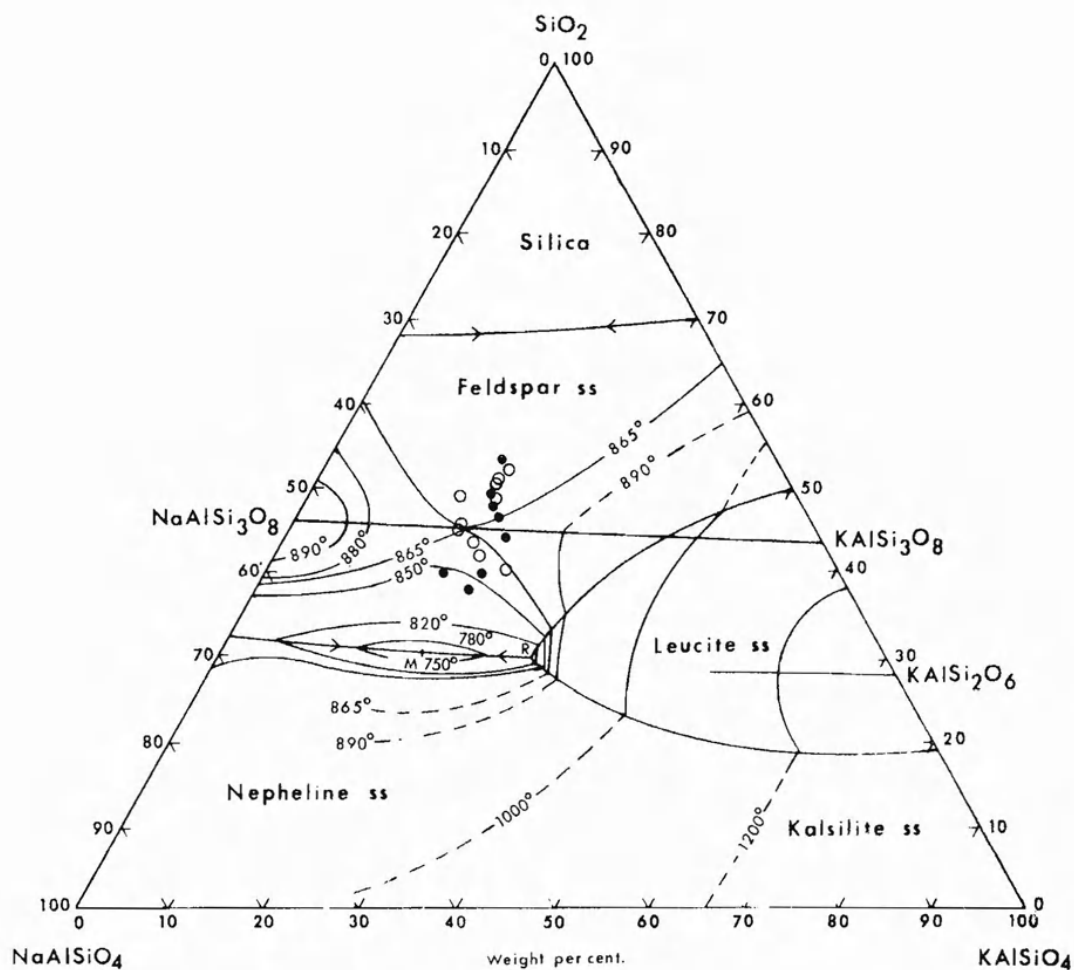


Figure 25-- Normative compositions of the Stettin rocks (closed circles) and the alkaline rocks of the Kangerdlugssuaq intrusion, East Greenland (open circles) (Wager, 1965) plotted in the system NaAlSiO₄ - KAlSiO₄ - SiO₂ at P_{H₂O} = 1000 bars (Fudali, 1963; Hamilton and MacKenzie, 1965).

How could such inward silica depletion be caused? Two possible explanations are:

- (1) Loss of the volatile phase in equilibrium with the melt. Such a volatile phase has alumina, alkali, and silica in the same proportion as feldspars (Tuttle & Bowen, 1958; Mackenzie, 1960). The presence of aplitic and pegmatitic phases and fenitization of the surrounding volcanics may be a reflection of separation of volatiles into a gaseous phase and eventual loss. The plot of the Stettin rocks close to cotectics in pertinent synthetic systems may be indicative of crystallization of major phases within narrow temperature limits. Short crystallization intervals are also related to silica and alkali content which control volatile distribution in liquid and gaseous phases (Sood & Edgar, 1970; Kogarko & Rhyaschikov, 1961).
- (2) The substitution of Fe^{+3} Al^{+3} in feldspars may contribute to silica depletion with crystallization of iron-rich albite ($\text{NaFe}^{+3}\text{Si}_2\text{O}_8$). Only a small amount of Fe-Al substitution is necessary to fix silica and cause the liquid to shift from silica saturated to silica undersaturated trend (Bailey & Schairer, 1966). The general iron-rich and alumina-deficient nature of the syenites in comparison to Nockold's (1954) averages and a limited Fe-content of feldspars favor such substitution.

The Nepheline syenite in the Stettin pluton may, therefore, represent last residual liquids injected into the sheared wall zone.

It may be concluded that alkaline rocks of Marathon County represent a "genetically related comagmatic series." The study of silicate systems and melting relations of rocks have amply demonstrated that magma composition lies close to the univariant lines or the invariant points, and very slight changes in initial liquid composition can give decidedly distinct liquid trends. Compositional differences in these alkaline rocks may be related to slight changes in magma composition by fractional crystallization or by wallrock assimilation, or both. It is important to further refine their genetic and tectonic relations. Systematic geochemical data both on rocks and minerals are needed to assess if these rocks are formed from mantle derived magmas (tentatively note the low Rb and Sr contents for Wausau rocks) which reached crust through recurrent fracture systems. Such information will also be useful in the estimation of economic mineral potential of this area. Such rocks form in environments favorable to the concentration of a wide variety of elements.

Comparison of the Wausau and Stettin Plutons

P.E. Myers

Despite obvious differences in size, shape, xenolith types, zoning sequences, and silica saturation, the Wausau and Stettin plutons share several significant similarities: (1) the pyroxene and amphibole syenites of the intermediate zone of the Stettin pluton are compositionally equivalent to the outer wall zone of the Wausau pluton, (2) the lensoidal quartz syenite and probably comagmatic Ninemile quartz monzonite of the Wausau pluton, are probably the silica-rich end-members which would have differentiated from the Stettin pluton after crystallization of the amphibole syenite. Koellner (1974, p. 31) reports contents of up to 15% in the pegmatitic phases of the amphibole syenite. The close spatial association of zoned granite pegmatite veinlets (Stop #3) and quartzite xenoliths suggests at least localized silification of quartzite and other sili-saturated wall rocks. The relative silica undersaturation of the Stettin pluton may be due in part to the low silica content of the volcanic rocks which it intrudes.

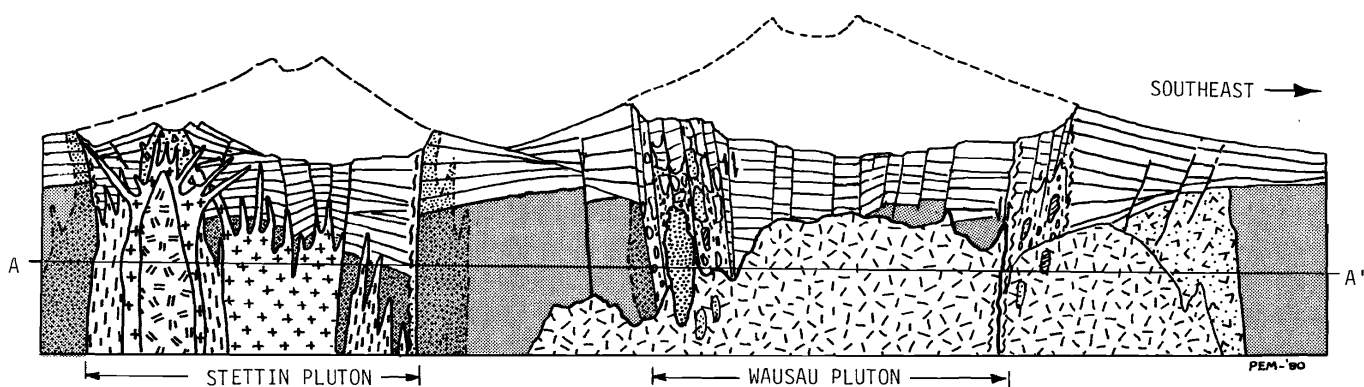
The Wausau and Stettin plutons probably represent the near-surface "roots" of two collapse calderas (Figure 26). Mirolitic cavities in the margin of the Ninemile quartz monzonite indicate that the quartz monzonite intruded the caldera core and part of its rim to within a short distance of the surface. Although probably related in some way to the rapakivi granites of the Wolf River batholith, Van Schmus (1980, in press) has determined that the Wausau syenite plutons were intruded at 1520 m.y. as contrasted with a 1500 m.y. age for the Wolf River batholith. Thus, the syenites appear to represent an early, shallow, volcanic manifestation of Wolf River batholith intrusive activity. Evidence suggesting that the Stettin pluton is the older is:

- (1) fragments of porphyritic trachyte (?) similar to that now exposed on both sides of the Wisconsin River at Brokaw are found in the Wausau syenite (Stop #3);
- (2) the Stettin pluton produced a wider halo of syenitization and contains fewer unassimilated xenoliths.

Shearing with chaotic vertical displacement and mixing of wallrock fragments was greatest in the intermediate zone of the Wausau pluton and less important in the wall zone of the Stettin pluton. Semi-detached wallrock slices, partly sheared away from the cylindrical wall, are seen on the east and south sides of the Stettin pluton. By contrast, xenoliths in the contaminated intermediate zone of the Wausau pluton were completely detached and show no essential relationship to contiguous wallrocks. Thus, there appears to have been significantly greater vertical transport of xenoliths in the intermediate (caldera rim) zone of the Wausau pluton. The occurrence of sillimanite in quartzite xenoliths at Rib Mountain (3-M quarry) and on a ridge about 1 1/2 mile northwest of Stop #4 suggests a derivation from a deeper metamorphic basement. However, the possibility of the metasomatic origin of sillimanite should not be ruled out. There is certainly ample evidence of metasomatism - syenitization - of xenoliths throughout the pluton.

There is little doubt of the close genetic relationship of the Wausau, Ninemile, and Stettin plutons. Based on field relations, the cross section reconstruction is proposed (Figure 26). The concentric xenolith-rich zones, which typically show effects of shearing, suggest that the vertical movement, probably up and down, was localized in these caldera rim collapse structures. This suggests that the floor of the Wausau syenite caldera foundered in the upwelling Ninemile quartz monzonite.

Our field and laboratory investigations are now focusing on the Wausau syenite and Ninemile plutons. After completion of this work, a much more detailed picture of magma emplacement conditions, sequence, and mechanism as well as its association with volcanism should be possible.



EXPLANATION

-  Ninemile quartz monzonite
-  Amphibole syenite
-  Pyroxene syenite
-  Gneissic nepheline and tabular syenite border facies
-  Syenitized volcanic rocks
-  Lensoidal quartz syenite with xenoliths of biotite schist and quartzite
-  Alkalic extrusives, probably pyroclastics and subordinate flows
-  Quartz diorite
-  Quartzite
-  Older calc-alkaline volcanic rocks, mainly andesite and rhyolite

Figure -- Hypothetical northwest-southeast section across the Stettin and Wausau syenite plutons as they would have appeared about 1450 m.y. ago. Line A-A' represents the present land surface. See Figure 4 for location of section A-A'.

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