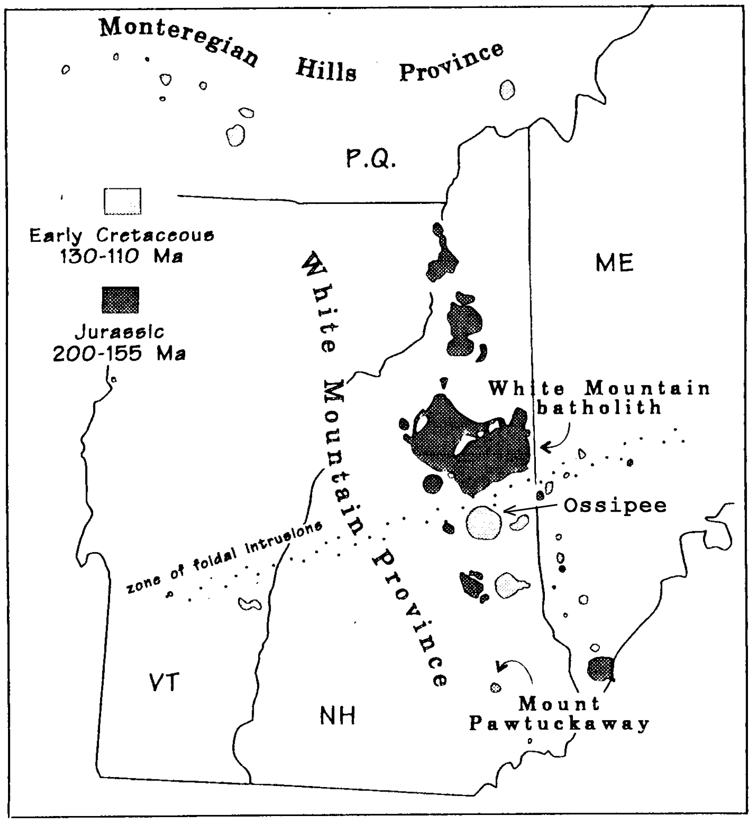
Third Hutton Symposium on Granites and Related Rocks

Pre-Conference Field Trip

Part I:
White Mountain Magma Series



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Part 1
White Mountain Magma Series

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Introduction

The White Mountain igneous province of New Hampshire is part of the New England-Quebec province of McHone and Butler (1984). In New England this province is represented by two periods of igneous activity: the older between 220-155 Ma and the younger between 130-100 Ma (Fig. 1). Plutons of the older White Mountain series are largely composed of alkali syenite, quartz syenites, and metaluminous and peralkaline granites. Silica-undersaturated rocks (nepheline syenites) have only been found at two localities; Rattlesnake Mountain in Maine and the Red Hill complex in New Hampshire. With the exception of the Belknaps, mafic igneous rocks are conspicuously absent. The largest intrusive complex is the White Mountain batholith which consists of multiple ring dikes intruded into and by composite plutons of metaluminous to peralkaline granite. Peralkaline rhyolites are preserved in several localities.

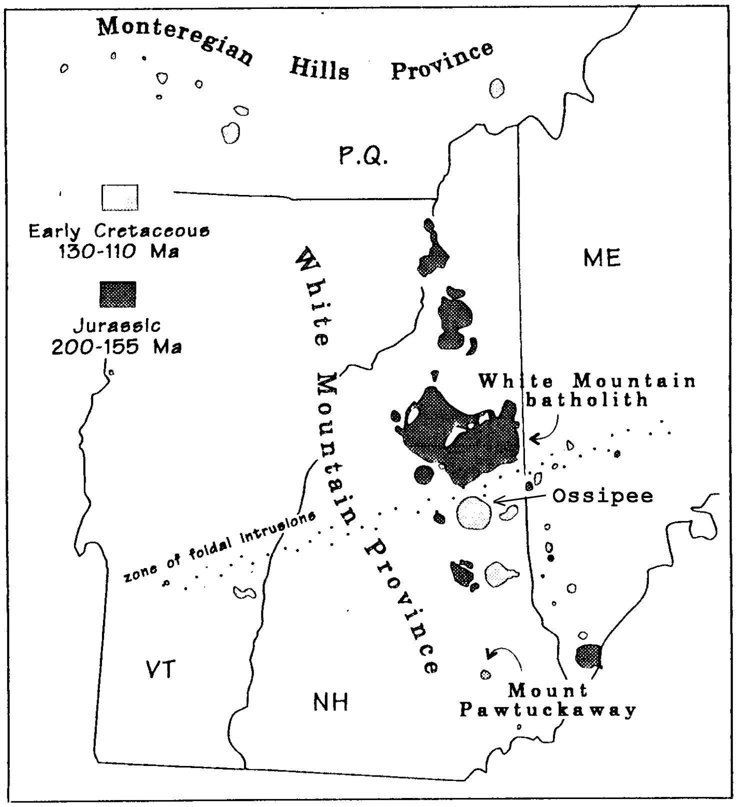

Figure 1. White Mountain and Monteregian Hills igneous provinces showing the location of the White Mountain batholith, Ossipee, and Mount Pawtuckaway (After Creasy and Eby, 1993).

The Monteregian Hills and younger White Mountain igneous provinces represent the younger period of igneous activity. The bulk of the magmatism occurred *ca.* 125 Ma, but younger ages have been obtained for Little Rattlesnake (114 Ma, Foland and Faul, 1977) and Cuttingsville (100 Ma, Armstrong and Stump, 1971). Plutons emplaced to the west of Logan's line (which roughly parallels the New

Hampshire-Vermont border) consist largely of mafic alkaline suites, many of which are nepheline normative. To the east of Logan's line, felsic rocks are much more important components of the intrusions and silica-undersaturated rocks are not found. Some of these younger plutons show ring-like structures (Ossipee and Pawtuckaway) while others appear to be small plugs (e.g. Little Rattlesnake, Ascutney and Tripyramid). Generally the most evolved rocks are syenites and quartz syenites, but biotite granite (Conway) is found at Ossipee and Merrymeeting Lake. An overview of both provinces can be found in Eby (1987).

The White Mountain igneous province is a classic example of A-type magmatism. Chemically the granitoids plot in the A_1 field of Eby (1992). While mafic rocks are scarce in the older White Mountain series, they are relatively abundant in the younger White Mountain series. Mafic volcanics (basalts and andesites) are exposed in the Ossipee complex and mafic plutonics ranging from pyroxenites to diorites are found at Mount Pawtuckaway. Given the presence of the mafic end members, evolutionary models which yield evolved felsic liquids by differentiation of mafic magmas have proven successful. Particularly in the case of Mount Pawtuckaway, low initial $^{87}Sr/^{86}Sr$ ratios indicate that the magmas were emplaced with little contamination by crustal material.

White Mountain Batholith

Introduction

The White Mountain batholith of central New Hampshire is Jurassic in age and has an areal extent of 1,000 km^3. The batholith consists of a number of overlapping centers of felsic magmatism (Fig. 2). The individual centers are defined by composite ring dikes of porphyritic quartz syenite. Thick sections of rhyolitic crystal tuffs, breccias, and subvolcanic granite porphyry are partially enclosed by the ring dikes. Multiple intrusions of subalkaline to peralkaline silica-oversaturated granitoids form the bulk of the batholith. A detailed description of the geology, geochronology, and geochemistry of the White Mountain batholith can be found in Eby et al. (1992).

Geology

The Mount Osceola Granite (green), a subalkaline to peralkaline amphibole granite, and the Conway Granite (red), a subalkaline biotite granite, comprise about 80% of the batholith. While the Mount Osceola Granite tends to be uniform in texture, chemistry, and radiometric age (187 Ma), rocks mapped as Conway Granite show a wide variety of textures and a range in chemistry and radiometric age (183-155 Ma). The next most abundant lithologies are the syenite and quartz-syenite porphyries which comprise the various ring dikes and several stocks. All of the units were emplaced into Lower Paleozoic schists, gneisses, and granites, which are locally preserved as screens within the batholith. In the eastern portion of the batholith two thick sequences of felsic volcanics (Moat volcanics) are interpreted as

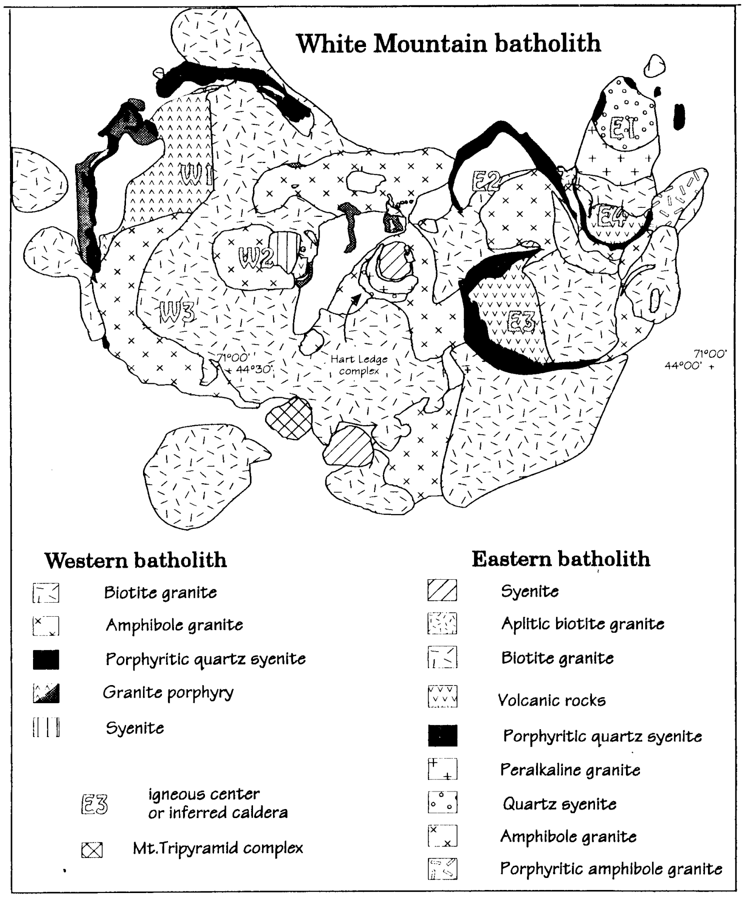

Figure 2. Geologic map of the White Mountain batholith from Creasy and Eby (1993).

calderas (Noble and Billings, 1967; Fitzgerald, 1987; Fitzgerald and Creasy, 1988). Only a few isolated outcrops of mafic rocks have been found in the batholith. Radiometric ages indicate an eastward progression of the magmatism. Igneous activity commenced in the western portion of the batholith with the intrusion of several ring dikes and granite porphyries between 200-190 Ma. This was followed by the emplacement of the Mount Osceola Granite in both the western and eastern half of the batholiths. Igneous activity continued with the emplacement of the "Conway Granite" plutons and the Albany Porphyritic Quartz Syenite ring-dikes in the eastern portion of the batholith. The eruption of the volcanics in the eastern portion of the batholith was essentially synchronous with the emplacement of the ring-dikes (173-168 Ma). The phase igneous activity ended with the emplacement of a small "Conway Granite" pluton at 155 Ma. The Hart Ledge complex which is found in the center of the batholith, and the Mount Tripyramid complex which occurs along the southern edge of the batholith, belong to the younger period of White Mountain igneous activity. The White Mountain batholith has been interpreted as a sub-horizontal slice through a caldera field at a depth of 1-2 km below the original land surface (Creasy and Eby, 1993).

Lithologic Descriptions

Brief descriptions are given for the major units in the White Mountain batholith. A number of lithologies that have only limited distribution are not described. Refer to Eby et al. (1992) and Creasy and Eby (1993), and the references therein, for more complete lithologic descriptions.

Mount Lafayette - porphyritic unit ranging in composition from syenite to granite. Perthite, quartz, fayalite, ferrohedenbergite, and ilmenite occur as phenocrysts while quartz, orthoclase, and ferrohastingsite are found in the groundmass. Accessory minerals are fluorite, allanite, titanite, and zircon.

Mount Garfield - porphyritic quartz syenite. Phenocrysts are quartz and microperthite and occasionally fayalite, ferrohedenbergite, and ilmenite. The fine-grained groundmass consists of quartz, orthoclase, and ferrohastingsite. Grunerite, annite, fluorite, allanite, titanite and zircon are accessory minerals.

Mount Carrigain - syenite porphyry and minor trachyte porphyry. The syenite porphyry has sparse orthoclase microperthite phenocrysts in a fine-grained groundmass of orthoclase microperthite, hastingsite, and minor quartz. The accessory minerals are opaque oxides, biotite, fluorite, and titanite. The trachyte porphyry consists of orthoclase microperthite phenocrysts in a very fine-grained matrix of feldspar and amphibole.

Mount Osceola Granite - medium- to coarse-grained hypersolvus granite that is dark green when fresh. Microperthite, quartz, and ferrohastingsite form a hypidiormorphic granular texture. Minor minerals are fayalite, ferrohedenbergite, ferrorichterite and riebeckite. Accessory minerals are fluorite, allanite, monazite, zircon, and titanite. Miarolitic cavities and pegmatite pods are locally abundant.

Conway Granite - medium- to coarse-grained, pink, biotite two-feldspar granite. Accessory minerals are zircon, allanite, apatite, and titanite. There is a great deal of variability in the lithology of the intrusions which are mapped as Conway granite. Some phases are fine-grained and pure white, but have still been included in the Conway. Detailed mapping in the eastern part of the batholith (Osberg et al., 1978) has shown that a number of individual intrusions can be delineated.

Albany Porphyritic Quartz Syenite - porphyritic quartz syenite and porphyritic syenite. Phenocrysts are micro-perthite, subordinate quartz, and minor ferrohedenbergite, fayalite, and ilmenite. The groundmass consists of quartz, alkali feldspar, and ferrohastingsite. The accessory minerals are allanite, titanite, zircon, and fluorite. In detail the Albany Porphyritic Quartz Syenite ring-dikes consist of multiple phases as shown by changes in the abundance of feldspar phenocrysts and total quartz. The porphyritic syenite is distinguished from the Albany Porphyritic Quartz Syenite *sensu stricto* by the decrease in the abundance of phenocrysts (<15%) and the absence of exsolution textures in the alkali feldspar.

Moat Volcanics - a volcanic sequence consisting of commendite, trachyte, and tuff-breccia. Recent mapping has indicated that the Moat represents an intra-caldera sequence. Refer to Creasy and Eby (1993) for a detailed discussion of the various units in the Moat.

Petrogenesis

A detailed model for the petrogenetic history of the White Mountain batholith can be found in Eby et al. (1992). In brief, the various granitoids that comprise the batholith consistently plot in the A_1 granitoid fields of Eby (1992). It has been suggested that granitoids which plot in the A_1 field originate by differentiation of mafic magmas derived from an OIB-like source. In terms of Sr isotopes there is a sympathetic relationship between the initial Sr ratio and the degree of silica saturation of the individual units. In general syenites are characterized by low initial Sr ratios, and there is a regular increase in initial Sr ratio as the quartz content of the rocks increases. For most of the units there is very little intra-unit variation in Sr initial ratios and magmatic evolution can be explained by closed-system crystal fractionation. In the case of the Conway Granite there is isotopic and elemental evidence that there was significant crustal involvement in marginal facies of the Conway Granite. The Moat Volcanics are highly evolved and, although they show high initial Sr ratios, the low Sr abundance of the Moat Volcanic magmas means that these high ratios could be achieved by relatively minor crustal contamination. The preferred model for the genesis of the various units of the White Mountain batholith envisions the ponding of mafic melts at the base of the crust. These melts undergo various degrees of interaction with the lower crust as they evolve. Melts tapped early in their evolution gave rise to syenitic magmas with low initial Sr ratios while those tapped later gave rise to quartz-bearing magmas with higher initial Sr ratios. In general there seems to have been little involvement with the crust during the emplacement of the various melts. Thus most of the interaction between crust and melt occurred at or near the base of the crust.

Ossipee

Introduction

The Ossipee ring-dike complex of central New Hampshire is a member of the younger White Mountain igneous province. The topography is shown on the 7.5' Tamworth, Ossipee Lake, Melvin Village, and Tuftonboro quadrangles. The complex is circular in plan view and has a diameter of 14 km (Fig. 3). The almost complete outer ring-dike forms a ridge around the inner basin on the eastern side and forms the outer slopes of the high hills in the western part of the complex. The western third of the complex has a rugged topography and is underlain by basalts and rhyolites. The eastern portion is an interior basin underlain by granite. Maximum relief is approximately 750 m. Ossipee has played a central role in models dealing with the origin of ring dikes (Billings, 1943, 1945; Chapman, 1976) and has long been considered a classic example of a ring-dike complex.

The bedrock geology of the Ossipee complex was originally mapped by Kingsley (1931). Portions of the Ossipee complex appear on the geologic maps for the Mt. Chocorua (Smith et al., 1939), Winnipesaukee (Quinn, 1941), Wolfeboro (Quinn, 1953), and Ossipee Lake (Wilson, 1969) quadrangles. With the exception of the Ossipee Lake quadrangle the geology was based on the original work of Kingsley (1931). The intrusion was remapped by Carr (1980), and his thesis is the basis for the geologic map of the Ossipee complex (Fig. 3) and much of the ensuing discussion of the geology and petrography of the complex.

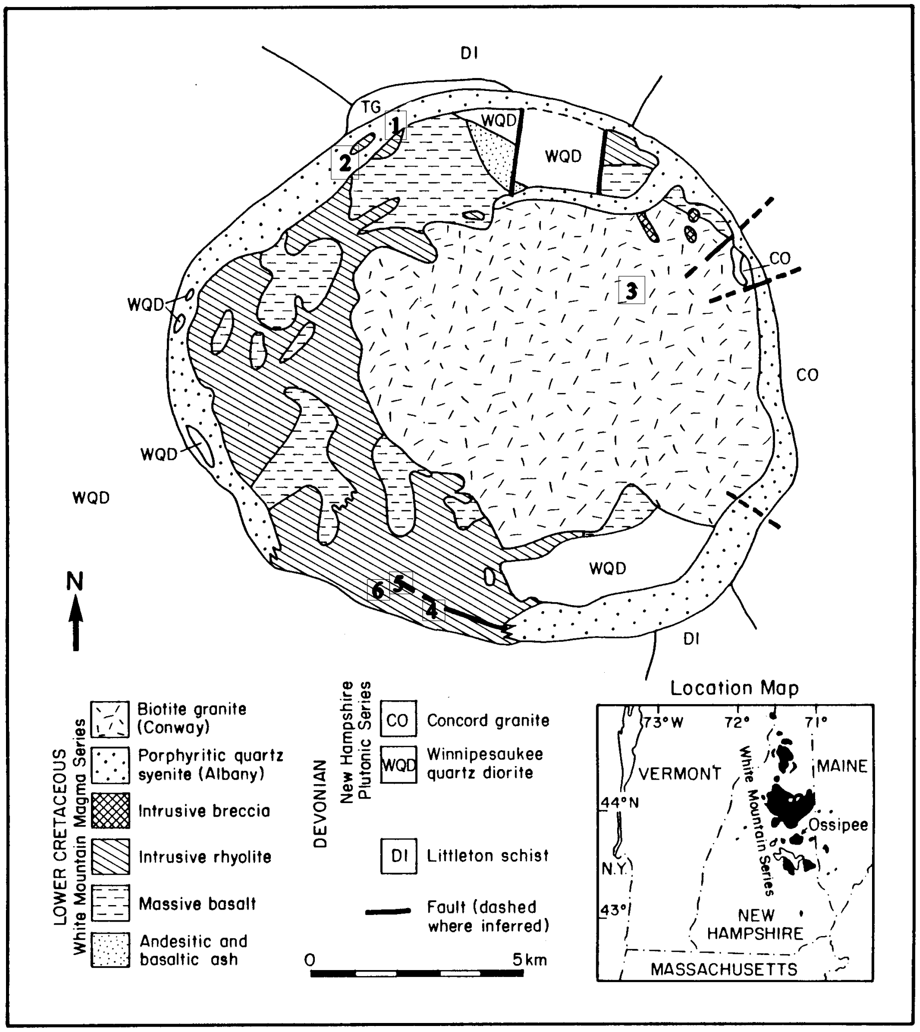

Figure 3. Geologic map of the Ossipee complex modified from Carr (1980). Numbers indicate the locations of the field trip stops.

General Geology

The Ossipee complex occurs within the Merrimack synclinorium and intrudes the Lower Devonian calc-alkaline Winnipesaukee quartz diorite and Concord granite (New Hampshire plutonic series). The outer margin is an almost complete ring-dike with multiple intrusive phases. Much of the ring-dike consists of medium to coarse-grained quartz syenite, but locally pink granite and/or porphyritic rhyolite are important components. The ring-dike is almost vertical, but slightly inward and slightly outward dips have been recorded. The complex is unique in the Younger White Mountain igneous province for the large amount of preserved basalt. The basalt generally occurs as inward dipping blocks in the rhyolite, but in places thick basalt-rhyolite sequences, which were apparently contiguous, have been preserved, thus suggesting that some of the basaltic and rhyolitic volcanism was contemporaneous. A sequence of thinly laminated beds of andesitic and basaltic ash, with shallow to moderate inward dips, occurs along the northeastern margin of the complex. The ash beds are interpreted to be caldera-type lake-bed deposits. Multiple phases of rhyolite have been identified, and on the basis of groundmass grain size it is believed that much of the rhyolite was subvolcanic (hence the name "intrusive" rhyolite). Some of the rhyolite, however, was erupted at the surface. The eastern portion of the complex is underlain by pink coarse-grained "Conway" granite. The granite is poorly exposed except at the tops of hills within the interior basin, where rounded and deeply weathered outcrops can be found. Gravity and magnetic data (Sharp and Simmons, 1978) indicate that the complex has a vertical core of mafic rock with a thin granitic carapace. In areas marked by maximum gravity or magnetic anomalies gabbroic and dioritic enclaves can be found in the granite.

Carr (1980) proposed the following sequence of events for the Ossipee complex. (1) Eruption of basaltic and andesitic magmas from a hypabyssal magma chamber forming ash and flows. (2) Intrusion of basaltic magmas through the volcanic pile forming massive basalts. (3) Rapid intrusion of rhyolitic magmas along dikes disrupting the pile of pre-existing ash and massive basalts and causing the collapse of the pile into the felsic magma. The presence of xenocrystic fragments of quartz and alkali feldspar, and the existence of intrusive breccia pipes with rhyolitic matrix, suggest that this may have been an episode of explosive magmatism. (4) Formation of the outer ring fractures and cauldron subsidence. (5) Emplacement of biotite granite. Since this granite occurs as a sheet above the mafic plug, which may represent the earlier basalt magma chamber, it was suggested that the granitic magma may have been emplaced along a cauldron fracture formed above the earlier magma chamber. (6) Emplacement of "lamprophyric" dikes.

Lithologic Descriptions

Mafic Units

Andesitic and basaltic ash - ash beds vary in thickness for 1 mm to tens of cms and vary in color from light gray to black. Many of the beds are finely laminated and graded. Identifiable minerals are plagioclase fragments, interstitial brown biotite and magnetite, and tiny euhedral apatites.

Basalt - two basic lithologies have been distinguished, one is coarsely porphyritic and the other is massive and sparsely- to non-porphyritic. Plagioclase is the dominant phenocryst phase and varies from 0.1 to 0.5 cm in size in the sparsely prorphyritic variety up to 1 cm in size in the coarsely porphyritic variety. Rare phenocrysts of altered clinopyroxene and biotite have been observed. The groundmass consists of plagioclase, altered clinopyroxene, amphibole, bitotite and magnetite. Some specimens are strongly magnetic. Extensive replacement of plagioclase by epidote has been observed in some specimens.

Felsic Units

Rhyolite - all of the rhyolites are mineralogically similar. Phenocrysts are angular to sub-angular alkali feldspar fragments and sub-rounded and embayed euhedral quartz grains. Rare plagioclase and amphibole fragments have been noted. The groundmass consists of quartz, K-feldspar, minor plagioclase, amphibole, and biotite. Basaltic and dioritic enclaves are common in the rhyolites. Hornblende syenite enclaves have also been observed. Many outcrops show a flow foliation. Texturally five varieties of rhyolite have been distinguished: (1) small pink alkali feldspar and clear quartz phenocrysts in a dense, black, very fine-grained matrix; (2) cream colored alkali feldspar and gray smoky quartz phenocrysts in a fine- to very-fine-grained dark gray matrix; (3) large pink alkali feldspar and gray smoky quartz phenocrysts in a fine-grained light brown matrix; (4) small cream colored alkali feldspar and gray smoky quartz phenocrysts in a medium- to fine-grained light brownish-gray matrix; and (5) large euhedral to subhedral phenocrysts of pink alkali feldspar and gray quartz in a fine-grained light brown to blue-gray matrix which shows spherulitic textures in thin section.

Porphyritic quartz syenite - alkali feldspar and sparse quartz phenocrysts in a medium- to fine-grained groundmass of alkali feldspar, quartz, biotite, hornblende and accessory magnetite, ilmenite and apatite and trace zircon. The quartz phenocrysts are partially resorbed by the groundmass minerals. The bulk of the quartz syenite is gray in color, but a somewhat finer grain pink variety has been identified. The groundmass of the pink variety contains abundant quench (graphic) textures. Hornblende syenite and basalt enclaves are found in the porphyritic syenite.

Subporphyritic granite - Subporphyritic, medium- to fine-grained, pink on fresh surfaces, and consists of quartz, alkali feldspar, minor oligoclase and biotite (often altered to chlorite). A characteristic feature is the intergrowth of quartz and alkali feldspar (graphic texture) in the somewhat finer-grained groundmass. Basalt enclaves are occasionally observed. This unit is one of the phases which comprise the ring dike.

Biotite granite - coarse- to medium-grained, phaneritic to subporphyritic, pink granite. Early maps of the Ossipee complex identify this granite as "Conway" (because of its pink color), but it is clearly not correlative with the Conway granite of the White Mountain batholith. Mineralogically the rock consists of rounded gray quartz, buff-colored alkali feldspar, minor plagioclase and biotite, and rare amphibole. The accessory minerals are fluorite, allanite, zircon, apatite, and opaque oxides. In the subporphyritic varieties quartz and alkali feldspar form the phenocrysts. Miarolitic cavities are common in some areas and often contain orthoclase and smoky quartz crystals up to 3 cm long. In many localities the granite is cut by pink to buff colored, fine-grained aplite dikes which are mineralogically similar to the granite. The dikes are usually less then 5 cm wide and show no preferred orientation.

Mount Pawtuckaway

Introduction

Mount Pawtuckaway, a member of the younger White Mountain igneous province, is located in Rockingham County, New Hampshire. The complex is centrally located along the northern edge of the 7.5' Mt. Pawtuckaway quadrangle and falls within the boundaries of Pawtuckaway State Park. The complex has a surface exposure of approximately 8 km^2, is roughly circular in plan view, and the maximum relief is on the order of 200 m (Fig. 4). The mafic rocks, which are easily eroded, underlie the lowlands while the more resistant monzonites and syenites form ridges. The low ridge along the southern edge of the complex is underlain by gabbros and troctolites. The Pawtuckaway magmas were intruded into the Precambrian Massabesic Gneiss Complex.

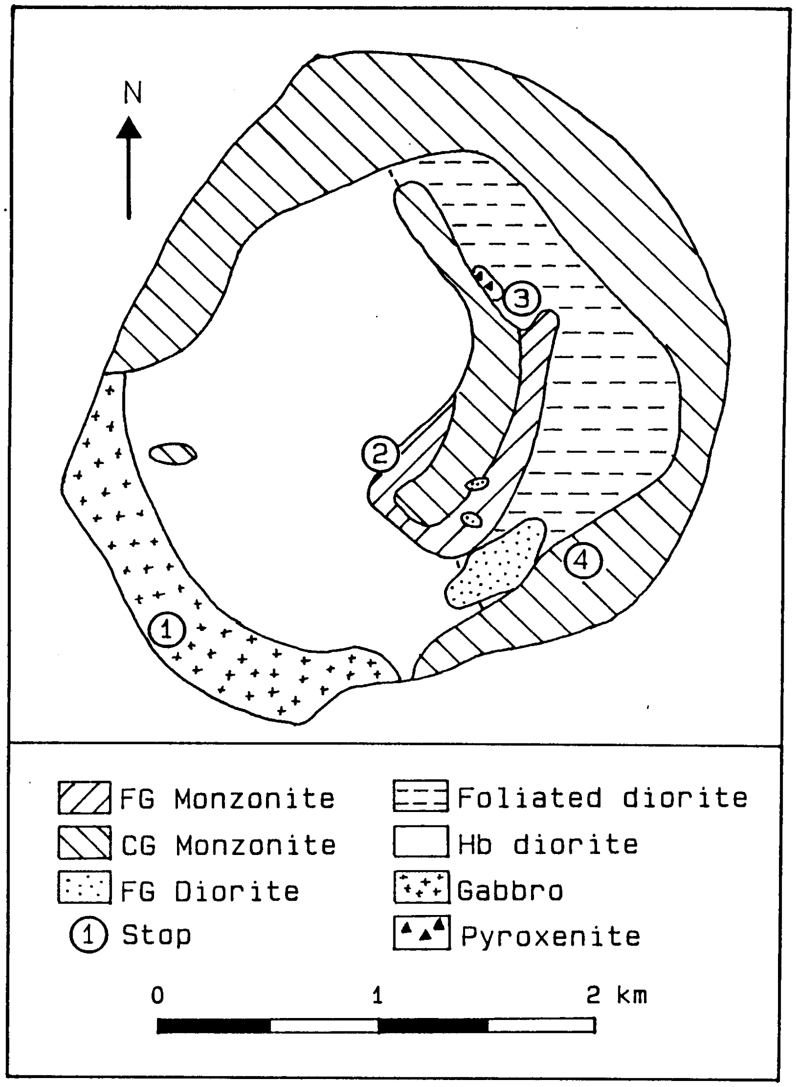

Figure 4. Geologic map of the Mount Pawtuckaway ring dike complex showing the locations of the field trip stops. From Creasy and Eby (1993).

The earliest studies of the Mount Pawtuckaway complex described the rocks as largely syenites and camptonites. Roy and Freedman (1944) were the first to completely map the complex and a further modification of the geology is found in Freedman (1950). Shearer (1976) did a geochemical study of the major units and Richards (1990) undertook a structural, petrographic and geophysical study. A series of senior projects (J. Dadoly, M. Kick, M. Lambert, and J. Plunkett) conducted at the University of Massachusetts, Lowell, have dealt with various aspects of the geology and geochemistry of the complex. The data of all these investigators has been used to construct the current version of the Mount Pawtuckaway geologic map.

General Geology

Modeling of geophysical data (Richards, 1990) indicates that the pluton is a plug-like structure extending to a depth of approximately 3 km. The units have steep contacts, and a body of high magnetic susceptibility occurs at depth. Field relations indicate that the mafic rocks were emplaced prior to the felsic rocks (see Fig. x for the locations of the various units). Based on apatite fission-track data Doherty and Lyons (1980) estimated that the rocks currently exposed at the surface were originally at a depth 3.0 to 3.6 km. A K-Ar biotite age of 124 ± 2 Ma (corrected to new decay constants) has been determined for the coarse-grained monzonite (Foland et al., 1971).

The earliest mafic rocks are pyroxenites which are preserved as blocks in the foliated diorite and medium-grained monzonite. Given the large size of some of these blocks, it is unlikely that they have undergone any significant upward transport, and they most likely occur close to their original level of emplacement. An arcuate body of gabbro occurs along the southern margin of the complex. This unit is distinguished by the anorthite content of its plagioclases (An_{60} to An_{46}), the essential absence of apatite (which is a common accessory in the other mafic units), and its distinctive trace element geochemistry. Troctolites occur within this unit. Locally the gabbro does show a foliation dipping inward at about 50°. The position of the gabbro in the sequence of mafic rock emplacement is ambiguous since it is not intruded by any of the other units. Several varieties of diorite are found: coarse-grained hornblende diorite, medium-grained foliated diorite and fine-grained diorite. The coarse-grained hornblende diorite is largely confined to the western portion of the complex. Locally this unit does show a weak foliation. The medium-gained foliated diorite is differentiated on the basis of its generally higher pyroxene/amphibole ratio and the presence of foliation due to the alignment of plagioclase laths. These rocks are largely confined to the eastern portion of the complex. The fine-grained diorite is a distinctive unit texturally and shows no foliation. Because of the absence of foliation it is inferred to be the last mafic unit emplaced in the complex.

The felsic rocks are monzonites and syenites. The outer ring of coarse-grained monzonite grades inward to coarse-grained syenite. An arcuate unit of coarse- to medium-grained monzonite occurs within the complex. The fine-grained monzonite partially surrounds this arcuate structure and is found as inclusions in the coarser-grained monzonite. Dikes of what appear petrographically to be fine-grained monzonite cut the outer coarse-grained monzonite. Most of these units are cut by mafic and felsic dikes which represent the last stages of igneous activity at Mount Pawtuckaway.

The pyroxenites are apparently the earliest rocks to be emplaced at Mount Pawtuckaway. The arcuate gabbro which outcrops at the southern edge of the complex may be related to the pyroxenite. In terms of both texture and geochemistry, the pyroxenite and gabbro can be interpreted as cumulus rocks. The initial phase of magmatic activity at Mount Pawtuckaway, therefore, may have consisted of the precipitation, from the wall inward, of minerals from a convecting mafic magma. The coarse- and medium-grained diorites were the next units to be emplaced. The foliation in these units dips towards the center of the complex and the dip increases as one moves inward (Kick, 1992, unpublished data), suggesting a funnel-shaped intrusion. The fine-grained diorite does not show any foliation, and does occur as inclusions in the medium-grained monzonite, thus it must be the last of the mafic units emplaced, but must predate at least some of the felsic units. The fine-grained monzonite occurs as inclusions in the medium- to coarse-grained monzonite of the central arcuate unit. If the fine-grained monzonite dikes in the outer coarse-grained monzonite are related to the central fine-grained monzonite then there are at least two periods of coarse-grained monzonite emplacement.

The sequence of events as deduced from the field relations indicate that a number of different magmas must have been involved in the formation of the Mount Pawtuckaway intrusion. The initial magmas were mafic. Later magmas were more felsic in composition. All of the felsic rocks are broadly similar in chemical composition, and their textural differences may be due to the water pressure at the time of crystallization. There is also evidence for several periods of subsidence. The first formed the outer ring of coarse-grained monzonite. This was followed by the emplacement of the fine-grained monzonite which, on textural grounds, may represent a magma which vented to the surface. Subsequently the central arcuate coarse- to medium-grained monzonite was emplaced. The last period of igneous activity is represented by the emplacement of mafic and felsic dikes which cut all of the other units.

Lithologic Descriptions

Mafic Units

Pyroxenite - The pyroxenites are coarse-grained and largely composed of cumulus olivine and augite with interstitial labradorite and opaque minerals. The augites show a pink tint and are spotted and rimmed by red-brown amphibole. The augites contain minute opaque inclusions which are oriented parallel to crystallographic directions. The opaques are titano-magnetite intergrown with hercynite. Apatite occurs in trace amounts.

Gabbro - The gabbros are medium- to coarse-grained and locally show a well-developed foliation due to the alignment of plagioclase laths. Plagioclase (An_{60} to An_{46}) and a light pink augite are the major minerals. Olivine is locally abundant. The augites contain oriented minute opaque inclusions and are rimmed and spotted by red-brown amphibole.

Hornblende diorite - The grain size is variable from medium-fine-grained to coarse-grained, and locally foliation can be found. The plagioclase is generally andesine, but can be zoned to oligoclase. The pyroxenes are generally light green, but pink cores are not uncommon. The pyroxenes are often extensively replaced by reddish-brown hornblende and green hastingsite. Red-brown biotite occurs both as separate grains and replacing pyroxene and amphibole. Apatite is a common accessory ranging in modal abundance from 1.6 to 3.5%. Olivine, extensively altered, is occasionally found.

Foliated diorite - The grain size is variable from fine- to coarse-grained, and most specimens show a foliation due to the alignment of plagioclase grains. The plagioclase is generally andesine, but may be zoned to oligoclase and occasionally labradorite cores are found. The pyroxenes are light pink and light green in color, and where the two varieties occur together the light pink pyroxene constitutes the core. The pyroxenes are invariably partly replaced by red-brown to green amphiboles. The pyroxenes contain oriented minute opaque inclusions, and the preservation of these inclusions in the amphiboles indicates the prior existence of pyroxene. Olivine is found in most specimens and locally is an important accessory. The biotites are straw brown to red brown and generally occur as large flakes. Apatite is an important accessory ranging in modal abundance from 1.0 to 2.6%.

Fine-grained diorite - The rock consists of a felted matrix of plagioclase (An_{41} to An_{26}), hornblende, minor biotite and trace apatite and opaques with minor small phenocrysts. The phenocrysts are plagioclase, some with alkali feldspar overgrowths, and hornblende. Aphanitic dark gray blebs of mafic minerals are also found.

Table 1. Representative Modes for the Mafic Rocks

	Pyrox-enite	Gabbro		Hb diorite		Foliated diorite		Fine-gr. diorite
	MP73	MP81	MP83	MP1	MP50	MP9	MP75	K22
Plag	8	61	67	46	64	45	63	57
Oliv	18	5	21	-	-	7	1	<1
Pyx	51	10	<1	16	1	11	6	10
Amph	18	19	6	20	25	24	20	15
Bio	-	-	-	9	1	2	4	15
Opaq	5	5	6	6	5	8	4	2
Apatite	<1	-	<1	3	4	3	2	<1

Felsic Units

Coarse-grained monzonite and syenite - The grain size varies from medium-to coarse-grained, and the monzonites and syenites are gradational into each other with changes in the K-feldspar/plagioclase ratio. The plagioclase is generally oligoclase and the alkali feldspars are microperthitic. The plagioclases are often rimmed by perthite. The pyroxenes are colorless to light green and are partly replaced by red-brown and dark green amphiboles. The biotites are reddish brown to straw brown and replace both pyroxene and amphibole. Quartz is interstitial, and some sections contain fayalitic olivine.

Fine-grained monzonite - The grain size varies from fine-grained to very-fine-grained. Some sections have phenocrysts of biotite and hornblende. The major minerals are oligoclase and microperthite. Quartz is a minor phase. The amphiboles are green to dark green and the biotites are reddish brown to straw brown. Pyrrhotite and apatite occur as accessories.

Table 2. Representative Modes for the Felsic Rocks

	Coarse-grained monzonites & syenites				Fine-grained monzonite
	MP8	MP12	MP15	MP49	R&F[1]
Plag	19	31	24	8	40
Kspar	46	34	54	84	35
Quartz	-	<1	2	3	2

	Coarse-grained monzonites & syenites				Fine-grained monzonite
	MP8	MP12	MP15	MP49	R&F[1]
Olivine	1	1	-	-	-
Pyroxene	12	14	4	<1	4
Amphibole	<1	6	11	3	7
Biotite	15	8	4	-	9
Opaque	5	5	1	2	3
Apatite	1	1	-	-	-

[1] Roy and Freedman (1944)

EXCURSION NOTES

DAY 1: White Mountain batholith

A number of stops will be made in the eastern portion of the White Mountain batholith. At several stops we will examine the various facies of the Albany Porphyritic Quartz Syenite which form the ring-dikes in the eastern batholith. We will also look at several facies of the subalkaline biotite-bearing "Conway Granite", and the subalkaline to peralkaline amphibole-bearing Osceola Granite.

Field trip starts at the White Mountain Forest Information Center which is located on Rt. 112 (Kancamagus Highway) at Exit 22 from I-93. Set odometer to 0. Going east on Kancamagus Highway at 13.9 miles picnic area (C.L. Graham Wangan Ground) on north side of highway. Scenic vista, restroom, and outcrops of Conway granite.

STOP 1-1: Coarse-grained Conway Granite

Good exposures of coarse-grained pink Conway Granite on both sides of road. This is the common variety of the Conway. In other locations this facies has mafic enclaves, but none have been found here.

Continue east on Kancamagus Highway. At 29.3 miles stop at Lower Falls picnic area on north side of road.

STOP 1-2: Fine-grained Conway Granite and Albany Porphyritic Quartz Syenite

On the south side of the road there are good exposures of fine-grained white granite intruded by Albany porphyritic quartz syenite. The granite is sheeted and has been mapped as part of the Conway Granite. This is the first of several stops to look at the various phases of the Albany Porphyritic Quartz Syenite. At this location dark fine-grained enclaves are abundant.

Continue east on Kancamagus Highway. At 30.2 miles stop at Albany covered bridge. Parking lot on south side of road. Walk across road to covered bridge.

STOP 1-3: Albany Porphyritic Quartz Syenite - type section

This is an optional stop. Outcrops of Albany Porphyritic Quartz Syenite are found at the covered bridge. This is probably the type locality for the Albany Porphyritic Quartz Syenite (Hitchcock, 1877), but exposures are not particularly fresh. The covered bridge may be the most photographed in New England and has appeared in a number of calendars.

Continue east on Kancamagus Highway. At 31.1 miles stop on south side of road immediately before curve.

STOP 1-4: Albany Porphyritic Quartz Syenite

Albany Porphyritic Quartz Syenite. Alkali feldspar phenocrysts, up to 1 cm in size, occur in a medium- to fine-grained groundmass. Partially digested enclaves are common.

Continue east on Kancamagus Highway. At 34.5 miles entrance to "The Moats" on south side of road.

STOP 1-5: Albany Porphyritic Quartz Syenite - subporphyritic, massive facies

Excellent fresh exposures of the more massive, subporphyritic phase of the Albany Porphyritic Quartz Syenite. This is private property and the entrance to a housing development. Effort has obviously been put into landscaping the area. NO HAMMERS. Pick-up only loose material that is NOT part of the landscaping.

At 40.4 miles juncture of Rt. 16. Turn left (north) onto Rt. 16. Follow road into and through North Conway (during the height of the tourist season this can be quite an adventure). At 47.0 miles turn left (west) towards Cathedral Ledge State Park. Follow road to top of Cathedral Ledge at 50.4 miles.

STOP 1-6: Conway Granite of the Birch Hill pluton

Conway Granite of the Birch Hill pluton is exposed at the summit of Cathedral Ledge.

At bottom of Cathedral Ledge access road (52.2 miles) turn left (north). At 54.8 miles stop on west side of road at Humphreys Ledge.

STOP 1-7: Mount Osceola Granite

Outcrops of medium- to coarse-grained green Mount Osceola Granite. At this locality the Mount Osceola Granite contains both fayalite and ferrohedenbergite.

Return to North Conway.

DAY 2: Ossipee Ring-dike Complex

The day will be spent at the Ossipee ring-dike complex. Several traverses will be made to examine the relationships between the various phases of the outer ring-dike, and the basalts and rhyolites. The "Conway Granite" of the eastern part of the complex will also be examined. While the present level of exposure is probably several kilometers below the original land surface, the preservation of a significant amount of volcanic rock provides an insight into the types of magmas which were responsible for the formation of the various plutons of the Younger White Mountain magma series.

Set odometer to 0 at the juncture of Rt. 16 and 25. Go west on Rt. 25. At 3.8 miles park on the south side of the road at the entrance to Chocorua Valley Lumber.

STOP 2-1: Granitic facies of the ring-dike

Good outcrops of pink fine- to medium-grained subporphyritic granite are exposed along the access road leading to the lumber yard. In thin section this rock has a finer-grained matrix with graphic intergrowths indicative of rapid cooling. Sparse partly digested basaltic enclaves are found in this unit. This granitic facies is just outward of the porphyritic quartz syenite which forms the bulk of the ring dike, and it is apparently part of the ring dike. Somewhat similar, but not as quartz-rich, rocks comprise the ring dike in the southwest corner of the Ossipee complex. Contacts have not been observed between this granitic phase and the quartz syenite porphyry.

Continue west on Rt. 25 to a road entrance marked by a flashing yellow light (5.4 miles at South Tamworth). Park by the side of the road or on a small road leading diagonally off to the northwest.

STOP 2-2: Porphyritic quartz syenite, basalt, rhyolite, and dikes-Cold Brook traverse

On the north side of the road the granitic facies of the ring dike is exposed in the Cold Brook. These outcrops are cut by several mafic dikes. Return to the road and proceed south up the Cold Brook. Virtually everyone who has mapped in the Ossipees has described the Cold Brook section, and no two geologists have ever agreed on the details of the section. Here's your chance to add additional opinions. The first outcrops encountered in the brook consist of what appears to be a large block of the granitic facies of the ring-dike, with numerous basaltic enclaves, immersed in basalt. Blocks of layered intrusive rhyolite are also found in the basalt. The host basalt is massive and contains enclaves of porphyritic basalt with plagioclase phenocrysts. Chemically the host basalt is more alkali rich then the common basalts of the Ossipee complex. Continuing up the Cold Brook the next set of outcrops form a mini gorge in the brook and consist of porphyritic quartz syenite. Large alkali feldspar and quartz phenocrysts occur in a fine-grained matrix, which in thin section has graphic intergrowths indicating rapid cooling. The quartz grains have resorption rims of alkali feldspar indicating a drop in water pressure. Continue up the Cold Brook to the road crossing. At this point basalt and rhyolite outcrops are encountered in the brook. The basalts are generally massive, but locally they are coarsely porphyritic with abundant plagioclase phenocrysts. Much of the plagioclase has been replaced by epidote giving the rock a greenish cast. Intrusive rhyolites, rhyolitic breccias, and rhyolites with eutaxitic textures are exposed in this section from just below the road crossing to about 100 m above the road crossing. Return to vehicles.

Return to juncture of Rt. 25 and 16 (10.8 miles). Turn right (south) onto Rt. 16. At 13.4 miles turn right (west) onto Pine Hill Road. At 16.7 miles there is a road to the right (north). Park at this intersection.

STOP 2-3: "Conway Granite" and aplite boulders stop

Perhaps reminiscent of an earlier Hutton field trip, this is a boulder stop. The "Conway Granite" is poorly exposed and most outcrops, which are found at or near the tops of hills, are rounded and deeply weathered. At this location construction of a road for a proposed development has exposed a number of fresh boulders of the Conway Granite. These boulders show the range of textures and mineral compositions which have been found in the field. A number of the boulders have aplitic layers which are a relatively common feature in the "Conway Granite".

At 16.9 miles turn left onto Connor Pond Road. Turn right (south) onto Ossipee Mtn. Road (18.2 miles). In Moultonville (19.6 miles) turn left (east) to Center Ossipee. Just before railroad tracks (20.5 miles) turn right (south) onto Chickville Road. Continue on to Tuftonboro (27.2 miles) and turn right (west) onto Rt. 171.

Continue for another 0.7 miles (27.9 miles) to a road marked Sentinel Lodge. This is an optional stop and is not included in the mileage log. Turn right (north) and proceed 1.0 mile to the top of the ridge. Turn right (east) onto Sentinel Baptist camp road and go 0.2 miles to a trail on the right side of the road labeled "Ledge".

STOP 2-3.5: Optional stop for intrusive rhyolite

Follow trail to the end (approximately 0.3 miles). Large cliff face of intrusive rhyolite. Numerous large basalt blocks and enclaves in the rhyolite along the trail before the ledge. A variety of basaltic enclaves are found in intrusive rhyolite exposed on the cliff face.

Return to intersection of Sentinel Lodge road and Rt. 171. Mileage log continues at this point. Turn right (west) onto Rt. 171. At 31.1 miles jeep trail departs on the right side of the road. Park along side of road. Proceed to the north on the jeep trail.

STOP 2-4: Porphyritic quartz syenite, rhyolite, and basalt-Hunter Brook traverse

Follow jeep trail until it comes to Hunter Brook (approximately 500 m). Porphyritic quartz syenite outcrops is the stream bed. Proceed up Hunters Brook. The outcrop at the beginning of this section is quite weathered but in the upstream direction the outcrop becomes fresher. The next unit encountered is intrusive rhyolite and the change from porphyritic quartz syenite to intrusive rhyolite seems to be gradational over a relatively short distance. Continue up stream to outcrops of massive basalt. The abundance of phenocrysts is quite variable, and most phenocrysts are less than 0.2 cm in size. At the upper end of this section a contact with fine-grained rhyolite is exposed. The contact dips steeply inward and there is evidence of shearing. The phenocrysts in the basalt increase in both size and number as the contact is approached. Return to vehicles.

At 33.5 miles turn right (north) into "Castle-in-the-Clouds" entrance road. There is an admission fee which at the time this field guide was written was $4.00/person. There are several points of interest on the entrance road, but the actual field trip stop will be at the visitors center. These additional points of interest are described below.

At 33.8 miles there is a parking area for a waterfalls. Walk in 200 m to the falls. Intrusive rhyolite is exposed at the falls and in the brook. The rhyolite contains numerous blocks of basalt with abundant small plagioclase phenocrysts.

At 34.9 miles there is a scenic view point to the left of the road. Good exposures of intrusive rhyolite. Outcrops at the base of the lookout platform contain a variety of enclaves: basalt with abundant small phenocrysts, basalt with sparse phenocrysts, phenocryst-free basalt with has been converted to a hornfels, and occasional fine-grained and coarse-grained diorite inclusions.

At 35.2 miles park in the Castle-in-the-clouds parking lot and walk to visitors center. Facilities in the center include restrooms and a snack bar. The actual field trip stop is the patio of the visitors center.

STOP 2-5: Intrusive rhyolite with abundant enclaves

The wall of the patio is constructed of intrusive rhyolite. A wide variety of enclaves can be found in the wall. NO HAMMERS! If time and the tram drivers permit, there are excellent exposures of intrusive rhyolite on the road which leads from the visitors center to the "Castle".

Return to vehicles and exit from Castle-in-the-Clouds. At 36.1 miles, after you have passed through the exit gate, stop at outcrop on right (west) side of the road. This is a blind curve so park well down the hill from the curve and be on the lookout for vehicles. While there is not much traffic the road is narrow.

STOP 2-6: Intrusive rhyolite and ring-dike

Porphyritic quartz syenite is not found in this region and the intrusive rhyolite occupies the apparent position of the ring-dike. This outcrop shows multiple phases of intrusion. Fine-grained rhyolite, which contains blocks of massive basalt, crops out at the lower end of the outcrop. In the uphill direction there is an abrupt change to a very porphyritic facies of the rhyolite. The fine-grained rhyolite may actually be a large block in the porphyritic variety.

Return to vehicles. At 37.0 miles intersection with Rt. 171. End of Ossipee field trip.

DAY 3: Mount Pawtuckaway Ring-dike Complex

This day of the field excursion will be spent at the Mount Pawtuckaway ring-dike complex. It is estimated that at the time of emplacement the current level of exposure was about 3 km below the surface. Gravity and magnetic data show that the complex is essentially cylindrical in shape. A number of lithologies are exposed in the complex and the four traverses which comprise today's excursion will allow participants to see all of these lithologies.

Entrance road to Pawtuckaway Mountains and fire tower. The entrance is marked by a small brown sign on the east side of NH Route 107, 3.2 miles north of the juncture of Routes 107 and 27. Set odometer to 0. At 2.0 miles park by a small farm cemetery on the south side of the road.

STOP 3-1: Gabbros of Meloon Hill

Follow the logging road departing from the west side of cemetery 300 feet to large flat outcrops of gabbro. Take left hand fork and continue another 1000 feet and then proceed southwesterly to SW side of Meloon Hill. Outcrop is essentially continuous along this side of the hill. The gabbro is medium-grained and locally shows a well-developed foliation. The foliation strikes parallel to the contact and dips steeply towards the center of the intrusion. This unit is cut by several fine-grained mafic dikes.

Return to vehicles. Turn left onto loop road. At 2.9 miles park on east side of road and walk east 200 feet along logging road. Stop at the small quarry located just to the north of the logging road.

STOP 3-2: Hornblende diorite, monzodiorite, coarse- and fine-grained monzonite

At the western end of the quarry hornblende diorite has been engulfed by fine-grained bluish-gray monzodiorite. These outcrops have a "marble cake" appearance and may represent mixing of partially crystallized melts. Isolated outcrops of the bluish-gray monzodiorite are found in the immediate area. Proceeding eastward in the quarry outcrops of hornblende diorite are observed. These outcrops are cut by both felsite and fine-grained monzonite dikes. Proceed southeastward from the quarry up Middle Mountain. A series of outcrops provide almost complete exposure of the fine-grained monzonite. **CAUTION:** This rock is very brittle and fragments come off the outcrop like shrapnel. Do not wound yourself or a fellow geologist. There are slight variations in grain size throughout this unit, but this variation does not appear to be correlated with distance from the contact. At the top of Middle Mountain outcrops of coarse-grained monzonite are found. Proceed a short distance eastward through this unit. In this area the outcrops are deeply weathered and fresh pieces are difficult to obtain. Inclusions of fine-grained monzonite are found in some outcrops of coarse-grained monzonite.

Return to vehicles. At 3.6 miles park at the intersection of the loop road and Round Pond road. During times of heavy rainfall the road may not be passable between Stop 3-2 and Stop 3-3. Walk back (west) along the road several hundred feet to a road leading north into a primitive picnic area.

STOP 3-3: Pyroxenites, foliated diorites, and monzonites

Outcrops of coarse-grained monzonite are found on either side of the road. These monzonites belong to the inner arcuate coarse-grained monzonite body (partial ring-dike?). Diorite and fine-grained monzonite inclusions are found in the coarse-grained monzonite. On the east side of the road are several outcrops of fine-grained monzonite which contain blebs of coarse-grained monzonite. In thin section no sharp boundaries are observed between the two types of monzonite. The boundaries are simply marked by a change in grain size. The origin of this texture is enigmatic. Suggestions are welcome. Return to the intersection and continue on the Round Pond road in an easterly direction. Outcrops of pyroxenite are found along the road approximately 400 feet from the intersection. Follow the ridge line northward about 300 feet to an outcrop of large pyroxenite blocks in medium-grained monzonite. Return to Round Pond road and continue eastward down an abandoned road. Outcrops of foliated diorite are found in and on both sides of the road. Both fine- and medium-grained varieties of the foliated diorite are observed. Where the two varieties are in contact, the fine-grained diorite appears to intrude the medium-grained diorite. Strike and dip measurements of the foliation indicate a partial funnel-like structure dipping towards the central fine-grained monzonite. Continue eastward to Round Pond. Outcrops of coarse-grained monzonite north of the road and just west of the brook carry inclusions of fine-grained diorite. A mafic dike cutting the monzonite is exposed in the stream bed.

Return to vehicles. Continue southward on loop road to parking area for fire tower trail (4.5 miles). Proceed up trail to top of South Mountain.

STOP 3-4: Coarse-grained monzonites and syenites of the outer ring-dike

Excellent exposures of the coarse-grained monzonite are found along the upper portion of the trail. Towards the center of the ring-dike the rock becomes a coarse-grained syenite. Several fine-grained monzonite dikes cut this unit. A number of mafic dikes are exposed in the immediate area of the fire tower. On a trail going southward from the fire tower is a small exposure showing mixing between felsic and mafic magmas.

Return to vehicles. Continue on loop road to juncture. Turn right and proceed back to Route 107.

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