Petrogenesis and Concentric Zonation of the Belchertown Intrusive Complex, West-Central Massachusetts

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The Petrogenesis and Concentric Zonation of the Belchertown Intrusive Complex,
West-Central Massachusetts

A Thesis Presented

by

KAREN JUNE VAN WAGNER

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

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Geosciences
The Petrogenesis and Concentric Zonation of the Belchertown Intrusive Complex,
West-Central Massachusetts

A Thesis Presented
by
KAREN JUNE VAN WAGNER

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To my husband and son, my perpetual cheerleaders: RJ and Nathaniel.

And to those absent before I finished: Nick Francis, Auntie Paula Cox, and Grandpa Roger Foltz.
ACKNOWLEDGMENTS

I would like to thank my advisor, Sheila Seaman, for her many years of patience, guidance, and support beginning in my undergraduate career. Thanks are also due Professor Emeritus Tony Philpotts, whose selflessly-given abundant knowledge and encouragement to think beyond what I first see will forever be invaluable to me. I would also like to extend my gratitude to Professors Stearne’s “Tony” Morse and Don Wise, for their critiques, comments, direction...and most of all for keeping me from allowing my thesis to run amok.

I wish to express my appreciation to everyone who volunteered assistance during the course of this project. A special thanks to Kiernan Gulick-Sherrill particularly, for resurrecting my laptop twice and saving my manuscript in the process. Thank you also to Renee Mackey who saved my shoulder when breaking rocks in the lab.

A special thank you to all those, friends and family, who supported me and helped me to stay focused and motivated throughout the course of this project.
ABSTRACT

THE PETROGENESIS AND CONCENTRIC ZONATION OF THE BELCHERTOWN INTRUSIVE
COMPLEX, WEST-CENTRAL MASSACHUSETTS

MAY 2017

KAREN JUNE VAN WAGNER, B.S., UNIVERSITY OF MASSACHUSETTS AMHERST

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The Belchertown Intrusive Complex is a ~164 km² Devonian pluton that intruded Paleozoic metasedimentary and metavolcanic rocks in west-central Massachusetts. Intrusion of the pluton was synchronous with Acadian deformation (Ashwal, 1974). The complex is concentrically zoned, with a core of orthopyroxene-biotite monzodiorite, a middle zone of clinopyroxene-hornblende-biotite granodiorite, and an outermost zone of hornblende-biotite granodiorite. Zoning from a more to less hydrous mineral suite from the outside to the inside of the pluton led Ashwal (1974) to suggest that metamorphic hydration most strongly affected the outermost zones of the complex. Basaltic inclusions occur most commonly near the edges of the pluton. Many of these inclusions preserve textures suggestive of mafic-felsic magma interaction. The abundance of basaltic enclaves on the edges of the complex may suggest a bowl-shaped structure, with lower more mafic-dominated rocks exposed on the edges of the complex. Bulk rock major element analyses of granitoids, basalts and gabbros, and diorites from all zones of the complex show that intermediate samples, regardless of zone, plot on a mixing line between mafic and felsic end members, supporting a model in which mafic and felsic
magmas may have mingled and mixed. Trace element analyses of intermediate-composition samples are similar across the entire complex, with enrichment in large ion lithophile elements and a pronounced Nb trough. In contrast, trace element concentrations in both the mafic rocks (basaltic enclaves and gabbroic inclusions), and in the granitoids, show considerable variation. The diversity of composition within both the mafic and felsic end-members suggests that either fractionation or differing degrees of partial melting of source rocks may account for these compositional ranges.

Sanukitoids comprise a majority of the inner zone, and point to the mixing of parental melts at depth in a subduction tectonic regime as a likely model of petrogenesis for the complex.
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CHAPTER 1

INTRODUCTION

The Belchertown intrusive complex (BIC) is an approximately circular pluton of roughly 164 km² located in west-central Massachusetts. U-Th-Pb zircon dating of the quartz monzodiorite member of the complex yielded an age of 380 +/- 5 million years old (Ashwal et al, 1979). The BIC consists of three concentric zones of rock of intermediate composition that grade from an interior of pyroxene monzodiorite and sanukitoid to an outermost zone of quartz granodiorite, with solid state deformational textures present in the outermost zone.

This study has two main purposes. The first is to explore the petrogenesis of the mafic and felsic melts preserved in the BIC. The second is to explore mechanisms of development of concentrically zoned intrusive complexes. Although mechanisms of emplacement and crystallization history of the Belchertown pluton have been studied in the past (Stoeck, 1971; Guthrie, 1972; Ashwal, 1974; Hall 1974), the origin of the parental magma(s) of the rocks preserved in the complex has not been published. Geochemical data collected in the present study from the main intermediate compositional component of the Belchertown batholith, and also from mafic and felsic outcrops within and around the complex, have been used to constrain the origins of the parental melt, of the concentric zonation of the pluton, and of the tectonic setting at the time of generation and emplacement of the melts. Major element analysis sheds new light on variation within the intermediate compositional suite of rocks. Trace and rare earth element concentrations document diversity within the felsic and mafic samples remnant from the parental magmas, and this has led to better understanding of tectonic processes during melt generation. Calculations have been used to constrain the composition of parental melts.
that generated the main body of intermediate rock, and provide percentages for crustal and mantle
inputs in the generation of the batholith.

Geochemical studies of zoned plutons in California (Clinkenbeard and Walawender, 1989; Coleman et al, 2009), Portugal (Antunes et al, 2008), and Morocco (Barbey et al, 2001) have opened
discussion on the idea of multiple pulses of emplacement in the building of batholiths and
differentiation of magmas before and during emplacement. With advances in recent years in the study
of pluton emplacement, and of emplacement of concentrically-zoned plutons in particular, new insights
and methods of testing have been published (Duschesne et al., 2008; Jackson et al., 2005; Lopez et al.,
2005; Martin et al., 2005; Pupier et al., 2008; Webster and Wintsch, 1987) that can be applied to the
Belchertown batholith to expand current understanding of its magmatic history. Models both of
incremental emplacement and solidification of magma without accumulation of large volumes of
magma at any stage (e.g., Coleman, Gray, Glazner, 2004), and models of pulsed additions of magma to
the shallow crust, accumulation, and subsequent differentiation (e.g., Sisson, 2005; Zak and Paterson,
2005; Hildreth and Wilson, 2007; Lipman, 2007; Moore and Sisson, 2008; du Bray et al., 2011) are
supported by field, geophysical, and geochronological evidence.
Figure 1. Units of the Massachusetts portion of the Bronson Hill Anticlinorium. The main body of the Belchertown Intrusive Complex (center) and the Hatfield pluton are shown in dark red. After Ashwal et al (1979).
CHAPTER 2

PREVIOUS WORK

The Belchertown Pluton

The BIC is concentrically zoned in terms of mineral assemblage and percentages of minerals. The center of the pluton is a pyroxene monzodiorite with orthopyroxene, 13.3% augite, and approximately 11.8% biotite. It covers an area of roughly 28.2 km$^2$ and is the second most abundant rock type in the complex. The transition zone surrounds the inner zone. It is the smallest unit of the three at approximately 22.7 km$^2$ and is a quartz monzodiorite containing 5.9% augite, 10.6% hornblende, 9.9% biotite and 9.7% quartz. The hydrous outer zone of the pluton is a quartz monzodiorite containing 21% hornblende, 9.7% biotite, with minor amounts of hematite (2.1%), magnetite (1.7%), epidote (3.9%), titanite (2.2%), and apatite (0.9%). It is the largest zone of the pluton at approximately 52.8 km$^2$.

The Hatfield Pluton has been suggested to be a part of the BIC (Stoeck, 1971). It is located to the northwest of the Triassic border fault, and is separated from the main body of the Belchertown pluton by the Upper Triassic New Haven Arkose and the lava flows of the Jurassic Hampden and Holyoke basalts (Figure 2). The Hatfield pluton was studied previously by Stoeck (1971), who petrographically related it to the main body of the quartz monzodiorite of the Belchertown Intrusive Complex. A gravity high trends to the northwest through the Belchertown complex; another one extends from the Hatfield Pluton across the Connecticut Valley towards the main body of the Belchertown complex (Stoeck 1971), further suggesting that the two might be connected at depth.
Figure 2. Color-enhanced tectonic map of Massachusetts, highlighting the Hatfield pluton and the Belchertown Intrusive Complex in royal blue, separated by the Triassic New Haven arkose and Jurassic basalts.
The Hatfield Pluton, like the BIC, is compositionally zoned. Models suggested to account for zoning in these complexes cover the range from zoning established during initial emplacement of the complexes to zoning resulting from secondary processes of metamorphism and hydration of existing plutonic rocks. Stoeck (1971) suggested that zoning in the Hatfield pluton resulted from two pulses of intrusion, on the basis of the bulk concentration of potassium in the granodiorite versus the tonalite. Ashwal (1974) suggested that the Belchertown pluton underwent both hydration and recrystallization as a result of regional Acadian metamorphism, as well as assimilation of sedimentary country rocks. Hall (1974) also suggested that the Belchertown batholith was intruded as a dry, crystal-rich (up to 50%) magma which, after crystallization, underwent amphibolite facies metamorphism to produce the outer and transition zones with their differing mineral compositions. Thus, since both primary, igneous scenarios and secondary, subsolidus metamorphic scenarios have been suggested to account for zoning in the Belchertown pluton, one of the goals of this work is to evaluate models for the zoning of the pluton.
Figure 3. Bedrock map of the BIC and surrounding rock units. After Ashwal et al (1979).
The Acadian Orogeny

The Belchertown pluton was emplaced ~380+/− 5 Ma (Ashwal et al., 1979), during the middle to late Devonian Acadian orogeny. Robinson et al. (1998) placed the Belchertown in the Medial New England terrane, with emplacement between the Acadian and the Neo-Acadian deformational periods. It is generally accepted that the Acadian orogeny began ca. 380 Ma, and was associated with the oblique convergence of the Meguma and Avalon terranes either during or just following the collision of Meguma with Laurentia (Murphy et al., 1999). Prior to docking with Laurentia, the Avalon terrane formed the western edge of a depositional basin that was flanked to its west by the Bronson Hill Anticlinorium. This basin is where the olistostromal facies of the Rangeley Formation in Maine were deposited; these were interpreted by Eusden et al. (1996) as having formed in a west-dipping subduction system located against the east margin of the Bronson Hill Anticlinorium.

Roughly 20 Ma following the onset of magma generation, voluminous magmatism abruptly ceased with the onset of deformation migrating northwestward. A 15 Ma period of quiescence was broken by intrusion of large granitic batholiths and associated lamprophyre dikes. Robinson et al. (1998) suggested that the plutonism of this time and the apparent high heat flow associated with it might be best explained by lithospheric delamination, although they also pointed out that the subduction of Medial New England under Avalon would be an unlikely cause of the delamination. Murphy et al. (1999) proposed that a mantle plume being overridden by the oceanic crust that was being subducted during orogeny as the best explanation of both the temporary cessation of magmatism earlier in the Acadian and the later emplacement of large batholiths with a positive gravity anomaly.
Towards the end of the Acadian, magmatism migrated from the Meguma into the Avalon terrane, and changed character from primarily mafic to bimodal. It is in this time period that the BIC intruded the central Massachusetts crust.
CHAPTER 3

LOCATION AND GEOLOGIC SETTING

The BIC sits within a line of gneiss domes that make up the Bronson Hill anticlinorium; it is bordered on the east by the Monson Gneiss of the Great Hill synclinorium, the Glastonbury Gneiss of the Glastonbury Dome to the south, the Portland Formation to the west of the Triassic border fault, and the Dry Hill Gneiss and rocks of the Pelham Dome to the north (Ashwal et al., 1979; Tucker & Robinson, 1990). The surrounding gneiss domes are Proterozoic to Ordovician age. The Connecticut Valley to the west of the border fault hosts younger Triassic and Jurassic sedimentary and volcanic units that are in fault contact with the Belchertown pluton.
Figure 4. Abandoned construction site on Route 181, Belchertown MA, location of samples BT-1 through BT-13 (points in northwest quarter of Palmer Quadrangle, Appendix A.)
Figure 5. Section of railroad through Belchertown MA where outcrops of tonalite and mafic cumulates are located (sampling sites of BT-RR2, BT-RR3, and BT-RR5).
Figure 6. Sampling site of BT-RR2.
Figure 7. Sampling site of BT-RR3. Points in this and preceding pictures are located in the Belchertown Quadrangle (Appendix A).
Figure 8. Outcrop on Mt Dumplin, Three Rivers MA. Samples from here were used to help discriminate other mafic samples in and around the main body of the BIC.
Figure 9. Source of BT-3RD samples from the Mount Dumplin site. Points in this and previous picture located in Palmer Quadrangle, Appendix A.
Figure 10. Source of mafic cumulate located near the edge of the pluton, along Warner Rd in Belchertown MA. Below, Sample piece of mafic cumulate, hammer for scale.
CHAPTER 4

METHODS

Field work was conducted at a previously abandoned construction site off Route 181 in Belchertown, MA, and along roadways and railroads located in Palmer, Belchertown, and Ludlow, MA. Field work consisted of outcrop mapping and sample collection.

Major and trace element analyses were conducted at the X-ray Fluorescence Laboratory at the University of Massachusetts Amherst under the supervision of Dr. J. Michael Rhodes and Pete Dawson. Samples collected in the field were washed by hand, cut by gravity and trim saws, further reduced in size by hammer, and ground to powder in a tungsten carbide shatterbox before being ignited at 500°C for 12 hours. The dried samples were then combined with a lithium borate flux and melted to form glass disks. Major element analyses were obtained from the glass disks on a Siemens MRS-400 X-ray spectrometer. Powdered samples were also pressed into pellets for trace element analysis. Trace element data were acquired with a Philips PW2400 sequential spectrometer. Rare earth element (REE) analyses were conducted at Union College in Schenectady, NY, under the supervision of Dr. Kurt Hollocher, using inductively coupled plasma mass spectrometry on a PerkinElmer Elan 6100 DRC ICP-MS. Sample preparation for isotopic analysis was carried out by Jason Kaiser, with isotopic analyses of Nd and Sm completed on an IsotopX IsoProbeT multicollector mass spectrometer at the Massachusetts Institute of Technology under the supervision of Dr. Sam Bowring.
CHAPTER 5

EMPLACEMENT AND CRYSTALLIZATION HISTORY

Following Guthrie (1972), Hall (1974) stated that it is possible that mafic and ultramafic inclusions within and around the Belchertown pluton could represent an earliest stage of crystallization, with the accumulation of mafic minerals (pyroxenes, olivine, hornblende) localized in a shell around the main body of the intrusion. He suggested that plagioclase crystals, aligned in an apparent flow pattern and broken and filled with microperthite, may indicate that the main body of the pluton was emplaced as a crystal-rich (perhaps 50%) mush, which may have caused the earlier ultramafic bodies to fracture and create a breccia field around the border. Finally, during the Acadian orogeny the intrusion was subjected to amphibolite facies metamorphism. Hall concluded that the more hydrous metamorphic assemblages of minerals in the outer zone of the pluton may have resulted from introduction of water during metamorphism.

Brecciated rocks have been described by Stoeck (1971), Hall (1974), and Ashwal (1974) around the edges of both the Belchertown and Hatfield plutons. The BIC was emplaced at about 10 km depth—probably too deep for it to have generated an eruptive event—suggesting that brecciation occurred during pluton emplacement (S. Seaman, *pers comm*.). No volcanic deposits are known that are likely to be genetically related to the BIC.

The Hatfield pluton is northwest of the main body of the Belchertown Complex and is co-genetic with it (P. Robinson, *pers comm*.; Stoeck 1971) Stoeck further postulated that the Hatfield Pluton was zoned as a result of differentiation of the parental magma at depth, hydration of the melt upon
emplacement into a water-rich country rock, and two pulses of intrusion. She further suggested that a relatively dry dioritic magma differentiated at depth in the crust, in contact with potassium-rich wet country rock and precipitated hornblende, plagioclase and possibly hypersthene. A tonalitic part of the melt intruded at a shallower crustal level. The remaining potassium-enriched crystal mush, granodioritic in composition now, intruded the tonalite later in a separate pulse.
CHAPTER 6

FIELD RELATIONS

The Belchertown pluton is situated in a north-south line of plutons and gneiss domes that extends from New Hampshire through Massachusetts and Connecticut and is known collectively as the Bronson Hill Anticlinorium. Rocks of the BIC have been mapped in the Ludlow, Belchertown and Palmer 7-1/2 minute USGS quadrangle maps. Directly south of the Belchertown pluton is the northern part of the Glastonbury Gneiss, an Ordovician massive granitic gneiss that extends into northern Connecticut. Directly north is the Proterozoic Dry Hill Gneiss of the Pelham Dome, a granitic microcline gneiss with local quartzite that has been interpreted as a metamorphosed rhyolite (Tucker & Robinson, 1990). Surrounding both of these and the Belchertown are the Ammonoosuc Volcanics, a series of Middle Ordovician eruptive products, gneiss, and quartzite that is overlain by the Partridge Formation which is exposed through most of the Bronson Hill Anticlinorium (Hollocher, 1993; Hollocher et al., 2002). To the east, and also part of the Bronson Hill anticlinorium, is the Monson Gneiss, a biotite gneiss with rare microcline augens overlain by the Ammonoosuc Volcanics and the sulfidic mica-schist of the Partridge Formation (Zartman & Naylor, 1984; Tucker & Robinson, 1990; Hollocher et al., 2002).

To the east of the Monson Gneiss are rocks that, unlike those surrounding rocks within the Bronson Hill, are of similar age to the Belchertown pluton. The Littleton Formation is part of the Merrimack Belt, which extends north into New Hampshire. The Littleton Formation consists of schists and phyllites (Eusden et al., 1996), and is intruded by the Hardwick Tonalite (Mook 1967). The Hardwick is a combination of biotite tonalite and granitic gneiss, and is moderately to strongly foliated.
(Robinson et al., 1998). Also intruding the Littleton Formation slightly to the south of the Hardwick pluton is the Coys Hill Gneiss, a coarse-grained microcline gneiss of metamorphosed granite that locally hosts garnet and sillimanite, and that is continuous with the Cardigan and Ashuelot plutons of the Kinsman Quartz Monzonite in New Hampshire (Robinson et al., 1998).

To the west of the Belchertown complex lies the Jurassic sedimentary Portland Formation, consisting of reddish to reddish-brown units of conglomerate and arkose, with interbedded lake bed deposit layers of gray sandstone and siltstone, and black shale. Normal faults striking to the southeast and northeast separate these units from the body of the batholith. The Portland Formation lies to the south of the Holyoke Range and to the east of the Mount Tom Range. These ranges are composed of Jurassic tholeiitic basalt flows known as the Hampden and Holyoke basalts in Massachusetts, and the Granby basaltic tuff. The basalts are overlain by the East Berlin Formation, which is a series of alluvial and lacustrine facies originally laid down in a continental depositional system.

Prior to the movement of the Eastern Border Fault, the basalts and tuffs erupted secondary to rifting associated with the opening of the Atlantic Ocean. Regional uplift brought on by movement on the border fault raised these rocks into the ridges and peaks seen today.
Figure 11. Examples of field relations in the Belchertown complex. Outcrop on the east side of the abandoned construction site. Diorite and tonalite fields are noted, all other fields are composed of monzodiorite.
Figure 12. Monzodiorite groundmass with mafic enclaves and schlieren and felsic veins. Exposure from the southeast of the abandoned construction site in Belchertown.
Figure 13. Dioritic groundmass with tonalite enclaves and aplitic veins. Located in the northeast of the abandoned construction site.
Figure 14. Area of outcrop with primary monzodiorite, diorite, and tonalite comingled within a single-meter area. Exposure from the abandoned construction site.
CHAPTER 7
PETROGRAPHY OF THE BELCHERTOWN BATHOLITH

Stoeck (1971) found that the two main intermediate components of the Hatfield pluton, an interior granodiorite and an exterior tonalite, cannot be related by fractional crystallization.

Additionally, Stoeck concluded that because the granodiorite did not fractionate from the tonalite, more abundant potassium concentration in granodiorites than in the tonalites indicates that the potassium must have concentrated in the center of the intrusive melt. An abundance of both quartz and biotite in the tonalite, and absence of quartz in the granodiorite, suggests a higher water activity in the tonalite. She postulated that as a drier dioritic melt intruded and heated local pelitic schists that contained both free water and hydrous minerals, higher water activity in the schist caused the water to enter the magma, carrying with it potassium and some silica that had been dissolved during contact metamorphism. Water present in the magma would have migrated toward the cooler zone near the wallrock, while water from the schist would enrich this tonalitic border zone and cause biotite to crystallize. The higher temperature melt at depth would have been more enriched in potassium; this would then intrude the tonalitic melt and produce the granodioritic core.

Ashwal (1974) proposed that the alteration of the plutonic rocks was as a result of regional metamorphism after emplacement. He showed that transformation of the component minerals was isochemical with respect to all major elements except water. He hypothesized that the mineral assemblage across the three zones of the pluton was a result of hydration of the batholith during metamorphism, a pattern that he suggests is consistent with the aeromagnetic pattern of the intrusion. Hall (1974) hypothesized that the pluton was emplaced as a relatively dry igneous intrusion, and also
suggested introduction of water to the batholith during metamorphism as a way of explaining the differences in mineral assemblage across zones.

In this study, major, trace and rare earth element concentrations of rocks of the three zones of the pluton have been evaluated to test the possibility that the zones have contrasting compositional characteristics, and to evaluate the origin of any contrasts. Following is a detailed description of the mineral assemblage and field characteristics of each of the zones of the pluton.

**Outer Zone**

Stoeck originally described the Outer Zone of the Hatfield pluton as a tonalite and the Inner Zone as a granodiorite. Field work conducted as part of the present study indicates that in the Outer Zone of the Belchertown Complex, tonalite is less abundant and lighter in color than the main granodiorite. Therefore, the bulk of the intermediate-composition Outer Zone rocks will be referred to as 'granodiorite' in this study.

The Outer Zone of the BIC is comprised mainly of hornblende-biotite granodiorite that is more hydrous than the monzodiorites of the Transition and Inner Zones; unlike rocks in the other zones, the granodiorite shows the textural effects of Acadian deformation. The Outer Zone hosts outcrops of both granite and tonalite. Mafic outcrops of hornblendite and pyroxenite occur within the Outer Zone and ring the pluton as blobs and small outcrops within the granodiorite gneiss. Pockets of brecciated rock have also been described by Hall (1974) on the northern edge of the pluton but were not found in the course of this study. The Outer Zone also hosts a septum of Partridge Formation in the northeast corner, extending inwards towards the edge of the Transition Zone boundary (Fig. 3).
Hand samples of the granodiorite are medium to coarse grained, with crystals 4 to 7 mm of plagioclase feldspar, potassium feldspar, biotite, and hornblende with trace quartz and ilmenite. The plagioclase is highly altered, with free clay minerals heavily obscuring the albite twin planes. Feldspar crystals are generally subhedral to anhedral, and tabular. Some grains of plagioclase appeared to have been bent; as these are the only minerals affected, it is the author's opinion that the Outer Zone was subject to deformation soon after emplacement as a melt, when plagioclase feldspar is more likely than other observed minerals to have crystallized out. Alkali feldspar, typically anhedral, has polysynthetic albite and pericline twinning patterns, indicating that it is microcline. Biotite in the Outer Zone is generally fine-grained and subhedral (2 to 4 mm), and commonly dark green to black. Hornblende occurs as both single crystals and as aggregates of many crystals. Hornblende crystals are medium-grained, 3 to 5 mm, and are generally elongated. The color of the hornblende in the outer zone varies, with a small population of darker olive-green hornblende and a larger [more numerous] population of lighter bluish-green hornblende. Hall (1974) suggested that the blue-green hornblende was of metamorphic origin. Epidote crystals are small (approximately 2mm), yellow-green, anhedal to euhedral crystals that occur near biotite and hornblende. Accessory minerals include small grains of apatite, titanite, zircon, and an opaque phase which could be ilmenite, magnetite, or hematite.

Felsic rock samples in the Outer Zone of the pluton are granites and tonalites. The tonalites are generally gray in hand sample and medium-grained, and bear large laths of plagioclase along with the biotite and hornblende typical of the intermediate outer zone rocks. Quartz is also present (10%), as is epidote (3%) and microcline (4%); apatite and opaques are the usual accessory minerals seen. The granite hosts lower concentrations of plagioclase (8%) relative to microcline (32%), as compared to the
tonalite.

Mafic outcrops are hornblendites and pyroxenites, and are found at the northern edge of the batholith. Guthrie (1972) suggested that they were “probably the basic forerunners of the main intrusion of the Belchertown Intrusive Complex”, and were later intruded and brecciated by the monzodioritic magma. Most outcrops of hornblendite are dark green to black, medium-grained, massive, and contain hornblende, plagioclase and biotite and are lacking in pyroxenes. Pyroxenites, which are also dark green to black, massive, and medium-grained, contain pyroxene, biotite and hornblende, but lack plagioclase.

**Transition Zone**

The Transition Zone is comprised mainly of clinopyroxene-bearing hornblende monzodiorite (42.9% plagioclase, 14.6% biotite, 12.3% augite, 11.1% hornblende, 9.4% alkali feldspar, 6.9% quartz, 2.8% accessory minerals) that has been less hydrated in relation to the hornblende-biotite granodiorite of the Outer Zone but is yet more hydrous than the dry monzodiorite of the inner zone. Unlike rocks of the Outer Zone, the rocks of this zone show little to no local deformation. Some rocks of felsic tonalitic composition are located in the Transition Zone, but unlike the outer zone the Transition Zone hosts no mappable mafic outcrops. Several aplitic and dioritic dikes cut rocks of the Transition Zone. Mafic and felsic enclaves occur in the monzodioritic groundmass, and felsic and mafic melts appear to have mingled prior to crystallization.
Inner Zone

The Inner Zone is the most anhydrous of the three zones, comprised entirely of orthopyroxene-bearing hornblende monzodiorite (48.8% plagioclase, 16.4% hypersthene, 6.85% alkali feldspar, 6.3% quartz, 2.25% hornblende) with primary biotite (9.0%). No deformation textures have been noted in rocks of the inner zone. No outcrops of felsic rock have been mapped in this zone. An outcrop on the Facing Hills of an apparently ultramafic cumulate was studied by Ashwal (1974) and is adjacent to the Transition Zone border.
CHAPTER 8

RESULTS

Petrographic Observation

Petrographic analysis of thin sections from all three zones included modal analyses, cataloging of microtextural features, and distinguishing sanukitoids from other monzodioritic rocks.

Outer Zone samples include granites, tonalites, granodiorites, and gabbros and diabases.

Plagioclase in all Outer Zone samples exhibit one or a combination of twin patterns to include polysynthetic, pericline, and Carlsbad twinning. Most plagioclase falls within the andesine range (Percy 1955, Stoeck 1971, Guthrie 1972, Ashwal 1974, Hall 1974) except for plagioclase in hornblendite that may possibly be labradorite (Guthrie 1972). Plagioclase crystals are large and subhedral to anhedral except in sample BT-QB-5, a gabbro, in which plagioclase occurs as phaneritic subhedral to euhedral groundmass crystals with occasional well-defined laths. Minor orthoclase occurs in BT-RR2, a granite. Pyroxene is minor and is about 50:50 orthopyroxene (hypersthene) and clinopyroxene (augite and diopside), all of which are anhedral, and many of which are partially replaced by amphibole. All exhibit exsolution lamellae; augite in hypersthene, and hypersthene and inverted pigeonite in augite. Augite has opaque exsolved ilmenite/magnetite and/or rutile. Quartz occurs in the granites and granodiorites. Amphibole occurs in mafic rocks and granodiorites in the Outer Zone, but not in the granites. Most of the Outer Zone amphiboles are pyroxene replacements and are distinguished from primary hornblende by color and pleochroism, with the replacement amphiboles being more blue-green instead of the olive-green to brown-green of the primary hornblende. The change in amphibole color to blue-green from olive-green or brown-green is due to higher aluminum
content in the IV-tetrahedral site of the chain silicate, which in turn is caused by exposure to higher grade metamorphism (Deer, Howie, Zussman 1963; Hietanen 1974). Epidote is a common accessory mineral in and around plagioclase grains.

In thin section, mafic samples BT-3R-D1A and BT-RR-3 have an obvious common fabric. In thin section, all minerals in BT-3R-D1A are aligned and slightly elongated, possibly resulting from subsolidus strain as this sample lies within a contact zone between the batholith and country rock. Pyroxene crystals in BT-RR-3 are preferentially oriented around masses of unlineated subhedral plagioclase laths, possibly resulting from magmatic flow around the laths. BT-QB-5 shows no lineation or preferred orientation, and may be a gabbroic cumulate.

Transition Zone samples include tonalites, diorites, hornblendites, granodiorites, and monzodiorites, as well as sanukitoids. Both alkali and plagioclase feldspars, and orthopyroxenes and clinopyroxenes are common throughout the zone; quartz is lacking only in the mafic rocks. Monzodiorites and sanukitoids also host biotite and hornblende.

Plagioclase feldspars dominate the tonalites, diorites and hornblendites. They display albite twinning and are subhedral to anhedral. They are andesine. Some tonalite plagioclase crystals are poikilitic with inclusions of quartz and clinopyroxene. Plagioclase in sanukitoids exhibit undulatory extinction patterns. Euhedral phenocrysts are present in the diorites in phaneritic groundmass of plagioclase + pyroxene. Alkali feldspar crystals are generally microcline with tartan or Carlsbad twinning, except, as noted by Stoeck (1971) in regards to the Hatfield, for some alkali feldspar crystals in tonalite that are orthoclase and exhibit no twinning.
Figure 15. Photomicrograph of a tonalitic sample from the transition zone of the pluton.
Figure 16. Photomicrograph of mafic cumulate sample from outer zone of the pluton.
Pyroxene is minor (< 1%) in the tonalite samples, but constitutes a larger component in the
diorites and hornblendites. In the monzodiorites, hypersthene is rimmed by hornblende and augite; in
the sanukitoids, augite crystals are generally larger than hypersthene crystals, which are partially
replaced by brown-green biotite, with opaque poikilitic anhedral minerals in both pyroxenes.
Hornblende is found in all intermediate rocks, where it is rimmed with smaller crystals of feldspars and
quartz. Dehydration reactions occurring around the hornblende with quartz yielded clinopyroxene +
orthopyroxene + plagioclase + water (Hollocher, 1991). Quartz is a trace mineral in tonalites (~6.5%)
and monzodiorites/sanukitoids (3.5% - 6.5%). It surrounds zircon crystals in both. Opaque blebs are
present in the diorite samples. They have been identified as ilmenite and have a blue-black reflectivity.
Anhedral garnet ~2mm in diameter, light pink in plane light, has been identified in thin sections of the
tonalitic samples, BT-6 and BT-7. Biotite crystals are anhedral and pleochroic from light brown to tan
to medium brown; except in BT-2 where they are green-brown and pleochroic from light brown to light
green-brown to medium green-brown. Ashwal (1974) and Hall (1974) noted that this is most likely a
difference in iron and titanium contents of the minerals, with the brown biotite having the higher
titanium.

Representative samples from the Inner Zone of the pluton are all sanukitoids in composition.
Andesine and microcline are the dominant minerals, and are subhedral to anhedral and 9 to 13 mm long.
Microcline is irregularly shaped, while andesine is mostly rectangular with ragged edges and fractures
filled in with pyroxene crystals; many grains of andesine show "dusty" inclusions, which may be
exsolved titanohematite as pointed out by Ashwal (1974), or may be an indication of plagioclase
reacting with a mafic melt as described by Choe and Jwa (2004).
Pyroxene crystals are ~45-50% hypersthene and 50-55% clinopyroxenes (augite and diopside).

Exsolution lamellae are rare. Phenocrysts of primary magmatic green hornblende are >12mm long anhedral to euhedral poikilitic grains, and are pleochroic from light brown to olive green and dark green. They have small (3mm) partial reaction rims of orthopyroxene and clinopyroxene where in contact with feldspar. The sanukitoids contain (>5%) garnet crystals that are anhedral and 3 to 4 mm diameter.

**Geochemistry**

**Major Elements**

Major element analyses for all samples that were analyzed as part of this study are listed in Table 1 and plotted on Harker variation diagrams (Fig. 17). The rocks of the outer zone span the entire compositional range, while those of the transition zone have a significantly smaller range (including mafic enclaves, but no major mafic outcrops), and the inner zone is composed solely of intermediate composition rocks.

Analyses define smooth curves on Harker variation diagrams, with the exception of K₂O and P₂O₅, which have scattered values. TiO₂, CaO, Fe₂O₃, MnO, and MgO decrease in abundance with increasing SiO₂ as expected (Fig. 17). Al₂O₃ shows a slight enrichment trend from the low to intermediate SiO₂ concentrations, and then a depletion into the high SiO₂ range. K₂O concentrations are scattered at high SiO₂ concentrations, but increase from low to intermediate SiO₂ concentration.

Intermediate composition rocks from all zones plot in a single clump on a straight line between mafic and felsic end-members within the Harker diagrams. These rocks have high MgO and P₂O₅ and
low (>2wt%) TiO₂ concentrations and are of about the same composition despite having been collected over a large geographic range, only differing from one other in water concentration, which Ashwal (1974) attributed to the mineralogical differences in the granodioritic and monzodioritic rocks across the body.

The majority of felsic composition rocks are rhyolitic (Fig. 18). BT-23 and BT-6 are granodiorite and quartz syenite respectively. Nearly all of the intermediate composition rocks are trachyandesitic to andesitic in composition and are quartz monzodiorites and quartz monzonites, except for BT-10 and BT-23 which are granodiorites. Five of the mafic rocks are basaltic (Fig. 18), and are texturally gabbros. Exceptions are BT-3RD1, BT-17, and BT-3RD2, which are a low-silica monzodiorite, a high-silica quartz monzodiorite, and a quartz monzonite respectively.
Table 1. Major element analysis data from samples of the Belchertown intrusive complex.

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Figure 17. Harker diagrams for samples from the Belchertown pluton. Samples are identified by pluton zone (red circle = outer zone, blue square = transition zone, black cross = inner zone); this identification is carried throughout the work.
Figure 18. LeBas diagram, plotting alkalis vs silica content.

Figure 19. AFM diagram to determine calc-alkaline and tholeiitic sources (after Irvine and Barager, 1971).
Trace Elements

Trace element analyses for all samples analyzed as part of this study are listed in Table 2 and plotted on trace element variation diagrams (Fig. 20). Samples of felsic and intermediate composition were normalized to upper continental crust (Taylor-McLennan, 1985) and mafic samples were normalized to EMORB (Sun-McDonough, 1989). Six felsic rock samples are from the Outer Zone, and two from the Transition Zone. The felsic rocks of the Outer Zone can be split into two groups based on relative concentrations of trace elements: four samples – BT-10, BT-18, BT-23, and BT-RR-2 – show troughs in Rb and peaks in Sr and Ba concentrations, along with negative Nb anomalies; the two remaining samples—BT-22 and BT-RR-5—show the opposite, with Rb peaks, and corresponding Sr and Ba troughs, and positive Nb anomalies. The felsic rocks of the transition zone, BT-6 and BT-7, make up a third group and exhibit pronounced Ba and Sr peaks, a discernable negative Nb anomaly, and enrichment in the large-ion lithophile elements (LILEs).
Table 2. Trace element analysis data of batholithic samples.

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Figure 20. Spider diagrams for trace element analysis of batholithic samples. Upper left are felsic samples ratioed to upper continental crust (UCC); center are intermediate samples ratioed to UCC; lower left are mafic samples ratioed to enriched mid-ocean ridge basalt (EMORB).
Intermediate monzodioritic and granodioritic rocks are uniform with respect to all trace elements across all three zones of the pluton. They exhibit enrichment in LILEs, Ba and Sr peaks, and a deep Nb trough.

Mafic samples are from the Outer and Transition Zones; those in the Transition Zone are close to the contact between of the Transition and Inner Zones. Mafic trace element concentrations have been compared to MORB, EMORB, and NMORB. Samples are most similar to EMORB compositions. All mafic samples show a Nb trough and Pb enrichment, most prominently in the samples from the Transition Zone. Outer Zone samples are split on Rb concentrations, with two samples (BT-AM and BT-RR-3) somewhat more depleted in Rb than the others (BT-19, BT-20, and BT-DIO). Transition Zone samples, BT-3R-D1 and BT-3R-D2, also have lower Rb concentrations compared to samples from the Outer Zone, and exhibit some enrichment in the LILEs. The mafic samples are not as similar to one another as the intermediate samples are, but they are not as different from one another as the felsic samples of the Outer Zone.

Rare Earth Elements

Rare earth element (REE) analyses are listed in Table 3 and are plotted in Figure 21.

The felsic rocks of the Transition Zone (BT-6 and BT-7) have REE concentrations that contrast with those of other felsic samples. The Transition Zone samples show a nearly perfect downward-trending REE pattern, with a positive Eu anomaly. The felsic rocks of the Outer Zone are again split in two groups, with one group of four samples (BT-10, BT-18, BT-23, and BT-RR-2) also exhibiting a downward-trending LREE pattern and a flat HREE pattern, along with a slight negative Eu
anomaly; the remaining two samples (BT-22 and BT-RR-5) exhibit LREE enrichment with a flatter HREE pattern, and little to no Eu anomaly.

The monzodiorites and granodiorites have similar REE concentrations across all zones of the batholith. They are enriched in LREEs and depleted in HREEs, with no Eu anomaly.

The majority of the mafic samples from the Outer and Transition Zones show a flat pattern across all REEs with no Eu anomaly. The remaining two samples are located in the Outer Zone: one, BT-RR-3, has a sloping REE pattern with relative enrichment in LREEs and depletion in HREEs and no Eu anomaly, not unlike the intermediate rocks; the other, BT-AM, shows an almost flat pattern in the LREEs except for slight depletion in La, and an almost flat yet slightly decreasing pattern in the HREEs with a negative Eu anomaly.

Intermediate rocks are uniform across all 3 zones of the pluton. They are LILE rich, exhibit Ba and Sr peaks and Nb troughs, are strongly LREE enriched, and are most similar to average continental crust. Felsic rocks from the Outer Zone, with the exception of two samples, have the same REE pattern, with slight LREE enrichment, though not as strongly enriched as the intermediate rocks. These samples can be split into two groups: the first group have troughs in Rb, peaks in Sr and Ba, and a negative Nb anomaly; the second group have peaks in Rb, troughs in Sr and Ba, and a positive Nb anomaly.
Table 3. Rare earth element (REE) analysis data for batholithic samples.
Figure 21. Rare earth element diagrams from analysis of new samples. Upper left are the felsic samples, center are the intermediate samples; both are normalized to UCC. Lower left are the mafic samples, normalized to Chondrites. Samples denoted by pluton zone.
There is a strong contrast between the Outer Zone and Transition Zone felsic rocks. Felsic rocks from the Transition Zone show LILE enrichment similar to that of the intermediate rocks. They are similar to the first group of Outer Zone felsic rocks with Ba and Sr peaks, a negative Nb anomaly, and strong LREE enrichment. They also show a strong HREE depletion.

Mafic samples are from the Outer and Transition Zones, as well as cumulates beyond the pluton edges. They have flat REE patterns, and all have negative Nb anomalies and positive Pb anomalies. The Outer Zone samples have some variation in Rb concentrations. The samples from the Transition Zone and beyond the pluton exhibit LREE enrichment with some LILE enrichment. The highest plotting sample on the REE diagram is undepleted OIB.

Nd/Sm Isotopes

Samarium/neodymium isotopic data were collected from three samples chosen to represent the three zones of the pluton: BT-SR1, a sanukitoid-like monzodiorite from the inner zone; BT-3, a granodiorite from the transition zone; and BT-QB5, a mafic cumulate from the outer zone. Results of these analyses are giving in Table 4. Epsilon Nd values were calculated based on a crystallization age of ~380 Ma (Table 5). The $\varepsilon_{Nd}$ value of the mafic cumulate outer zone sample, is 1.58. That of the transition zone sample, is -1.64, and that of the inner zone sample is -2.04. Plotting of initial $^{143}$Nd/$^{144}$Nd vs $^{147}$Sm/$^{144}$Nd (Fig. 22) demonstrates that the samples are not co-linear, and thus are not related by fractional melting/crystallization from a common parent. The petrogenetic significance of the contrasting $\varepsilon_{Nd}$ values is discussed below.
Table 4. Data from isotopic analysis of three representative samples of the Belchertown pluton: BT-3, a monzodiorite from the transition zone; BT-SR-4, a sanukitoid-like monzodiorite from the inner zone; and BT-QB-5, a mafic cumulate from the edge of the outer zone.

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<th>2-sigma s.e. (3)</th>
<th>147Sm/144Nd (4)</th>
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(1) Corrected for fractionation, using 149Nd/144Nd = 0.7299. Measured value of the Ndi-1 standard is 0.512201 ± 0.000007 (2σ; N = 25), compared to a recommended value of 0.512215.
(2) Within one precision of individual analysis.
(3) Nd and Sm concentrations determined by isotope dilution using a 193Sm-149Nd spike; errors are one sigma.
Figure 22. Lack of co-linearity indicates that these rocks neither melted out of a common source nor fractionally crystallized from a single parent magma.
Elemental Identification of Sanukitoids

Dr. Gilbert Hanson of SUNY Stonybrook characterized the Belchertown pluton as a sanukitoid (pers comm., Peter Robinson, 2009), which is a high-Mg granitoid rock found in convergent margin settings. Sanukitoids are plutonic rocks containing 55-60% SiO$_2$, MgO >0.6, K$_2$O >1 %, Ni >100ppm, Cr >200ppm, Rb/Sr ratio <0.1, Ba >500ppm, Sr >500ppm, with enrichment in LREEs and little to no Eu anomaly (Lopez et al. 2005, Stevenson et al., 1999). They represent magmatism characterized by high water and K$_2$O contents (Stern et al., 1989).

Samples from this study that fit the sanukitoid definition have come from all three zones of the Belchertown batholith, and are all from the southwestern corner of the complex: BT-FH1 and BT-SR1 from the Inner Zone; BT-4, BT-8, BT-9, and BT-12 from the Transition Zone; and BT-14 and BT-16 from the Outer Zone. The data for this and previous authors' samples that most closely fit the elemental criteria can be found in Table 6. The REE diagram for samples analyzed as part of this study are given in Figure 23.
Table 5. Discrimination of sanukitoid-like samples in the Belchertown batholith through elemental analysis.

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<th>Rb/Sc</th>
<th>La</th>
<th>Pr</th>
<th>Ce</th>
<th>Eu</th>
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<td>2.75</td>
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<td>2582</td>
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<td>100</td>
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<td>540</td>
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<td>478</td>
<td>0.08</td>
<td>34.5</td>
<td>12.64</td>
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</table>
Figure 23. REE diagram of the identified sanukitoid-like samples, normalized to Chondrites. All show the characteristic lack of Eu anomaly. Samples are from all three zones of the pluton: Inner Zone (black cross), Transition Zone (blue square), and Outer Zone (red circle).
Discrimination Diagrams

Mafic Melt Sources

The AFM diagram (Fig. 19) is used to differentiate tholeiitic from calc-alkaline igneous rocks and fractionation paths. Most of the felsic samples in this study plot in the alkali corner of the plot, except for BT-23, which plots near the boundary between the calc-alkaline and tholeiitic fields.

Wood (1980) used ternary plots of various trace elements to discriminate mafic melt sources. On a Th-Ta-Hf/3 plot (Fig. 24), most samples are clustered in the arc basalt field, while a few others occupy the EMORB and OIB fields. On a Th-Nb/16-Hf/3 plot (Fig. 25), again, most samples plot in the arc basalt field with a few in the NMORB or OIB fields. A similar distribution occurs on a plot of Th-Nb/16-Zr/117 (Fig. 26).

Pearce and Cann (1973) used ternary diagrams of Zr-Ti/100-Y/3 or Sr/2 to classify sources of basalts (Fig. 27). On these plots, most samples plot outside of the designated fields because they are Sr- or Zr-richer than typical basalts. Those that do plot on the diagrams are distributed between the island arc, OIB, and calc-alkaline basalt fields.
Figure 24. Th-Hf/3-Ta melt source discrimination diagram after Wood (1980).
Figure 25. Th-Hf/3-Nb/16 melt source discrimination diagram after Wood (1980).
Figure 26. Th-Zr/117-Nb/16 melt source discrimination diagram after Wood (1980).
Figure 27. Zr-Ti/100-Y*3 melt source discrimination diagram and Zr-Ti/100-Sr/2 melt source discrimination diagram, after Pearce and Cann (1973).
Magma Mixing

The IGPET program of Carr(2001) and mass balance equations were used to model possible parental melts and their proportions for the production of the intermediate suite. All felsic and mafic samples were first run through straight-line mixing models in IgPet against Harker diagrams of the 9 major oxides. A criteria point system based on the number of sanukitoid samples out of eight that plotted on the mixing line was used to further constrain the best possible combinations of felsic and mafic end members to produce a monzodiorite. The top combinations were then run through the trials of mass balance equations using weight-based oxides to determine both the best fit to the mixing model and an average percentage of felsic to mafic melt that would be required to produce the observed compositions.

The felsic and mafic samples were each divided into three groups in order to facilitate the work, and to see if specific composition had any effect on the trials. The felsic samples were grouped as Tonalites (BT-6 and BT-7), Granites/Granitoids (BT-10, BT-18, BT-23, and BT-RR-2), and Felsic Cumulates (BT-22 and BT-RR-5). The mafic samples were grouped as Calc-Alkaline Mafics (BT-20 and BT-RR3), Transition Zone Tholeiites (BT-3R-D1 and BT-3R-D2), and Outer Zone Tholeiites (BT-19, BT-AM, and BT-DIO). The criteria point system assigned a point value to the number of samples that lay on a mixing line between the two proposed parental samples, with a value of 0 for no samples to a value of 4 for 7 to 8 of the 8 total samples. The top three felsic-mafic sample mixtures that produced hybrids similar to analyzed samples were BT-22 + BT-RR-3 (12 points), BT-7 + BT-RR-3 (10 points), and BT-RR-5 + BT-RR-3 (9 points). The rest of the combinations were excluded from further modeling trials.
For each of these three combinations, the percentage of felsic and mafic end members necessary to produce the observed sample composition was determined. The residual sum of squares (RSS) of the differences between the calculated and observed composition is shown in Table 7. The data for all 8 intermediate samples were then averaged to determine an average mixed composition for each parental combination, as well as an RSS average to determine the best possible end-member mixture. The averages for the three combinations are:

Table 6. Mixing trials data with parental percentages and residual sum of squares (RSS).

<table>
<thead>
<tr>
<th>Felsic Parent</th>
<th>Mafic Parent</th>
<th>Total Avg. % Felsic</th>
<th>Total Avg. % Mafic</th>
<th>Total Avg. RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT-22</td>
<td>BT-RR-3</td>
<td>64.27</td>
<td>35.73</td>
<td>1.175</td>
</tr>
<tr>
<td>BT-7</td>
<td>BT-RR-3</td>
<td>62.11</td>
<td>37.89</td>
<td>1.856</td>
</tr>
<tr>
<td>BT-RR-5</td>
<td>BT-RR-3</td>
<td>62.42</td>
<td>37.58</td>
<td>0.895</td>
</tr>
</tbody>
</table>

Finally, the three combinations were plotted on Harker diagrams with a straight-line mixing line drawn between the end-member parental melts (Fig. 28 - 30). The resulting graphs showed that not all samples fell onto the line for each Harker diagram in each combination, but the sanukitoid samples did group together and always fell on the same side of the mixing line when they didn't fall directly on it. On FeO₂, MgO, and MnO diagrams the sanukitoid samples are on or are grouped close to the mixing line. On Al₂O₃ and Na₂O diagrams the sanukitoids group above the mixing line for the mixture of BT-7 and BT-RR-3 (Fig. 28), possibly pointing to an accumulation of albite plagioclase; otherwise, Na₂O diagrams showed sanukitoids plotting below the mixing line. On CaO, K₂O, P₂O₅, and TiO₂ diagrams the sanukitoids group below the mixing line; this could point to the fractional crystallization of labradorite ((Ca,Na)(Al,Si)₄O₁₂) with extraction of some additional Al₂O₃, perovskite (CaTiO₃), titanite...
(CaTiSiO$_5$), or apatite (Ca$_5$(PO$_4$)$_3$OH) from the melt and precipitation of these minerals within the monzodiorite and granodiorite of the pluton, or as part of the mafic cumulates occurring within and around the pluton.
Figure 28. Mixing model for samples BT-7 and BT-RR3, based on Harker diagrams and using straight-line method.
Figure 29. Mixing model for samples BT-22 and BT-RR3, based on Harker diagrams and using straight-line method.
Figure 30. Mixing model for samples BT-RR-5 and BT-RR3, based on Harker diagrams and using straight-line method. No graph was generated for MgO, as the value for it in sample BT-RR-5 was 0.

Tectonic Setting

Samples were plotted on three tectonic discrimination plots by Pearce et al., 1984. On all three plots (Figure 31), most samples plot in the volcanic arc region. On an MgO-Al$_2$O$_3$-FeO plot (Pearce et al., 1977; Fig. 32), the samples are scattered between continental and ocean island fields.
Figure 31. Tectonic discrimination diagrams after Pearce et al. (1984): Upper left is Y+Nb vs Rb (Fig. 31A), center is Yb+Ta vs Rb (Fig. 31B), and lower left is Yb vs Ta (Fig. 31C)
Figure 32. MgO – FeO – Al₂O₃ tectonic discrimination diagram after Pearce et al (1977).
Felsic and Mafic Rock Compositional Variations

At least two groups of felsic rocks in the Outer Zone (but only one group in the Transition Zone) can be differentiated on the basis of trace and REE concentrations. On the same basis, there appear to be three groups of mafic rocks across the Outer and Transition Zones.

Two felsic samples from the Transition Zone exhibit pronounced Ba and Sr spikes and a discernable Nb trough, show a slight enrichment in LREEs, a strong depletion in HREEs, and a positive Eu anomaly. The LREE-enriched trend of the REE pattern of these samples suggests a garnet-bearing source for their parental melt. The positive Eu anomaly signifies an accumulation of plagioclase, possibly by fractional crystallization from a basaltic parent, during cooling and formation.

Of the six other samples in the Outer Zone, four samples show troughs in Rb and spikes in Sr and Ba, along with negative Nb anomalies, a negative Eu anomaly, a downward-trending line across the LREEs and a flattening of the pattern with respect to the HREEs. Unlike the tonalites, these samples lack an abundance of plagioclase, which may have remained as a cumulate in their parental melt. The flat pattern also suggests a non garnet-bearing source, suggesting that partial melting of country rock may not account for the origin of this parental melt. The remaining two samples show exact opposite trace element data, with Rb spikes, corresponding Sr and Ba troughs, and positive Nb anomalies; these exhibit a flatter pattern overall, and little to no Eu anomaly. These are possible felsic cumulates.

All mafic samples exhibit a Nb trough and a Pb spike, although the spike is much more prominent.
in the samples from the Transition Zone. The majority of the mafic samples show a flat pattern across all REEs with no Eu anomaly, and encompass samples from both the Outer and Transition Zones. These flat REE patterns indicate that they are derived from a non-garnet bearing, but possibly olivine-bearing, source. The two samples that are distinct from the rest are both from the Outer Zone: one, BT-RR-3, has a gently sloping curve with relative enrichment in LREEs and depletion in HREEs and no Eu anomaly, and is consistent with arc magmatism. The other, BT-AM, shows an almost flat pattern in the LREEs except for slight depletion in La, an almost flat yet slightly downsloping line in the HREEs, with a negative Eu anomaly.

An argument can be made that there are as many as three distinct patterns within the trace element variation diagram for the mafic rocks (Figure 20), and that the samples represented by these three groups occur across the zones of the pluton. The first pattern shows a slight downward-facing open curve in Rb-Ba-Th before the Nb trough; the second pattern shows depleted Rb in relation to Ba-Th before the Nb trough; the third pattern shows similar Rb-Ba with a slight enrichment in Th before the Nb trough, and this latter pattern is seen in the mafic rocks of the Outer Zone only. These distinctions suggest that there may be three different sources for the mafic samples. The REE diagrams also show three distinct mafic groups within the Outer and Transition Zones of the pluton, with the less common types occurring in the Outer Zone. This grouping is consistent with the groups identified on the basis of variations in trace element concentrations. Possibly mafic melt from different sources either underplated the magma chamber, or was injected into it before or during emplacement. Most samples have neither accumulated plagioclase nor lost it by fractional crystallization. The second remaining sample has a negative Eu anomaly, showing that fractionation of plagioclase from the parental melt
occurred. Both of these remaining samples have REE concentrations most similar to EMORB or OIB.

The distribution of samples plotted on tectonic discrimination diagrams is equivocal, with basalt plotting in arc basalt, MORB and ocean island fields.

Significance of Sanukitoid composition of rocks

Sanukitoids are thought to form by melting of a mafic igneous protolith that has been metamorphosed to eclogite or garnet-amphibole assemblages (Rapp et al., 1991; Thorkelson & Breitsprecher, 2005). Melts derived from the eclogite or garnet-amphibole slab are strongly enriched in Sr with no plagioclase residue, and depleted in HREE. This melt reacts with the mantle to create the characteristic high Sr and high LREE/HREE ratios (Drummond & Defant, 1990). Sanukitoids from the southern Karelian domain in East Finland were suggested to have formed from a mantle-wedge source enriched in LILE, U, Th, and Pb by recycling of continental material in subduction-related slab dehydration processes (Halla 2005). The hypothesis that continental materials, tonalites in particular, are recycled into granodiorites via addition of K₂O and water released from a K-rich mafic mantle-derived magma of sanukitoid-similar composition is supported also through the experimental modeling of Lopez et al. (2005). Their experiments show that only a small fraction of hydrous mantle material is required to generate a large proportion of granodioritic melt from recycling of older tonalitic continental crust.

Ratios of Rb/Sr in sanukitoids are less than 0.1. Sanukitoids also have little to no Eu anomaly, implying that plagioclase in the crystallizing magma was neither removed by fractional crystallization nor accumulated. The samples listed in the following section that have been identified as sanukitoids fit these criteria, with Rb/Sr ratios falling between 0.033 and 0.058, and no negative or positive Eu
anomaly.

Identification of Sanukitoids

Eight samples that were collected as part of this study were found to fit the sanukitoid criteria. All of these are quartz monzodiorites. The samples occur across the three zones of the pluton: BT-FH1 and BT-SR1 are located in the Inner Zone; BT-4, BT-8, BT-9, and BT-12 are located in the Transition Zone; and BT-14 and BT-16 are located in the Outer Zone. All samples can be found, regardless of zone, in the south-western area of the pluton. Data from other authors who have worked on the Belchertown batholith in the past were also evaluated. Ashwal et al. (1979) used thirteen samples, five of which loosely fit the sanukitoid criteria; there were no data supplied for Ba, Sr, Rb, or Eu. These five samples were all quartz monzodiorites, occurred in the Inner and Transition zones, and were found in the same area of the pluton as the author's sanukitoid-like samples. Malcolm Hill (1989) used five samples from the Belchertown intrusion, three of which ultimately fit the criteria for sanukitoids, and were also quartz monzodioritic compositions. There are no specific locations for these samples listed.

Samples from other plutonic New England rocks of Acadian age were checked for sanukitoid composition as well. Two of the eight samples from Red Hill, New Hampshire (Billings and Wilson, 1964), being nepheline-sodalite syenites, could be said to loosely fit the parameters, although no data beyond the major elements and Ba concentrations are given. Sample 93, a high-Nb amphibolite from the Monson dome (Hollocher et al., 2002) fit all criteria except the Sr concentration. Other samples from plutonic Acadian rocks and/or those located within the Bronson Hill anticlinorium do not classify as sanukitoids.
Source rocks of Sanukitoids

A mantle origin is the preferred explanation for the petrogenesis of sanukitoids. The most common source for sanukitoids is probably a portion of the mantle that has been metasomatised previously by the melting of a hot, young, subducting slab. Suites that are LREE-enriched and that have a high concentration of REEs imply derivation from an enriched mantle source (Stevenson et al., 1999). A steep LREE pattern is indicative of an enriched rather than depleted peridotite mantle, which may also indicate equilibration with garnet during melting in the source region. LREE enrichment of sanukitoids is commonly interpreted as a result of the enrichment of their mantle source by LILE-enriched magma or metasomatic fluids (Halla 2005). The combination of a magnesium-rich mafic melt with tonalitic crust must be considered. Two-layered melting experiments run by Lopez et al. (2005) on hydrous mafic synthetic glass and finely crushed powder of natural tonalite at 6 kbar pressure and temperature of 950° C suggest similar rocks in the crust and mantle as parental sources of granodiorite-dominated complexes.

The mafic facies of the Bulai pluton in South Africa has chemical characteristics similar to high-Ti sanukitoids and consistent with an origin in mantle previously enriched by metasomatism and hybridized with TTGs (Laurent et al., 2011). These rocks are relatively low SiO₂, high in Fe and Mg, and very high in LREE and HFSE concentrations. High HFSE content in rocks is taken as an indicator that the enrichment source for metasomatism of a mantle wedge must be non-fluid, as elements such as Nb and Ti are not mobile in water, and a hydrous melt is more efficient at transporting these elements into a mantle source (Laurent et al., 2011). In their study, they concluded that the involvement of
terrigenous sediments accounts for K$_2$O enrichment along with Sr depletion in the mafic facies.

However, the sanukitoid-like rocks of the Belchertown complex show Sr enrichment; taking the study of Laurent et al. into consideration, it is unlikely that terrigenous sediments played a role in the genesis of the sanukitoid and granodiorite rocks of the Belchertown batholith.

**Petrogenesis of the Parental Melts**

The $\varepsilon_{\text{Nd}}$ values of outer, transition, and inner zone rocks contrast strongly, suggesting different source materials, and they do not plot on a straight line on a plot of $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{147}\text{Sm}/^{143}\text{Nd}$, indicating that they do not share a common parent material. Further, since not all the Harker diagrams of samples from the Outer Zone have smooth curves and/or trends, we can surmise that the various types of rocks are not related to each other by mixing and fractional crystallization, and probably do not come from one parental melt. Within the Transition Zone, there is a greater possibility that these rocks are petrogenetically related, but samples do not vary smoothly across all the graphs. The intermediate rocks of the Inner Zone are more likely to be genetically related on the basis of similarity in major, trace, and rare earth element concentrations.

The LILE enrichment and Nb trough in the trace element data of the mafic rocks across the batholith indicate that these rocks do not have a primitive mantle source, but their positive $\varepsilon_{\text{Nd}}$ does indicate a mantle source. Their trace element patterns most closely resemble enriched mid-ocean ridge basalts (EMORBs), which are often associated with plumes having a deeper mantle source, and proposed also to have enrichment sources from either fractionation during melting or metasomatic events. The trace element analyses further point to the end-member magmas, both felsic and mafic,
having each undergone either fractional crystallization or partial melting. The REE data however suggests that the majority of the mafic samples tested, which bear the flatter pattern, may have a more-primitive olivine-bearing mantle source, whereas the two samples exhibiting a steeper curve probably have a separate source coming from an EMORB or OIB source that experienced plagioclase fractionation. The flatter pattern in the mafic samples further suggests MORB, arc-basalt, or flood-basalt for tectonic melt setting.

The origin of the monzodiorites is best interpreted from the less-mobile REEs. Augite fractional crystallization cannot relate the intermediates to the felsic rocks because LREE values in the felsics are not high enough. Fractional crystallization of plagioclase from the intermediates would produce a negative Eu anomaly in the felsic rocks. However there would need to be another phase of fractional crystallization after that to retain the LREEs. Therefore we can surmise that the intermediate and felsic suites are not related through fractional crystallization.

The major element analyses appear to favor an environment of mixing of two end-member magmas in a chamber to produce an intermediate monzodioritic magma. While the intermediate rocks do plot between the felsic and mafic end-members on a straight line in the Harker diagrams, fractional crystallization is not supported as a mechanism for derivation of magmas. As noted, many of the curves in the major element diagrams are smooth except in potassium and phosphorus, where the data are scattered throughout the graph.

The REE patterns of the intermediate suite are the same across the pluton, and include no Eu anomaly. If the tonalitic felsic rocks (samples BT-6 and BT-7) are mixed with the LREE-enriched mafic rocks found in BT-RR3, melt with an intermediate composition and no Eu anomaly would result.
This would also explain why there is relatively little of these sample types remaining within and around the pluton. In the REE patterns for the felsic samples from the transition zone, a positive Eu anomaly indicates plagioclase enrichment, and LREE-enrichment, pointing to a probable garnet-bearing melt source. Coupling this with the enrichment of the HFSEs in the intermediate suite, extraction from garnet-rich schists in the surrounding country rock is a more likely alternative (Hollocher, *pers. comm.*).

**Significance of Neodymium and Samarium Analyses**

Nd isotope ratios indicate generally how close to bulk earth composition a specific melt is. The present bulk earth $^{143}\text{Nd}/^{144}\text{Nd}$ ratio is 0.512265; as $^{147}\text{Sm}$, which decays to $^{143}\text{Nd}$, is more compatible with Nd, higher $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are indicative of mantle origin. The mantle vs crustal Nd signatures of igneous rocks is most easily evaluated using the initial $\varepsilon_{\text{Nd}}$ value of the rock:

$$\varepsilon_{\text{Nd}} = \left[ \frac{^{143}\text{Nd}_{\text{sample}}(t)/^{143}\text{Nd}_{\text{CHUR}}(t) - 1}{^{143}\text{Nd}_{\text{CHUR}}(t) - 1} \right] \times 10000$$

where CHUR = chondritic uniform reservoir and $t$ is the time of crystallization of the rock.

Positive $\varepsilon_{\text{Nd}}$ values indicate a mantle origin and negative values indicate a crustal origin. The $\varepsilon_{\text{Nd}}$ value of BT-3 (transition zone) is -1.64, that of BT-SR1 (inner zone) is -2.04, and that of BT-QB5 (mafic cumulates from the outer zone) is 1.58.

The outer zone rock, BT-QB5, is mafic cumulate material, consistent with its representing the lowermost exposed level of a layered, possibly bowl-shaped magma chamber, similar to the mafic and silicic layered complexes of Wiebe (1993). This mafic material has a positive $\varepsilon_{\text{Nd}}$, consistent with its origin as a partial mantle melt that has undergone contamination by crustal material. The rocks of the
transition and inner zones, BT-3 and BT-SR1, both have negative $^{143}$Nd values, consistent with their origins as partial melts of crustal rocks. The zoned nature of the pluton is thus consistent with a layered, bowl-shaped pluton with the most primitive, mantle-derived rocks, representing the lowest zone of the pluton, exposed in the outermost area.

**Tectonic Setting**

The Acadian Orogeny

The Salinic and Acadian orogenies saw the suturing of the Avalon terranes onto what is now the eastern seaboard of the North American continent. The onset is generally accepted as being associated with the docking of the Ganderian and Avalonian exotic terranes; followed by the oblique convergence of the Meguma and Carolinian terranes either during or just following the collision of Meguma with Laurentia, c. 380Ma (Murphy et al., 1999; Murphy et al., 2007). The docking of these island arcs with the craton was driven primarily by westward-trending subduction, which occasionally reversed after suturing was completed. Voluminous magmatism occurred with the docking of these terranes, but ceased between 360 – 345 Ma. Between 345 and 335Ma, magmatism resumed within the Meguma terrane with the intrusion of the biggest granitoid batholiths. Around 335Ma, magmatism migrated northwards into the Avalon terrane, and became more bimodal. Much of the igneous activity that resulted has been proposed by Robinson et al. (1998) as a product of delamination of mantle lithosphere from the descending plate in the subduction zone and upwelling of asthenosphere towards the continental base. Murphy et al. (1999) suggested that the Acadian orogeny in the northern Appalachians was modified by the overriding of a mantle plume.
The overriding-plume model of Murphy et al. (1999) starts with a magmatic arc, soon to be obducted onto the continental margin, situated on oceanic crust and over a mantle plume. When the subduction of the oceanic crust begins, the plume is overridden, which results in a subhorizontal subduction angle and the temporary cessation of magmatism. The plume head then thermally erodes the subducted oceanic plate, causing the hotter plume to come into contact with and begin melting the lower continental lithosphere, producing some minor mafic magmatism. Murphy stated that the presence of continental mafic rocks with plume-related chemistry is important in identifying this process. Murphy suggested that the overriding-plume model better correlates anomalous activities such as the magmatic gap and plume-related magmatism that have both spatial and time gaps, and better explains them than previous ideas of Andean flat slab-type setting or crustal delamination.

Sanukitoid Emplacement

Negative anomalies in Nb and other HFSEs are characteristic of subduction-related magmas. Stevenson et al. (1999), in their work on sanukitoid rocks within the Western Superior Province in Canada, concluded that sanukitoids were emplaced in a major pulse of magmatism following the accretion of a province.

Stevenson et al. (1999) also suggested, as a heat source responsible for melting, that the more likely scenario is delamination of the subducting lithosphere into the mantle, allowing hotter rock of the asthenosphere to upwell and induce adiabatic melting in the mantle, along with crustal melting where the asthenosphere comes in contact with the base of the crust. In the case of the Panozero pluton (Lobach-Zhuchenko et al., 2008), a distinct cause of melting was unknown, although the authors stated
that the upwelling of asthenospheric mantle following slab break-off was consistent with the
geochemical evidence for enrichment of the subcontinental mantle under the Karelian craton by
subduction fluids (Lobach-Zhuchenko et al., 2008).

Trace and rare earth element abundances in the Belchertown pluton are consistent with both
tonalitic and granitic sanukitoids, having been produced in a volcanic setting in which slab
delamination or considerable crustal extension permitted the upwelling and partial melting of
asthenospheric mantle.

Concentric Zonation

Several zoned plutons have been the subject of studies of the petrogenetic and emplacement
history of such bodies. Antunes et al. (2008) used differing initial $^{87}$Sr/$^{86}$Sr ratios in 5 concentrically
zoned granitoid members of the reversely-zoned Castelo Branco pluton in central Portugal to identify
three different pulses of magmatism. Barbey et al. (2001) concluded that the three-zoned Tarcouate
pluton of Morocco was produced through both magma differentiation at depth and successive pulses of
these variably differentiated magmas and synplutonic dykes. Clinkenbeard and Walawender (1989)
determined through observation of mineralogical differences in the La Posta pluton that the late
intrusion of the tail of a diapir into the magma chamber, and the successive pulse of emplacement of
the hybridized melt into the center of the partially solidified pluton, led to zoning in that intrusion. The
Timbarra Tablelands pluton, studied by Mustard (2004), is comprised of seven zones that can be
chemically discriminated, and for which a three-stage emplacement model based upon geological,
geochemical, and textural evidence was proposed. The Tuolumne Intrusive Suite is also a chemically
zoned pluton, for which emplacement as a series of small intrusions has been proposed (Coleman et al., 2009).

The authors of all of these studies concluded that emplacement of the respective plutons was through not one but several consecutive intrusive pulses. Earlier studies of the Belchertown pluton reached similar conclusions: Stoeck (1971) proposed for the Hatfield pluton, which is recognized as co-genetic with the Belchertown, that the concentric zonation was a result of two pulses of intrusion. As noted in the introduction, her speculation was based upon the presence of abundant potassium in the interior granodiorite component of the Hatfield as opposed to the exterior tonalite, which she could not explain by metamorphic processes to produce zoning in the pluton. She stated therefore that the zonation of the Hatfield pluton—and by extension, the Belchertown pluton—had to be a primary feature resulting from two pulses of intrusion, the interior pulse having been enriched in potassium from contact with wallrocks at depth and prior to emplacement.

Expanding upon Stoeck's findings to explain the third zone found in the Belchertown pluton, it is necessary to suggest a third intrusive pulse for the Inner Zone, which is the dry sanukitoid. First, it should be noted that the Transition and Outer Zones of the Belchertown pluton correspond to the two zones found in the Hatfield pluton, including the potassium abundance in the monzodiorites of the Transition (Hatfield interior) Zone as opposed to the granodiorites of the Outer Zone. The sanukitoid comprises the whole of the Inner Zone and is unique to the Belchertown. Within the Transition Zone, mingling between the sanukitoid melt and the semi-wet monzodiorite melt can be identified near the contact area with the Inner Zone. This implies that the first intrusion was not completely crystallized at the time of the second intrusion, and that these two pulses occurred one very soon after the other. Like
the monzodiorite, the sanukitoid also has a higher potassium concentration than the granodiorite; it is likely that the increase in potassium, as well as the increase in hydrous mineral phases in the non-sanukitoids, is a product of metasomatism by contact and mixing with a hydrous melt.

The zonation of the pluton occurs as a function of three separate pulses of intrusion of melt from the magma reservoir or chamber in the lower crust. Within the reservoir, the melt mixed to produce an intermediate composition throughout with horizontal variations in composition and degree of hydration. This model predicts a drier potassium-rich sanukitoid in the upper part of the reservoir and a wetter potassium-poor granodiorite in the lower part, with the semi-wet and potassium-rich monzodiorite melt in between. The reservoir would have been evacuated sequentially in this order, emplacing the sanukitoid at mid-crustal level first, and followed soon after by a second emplacement pulse that brought up the monzodiorite around the sanukitoid. A third, later pulse would then bring up the granodiorite to surround the two previous zones.
CHAPTER 10

CONCLUSIONS

The following petrogenetic model for the Belchertown batholith is suggested:

1. Young hot oceanic crust, subducted during the Acadian Orogeny as part of the docking of a terrane with the proto-continent, partially melted and produced hydrous silica-, LILE- and LREE-rich mafic magma.

2. The remaining subducting slab delaminated, providing room for hot depleted upper mantle rock to upwell.

3. The hydrous melt interacted with the mantle wedge, producing an enriched metasomatised sanukitoid-similar mafic melt through partial melting and magma mixing. This was the mafic parental melt to the batholith. The representative of this melt is the sample BT-RR3, a calc-alkaline arc intrusion with signatures of subducted oceanic origin.

4. The sanukitoid melt came in contact with the garnet-bearing base of the crust, inducing partial melting of the crust to produce a tonalitic melt, the felsic end-member parental melt. Representatives of this melt are the samples BT-6 and BT-7; thin section analysis confirms the presence of remnant garnet within these tonalites.

5. The tonalitic melt reacted and mixed with the enriched mafic melt to produce an intermediate composition melt, with further potassium and water enrichment producing the monzodiorite and granodiorite melts respectively through magma mixing and differentiation within a lower reservoir prior to emplacement at the mid-crustal level. Mass balance equations indicate that 35.6% - 37% mantle component, mixed with a 63% - 64% crustal component produce a sanukitoid composition.
While this seems to be a rather high approximation of mafic parental melt, it is worthwhile to note that the generation of monzodiorite and granodiorite within the same reservoir was not taken into account in this particular model. It is possible that a greater percentage of tonalitic melt was present in the reservoir at the time of generation of the intermediate compositions than is accounted for in this data set.

6. The batholith was emplaced through three successive pulses, beginning from the upper part of the chamber with the dry potassium-rich sanukitoid, which is followed closely by a pulse of semi-wet potassium-rich monzodiorite around it, and then followed later by a third pulse of wetter potassium-poor granodiorite around the two. The close timing of the first two pulses is suggested and corroborated by the observation that sanukitoid and monzodiorite rocks mingle within the transition zone, suggesting that the sanukitoid was not completely crystallized at the time of emplacement of the monzodiorite. The same observation was not made for the monzodiorites and granodiorites in the outer zone.
APPENDIX A

LUDLOW QUADRANGLE SAMPLE MAP
APPENDIX B

BELCHERTOWN QUADRANGLE SAMPLE MAP
APPENDIX C

PALMER QUADRANGLE SAMPLE MAP
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