Bulletin 45

Bedrock Geology of the Kittery 1:100,000 Quadrangle, Southwestern Maine and Southeastern New Hampshire

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Published by the Maine Geological Survey
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This bulletin is a companion to

Maine Geological Survey Geologic Map 16-6 by Hussey and others (2016)

Published
by the
Maine Geological Survey
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Cover photograph:

Thin-bedded metaturbidites of the Silurian Kittery Formation interpreted to be deposited in distal parts of submarine fan lobes. Alternations of light and dark brownish gray rock are thin graded beds, each representing a separate turbidity flow. The light greenish gray beds between may represent accumulation of calcareous mud between flow intervals. *1 kilometer north of Bald Head Cliff, York, Maine*. Photo credit: Arthur M. Hussey II.

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Bedrock Geology of the Kittery 1:100,000 Quadrangle, Southwestern Maine and Southeastern New Hampshire

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ABSTRACT

This report accompanies the bedrock geologic map of the Kittery 1:100,000-scale quadrangle. This area is underlain by Silurian to Devonian metamorphosed quartzose wackes and aluminous and rusty shales of the Shapleigh Group (Rindgemere Formation, Gully Oven Formation, Towow Formation and Merchants Row Grits, East Rochester Formation, and an unnamed discontinuous unit between the Merchants Row and the East Rochester units) of the Central Maine Basin; metamorphosed Silurian-Devonian quartzo-feldspathic and calcareous wackes (Berwick Formation) and strongly sheared aluminous pelite of uncertain origin (Phyllonite at Church Road) deposited in either or both the Merribuckfred Basin or the Central Maine Basin; metamorphosed Silurian quartzo-feldspathic and calcareous turbidites of the Merrimack Group (Eliot and Kittery formations) that accumulated in the Merribuckfred Basin; and metamorphosed and extensively sheared Cambrian and Ordovician rocks of the Rye Complex. These sedimentary packages have been pre-, syn-, and post-tectonically intruded by felsic and mafic plutonic rocks ranging in age from Cambro-Ordovician to Early Cretaceous. Three major orogenies and episodes of metamorphism have affected these rocks. The earlier one, variously referred to as Salinic or early Acadian, at the end of the Silurian and beginning of the Devonian Period resulted in extensive recumbent folding of the Merrimack Group, thrust faulting, and regional greenschist to amphibolite facies metamorphism. The later one, Acadian, produced upright folding in the Merrimack Group and large-scale recumbent folding, thrust faulting and upright folding and amphibolite facies regional metamorphism of the Shapleigh Group in the Central Maine Basin. Alleghanian orogenic activity is represented by intrusion of the Permian Lyman pluton (288 Ma) and associated pegmatites there, variably imprints the rocks of the Merribuckfred Basin, and most strongly affects the Rye Complex. The presence of 432 Ma detrital zircons in the Merrimack Group makes a correlation of that group with the lithically similar formations of the Fredericton Basin still a possibility. Given the 418 Ma age of the cross-cutting Newburyport pluton, an implication of these detrital ages is that of a very short interval of time between deposition of the Merrimack Group and multiple episodes of deformation, metamorphism, and post-tectonic intrusion. New high-precision age dates presented here for nine plutons demonstrate that plutonic activity spanned most of the Devonian, including the Exeter (407 Ma), a large volume of granite at 383 Ma (Biddeford, Webhannet, and Nisbitt Pond plutons), and diorite at 361 Ma. Mesozoic intrusive activity is represented by the 239 Ma Agamenticus Complex of Triassic age; simple, composite, and multiple dikes of basalt and related rocks of probable Triassic to Jurassic age; and Early Cretaceous mafic to intermediate funnel intrusions and explosive breccias. These Mesozoic intrusive rocks are related to initial right-lateral shearing and subsequent extensional breakup of Pangea related to the opening of the Atlantic Ocean.

I. INTRODUCTION

The area of the Kittery 1:100,000 map sheet (Figure 1) is located in the southwestern tip of Maine and adjacent parts of southeastern New Hampshire, with a shoreline extending from Saco, Maine southwestward to Rye, New Hampshire. The bordering shoreline consists mostly of rocky headlands with abundant bedrock exposures, but also includes long sandy beaches such as Rye Beach in New Hampshire and Long Sands Beach, Ogunquit Beach, Wells Beach, and Old Orchard Beach in Maine. That scenery is an important attraction for tourists on which the economy of the region is significantly dependent.

Some of the principal cities and towns (with populations in parentheses) include Biddeford (20,942), Sanford (20,306), Saco (16,822), and York (12,854), Maine, and Rochester (30, 654), Dover (28,609), and Portsmouth (20,443), New Hampshire (Figure 1). The population of coastal towns swells to more than double the year-round residents during the summer tourist season. Coastal communities become quite congested, and beaches are thronged by tourists and residents seeking relief from summer heat.

Physiographically, the area can be divided into the coastal lowlands zone extending roughly 20 kilometers inland from the shoreline, with elevations seldom exceeding 100 meters, and the interior hilly zone – foothills of the White Mountains – with elevations up to 300 meters. Major hills in the area are Mount Agamenticus in York, Maine (200 meters), Bauneg Beg Mountain in North Berwick, Maine (250 meters) and unnamed hills in the Milton, New Hampshire, area (just over 300 meters). Much of the area of the coastal lowland is blanketed with post-glacial mud, sand and gravel. The interior hilly zone is covered by a variable thickness of glacial drift with common ice-streamlined shapes (drumlins), stoss-lee profiles of major hills, and roches moutonnées of lesser bedrock knolls. Outcrops of bedrock vary from extensive in the bold and rocky shorelines to scarce in much of the coastal lowlands and interior hilly zone where glacial and post-glacial sediments form an extensive blanket. Within the coastal lowland zone, igneous plutons account for low hilly topography, whereas metamorphosed sedimentary rocks underlie much of the interior.

This bulletin describes the bedrock of the Kittery 1:100,000 map sheet (Hussey and others, 2016) which includes Cambrian to Early Devonian metamorphosed clastic sedimentary rocks, and intrusive igneous rocks varying in composition from granite to gabbro, and in age from Ordovician to Cretaceous. Hussey and others (2010) have divided the metamorphosed sedimentary rocks into the pre-Silurian Rye Complex and the Silurian and lower Devonian Merribuckfred and Central Maine basins. The intrusive igneous rocks include elongate plutons up to 25 kilometers in length, circular to ovate plutons, ring complexes, and a host of basaltic to granitic dikes and sills that intrude the metasedimentary rocks and older plutons.

Twelve new high-precision U-Pb zircon ages are reported for samples from six major plutons, three minor intrusive bodies, and one quartzo-feldspathic gneiss unit. The bodies are within or across the boundaries between the three zones within the map area: Central Maine Basin, Merribuckfred Basin (Hussey and others, 2010), and Rye Complex (Lyons and others, 1997). Results are incorporated in the discussion of each unit. Sample localities are described in Appendix 1. Analytical methods are summarized by Dr. Robert Buchwaldt (written communication, 2010) and included in Appendix 2 with a table of analytical data.

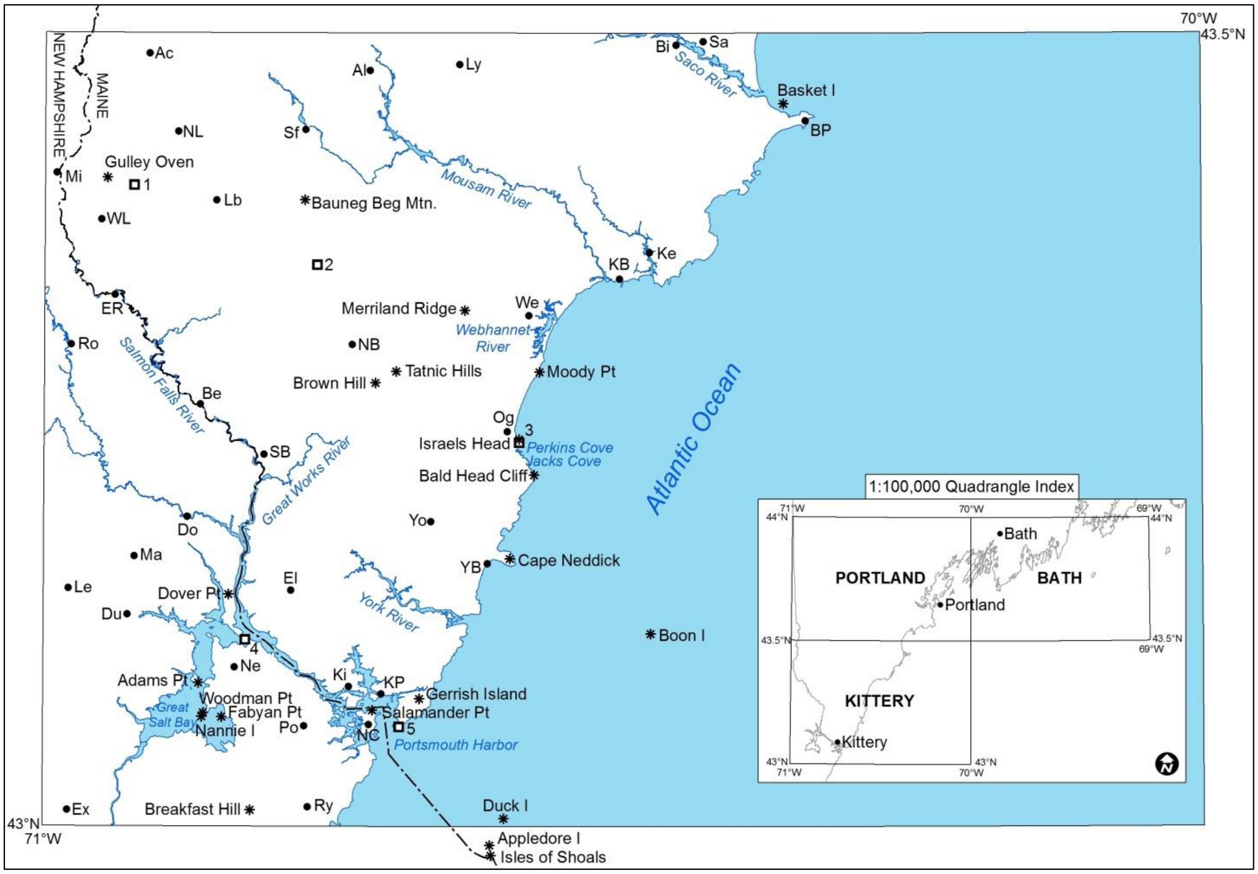

Figure 1. Location of the Kittery 1:100,000 map sheet, showing localities mentioned in the text. Inset map shows location of the Portland and Bath 1:100,000 quadrangles to the northeast.

Towns shown by black circles:

Ac	Acton	Ex	Exeter (NH)	Mi	Milton (NH)	Sa	Saco
Al	Alfred	KB	Kennebunk Beach	NC	New Castle (NH)	Sf	Sanford
Be	Berwick	Ke	Kennebunkport	Ne	Newington (NH)	SB	South Berwick
Bi	Biddeford	Ki	Kittery	NB	North Berwick	We	Wells
BP	Biddeford Pool	KP	Kittery Point	NL	North Lebanon	WL	West Lebanon
Do	Dover (NH)	Lb	Lebanon	Og	Ogunquit	Yo	York
Du	Durham (NH)	Le	Lee Five Corners (NH)	Po	Portsmouth (NH)	YB	York Beach
ER	East Rochester (NH)	Ly	Lyman	Ro	Rochester (NH)		
El	Eliot	Ma	Madbury (NH)	Ry	Rye (NH)		

Cultural places shown by squares:

1. Merchants Row, Lebanon, Maine
2. Church Road, Meeting House Road, North Berwick, Maine
3. Marginal Way, footpath, Ogunquit, Maine
4. General Sullivan Bridge, Newington, NH
5. Fort Foster, Gerrish Island, Kittery, Maine

II. STRATIFIED ROCKS

Stratified rocks of the Kittery 1:100,000 map sheet consist of five separate lithostratigraphic packages, with units ranging in age from Cambrian to Early Devonian. From northwest to southeast these include the Silurian–Early Devonian Shapleigh Group that accumulated in the Central Maine Basin, the Silurian Berwick Formation and Silurian(?) Phyllonite at Church Road that may have been deposited in either the Central Maine Basin or the Merribuckfred Basin, the Silurian Merrimack Group that accumulated in the Merribuckfred Basin (Hussey and others, 2010), and the Cambrian–Early Ordovician Rye Complex of uncertain provenance.

Shapleigh Group

This group consists of the Rindgemere, Gully Oven, Towow, an unnamed unit, and East Rochester formations, from oldest to youngest. These rocks are mostly pelitic mica schists and quartz-mica schists, of presumed Silurian to Early Devonian age. They are correlated with a similar sequence of rocks in the Rangeley area (Thompson, 2004) and more locally in the Portland 1:100,000 sheet (Berry and Hussey, 1998) or the Portland 2-degree sheet (Hussey, 1985). Correlation with stratigraphic units in the Mt. Blue area, suggested by Hussey (1985), is no longer favored (Eusden and others, 1987).

Rindgemere Formation (revised)

The Rindgemere Formation (**Sr**[1]) was named originally by Katz (1917), modified by Hussey (1962), and revised further by Eusden and others (1987) and Thompson and others (2004). We follow here the usage of Thompson and others (2004). In the area of the Kittery sheet, it is a variable unit dominated by massive coarse-grained mica schist (metashale) and feldspathic granofels (metasandstone) with minor calc-silicate beds and boudins (originally calcareous concretions, Figure 2). The schist weathers gray to reddish to rusty, and at sillimanite to sillimanite + K-feldspar grade of metamorphism it is commonly migmatitic. The Rindgemere Formation as used here is correlated with the Rangeley Formation of northwestern Maine (after Eusden and others, 1987). The contact with the overlying Gully Oven Formation is not exposed but is inferred to be conformable based on similarity of dips and strikes of the bedding and foliation within the two formations.

Gully Oven Formation (of Thompson, 2004)

The Gully Oven Formation (**Sgo**) is an interbedded sequence of generally thin- to medium-bedded light silvery-gray mica schist (metashale) and feldspathic quartzite (metasandstone), often with thin pink coticule lenses (Figure 3). The schist typically contains andalusite, or sillimanite after andalusite, or pseudomorphic lumps of muscovite+quartz after andalusite (colloquially referred to as “andalumps”). Bedding in the metasandstone is sharp and commonly not graded. The Gully Oven Formation is correlated with the Perry Mountain Formation of northwestern Maine (Moench, 1971; Eusden and others, 1987; Thompson, 2004). The contact with the overlying Towow Formation is not exposed but is inferred to be conformable on the basis of conformity of strikes and dips of the two formations and their map pattern.

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[1] Letter symbols in **bold** are used throughout the text to identify rock units shown on the Kittery map sheet (Hussey and others, 2016).

Figure 2. Pelitic migmatite of the Rindgemere Formation (**Sr**) with large calc-silicate concretion. Red pocket knife for scale. *Route 16 exit, Milton, New Hampshire.*

Towow Formation and Merchants Row Grits

The Towow Formation (**St**) (Katz, 1917) is mostly a rusty-weathering, massive to thin-bedded metashale and metasiltstone at sillimanite grade. Abundant pyrrhotite gives most of the formation a high magnetic signature on aeromagnetic maps (Bromery and others, 1956). It was the source of significant rusty glacial outwash and, when drilled for domestic wells, produces iron-tainted water; both features have facilitated mapping this unit in areas of poor outcrop exposure (Thompson, 2004). The Towow Formation is correlated with the Smalls Falls Formation (Eusden and others, 1987; Thompson, 2004).

The Merchants Row Grits (new name) (**Stmr**), a member at the top of the Towow Formation, consists of rusty-weathering phyllite (metashale) with irregular, discontinuous lenses containing matrix-supported blue and white quartz granules and rare fine-grained dark gray rock fragments (Figure 4). The grits were described by Hussey (1985), mapped by Thompson (2004), and included in a field guide by Thompson and others (2004, Stop 2). It occurs locally at the top of the Towow Formation and provides an important stratigraphic marker for the area. The Merchants Row Grits are equivalent to the Wild Goose grits in New Hampshire (Hussey, 1985; Eusden and others, 1987). These grits may represent a local disconformity between the rusty-weathering schists of the Towow Formation and the overlying unnamed formation of calc-silicate granofels and biotite granofels. An erosional disconformity may account for the variable thickness and local absence of the overlying unnamed formation.

Unnamed formation

A unit of thin- to medium-bedded, light greenish gray, calc-silicate granofels and biotite granofels (**DScb**) occurs discontinuously at the contact between the Towow and East Rochester formations (Figure 5). It contains quartz, plagioclase, diopside and hornblende as principal phases in what were the more calcareous layers interbedded with non-calcareous biotite metasandstone, metasiltstone, and very minor metashale. The metamorphic grade ranges from

andalusite + staurolite zone to sillimanite zone. This unit is correlated with the Madrid Formation by Eusden and others (1987). The contact with the overlying East Rochester Formation is not exposed but is inferred to be conformable on the basis of parallelism of strike and dip of bedding and foliation of the two formations.

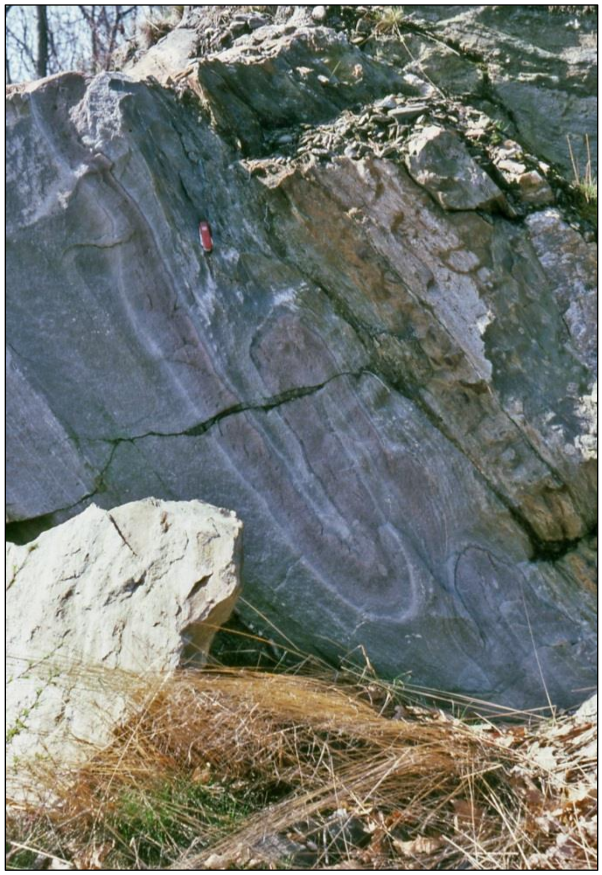

Figure 3. Gully Oven Formation (**Sgo**) with folded reddish garnet coticule bed. *Route 16 near East Rochester, New Hampshire.*

East Rochester Formation (new name)

The East Rochester Formation (**Der**) consists of interbedded aluminous gray schist (metashale) and metasandstone, commonly with well-preserved graded bedding. Bedding thickness ranges from a few centimeters to a few tens of centimeters. Gray weathering, glacially polished surfaces are commonly decorated with small garnets (or weathered pits). In the more pelitic layers, turkey-tracks of fresh andalusite or “andalumps” (muscovite pseudomorphs after andalusite) up to 10 centimeters in length dominate the originally finer-grained, clay-rich tops, metamorphically reversing the original depositional grain size of the graded beds (Figure 6). Its metamorphic grade in the map area ranges from andalusite + staurolite zone to sillimanite zone. Lithologically somewhat similar to the Gully Oven Formation to the northwest, the East Rochester Formation was differentiated from it by Thompson (2004) on the basis of thicker metasandstone beds, gray rather than white metasandstones, and more common graded beds. Also, graded beds near the contact indicate it lies stratigraphically above the Towow. The East Rochester Formation is correlated with the Littleton Formation of New Hampshire and the Carrabassett Formation of northwestern Maine (Eusden and others, 1987).

Figure 4. Merchants Row Grits member of the Towow Formation (**Stmr**). Coarse, light colored feldpathic granule conglomerate with sparse blue quartz, intermingled with black non-rusty and rusty phyllite lenses.

Figure 5. Unnamed quartzite and calc-silicate unit (**DScb**). *Along the Salmon Falls River north of the U.S. Route 202 bridge, East Rochester, New Hampshire.*

Phyllonite at Church Road

Strongly sheared, very aluminous, pelitic rock occurs in a continuous 1-2 km wide belt between the Berwick Formation and the Central Maine sequence. It is truncated by the Permian Lyman pluton to the northeast and by the Devonian Barrington pluton to the southwest beyond which, farther to the southwest, it may continue as the Gove Member of the Berwick Formation.

The map unit was previously called the Gonic Formation but, for reasons explained by Hussey and others (2010), is now defined as the Phyllonite at Church Road (**Scr**). We recommend the abandonment of the name "Gonic Formation." The unit name comes from Church Road in North Berwick, shown on USGS topographic maps for the Berwick 15' quadrangle (1958) and Somersworth 7½' quadrangle (1998), although the road is now called Meeting House Road (Figure 1). Whether a stratigraphic unit (as preferred by AMH) or a very aluminous dismembered lens that was exploited by deformation (as preferred by WAB, PJT), the unit is a distinctive staurolite-garnet-biotite metapelite with anastomosing foliation, discontinuous quartz vein lenses and inclusion-rich garnets (Figure 7).

Figure 6. Well bedded quartz-rich granofels (metasandstone) and schist (metashale) of the East Rochester Formation (**Der**). Note weak graded bedding, cleavage, and suggestion of cross-bedding in the quartzose beds. *Bank of the Salmon Falls River near the Boston Felt Company plant, East Rochester, New Hampshire.*

Merrimack Group

The Merrimack Group consists of metamorphosed calcareous quartzo-feldspathic flysch deposits that accumulated in the Merribuckfred Basin (Hussey and others, 2010). These rocks include the Eliot and Kittery formations, and possibly the Berwick Formation, ranging in age from Silurian to earliest Devonian(?). Age assignments of these unfossiliferous rocks are based on cross-cutting relations of dated intrusives and, most recently, by the population of detrital zircons that have provided both maximum age and important provenance information.

The U-Pb age determinations of youngest detrital zircons from all three units range from ~409±19 Ma (Eliot and Berwick) to ~413±12 Ma (Kittery) by the LA-ICP-MS method (Sorota, 2013). The LA-ICP-MS data provide youngest ages with large 1-sigma errors for each unit that suggest very short time intervals (~7 million years) between deposition and deformation of each prior to intrusion of well-dated plutons (using the 418 Ma Newburyport; Bothner and others, 2009). As a consequence, the four youngest zircons from the Kittery Formation were reanalyzed by the ID-TIMS method. Sorota (2013) reports a youngest detrital zircon age of 432 Ma for the

Kittery and prefers to use 426 Ma as her chosen age, but either provides a more reasonable 8-14 Ma interval between sedimentation and intrusion of the Newburyport pluton. We contend that the younger zircons from the Eliot and Berwick (409±19 and 409±11 Ma) would yield older, more compatible ages if subjected to the same ID-TIMS analysis as was performed on the Kittery, placing all three units comfortably within the Silurian (Hussey and Bothner, 2013).

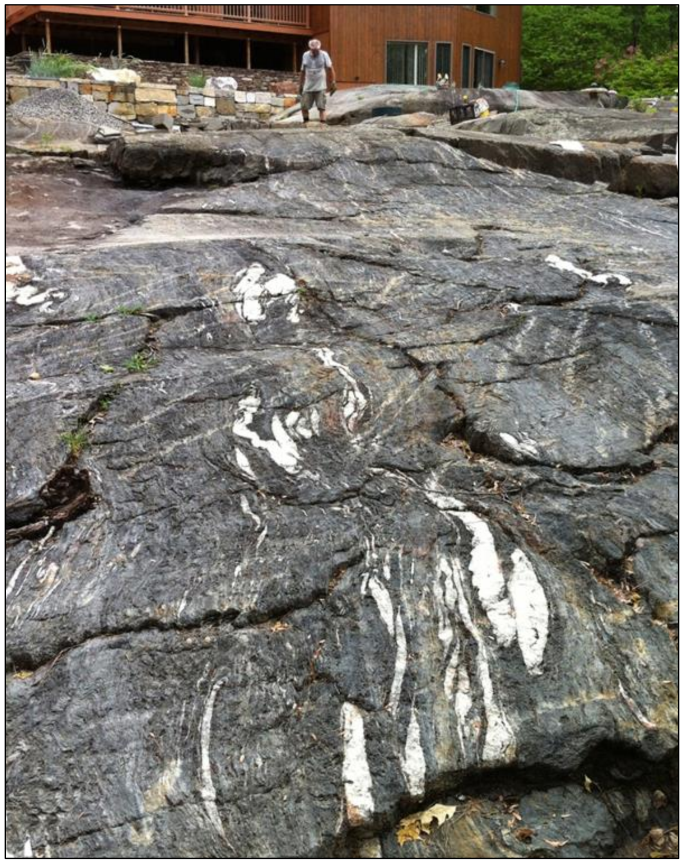

Figure 7. Highly sheared and quartz-injected exposure of the Phyllonite of Church Road (**Scr**). *Near Pine Hill, Berwick, Maine.*

Eliot Formation

The older unit of the Merrimack Group is the Eliot Formation (**Se**). It consists of thin-bedded alternations of medium buff to gray-weathering calcareous metasiltstone and dark gray slate or phyllite (metashale; Figure 8). Primary structures other than relict bedding are rare. Novotny (1963) notes increased "argillaceous layers" in the transition between the Eliot and Kittery formations and T. R. Meyers' 1969 edit of Novotny's thesis work reports "a gray quartz conglomerate resting unconformably across the Kittery–Eliot contact at the confluence of the Great Works and Salmon Falls River, South Berwick, Maine" (Novotny, 1969, p.11) that he interprets as evidence that the Eliot is younger than the Kittery. That outcrop was not recoverable in more recent mapping. Instead, the best evidence for the topping direction is from graded beds found at and near the contact along the perimeter road at the Newington (New Hampshire) Mall, in a drill core at Fabyan Point in the Great Bay, Newington, and in exposures, now buried, where a new fire station now stands in Madbury, New Hampshire (Escamilla-Casas, 2003) (Figure 1).

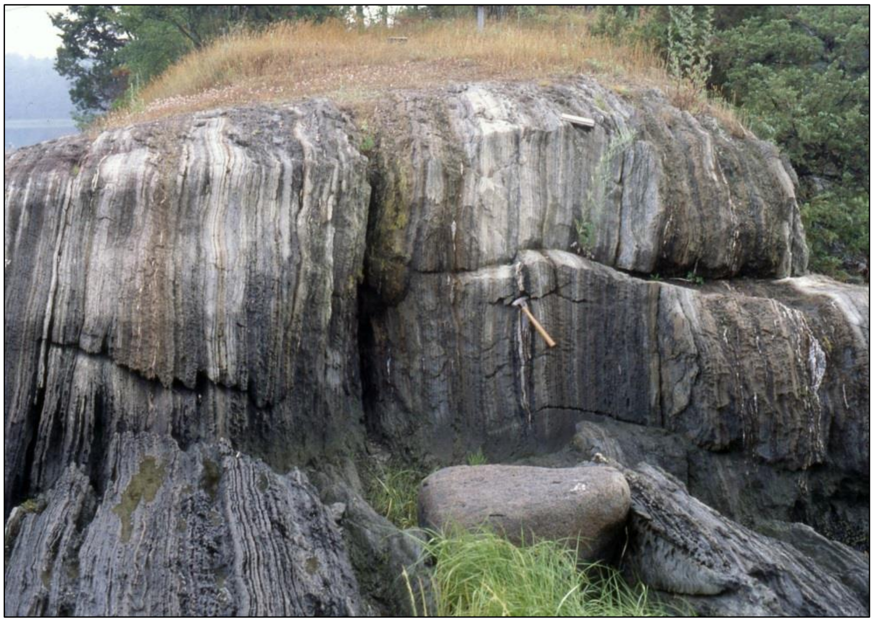

Figure 8. Thinly interlayered and variably sheared calcareous metasiltstone and phyllite of the Eliot Formation (**Se**). Hammer for scale. *Shoreline exposure at Woodman Point, Great Bay Estuary, Newington, New Hampshire (Figure 1).*

The Eliot everywhere is characterized by low-grade regional metamorphism. At the lowest grade, weathering of ankerite to limonite imparts a typical speckly rusty-weathering character to metasiltstone beds. At slightly higher grade where ankerite is absent in the metasiltstone the rock lacks the rusty-weathering appearance. The lower contact is not exposed in the Kittery 1:100,000 map sheet, but to the north, in the Portland, Maine, area, rocks of Eliot affinity (previously the Macworth Formation of Katz, 1917) are conformably interlayered with the Jewell Formation, the uppermost unit of the Ordovician Casco Bay Group (Hussey and others, 2010). The contact with the overlying Kittery Formation is inferred to be conformable. The contact with Berwick Formation was inferred as a fault by Meyers (1940) and is mapped as a fault, the Calef fault in New Hampshire (Loveless and Schulz, 2002; Escamilla-Casas, 2003) and the Nonesuch River fault in Maine (Hussey, 1988).

Kittery Formation

The Kittery Formation (**Sk**) is a variably thin- to thick-bedded sequence of fine-grained calcareous and feldspathic metawacke and lesser dark gray to brownish gray metashale. Individual beds are typically graded (Figure 9), occasionally with granule grains at the base (Figure 10). It should be noted that in the Kittery Formation, graded bedding is indicated more by color gradations than by actual grain-size variation in the metamorphic rock. In a graded couplet the lighter part represents the silty or sandy sediment in the lower part of the couplet, and this grades upward into the darker pelitic top. These rocks were deposited in a continental rise environment by turbidity currents, forming a complex of shifting submarine fan lobes (Rickerich, 1983). Rickerich suggests that the thicker-bedded parts of the formation (Figure 11) represent fan channel deposits, and thinner-bedded sequences (Figure 12) formed in distal areas of a lobe.

Figure 9. Graded beds of the Kittery Formation (**Sk**) at low metamorphic grade. The coarser silty buff-gray weathering base of a couplet grades upward (toward the knife) into the darker gray metashale with an abrupt change at its top to the next couplet. This set of beds is younger toward the knife. *Wells Beach, Maine.*

Figure 10. Coarse sand grains at the base of one of the thicker graded beds in the Kittery Formation (**Sk**). The sand grains gradually become finer toward the bottom of the photo, indicating the direction of younging. *Marginal Way, Ogunquit, Maine (Figure 1).*

Analysis of the orientation of small-scale cross-lamination of climbing ripples (Figure 13) indicates a direction of sedimentary transport from southeast to northwest (Rickerich, 1983; Hussey and others, 1984). Asymmetric flute casts at the base of a bed in the Kittery Formation in Wells (Figure 14), when retrodeformed, indicate the same (Hussey, 2013). Other primary sedimentary structures include flame structures, load casts, rip-ups (Figure 15), channel cut and fill (Figure 16), and calcareous concretions (Figure 17). Those primary sedimentary structures that portray a younging sense are invaluable tools in working out sequence of deposition and recognition of multiple folding as described in the section on structural geology.

The contact between the Kittery Formation and the Eliot Formation is interpreted to be conformable as noted above. The Kittery Formation is bounded to the southeast by the Portsmouth Fault, which separates it from the Rye Complex.

Figure 11. Thick-bedded Kittery Formation (**Sk**). These beds are mostly feldspathic metawacke with thin intervals of dark phyllite between them. No sense of topping direction is evident at this locality. *Near Perkins Cove, Ogunquit, Maine (Figure 1).*

Figure 12. Thin-bedded Kittery metaturbidites interpreted by Rickerich (1983) to be deposited in distal parts of submarine fan lobes. The thin alternations of light and dark brownish gray material are thin, graded metaturbidite beds, each representing a separate flow. The light greenish gray beds between may represent accumulation of calcareous mud between flow intervals. *1 km north of Bald Head Cliff, York, Maine (Figure 1).*

Figure 13. Cross-laminations of current ripples in the Kittery Formation. The current flow direction was determined at several sites by analysis of ripples such as this (Rickerich, 1983). *Adams Point, Durham, New Hampshire (Figure 1).*

Figure 14. Asymmetric flute casts on the base of a bed of medium bedded Kittery Formation. When this bed is unplunged and unfolded the asymmetry of the flute casts indicates a direction of transport generally from southeast to northwest. *Moody Point, Wells, Maine (Figure 1).*

Figure 15. Flame structures, load casts and rip-ups in the Kittery Formation. *Fort McClary, Kittery, Maine.*

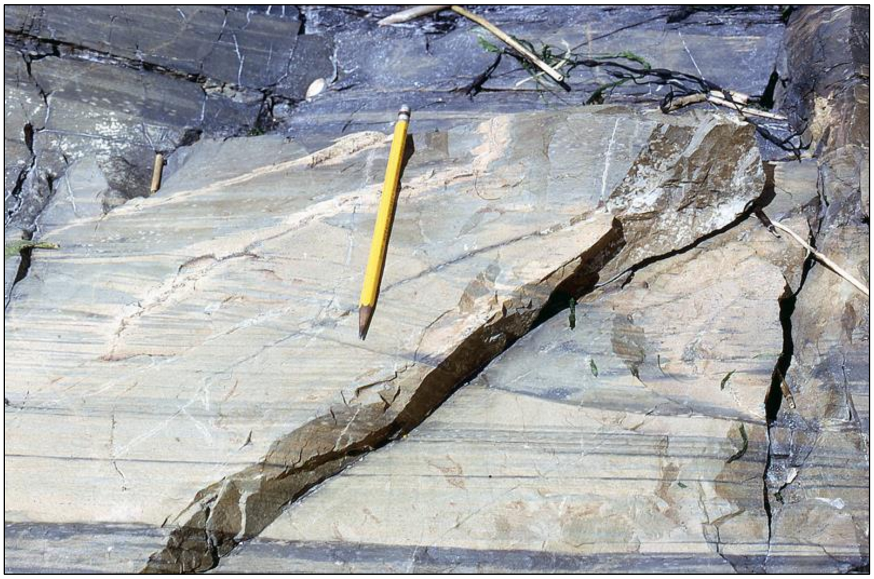

Figure 16. Small-scale channel-cut-and-fill structure in the Kittery Formation. Younging direction is toward the top of the photo. *York Shores, Maine.*

Figure 17. Calcareous concretion in a thick metasandstone bed in the Kittery Formation. The weathering out of calcite in these concretions is the cause of the indentations in the outcrop surface. *Marginal Way, Ogunquit, Maine*.

Berwick Formation

The Berwick Formation (**DSb**) is an interbedded sequence of originally dirty calcareous and non-calcareous feldspathic metawackes with minor biotite-rich schist (metashale). Metamorphic grade varies from greenschist facies to epidote-amphibolite facies. The most common lithology is medium brownish gray quartz-plagioclase-biotite granofels and schist with scattered interbeds of green calc-silicate granofels (Figure 18). Mineralogically, the Berwick Formation is very similar to the Kittery Formation. However it is generally more evenly bedded, and primary sedimentary structures are uncommon. Aluminum-rich pelitic schist in the Berwick Formation is

rare in the area of the Kittery map sheet, although just to the south, the formation includes the Gove Member (Freedman, 1950; Allard and others, 2009), a muscovite-biotite-garnet-staurolite±sillimanite schist, with minor quartz schist. Because of the lithologic similarity with the Kittery Formation, the Berwick Formation was originally included with the Merrimack Group (Billings, 1956). The Berwick Formation is also very similar lithologically to parts of the Vassalboro Group of the Central Maine Basin (Marvinney and others, 2010). No field data exists to suggest it is conformable with the Kittery Formation. In the Kittery map sheet, the Berwick Formation is in contact with the Eliot Formation along a fault known as the Calef fault in New Hampshire and the Nonesuch River fault in Maine.

Figure 18. Berwick Formation (**DSb**) at type location, Salmon Falls River, South Berwick, Maine. A sample from this site was analyzed for detrital zircon geochronology reported by Wintsch and others (2007).

Rye Complex

The Rye Complex (**OЄr**) is an enigmatic package of highly tectonized pelitic and nonpelitic schists and gneisses at andalusite-staurolite grade to sillimanite grade of metamorphism. Protoliths include aluminous shale, calcareous siltstone, feldspathic and argillaceous sandstone, minor limestone, carbonaceous shale, limey mudstone, and mafic volcanic rock. The package is, in part, highly migmatized and variably mylonitized and/or blastomylonitized throughout. The Rye Complex is separated from the Kittery Formation by the Portsmouth Fault.

Exposures of the Rye Complex dominate the 25-km-long New Hampshire coastline. It forms all of the rocky headlands north of Hampton Beach, many of the islands of New Castle and Portsmouth harbors in New Hampshire (Carrigan, 1984a), most of Gerrish Island in Kittery, Maine (Hussey, 1980), the Isles of Shoals (Fowler-Billings, 1959; Blomshield, 1975), Boon Island (Bothner, unpublished notes, 1983), and the sea bottom in between (Brooks, 1986) (Figure 1). The Isles of Shoals and Boon Island are dominated by strongly foliated gray granitic gneisses, often with aligned enclaves of pelitic schist, amphibolite, and minor calc-silicate granofels, some through-going coarse-grained blastomylonitic quartzo-feldspathic gneiss, and,

on Appledore Island, weakly foliated diorite with a U-Pb zircon age of 361.1 ±0.4 Ma (Dorais and others, 2014). Strong dextral shear fabrics are developed at scales ranging from thin section to outcrop and include boudinage, asymmetric folds, and mega "sigma"clasts. Figures 19a–19d show typical lithologies and structural features of the Rye Complex.

Figure 19a. Faulted ultramylonite in the Fort Foster Brittle Zone at Fort Foster, Gerrish Island, Kittery, Maine (Figure 1).

Figure 19b. Metadiorite, intrusive into the Rye Complex (**O€r**). *Appledore Island, Isles of Shoals, Maine (Figure 1).*

Figure 19c. Deformed gray granite and metadiorite, intrusive into the Rye Complex. *Appledore Island, Isles of Shoals, Maine.*

Figure 19d. Mylonitic quartzo-feldspathic migmatite of the Rye Complex, cut by Mesozoic basalt dike. *Gerrish Island, Kittery, Maine.*

Early attempts to date the Rye were fraught with difficulty because of excess radiogenic argon or remobilization in the Rb-Sr system, but did point to a pre-Silurian high-grade metamorphic event (West, 1993) and one or more Ordovician(?) magmatic event(s) (Gaudette and others, 1984). One quartzo-feldspathic blastomylonite sampled during this study, however, has yielded a suite of zircons, probably detrital, the youngest of which is 451.1 ±0.7 Ma (grain z10, Figure 20; Table 3). That result spurred Kane and others (2014) to examine detrital zircons

from two layered and strongly mylonitized quartz-rich rocks within the metasedimentary package. A micaceous quartzite yielded a broad spectrum of LA-ICP-MS ages that hint at either Avalonian or Ganderian basement sources and a youngest detrital zircon age of 529.7 ±8.8 Ma, with an average of the three youngest grains at ca. 539 Ma. This provides an Early Cambrian or younger age for the Rye. Zircons from a mylonitized quartzo-feldspathic layer plotted as a single peak at 482 Ma that is interpreted as the crystallization age of a strongly deformed early Ordovician intrusive. Stoesz and others (2013) report a $^{40}Ar/^{39}Ar$ age of ~475 Ma for hornblende from interlayered amphibolite that indicates an Ordovician or older age for the Rye. So the sedimentary protolith for the Rye is Cambrian to very earliest Ordovician.

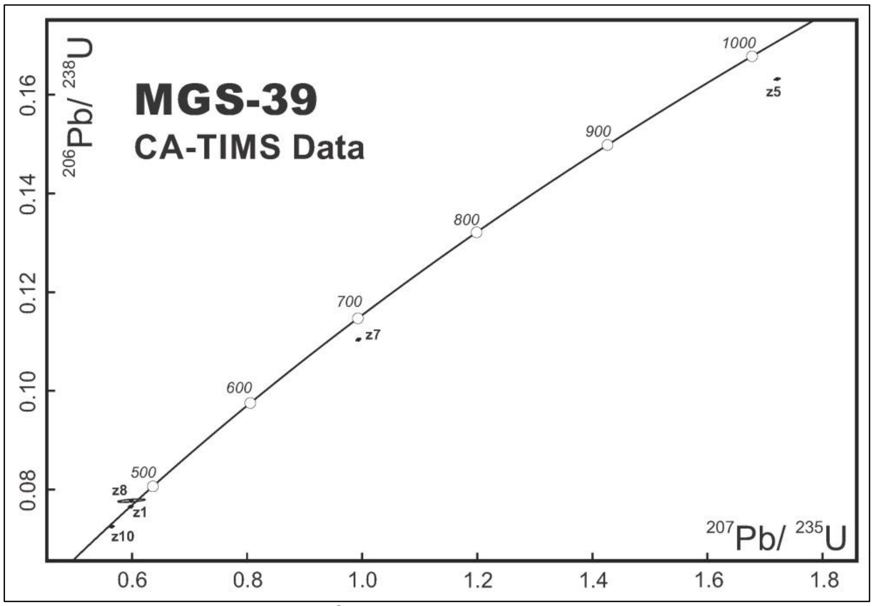

Figure 20. Concordia diagram[2] for blastomylonitic quartzofeldspathic gneiss of the Rye Formation (**O€r**). Analyses of individual zircon grains are labeled. Grain z10 is the youngest grain, probably detrital.

The metasedimentary and early igneous components of the Rye are cut, usually with very low-angle (transposed) intrusive contacts, by variably foliated light gray-weathering two-mica granite (403 Ma Breakfast Hill granite) and medium-grained dark gray-weathering diorite (380 Ma Salamander Point diorite), both now recognized to be of Devonian age (this report). The time of deformation is further constrained by new $^{40}Ar/^{39}Ar$ ages from a deformed pegmatite indicating cooling of deformed coarse muscovite at ~ 340 Ma, growth of new, fine-grained muscovite during mylonitization at ~ 240 Ma, and cooling of K-feldspar through 250°C at ~280 Ma and through 150°C at ~190 Ma (Stoesz and others, 2013). Two high-strain zones characterized by thinly laminated ultramylonites, often with pseudotachylyte parallel to slip surfaces and injected into "tear" fractures define the Portsmouth fault and the Great Common fault zones in New Hampshire (Carrigan, 1984a; 1984b) and the Fort Foster brittle zone of Swanson (1988) in southern Maine. Details of the history of deformation for the Rye are discussed more fully below.

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[2] For all analyses presented in concordia diagrams, see Appendix 1 for sample descriptions, and Appendix 2 for analytical data and explanation of concordia diagrams used in this report.

III. INTRUSIVE ROCKS OF MESOZOIC AGE

Mesozoic magmatic activity is very well represented by five major intrusive complexes, several explosion breccias and numerous dikes onshore; an additional central complex has been identified a short distance offshore. All of these relate to the breakup of Pangaea and the progressive evolution of the Atlantic Ocean. They are associated with the White Mountain Plutonic-Volcanic Series in central northern New England, which provides an intermediate link geographically between the Monteregian Hills in Quebec, Canada, and the New England Seamount chain off the coast and beyond the Gulf of Maine (Thompson and others, 1993). Many plutons in the White Mountain Series, including those in the Kittery map area, represent the internal plumbing systems of deeply eroded alkalic volcanic complexes like those seen in today's continental rift systems. Some preserve surface volcanic members in down-dropped blocks associated with cauldron subsidence as well as other characteristic features of emplacement at high crustal levels including ring dikes, cone sheets, intrusive breccias, partial fusion of country rock, and high-temperature contact metamorphism as described below. Map patterns and geophysical models of the three-dimensional configuration of these complexes have provided a means to compare them to late Paleozoic central complexes from the Oslo Graben, Norway, to Tertiary complexes of western Scotland and San Juan Mountains of southwestern Colorado, to Quaternary Valles and Yellowstone volcanic complexes, and even to modern plutonic/volcanic systems of the East African Rift system.

The intrusive and extrusive rocks of the White Mountain Series have attracted geophysical interest for many decades because of the common gravity and aeromagnetic anomalies they produce (Figure 21). Geophysical models are used for estimating body shape and thickness, testing magmatic emplacement hypotheses and evaluating geothermal potential of higher than normal radioactivity associated with abundant granites (e.g., Joyner, 1963; Bothner and Harrower, 1973; Sharp, 1976; Weston Geophysical Research, Inc., 1977; Osberg and others, 1978; Benson and Van Baalen, 2010). All or most bodies are steep, sub-vertical cylindrical to funnel-shaped (conical) intrusions that extend many kilometers into the subsurface.

Cretaceous Plutons

Three relatively small (up to 4 km in maximum dimension on the map) oval ring complexes of predominantly mafic to intermediate composition are present within the Kittery 1:100,000 map sheet. These are the Alfred Complex, the Cape Neddick Complex, and the Tatnic Complex. In addition, three minor gabbro bodies of limited dimension are shown on the Kittery map sheet: the Lebanon gabbro-diorite, the Jacks Cove Gabbro in Ogunquit, and an unnamed body in the outcrop belt of the pink biotite granite of the Webhannet pluton.

Alfred Complex

The Alfred Complex (Figure 22) intrudes the Rindgemere Formation and consists of three principal phases (Hussey, 1962). The oldest phase forms a truncated funnel intrusion composed of gabbronorite (**Kagn**). A well-developed igneous lamination, marked by aligned plagioclase laths, parallels the inferred walls of the funnel. The lamination is weakest close to the contact with the Rindgemere Formation and becomes both more prominent and slightly gentler toward the center of the funnel. The gabbronorite is brownish gray on fresh surfaces and varies from medium- to fine-grained. Its texture is hypidiomorphic-granular. The gabbronorite is composed

of compositionally zoned plagioclase, augite, and hypersthene, with variable but generally minor amounts of hornblende, biotite, idiomorphic apatite, and opaque minerals. Quartz occurs in minor amounts interstitially between plagioclase and the other major phases. Biotite in the non-laminated marginal parts of the gabbronorite is greenish, while in the central laminated part of the funnel it is brownish. In the marginal parts of the gabbronorite zoned plagioclase shows a higher range of marginal sodium enrichment than in the central part of the funnel. These spatial variations may be due to interaction of the magma and wall rock, or they may be the result of a special type of filter pressing, that is, greater compaction of the crystal mush in the central, thicker, parts of the funnel, leading to development of the inward-dipping igneous lamination. Lower temperature and more sodic and iron rich fluids would have migrated upward along the lamination and toward the margin resulting in these alterations.

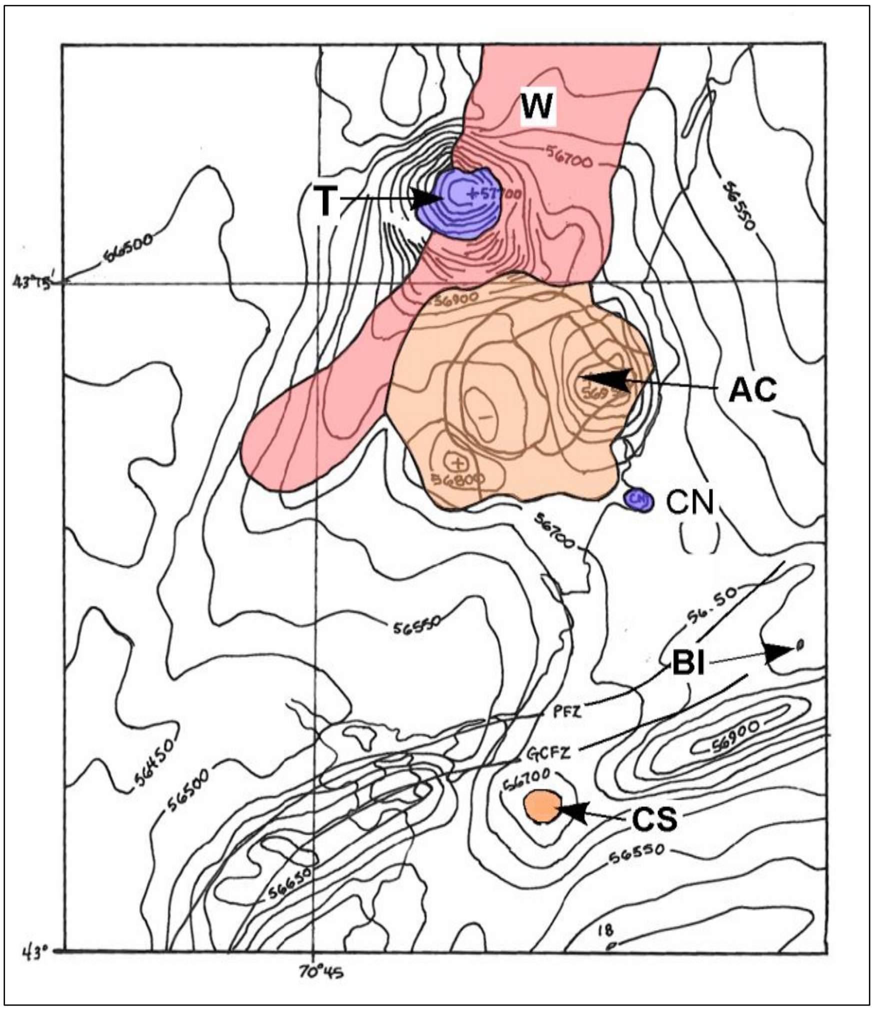

Figure 21. Aeromagnetic map (from Boston Edison, 1976) of a portion of the Kittery 1:100,000 map sheet showing magnetic anomalies associated with the Tatnic complex (T), Agamenticus Complex (AC), and Chase Stock (CS). Note that the Cape Neddick complex (CN) has no magnetic signature. BI: Boon Island; GCFZ: Great Common fault zone; PFZ: Portsmouth fault zone; W: Webhannet pluton. Contour interval 50 gammas.

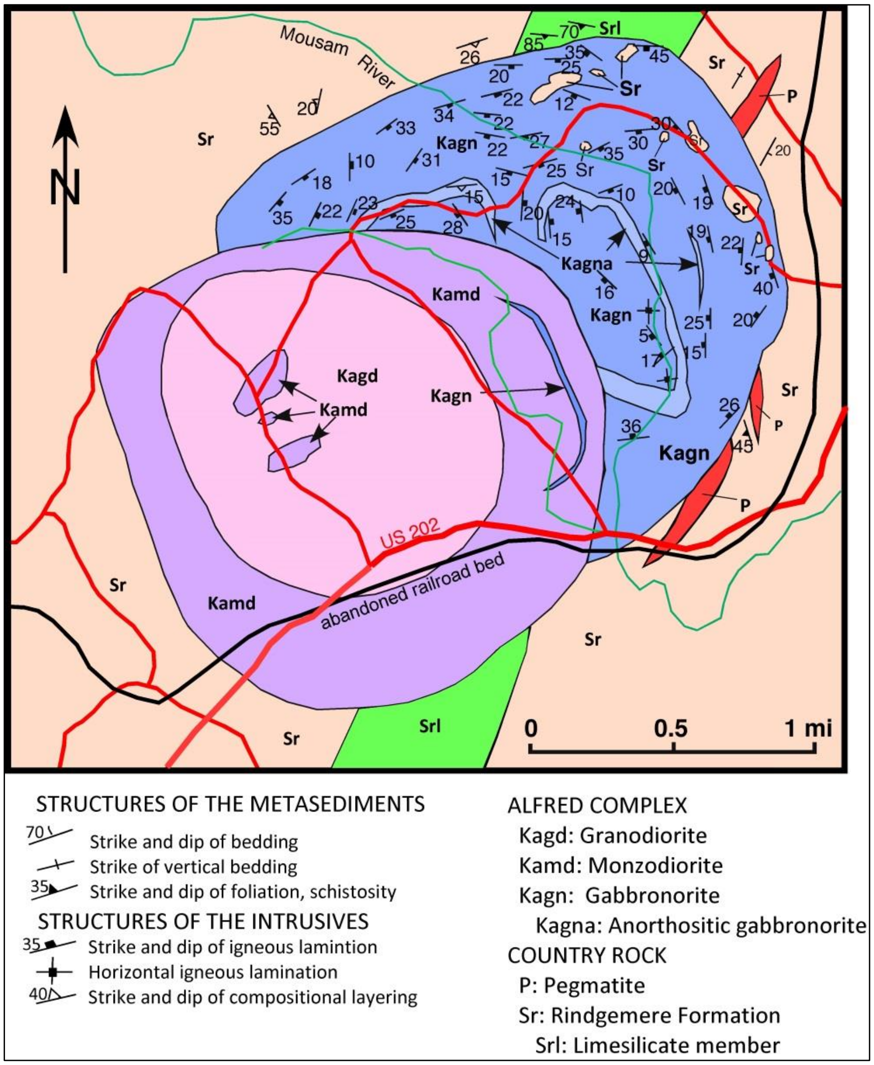

Figure 22. Geologic map of the Alfred Complex, Alfred, Maine (after Hussey, 1962). Letter symbols identifying map units correspond with those used on the Kittery 1:100,000 map sheet (Hussey and others, 2016).

A ring structure of monzodiorite (**Kamd**) and a central stock of porphyritic granodiorite (**Kagd**) complete the Alfred Complex (Hussey, 1962). The monzodiorite is light gray to buff gray in color with a medium-grained hypidiomorphic-granular texture. Well-digested inclusions of unidentifiable rock types are common. The monzodiorite is composed of plagioclase (andesine to labradorite), biotite, hornblende, interstitial quartz and alkali feldspar with minor apatite, augite, hypersthene, and zircon. The porphyritic granodiorite, which is medium gray and fine- to medium-grained, forms a central stock within the monzodiorite. It is composed of plagioclase, quartz, alkali feldspar, biotite and hornblende. Phenocrysts are composed of intermediate plagioclase and range up to 8 mm in size. The reader is referred to Hussey (1962) for additional details and discussion.

Sharp (1976) calculates from gravity data that the gabbronorite is a funnel-shaped body extending to a depth of 4.5 km. A gabbronorite of the Alfred Complex yielded a K-Ar age of 123 ± 2 Ma (reported as 120 ±2 Ma by Foland and Faul, 1977; corrected here according to Dalrymple, 1979). The granodiorite and monzodiorite of the complex were not dated.

Tatnic Complex

The Tatnic Complex, a roughly circular complex approximately 3.5 km in diameter straddling the towns of Wells and South Berwick, intrudes the Webhannet pluton and the Kittery Formation (Figure 23). It consists of two separate plutons. The older one, an inferred funnel intrusion along the northern and eastern portion of the complex, is composed of dark brownish gray fine- to medium-grained gabbronorite (**Ktgn**) that grades inwards and upwards into medium- to coarse-grained anorthositic gabbronorite (**Kta**). The gabbronorite and anorthositic gabbronorite are composed of plagioclase, augite, hypersthene, hornblende, magnetite and biotite. Minor olivine was originally present but has been altered to serpentine. Pronounced inward-dipping igneous lamination caused by parallelism of plagioclase laths emphasizes the inferred funnel shape of this pluton. Compositional layering is generally rare. In the eastern edge a separate unit (**Ktpg**) is distinguished by distinct poikilitic hornblende grains up to 5 cm in length (Figure 24). These poikilocrysts are elongated parallel to the lamination of the enclosing gabbronorite. Xenoliths are virtually absent from the gabbronorite and anorthositic gabbronorite. This older funnel extends to a depth of 4 km based on gravity modeling (Sharp, 1976). The gabbronorite of the Tatnic Complex has a K-Ar age of 125 ± 2 Ma (reported as 122 ±2 Ma by Foland and Faul, 1977; corrected here according to Dalrymple, 1979).

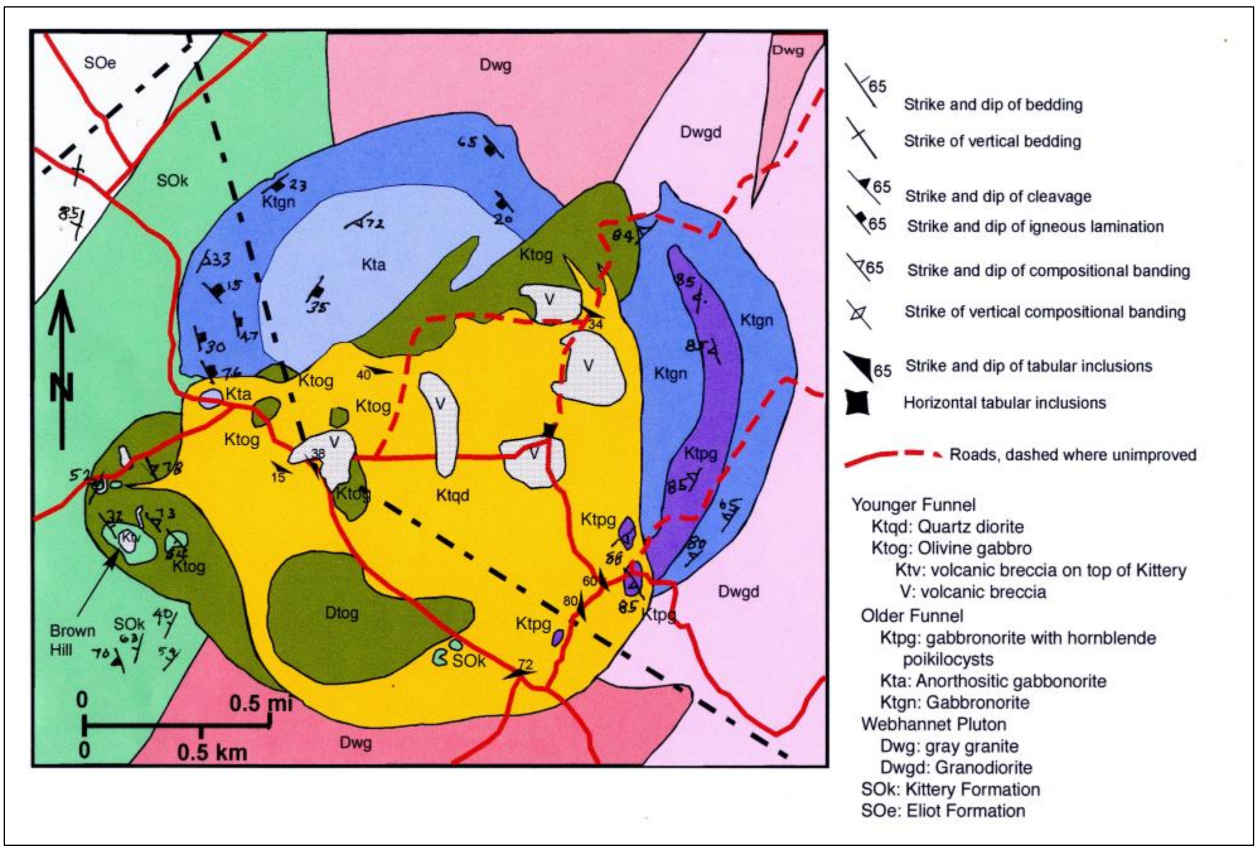

Figure 23. Geologic map of the Tatnic Complex, Wells and South Berwick, Maine (after Hussey, 1962). Letter symbols identifying map units correspond with those used on the Kittery 1:100,000 map sheet (Hussey and others, 2016).

The younger pluton consists of dark gray to black olivine gabbro (**Ktog**) and younger light gray to brownish gray quartz diorite (**Ktqd**) and associated variants (Hussey, 1962; Nealon, 1999) with abundant well digested xenoliths of the Kittery Formation and granite inclusions and

possibly some autoliths of chilled margins. These two phases probably formed a compositionally zoned magma chamber with gabbro magma below and quartz diorite above. The quartz diorite was likely produced by contamination of the gabbro magma through assimilation of xenoliths and partial melting of the roof of the chamber. After at least partial consolidation of the gabbro magma, fracturing of the solidified part of the chamber allowed intrusion of the quartz diorite magma into the gabbro.

Figure 24. Poikilitic hornblende gabbronorite phase (**Ktpg**) of the older funnel of the Tatnic Complex. The layering is accentuated by the development of elongate masses of hornblende after augite.

In addition to the abundant small xenoliths that characterize the quartz diorite, several large blocks of various rock types are present only within the limits of the younger pluton. These blocks include the Kittery Formation, anorthositic gabbronorite from the older pluton, volcanic breccia, and dark aphanitic and aphanitic-porphyritic material that may represent surface basalt flows, and perhaps chilled phases of the olivine gabbro. The most interesting of the volcanic breccia blocks (**Ktv**) is to be seen at the top of Brown Hill (Figure 23). Here, volcanic breccia consisting of light and dark gray aphanites appears to sit on the surface of a large block of the Kittery Formation stoped from the roof of the magma chamber. This breccia consists of light and dark aphanitic volcanic rocks, anorthositic gabbronorite, gabbronorite, and porphyritic basalt (possibly from chilled margins of the older intrusive sequence). The presence of gabbronorite and anorthositic gabbronorite clearly establishes that this explosive volcanic activity occurred later than the older funnel intrusion but prior to the younger funnel.

Cape Neddick Complex

Although the smallest of the three gabbro complexes, the one at Cape Neddick is the best exposed, best preserves original layering structures, and is the most extensively studied. The complex consists of two distinct intrusive gabbro funnels (Figure 25) and a marginal breccia that predates the gabbro intrusions (Figure 26). The older intrusion was injected into the Kittery Formation as a steep-sided, inwardly dipping funnel of gabbro (**Kcg**) that grades into a central plagioclase-enriched anorthositic gabbro (**Kca**) (or leucogabbro in terminology of LeMaitre, 2004). This older funnel is composed of labradorite, augite, hornblende, biotite and magnetite

with minor serpentine (probably after original olivine), chlorite, apatite, and quartz. Orthopyroxene has not been observed. The plagioclase shows little compositional change from the marginal gabbro to the central anorthositic gabbro.

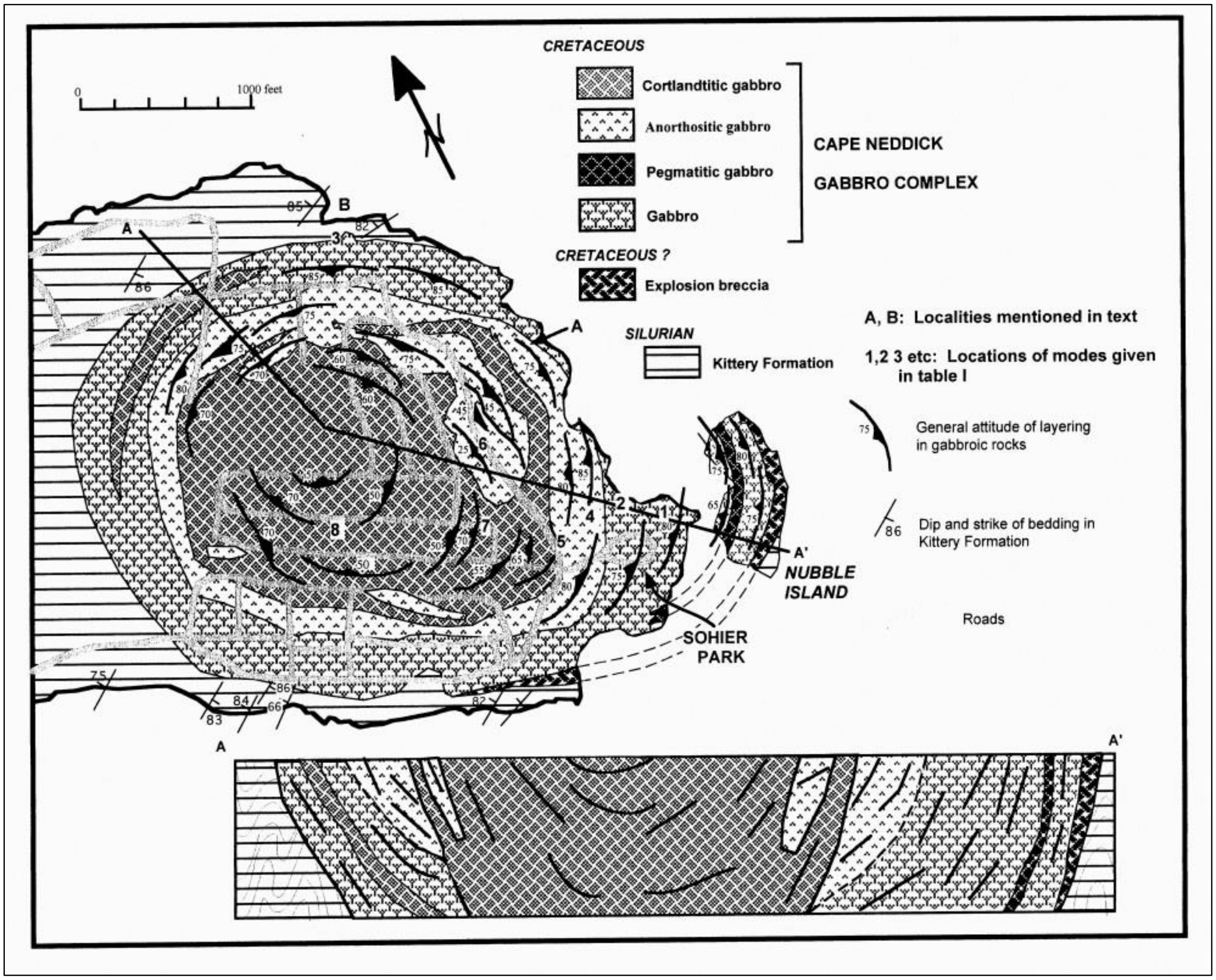

Figure 25. Geologic map and cross section of the Cape Neddick Complex, York, Maine (from Hussey, 2015).

The younger intrusive phase of the complex consists of dark gray cortlandtitic gabbro (**Kcc**) (hornblende-rich melagabbro of LeMaitre, 2004). This was injected as a central funnel and as irregular cone sheets into the older intrusion. The cortlandtitic gabbro is composed of plagioclase (labradorite), poikilitic megacrysts of hornblende up to 5 cm, augite, biotite, magnetite, and olivine. Mineral proportions vary from a marginal zone with 19% plagioclase and 76% hornblende, augite, olivine, and biotite combined (close to a true cortlandtite[3]), to a central zone with 59% plagioclase, and 38% combined ferromagnesian minerals (typical gabbro). Throughout the body, however, it is characterized by hornblende poikilocrysts, and fresh to partially serpentinized olivine grains that are readily visible in hand specimen. Similar dark cortlandtitic gabbro forms cone sheets up to 20 meters in width within both the gabbro and anorthositic gabbro of the older funnel (Figure 27).

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[3] Cortlandtite is an ultramafic rock, a variety of pyroxene-olivine hornblendeite composed of large crystals of poikilitic hornblende enclosing olivine, orthopyroxene and augite (LeMaitre, 2004).

Figure 26. Explosion breccia of Cape Neddick Complex. This oval body was mostly removed by intrusion of the older gabbro funnel. Light fragments may represent surface volcanic rocks. The darker blocks may be fragments of basalt dikes that intrude the Kittery Formation, and possibly surface basalt flows.

Figure 27. Contact of dark cortlandtitic gabbro with anorthositic gabbro. Anorthositic gabbro represents upper part of the older intrusive funnel. Cortlandtitic gabbro is a cone sheet related to the younger intrusive funnel. Location is about 500 feet southeast of locality 6 on Figure 25.

Layering, which is typical of many gabbro bodies, is spectacularly developed in the gabbro and anorthositic gabbro of the older funnel. In general, layering dips steeply toward the center of the complex. Four types of layering have been described by Hussey (1962, 1965). The most common is non-graded layering marked by 2-5 cm wide bands of plagioclase-enriched gabbro separated by gabbro or anorthositic gabbro of the host phase. The feldspathic bands may occur separately with no regular spacing, or they may be very rhythmic (Figure 28) resembling the inch-scale layering described by Hess (1960) for the Stillwater Complex in Montana. The second type of layering, relatively rare, is rhythmic graded layering. Individual layers range in thickness from 3 to 10 cm and are characterized by slight enrichment of mafic minerals on the

side of the layer away from the center of the intrusion. This graded layering is only always seen in the outer gabbro. The third type of layering, seen mostly in the innermost part of the anorthositic gabbro and throughout the cortlandtitic gabbro, consists of diffuse, thin, non-persistent wispy concentrations of either plagioclase or dark minerals. This type of layering is sporadic and non-rhythmic. The fourth and most intriguing type is what is informally referred to as horsetail layering (Hussey, 2002), illustrated in Figures 29 and 30. Skaergaard investigators would probably have called this "cross-bedded layering" (Wager and Deer, 1939; Wager and Brown, 1967). Three observations argue against relating this to sedimentation from a convecting magma: 1) the layers are steep; 2) instead of indicating younger layers toward the center of the magma chamber their "cross-bedding" sense would indicate they are "topping" toward the margin of the complex which would have been already solidified; and 3) the nature of the truncations resembles more the geometry of horsetail veins familiar to ore-deposit specialists than to cross-bedded structures of sedimentary rocks (note particularly Figure 30).

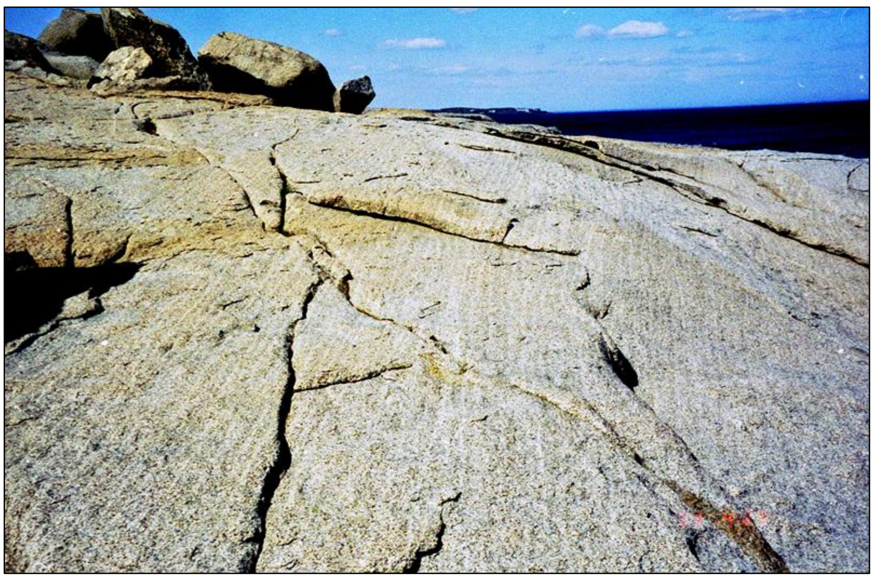

Figure 28. Rhythmic layering in the anorthositic gabbro of the older intrusion, Cape Neddick Complex. The layering in the form of very felsic bands and regular anorthositic bands is very similar to "inch-scale layering" in the Stillwater Complex, Montana, described by Hess (1960).

The area of locality A on the detailed geologic map of the complex (Figure 25) warrants further discussion. This is a zone of thin slabs of gabbro characterized by the strongest horsetail layering, and occurs between gabbro and very leucocratic anorthositic gabbro. A considerable portion of the transition between the two, which is present at Sohier Park appears to be missing. Elongate concentric slabs of gabbro 1 to 5 meters thick occupy this gap (Figure 29). The margins of these slabs have large branching grains of augite that project inwardly toward the center of the complex in a harrisitic texture, indicating nucleation on solid gabbro and growth into the liquid magma (Figure 31). Within these slabs, horsetail layers bifurcate away from each other in the direction of the outer wall of the pluton. This zone of slabs and the abrupt transition from gabbro to very feldspathic anorthositic gabbro is interpreted to represent an area in which much of the partially solidified transition gabbro broke away and slid into lower levels of the still liquid center of the older funnel.

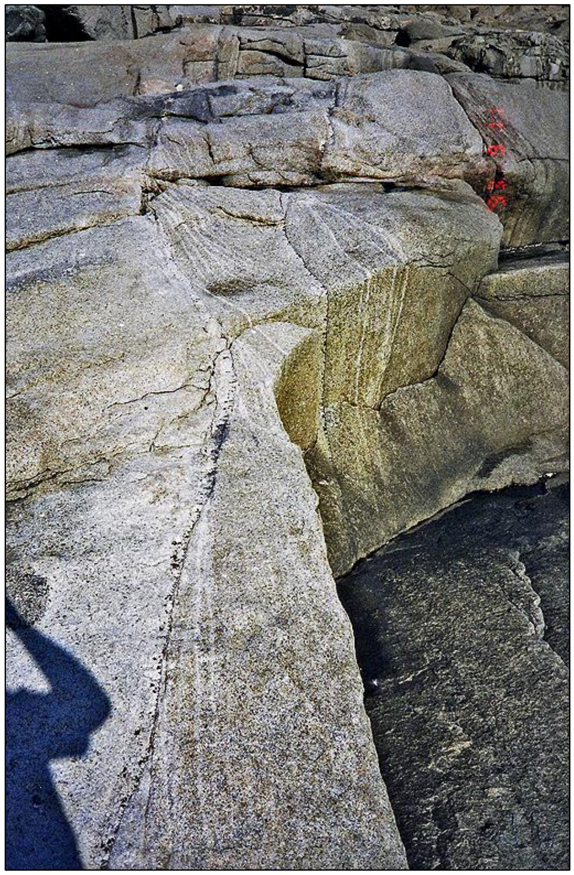

Figure 29. Thin slab of intermediate gabbro/anorthositic gabbro showing horsetail type layering, Cape Neddick Complex.

Figure 30. Detail of the horsetail layering in the slab pictured in Figure 29. Because the outer margin of this funnel is to the right, these bifurcating layers cannot have formed as cross beds deposited by a convecting magma as described by Wager and Deer (1939) in the Skaergaard Complex of East Greenland. The area to the right must have already crystallized.

Figure 31. Details of harrisitic augites on one side of the slab shown in Figure 29. Not evident in this photo is that the plagioclase of the groundmass gabbro surrounding the augites is finer grained at the contact and gets coarser inward toward the center of the funnel.

An explanation for the origin of the rhythmic and non-rhythmic layering must be compatible with the fact that the layers are steep near the margin, essentially parallel to the contact of the funnel with the Kittery wall rock. The steep orientation argues against crystal settling from an episodically convecting magma as has commonly been proposed for other layered gabbros, such as the Skaergaard Complex of East Greenland (Wager and Deer, 1939), and Stillwater Complex of Montana (Hess, 1960). Dakin (1968) proposed that differentiation of layers in the Cape Neddick gabbro is a result of lack of balance between the rate of ionic diffusion and rate of fall of temperature. Both graded and non-graded layering could be determined by this process, the graded layering being a result of a fluctuating, rather than steady, temperature gradient. McBirney and Noyes (1979) suggest that rhythmic layering involves *in situ* processes of nucleation and crystal growth at the interface between magma and previously crystallized mush. Alternation between mafic-rich and plagioclase-rich crystallization is governed by a complex interplay between rates of component depletion and replenishment by diffusion and convection in the magma. Taubeneck and Poldervaart (1960) proposed a similar mechanism for steep wall-parallel layering in the Willow Lake intrusion in Oregon. Cryptic layering within both the older and younger funnels is manifest in the gradual enrichment in plagioclase relative to mafic minerals – in the older funnel from normal gabbro to anorthositic gabbro, and in the younger funnel from cortlandtitic gabbro to normal gabbro (see modes in Table 1). This may be due to the early depletion of both magmas in mafic components relative to feldspathic components. The mechanism for the formation of the horsetail layering is enigmatic and awaits further study.

The latest magmatic activity in the Cape Neddick Complex was the formation of a system of small-scale dikes (Gaudette and Sakrison, 1959; Gaudette and Chapman, 1964). The dikes seldom exceed 5 cm in width, and commonly occur as multiple dike sets of basaltic to fine-grained quartz diorite composition, forming a radial pattern relative to the contacts of the older funnel with the Kittery Formation. Gaudette and Chapman (1964) indicate that they are almost exclusively found in the normal gabbro and anorthositic gabbro. They relate this activity to a

sudden doming action in the solid complex after the intrusion of the younger funnel of cortlandtitic gabbro.

Table 1. Mineral contents of some rock types of the Cape Neddick Complex. Modes in volume percent, based on 1000 points counted per specimen (after Hussey, 1965). Numbered localities are shown in Figure 25.

	Normal Gabbro			Anorthositic Gabbro			Cortlandtitic Gabbro	
	1	2	3	4	5	6	7	8
Plagioclase	65.5	70.0	20.9	71.1	83.2	85.3	19.3	58.6
K-feldspar			6.9			0.8		
Clinopyroxene	7.4	8.3	29.2	9.8	5.5	2.2	28.4	7.8
Orthopyroxene			0.9			0.5	tr	
Olivine			24.9	0.6			6.3	0.5
Hornblende	10.2	2.4	2.8	8.5	1.8	1.2	29.8	12.2
Biotite	2.6	5.3	5.9	2.3	1.2	2.3	3.2	3.0
Opaque	7.3	4.8	5.5	3.2	4.9	1.5	11.6	6.7
Apatite	tr	0.6	1.2	tr	0.8	0.6	0.5	tr
Serpentine	0.5	tr	tr	1.2	tr	tr	0.6	2.7
Calcite	1.3	1.9		1.4	tr	2.1	tr	3.5
Quartz	tr	0.6	1.0	tr	0.5	0.6		
Zircon						1.4		
Fibrous Amphibole	3.7	4.8	tr	0.5	0.6	1.2	tr	2.2
Chlorite	1.2	0.9	tr	1.2	1.0	tr	tr	2.6
Total	99.7	99.6	99.2	99.8	99.5	99.7	99.7	99.8

Locations on Cape Neddick map (Figure 25)
1. Near 1
2. Near 2
3. Olivine-rich pocket near 3
4. At 4
5. 200 feet west of 4
6. At edge of road 600 feet NNW of 4
7. At 7
8. At 8

The contact of the gabbro of the older funnel (**Kcg**) with the Kittery Formation (**Sk**) is well exposed along the northern shore of Cape Neddick (Locality B, Figure 25). An excellent study by Mershon (1994) details wall rock structures and mineral composition at this locality. Close to the contact, the rocks of the Kittery Formation have been metamorphosed to sanidinite and pyroxene hornfels facies. Beds of biotite phyllite have been transformed into a contact aureole with abundant blue cordierite, clinopyroxene, and spinel within 20 meters of the contact. The feldspathic quartzwacke beds have the mineral sanidine and show effects of partial melting. Most of the diabase dikes that intrude the Kittery Formation (see below) are not coeval with the gabbros of the Cape Neddick Complex, but are cut by the gabbro of the older funnel and were recrystallized (contact metamorphosed) to a more granoblastic texture while retaining rigid and

brittle characteristics. The biotite phyllite beds remained refractory and rigid whereas the quartzo-feldspathic beds melted or became sufficiently plastic to be injected into joints of the diabase dikes and the fractures of the biotite phyllite beds. These relations present a fascinating picture of the condition that prevailed during the early stages of consolidation of the gabbro: a funnel-shaped marginal shell of hot, yet solid gabbro with a molten interior, sitting in partially molten, plastic country rock with rigid mafic dike and biotite phyllite struts. Figures 32-35 illustrate some of the rheological aspects of this contact zone. Swanson (1992) has noted the presence of a fine network of felsic veinlets in both the Kittery Formation and the pre-complex mafic dikes that cut the Kittery Formation. This, along with the fact that many of the dikes show dilation in this zone of apparent compressional stress is ascribed to post-consolidation explosive activity that may have resulted also in the injection of the radial minor dikes within the older funnel of the complex.

Figure 32. Partially melted quartzo-feldspathic beds of the Kittery drawn into a dilated fracture in a diabase dike. Darker beds, originally biotite phyllite, are brittle and occur as xenoliths in the felsic dike. Cape Neddick Complex contact zone.

The gabbro of the outer, older, funnel has a K-Ar age of 119 ± 2 Ma (reported as 116 ±2 Ma by Foland and Faul, 1977; corrected here according to Dalrymple, 1979). The inner funnel was not dated. Gravity models suggest that the funnel extends to a depth between 2 and 3 km below the present erosion level (Bothner and Harrower, 1973).

Other mafic plutons of possible Cretaceous age

Three other gabbroic bodies shown on the Kittery 1:100,000 map sheet (Hussey and others, 2016) are the Lebanon gabbro-diorite (**Klg**), a gabbro in the northern edge of the pink granite of the Webhannet pluton (**KJd**), and the Jacks Cove Gabbro (**KJg**) just south of Perkins Cove in Ogunquit (Figure 1). The Lebanon gabbro-diorite is a poorly exposed oval pluton 1.3 x 0.7 km in dimension, composed of plagioclase, augite, hornblende, biotite, and magnetite. Most exposures are deeply weathered. It has a hypidiomorphic granular texture; no igneous lamination was observed. This pluton has yielded a K-Ar age of 128 ± 3 Ma (published as 125 ±3 Ma by Foland and Faul, 1977; corrected here according to Dalrymple, 1979)

Figure 33. Cordierite hornfels in the Kittery Formation within 15 meters of the contact with the outer gabbro, Cape Neddick Complex. The aureole paragenesis also includes spinel, pyroxene, and sanidine (in the original quartzo-feldspathic beds).

Figure 34. Broken basalt dike "afloat" in plastic quartzo-feldspathic material of the Kittery Formation near contact with the outer gabbro, Cape Neddick Complex.

Exposures of the gabbro in the pink granite of the Webhannet pluton are also heavily weathered. It is dark brownish gray in color and has a coarse diabasic texture. From the known outcrops it is at least 100 x 250 meters in dimension. In one "rotten rock" pit, coherent, but slightly weathered gabbro is overlain by 3+ meters of very weathered grus which can be dug with a backhoe. The grus still preserves the texture and joint systems of the original gabbro. Nearby exposures of the pink granite are mostly fresh, suggesting the deep weathering may have been developed prior to latest glaciation and is preserved in pockets not scoured out by passage of glacial ice. Alternatively, Evans and Bothner (1993) suggest the deep weathering may be the

result of forced hydrothermal alteration, an explanation proposed by them for similar deep weathering zones of the Conway granite in New Hampshire.

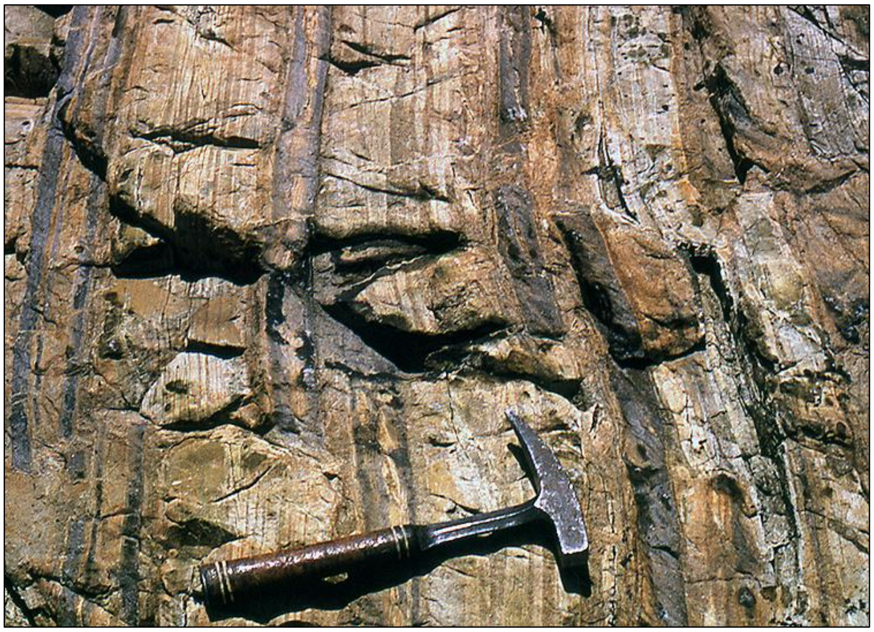

Figure 35. Rigid struts of the contact-metamorphosed biotite phyllite beds in the Kittery hornfels offset and telescoped parallel to each other within the mush of the partially melted quartzo-feldspathic material. Cape Neddick Complex contact zone.

The Jacks Cove Gabbro (**KJg**) is a small body not exceeding 150 meters in maximum dimension (Hussey, 1960, unpublished mapping). Originally thought to be a wide dike, it has not been encountered in any outcrops far removed from the exposures at Jacks Cove, Ogunquit, Maine. It appears to be a small oval pluton possibly related in history to the other circular mafic intrusions. It is a coarse, slightly rusty-weathering, dark gray diabase (Figure 36) composed principally of plagioclase, augite, hornblende, biotite and magnetite. Swirled layering marked by concentrations of plagioclase is present (Figure 37) and well-digested xenoliths of similar, but lighter colored mafic phases, are aligned parallel to the compositional layering.

A suite of dark gray mafic dikes with a predominant north-south strike is present along the shore between Bald Head Cliff in York and Israels Head (Figure 38) in Ogunquit (Figure 1). These dikes are younger than the numerous northeast trending dikes. They may relate to mafic intrusive activity at Cape Neddick 7 km to the south. One of these dikes cuts the Jacks Cove Gabbro.

Cretaceous-Jurassic(?) Explosion Breccias

Three explosion breccias (**KJeb**) are present in coastal exposures from Kittery to Cape Neddick. The most impressive one is located on Gerrish Island, Kittery (Figure 1). It consists of closely packed angular blocks ranging from 1 cm to 1 m in diameter, with essentially no fine-grained inter-block matrix. The blocks are primarily fragments of local lithologies of the Rye Complex including migmatized blastomylonite, calc-silicate rock, and amphibolite. Also included are blocks of diabase and basalt representing an earlier phase of mafic dike intrusion into the Rye Complex, and small blocks of light gray spherulitic felsite possibly representing

surface felsic volcanic rocks and/or dikes which intrude the Rye Complex. The breccia is cut by a second set of diabase dikes (Figure 39) including a major one 30 m wide and trending northwest. A light buff felsite porphyry dike ¼ to 3 m wide that is cut by the younger set of diabase dikes occurs between the breccia and the unbroken Rye Complex. Because they are bracketed by these dikes, we assign a Cretaceous-Jurassic age to the breccias.

Figure 36. Medium-grained reddish-weathering gabbro with inclusion of non-reddish weathering Jacks Cove Gabbro (**KJg**). *Ogunquit, Maine.*

Figure 37. Swirled layering in the Jacks Cove Gabbro (**KJg**). *Ogunquit, Maine.*

The second explosion breccia is poorly exposed along the eastern shore of Gerrish Island ¾ km to the north of the first. It consists of 10 cm to 5 m blocks of the Rye Complex and Kittery Formation. A large block of Kittery suggests proximity at this locality to the Kittery-Rye contact.

Figure 38. Late north-trending composite diabase dike cutting the Kittery Formation at the footbridge, Marginal Way, Ogunquit, Maine. This dike may relate to intrusive activity of the nearby Jacks Cove Gabbro.

Figure 39. Larger of the two explosion breccias (**KJeb**) exposed along the eastern shore of Gerrish Island, Kittery, Maine. The explosion breccia consists of closely packed blocks of the Rye Complex and older basalt dikes. It is cut by a younger basalt dike.

The third explosion breccia occurs along the southwest and south edge of the outer gabbro funnel at Cape Neddick. This is discussed above.

Jurassic-Triassic Dike Swarm

Mafic and felsic dikes are common in exposures of the Kittery Formation and Rye Complex in a 15-km wide, north-northeast-trending coastal belt from south of Rye, New Hampshire, to Biddeford Pool, Maine. Within the Kittery Formation, most dikes are injected parallel, or nearly parallel, to bedding in the host rock but are not properly classified as sills because they are not folded as is the bedding. Within the Rye Formation, particularly well exposed at Kittery Point, dikes were intruded with a north-northeast strike. In this belt, mafic dikes constitute between 15 and 35% of the exposures. Outside this coastal belt mafic dikes are widespread but much less common.

The petrology and structural relations of dikes of the southern coastal area of Maine have been described by Keeley (1914, 1924), Haff (1939), and Swanson (1992). The dikes are composed mostly of basalt or diabase (both equigranular and porphyritic), commonly showing a variety of deuteric alteration effects. A few representative dikes are shown by red lines on the geologic map (Hussey and others, 2016). It is not uncommon that in one dike plagioclase phenocrysts are completely saussuritized, and dark minerals (augite, pigeonite, and olivine) are unaltered whereas in the adjacent dike the reverse is true. Causes of this alteration deserve detailed study. Less common dikes include camptonite and monchiquite (lamprophyres), trachyte, alkaline vitrophyre, andesite, and felsite; some of these may be related to the Agamenticus Complex.

At Cape Neddick, mafic dikes are recrystallized in the contact metamorphic aureole of the Cretaceous Cape Neddick Complex. In the nearby Agamenticus Complex, similar mafic dikes cut the Triassic-age alkalic phases, but have not been observed cutting the central biotite granite stock, suggesting a Triassic age or older for the dikes. Trachyte dikes are occasionally present in proximity to the Agamenticus Complex. These commonly have bluish chilled margins due to the presence of minute needles of the sodic amphibole riebeckite (Brooks, 1990). Interiors of these dikes are buff-colored and aphanitic (Figure 40). Thin bluish trachyte dikes in the York Beach to Ogunquit area show strong flow banding and are interpreted to be apophyses from the alkaline syenite of the Agamenticus Complex. They do not cut across dikes of the mafic swarm.

Inclusions of a variety of rock types are common in basalt, diabase, and camptonite dikes. Among the rock types noted are local country rock, alkalic granite and syenite presumably from the Agamenticus Complex (Figure 41), granite of uncertain affinity, angular fragments of quartz, gabbro, ultramafic rocks, and high grade graphitic, garnetiferous, quartzo-feldspathic gneiss (Figure 42) possibly related to the Rye Formation or unexposed high-grade basement terrane. The two dikes in Figures 41 and 42 were mentioned by Powers (1915) in his studies of the origin of inclusions in dikes. At two localities occurrences of angular quartz fragments in diabase (Figure 43) may be related to sampling of a silicified zone, possibly representing a southern extension of the Cape Elizabeth Fault in the Portland 1:100,000 map sheet (Berry and Hussey, 1998).

Figure 40. Triassic trachyte dike, probably an apophysis from one of the phases of the nearby Agamenticus Complex. The blue color of the chill margin is due to fine needles of riebeckite.

Cross-cutting of mafic dikes in the northeast-trending swarm (Figure 44) indicate up to four episodes of injection. All of these involved rapid intrusion and cooling with no noticeable contact metamorphic effects. Chilled margins are common where one dike crosses another. Although radiometric data are lacking for these dikes, Swanson (1992) suggests a Triassic (post-dating the Agamenticus Complex) to Early Jurassic time for intrusion of the east-northeast-trending dike swarm, and a Late Jurassic to Early Cretaceous age for the north-northeast-trending swarm on Gerrish Island at Kittery Point (Figure 1). It is interesting to note that the Gerrish Island dikes cause, by their cumulative dilation effects, a change in the regional strike from east-northeast to almost east for bedding and the Rye-Kittery contact on Gerrish Island.

Triassic Complex

Agamenticus Complex

The Agamenticus Complex is a roughly circular body about 10 km in diameter composed of five or more plutons of alkalic and subalkalic composition (Figure A-1). It was studied by Wandke (1922), Woodard (1957), Hussey (1962), and in detail by Brooks (1990). Age relations are established between units by cross-cutting relationships and compositional trends. The youngest unit, of biotite granite, has yielded a K-Ar age of 233 ±5 Ma (published as 228 ±5 Ma by Foland and Faul, 1977; corrected here according to Dalrymple, 1979). Foland and Allen (1991) report an Rb-Sr age of 236 ±2 Ma. We have resampled that central biotite granite and report a new high-resolution CA-TIMS U-Pb zircon age of 238.9 ± 0.3 Ma (Figure 45) establishing a Triassic or older age for the entire complex.

The following discussion is primarily after Brooks (1990) who modified Hussey's (1962) map by defining zones of magmatic interaction between adjacent units as distinct phases: alkalic syenite (**TRs**), aenigmatite syenite (**TRas**), a zone of syenite to quartz syenite (**TRqs**), alkalic aegirine

granite (**TRag**), and alkalic granite (**TRg**). Biotite granite (**TRb**) remains as previously mapped. Detailed maps were compiled recently by Hussey and Brooks (2014a; 2014b). A generalized map of the Complex is given in Figure A-1.

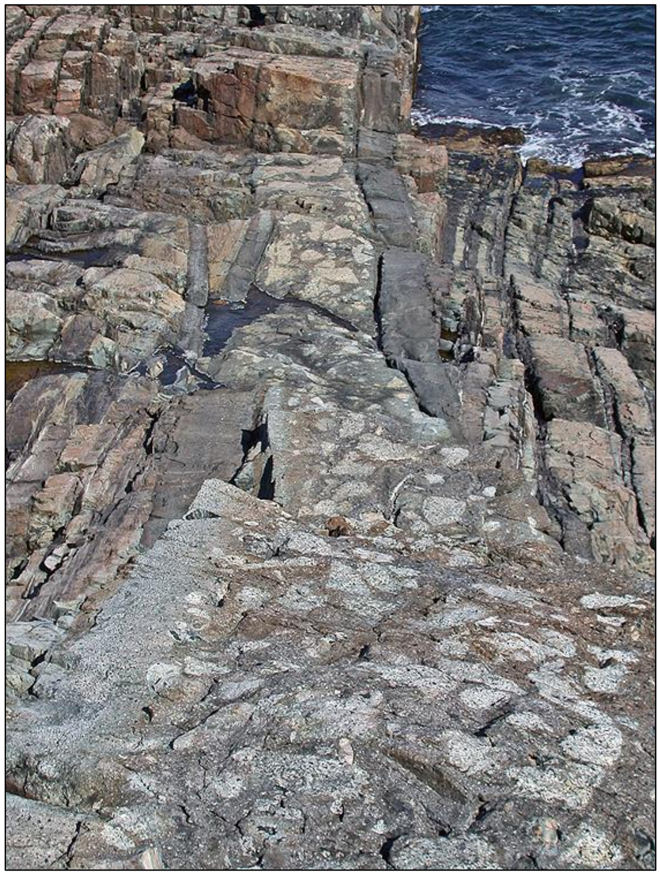

Figure 41. 1-meter diabase dike of Triassic to Jurassic age cutting the Kittery Formation along the coast, York, Maine. This dike has a central zone choked with angular blocks of coarse syenite that may have been derived from the nearby alkalic syenite of the Agamenticus Complex.

The youngest unit in the Complex is a central stock of biotite granite (**TRb**) that is comprised of gray to pink fine-grained to medium-grained porphyritic granite composed of a matrix of albite, orthoclase, quartz, and biotite with subordinate hastingsite, apatite, ilmenite and zoned tan to brownish-orange allanite. Phenocrysts consist of zoned plagioclase (An_{50}-An_{1}) and orthoclase. A finer-grained portion (chilled margin) of the biotite granite near the contact with the alkalic syenite (**TRs**) suggests that the biotite granite intruded into an older and colder alkalic complex.

Aegirine alkalic granite (**TRag**) crops out in a southeastern lobe near Cape Neddick. It is medium-grained gray to light-pinkish gray granite somewhat similar to **TRrg**, but with aegirine as solitary grains and in clumps associated with arfvedsonite, fluorite, and calcite. Light colored minerals include euhedral to subhedral perthite, antiperthite, microcline, and quartz.

Alkalic granite (**TRg**) forms a ring-shaped pluton along the northern and western edges of the complex. It is a medium-grained light gray granite composed of perthitic orthoclase and anorthoclase, myrmekite (near western contact with the Kittery Formation), anhedral to

interstitial quartz, with a variety of dark sodian and ferroan amphiboles (including arfvedsonite, barroisite, kataphorite-richterite, and riebeckite), fayalite, hedenbergite, interstitial fluorite, and interstitial calcite. Brooks describes parts of this belt as transitional to quartz syenite.

Figure 42. Diabase dike with rounded to subangular inclusions of high grade gneiss very similar to some of the lithologies of the Rye Complex.

Figure 43. Diabase dike. The light colored angular fragments are mostly milky quartz. These may be derived from the silicified shear zone in the Kittery Formation east of the Webhannet pluton. *Near junction of US Route 1 and Moody Road, Wells, Maine (Figure A-1).*

Figure 44. Complex swarm of Triassic to Jurassic basaltic dikes cutting the Kittery Formation. At least four episodes of dike injection are indicated by cross-cutting relations. *2 km south of Perkins Cove, Ogunquit, Maine (Figure 1).*

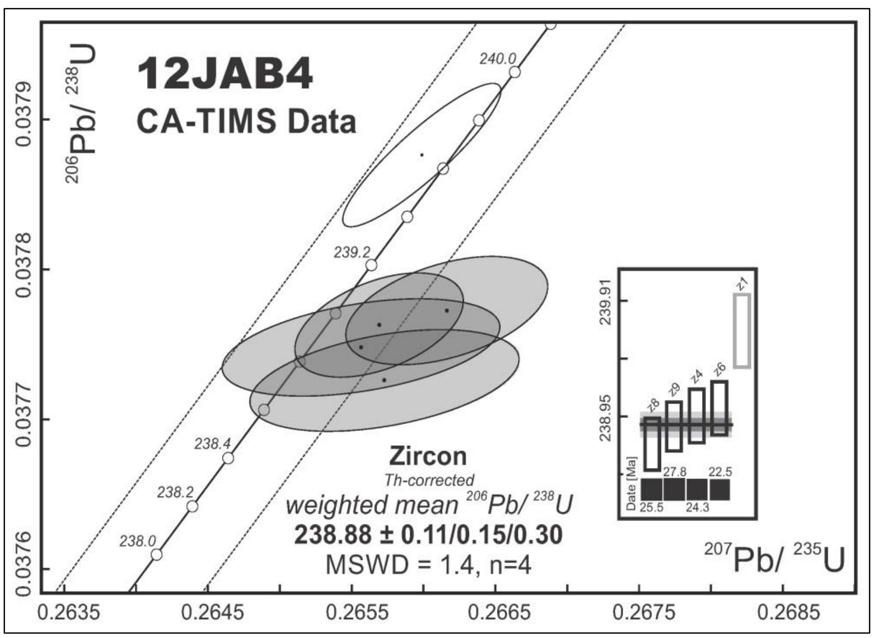

Figure 45. Concordia diagram for igneous zircons from the biotite granite of the Agamenticus Complex (**TRb**) indicating a Triassic age of 238.9 ±0.3 Ma.

Alkalic syenite to quartz syenite (**TRqs**) forms a heterogeneous ring of light to medium buff-gray fine- to medium-grained moderately quartz-rich syenite, locally with numerous xenoliths of country rock and unidentified alkalic phases especially in the northeastern part of the body. It cuts through the alkalic syenite and is in contact with aegirine granite, alkalic granite, biotite granite and Kittery Formation. Where inclusions are absent or rare, the quartz syenite consists of

medium- to fine-grained slightly light-buff gray hypidiomorphic-granular syenite with untwinned plagioclase, perthitic orthoclase, interstitial quartz (up to 10%), arfvedsonite, aegirine augite, aenigmatite, barroisitic amphibole and apatite.

Alkalic syenite (**Ŧs**) occurs in a central stock in the central and northeastern part of the complex, and is cut by **Ŧqs**. This a medium- to coarse-grained olive-green syenite composed primarily of microperthite. Quartz, in amounts less than 2%, occurs interstitially. Dark minerals include a wide assemblage of sodic and ferroan pyroxenes and amphiboles, including hedenbergite, aegirine-augite, aegirine riebeckite, arfvedsonite, and aenigmatite. Accessory and secondary minerals include apatite, ilmenite, fayalite (altered to iddingsite), and fluorite.

Porphyritic aenigmatite syenite (**Ŧas**) forms a crescent shaped lens between the complex quartz syenite ring (**Ŧqs**) and the small stock of aegirine granite (**Ŧag**) in the southeastern part of the complex. It is dark to medium green, compositionally varied, appears mottled in outcrop, and has poorly constrained contacts with **Ŧqs** and occurs as xenoliths within aegirine granite (**Ŧag**). Well-formed perthitic alkali feldspar phenocrysts are set in a finer-grained matrix of medium- to fine-grained aenigmatite, aegirine-augite, plagioclase, microcline, quartz, and opaque minerals.

The following model (Figure 46), modified after Brooks and others (1989) and Brooks (1990), seems to best represent the order of emplacement of major units of the Agamenticus Complex from oldest (1) to youngest (7). A three dimensional gravity model indicates that this body extends to a maximum depth of 5 km below the present erosional surface (Weston Geophysical Research,1977) and this sketch is consistent with that estimate.

1. Intrusion of hydrous aenigmatite syenite (**Ŧas**), now exposed in the southeastern part of the body.
2. Emplacement of alkalic syenite (**Ŧs**) as a central stock.
3. Intrusion of porphyritic quartz syenite (**Ŧqs**), likely associated with cauldron subsidence that taps an upper, more siliceous layered magma chamber and forms a complete ring that cuts parts of the alkalic syenite and aenigmatitic syenite, and includes clasts of the latter as xenoliths (Brooks, 1990).
4. Intrusion of alkalic granite (**Ŧg**) that in places is transitional to and/or pervasively invades quartz syenite along its western contact (syenite-quartz syenite zone, SQSZ of Brooks, 1990).
5. Intrusion of aegirine granite (**Ŧag**). It is possible that the aegirine granite exposed in the southeasternmost part of the complex represents an altered (higher level?), older(?) phase of the alkalic granite.
6. Intrusion of a northeast-trending basaltic dike swarm through the alkalic phases of the Agamenticus Complex, shown schematically on Figure 46 as Trba. Brooks (1990) recognizes that these dikes are identical to the mafic dike swarm in the Kittery Formation (Swanson, 1992), which suggests a pre-Jurassic age for the alkalic rocks of the complex and indicates that these rocks had cooled to a brittle stage prior to basalt injection.
7. Intrusion of biotite granite (**Ŧbg**). The lack of diabase dikes within the biotite granite and a finer-grained southern "chilled" margin against alkalic quartz syenite (Brooks, 1990)

indicate that this body must be slightly younger than the surrounding members of the complex.

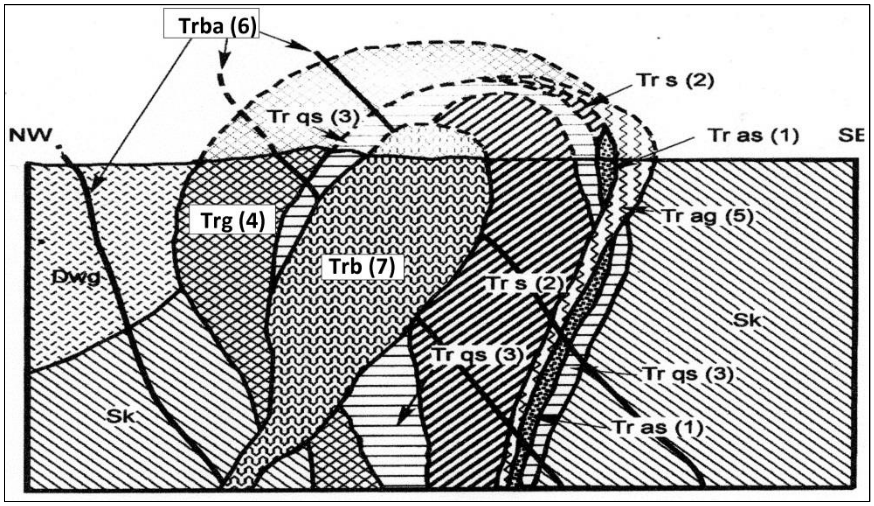

Figure 46. Schematic cross-section showing the order of intrusion (given by numbers in parentheses) of the units of the Agamenticus Complex (after Brooks and others, 1989). Unit abbreviations correspond with those used in the accompanying text, in Figure A-1, and on the geologic map (Hussey and others, 2016). Tr indicates Triassic age. Trba indicates Triassic basalt and diabase dikes.

Chase Stock

An underwater stock, here called the Chase Stock (**Mzc**), was recognized by Brooks (1986, dive site 13) and is located ~5 km east of the mouth of Portsmouth Harbor in a semi-circular topographic high (Figure 47). It is composed of medium-grained, gray quartz syenite containing perthitic alkali feldspar, quartz, plagioclase and the complete discontinuous Bowen's reaction series minerals: olivine, pyroxene, amphibole, and biotite. The size of the stock is not well constrained. Brooks' map suggests a diameter of perhaps 1 km, while Swanson (1992), by including the explosion breccias on Gerrish Island, suggests a diameter of 4 km. A circular 50-100 gamma aeromagnetic anomaly that interrupts a linear trend associated with the Rye Complex (Bothner and others, 1988) suggests a 2-3 km diameter for this stock.

Examination of older bathymetric maps and a newly acquired high-resolution bathymetric map with back-scatter imagery (Figure 47b, 47c; unpublished data, 2012) define several bedrock highs within a 2.5-km, northeast-trending, oval-shaped envelope. The irregular surface character and lack of east-northeast fabric elements of these bedrock highs contrast strongly with the fabric normally associated with the Rye Formation. While only the southwesternmost high (dive site 13) has been sampled to date, confirming its lithologic relation with the White Mountain series complexes, the other 3 highs are interpreted similarly. Together they suggest an offshore central complex wanting of further study. If this new interpretation is correct, the size of this body is intermediate between the estimates of Brooks and Swanson. Rocks from this intrusive have not been dated.

47a

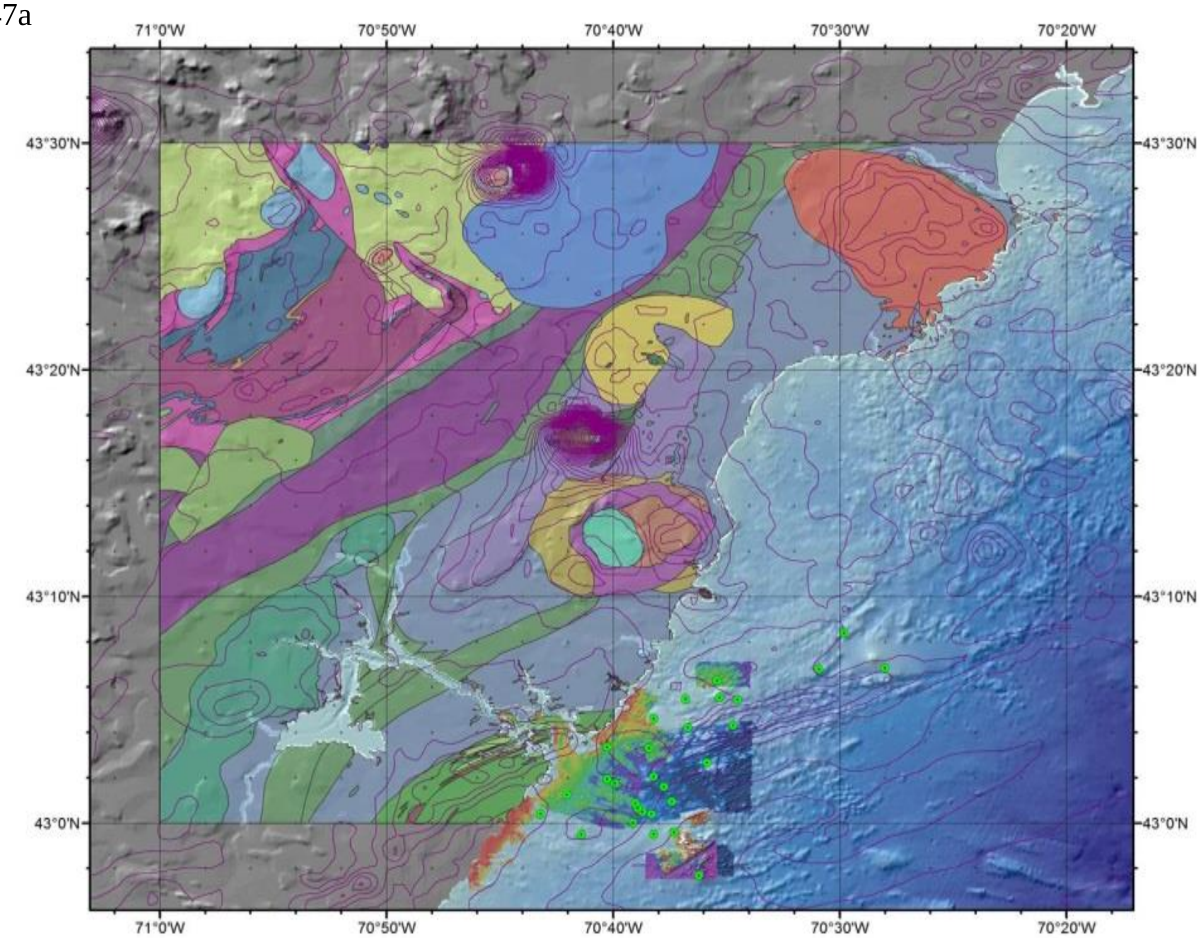

Figure 47a. Evidence for the Chase Stock (**Mzc**), an inferred Mesozoic(?) pluton about 5 km offshore from Portsmouth Harbor, Maine–New Hampshire. Red lines are 50 gamma aeromagnetic contours and green dots are dive sites on all three maps. White dotted line in figures b and c is the possible outline of the Chase Stock. a. Aeromagnetic contours for the Kittery 1:100,000 sheet. Bedrock units mapped on land are colored. Note magnetic signatures of mapped plutons. b. High-resolution bathymetric map of the area of the Chase Stock. Bathymetric contours are color coded by depth in ~5 m intervals; hotter colors are closer to the surface. Quartz syenite was recovered from dive site DS13 (Brooks 1986). c. High resolution backscatter image (grayscale) around dive site DS13.

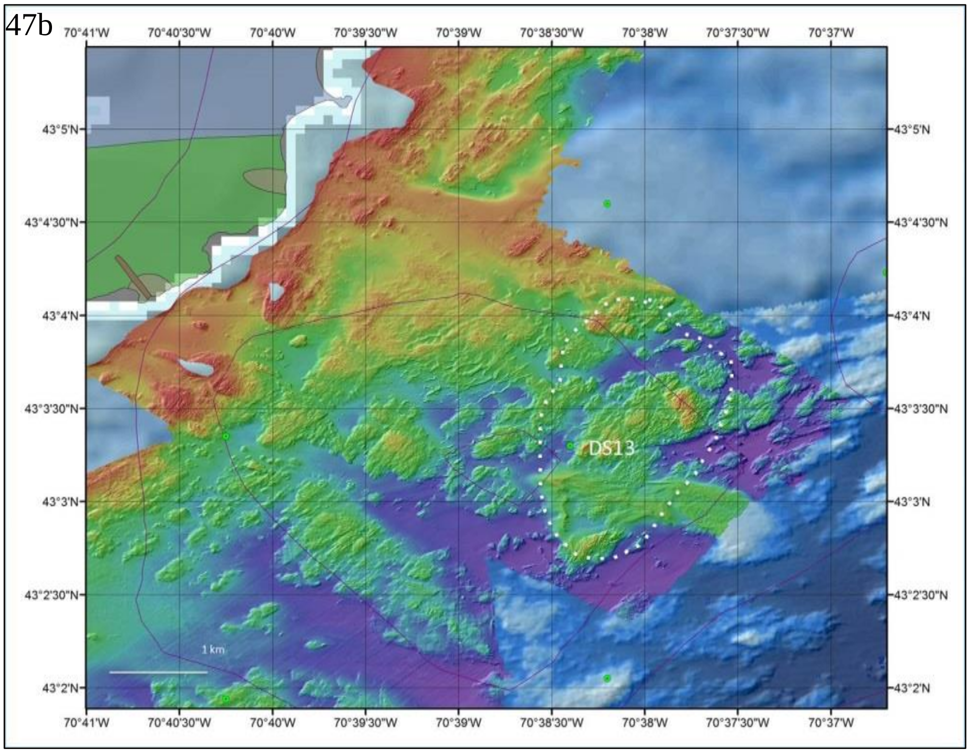

Figure 47b.

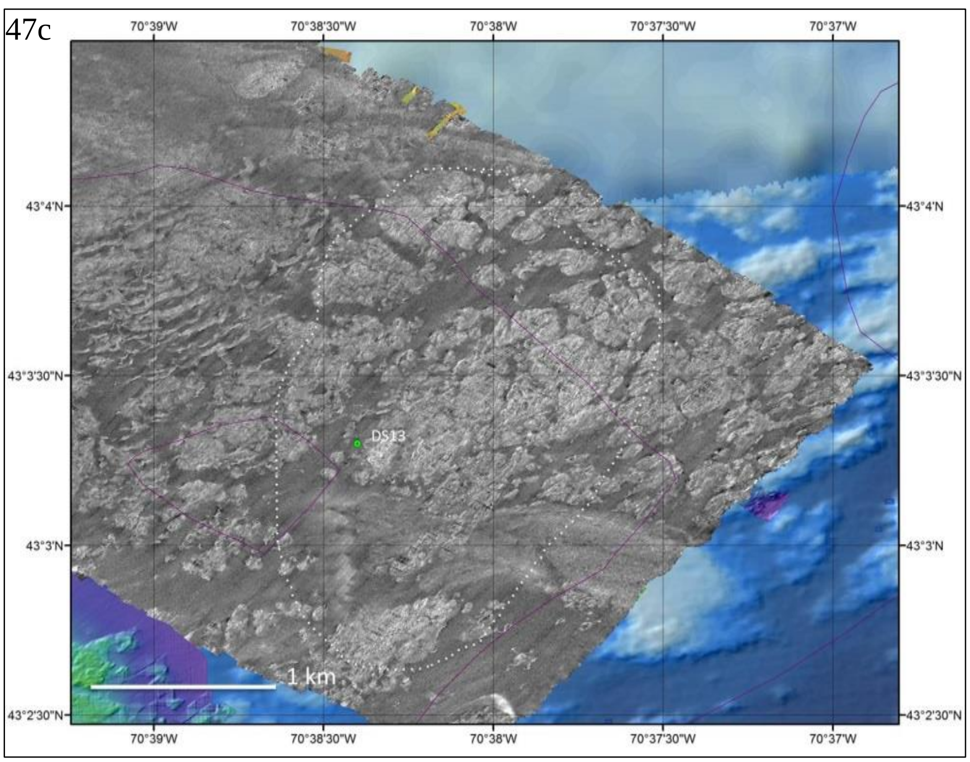

Figure 47c.

IV. INTRUSIVE ROCKS OF PALEOZOIC AGE

Whereas the high-level plutons of Mesozoic age reflect continental breakup, rifting and drifting, those of the Paleozoic are associated with continental amalgamation during three orogenic events: the compressive Salinic and Acadian orogenies, and the transpressional Alleghanian orogeny. The compositional range (calc-alkalic to peraluminous) and age range (407 to 288 Ma) may be interpreted to represent a subduction-related continental magmatic arc (Watts and others, 2000; Hon and others, 1986), melting above a slab window (Kuiper, 2015), to anatectic melting in overthickened crust (Sebago and Lyman, Tomascak and others, 1996b). Map patterns, relationships to country rock (partly to mostly concordant contacts, variable extents of contact metamorphic aureoles) and geophysical expression (significant to essentially non-existent) reflect subsurface mass distributions that contrast markedly with the younger high level intrusives of the Mesozoic. Most of the Paleozoic intrusive bodies were emplaced at greater depth, are apparently thinner and have a more sill-like geometry. Some, like the peraluminous two-mica granites have a greater potential as a geothermal resource than the calc-alkalic bodies of intermediate composition. None have known economic value beyond building stone.

Permian Pluton

Lyman Pluton

The southern third of the Lyman pluton (**Plg**) is exposed in the Kittery 1:100,000 map sheet in Alfred and Lyman, Maine. It consists of light gray, fine- to medium-grained, non-foliated to weakly foliated granite. Essential minerals are microcline, quartz, and plagioclase (albite to oligoclase). Varietal minerals are biotite and muscovite. Accessory minerals include tourmaline, apatite, zircon, and garnet. The plagioclase is weakly altered to saussurite, and the microcline is clouded with argillic alteration products. Pegmatite lenses and irregular pods of similar composition to the granite are abundant throughout the pluton. As a generality, muscovite is more common and the texture finer-grained to the north in the area of the Portland 1:100,000 map sheet. It is possible that the finer-grained, more muscovite-rich phase to the north represents a separate magma from the coarser phase to the south, but as yet, no contact between the two has been observed or delineated.

The pluton is elongate in the north-northeast direction at a moderate angle to the regional structural trend of the host metasedimentary rocks. Hussey (1985) suggests that the pluton is a thin sheet dipping moderately to the east. To the north of the Kittery map sheet below the Skelton dam on the Saco River in Dayton and Buxton, Maine (Stop 3 of Marvinney and others, 1995), the northeast edge of the pluton is parallel to a younger schistosity (S_3) in the country rock trending at nearly right angles to an earlier schistosity (S_2) which is parallel to axial planes of larger folds (F_2) visible in outcrop (Figure 48). Recumbent folds (F_1) are not seen in outcrop in the area. The later schistosity (S_3) is most strongly developed close to the contact, but can still be detected at least a half kilometer northeast of the pluton contact. The S_3 schistosity is parallel to axial planes of the later minor folds, F_3, suggesting forceful injection of the granitic magma and shouldering aside of the Berwick Formation country rock (Figure 49).

Zircons from the central part of the Lyman pluton yield a concordant $^{206}Pb/^{238}U$ age of 287.6 ±0.4 Ma **(**Figure 50**)**. This important result, which replaces an earlier Rb-Sr determination of

322 ±12 Ma for the Lyman (Gaudette and others, 1982), supports the hypothesis that the Lyman pluton is related to the larger Sebago Batholith (Hayward and Gaudette, 1984; Hayward, 1989), well exposed in the Portland 100,000 sheet (Berry and Hussey, 1998; Guzofski, 2004). The most recent reliable ages from the Sebago are a $^{207}Pb/^{235}U$ monazite age of 293 ±2 Ma by Tomascak and others (1996a), and a U-Pb zircon age of 296 ±3 Ma by Aleinikoff (in Foord and others, 1995). These results supplant previously reported Carboniferous ages (Hayward and Gaudette, 1984; Aleinikoff and others, 1985) and further support Permian magmatism in central coastal New England.

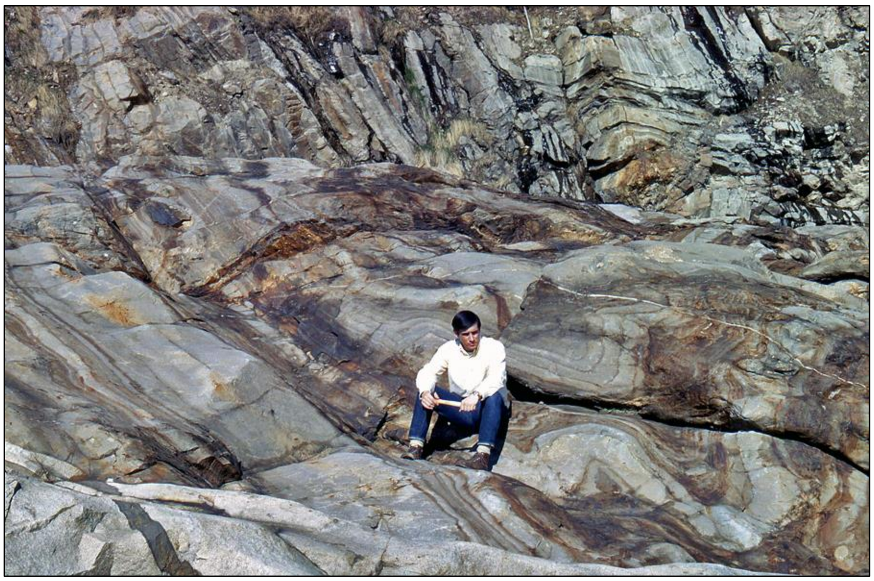

Figure 48. Exposure of the Berwick Formation (**DSb**) showing upright F_2 syncline. *At Union Falls below the Skelton dam on the Saco River, Buxton, Maine.*

Figure 49. F_2 syncline, Berwick Formation showing S_3 schistosity at nearly right angles to axial plane of F_2. Red lines indicate the direction of S_3. *Union Falls, Buxton, Maine.*

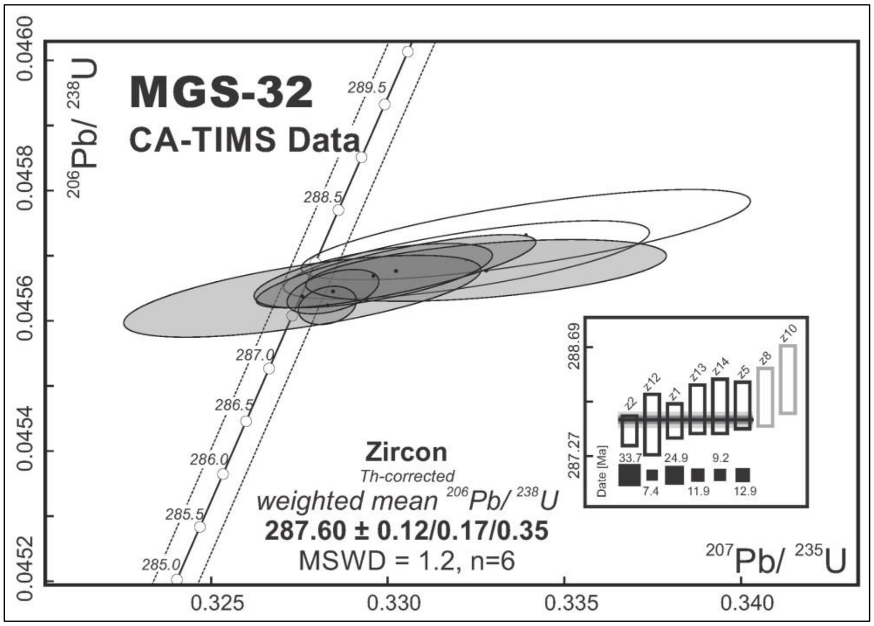

Figure 50. Concordia diagram for the Lyman pluton (**Plg**) indicating an Early Permian age of 287.6 ±0.4 Ma.

Carboniferous or Devonian Pluton

Saco Pluton

Only the very southern edge of the Saco pluton (**CDsg**) crops out along the northern edge of the Kittery map sheet; most of the pluton occupies the southern edge of the Portland 1:100,000 map sheet in the Bar Mills 7½' quadrangle (Marvinney, 1995). It is a highly sheared intrusive gabbro or diorite, in which the essential minerals have been strongly altered to secondary phases; plagioclase is altered to saussurite, and original dark minerals (probably hornblende and augite) to fibrous amphibole. Gaudette and others (1982) report an age estimate of 307 ± 20 Ma based on an Rb-Sr whole-rock two-point reference isochron. This age is anomalously low and may have been perturbed by extensive shearing and deuteric alteration possibly associated with Alleghanian deformation.

Devonian Plutons

Barrington pluton

The Barrington pluton (**Dbag**) intrudes metasedimentary rocks of the Shapleigh Group, the Phyllonite at Church Road and the Berwick Formation in the western part of the Kittery sheet. It is cut by a north-northeast trending fault, the Gonic fault, which separates the Rochester Lobe from the larger Barrington pluton, only a small portion of which is present in this map area (see inset map in Hussey and others, 2016). Overall, the Barrington is a two-mica granite with numerous associated pegmatites. Some of the pegmatites, including the Parker Mountain complex pegmatite, were exploited during World War II for lithium (Cameron and others, 1954). A $^{207}Pb/^{206}Pb$ monazite age of 364 Ma was obtained by Eusden and Barriero (1988) for the Barrington granite, indicating a late Devonian age, although their $^{206}Pb/^{238}U$ age is somewhat younger.

Appledore diorite

The Appledore diorite crops out on the eastern shore of Appledore Island, just south of Duck Island, the northernmost of the Isles of Shoals, some 15 km off the New Hampshire–Maine mainland (Figure 1). It is barely off the southern margin of the Kittery sheet but is included here because the rocks comprising the Isles of Shoals represent an important link to the Rye Complex onshore (Brooks,1986). The diorite on Appledore Island was described by Fowler-Billings (1959) who considered it to be part of the Exeter pluton. Weakly metamorphosed, it had a preliminary Rb-Sr age that overlapped with that of the Exeter (475±20 Ma, Gaudette and others, 1984) and shared many of the petrographic characteristics of the Salamander Point diorite described below: the same mineral assemblage and an intrusive relationship with a gray granite. A zircon $^{206}Pb/^{238}U$ age of 361.1 ±0.4 Ma (Figure 51) for the Appledore diorite, however, distinguishes it from both the Exeter pluton and the diorite at Salamander Point, and points to a long period of intermediate magma generation during the Devonian (Dorais, 2013; Dorais and others, 2014).

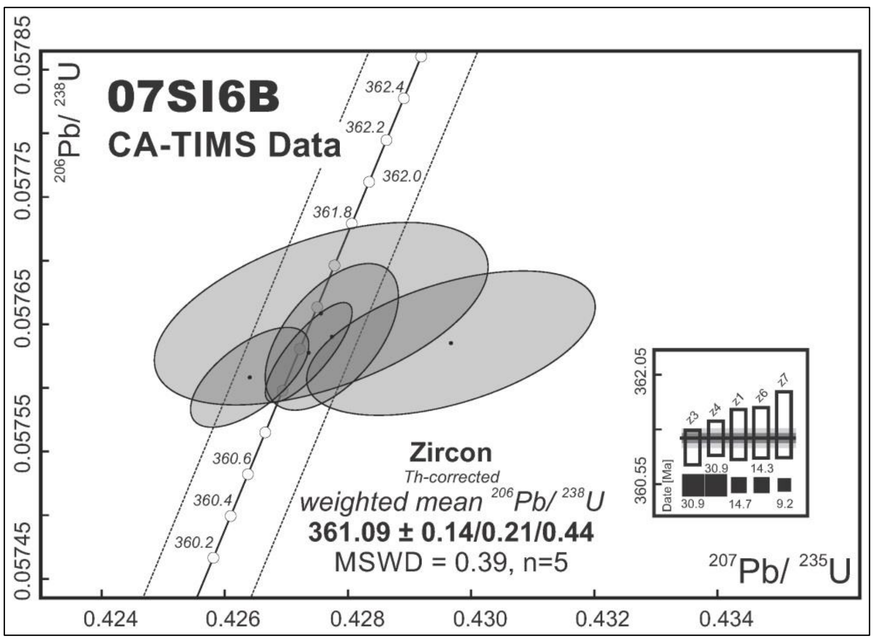

Figure 51. Concordia diagram for the Appledore diorite indicating a Late Devonian age of 361.1 ±0.4 Ma.

Salamander Point diorite

The Salamander Point diorite (**Dd**) crops out irregularly along the northeast shore of New Castle Island, New Hampshire, and on Fishing Island in Maine, a little over 1 km to the east in Portsmouth Harbor (Figure 1). It appears lenticular in map view, perhaps 1 by 0.5 km in size, and is parallel to the strong northeast-trending foliation in the host Rye Complex (**O€r**). It is poorly foliated and intimately injected by fine-grained gray granite, also poorly foliated. The diorite contains plagioclase, pale green hornblende, biotite, and quartz, plus accessory sphene, apatite, opaque minerals, and zircon. The cross-cutting granite has a well granulated, mildly cataclastic texture composed of quartz, perthitic microcline, and minor biotite with exsolved sagenitic rutile and pleochroic haloes around included zircon. Undulatory quartz is not recovered. The diorite at Salamander Point provided a high-precision $^{206}Pb/^{238}U$ zircon age of

380.1 ±0.5 Ma (Figure 52) The Appledore diorite has many of the same field and petrographic characteristics but is some 20 million years younger.

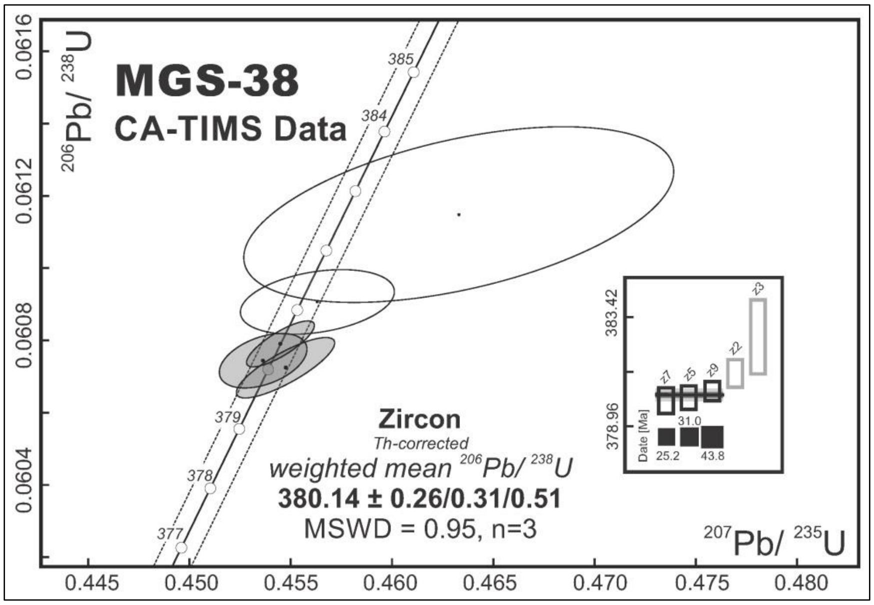

Figure 52. Concordia diagram for the Salamander Point diorite (**Dd**) indicating a Late Devonian age of 380.1 ±0.5 Ma.

Biddeford Pluton

The Biddeford pluton (**Dbig**) extends from Biddeford, Maine, to the ocean at Kennebunkport and Biddeford Pool (Figure 1). It intrudes the Kittery Formation (**Sk**). The pluton consists of hypidiomorphic-granular, medium-grained, non-foliated, medium to light gray granite (Figure 53). Essential minerals are microcline, plagioclase (oligoclase), and quartz. Varietal minerals are biotite; muscovite is rare. Accessory minerals are apatite, tourmaline, and zircon. The granite is generally fresh at the surface. However, the northwest third of the pluton has been weathered to a 1 to 4 m zone of grus that has locally been dug out for driveway and footpath dressing stone (Figure 54).

The pluton is elongate in the northwest-southeast direction at nearly a right angle to the regional structural trends of the metasedimentary rocks; however, within close proximity to the contacts on both the northeast and southwest edges of the pluton, the trend of bedding and foliation in the host Kittery Formation are parallel to the contacts. The elongation direction of the pluton may be related to this structural divergence. At the southeast end of the pluton in the Kennebunk-Biddeford Pool area, apophyses of granite alternate with Kittery blocks or roof pendants (Figure 55), and the contact is thus very convoluted. In contrast, the eastern, northern, and western parts of the contact lack apophyses. At none of these contacts is there an indication of chill effects against the Kittery Formation; however, the latter shows moderate grade contact metamorphism. Calcareous beds and concretions commonly contain grossularite and diopside within 100 ± meters of the contact.

Zircons from two samples of two-mica granite (ME-10 and ME-25) provide similar $^{206}Pb/^{238}U$ ages of 383.3 ±0.5 and 382.7 ±0.5 Ma (Figures 56 and 57) that clearly record continuous magmatism at the boundary between Middle and Late Devonian time.

Figure 53. Evenly textured granite of the Biddeford pluton (**Dbig**). *Biddeford Pool area, Maine (Figure 1).*

Figure 54. "Gravel" pit in deeply weathered grus (rottenstone) of the northern end of the Biddeford pluton.

Webhannet Pluton

The Webhannet pluton is a northeast-trending composite pluton extending from Eliot to Wells, a distance of approximately 28 km parallel to regional structural trends of the Kittery Formation. It intrudes the Kittery and Eliot formations. It consists of three phases: granodiorite (**Dwgd**), gray biotite granite (**Dwg**), and pink to light gray biotite-muscovite granite (**Dwb**). Typical mineralogy of the granodiorite (**Dwgd**) is quartz, plagioclase, microcline, biotite, and

hornblende with accessory opaque minerals, sphene, apatite, and epidote. It is fine- to medium-grained with distinct phenocrysts of plagioclase feldspar (oligoclase to andesine composition), and weak foliation formed by the orientation of biotite flakes. The gray biotite granite that makes up the bulk of the pluton (**Dwg**) is fine- to medium-grained, equigranular to slightly foliated, and locally slightly porphyritic. It is composed of microcline, oligoclase, and quartz as the essential minerals, with biotite, and sparse muscovite as varietal minerals. Accessory minerals include epidote, sphene, apatite, and opaque minerals. Secondary alteration minerals include saussurite and calcite as partial alteration of plagioclase, sericite as partial alteration of microcline, and chlorite as partial alteration of biotite. The pink granite phase that forms much of the northern quarter of the pluton (**Dwb**) is generally medium-grained, non-porphyritic, and unfoliated (Figure 58). The essential minerals are quartz, plagioclase (oligoclase), and microcline. Varietal minerals are biotite and muscovite, the latter being slightly more abundant than in the gray phase. Accessory minerals include apatite, opaque minerals, and rare sphene, but no epidote. Secondary minerals are essentially the same as in the gray granite. One observed contact between the pink and gray granite (Figure 59) shows that both phases are intermingled suggesting either magma mixing, or intrusion of the pink granite while the gray granite was still plastic. Neither shows any chill effects against the other.

Figure 55. Shoreline exposure near Biddeford Pool, Maine, showing medium-grained evenly textured stringers of Biddeford granite alternating with contact-metamorphosed Kittery Formation.

The Webhannet pluton has been dated by several methods. Gaudette and others (1982) reported a Rb-Sr whole rock age of 390 ±10 Ma from five samples, and a low-precision ^{207}Pb/^{206}Pb age of 403 +14/-12 Ma from four discordant zircon separates, two each from the pink and gray phases of the Webhannet. Figures 60 and 61 show two new high-precision ^{206}Pb/^{238}U dates that supersede earlier determinations and yield ages of 382.9 ±0.5 Ma for the gray granodiorite phase (MGS-34) and 383.1 ±0.5 Ma for the gray granite (MGS-33). The pink two-mica granite phase, presumably younger, was not dated. These ages are the same within uncertainty, but allow that the granodiorite may be slightly younger than the granite phases of the Webhannet pluton. As illustrated in Figure 59, both the pink and gray granite phases may have been intruded more or less simultaneously from separate source areas. The ages of the Biddeford pluton and the Webhannet pluton are virtually indistinguishable.

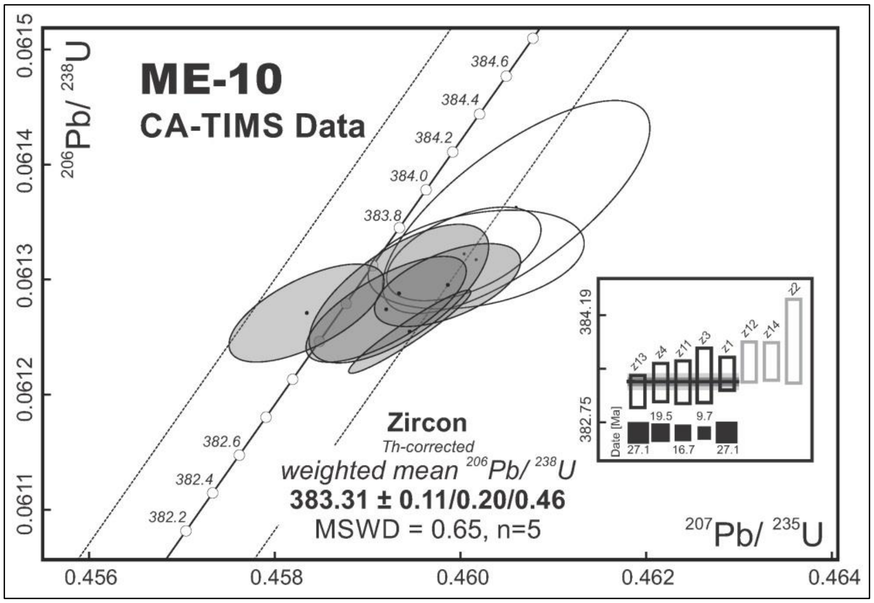

Figure 56. Concordia diagram for granite from the north end of the Biddeford pluton (**Dbig**), indicating an age of 383.3 ±0.5 Ma which overlaps the boundary between Middle and Late Devonian.

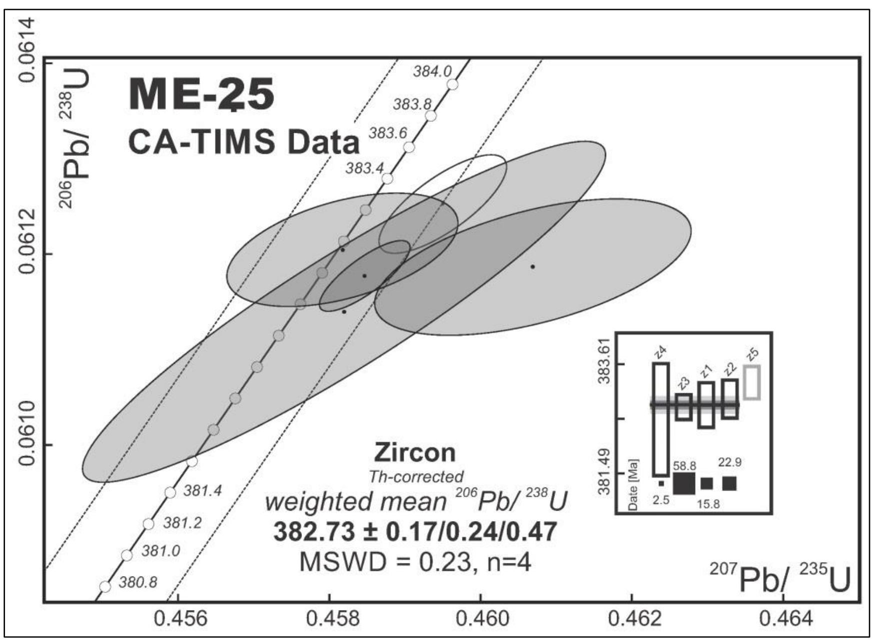

Figure 57. Concordia diagram for granite from the southeast part of the Biddeford pluton (**Dbig**), indicating an age of 382.7 ±0.5 Ma which overlaps the boundary between Middle and Late Devonian.

Nisbitt Pond, Spaulding Pond, and Orchard Road plutons

The Nisbitt Pond (North Lebanon, Maine), Spaulding Pond (West Lebanon, Maine) and Orchard Road (Acton, Maine) plutons, all named here, are 6-10 km^2 stocks that intrude the Rindgemere, Gully Oven, and Towow formations in the northwestern part of the map area. The Nisbitt Pond and Orchard Road plutons crop out sparsely on opposite sides of the northwest-trending Silver Mine normal fault; the Orchard Road pluton is cut by the fault, and suggests that

the two may have been part of the same body. They are typical porphyritic two-mica granites containing feldspar phenocrysts up to 3 cm long, quartz, muscovite, and biotite that define a swirly foliation pattern more likely of igneous than metamorphic origin. Associated coarse pegmatite veins occur in the host granites and in stratified country rock, particularly common in the more migmatitic phases of the Rindgemere Formation. Zircons from the Nisbitt Pond granite (**Dnp**) yielded a $^{206}Pb/^{238}U$ age of 383.1 ±0.5 Ma (Figure 62), indistinguishable from the ages determined for the larger Webhannet and Biddeford plutons. The Spaulding Pond and Orchard Road plutons (**Dg**) are undated; all share the same (or similar) characteristics and are thus assigned to the Devonian.

Figure 58. Monolithic, slightly banded pink granite of the Webhannet pluton (**Dwb**). *Near the High Pine Fire Station, Wells, Maine.*

Breakfast Hill granite

The Breakfast Hill granite and pegmatite was named and described by Novotny (1963, 1969) as small sills, lenses, or dikes of variably foliated, two-mica granite to coarse pegmatite in the Rye Formation. Primarily occurring as bodies from less than an inch to 30 feet in thickness, the only outcrop large enough for Novotny (1963, 1969) to show on his map is at Breakfast Hill, Rye, New Hampshire (Figure 1). On the bedrock map of New Hampshire (Lyons and others, 1997), the term "Breakfast Hill granite" was applied to this mappable pluton. Breakfast Hill itself was named for an historically significant set of glacially polished ledges where Native Americans ate breakfast while holding early colonists captive from a June 26, 1696 assault near Rye (Brewster, 1859). Gneissic granite is a common feature of the Rye Complex, often as a discontinuous, variably sheared mass as far as Portsmouth Harbor, but only the body at Breakfast Hill and a smaller body just to the east are large enough to be shown on the accompanying geologic map as Breakfast Hill granite (**Dbh**, Hussey and others, 2016). It is comprised of microcline, plagioclase, quartz, muscovite and biotite in a variably granulated fabric. Early attempts to date this rock using U-Pb on sphene were fraught with large errors around a 380 Ma age, but high precision $^{206}Pb/^{238}U$ analysis of zircon from the same mapped body at Breakfast Hill yields an Early Devonian age of 402.9 ±0.5 Ma (Figure 63).

Figure 59. Intermingled gray granite (**Dwg**) and pink granite (**Dwb**) of the Webhannet pluton. No relative age sequence of the two phases is evident. Pavement exposure temporarily exposed during a gravel mining operation in 1966. *Merriland Ridge, Wells, Maine (Figure 1).*

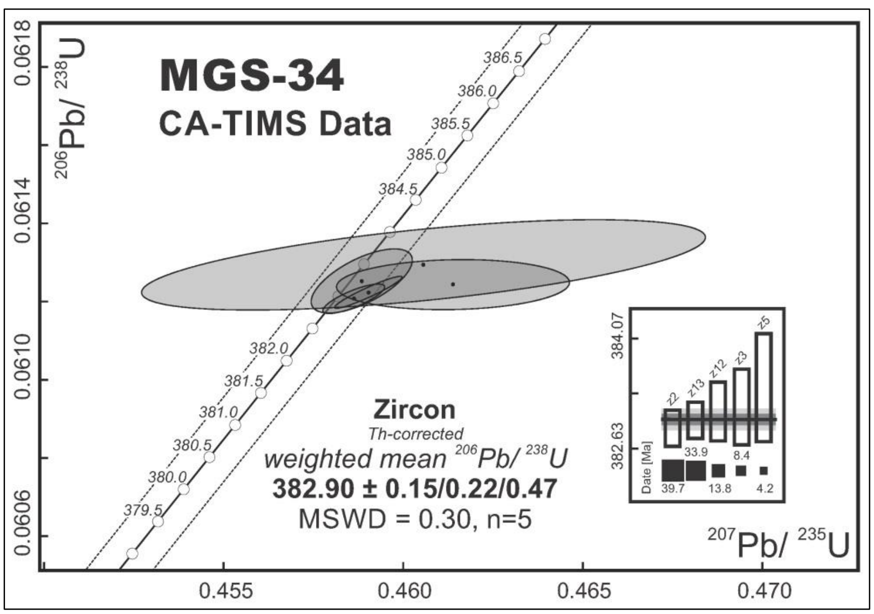

Figure 60. Concordia diagram for medium gray porphyritic biotite-hornblende granodiorite of the Webhannet pluton (**Dwgd**), indicating an age of 382.9 ±0.5 Ma which overlaps the boundary between Middle and Late Devonian.

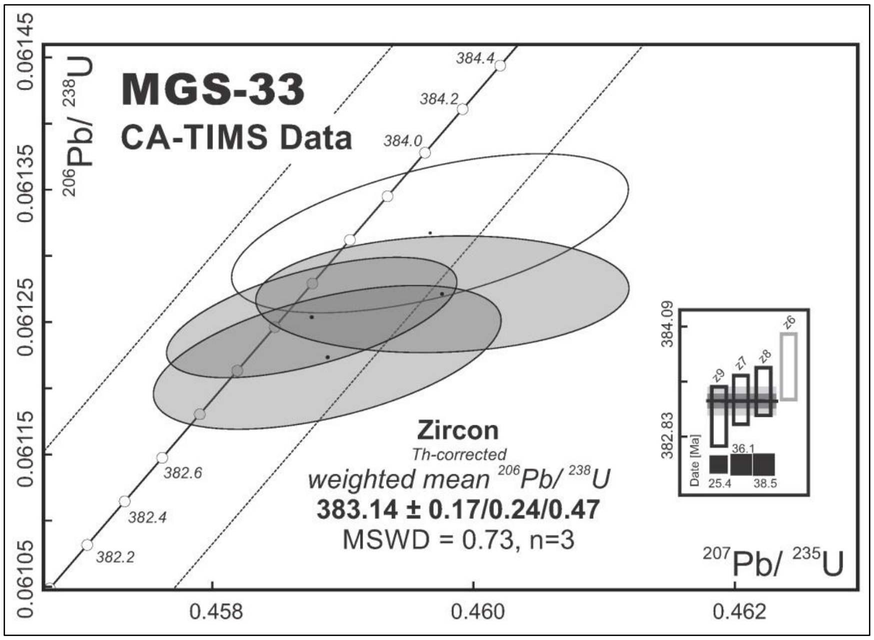

Figure 61. Concordia diagram for light gray biotite granite with coarse sphene of the Webhannet pluton (**Dwg**), indicating an age of 383.1 ±0.5 Ma which overlaps the boundary between Middle and Late Devonian.

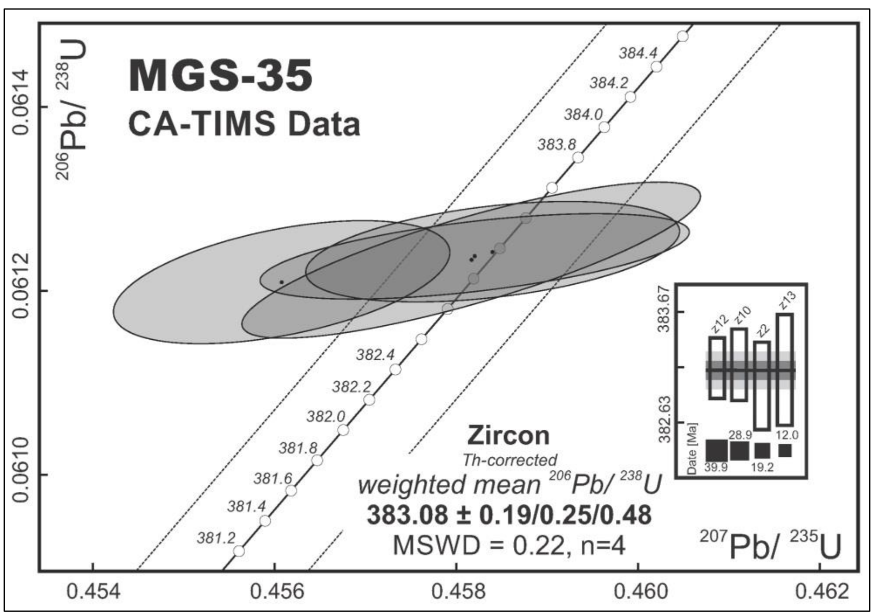

Figure 62. Concordia diagram for the Nisbitt Pond granite (**Dnp**) indicating an age of 383.1 ±0.5 Ma which overlaps the boundary between Middle and Late Devonian.

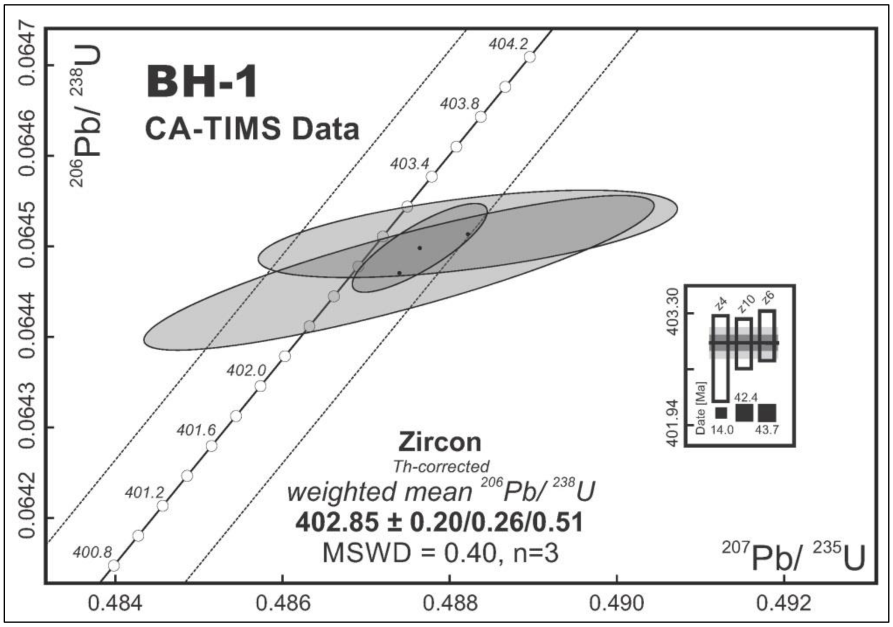

Figure 63. Concordia diagram for the Breakfast Hill granite (**Dbh**) indicating an Early Devonian age of 402.9 ±0.5 Ma.

Exeter Pluton

The Early Devonian Exeter pluton (**Deg**) has a "ten-pin" shaped map pattern elongate in a northeast-southeast direction, parallel to regional grain, with dimensions of approximately 32 x 7 km. Novotny (1969) maps additional satellitic diorite bodies southeast of the main intrusion, all with same northeasterly elongation, but only two of which crop out just south of Great Bay on the Kittery 1:100,000 map (**Dd**, Hussey and others, 2016). An additional body is located at Adams Point on the west shore of the Great Bay estuary. Hussey (1962) maps a small body on strike in North Berwick, Maine, also designated as **Dd**.

At map scale the Exeter pluton is generally concordant. At outcrop scale, however, contacts are commonly discordant and host metasedimentary rocks are broken, displaced, veined or diked, and strongly altered. Contact metamorphism has raised the regionally low-grade host rocks to the pyroxene hornfels facies (diopside, enstatite or sillimanite-bearing depending on composition of the host). Abundant xenoliths, sometimes partially digested, sometimes showing biotite concentrations at the margins, occur near contacts and, importantly, in areas often greater than 100 m^2 within interior regions of the pluton or as unbroken pendants of the same general scale. These relationships suggest that the roof of the magma chamber was not too far above the present erosional level. Given that total topographic relief is less than 70 m over the extent of the body, the roof must have been irregular. The geometry of the floor of the pluton is conjectural; gravity models depict planar surfaces that dip downward toward the center (Bothner, 1974).

Layering in the host Kittery and Eliot formations may be rotated 60 to 90° along the southeastern margin of the Exeter pluton, which raises questions about emplacement mechanics. Magmatic shouldering may have occurred during emplacement and/or shear along one of several faults shown in the Great Bay area (Nanny Island Shear Zone, Great Bay fault and its splays, the Dover Point and General Sullivan faults; Hussey and others, 2016). Contacts of the smaller, satellitic diorite bodies with host rocks are not exposed.

The pluton is compositionally varied, but not layered. It is generally more mafic (in one instance ultramafic) in the southwest and more felsic to the northeast, but otherwise highly variable (Figure 64); there are no clear contacts between lithologies suggesting gradations between lithic phases (Bothner, 1974; Birch, 1979; Watts and others, 2000). Coarse-grained biotite-hornblende quartz diorite to tonalite is the dominant lithology in the Exeter pluton. Alkali feldspar (interstitial microcline) and rutilated biotite, often hosting zircons and other accessories (commonly sphene and apatite), complete the common assemblage. Textures vary from hypidiomorphic-granular to rare porphyritic. Plagioclase preserves normal zoning even where slightly saussuritized and/or sericitized; quartz is interstitial. Ferromagnesian phases include uralitized hornblende, largely altered to greenish, nonpleochroic actinolite and some epidote; clinopyroxene and orthopyroxene, when present are less altered or mantled by what was amphibole; olivine in gabbroic phases is largely altered to serpentine minerals and chlorite. Biotite is commonly ragged, strongly pleochroic red-brown, with abundant sagenitic rutile, suggesting that original biotite was Ti-rich. Alteration may reflect post-intrusive low-grade regional metamorphism.

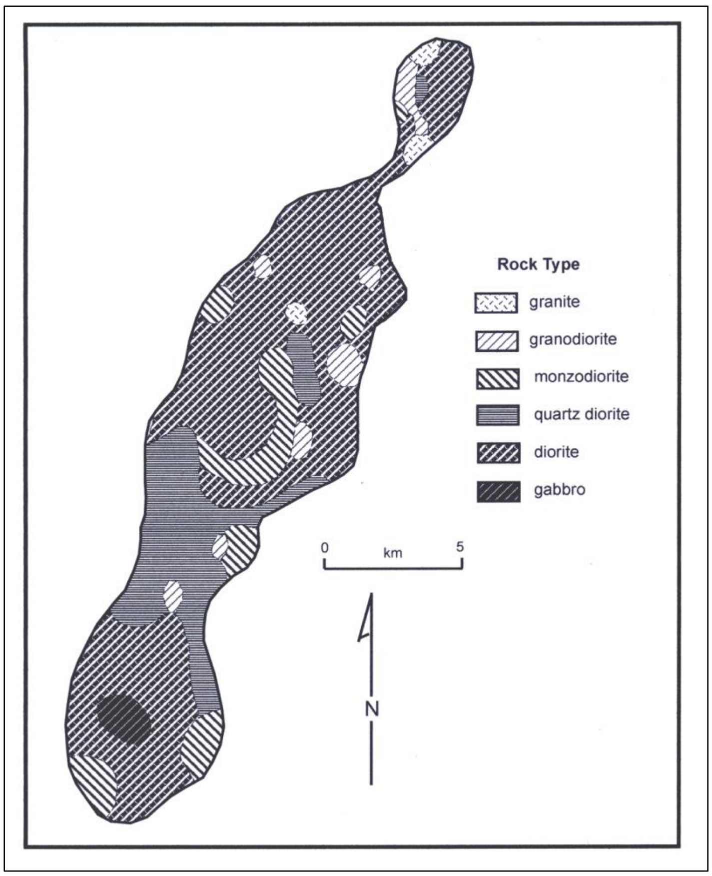

Figure 64. Map of the Exeter pluton showing lithologic variability (after Birch, 1979; Watts and others, 2000).

Zircons from the dioritic phase of the Exeter pluton yield a high-precision $^{206}Pb/^{238}U$ age of 407.4 ±0.5 Ma (Figure 65). Additional samples representing the full mafic to felsic compositions of the Exeter range from 407.37 ±0.11 to 407.80 ±0.11 Ma (using 95% confidence internal errors only, for comparison) indicating that the emplacement and crystallization of this

small batholith took between 210,000 and 650,000 years (this report; Bothner and others, 2009; Bothner and others, unpublished data).

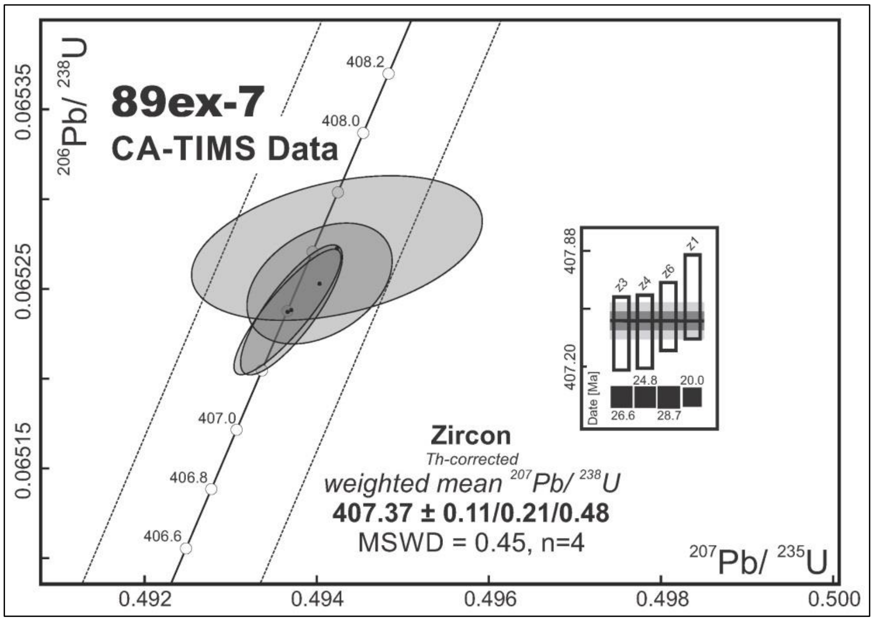

Figure 65. Concordia diagram for the Exeter diorite (**Deg**) indicating an Early Devonian age of 407.4 ±0.5 Ma.

Adams Point body

The Adams Point satellite body (**Dd**) occupies an area of approximately 0.5 km^2 and varies as much as the Exeter body itself. A very magnetic cortlandtitic gabbro crops out at the western shore of the point and varies to medium-grained hornblende-biotite diorite to aplitic two-mica granite (apparently a separate body) over a distance of less than a kilometer. All are cross-cut by coarse-grained Mesozoic diabase dikes that in places are coarse enough that they are distinguished from the diorite only by the absence of biotite. The Adams Point diorite clearly cuts tight upright south-verging folds of the Kittery Formation and is in turn cross-cut by abundant Mesozoic diabase dikes that swarm in the seacoast region of New Hampshire and southwestern Maine (Swanson, 1992).

Rochester plutons

Biotite diorite (**Dqd**) crops out in two northeast-trending elongate sill-like bodies that intrude the Gully Oven Formation just north of the Barrington pluton in Rochester, New Hampshire (Eusden and others, 1984). They occupy a larger area west of the map area of this report. In a review of calc-alkaline plutons in the Merrimack belt, Watts and others (2000) note the textural similarity of the Rochester plutons with the nearby Exeter pluton, a dominantly plagioclase and biotite, minor quartz and abundant opaque mineral assemblage, but with a geochemical signature more similar to the 360 Ma Hardwick tonalite of central Massachusetts than to its closer neighbors the Exeter and Webhannet plutons.

V. STRUCTURE OF THE METASEDIMENTARY ROCKS

Folds

Merrimack Group

Major folds in the Merrimack Group are inferred from outcrop distribution and apparent relative age of the Kittery and Eliot formations. Little information is available about the geometry of these folds. They include an anticline that extends through Great Bay and bifurcates into two branches, one extending northeast to the edge of the Agamenticus Complex, and the other extending more northerly parallel to the Piscataqua River to South Berwick, Maine. The northern termination of the more northerly branch in the South Berwick area is uncertain. The Exeter pluton has been intruded into the axial zone of a syncline extending from South Berwick southward through and beyond Exeter, New Hampshire.

Between Wells and Kennebunk Beach (Figure 1), strikes of bedding and cleavage in the Kittery Formation gradually shift from north-northeast to east-west then to northwest close to the southern contact of the Biddeford pluton. Similarly, on the northeast side the same structures change in strike from northeast to northwest parallel to the contact of the pluton. This major divergence, here named the Biddeford Dextral Flexure, suggests that a northwest-trending regional dextral shear zone may have controlled the direction of elongation of the pluton. On a broader regional scale no evidence of the shear has been seen in the map pattern of formational contacts northwest of the pluton. Orientation of minor parasitic folds in the Kittery Formation between Wells and Kennebunk Beach, Maine, is deflected congruently with the bedding trends suggesting that the flexure postdates the latest upright folding (F_2) described below. The origin of this flexure is uncertain, but we speculate that it might be related to a Devonian-age dextral transform fault that offsets the spreading center of the Falmouth-Brunswick–Casco Bay volcanic arc. A regional structural hypothesis similar to this is proposed by Kuiper (2015). This would account for the absence of the island arc southwest of the Biddeford pluton. Further structural analysis is needed to evaluate these suggestions.

Early recumbent folds (F_1, Figure 66) and late upright folds (F_2, Figures 67 and 68) are well exposed in the Kittery Formation in the coastal exposures between Kennebunk Beach and Kittery, Maine (Figure 1). Where recumbent hinges are not exposed they may be inferred with the aid of primary structures as illustrated in Figure 69. This photo of an outcrop on Basket Island in the Biddeford Pool area shows upright folds, but beds are clearly upside down based on graded bedding. These downward-facing F_2 folds clearly imply earlier F_1 folding. Compare this with Figure 67 which shows upright folds; grading in these turbidite beds indicates they face upward, but it is uncertain whether they lie on the upright limb of a major F_1 recumbent fold system or not. Except for outcrops at Lee Five Corners, New Hampshire (Figure 70), minor folds are uncommon in the Eliot Formation.

Berwick Formation

Similar folds are present in the Silurian Berwick Formation across the Calef and Nonesuch River faults within the map area. F_1 folds are nowhere observed in outcrop and F_2 folds are quite rare. With the exception of the type locality in Berwick, Maine, and in the exposures below the Skelton Dam in the Saco River, primary bedding is obscured by strong transposition of layering. Calc-silicate layers and pods may have represented original calcareous layers and are now

discontinuous masses measured at meter scale. Weakly to strongly developed cleavage (F_2 axial plane) is restricted to thin pelitic interlayers. Escamilla-Casas (2003) reports minor folds related to shear fabric where the Calef phyllonite is absent near the contact with the Eliot Formation in Dover, New Hampshire.

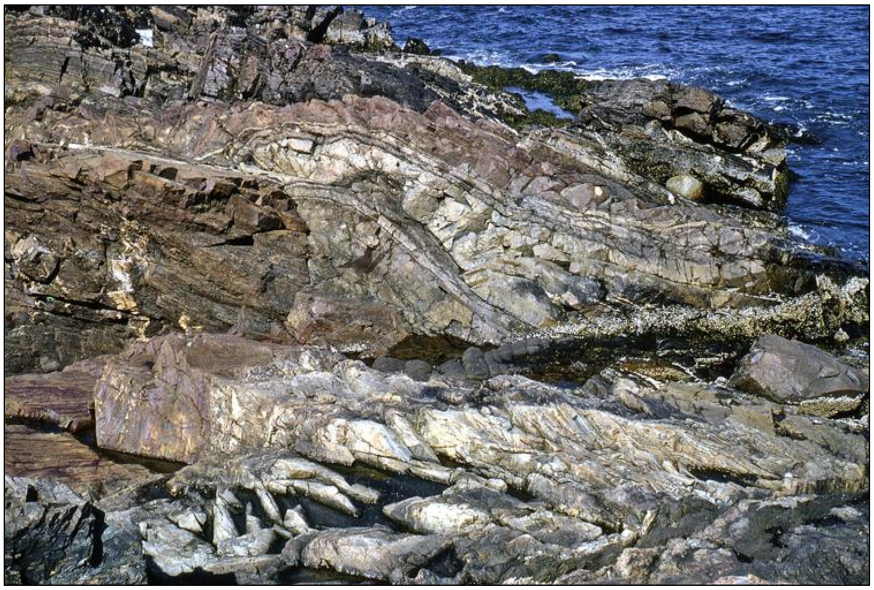

Figure 66. F_1 recumbent fold of thin- to medium-bedded Kittery Formation (**Sk**) along the Marginal Way, Ogunquit, 100 meters south of the Devils Kitchen (Figure A-2). This is refolded by gentle, open, upright F_2 folds.

Shapleigh Group

The distribution and repetition of Siluro-Devonian metasedimentary units northwest of the Phyllonite at Church Road is the result of the interference pattern between two sets of folds: a southeast-vergent nappe pair (F_1) that is refolded by asymmetric northeast-trending tight folds (F_2) (Eusden and Lyons, 1993). The earlier and larger structure is best exposed in New Hampshire where it is referred to as the Blue Hills nappe (Eusden and others, 1987). In their interpretation the Blue Hills nappe would be responsible for the largely northwest-dipping inverted sequence exposed from East Rochester to Milton, New Hampshire, on the Kittery sheet (Hussey and others, 2016). The axial trace of the nappe lies beyond the northwest corner of the Kittery sheet and not as clearly defined in Maine. Eusden and others (1987) project it to lie north of the Spaulding Pond pluton in the Milton Ponds (New Hampshire) area. In Maine the Bauneg Beg syncline, named for exposures on Bauneg Beg Mountain, Sanford, Maine (Figure 1), is an F_1 syncline below the Blue Hills Nappe. It is cored by a narrow belt of the East Rochester Formation. Its folded trace is shown from New Hampshire trending easterly, southeasterly and northeasterly to the Salmon Falls River as a function of fold interference or plutonic emplacement. Beyond the Salmon Falls River its northeast trace is offset by both strands of the Silver Mine fault, then strongly deflected to the northwest, likely caused by intrusive shouldering by the 288 Ma Lyman pluton, before disappearing in a sea of Rindgemere migmatitic schists near the Lebanon gabbro in Sanford, Maine.

Figure 67. Upright F_2 folds of thin bedding in the Kittery Formation. Note extensive transposition of bedding along S_2 cleavage planes. Quartzose beds are pale greenish due to the development of epidote in the contact aureole associated with intrusion of the Agamenticus Complex. *Along the York shore, approximately 2.4 km southwest of Perkins Cove, Ogunquit, Maine (Figure 1).*

Figure 68. Gently plunging overturned F_2 fold in the Kittery Formation. The thick quartzose bed is steeply overturned on the left (west) side of the fold hinge based on presence of well developed flute casts (Figure 14). *Moody Point, Wells, Maine (Figure 1).*

Figure 69. Inverted graded beds of the Kittery Formation folded by F_2 folds with steep axial planes. *Basket Island near Biddeford Pool, Maine (Figure 1).*

Figure 70. Upright F_2 folds in the Eliot Formation at Lee Five Corners, Lee, New Hampshire (Figure 1).

In Maine the broad expanse of inverted Towow and East Rochester formations northeast of Rochester, New Hampshire, is best explained by F_2 folding of the mostly flat overturned limb of the Blue Hills nappe (see cross-section A-A' on the geologic map). By this interpretation, the lenses of the Towow within the East Rochester Formation farther east are interpreted as F_2 synclines. The occurrence of Merchants Row Grits within the Towow is interpreted as an F_2 anticline. In support of such an interpretation, Eusden and others (1987) recognized a grit member in New Hampshire at the upper contact of the Towow, between the Towow and Littleton formations; if the Merchants Row Grits are at the same stratigraphic position, it provides a strong suggestion that the stratigraphically younger East Rochester Formation lies at a shallow depth below the sea of rusty Towow (Thompson and others, 2004) as illustrated on the cross-section. We infer an antiformal closure below upright Towow and Gully Oven towards a folded thrust contact with the Phyllonite at Church Road, as shown in our cross-section.

The extent of the Bauneg Beg syncline had not been recognized when Eusden and others (1984; 1987) and Thompson and others (2004) drew cross-sections in New Hampshire to account for the F_2 folded inverted section. Eusden and others (1987) did note the presence of an F_1 fold at Bauneg Beg that they also interpreted as southeast-facing. To account for the inverted section in New Hampshire, Eusden and others (1984) defined the F_2 Lebanon antiformal syncline that, based on facing directions in the Gully Oven Formation across a splay of the Flint Hill fault, folds the overturned limb of their Blue Hills nappe (cross-section 2A of Figure 71). Alternatively, Thompson (in Thompson and others, 2004) would have all the rocks lie in the overturned limb, with the East Rochester Formation continuing all the way southeast to the Phyllonite at Church Road (cross-section 2B of Figure 71). The folded pattern of the Towow Formation on the upright, buried F_1 limb in New Hampshire, shown on the geologic map north of Rochester, is based on magnetic signature, not on outcrop. The rocks south and southeast of the Towow could be the East Rochester Formation (**Der**) rather than the Gully Oven Formation (**Sgo**), for they are very similar rock units. The structural implications of such an interpretation remain to be resolved. All interpretations account for the Towow in similar ways in Maine and in New Hampshire, but differ in the exact extent of the early folds. In all interpretations, the nappe(s) verged easterly before F_2 folding. Interpretations differ, however, in the role played by the Phyllonite at Church Road: Did this shear zone develop during easterly transport of the nappes of the dorsal zone of Eusden and Lyons (1993) as inferred by Thompson and others (2004)? Or was an earlier zone of weakness exploited by the westerly vergence of the Berwick(?) and Merrimack Group rocks onto the Central Maine prior to or very early in the Acadian? It is clear that all had been assembled prior to F_2 folding and before intrusion of the Rochester plutons. The regional tectonic history is discussed further below.

Cleavage and Schistosity

Bedding is best preserved in the Kittery, Gully Oven, and East Rochester formations and confidently assigned S_0, following standard nomenclature in which the relative age of a structural surface (S) is indicated by a numerical subscript. Bed-parallel schistosity S_1 is often the principal foliation and is most notably displayed in the more pelitic (metashale) interbeds. In the Eliot Formation of the Merrimack Group, the Berwick Formation, the Shapleigh Group, and the rocks of the Rye Complex S_1 is the dominant schistosity and typically is parallel to lithologic layering. Rarely, S_1 is seen cross-cutting F_1 fold hinges; in the Eliot Formation, in particular, it serves as the early transposition surface. Strongly and pervasively developed S_2 axial plane

cleavage more commonly can be related easily to F_2 mesoscopic folds in the Kittery and Eliot formations at lower metamorphic grade (Figure 67). S_2 is also well represented in the more pelitic components of the Shapleigh Group. In conjunction with variably preserved sedimentary structures (graded bedding most commonly) S_2 has been useful in characterizing the larger fold structures in the map area.

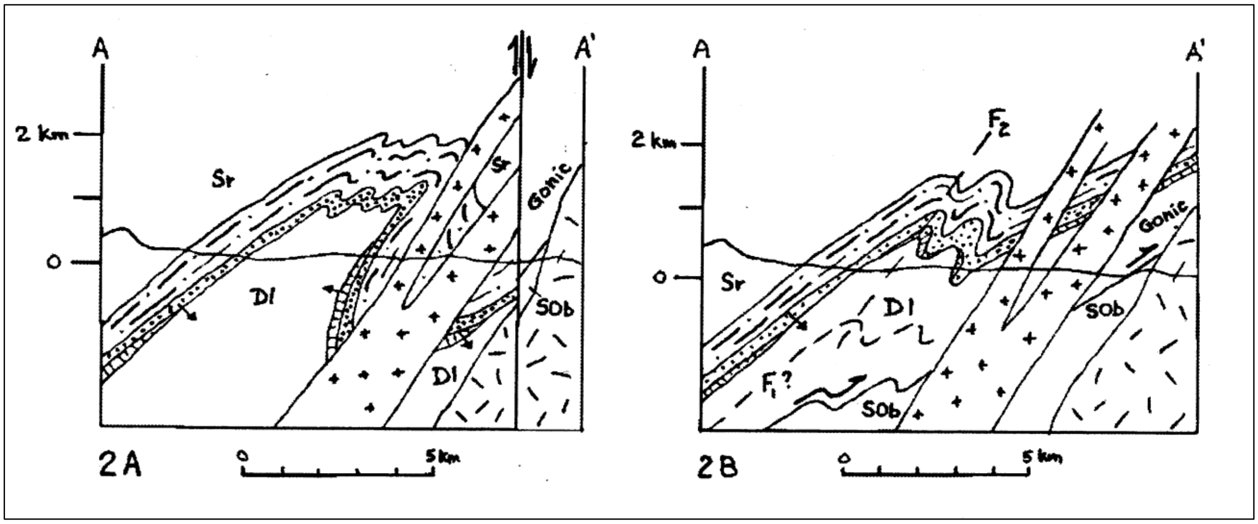

Figure 71. Cross-sections illustrating alternative interpretations of the structure of the Shapleigh Group. Northwest is to the left. Sr = Ringemere Formation; dot-dash pattern = Gulley Oven Formation; stippled patterns = Towow Formation and calc-silicate unit, with small arrows indicating stratigraphic tops; Dl (formerly Littleton Formation) = East Rochester Formation; SOb = Berwick Formation (now **DSb**); plus (+) pattern = Rochester plutons; slash (/) pattern = Barrington pluton; dashed lines in 2B show inferred axial traces of F_1 and F_2 folds. Arrows with single barb indicate fault motion. *Figure 2 of Thompson and others (2004).*

Shear fabric (discussed below) dominates zones of high strain in the Eliot Formation, the Phyllonite at Church Road (formerly Calef Member of the Berwick Formation of Freedman, 1950) and much of the Rye Complex. Fargo and Bothner (1995) identified that surface as S_3 in the Eliot and we assign that designation to the dominant fabric in the Phyllonite at Church Road.

Carrigan (1984a) used S_2 to signify the dominant foliation defining compositional layering in the Rye Complex. It is typically steeply dipping, bounds discontinuous or rootless isoclinal folds, and may anastomose in areas of higher strain. Porpoising lineations commonly decorate the S_2 and plunge up to 20° NE or SW typically over hundreds of meters. S_3 is variably but often elegantly developed as S-C fabric in mylonitic felsic gneiss in many coastal outcrops (Bothner and others, 2014; Hussey and Bothner, 1995)

Relative ages of penetrative surfaces are readily determined by cross-cutting in outcrop and are reflected in the numbering system used for the group designation. Between groups, however, that system is not easily correlated. To resolve the potential difficulty, radiometric age determinations of minerals interpreted to have grown during cleavage or schistosity development have provided some help. Wintsch (1995, written communication to WAB) has obtained an $^{40}Ar/^{39}Ar$ correlation age of ~252 Ma for muscovite formed during cleavage formation in the Eliot Formation, presumably related to the Alleghanian, rather than the long held view that much of the deformation in the Merrimack is late Silurian to earliest Devonian (Salinic or Acadian), based in large measure on the contact metamorphic overprint of the 407 Ma Exeter pluton, which postdates deformation there. The Exeter preserves cooling ages in amphibole of ~390 Ma (Wintsch, 2012, written communication to WAB) and in biotite of 380 Ma (Lux and West, 1990,

written communication) but the cooling ages do not help constrain the timing of shearing in the host rocks, which may be partitioned around it.

Stoesz and others (2013) provide a strong suggestion that mylonitic fabric (S_2) development in the Rye began at 475 Ma based on $^{40}Ar/^{39}Ar$ spectra from amphibole, confirming earlier estimates of West (1993). Later growth at lower temperatures of two muscovite generations (at ~340 and ~240 Ma) and K-feldspar (at ~280 and ~190 Ma) may be interpreted as a cooling continuum or as multiple foliation-forming events (Stoesz and others, 2013; Bothner and others, 2014). Metamorphic overprints, multiple generations of muscovite, and inclusion trails support multiple foliation events, but we recognize the possibility of a very long strain continuum as an exotic Rye block was jostled and accreted through the Permian.

Major Faults and Shear Zones

Both ductile and brittle faults of several ages are present in the Kittery sheet (Hussey and others, 2016). Two major and several smaller shear zones subdivide the map area into northeast strike-parallel zones, from northwest to southeast as follows. The Phyllonite at Church Road has an outcrop width of 1.4-2 km and forms the boundary between the rocks of the Shapleigh Group to the northwest and those of the Berwick Formation to the southeast. The Calef-Nonesuch River fault forms the boundary between the Berwick Formation and the Merrimack Group, and the Great Bay-General Sullivan shear zone, the Dover Point splay and the Nannie Island shear zone occur between and within the variably calcareous metasedimentary units of the Merrimack Group. The Portsmouth fault marks the break between the Merrimack Group and the Rye Complex. Within the Rye are the Great Common fault and the Fort Foster brittle zone.

Post-metamorphic brittle faults, presumably Mesozoic in age, are found throughout the map area and are identified by zones of silicification, alteration and/or minor mineralization, zones of variable brecciation, and gouge. We have observed no brittle faults cut by the abundant Mesozoic diabase dikes in this area.

Phyllonite at Church Road

The Phyllonite at Church Road (**Scr**) is a mappable shear zone 1.4-2 km wide. Its lithology is discussed above. We interpret this tectonite to be a phyllonite on the basis of its strong strain-related features that show various shear senses: some dextral, some sinistral, some with both senses in the same outcrop (Thompson and others, 2004; Allard and others, 2009; Lynn and Allard, 2012; Figure 7). In cross section (Hussey and others, 2016) we show this zone as a folded thrust fault with a dextral shear component, perhaps like the Messalonskee Lake thrust of Tucker and others (2001) in south central Maine and hypothesized by Hussey (1996) to separate similar lithologies on strike less than 50 km to the northeast. Early west-vergent thrusting (Salinic?) is interpreted to bring Berwick and MT lithologies over rocks of the CMT as the Merribuckfred Basin closed, followed by Acadian east-vergent nappes (e.g., the Blue Hills nappe and Bauneg Beg syncline) and thrusts, consistent with the dorsal zone of Eusden and Lyons (1993) for central New Hampshire. Later F_2 folds affect both sequences resulting in an apparent CMT over MT relationship in cross-section. The Church Road structures are constrained in age to be older than the cross-cutting ca. 364 Ma Barrington pluton. The phyllonite is also truncated at its northeast end by the 288 Ma Lyman pluton.

Nonesuch River fault and Calef fault

The Nonesuch River fault in Maine, continuing into New Hampshire as the Calef fault, forms the boundary between the Berwick and Eliot formations (inset map of Hussey and others, 2016). The Calef phyllonite was defined originally as the Calef Member of the Eliot Formation by Freedman (1950), consisting of carbonaceous black phyllite. The degree of layer-parallel transposition, shear fabric development, accompanied by dismembered quartz pods suggested to Loveless (2002) and Loveless and Schulz (2002) that this discontinuous sheared body represents a fault zone. In areas where no phyllonite crops out at the contact between the Eliot and Berwick formations, Escamilla-Casas (2003) describes dismembered beds in duplex arrangements at the boundary between the Eliot and Berwick on strike with the carbonaceous phyllonite. Along the trace of the Nonesuch River fault on strike farther northeast in Maine, breccia and silicified zones with drusy quartz veins are present along the linear trend of the Nonesuch River in the Old Orchard Beach 7.5 map sheet (Hussey, 2003) separating the Berwick Formation at lower amphibolite (staurolite) metamorphic grade from the Eliot Formation at low greenschist (albite-chlorite facies) grade. These faults are interpreted to represent segments of the Norumbega fault system in the Kittery 1:100,000 map sheet. The Nonesuch River/Calef fault post-dates the regional metamorphism of probable Acadian age. It cuts the Saco pluton but does not intersect other major Salinic or Acadian-age plutons. ^{40}Ar/^{39}Ar analysis of hornblende, muscovite, biotite, and K-feldspar across the related Flying Point Fault in the Portland 100,000 sheet (West and others, 1993) suggests that renewed displacement may have continued into the Mesozoic era, with approximately 4 km of west-side-up cumulative motion since inception.

Great Bay, Dover Point, General Sullivan, and Nannie Island faults

Shear zones also occur in the Great Bay area within and between the Eliot and Kittery formations in well-exposed shoreline outcrops at Dover Point, General Sullivan Bridge, Thomas Point, and Woodman Point/Nannie Island (Figure 1). They are named for these localities. Great Bay and Dover Point faults and General Sullivan splay and the Nannie Island fault show extreme levels of layer transposition, subvertical closely spaced foliation, dismembered metashale layers, isolated fold hinges and "phyllitic fish." These kinematic indicators record a dominant dextral shear sense, but both senses of shear are present (Fargo and Bothner, 1995). Lack of outcrop and strike parallelism prevent extension of these structures farther northeast.

Portsmouth fault

The Portsmouth fault apparently has a long history. It separates the Rye Complex from the Kittery Formation. Strongly sheared amphibolite-facies schists, quartzo-feldspathic mylonitic gneisses, and variably sheared felsic intrusives that characterize the Rye are typical of this complex. They are juxtaposed against feldspathic and variably calcareous metasandstones and minor metashales at lower greenschist facies of the Kittery Formation across a transition zone 200-500 meters wide in the Portsmouth Harbor area (Carrigan, 1984a; Rickerich, 1983) and less than 100 meters on Gerrish Island (Hussey, 1980). Little or no shear fabric is developed in the adjacent Kittery Formation. Fault breccia consisting of clasts of both Rye and Kittery lithologies, slickensided blocks with a range of orientations, and minor hydrothermal alteration along the fault indicate that the last motion was brittle. Slip sense deduced from slickensides, breccia and abrupt change in metamorphic grade (first recognized by Novotny, 1969) suggest a steep west-dipping normal fault, west side down. The age of this movement may be as young as Mesozoic. No dikes have been traced across the Portsmouth fault zone within the area of the

Kittery map, but K-Ar dated diabase dikes (290-300 Ma) cut brecciated Rye in New Castle Harbor (Rand, 1974) and in the Seabrook area (Bellini and others, 1982).

Great Common fault zone and Fort Foster brittle zone

Named for New Castle's colonial park (Carrigan, 1984b; 1984c), the Great Common fault zone is traceable across Portsmouth Harbor where it continues as the Fort Foster brittle zone in Maine (Swanson, 1988). Pervasive ductile structure occurs throughout the Rye, but shear is concentrated in the Portsmouth fault zone and in the Great Common fault zone. The latter, originally mapped as an internal boundary in the Rye separating metavolcanic from metasedimentary members (Novotny, 1969; Billings, 1956), is now recognized as a laminated ultramylonite 100-200 meters wide. The high strain zone consists of chocolate brown ultramylonite where protoliths are quartzo-feldspathic, and dark greenish black ultramylonite where dominated by calc-silicate protoliths (para-amphibolite). Some very fine examples of simple shear deformation features are preserved, such as S-C structure, sigma clasts, mica fish, asymmetric boudins at varying scales, and many others. Swanson (in Swanson and Carrigan, 1984) describes ultramylonites on Gerrish Island, Kittery, Maine (Figure 19a). Swanson (1988) describes pseudotachylyte generation zones parallel to ultramylonite laminations that locally 'feed' fused host rock into cross (gash) fractures (Figure 72).

Figure 72. Blastomylonitic quartz-feldspar gneiss of the Rye Complex. Irregular masses of buff-weathering pseudotachylyte fill late gash veins. *Just west of the Coast Guard station and UNH marine dock, New Castle town park, New Hampshire.*

The age of latest brittle motion in the Great Common Fault zone predates the emplacement of widespread Mesozoic diabase dikes in the Rye Complex. Hussey (1980) and Swanson (1988) map several dikes that clearly cut the Fort Foster Brittle Zone (and intrusive breccia) on Gerrish Island. In the absence of radiometric age determinations of deformed, presumably Devonian igneous rocks within the Complex, these observations constrain movement to the middle to late Paleozoic (Alleghanian?) movement on a probable Norumbega strand (Swanson, 1992).

Boeckeler (1994) sampled pseudotachylyte from slip surfaces and gash fracture fillings in ultramylonite in the fault zone and obtained a poorly constrained 298 ±31 Ma Rb-Sr isochron, consistent with Alleghanian deformation. Subsequent work by O'Brien and van der Pluijm (2012, personal communication to WAB) suggests last, but brittle motion as young as 235-238 Ma, similar to the time of emplacement of the Agamenticus Complex, but before emplacement of many of the Mesozoic dikes.

The timing of earlier ductile motion, as well the number of discrete strain events in the Rye, is more difficult to constrain, even with many new radiometric ages. A 482 Ma U-Pb zircon age is so far the oldest recognized intrusive age from a metaigneous rock in the Rye (Kane and others, 2014). Blastomylonitic quartzo-feldspathic gneiss (451 Ma, U-Pb zircon; Figure 20), the variably strained 403 Ma Breakfast Hill granite, 380 Ma Salamander Point and 361 Appledore Island diorites and other felsic intrusions in the Rye show variable shear fabrics (Bothner and others, 2014). These may be interpreted to represent a single and shorter late Paleozoic event or support a long strain history beginning much earlier. Stoesz and others (2013) use a $^{40}Ar/^{39}Ar$ amphibole cooling age of 475 Ma from amphibolite to suggest initial ductile strain in the Ordovician. Bothner and others (2014) include those data to place the age of major mylonite fabric development between about 400 and 240 Ma and suggest, following some of Swanson's (1992) and Bothner and Hussey's (1999) arguments that initial ductile motion transitioned to brittle during uplift in a restraining bend of the Norumbega system.

Along the Marginal Way in Ogunquit and southward toward Bald Head Cliff in York (Figure 1), late brittle faults and shear zones are common. They are generally marked by slightly offset basalt dikes and rusty-weathering zones in the Kittery Formation caused by weathering of hydrothermally introduced calcite, ankerite, and pyrite. Two of these zones, the Little Beach and the Devil's Kitchen fault zones, are significant in that they have caused severe erosional damage to the Marginal Way footpath (for location see Appendix 3, Figure A-2). The Little Beach fault zone (Figure 73), is responsible for the development of the Little Beach reentrant along the Marginal Way. This fault is a zone approximately 40 meters wide of hydrothermally altered rusty-weathering brecciated Kittery Formation in the midde of which is a 2-4 cm zone of finely comminuted gray gouge (Figure 74). Continued wave attack here required the building of a retaining wall along the path in 2007 to prevent further erosion. However, part of the gouge and rusty-weathered zone is still exposed below the footing of the wall and poses a threat of continued backward erosion that would undermine the retaining wall, resulting in further erosion to the footpath. Approximately 300 meters south of the Little Beach fault, another late fault along the Marginal Way approximately subparallel to the Little Beach Fault is inferred. This has caused a deep reentrant known as the Devil's Kitchen to be formed by wave erosion, and poses a threat to the Marginal Way footpath, requiring extensive placement of rip-rap boulders to protect the footpath from further erosion, and repair to the fencing that protects users of the path. At the Devil's Kitchen a minor right-lateral north-northwest trending fault cuts across the reentrant and is responsible for a marked topographic notch. Movement along this has offset nearby basalt dikes approximately 0.5 to 1 meter. Observed offsets along similar minor faults are common in the Kittery Formation elsewhere and seldom exceed 1 meter.

Figure 73. Little Beach fault along the Marginal Way, Ogunquit, Maine (Figure A-2). Metamorphosed wacke and phyllite of the Kittery Formation are very rusty in this zone due to the weathering of iron carbonate and iron sulfide introduced by hydrothermal fluids during shearing. Footwall of the fault is to the right.

Figure 74. Knife blade in fine gouge along the Little Beach Fault. Gouge is the consistency of fine clay.

The bedrock exposure along the Marginal Way near bench #2 (about 150 meters north of the Little Beach fault, Figure A-2) reveals important relative age data between diabase/basalt dike intrusion and development of rusty-weathering shear zones. Here several northeast-trending diabase and basalt dikes cut the Kittery Formation. Several rusty shear zones trending nearly north-south cut these dikes but the offset is generally less than 10 centimeters. At this locality, a nearly north-south-trending diabase dike (possibly an extension of the dike at the footbridge) is bounded at both contacts by a rusty zone that does not appear to alter the dike margins. This suggests two possibilities: 1) the rusty zone was developed before the intrusion of the dike and

that the dike merely dilated the rusty zone (preferred by AMH); or 2) two rusty zones developed independently, guided in their orientation by the difference between the rheologies of the ~N-S–trending dike and the Kittery Formation. These two rusty zones also cut the earlier set of northeast-trending zones. The question still remains whether there is close contemporaneity between the ~N-S dike and the shearing.

Brittle faults and silicified zones

Brittle faults occur in the western and northwestern part of the Kittery 1:100,000 sheet. The Gonic fault cuts the probable northeast continuation of the Campbell Hill–Hall Mountain fault in the Rochester, New Hampshire, area (see inset map of Hussey and others, 2016). Both are characterized by silicification and milky quartz accumulations and they offset both the Phyllonite at Church Road and the Barrington pluton. The Gonic fault at its south end is apparently cut by the Hetnar fault (of Schulz, 2004), which connects with the Calef fault just west of the Kittery sheet. The Silver Mine fault in Lebanon, Maine, is a subvertical north-northwest trending structure that has about 1 km right strike separation across the fault near the northwestern end, and perhaps twice that distance where it offsets the axial region of the major nappe fold to the southeast before terminating in the steeply dipping Phyllonite at Church Road. It then disappears in the Berwick Formation. Horsetails develop at about the midpoint where the larger splay trends increasingly parallel to northeast-striking beds of the East Rochester Formation. Vertical offset may be as much as 1-2 km in the area of the offset axial trace, but diminishes rapidly to the southeast. The Silver Mine fault did provide an important zone for silicification and open stockwork lead-silver mineralization. This was the site of the Acton-Lebanon silver prospecting activity in the latter part of the 19th century (King, 2000; Thompson, 2004).

At two localities east of the Webhannet pluton in the town of Wells, silicified lenses composed of massive milky quartz occur within the Kittery Formation. They are on strike with two other localities, where diabase dikes are crowded with angular milky quartz xenoliths (Figure 43). These four localities define a north-northeast–trending line nearly on strike with the Cape Elizabeth fault zone in the Casco Bay area (Berry and Hussey, 1998), which is also characterized by massive milky quartz pods and lenses. Silicified zones have not been observed in the Agamenticus Complex or Biddeford pluton. This suggests either that the silicified zones are discontinuous and did not extend to the margins of these plutons or the silicified zones are older than the 383 Ma Biddeford pluton.

VI. METAMORPHISM

Kittery and Eliot Formations

Regional greenschist-facies metamorphism characterizes the Kittery and Eliot formations in the map area. Two subfacies are recognized on the basis of mineral assemblages in calcareous beds; these are usually in the coarser-grained bottoms of turbidites. The lower grade is characterized by the assemblage chlorite-albite-ankerite-calcite-quartz. These rocks typically weather slightly rusty due to the alteration of ankerite to limonite. The higher grade is characterized by the assemblage chlorite-biotite-calcite-plagioclase-quartz and is not rusty weathering. Mica-rich beds (usually the upper parts of turbidite beds and rare individual metashale beds) generally lack sufficient aluminum to produce high-grade aluminous minerals such as staurolite, andalusite, or sillimanite.

Contact metamorphic aureoles are present around the large plutons and the small gabbro complexes. These hornfelsic contact rocks are commonly characterized by higher-grade calc-silicate minerals such as actinolite, hornblende, diopside, and grossularite. In a few places pyroxene and sillimanite have been observed in the Kittery and Eliot at the contact with the Exeter pluton in New Hampshire, and pyroxene, cordierite (Figure 33), mullite? and sanidine in the Cape Neddick Complex contact aureole at Cape Neddick, Maine.

Berwick Formation

Biotite and calc-silicate granofels of the Berwick Formation, like the nearby Kittery and Eliot formations, do not lend themselves compositionally to produce typical index metamorphic minerals. The assemblages in the Berwick consist of quartz, plagioclase, actinolite or hornblende, diopside and grossularite in the calc-silicate parts, and biotite and occasionally garnet in the more quartzo-feldspathic layers. These assemblages are compatible with the upper greenschist and epidote-amphibolite facies of metamorphism (Guidotti, 1985; Lyons and others, 1997). Metamorphic zones are parallel to the northeasterly regional strike of the affected units.

Shapleigh Group

Metamorphic zones of lower to upper amphibolite facies metamorphic rocks of the Shapleigh Group crop out northwest of Campbell Hill-Hall Mountain and the Phyllonite at Church Road (previously the Gonic Formation); they are parallel to the regional strike. As demonstrated by Eusden and others (1984) and illustrated in New Hampshire by Lyons and others (1997) and in Maine by Guidotti (1985), metamorphic grade does not increase progressively perpendicular to the northeast strike but rather, the lower grade garnet-staurolite-andalusite zone is repeated, as if folded, with staurolite-absent sillimanite rocks on either side of it. In New Hampshire these metamorphic zones cross the contacts between the Gully Oven, Towow, and East Rochester formations and are only slightly offset by late brittle faults.

On strike in Maine, the metamorphic zone repetition is less well constrained. Metamorphic grade increases northwesterly in part perhaps because of the broader expanses of the East Rochester and Towow formations. Coarsely porphyroblastic andalusite-garnet schists are characteristic of the East Rochester Formation through much of its extent, and schists of the Gully Oven similarly have large porphyroblasts of andalusite in the more southeastern belt and sillimanite after andalusite in the more northwesterly belt. The increasing metamorphic grade

between the two belts is less well defined than might be expected because of the intervening belt of finer-grained more sulfidic rocks of the Towow Formation. Its bulk composition is less likely to produce the key index minerals to identify such a smooth trend.

Much of the Rindgemere Formation in the northwestern part of the map consists of sillimanite + muscovite and sillimanite + K-feldspar bearing rocks that are migmatitic and contain abundant pegmatite. In a few rare places calc-silicate nodules 1 meter or more in diameter occur in a chaotic matrix of schist and migmatite. Biotite-muscovite granite bodies are more common in this unit than in the others and may be locally derived by partial melting (Thompson, 2004).

Rye Complex

Rocks of the Rye Complex are metamorphosed to epidote-amphibolite to middle amphibolite facies onshore, and upper amphibolite facies offshore (Brooks, 1986). At least two episodes of regional metamorphism are recorded in its complex polydeformational history. Increasing grade, from northwest to southeast, has long been recognized: Novotny (1969) mapped chlorite, biotite, oligoclase-actinolite, and sillimanite zones from the Portsmouth Fault to the coast; Billings (1956), based in part on Novotny's dissertation work in 1953-54, showed biotite, garnet, staurolite, and sillimanite isograds that define a metamorphic dome truncated on the southeast by the ocean. Carrigan (1984a; 1984c) refined the distribution of isograds in pelitic and calc-silicate protoliths. He identified a lower grade, greenschist facies zone within both the Kittery and his Kittery/Rye transition zone, thus expanding the width of the Portsmouth Fault and convincingly argues for a metamorphic break beyond that zone parallel to the Great Common Fault Zone. Grade continues to increase again offshore to upper amphibolite faces (Brooks, 1986). Welch (1993) conducted microprobe analyses on plagioclase-amphibole pairs in amphibolite and garnet-biotite in pelitic rocks from opposite sides of the Great Common fault zone in New Castle, New Hampshire. Thermobarometry from lower grade andalusite-garnet-biotite schist, quartzite, and minor calc-silicate rocks suggests a difference in metamorphic conditions of ~150°C and 1 kb lower than in strongly sheared sillimanite-garnet schist and undeformed amphibolite exposed north of the fault. Assuming equilibrium of garnet-biotite pairs prior to faulting, these values suggest about a 3 km vertical component of post-metamorphic, west-side-up displacement on the Great Common Fault

VIII. SYNOPSIS OF SEDIMENTATION, TECTONIC, AND INTRUSIVE HISTORY

Hussey and others (2010) discussed evidence bearing on the sedimentation history of southern Maine and New Hampshire. Metasedimentary rocks of the Rye (amphibolite-facies pelitic and carbonaceous schists, quartzo-feldspathic and calc-silicate granofels and rare marble, and amphibolites) indicate deposition of clastic, carbonate, and volcanic(?) rocks in Cambrian – Early Ordovician time based on detrital zircon data. We suspect this assemblage was deposited on Ganderian basement based on Nd signatures of Devonian igneous rocks intruding the Rye Complex (Dorais and others, 2014) and interpretations of the nearby Massabesic Gneiss Complex just southwest of the Kittery sheet in New Hampshire (Dorais and others, 2012). The Rye Complex was metamorphosed and deformed during and after Ordovician intrusion, perhaps multiple times.

Rocks of the Merrimack Group accumulated in the southern extension of the Merribuckfred Basin during early Silurian time as interpreted by Hussey and others (2010), but evidence for a positive landform separating the Central Maine and Merribuckfred basins within the Kittery 1:100,000 map area south of the Biddeford pluton during Silurian to Early Devonian time is lacking. To the north in the Portland and Bath 1:100,000 map sheets, however, where the Eliot and Jewell formations interfinger, these two basins were separated by the Falmouth-Brunswick–Casco Bay volcanic arc during that time interval (Hussey and others, 2010).

Important evidence from primary sedimentary structures (flute casts and foreset beds of climbing ripples previously discussed) suggests that the Kittery Formation and probably the Eliot Formation were derived from peri-Gondwanan source areas to the east. This does not rule out contributions from Bronson Hill and Laurentian sources to the west. Detrital zircon age spectra reported for these rocks by Sorota and others (2012) and Sorota (2013) point to both peri-Gondwanan and Laurentian sources. Rapid deposition of these turbidite sediments, a major deformation (Salinic), and associated regional metamorphism are strongly implied before post-tectonic intrusion of the Newburyport pluton in latest Silurian time (418 Ma) and the Exeter pluton in Early Devonian time (407 Ma).

By Late Silurian time the basin had been uplifted to a mountainous terrane that likely underwent erosion to supply Latest Silurian to Early Devonian sediments to the Central Maine Basin. This is consistent with conclusions of Bradley and Hanson (2002) about an easterly provenance for the Early Devonian Carrabassett Formation (probable correlative of the East Rochester Formation) and Late Silurian to Early Devonian Madrid Formation in the Rangeley area. Accepting the older 432 Ma age for the youngest detrital zircon as representative of the Merrimack rocks does not rule out correlation of the Merrimack Group with rocks of the Fredericton trough in which Ludman and others (2014) have reported a compatible 431 ±3 Ma youngest detrital zircon population from the Flume Ridge Formation. That sequence similarly is intruded post-tectonically by plutons of Late Silurian age, for example, the Pocomoonshine gabbro (423 ±3 Ma) reported by West and others (1992).

The Shapleigh Group accumulated in the Central Maine Basin in Silurian to Early Devonian time. Rocks as old as Late Cambrian underlie correlative formations near Rangeley, Maine, but are not exposed here. Provenance for the Silurian and older formations is interpreted to be Laurentia to the west based on regional facies considerations in the Rangeley area. Early

Devonian sedimentary rocks in the Central Maine Basin in the Rangeley area (Madrid and Carrabassett formations) have an easterly provenance based on the sedimentological analysis of Bradley and Hanson (2002) and may have been derived mostly from cannibalization of the previously uplifted, intruded, and deformed Merribuckfred Basin rocks. The formations of the Central Maine Basin were multiply deformed and metamorphosed during the main Acadian event and intruded by Early Devonian plutons during a later phase of the Acadian orogeny (Neo-Acadian). The intrusion of the Lyman pluton and other granitoid plutons and pegmatites to the north suggests a relation to the Alleghanian orogeny of Carboniferous-Permian age, although major deformational features associated with this thermal event have not been identified in the area of the Kittery map sheet.

How the Berwick Formation fits into the sedimentary and tectonic framework remains a challenge. If the Berwick Formation is a facies of the Late Silurian to Early Devonian Madrid Formation or rocks of the Vassalboro Group, then those sediments may have been derived from a mix of sources: Laurentian sources to the west, peri-Gondwanan sources to the east and/or cannibalization of uplifted Merribuckfred Basin rocks (Hussey and others, 2010). By the time of its Silurian to Early Devonian deposition likely no distinction between the Merribuckfred and Central Maine basins existed.

Deformation and regional metamorphism in the Kittery 1:100,000 area are related to two principal compressional events, the late Silurian Salinic orogeny and the Early to Middle Devonian Acadian orogeny (Hussey and others, 2010). These are constrained in age by the radiometric ages of widespread plutons. Figure 75 summarizes graphically the ages of the plutons related to these orogenies. Table 2 summarizes the best available geochronology. The Exeter (407 Ma) and Breakfast Hill (403 Ma) plutons were intruded immediately following the Salinic orogeny, and the Nisbitt Pond (383 Ma), Webhannet (383 Ma), Biddeford (383 Ma), and Salamander Point (380 Ma) plutons were emplaced after the main pulse of the Acadian orogeny. The Appledore (361 Ma) and Barrington (ca. 364 Ma) plutons are distinctly later (Late Devonian to Early Carboniferous). The Early Permian Lyman pluton (288 Ma) and the Sebago pluton (ca. 296 Ma) (just north of the Kittery map sheet) are best tied to the Alleghanian orogeny, a transpressional event (Brooks and Bothner, 1989) associated with amalgamation of continents to form the supercontinent Pangea by Late Permian time. Intrusion of the basalt dike swarms in Triassic to Jurassic time results from the initial break up of Pangea, which in this area led to a separation of North America from Africa. Intrusion of the Triassic Agamenticus Complex (completed at 239 Ma) and the Cretaceous mafic complexes are probably related to separation of the two continents due to continued widening of the Atlantic Ocean, perhaps as the North American plate passed over one or more hot spots (Duncan, 1984; Thompson and others, 1993).

Thrust faulting that resulted in the juxtaposition of the Merrimack Group against and over the Berwick Formation and the Shapleigh Group and took place after the most recent regional metamorphism presumably related to the Acadian orogeny. East vergent folding and thrusting related to Eusden and Lyons's (2003) dorsal zone in central New Hampshire may be responsible for the east verging folds of the Blue Hills nappe and inferred in the Church Road and Calef faults. In the northern part of the map sheet the Berwick Formation has been metamorphosed to high greenschist facies and low amphibolite facies, while the adjacent Eliot and Kittery formations are at low greenschist facies. It is possible that the Church Road and Calef faults may be associated with Alleghanian transpression in late Carboniferous to Early Permian time. The Portsmouth Fault, which separates the Rye Complex and Merrimack Group, the Great Common

Fault, and the shear zone represented by the Phyllonite of Church Road may be of similar age and origin. The age of the Dover Point and the related General Sullivan and Nannie Island faults is pre-Mesozoic because the Dover Point fault is inferred to be cut by a major diabase dike as it is projected beneath Great Bay. The numerous minor shear zones with gouge and carbonate mineralization such as the Little Beach fault along the Marginal Way in Ogunquit (described above), and the silicified zone east of the Webhannet pluton, are not well known. If not all, at least some of them are likely Mesozoic high-angle faults.

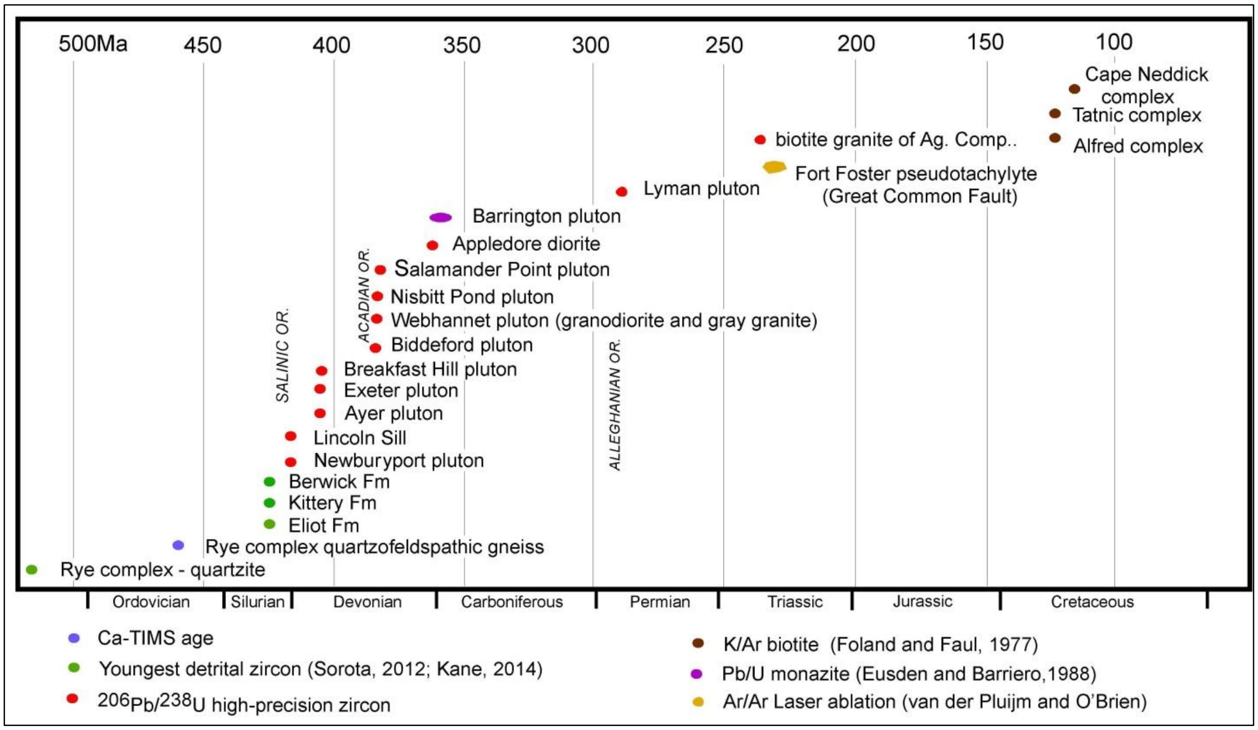

Figure 75. Graphical summary of radiometric ages reported in the text related to various orogenic events. The CA-TIMS age from the Rye Complex, and the youngest detrital zircon ages constrain protolith ages of sedimentary and metamorphic rocks. The Ar/Ar age for pseudotachylyte approximates the time of deformation. All other ages are interpreted to date the time of pluton crystallization.

Table 2. Summary of isotope geochronology of the Kittery 1:100,000 sheet.

Rock Unit	Isotopic System	Age (Ma)	Source
Pluton crystallization ages			
Cape Neddick Complex, gabbro	$^{40}Ar/^{39}Ar$ biotite	120.6 ± 0.4	3
Tatnic Complex, quartz diorite	$^{40}Ar/^{39}Ar$ biotite	122 ± 2	3
Alfred Complex, monzodiorite	$^{40}Ar/^{39}Ar$ biotite	120.4 ± 1.0	3
Lebanon diorite	$^{40}Ar/^{39}Ar$, biotite	125 ± 3	4
Agamenticus Complex, granite	U-Pb, zircon	238.9 ± 0.3	1
Lyman pluton, biotite granite	U-Pb, zircon	287.6 ±0.4	1
Barrington pluton, granite	U-Pb, monazite	ca. 364	2
Appledore diorite	U-Pb, zircon	361.1 ±0.4	1
Salamander Point diorite	U-Pb, zircon	380.1 ±0.5	1
Nisbitt Pond pluton, granite	U-Pb, zircon	383.1 ±0.5	1
Webhannet pluton, granodiorite	U-Pb, zircon	382.9 ±0.5	1
Webhannet pluton, granite	U-Pb, zircon	383.1 ±0.5	1
Biddeford pluton, granite	U-Pb, zircon	382.7 ±0.5	1
Biddeford pluton, granite	U-Pb, zircon	383.3 ±0.5	1
Breakfast Hill granite	U-Pb, zircon	402.9 ±0.5	1
Exeter pluton, diorite	U-Pb, zircon	407.4 ±0.5	1
Rye Complex, sheared granite	U-Pb, zircon	482	6
Ages of youngest detrital zircon			
Berwick Formation	U-Pb, zircon	409 ±11*	5
Eliot Formation	U-Pb, zircon	409 ±19*	5
Kittery Formation	U-Pb, zircon	413 ±12*	5
Kittery Formation	U-Pb, zircon	432.2 ±0.7	5
Rye Complex, mylonitic gneiss	U-Pb, zircon	451.1 ±0.7	1
Rye Complex, micaceous quartzite	U-Pb, zircon	529.7 ± 8.8*	6

* Uncertainty for LA-ICPMS ages is 1σ; all others are 2σ.

Geochronology Sources: 1. This report; 2. Eusden and Barreiro (1988); 3. attributed to Hubacher and Foland (1991) by McEnroe (1996); 4. McEnroe (1996); 5. Sorota (2013); 6. Kane and others (2014).

VIII. ECONOMIC GEOLOGY

The principal bedrock mining and quarrying activities, past and present, in the Kittery 1:100,000 map sheet center around the production of monuments, dimension stone, rip-rap, and crushed stone from granite and other igneous rocks. These rocks are generally referred to by quarrymen and marketers as various colors of granite, even though, technically, they include syenite, monzodiorite, and gabbro in addition to true granite. The only granite quarries in operation at the present time are in the Webhannet pluton (Millennium Granite Company in Wells, and Pike Corporation with large crushed rock quarries in Eliot and Wells). During the late 1800's mining boom, considerable interest was expressed in the silver, lead, and zinc potential along the Silver Mine fault in the Acton area (Figure 1). Semi-precious mineral collecting localities are relatively few, but include notably the vesuvianite locality in South Sanford (King, 2000). Rose quartz has been collected from a pegmatite associated with the Biddeford pluton in the Cape Porpoise area of Kennebunkport. These are discussed briefly below. It should be understood that the greatest value of commodities produced comes from surficial sand and gravel deposits throughout the area, and clay for the making of brick, but a more thorough discussion of these is out of the purview of this bulletin dealing with bedrock geology.

Alfred Complex

The Bennett quarry (Dale, 1907), located in the town of Alfred 1 mile southwest of Alfred village, was opened prior to 1875 and operated by the Bennett brothers of Alfred, Maine. The rock quarried was a buff gray medium-grained monzodiorite (quartz diorite of Dale, 1907). In 1905 the quarry measured 60 by 150 feet and had a depth up to 30 feet. The quarry was inactive in 1905 at the time of Dale's visit, and no records indicate any activity since. Transport of the granite was by cart 1 mile to the Alfred railroad station. Monzodiorite from the Bennett quarry was used for curbing and buildings. An example is the Parsons Memorial Library in Alfred village, Maine (Dale, 1907).

Tatnic Complex

Gabbronorite ("black granite" of commercial operators) from the Tatnic Complex has been quarried from three openings. Two of these, the Miniutti quarry and the Spence and Coombs quarry were located on Welch Hill (Austin and Hussey, 1958), and the other, Swenson black granite quarry, located on the hill 1 km east-northeast of the Miniutti quarry. The Spence and Coombs and the Miniutti quarries were operated intermittently during the early 1900s, producing monument stones. The Swenson black granite quarry was opened about 1958 (Figure 76) but was abandoned by 1960 because of irregularly-spaced white veins, and the inconsistent color quality of the stone. By the time of this writing, the nearby Pike stone quarry in the town of Wells had reached the edge of the Tatnic Complex and may have obliterated the Swenson opening.

Agamenticus Complex

In the early 1960's the Swenson Granite Company of Concord, New Hampshire opened a quarry at Pine Hill in the alkalic syenite near the town of Ogunquit. Marketed as Swenson green granite, it is the only green granite produced in the United States. Structures made with Swenson

Green can be seen in the Prudential Center in Boston and the public library in Detroit, Michigan (Peter Moore in York Weekly, February 22, 2006). Irregular blocks that were rejected as dimension stone because of their color variability or their irregular shape have been used extensively as rip rap in many nearby coastal communities.

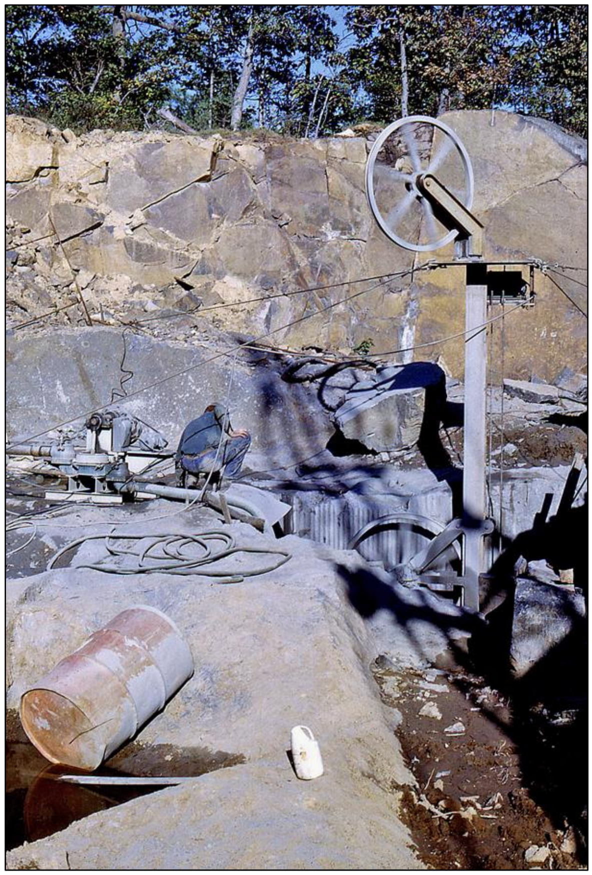

Figure 76. Swenson "black granite" opening in the gabbronorite of the Tatnic Complex. Vertical cuts in the gabbronorite were made with wire saws charged with silicon carbide grit. Vertical lift was done along sheeting surfaces using splitting wedges.

Biddeford Pluton

Several granite quarries were opened in the Biddeford pluton, producing dimension stone beginning as early as 1862 (Dale, 1923), but none were active in 1958 when the senior author (AMH II) first visited them. The granite produced from these quarries was non-foliated, medium- to coarse-grained in texture, light gray with a slight pinkish or bluish cast, and had a distinct contrast between light minerals (quartz, plagioclase, microcline) and moderately large mica books.

Two of these quarries, the Day quarry and the Ross quarry, are located in the town of Arundel (originally North Kennebunkport) about 8 miles west of Biddeford. The Day quarry was opened about 1899. According to Dale (1923) the product was used in bridge work, particularly for the Boston and Maine Railroad, and in construction of the drydock at the Kittery Naval Shipyard. The Ross quarry was opened in 1887, and according to Dale (1907) had

reached dimensions of 200 feet by 200 feet, and 35 feet depth. Specimen structures of the Ross quarry granite are the Hope Cemetery gateway in Kennebunk, and the railroad bridge in Haverhill, Massachusetts (Austin and Hussey, 1958.)

Quarries in Biddeford are located just southeast of the built-up area of the city. Included are the Ricker quarry, Gowen Emmons quarry, Marcelle and Wormwood quarry, Andrews and Perkins quarries, and Goodwin quarry. The Ricker quarry opened in 1865 and supplied mostly monument stones. The Gowen Emmons quarry, which opened around 1865 was one of the largest of the granite quarries in the Biddeford pluton. One pit measured 200 feet long by 100 feet wide by 30 to 70 feet depth, and the other 250 feet by 200 feet, 10-60 feet depth. According to Dale (1907) the plant boasted 5 derricks, 2 hoisting engines, and 2 polishers. Specimen structures of granite from this quarry include the Lincoln Monument in Springfield, Illinois, and a hospital (name not specified) in Dover, New Hampshire. The Marcille and Wormwood quarry, a relatively small opening, supplied granite for trimmings on St. Joseph's Church and Saint Mary's Convent in Biddeford, and the dry dock in Charlestown, Massachusetts. The Andrews and Perkins quarry opened in 1862 and by 1907 had 10 derricks, 3 hoisting engines, 4 steam drills, and 4 water pumps (Dale, 1907). Specimen structures include the Tribune Building in New York, General Dix monument at Fort Monroe, Virginia, granite blocks for the Saco and Delaware Rivers and curbstones for Dover and Rochester, New Hampshire. Production and specimen structures from the Goodwin quarry, a little southeast of the Andrews and Perkins quarry, are not given by either Dale (1907) or Austin and Hussey (1958).

Webhannet Pluton

Four major quarries in the Webhannet pluton include the Millennium Granite quarry at Bald Hill in Wells, Maine, the Hanscomb quarry in South Berwick, the Pike Industries quarry in Eliot, and the Pike Industries quarry straddling the town line between Wells and South Berwick. The Millennium quarry (previously known variously as the Bald Hill quarry, Swenson pink granite quarry, and High Pine quarry) is the only active quarry that produces dimension stone for monuments, building facings, and landscaping. Operations at the Bald Hill quarry were begun by Albino Miniutti, brother of Angelo who operated the Miniutti black granite quarry. In 1927 the Bald Hill quarry was sold to John Swenson Granite Company of Concord, New Hampshire, that operated the quarry until the mid-1970's. In 1958 the quarry had a maximum depth of 105 feet (Figure 77). Figure 78 is an aerial view of the quarry at the peak of its development. Specimen structures for which the stone was supplied when operating as the Swenson pink granite quarry include plaza at Tomb of the Unknowns in Arlington, Virginia, House of Seagram building in New York, part of the Pentagon building in Washington, D.C., John Hancock building in Boston, Massachusetts, and many other buildings throughout the eastern part of the United States. Irregular blocks of "Swenson pink" were used as rip-rap to form the extensive north and south jetties at the mouth of Wells Harbor. During a short interval of time after World War II, a railroad spur off the old Eastern Division of the Boston and Maine Railroad (Figure 78) provided rail transportation for much of their products, including crushed rock for paving aggregate and ballast. All finishing was done at the home plant in Concord, New Hampshire. The Bald Hill quarry remained idle until the about 2000 when the Millennium Granite Company of Wells resumed operations and started producing finished dimension stone of various types, including monument stones, thin slabs for counter tops, and landscaping stone. Stone finishing, including polishing, is now done on site (Figure 79).

Figure 77. Bald Hill quarry in the Webhannet pluton, Wells, Maine, active in 1958. The bottom of the pit where the workmen are cleaning rubble from the floor was approximately 105 feet below the surface. Boiler halves beside the workers are used for hoisting rubble to the surface, and moving quarrying equipment in the opening.

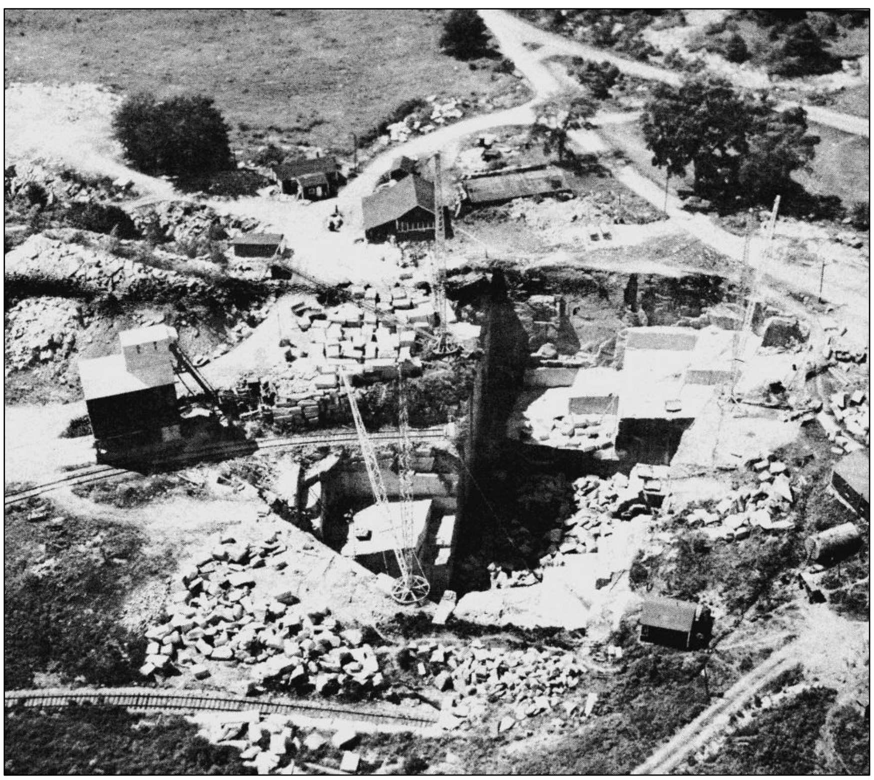

Figure 78. Aerial view of Swenson's Bald Hill quarry about 1950 showing two railroad sidings, crushed rock loading shed, derricks, and equipment buildings. Quarried blocks were loaded on railroad cars and flatbed trailers for shipment to Swenson's main finishing plant in Concord, New Hampshire.

Figure 79. Cutting shed of Millennium Granite Company, successor to Swenson Granite Company operations at the Bald Hill quarry.

The Hanscom quarry in the town of South Berwick provided the building stones for Berwick Academy in South Berwick, and curbing.

The Pike quarry in Wells and South Berwick is the largest rock quarry in the Kittery map sheet. Opened in the late 1970's, it produces crushed stone from both the Kittery Formation and the gray granite phase of the Webhannet pluton. It may now be producing from the gabbronorite phase of the Tatnic Complex. Figure 80 shows the extent of development in 2004, and Figure 81 shows the much larger pit in 2013. Figure 82, a closeup of the southern wall of the pit seen in the background of Figure 81, shows the contact of the light-colored Webhannet gray granite dipping westward under Kittery hornfels. Note the basaltic dikes of Triassic to Jurassic age that cut the granite. The plant produces over 700,000 tons per year of crushed rock for use primarily in the highway construction industry.

Two crushed stone quarries in Eliot, Maine, were opened in the southern end of the Webhannet pluton, the larger one by Pike Corporation (Figure 83) opened in 2005, and the smaller one just northwest of the Pike quarry, opened in 2011. Both produce crushed stone for use as paving aggregate, and roadway and construction fill.

Figure 80. Pike rock quarry near North Berwick, Maine, showing extent of development as of 2004. Rock in the background is the gray granite of the Webhannet pluton (**Dwg**) cut by several steeply dipping basalt dikes of various widths.

Figure 81. Same Pike rock quarry as pictured in Figure 80 but showing the much greater development by 2012. On the wall in the background can be seen the contact between the gray granite of the Webhannet pluton (**Dwg**) and the dark-colored hornfels of the Kittery Formation (**Sk**).

Figure 82. Close-up of the far wall of the pit shown in Figure 81 showing the gray granite of the Webhannet pluton dipping westward (right) beneath the intruded dark gray hornfels of the Kittery Formation. Note the basalt dikes of probable Triassic to Jurasic age that cut both the granite and the hornfels.

Figure 83. Pike quarry, Eliot, Maine. This was opened in 2005, and produces crushed rock for paving and construction work.

IX. SUMMARY

1. Stratified rocks of the Kittery 1:100,000 quadrangle are assigned to five tectonostratigraphic units: the Shapleigh Group, the Phyllonite at Church Road, the Berwick Formation, the Merrimack Group, and the Rye Complex.
2. Formations deposited in the Merribuckfred Basin include, in ascending stratigraphic order, the Eliot and Kittery formations of the Merrimack Group. The position of the Berwick Formation is equivocal. Youngest detrital zircons suggest a maximum age of ~432 Ma for the Kittery, and by extension the Eliot formation; the Berwick Formation probably shares the same age. If so, all indicate deposition in Mid- to Late Silurian, although we recognize the possibility of a Late Silurian to Early Devonian age for the Berwick.
3. Rocks deposited in the Central Maine Basin include the units of the Shapleigh Group. In ascending stratigraphic order, they are the Rindgemere Formation, Gully Oven Formation, Towow Formation, Merchants Row Grits, an unnamed biotite and calc-silicate granofels unit, and the East Rochester Formation. They range in age from Early Silurian to Early Devonian. The basis for the age assignment of these unfossiliferous rocks is correlation with a similar sequence of fossiliferous rocks in the Rangeley, Maine, area. The Berwick Formation and the protolith of the Phyllonite of Church Road may have been deposited also in the Central Maine Basin.
4. The Rye Complex is a highly sheared assemblage of pelitic and quartzo-feldspathic rocks, commonly migmatized, with lesser amphibolites, marble, and graphitic schist. The metasedimentary package is cross-cut at shallow angles by variably sheared felsic and intermediate igneous intrusives, and at high angles by abundant Mesozoic diabase dikes. The depositional age of the protoliths is middle Cambrian to early Ordovician. The age of penetrative mylonitization is probably Late Carboniferous to Permian.
5. The rocks of the Merribuckfred Basin were derived principally from a peri-Gondwanan source area to the east with possible contributions from Laurentian terranes on the west. Rocks of the Central Maine trough had contributions from both Laurentian terranes to the west and peri-Gondwanan terranes to the east. Provenance of sedimentary detritus in metamorphic rocks of the Rye Complex is uncertain, but of a suggested Ganderian source.
6. The lithotectonic belts are separated by significant regional faults: the Portsmouth, Nonesuch River/Calef, and Phyllonite at Church Road. All are inferred to have been west-vergent thrusts during Salinic time, followed by Acadian east vergence for at least the Church Road and possibly the Nonesuch River/Calef fault. Alleghanian dextral shear affected the Portsmouth and related Great Common faults and probably the smaller shear zones in the Great Bay area. Mesozoic normal faulting is recognized in the Portsmouth Fault and potentially the Silver Mine fault. Major folds include the Blue Hills nappe and Bauneg Beg syncline and the regional folds outlined by the distribution of the Eliot and Kittery formations.
7. A complex deformation history involves at least three major orogenic events – two compressional and one transpressional in the Middle and Late Paleozoic Era and prior to the breakup of Pangaea in the earliest Mesozoic. The compressional Salinic orogeny initiated deformation in late Silurian-early Devonian time, followed by the main compressional pulse of the Acadian orogeny in the middle Devonian, and terminated by the

transpressional Alleghanian orogeny during the Carboniferous and earliest Permian periods. Multiple metamorphic events are associated with each belt: probable Ordovician, Devonian and Permian events in the Rye Complex; Silurian (Salinic) and Devonian (Acadian) in the Merrimack and Berwick belts, with probable Permian (Alleghanian) overprints; and Devonian (Acadian) and probable Permian (Alleghanian?) for the Shapleigh Group in the eastern part of the Central Maine Basin.

8. Magmatic activity of the Paleozoic is associated with continental amalgamation during the compressive Salinic and Acadian (and Neoacadian) orogenies, and the transpressional Alleghanian orogeny. High-level magmatism characterizes the Mesozoic from large intrusive-extrusive central complexes to widespread mafic dike swarms, not only in the area of this quadrangle but through much of central and northern New England. The high-level plutons of Mesozoic age reflect continental breakup, rifting and drifting.

ACKNOWLEDGMENTS

Most of the fieldwork in Maine has been carried out under the auspices of the Maine Geological Survey. Funds to obtain the new U-Pb zircon ages were provided as part of the USGS StateMap program to the Maine Geological Survey. Samples ME-10 and ME-25 were collected and mineral separates provided generously by David P. West, Jr. Arthur M. Hussey II gratefully acknowledges the support and encouragement of the many state geologists he has worked under – John Rand, Robert Doyle, Walter Anderson, and Robert Marvinney.

Work in New Hampshire has been carried out by many graduate students at the University of New Hampshire under the direction of Wally Bothner, Jo Laird, and Peter Thompson. We are indebted to the UNH Earth Sciences 992 Ocean Mapping class of 2012 and Professors Andy Armstrong and Larry Mayer, Director of the Center for Coastal and Ocean Mapping (CCOM) at the University of New Hampshire for applying high resolution bathymetric survey methods to a local geologic question.

We are grateful for the many discussions with and visits by colleagues who share mutual interest in the Kittery area, including Robert Wintsch, Allan Ludman, Mark Swanson, Henry Berry, and David West.

We especially appreciate the expert and thorough review of the manuscript by Henry Berry, and the preparation of the map and manuscript for publication by Robert Tucker, Susan Tolman, and Christian Halsted of the Maine Geological Survey.

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APPENDIX 1. GEOCHRONOLOGY SAMPLE DESCRIPTION

U-Pb zircon geochronology for 12 samples is reported in this bulletin. This appendix gives the sample number, location, rock unit, and rock description for each of the analyzed samples. Location is given by north latitude, west longitude coordinate and by reference to local geographic features and USGS 7½' quadrangle. Locations are shown on the accompanying geologic map (Hussey and others, 2016). Analytical results are presented in the text and in Appendix 2.

MGS-038 [43.07324, -70.71537; Shoreline outcrops in front of flat stone wall below houses, Salamander Point, New Castle, New Hampshire; *Kittery, ME–NH, quadrangle*]. Salamander Point diorite (**Dd**). Metadiorite, intrusive into the Rye Complex (**O€r**), is weakly foliated and consists of oriented hornblende, plagioclase, quartz and biotite. Sphene is an abundant accessory mineral. The metadiorite is cross-cut by fine-grained, weakly foliated pink granite in glacially smoothed, wave washed ledges on the southwest shore of Portsmouth Harbor, and on Fishing Island on the Maine side of the harbor.

MGS-039 [43.07164,-70.71299; Coastal ledges north of UNH Pier, Fort Constitution, New Castle landing, New Castle, New Hampshire; *Kittery, ME–NH, quadrangle*]. Rye Complex (**O€r**). Well layered fine- to medium-grained biotite quartzo-feldspathic blastomylonitic gneiss. Small sigma grains of K-feldspar are obvious at the outcrop consistent with right-lateral ductile shear, confirmed by petrographic observation. Outcrop is cross-cut by later ductile shear and brittle faults, all with dextral shear sense, followed still later by diabase dikes 2-4 m thick.

MGS-032 [43.41903, -70.73499; Low road cut southwest side of Gavel Rd., southeast of intersection with Alfred Rd. (Rt. 4), 0.6 miles northeast of South Sanford; *Alfred, ME, quadrangle*]. Lyman pluton (**Plg**). Medium-grained biotite granite with minor muscovite.

MGS-033 [43.27313, -70.65024; Low road cut, north side of Tatnic Rd., Wells; *North Berwick, ME, quadrangle*]. Webhannet pluton. Light gray, medium- to coarse-grained biotite granite with coarse sphene. Coarsest-grained phase of the Webhannet pluton (**Dwg**) (Porphyritic biotite quartz monzonite of Hussey, 1962)

MGS-034 [43.26382, -70.68006; Outcrops and blasted blocks east of T-intersection of Bennett Lot Rd. and Ogunquit Rd., South Berwick; *North Berwick, ME, quadrangle*]. Webhannet pluton. Medium gray porphyritic biotite-hornblende granodiorite with dispersed small mafic clots (**Dwgd**).

MGS-035 [43.45632, -70.91094; Road cut, southwest side of Milton Mills Rd., Lebanon; *Milton, NH–ME, quadrangle*]. Nisbitt Pond pluton (**Dnp**). White, coarse-grained muscovite-biotite granite with biotite schlieren, weak feldspar alignment.

ME-10 [43.4883, -70.4931; Large outcrops on the east side of Maine Turnpike, ~0.5 miles north of the Biddeford Exit; *Biddeford, ME, quadrangle*]. Biddeford pluton (**Dbig**), at its northern end. Light gray, medium-grained, hypidiomorphic granular biotite-muscovite granite.

ME-25 [43.4225N, -70.4066W; Rt. 9/Scablock Mill Rd., Biddeford, north of Goose Rocks Beach, Kennebunkport; *Biddeford, ME, quadrangle*]. Biddeford pluton (**Dbig**). Gray, medium-grained biotite-muscovite granite.

07SI-06B [42.9884, -70.6106; Northeast shore of Appledore Island; *Isles of Shoals, ME–NH, quadrangle*]. Appledore diorite. Dark gray, weakly foliated hornblende-biotite diorite with intermingled granite, like Salamander Point diorite.

BH-1 [43.0079, -70.8080; Low pavement outcrops 10-30 m north of a memorial plaque, Breakfast Hill Rd., ~0.1 mile west of US Rt. 1, Rye; *Portsmouth, NH–ME, quadrangle*]. Breakfast Hill granite (**Dbh**). Weakly to strongly foliated medium-grained biotite-muscovite granite.

89ex-7 [43.1385, -70.9096; Long east-west road cut on north side of exit ramp from US Rt. 4 to NH Rt. 108, Durham; *Dover West, NH, quadrangle*]. Exeter pluton (**Deg**). Medium gray, medium-grained quartz-biotite diorite, cross-cut elsewhere in the outcrop by several aplite dikes 10-30 cm thick.

12JAB4 [43.2015, -70.6441; North side of Cat Mountain Road just west of the I-95 bridge, York; *York Harbor, ME, quadrangle*]. Biotite granite of the Agamenticus Complex (**TRb**), the youngest unit of the Complex. Pink, medium-grained biotite granite. (Unit **pbg** of Hussey, 1962.)

APPENDIX 2. GEOCHRONOLOGICAL METHODS AND DATA

By Dr. Robert Buchwaldt, analyst

Zircon grains were separated from bulk rock samples by standard crushing, heavy liquid, and magnetic separation techniques, and subsequently handpicked under the binocular microscope based on clarity and crystal morphology. To minimize the effects of Pb loss, the grains were subjected to a version of the thermal annealing and acid leaching (also known as chemical abrasion or CA-TIMS) technique of Mattinson (2005) prior to isotope dilution thermal ionization mass-spectrometry (ID-TIMS) analyses using a mixed ^{205}Pb-^{233}U-^{235}U tracer solution (spike). Details of zircon pre-treatment, dissolution and U and Pb chemical extraction procedures are described by Ramezani and others (2007).

U and Pb isotopic measurements were performed on a VG Sector-54 multicollector thermal ionization mass spectrometer at MIT, Cambridge, Massachusetts. Pb and U were loaded together on a single Re filament in a silica-gel/phosphoric acid mixture (Gerstenberger and Haase, 1997). Pb isotopes were measured by peak-hopping using a single Daly photomultiplier detector and U isotopic measurements were made in static mode using multiple Faraday collectors. Details of fractionation and blank corrections are given with the analytical data in Table 3. Data reduction, age calculation, and the generation of concordia plots were carried out using the method of McLean and others (2011), and the statistical reduction and plotting program REDUX (Bowring and others, 2011). Errors on U-Pb analyses from this study are reported on the diagrams as: ±X/Y/Z, where X is the internal error in absence of all systematic errors, Y includes the tracer calibration error, and Z includes both tracer calibration and decay constant errors of Jaffey and others (1971). Unless otherwise indicated, weighted mean ages reported in the text are reported with the Z error. Plots used as figures in the text show individual zircon analyses (black dots) within error ellipses at 95% confidence level (internal error, X, only) on Concordia curve and the 95% confidence interval drawn on both sides of that curve. Zircons used to calculate the reported weighted mean $^{206}Pb/^{238}U$ age are enclosed within shaded error ellipses and shown also in bar inset on each diagram.

Table 3. Analytical data for high-precision U-Pb zircon geochronology of 12 samples reported in this bulletin. Sample descriptions and locations are presented in Appendix 1. Results and concordia diagrams are given in figures and discussed in the text.

	Composition			*Isotopic Ratios*								*Dates [Ma]*						
Fraction	Th/U [(a)]	Pb* [(b)] [pg]	Pb*/Pbc [(d)]	$^{206}Pb/^{204}Pb$ [(e)]	$^{208}Pb/^{206}Pb$ [(f)]	$^{206}Pb/^{238}U$ [(f,g)]	±2σ [%]	$^{207}Pb/^{235}U$ [(f)]	±2σ [%]	$^{207}Pb/^{206}Pb$ [(f,g)]	±2σ [%]	$^{206}Pb/^{238}U$ [(g,h)]	±2σ [abs.]	$^{207}Pb/^{235}U$ [(h)]	±2σ [abs.]	$^{207}Pb/^{206}Pb$ [(g,h)]	±2σ [abs.]	Corr. coef.
07SI06B: Zircon																		
z1	0.18	0.4	19.75	1310.7	0.056	0.057617	0.11	0.42925	0.72	0.054057	0.697	361.115	0.378	362.641	2.20	372.41	15.7	0.30
z3	0.90	0.3	91.43	4975.5	0.284	0.057595	0.07	0.42638	0.26	0.053717	0.227	360.983	0.242	360.606	0.78	358.18	5.1	0.54
z4	0.67	0.4	98.91	5686.7	0.212	0.057616	0.07	0.42745	0.20	0.053831	0.160	361.113	0.241	361.362	0.60	362.96	3.6	0.65
z6	0.87	0.4	73.14	4009.4	0.275	0.057627	0.10	0.42772	0.30	0.053855	0.265	361.176	0.354	361.556	0.90	364.00	6.0	0.46
z7	0.76	0.6	27.24	1547.8	0.238	0.057639	0.13	0.42730	0.75	0.053791	0.710	361.249	0.455	361.257	2.28	361.31	16.0	0.39
z8	0.87	0.9	38.40	2116.4	0.273	0.057704	0.17	0.42633	0.59	0.053608	0.487	361.648	0.600	360.565	1.78	353.60	11.0	0.68
89ex-7: Zircon																		
z1	0.72	0.7	36.00	2058.9	0.225	0.065249	0.07	0.49345	0.45	0.054873	0.442	407.471	0.266	407.258	1.52	406.05	9.9	0.21
z3	0.76	0.6	183.86	10321.0	0.239	0.065225	0.05	0.49325	0.14	0.054872	0.102	407.321	0.212	407.123	0.47	406.00	2.3	0.78
z4	0.91	0.6	179.24	9719.7	0.285	0.065226	0.06	0.49330	0.13	0.054876	0.102	407.328	0.220	407.154	0.45	406.17	2.3	0.71
z6	0.62	0.4	98.74	5754.8	0.194	0.065236	0.05	0.49344	0.20	0.054883	0.191	407.390	0.207	407.250	0.67	406.45	4.3	0.29
BH-1: Zircon																		
z1	0.53	0.7	65.27	3893.4	0.166	0.064961	0.06	0.50471	0.25	0.056374	0.221	405.727	0.245	414.885	0.85	466.14	4.9	0.55
z2	0.15	0.7	83.37	5275.6	0.047	0.187961	0.07	2.70918	0.14	0.104583	0.095	1110.322	0.720	1330.975	1.02	1706.17	1.8	0.75
z3	0.19	1.1	31.26	2020.4	0.060	0.121498	0.22	1.23591	0.40	0.073810	0.304	739.178	1.565	817.028	2.25	1035.36	6.1	0.66
z6	0.47	0.3	33.06	2014.7	0.147	0.064495	0.08	0.48717	0.60	0.054808	0.567	402.905	0.312	402.980	1.99	403.41	12.7	0.44
z7	0.56	0.5	34.62	2062.1	0.174	0.064454	0.14	0.48664	0.69	0.054783	0.597	402.657	0.528	402.616	2.30	402.38	13.4	0.76
z10	0.50	0.8	122.32	7349.2	0.156	0.064487	0.08	0.48726	0.18	0.054826	0.139	402.855	0.298	403.042	0.62	404.11	3.1	0.72
ME-10: Zircon																		
z1	0.41	0.9	93.48	5731.7	0.128	0.061284	0.06	0.45948	0.17	0.054401	0.145	383.431	0.219	383.895	0.55	386.69	3.3	0.57
z2	0.78	0.5	87.39	4874.9	0.245	0.061350	0.15	0.46012	0.31	0.054418	0.225	383.831	0.562	384.339	1.00	387.40	5.1	0.74
z3	0.72	0.7	115.59	6535.6	0.227	0.061277	0.10	0.45894	0.21	0.054344	0.161	383.384	0.366	383.520	0.67	384.34	3.6	0.67
z4	0.98	1.1	110.42	5876.0	0.307	0.061260	0.07	0.45799	0.18	0.054246	0.146	383.286	0.258	382.858	0.58	380.27	3.3	0.65
z10	0.59	1.0	67.50	3952.8	0.184	0.068100	0.07	0.52042	0.23	0.055450	0.201	424.696	0.272	425.432	0.80	429.42	4.5	0.56
z11	0.75	1.5	92.76	5216.7	0.234	0.061264	0.08	0.45885	0.19	0.054345	0.143	383.308	0.279	383.460	0.60	384.38	3.2	0.72
z12	0.94	1.8	55.37	2981.4	0.295	0.061306	0.07	0.45979	0.25	0.054418	0.239	383.566	0.260	384.111	0.81	387.40	5.4	0.33
z13	0.38	1.1	129.35	7973.1	0.121	0.061245	0.06	0.45912	0.14	0.054394	0.088	383.191	0.219	383.646	0.46	386.39	2.0	0.95
z14	0.43	2.5	77.38	4714.6	0.136	0.061313	0.07	0.45972	0.18	0.054404	0.157	383.603	0.247	384.061	0.58	386.82	3.5	0.51
ME-25: Zircon																		
z1	1.22	0.6	40.26	2047.2	0.383	0.061163	0.12	0.45985	0.54	0.054553	0.507	382.691	0.446	384.151	1.74	392.96	11.4	0.41
z2	1.04	1.0	48.55	2569.1	0.325	0.061187	0.10	0.45763	0.41	0.054268	0.386	382.842	0.370	382.608	1.31	381.19	8.7	0.35
z3	0.53	0.5	227.59	13545.6	0.166	0.061166	0.06	0.45810	0.14	0.054343	0.099	382.712	0.226	382.936	0.44	384.29	2.3	0.76
z4	0.85	1.4	42.78	2364.5	0.268	0.061123	0.29	0.45768	0.80	0.054332	0.564	382.450	1.090	382.646	2.55	383.83	12.7	0.86
z5	1.00	1.0	187.33	9933.9	0.315	0.061241	0.08	0.45916	0.19	0.054401	0.145	383.171	0.314	383.671	0.62	386.69	3.3	0.72
MGS-32: Zircon																		
z1	0.94	1.1	32.00	1736.3	0.298	0.045630	0.08	0.32798	0.54	0.052154	0.525	287.635	0.229	288.021	1.36	291.15	12.0	0.27
z2	0.88	0.8	48.23	2649.8	0.277	0.045610	0.07	0.32785	0.35	0.052156	0.345	287.515	0.190	287.921	0.87	291.22	7.9	0.13
z5	0.99	2.5	7.54	419.1	0.312	0.045644	0.17	0.33188	2.19	0.052759	2.178	287.720	0.486	291.001	5.54	317.42	49.5	0.10
z7	0.93	0.7	50.92	2758.7	0.294	0.049298	0.08	0.36073	0.42	0.053094	0.372	310.211	0.239	312.758	1.12	331.79	8.4	0.62
z8	1.03	5.8	7.27	401.3	0.324	0.045663	0.20	0.33153	2.26	0.052682	2.221	287.839	0.551	290.736	5.71	314.09	50.5	0.24
z10	0.80	6.9	5.64	331.2	0.254	0.045697	0.23	0.33313	2.76	0.052896	2.711	288.048	0.657	291.955	7.00	323.33	61.6	0.24
z12	0.80	2.1	7.80	452.2	0.252	0.045604	0.19	0.32665	2.13	0.051973	2.086	287.479	0.528	287.008	5.32	283.18	47.7	0.27
z13	0.87	4.4	11.10	625.3	0.274	0.045647	0.14	0.32904	1.46	0.052304	1.428	287.740	0.398	288.834	3.67	297.70	32.6	0.26
z14	0.73	2.0	9.74	569.0	0.231	0.045648	0.16	0.32945	1.66	0.052367	1.605	287.749	0.448	289.144	4.17	300.44	36.6	0.37

Table 3. Continued

MGS-33: Zircon																		
z6	1.23	1.2	46.04	2333.8	0.386	0.061309	0.10	0.45913	0.42	0.054338	0.393	383.583	0.376	383.651	1.35	384.06	8.8	0.40
z7	1.40	1.3	70.99	3463.0	0.439	0.061248	0.08	0.45832	0.30	0.054296	0.274	383.208	0.283	383.087	0.96	382.36	6.2	0.44
z8	1.00	0.9	43.45	2320.3	0.314	0.061263	0.08	0.45916	0.41	0.054382	0.411	383.303	0.282	383.671	1.30	385.89	9.2	0.04
z9	0.93	1.0	72.34	3909.7	0.293	0.061220	0.09	0.45843	0.33	0.054334	0.301	383.043	0.334	383.165	1.05	383.90	6.8	0.43
MGS-34: Zircon																		
z2	1.09	0.8	103.89	5415.5	0.341	0.061194	0.06	0.45819	0.22	0.054329	0.183	382.882	0.232	382.998	0.70	383.70	4.1	0.66
z3	1.03	1.2	57.36	3033.5	0.325	0.061237	0.14	0.45836	0.37	0.054311	0.317	383.146	0.502	383.119	1.17	382.95	7.1	0.53
z5	1.28	1.0	7.52	392.8	0.400	0.061226	0.24	0.45834	2.36	0.054318	2.303	383.077	0.892	383.103	7.53	383.25	51.8	0.28
z10	0.53	1.5	42.19	2512.5	0.166	0.072769	0.17	0.61298	0.40	0.061121	0.243	452.816	0.736	485.436	1.53	642.54	5.2	0.95
z12	1.00	1.4	19.19	1033.8	0.315	0.061216	0.12	0.46056	0.92	0.054591	0.928	383.018	0.438	384.650	2.95	394.49	20.8	0.01
z13	1.11	1.3	153.80	7963.7	0.349	0.061212	0.07	0.45868	0.22	0.054371	0.162	382.995	0.250	383.341	0.70	385.43	3.7	0.88
MGS-35: Zircon																		
z1	0.37	0.8	223.58	13524.5	0.108	0.255520	0.08	3.28162	0.12	0.093145	0.062	1466.881	1.080	1476.703	0.93	1490.85	1.2	0.86
z2	1.39	1.0	51.37	2515.3	0.437	0.061207	0.11	0.45583	0.47	0.054013	0.443	382.963	0.415	381.354	1.51	371.60	10.0	0.39
z10	0.93	1.1	33.22	1808.7	0.291	0.061238	0.09	0.45808	0.56	0.054253	0.545	383.149	0.351	382.923	1.80	381.55	12.3	0.27
z12	0.92	1.4	22.16	1214.7	0.289	0.061229	0.09	0.45778	0.72	0.054225	0.704	383.093	0.331	382.712	2.31	380.41	15.8	0.28
z13	0.52	6.2	22.16	1338.3	0.164	0.061231	0.14	0.45803	0.72	0.054252	0.646	383.109	0.539	382.886	2.29	381.53	14.5	0.57
MGS-38: Zircon																		
z2	0.83	0.5	15.13	852.7	0.261	0.060878	0.16	0.45487	1.11	0.054214	1.093	380.964	0.598	380.681	3.52	378.96	24.6	0.17
z3	0.49	0.6	4.67	298.9	0.153	0.061094	0.45	0.46035	3.15	0.054674	3.065	382.277	1.653	384.498	10.10	397.89	68.7	0.27
z5	0.55	1.1	25.44	1522.2	0.173	0.060725	0.13	0.45300	0.63	0.054129	0.603	380.031	0.478	379.378	1.98	375.39	13.6	0.28
z7	0.50	4.8	22.81	1383.2	0.158	0.060708	0.14	0.45430	0.69	0.054299	0.623	379.927	0.531	380.285	2.20	382.46	14.0	0.57
z9	0.69	2.9	36.79	2120.2	0.215	0.060776	0.11	0.45408	0.47	0.054212	0.414	380.344	0.398	380.135	1.48	378.86	9.3	0.59
MGS-39: Zircon																		
z1	0.58	1.1	15.81	945.4	0.180	0.076556	0.13	0.59704	0.95	0.056562	0.911	475.533	0.599	475.353	3.60	474.49	20.1	0.36
z5	0.34	0.9	21.78	1358.4	0.103	0.163133	0.12	1.71956	0.44	0.076450	0.407	974.164	1.049	1015.862	2.85	1106.87	8.1	0.44
z6	0.33	1.7	68.61	4284.6	0.102	0.087793	0.10	0.78885	0.36	0.065168	0.250	542.470	0.519	590.521	1.60	779.77	5.3	1.05
z7	0.52	0.8	35.32	2108.9	0.161	0.110375	0.23	0.99264	0.47	0.065226	0.384	674.926	1.452	700.068	2.40	781.63	8.1	0.60
z8	0.27	1.0	2.31	165.6	0.085	0.077578	0.57	0.59280	5.70	0.055421	5.583	481.649	2.655	472.656	21.52	429.23	124.5	0.25
z10	0.22	0.5	13.09	864.0	0.068	0.072478	0.17	0.56300	1.05	0.056338	1.005	451.068	0.739	453.476	3.82	465.70	22.3	0.32
12JAB4: Zircon																		
z1	0.64	0.4	144.99	8402.4	0.203	0.037876	0.13	0.26599	0.21	0.050955	0.108	239.656	0.297	239.481	0.44	237.77	2.5	0.90
z4	0.80	0.3	116.65	6500.0	0.254	0.037763	0.09	0.26569	0.22	0.051051	0.195	238.951	0.216	239.243	0.47	242.10	4.5	0.46
z6	0.62	0.3	71.27	4163.8	0.196	0.037773	0.10	0.26616	0.26	0.051129	0.237	239.011	0.224	239.620	0.56	245.59	5.5	0.45
z7	0.29	0.3	274.13	17400.5	0.091	0.057889	0.09	0.43027	0.13	0.053931	0.070	362.775	0.316	363.371	0.39	367.18	1.6	0.85
z8	0.57	1.2	48.65	2884.4	0.180	0.037726	0.09	0.26573	0.35	0.051108	0.325	238.722	0.211	239.273	0.75	244.68	7.5	0.42
z9	0.56	0.7	50.77	3016.2	0.178	0.037748	0.09	0.26557	0.36	0.051047	0.336	238.859	0.202	239.142	0.78	241.92	7.8	0.42

Blank and Oxygen composition: $^{206}Pb/^{204}Pb = 18.42 \pm 0.35$; $^{207}Pb/^{204}Pb = 15.35 \pm 0.23$; $^{208}Pb/^{204}Pb = 37.46 \pm 0.74$; $^{18}O/^{16}O = 0.00205 \pm 0.00002$

(a) Th contents calculated from radiogenic ^{208}Pb and the $^{207}Pb/^{206}Pb$ date of the sample, assuming concordance between U-Th and Pb systems.

(b) Total mass of radiogenic Pb.

(c) Total mass of common Pb.

(d) Ratio of radiogenic Pb (including ^{208}Pb) to common Pb.

(e) Measured ratio corrected for fractionation and spike contribution only.

(f) Measured ratios corrected for fractionation, tracer, blank and initial common Pb.

(g) Corrected for Initial Th/U disequilibrium using radiogenic ^{208}Pb and Th/U [magma] = 2.8

(h) Isotopic dates calculated using the decay constants λ_{238} = 1.55125E-10, λ235 = 9.8485E-10 (Jaffey et al. 1971), and for the $^{238}U/^{235}U = 137.818 \pm 0.045$ (Hiess, J. et al. 2012)

APPENDIX 3. LOCAL GEOLOGIC MAPS

This appendix presents detailed geologic maps of the Agamenticus Complex, York, Maine (Figure A-1) and the Marginal Way, Ogunquit, Maine (Figure A-2).

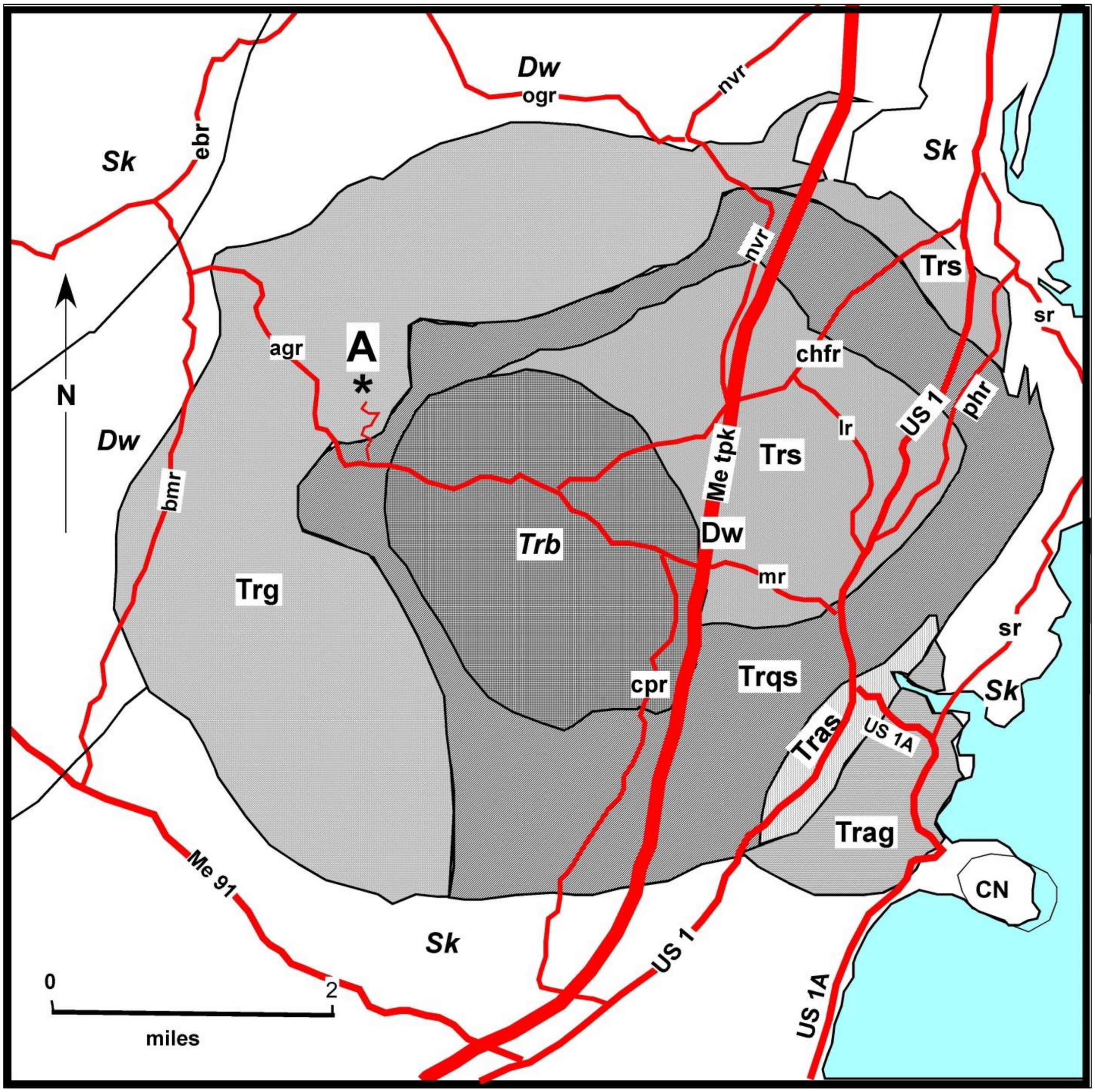

Figure A-1. Simplified geologic map of the Triassic Agamenticus Complex (Tra), showing relationships of units within the Complex in shades of gray. Geologic units: Sk = Kittery Formation; Dw = Webhannet pluton; Trag = alkalic aegirine granite; Tras = porphyritic aenigmatite syenite; Trs = alkalic syenite; Trqs = alkalic quartz syenite; Trb = biotite granite; CN = Cape Neddick Complex. Roads (in red): agr = Agamenticus Rd.; bmr = Bell Marsh Rd.; chfr = Clay Hill Farm Rd.; cpr = Chases Pond Rd.; ebr = Emerys Bridge Rd.; lr = Logging Rd.; Me tpk = Maine Turnpike; mr = Mountain Rd.; nvr = North Village Rd.; ogr = Ogunquit/Berwick Rd.; phr = Pine Hill Rd.; sr = Shore Rd. A = Mount Agamenticus. *Coastal York and Wells, Maine.*

Figure A-2. Detailed geologic map and cross sections of the coastal bedrock exposure along the Marginal Way footpath, Ogunquit, Maine (Figure 1). Well bedded metamorphic rocks of the Kittery Formation are folded and intruded by dikes. The Little Beach fault and Devils Kitchen fault are discussed in the text. North is to the left.