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Unraveling the Geologic History of the Avalon Terrane in MA

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Unraveling the Geologic History of the Avalon Terrane in MA

BY ERIN NEVENS

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Abstract

Field and petrographic analysis of rocks at Black Rock Beach in Cohasset, MA record at least two phases of metamorphism and magmatic activity and three episodes of deformation. The earliest phase of metamorphism and deformation are recorded by mafic gneiss xenoliths. These xenoliths preserve a mylonitic texture, which represents development in a ductile deformation environment. The xenoliths occur as large blocks that were later incorporated into the intruding magma of the Dedham granodiorite. Following crystallization, the Dedham granodiorite experienced an episode of plastic deformation. This event resulted in the development of a weak foliation defined by aligned feldspar porphyroclasts. Quartz and feldspar microstructures indicate deformation occurred between 350-450°C. A second phase of magmatic activity was associated with the intrusion of several 1-2 meter wide porphyritic basalt dikes that cross-cut both the xenoliths and granodiorite,.and resulted in the brittle cataclasis of the Dedham granodiorite, The basalt dikes were emplaced during a time of crustal extension and subsequently experienced a late-stage hydrothermal alteration.

The absolute timing of these tectonic events is difficult to determine unequivocally due to the lack of precise geochronologic data available. The crystallization age of the Dedham granodiorite has previously been reported as 622 Ma. Thus, the earliest phase of metamorphism recorded by the xenoliths must pre-date 622 Ma, whereas the youngest deformation and emplacement of the basaltic dikes must post-date this age.

Introduction

The geology of Massachusetts is the result of a complex and prolong history involving several major mountain building events separated through time and

space. The bedrock geology can be described in terms of an amalgamation of different geologic terranes. The most prominent terrane in eastern Massachusetts is the Avalon terrane. In an effort to decipher the geologic history of a portion of the Avalon terrane we applied basic field observations along with detailed petrographic analysis.

Rocks located at Black Rock Beach, Cohasset, MA, record multiple deformation and metamorphic events that reflect the complex nature and geologic history of the Avalon terrane prior to its accretion to the North American continent during the Acadian Orogeny (380-360 Ma). We attempt to unravel this history by combining mesoscopic observations and microscopic analysis in order to determine the relative age of geologic events and the conditions of metamorphism and deformation. Identification of microtextures in certain minerals can be used to provide information on the temperature conditions and style of deformation (i.e. plastic vs. brittle). Previously published U-Pb geochronology is used in conjunction with field relationships to place some constraints on the timing of these tectonic events and to decipher a clearer picture of the geologic history. Our results will add to the recent recognition of a more complex history involving several overprinting orogenic events that affected the Avalonian terrane throughout Proterozoic-Paleozoic time.

Geologicic setting

Massachusetts can be subdivided into a series of geologic terranes, each of which consists of distinctive rock types that have different affinities and geologic histories. These terranes include from west to east: Laurentia (North America), Merrimack, Nashoba, Avalon, and Meguma (Figure 1). The latter four terranes have origins with Gondwana (African) affinities. Through a series of tectonic events, these terranes were successfully accreted to the eastern margin of Laurentia over a span of several hundred million years (Skehan, 2001). This study concentrated on crystalline rocks that occur within the eastern portion of the Avalon Terrane (Figure 1). Avalon formed as a volcanic arc along the western margin of Gondwana in Late Proterozoic time. During the Late Proterozoic, the margin of Gondwana underwent a phase of sinistral shear producing what is now known as the Burlington Mylonite Zone (BMZ). The BMZ has had a history of multiple phases of movement and shearing. Presently, it forms the western boundary of the Avalon terrane with the Nashoba terrane. Avalon rifted away from Gondwana ~465 Ma (Veevers, 2003) and began a slow trek across a proto-Atlantic ocean where it experienced several major orogenic events and its final collision with Laurentia. The Acadian Orogeny (~425-370 Ma) was a time in which the Avalon volcanic arc collided with the eastern margin of Laurentia (North America) resulting in widespread high-grade metamorphism and plutonism. Later, during the Carboniferous Alleghanian Orogeny (354-250 Ma), Avalon was involved in the final collision between North America and Africa forming the supercontinent Pangea. This event resulted in another phase of high-grade metamorphism and minor plutonism. The youngest orogenic event to affect Avalonian rocks was the subsequent break up of Pangea during Triassic-Jurassic time (Skehan, 2001). Breakup was associated with tensile stresses and brittle deformation that allowed basaltic magma to intrude along a series of predominately E-W and NE-SW fracture sets.

Results

Field Relationships

The outcrop of interest at Black Rock Beach contains three distinct rock types: Dedham granodiorite, mafic gneiss, and porphyritic basalt. Each rock records a small portion of geologic time, but together they allow us to decipher the events that affected this part of the Avalon terrane and reconstruct the geologic history.

Beginning in the southeast portion of the beach and traversing to the northwest corner of the beach, the rocks con-

sist mainly of mafic gneiss. The gneiss occurs as xenoliths within the younger Dedham granodiorite. The xenoliths display a strong gneissic foliation defined by altering layers of felsic and mafic minerals, and is intensely folded and distorted (Figure 2A). Xenolith abundance decreases towards the middle of the outcrop where it is equally mixed with granodiorite, but the mafic gneiss still dominates the eastern portion of the outcrop.

Another lithology present in the outcrop is mildly deformed to undeformed Dedham granodiorite. These rocks display a phaneritic to porphyritic texture with large megacrysts of orthoclase feldspar (Figure 2B). Traversing to the southeast the granodiorite develops a weak deformational fabric defined by the alignment of feldspar megacrysts (Figure 2C).

There are also at least four large mafic dikes that occur within the outcrop (Figure 2D). They are dominantly porphyritic basalt dikes that have a greenish tint due to the presence of chlorite and/or epidote. Phenocrysts consist of plagioclase feldspar ranging from 0.01 to 2.0 cm in size that are aligned in places perhaps in response to flowage. Two of the basaltic dikes have a northeast-southwest trend, whereas the third and fourth dikes have an east-west trend. On the basis of cross-cutting relationships we can determine that the east-west trending dikes cut across the NE-SW dikes and are thus the youngest igneous feature. Also present throughout the outcrop are numerous small quartz veins.

Petrographic Analysis

Initially, the majority of the samples analyzed were obtained from the mafic gneiss xenoliths in an effort to document the metamorphic mineral assemblages and constrain the conditions of metamorphism (temperature & pressure). In addition, samples of the Dedham granodiorite were also collected to investigate evidence of post-intrusion deformation that affected this felsic pluton following crystallization. Finally, several samples from the porphyritic basalt dikes were studied to determine the mineralogy and to see if these dikes were deformed and the extent of hydrothermal alteration following emplacement.

Mafic Gneiss Xenolith

Sample 1: This sample contains medium to small subhedral crystals of plagioclase and orthoclase, which are slightly altered to clay sericite and display undulose extinction. Other minerals include small to medium sized anhedral quartz crystals, epidote and clinozoisite veins with small subhedral crystals, and medium sized subhedral chlorite altering after biotite. Quartz crystals display undulose extinction, deformation lamellae, and grain boundary migration recrystallization (GBM). An epidote vein is also cross-cut by a secondary quartz vein. The bulk composition is 40% feldspars, 25% quartz, 5% chlorite, 1% biotite, 9% epidote, 1% clinozoisite, 3% sericite, 10% undetermined matrix, and 6% opaque minerals. The overall rock texture of this sample is slightly mylonitic (Figure 3A).

Sample 2: This sample has medium grained, subhedral plagioclase and orthoclase crystals. These feldspars are altered to fine-grained sericite. Some of the orthoclase feldspar crystals have a perthitic exsolution texture. There is abundant chlorite in stringy subhedral crystals altering from biotite in the sample, as well as a few epidote veins and individual crystals. Anhedral crystals of quartz occur in varying sizes. The boundaries between the quartz crystals are highly irregular and sutured. Quartz and feldspar both display undulose extinction. The quartz crystals also show signs of GBM and deformation lamellae. It is apparent the epidote veins formed last, because they transect other crystals. Petrographically, this sample appears multi-textured with the middle displaying a more mylonitic texture, whereas feldspars near the edge are larger and relatively undeformed. The matrix is intertwined with the chlorite and in between are quartz and feldspar crystals. The bulk composition of sample is 33% feldspars, 23% quartz, 8% epidote, 9% chlorite,

3% biotite, 15% sericite, and 9% of matrix.

Sample 4: This thin section contains orthoclase (microcline variety) (Figure 3B) and plagioclase feldspar porphyroclasts that are generally medium grained and subhedral. Some crystals display minor sericite alteration. Other feldspar crystals possess perthitic textures and some exhibit undulose extinction. Also present in the sample is chlorite that is generally clustered around feldspars, altering from biotite and very stringy in appearance. Epidote veins occur throughout this sample. Also, small to medium grained anhedral quartz crystals are found in clusters. The quartz crystals display GBM, undulose extinction, and deformation lamellae. Sericite can be found as both large individual grains as well as fine-grained matrix within veins. The overall sample has a slight mylonitic texture to it with a mostly fine-grained matrix with visible chlorite and sericite. The bulk composition of the sample is 37% feldspars, 23% quartz, 8% chlorite, 3% biotite, 9% epidote, 16% sericite, and 4% of a matrix of unknown composition.

Sample 6: This thin section contains significant clay alteration of feldspars and clusters of small anhedral quartz crystals and chlorite, biotite and epidote subhedral crystals. Undulose extinction occurs in both the quartz and feldspar grains. The quartz crystals also exhibit deformation lamellae and GBM. The sample has a mylonitic texture characterized by augen shaped quartz. The matrix consists of sericite, chlorite and abundant fine-grained unidentifiable minerals. The bulk composition of this sample is 15% feldspars, 25% quartz, 10% chlorite, 3% biotite, 10% epidote, 2% clinozoisite, 17% sericite, and 18% of a matrix of unknown composition.

Sample 7: This sample contains two very distinct mineralogic domains. One is an altered clay rich zone, whereas the other is clay-poor. In the least altered portion feldspars aregenerally not altered to clay and are medium grained and subhedral. Also present, in a range of grain sizes, are anhedral quartz and traces of chlorite and epidote. The more altered, clay-rich domain contains small subhedral crystals of quartz and feldspars within an unidentified matrix. Some of the feldspars that are not completely altered preserve a perthitic texture. There is undulose extinction in quartz and feldspar. The quartz crystals also display GBM. This thin section contains abundant epidote veins. The overall composition of this sample is 18% feldspars, 22% quartz, 9% chlorite, 3% biotite, 10% epidote, 2% clinozoisite, 18% sericite, and 18% of a fine grained matrix.

Sample 8: Variable sized subhedral feldspar crystals appear in the sample, many of which are highly altered to clay. Some of the feldspars display a perthitic texture, bent twin striations, and strong undulose extinction. Medium grained, subhedral chlorite, small anhedral quartz, and small subhedral epidote veins and crystals are also present within this sample. The quartz crystals exhibit GBM and undulose extinction. The texture of the thin section is generally mylonitic. The matrix making up the mylonitic texture is chlorite, sericite, and other fine-grained minerals and augens, which are quartz. The bulk composition of this sample is 16% feldspar crystals, 22% quartz, 8% epidote, 10% chlorite, 3% biotite, 3% opaque minerals, 20% sericite, 2% clinozoisite, and 16% matrix of unknown composition.

Sample 9: This thin section has variable sized feldspar crystals that experienced clay alteration and display minor relict undulose extinction. Some feldspar crystals have a perthitic texture. The other minerals present are small anhedral quartz crystals, subhedral opaque minerals, subhedral epidote and clinozoisite crystals, and small to medium sized sub-anhedral chlorite crystals. Some of the quartz crystals have deformation lamellae and most display GBM and undulose extinction. This thin section has a mylonitic texture throughout with a matrix of mostly fine grained minerals, but also some sericite and chlorite. The augens consist of quartz. The bulk composition of the sample is 29% feldspars, 20% quartz, 17% sericite, 3% clinozoisite, 8% epidote, 8% chlorite, 5% biotite, 3% opaque minerals, and 7% opaque minerals.

Sample 10: This sample contains subhedral feldspar crystals, some of which are altering to clay, and display either undulose extinction and/or a perthitic texture. This sample also contains anhedral quartz of varying sizes, medium subhedral chlorite crystals altering from biotite, and small subhedral epidote crystals. The quartz crystals preserve GBM and undulose extinction. When seen as a whole, the thin section has a matrix of sericite, chlorite, and fine-grained minerals that are wrapped around augens of quartz forming the mylonitic texture. The overall composition of the sample is 29% feldspars, 20% quartz, 9% chlorite, 4% biotite, 10% epidote, 2% clinozoisite, 16% sericite, 3% opaque minerals, and 7% of a matrix of unknown composition.

Dedham Granodiorite

Sample 3: In sample 3 the quartz crystals display GBM, deformation lamellae, and undulose extinction (Figure 4A). It also contains large subhedral orthoclase (microcline variety) and plagioclase feldspar crystals that have several microfractures (Figure 4B), bent striations, and undulose extinction. Some feldspar grains are altering to clay, while others display a perthitic texture. The most distinguishing feature of this sample is the extremely fractured and cataclastic nature of the feldspars. Feldspars contain numerous microfractures and have been brittely deformed resulting in a significant reduction of grain size. Other minerals present include epidote, which occur as veins with small subhedral crystals; euhedral medium chlorite crystals; and medium anhedral quartz crystals. It also contains an epidote vein that cuts across other minerals, but then has small anhedral quartz crystals within it. The bulk composition of the thin section is 43% feldspars, 25% quartz, 14% chlorite, 9% epidote, 3% clinozoisite, and 6% sericite.

Sample 5: Sample 5 has medium-coarse grained subhedral orthoclase and perthitic plagioclase many of which are altering to clay and typically show undulose extinction. Some of the plagioclase grains have bent twin striations. Other minerals present include elongated subhedral chlorite, anhedral quartz, and epidote veins. Quartz show signs of GBM, undulose extinction, and deformation lamellae. The bulk composition of the thin section is 42% feldspars, 26% quartz, 10% chlorite, 15% epidote, and 7% sericite.

Sample 14: This sample contains abundant coarse-grained subhedral crystals of feldspar, several of which are altering to sericite. The feldspars commonly exhibit undulose extinction. The polysynthetic twin planes in plagioclase are extremely deformed. Orthoclase commonly displays Carlsbad twinning although it is obscured as a result of clay alteration. Many of the feldspar grains contain microfractures that are filled or sealed by small epidote crystals. A large epidote vein cuts this sample and consists primarily of small subhedral crystals. Also, present in the sample are medium-grained subhedral chlorite crystals and small anhedral quartz crystals. The quartz crystals display undulose extinction, GBM, and deformation lamellae. The overall modal composition of this sample is 43% feldspar, 17% sericite, 17% quartz, 11% chlorite, and 12% epidote.

Sample 15: This sample contains predominately large subhedral feldspar crystals many of which experienced alteration to clay. Plagioclase crystals display bent twin planes and undulose extinction. K-feldspar displays a perthitic texture and most of the crystals are cut by brittle microfractures. Small subhedral epidote crystals occur within the microfractures and veins. The thin section also contains medium-grained subhedral chlorite grains and small anhedral quartz crystals. Quartz exhibits signs of plastic deformation in the form of deformation lamellae, GBM, and undulose extinction. The overall composition is approximately 50% feldspar, 20% quartz, 10% sericite, 15% epidote, and 5% chlorite.

Sample 16: This sample possesses large subhedral feldspar crystals that contain abundant microfractures. Some of the microfractures contain epidote crystals. The feldspar crystals display undulose extinction. The plagioclase crystals contain bent striations and the orthoclase crystals have

weakly developed Carlsbad twinning. Also present are small subhedral epidote and chlorite, as well as, small anhedral quartz crystals. Quartz commonly displays undulose extinction, GBM, and deformation lamellae. The modal composition for this sample is 44% feldspar, 17% quartz, 12% sericite, 11% chlorite, 11% epidote, and 5% opaque minerals.

Sample 19 a&b: These thin sections contain many large feldspar crystals some of which have altered to sericite and some contain small inclusions of quartz or plagioclase. The plagioclase crystals have bent striations and Carlsbad twinning can be seen in some of the orthoclase crystals. Most of the feldspar crystals have microfractures, some of which are filled by small epidote crystals. The remainder of the sample consists of subhedral chlorite crystals altering from biotite, small subhedral epidote crystals, and small anhedral quartz crystals. The quartz crystals display undulose extinction, GBM, and deformation lamellae. The modal composition of this sample is 45% feldspar, 18% quartz, 12% sericite, 10% chlorite, 10% epidote, and 5% opaque minerals.

Porphyritic Basalt Dikes

Sample D1 b: This sample was obtained from an E-W trending dike. It is aphanitic with a rather even distribution of subhedral plagioclase and epidote crystals. It also contains subhedral chlorite crystals and anhedral opaque crystals. The overall composition of the rock is 35% plagioclase, 35% epidote, 20% chlorite, and 10% opaque minerals.

Sample D2: This sample is from an NE-SW trending dikes. It contains both small subhedral plagioclase crystals and larger phenocrysts of plagioclase that are altering to sericite (Figure 5). It also has small anhedral epidote and chlorite crystals. Veins of epidote are also present within this sample. The modal composition is 50% plagioclase, 35% epidote, and 15% chlorite.

Sample D3: This sample is another of the NE-SW trending dike. It is fine-grained, but the grain size is a few millimeters larger than that observed in sample D1b. The sample contains small subhedral plagioclase grains and larger plagioclase phenocrysts that are altering to sericite. There are also subhedral epidote and chlorite crystals in the sample. Throughout the sample there are a few opaque minerals. The overall composition is 43% plagioclase, 30% epidote, 15% chlorite, and 10% opaque minerals.

Discussion

The geologic history of this portion of the Avalon terrane can be deciphered by studying the field relations, mineral assemblages, and microtextures in the lithologies present at Black Rock Beach. The first geologic event that we document is the formation of the protolith, or parent material, for the mafic gneiss. However, the actual lithology cannot be readily identified because it is extremely difficult to determine the original rock since it has been subjected to a phase of intense ductile deformation and metamorphism. Some time prior to 622 Ma (the crystallization age of the Dedham granodiorite), metamorphism and deformation transformed the protolith into gneiss that locally preserves a mylonitic texture. The mafic gneiss most likely developed during a phase of ductile shearing possibly related to the Burlington mylonite zone. The absolute time of the first episode of metamorphism is not precisely known since no radiometric dates exist for these rocks. However, these rocks must be the oldest since they are intensely metamorphosed and deformed and occur as xenoliths within the 622 Ma Dedham granodiorite and both are cross-cut by the basaltic dikes.

Conditions of Metamorphism in Xenoliths

As part of reconstructing the geologic history of the area we attempted to determine the conditions of metamorphism in the mafic gneiss xenoliths. However, the mineral assemblages preserved within the mafic xenoliths do not reflect the prograde or peak metamorphic mineral assemblage. The assemblages reflect the retrograde alteration that followed peak metamorphism. Thus, only a minimum estimate can

be provided on the metamorphic conditions prior to their incorporation as xenoliths within the Dedham granodiorite. On the basis of the mineral assemblage preserved (epidote, plagioclase, chlorite), we interpret these rocks as experiencing at least greenschist to epidote-amphibolite facies metamorphic conditions (~300-500°C & ~5 kilobars). However, the intensely foliated and folded nature of the gneissic layering suggests even higher metamorphic conditions. The folds present in the xenoliths formed in a compressive tectonic environment suggesting the first episode of metamorphism and deformation was associated with a large-scale plate collisions.

Several of the mafic xenoliths preserve a microtexture that resembles a mylonitic shear fabric (Figure 3A). Mylonites are formed in ductile shear zones and represent crustal discontinuities that accommodate movement within or between lithodpheric plates. The only major mylonite forming around the probable time that the mafic gneiss was being deformed was the Burlington mylonite. The Burlington mylonite developed in the Precambrian when the western margin of the Gondwana continent experienced a period of ductile shearing (Skehan, 2001). Reactivation of the Burlington mylonite occurred during the Silurian as the Avalon terrane subducted beneath the Nashoba terrane (Skehan, 2001). If a Silurian collision was responsible for the mylonitic texture in the gneiss than the Dedham granodiorite should also display a pervasive mylonitic texture, however, it does not. A more reasonable interpretation for the mylonitic fabric observed in the mafic xenoliths is that they represent blocks of Burlington mylonite that formed during the Precambrian and were subsequently broken off and later incorporated into the intruding Dedham granodiorite magma prior to 622 Ma.

Conditions of Deformation in Dedham Granodiorite

Even though the Dedham granodiorite does not display a pervasive mylonitic fabric, it has experienced post-crystallization plastic and brittle deformation. Crystal-plastic deformation in quartz and feldspar occurs at temperatures above 300 ± 50°C and 450 ± 50°C, respectively (Tullis, 1983; Tullis and Yund, 1977; Voll, 1967). By using microtextures preserved in quartz and feldspar we were able to identify an episode of deformation that occurred predominantly between 350° to 450°C. Quartz commonly displays sutured grain boundaries which is indicative of grain boundary migration recrystallization, undulose extinction, deformation lamellae, and subgrain formation (Figure 4A). These textures are developed during intracrystalline plastic deformation, which for quartz begins around 350°C (Tullis, 1983; Tullis and Yund, 1977; Voll, 1967). The onset of intracrystalline deformation in feldspar occurs when temperatures exceed 450°C. Feldspars from the Dedham granodiorite display only minor effects of intracrystalline deformation and include undulose extinction and bent twin striations (Figure 4A). Following this episode of plastic deformation, the Dedham granodiorite also experienced a phase of intense cataclasis and brittle deformation resulting in the fracturing and cataclasis of quartz and feldspar (Figure 4B) indicating temperatures of these rocks were well below 300°C.

Sequence of Events

The Dedham granodiorite represents a period of felsic magmatism during subduction beneath the Avalon terrane. In an effort to determine the timing of crystallization of the Dedham pluton, Zartman & Naylor (1984) performed U-Pb dating of zircon. Results yielded a discordant array of data in which a chord can be drawn through the data points. This chord resulted in a lower intercept of 4 Ma and an upper intercept of ~622 Ma (Figure 6). The upper intercept is interpreted as the time of crystallization and thus provides a minimum age for the first episode of deformation and metamorphism recorded by the mafic xenoliths. The lower intercept age is geologically meaningless and may reflect a later hydrothermal/chemical alteration event. Following emplacement of the Dedham granodiorite at 622 Ma, a portion of

this pluton experienced a phase of plastic deformation along with the mafic gneiss. This deformation may have been in response to a collision between Avalon and some exotic lithosphere plate. The final episode of deformation that affected the Dedham granodiorite was low temperature brittle deformation and cataclasis. The formation of the Ponkapoag fault, which extends through this area may be responsible for this phase of brittle deformation although its absolute age is uncertain. Although it does not display any obvious surficial expression, the presence of the fault is inferred because just north of the study area an outcrop of Cambrian-age Roxbury Conglomerate has sedimentary bedding that tilts southward 15° and would project beneath the crystalline rocks of the Dedham granodiorite.

The final igneous event to affect rocks at the Avalon terrane, and associated with the brittle deformation, was the intrusion of two pulses of basaltic magma along NE-SW trending and E-W trending fractures. The first pulse was associated with, and emplaced along, NE-SW trending fractures. The second pulse of basaltic magma was emplaced along E-W trending fractures and cross-cut the older NE-SW dikes. The basaltic dikes have also been affected by a post-emplacement, low temperature hydrothermal event. The age of emplacement for these basalt dikes is uncertain due to the lack of radiometric age control. All we can say for certain is they are younger than 622 Ma and that the E-W trending dikes are younger than the NE-SW trending dikes. The dikes themselves were emplaced during a time of crustal extension and rifting. One possibility is they are Jurassic in age and represent the break-up of the supercontinent Pangea that formed at the close of the Paleozoic. Break-up began in the Triassic approximately 240 Ma with the entire eastern margin of North America intruded by basaltic dikes at 200 Ma. Alternatively, these dikes could represent an earlier rifting event in the Late Proterozoic or Early Paleozoic possibly when Avalon was separating from Gondwana. Without precise isotopic dates we cannot distinguish between these two models.

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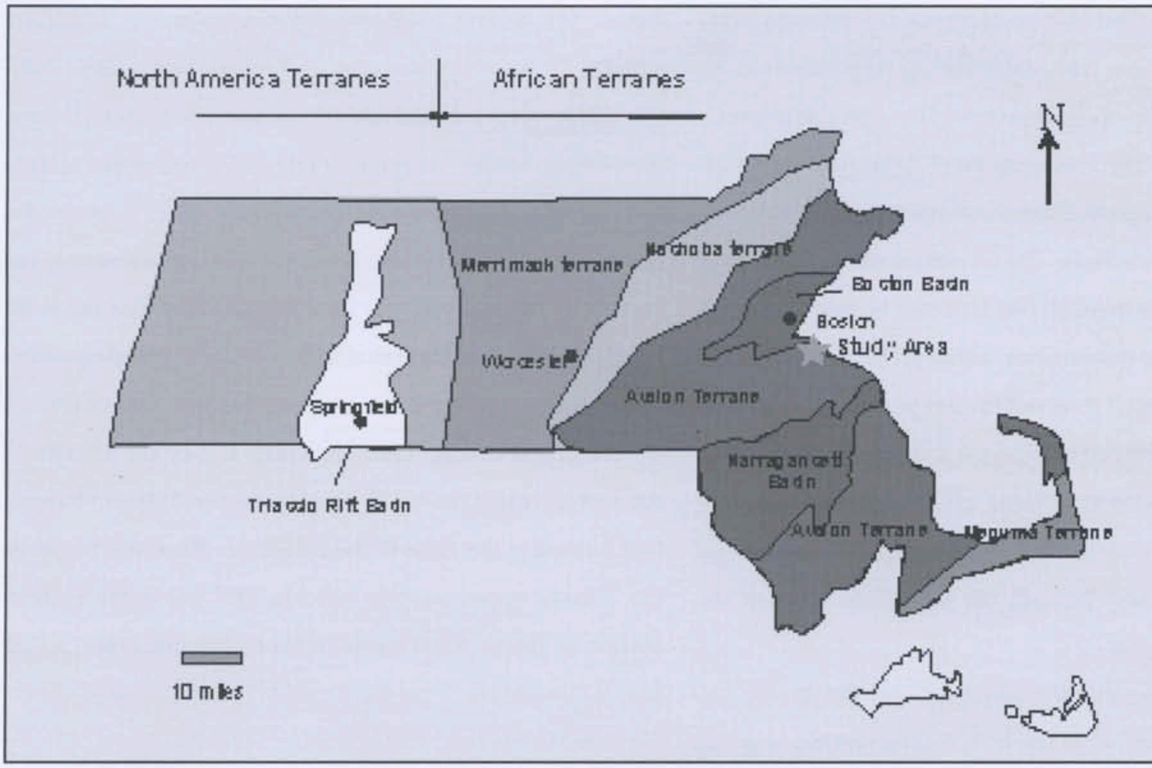


Figure 1. Generalized terrane map of Massachusetts. Modified from Skehan (2001).

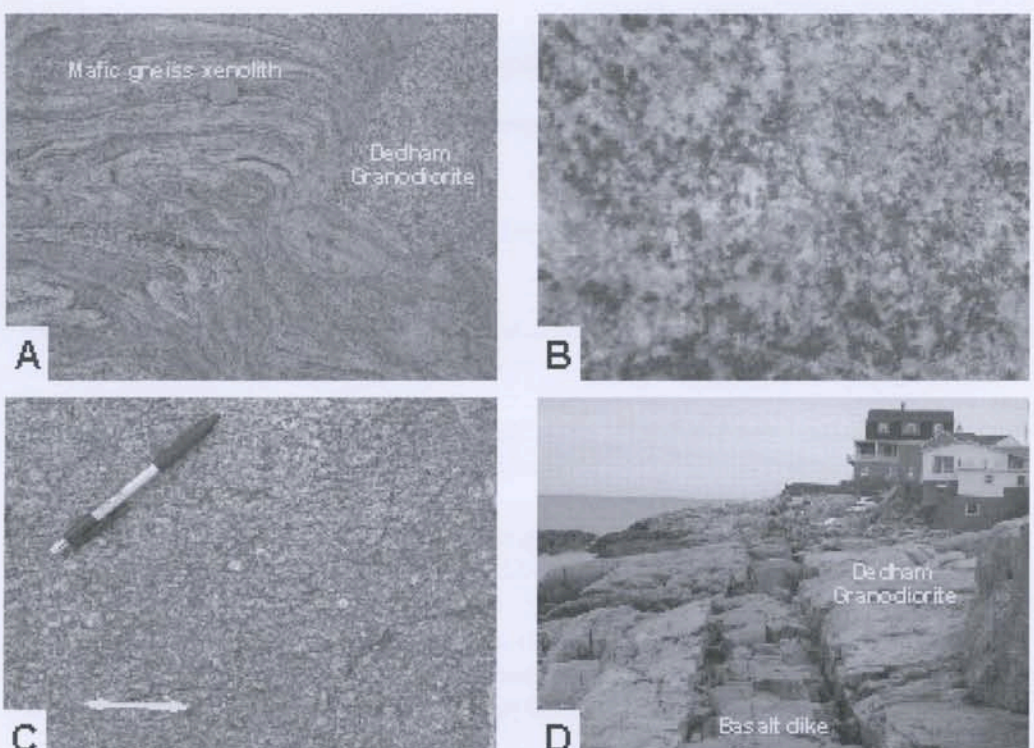


Figure 2. Field photographs of rock units exposed at Black Rock Beach. A) folded and intensely foliated mafic xenolith incorporated in weakly deformed Dedham granodiorite (quarter for scale); B) Undeformed Dedham granodiorite; C) Deformed and weakly foliated Dedham granodiorite (arrow shows alignment of feldspar clasts); D) undeformed, E-W trending, porphyritic basalt dike (view towards the east).

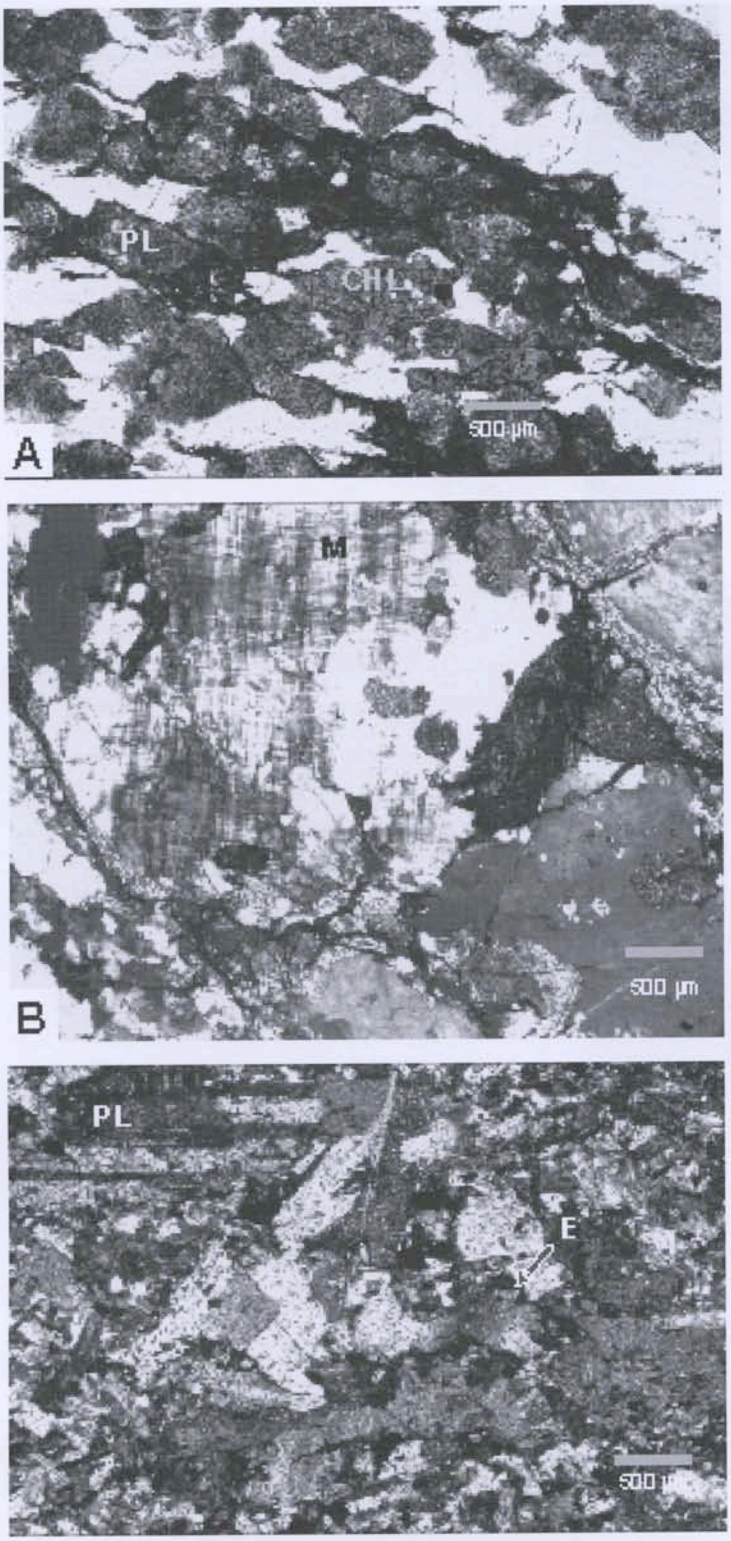
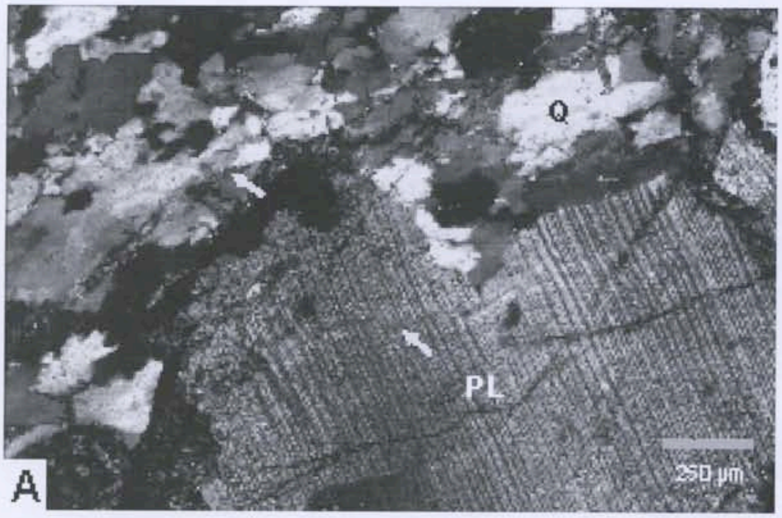


Figure 3. Photomicrographs of mineral assemblages in rocks at Cohasset. A) Mafic gneiss, plagioclase is highly altered clay (PL) and chlorite is abundant (CHL); B) Dedham granodiorite with microcline (M); C) porphyritic basalt dike. Phenocrysts of plagioclase (PL) set in a fine grain matrix of plagioclase laths. Abundant epidote (E) suggests post-emplacement hydrothermal alteration. All photographs are in cross-polarized light (XPL) except A, which is in plane polarized light (PPL).



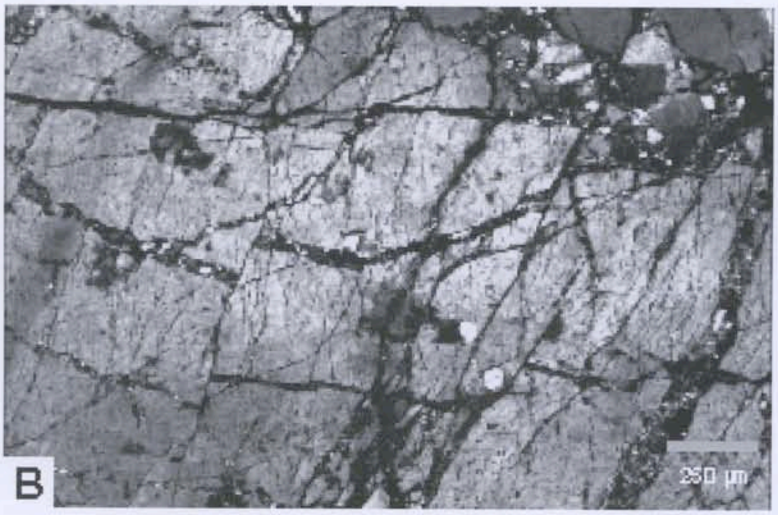


Figure 4. A) Photomicrographs of sample 3 showing quartz and feldspar microstructures in the Dedham Granodiorite. Quartz (Q) exhibits sutured grain boundaries, undulose extinction, and subgrain formation, all indicative of plastic deformation at temperatures above 300°C. Feldspar (PL) exhibits only minor plastic deformation in the form of undulose extinction and bent twin lamellae suggesting temperatures exceeded 450ºC, locally (XPL). B) Cataclastic microfracturing in feldspar from the Dedham granodiorite (XPL).

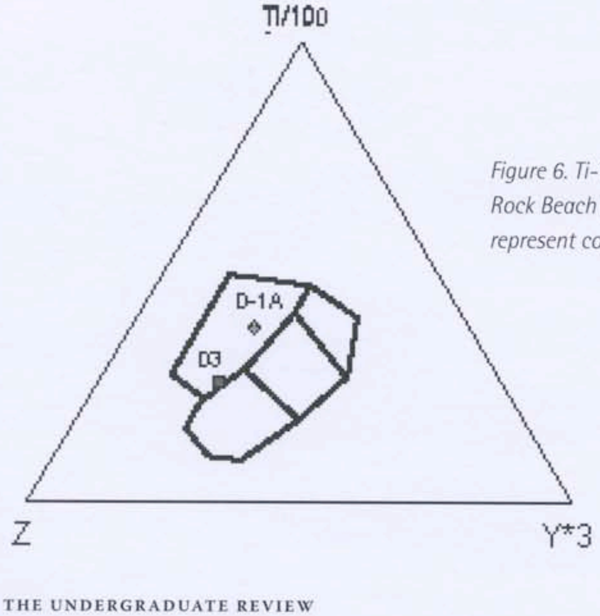


Figure 6. Ti-Y-Zr tectonic discrimination diagram shows results from two basalt dikes at Black Rock Beach (after Pearce and Cann, 1973). Both samples fall in the within plate field and represent continental rifting.