MULTIPLE EPISODES OF MAGMATISM, DEFORMATION, AND METAMORPHISM IN THE AVALON TERRANE OF EASTERN MASSACHUSETTS

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ABSTRACT

Crystalline rocks at Black Rock Beach, Cohasset are part of the Avalon terrane of eastern Massachusetts and record a polyphase geologic history. Field and petrographic analysis reveal evidence of two phases of metamorphism and magmatic activity and three episodes of deformation. Lithologies present in the study area include; highly deformed mafic gneiss, Dedham granodiorite, and basaltic intrusions. The earliest phase of metamorphism and deformation are recorded by mafic gneiss which occur as large xenoliths within the more extensive 622 Ma Dedham granodiorite. The mafic gneiss is folded and preserves a mylonitic texture that may be remnants of the Burlington Mylonite Zone. 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 display undulatory extinction and sutured grain boundaries, which suggest deformation occurred at temperatures that exceeded 450°C. A second phase of magmatic activity affected this area and resulted in the intrusion of several 1-2 meter wide, NE and E-W trending, porphyritic basalt dikes. These dikes cut across both the xenoliths and the foliation in the granodiorite and were emplaced during a time of crustal extension and brittle deformation and later experienced hydrothermal alteration. The different orientations of the dikes indicate two episodes of magmatism within a changing stress regime. During the time of emplacement of the dikes, the Dedham granodiorite also experienced brittle deformation and was highly fractured and brecciated. The absolute timing of the events mentioned above is difficult to determine unequivocally due to the lack of precise geochronologic constraints for this area. The crystallization age of the Dedham granodiorite has previously been reported as 622 Ma (Zartman et al., 1984). Thus, the earliest phase of metamorphism indicated by the presence of gneiss xenoliths must pre-date 622 Ma, whereas the plastic deformation preserved in the Dedham granodiorite and the emplacement of the basaltic dikes and brittle deformation must post-date this age.

INTRODUCTION

The geology of Massachusetts is the result of a complex and prolong history involving major mountain building events separated through time and space. The bedrock geology of Massachusetts can be describe in terms of an amalgamation of different geologic terranes. The most prominent terrane in eastern Massachusetts is the Avalon terrane. This study investigated rocks that are exposed at Black Rock Beach in Cohasset, MA. Field observations revealed the presence of metamorphic gneisses, although existing maps of the area show the bedrock consists of Dedham granodiorite (1, 2). In an effort to decipher the geologic history of a portion of the Avalon terrane we applied basic field observations and detailed petrographic and microstructural analysis to a variety of lithologies, each containing a small piece of geologic information.

Rocks at Black Rock Beach record multiple deformation and metamorphic events that reflect the complex nature and history of Avalon and the evolution of the North American continent. We will unravel this history by determining the conditions of metamorphism such as temperature and pressure that these rocks experienced. Identification of microtextures in certain minerals can be used to provide information on the conditions of deformation. Previously published U-Pb geochronology is used to place constraints on the timing of the metamorphic and deformational events contained in these rocks. Our results will add to the recent recognition of a more complex history involving several overprinting orogenic events that have affected the Avalonian terrane of Massachusetts.

GEOLOGIC 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 accreted to the eastern margin of Laurentia over a span of several hundred million years (2). This study concentrated on rocks that occur within the Avalon terrane (Figure 1).

Avalon began forming as a volcanic arc along the western margin of Gondwana in Late Proterozoic time. It rifted from Gondwana ~465 Ma (5) and began a slow trek across a proto-Atlantic ocean where it experienced several major orogenic events and its final collision with Laurentia. During the Acadian Orogeny (~425-370 Ma) 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, again causing high-grade metamorphism and minor plutonism. The last major orogenic event to affect Avalonian rocks was the subsequent break up of Pangea during Triassic-Jurassic time. Breakup resulted in tensile stresses and brittle deformation that allowed basaltic dikes to intrude along a series of E-W and NE-SW fracture sets (2).

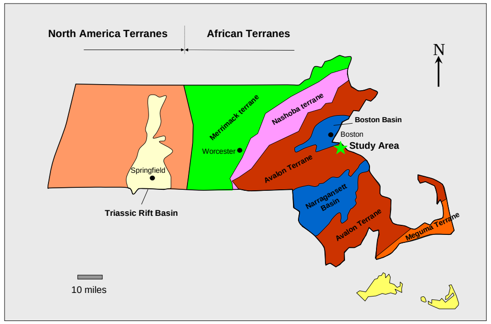

Figure 1. Generalized terrane map of Massachusetts. Modified from (2).

RESULTS

FIELD RELATIONS

Field work identified three distinct rock units; mafic gneiss xenoliths, granodiorite, and porphyritic basalt. Each rock records a portion of the geologic history that allow us to decipher the events that affected this part of the Avalon terrane and reconstruct the geologic history.

Mafic Gneiss (Figure 2A)

- Occur as xenoliths in granodiorite
- Highly folded and strongly foliated and mylonitic
- Folds formed in a compressive tectonic environment associated with the first episode of metamorphism

Dedham Granodiorite (Figure 2 B & 2C)

- Undeformed to weakly deformed coarse-grained plutonic rock
- Weakly developed foliation defined by K-feldspar porphyroclasts indicates post-crystallization deformation

Porphyritic Basalt Dikes (Figure 2D)

- Occur in two dominant orientations; older dikes trend NE-SW; younger dikes trend E-W
- Emplaced during a period of crustal extension
- Undeformed, but hydrothermally altered

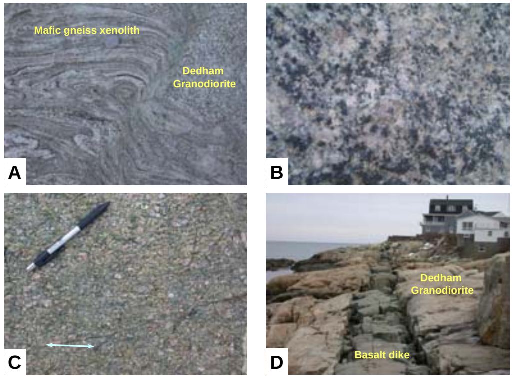

Figure 2. Field photographs of rock units exposed at Black Rock Beach. **A)** highly folded and intensely foliated mafic xenolith incorporated in weakly deformed Dedham Granodiorite (quarter for scale); **B)** Undeformed Dedham granodiorite; **C)** Deformed and weakly foliated Dedham Granodiorite (blue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

PETROGRAPHIC ANALYSIS

Samples were analyzed from the mafic gneiss xenoliths in an attempt to constrain the conditions of metamorphism (temperature & pressure). Samples of the Dedham Granodiorite were studied to investigate evidence of post-intrusion deformation that affected the granodiorite. Finally, three samples from the porphyritic basalt dikes were studied to determine the mineralogy of these mafic dikes, and the extent of hydrothermal alteration.

Mineral Assemblages:

Mafic Gneiss Xenoliths
quartz + plagioclase + epidote + chlorite + perthite + sericite + biotite + opaque

Dedham Granodiorite
quartz + microcline + plagioclase + perthite + chlorite + epidote

Porphyritic Basalt Dikes
plagioclase + epidote + chlorite + sericite

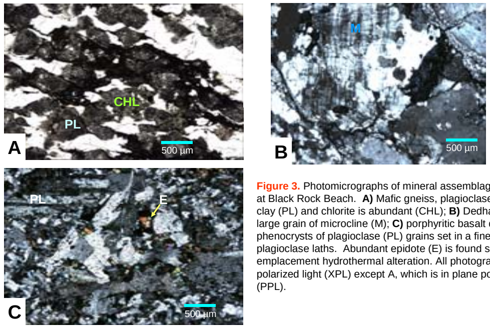

Figure 3. Photomicrographs of mineral assemblages in rock units at Black Rock Beach. **A)** Mafic gneiss, plagioclase is highly altered clay (PL) and chlorite is abundant (CHL); **B)** Dedham Granodiorite, large grain of microcline (M); **C)** porphyritic basalt dike. Large phenocrysts of plagioclase (PL) grains set in a fine grain matrix of plagioclase laths. Abundant epidote (E) is found suggesting post-emplacement hydrothermal alteration. All photographs are in cross-polarized light (XPL) except A, which is in plane polarized light (PPL).

CONDITIONS OF METAMORPHISM IN MAFIC GNEISS XENOLITHS

The mineral assemblages contained within the mafic xenoliths do not reflect a prograde or peak metamorphic mineral assemblage. It reflects a retrograde alteration assemblage that followed peak metamorphism. Thus, only a minimum estimate can be provided on the metamorphic conditions prior to their incorporation as xenoliths in the Dedham Granodiorite. On the basis of the mineral assemblage preserved, we interpret these rocks as experiencing at least greenschist to epidote-amphibolite facies metamorphic conditions (~300-500°C & ~5 kilobars), however, the highly foliated texture in these rocks suggest a more intense set of conditions.

DEFORMATION IN DEDHAM GRANODIORITE

Crystal-plastic deformation in quartz and feldspar occurs at temperatures above 300±50°C and 450±50°C, respectively (3, 4, & 6). By using the microtextures preserved in quartz and feldspar we were able to identify an episode of deformation following crystallization as occurring predominantly between 350° to 450°C (Figure 4A). Following this episode of plastic deformation, the Dedham Granodiorite experienced a phase of intense cataclasis and brittle fracturing (Figure 4B).

Quartz Microtextures	Feldspar Microtextures
subgrain formation	undulose extinction
sutured grain boundaries	bent twin lamellae
undulose extinction	cataclastic microfracturing

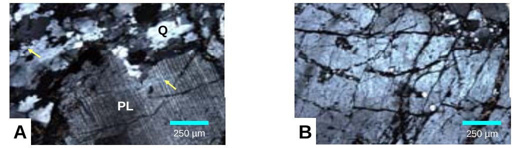

Figure 4. **A)** Photomicrographs of sample 3 showing quartz and feldspar microstructures in the Dedham Granodiorite. Quartz (Q) exhibits sutured grain boundaries, undulose extinction, and subgrain formation, all indicative of plastic deformation at temperatures above 300°C. Feldspar (PL) exhibits only 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).

TIMING OF METAMORPHISM

The absolute timing of metamorphism of the mafic xenoliths is unknown due to a lack of radiometric age constraints. U-Pb zircon dates from the Dedham Granodiorite (Figure 5) yield discordant results with a lower intercept of 4 Ma and an upper intercept of ~622 Ma (7). The upper intercept is interpreted as the age of crystallization and thus provides a minimum age for the first episode of deformation and metamorphism. The lower intercept age is geologically meaningless and reflects a later hydrothermal/ chemical alteration event.

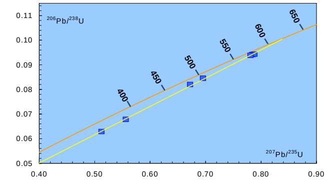

Figure 5. U-Pb age data for zircons from the Dedham Granodiorite. Reproduced from (7).

SEQUENCE OF GEOLOGIC EVENTS @ BLACK ROCK BEACH

- Formation of protolith to mafic gneiss some time prior in the Proterozoic (?)
- Metamorphism & deformation of mafic protolith into gneiss prior to 622 Ma
- Intrusion & crystallization of Dedham Granodiorite at 622 Ma
- Medium temperature plastic deformation of Dedham Granodiorite after 622 Ma
- Low temperature brittle deformation & cataclasis of the Dedham Granodiorite
- Intrusion of basaltic magma along NE-SW fractures & along E-W trending fractures possibly during Triassic-Jurassic crustal extension and breakup of supercontinent Pangea
- Alteration of basaltic dikes during low temperature hydrothermal event

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