GEOLOGY OF MASSACHUSETTS

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INTRODUCTION

Massachusetts displays some of the most fascinating geology in the country and has a long and rich history of research. Early geologists such as Edward Hitchcock, Charles Lyell, Rafael Pumpelly, William Otis Crosby, Nathaniel Shaler, B.K. Emerson, and J.B. Woodworth made many fundamental discoveries prior to World War I. Then after a hiatus in mapping, an out pouring of work of the Boston Office of the U.S. Geological Survey in the 1960s and 70s and a later program of the U.S. Nuclear Regulatory Commission completely changed the understanding of the geology of the State, as well as the Appalachian orogen, from theories that had developed in mid-century. This work contributed to J.T. Wilson's (1966) formulating the concept of ancient plate collision and this "type collision zone," which crosses the east-central part of the State, is now perhaps, the best studied one in the world. By the end of these studies it was proven that the basement rock was not principally multi-folded metamorphosed Paleozoic strata and Devonian granite as theorized, but thrusted Precambrian strata and granite. Unfortunately, much of the work is unpublished and the published State geologic map (Zen, 1983) and its description (Hatch, 1988) present the earlier theories despite their later publication date.

The mapped data in Massachusetts is extremely valuable for engineering, environmental and water resource needs. Regretfully, it has been estimated that directly or indirectly, the State or other private entities have invested hundreds of million dollars in the past 20 years in geologic engineering studies and remedial costs because vital geologic information has been lacking or unavailable due to non-publication. A newly reestablished Office of State Geologist hopes to provide these data and prevent further loss.

GEOLOGIC FRAMEWORK

Massachusetts is formed of a Precambrian basement that has a thin veneer of Paleozoic strata west of the Connecticut River valley, local fault basins of Eocambrian to Jurassic strata elsewhere, and an offshore apron of Cretaceous and Tertiary deposits, all typically masked by a thin mantle of glacial deposits (Woodhouse and Barosh, 1991). The four major terranes of metamorphic and granitic rock making up the basement record a plate collision between Grenville-aged North America (Laurentia) and northwestern proto-Africa (Gondwana). The Middle Proterozoic Grenville rock at the western edge of the State overrides greater than 22.5 km of strata of the Sturbridge terrane that had built out east of it during the Late Proterozoic, and now forms the center of the State (Peper and others, 1976; Barosh and Moore, 1988; Pease, 1989; Barosh, 1998).

The Sturbridge terrane, in turn, overrides terranes to the east, which locally show through as windows. It collided with over 18 km of volcaniclastic strata in a great northwest-dipping thrust belt, between the Clinton-Newbury and Bloody Bluff Fault Zones, forming the Nashoba Terrane that extends northeastward across the east-central part of the State and out to sea (Bell and Alvord, 1976). The collision generated the Southeast New England Batholith, which forms the eastern part of the State, 620-630 million years ago (Barosh, 2005). This pan-African batholith rose quickly into a high range and the extensional and topographic Boston Basin formed on its eastern flank at the end of the Proterozoic and filled with volcanic debris and argillite (Woodhouse and Barosh, 1991).

Very small remnants of a Cambro-Ordovician marine overlap sequence flank the basin in the east, and a much thicker section covers much of the Grenville in the west. These sections were divided near the collision zone by sea and land that separated the famous distinct "American" and "European" fauna. The final closing of the sea at the end of the Ordovician produced granite and volcanic rock on both sides of the Boston Basin and in the collision zone besides many thrust faults. Most of the State remained elevated thereafter and fault troughs of terrestrial to near-shore deposits formed periodically. Small grabens containing Siluro-Devonian arkosic redbed and volcanic rock are present in northeast east Massachusetts and south of Boston lies the large Carboniferous Narragansett Basin that extends into Rhode Island.

The large Hartford Basin graben filled with Upper Triassic and Lower Jurassic arkosic strata and basalt flows crosses west-central Massachusetts and forms the Connecticut River valley. This and many other faults of similar age in the State developed due to the regional extension that initiated the creation of the present North Atlantic Basin. As the new edge of the continent sagged down into the basin a wedge of Cretaceous-Tertiary deposits built seaward from it. These deposits remain almost entirely submerged to the east. Pleistocene glaciations smoothed the landscape and left a complex cover of till, glaciofluvial, and glaciolacustrine deposits. This debris mantle is generally thin, except in deep pre-glacial valleys and over portions of southeastern Massachusetts, Cape Cod, Martha's Vineyard, and Nantucket Islands, where glacial sand and gravel is hundreds of feet thick. Holocene marine inundation followed glacial rebound and formed coastal-fringing salt marshes and barrier island and spit complexes. Inland, freshwater wetlands developed in many glacial landforms and several large river systems evolved and began excavating ancient fault-controlled valleys.

GEOMORPHOLOGY AND NEOTECTONICS

The relative softness of the different terrains and fault troughs is well expressed as highlands and valleys, and the myriad faults present have been etched out by Pleistocene glaciers that also contributed many landforms. The Grenville terrane forms the high western Berkshire and Taconic hills of the Green Mountains, with intervening valleys of Cambrian limestone (Pumpelly and others, 1894). The metasedimentary rock of the Sturbridge and its local early Paleozoic veneer, form a lower hilly area traversed by the Connecticut and Nashua river valleys that occupy softer strata within fault troughs. Elongate granite bodies at the eastern edge of the Sturbridge form northerly trending hills. The metamorphosed strata and granite of the Nashoba thrust belt form slightly higher northeast-trending ridges to the east. The batholith farther east forms a lower rolling region with the Boston Basin forming an east-trending lowland and bay area between the higher Ordovician granite in the Blue Hills and Cape Ann. The broad lowland over the Carboniferous Narragansett basin descends southward into Rhode Island's Narragansett Bay. Recessional and interlobate moraines with associated glaciofluvial sand and gravel from a glacial stand in Cape Cod bay constitute the flexed arm of Cape Cod, while Martha's Vineyard and Nantucket Islands to the south are remnants of the earlier, southernmost glacial limit (Oldale and Barlow, 1986). Neotectonic subsidence and post-glacial sea-level rise result in a drowned shoreline in rocky areas. Bluffs on the southern and eastern sides of the Cape and Islands are subject to erosion rates that commonly approach three feet per year.

The north and northwest-trends of the youngest fault sets are particularly noticeable in stream and river courses across the region, especially the latter which controls the locations of many of the old roads (Hobbs, 1904). These generally small faults are commonly more prominent than glacial features. Most are shown to be post-Early Jurassic in age where they can be dated. They form the young and still active horst and graben system that makes up Narragansett Bay.

Most earthquakes in the region happen at fault intersections along the northwest-trending faults (Barosh, 1990). A zone of northwest-trending faults across New Hampshire extends offshore east of Boston through the epicenter of the 1755 Cape Ann earthquake, which had an apparent Intensity of VIII and an estimated mb magnitude of 5.8 and is the largest recorded for the northeastern U.S. (Woodhouse and Barosh, 1991). Such faults are believed to be related to the transform faults in the North Atlantic Basin and apparently are due to its continued expansion. In addition to fault movement, different types of crustal warping are affecting the State at present.

WATER RESOURCES

Massachusetts receives approximately 40 to 42 inches of annual precipitation distributed fairly evenly throughout the year. This feeds numerous large and small river systems and scattered fresh-water lakes which provided readily available potable water during settlement, and sustained substantial population growth across the state after 1750. However, the industrial development in urban centers following the Civil War threatened local water supplies by overuse, sewage discharge, and industrial contamination. These were recognized as public health issues by 1880 and the State's urban centers were at the forefront in developing municipally-managed drinking water and wastewater systems. Metropolitan Boston faced a dilemma in attacking the growing problem as the large rivers lay to the north or far west and lacked reaches that could be easily dammed. The challenge was met by creating an elaborate system of reservoirs linked by bedrock tunnels across the eastern two-thirds of the State and Massachusetts Bay to move water across the natural drainage of the region. An extensive network of bedrock sewer tunnels also was built. Today this is managed by the Massachusetts Water Resources Authority (MWRA), which daily delivers an average of 239 million gallons of potable water and treats 350 million gallons of sewage for over 2.5 million residents in 61 communities.

NATURAL RESOURCES

Massachusetts has few natural resources other than granite and glacial sand and gravel: the promise of offshore oil and gas has yet to materialize (Farquhar, 1982). Tectonic activity has been unfriendly to mining by eroding away mineral deposits, breaking stone and metamorphosing coal.

A brief iron industry based on bog iron occurred in early colonial times along with limited glass production from sand deposits in eastern Massachusetts. Statewide, local workings of very limited massive sulfide ore deposits occurred in the 19th century that are now of historical interest along with iron, copper, manganese and zinc extracted in the west in the Hawley mineral belt and Charlemont areas, and pig iron from the Richmond area. It was not until dimension and building stone quarries opened north and south of Boston in the early 1800s that there was a commodity for export. Small quarries in the foliated Proterozoic granite exist across the State; however, the nonfoliated Late Ordovician granite near Boston provided both a superior product and one that is located on the coast for easy shipping. Quarrying of the Mesozoic "brownstone" sandstone of the Connecticut valley supplied a regional market, especially in Victorian times for row houses. Now, however, stone productions is limited to crushed rock for construction and concrete aggregate, and curb stone for local use. Minor production of pegmatite minerals and graphite occurred in the past and small coal mines have supplied local needs at times, but most have been "money pits" and no seams of sufficient quality and size to sustain an industry have materialized. The promise of coal from the Narragansett basin, like offshore oil and gas, has proved elusive.

NATURAL CONTAMINANTS

Natural contaminants cause many local problems principally in the central portion of the State. A Late Proterozoic volcaniclastic unit, the Paxton group (Barosh and Moore, 1988), that crosses eastern New England, is arsenic-bearing and poses a health threat in drinking water where wells intersect tiny veinlets of arsenopyrite. Radon is produced from many of the Proterozoic granites, perhaps chiefly from the two-mica ones, and enters buildings through foundations and basements or water supplies at amounts exceeding public health advisory limits. Pyrrhotite is very common in the rocks of central Massachusetts, and can quickly breakdown into oxides, weakening the rock sufficiently in some units to cause rockfalls in cuts, and commonly the “rust” enters water supplies through bedrock and gravel wells to both affect taste and stain.

SHAPING HUMAN HISTORY

Geologic factors helped shape the rugged independent character of the early inhabitants of Massachusetts. The lack of mineral resources and the limited fields that grew rocks every spring did not favor the development of large plantations with a landed gentry and a subclass of farm laborers. Even lime for fields was lacking except in the western mountains where it was of limited value. The drowned offshore coastal plain deposits, however, provided banks that suited the growth of cod and attracted whales. This led eventually to Massachusetts becoming a leader in world-wide whale hunting and maritime trade, an endeavor aided by fine harbors at the home ports. Quarrying of granite near Boston also led to the development of the first railway in the country to connect to the docks for shipping of the stone to East and Gulf Coast cities. The trade in overseas manufactured goods led to promoting local manufactories that made full use of the water power that could developed at dams across the rocky terrain. From the very first, settlers proposed modifying the sometimes hostile land to fit their needs; draining coastal marshes for hay fields and building some of the first canals, railroads, railroad tunnels, water tunnels and now depressed expressways in the country, all of which required some understanding of the geology.

GEOLOGIC IMPACT ON ENGINEERING

The development of Boston with its complex geology led to many advances in engineering geology. Early workers did much to unravel the geology, but the practical understanding of the interaction between geology and engineered structures remained relatively unrefined until the 1890’s (Miller, 2002), when some excellent work was done on dam foundations and tunnels for water supply. Through the 1870s, early area buildings, bridges and other structures utilized comparatively simple soil-supported foundations. These were usually constructed on brick or mortared stone footings. Later, tapered wood-piles driven into the desiccated, stiffer marine clays commonly supported waterfront structures (Parkhill, 1998).

Advances in foundation engineering grew along with rapid growth in urban areas in the early 20th century United States. In Boston, emigration, industrial advances, desire for larger buildings and the economic expansion between 1880 and the mid-1920s fueled demands for new construction on filled lands outside the old urban core. This core constituted the original small peninsular, which is mostly underlain by typically dense, stable glacial deposits. The “made land”, which was marginal even for simple construction purposes, generally consists of a combination of unstable fill, soft organic peat and silt, and thick compressible marine clay (Woodhouse and Barosh, 1991). If loaded beyond a certain point, these materials could potentially deform, leading to settlement of the structure with consequent shifting and likely damage (Miller, 2002).

The influence of geology on urban foundation construction, therefore, became an interest of study. Irving B. Crosby published engineering geology maps in the early 20th century, including possibly the first detailed seismic studies of an urbanized area in 1903 and 1932 that depicted relative stability of the local terrain to earthquake-induced ground motions. This was aided by a new geologic map of the metropolitan area by LaForge (1932). In an odd twist of fate, differential settlement observed in the foundations of what was then the new Massachusetts Institute of Technology campus in Cambridge attracted the interest of scientist Karl Terzaghi who arrived at the school in 1925. By the early 1930s, Terzaghi and Arthur Casagrande examined the relationship between laboratory experiments on the strengths and properties of undisturbed cohesive soils, including the Boston Blue Clay, and the predictions for how these soils would behave under construction conditions (Parkhill, 1998). Their careful analyses of cohesive strengths and characteristics of other soils identified general properties, behaviors and limitations that were formative to the discipline of soil mechanics. Many of the theories formulated then are still applicable to major constructed works and deep excavations worldwide.

As foundation demands for larger buildings shifted from overburden based systems in the late 1940's to 1950's, the level of investigation and geologic interpretation of deeper glacial soils and knowledge of the bedrock characteristics increased. This was generally through exploratory soil borings and diamond core drilling methods performed for geotechnical design purposes. However, only the upper five to ten feet of the bedrock was typically evaluated. A comprehensive structural understanding of the bedrock chiefly composed of latest Precambrian, sandstone, conglomerate, volcanic material, argillite, and younger crosscutting mafic dikes, remained elusive, as the majority of the bedrock surface still remained masked by the thick overburden.

Further complexities in the deep bedrock basin structure of metropolitan Boston were revealed and examined in six major bedrock water-supply and sewer infrastructure tunnels between 1947 and 1974. The majority of one, the Dorchester Tunnel constructed between 1968 and 1974, was reportedly driven employing the first application of a mechanized, tunnel-boring machine, now a commonly used construction technique for bedrock tunnel advancement. Less than ideal bedrock conditions were observed in sections of almost all tunnels studied and commonly caused by areas of softer, kaolinized and decomposed bedrock resulting from possible hydrothermal alteration, which were commonly associated with major shear zones, breccias, fault gouge or fault zones (Woodhouse, 1989). Clifford Kaye of the then Boston Office of the U.S.G.S. did much to understand this geology for engineering purposes (Kaye, 1982). The structurally weaker rock was accommodated within the tunnels by concrete lining, steel support, rock bolts or other construction methods in response to the problematic ground conditions.

The maximum expected earthquakes for Boston and the region were evaluated for the adequacy of seismic design for critical facilities along with determining the cause of earthquakes in New England by a program of investigations developed for the U.S. Nuclear Regulatory Commission (Barosh 1990; Woodhouse and Barosh, 1991)); a program that was followed in both the central and eastern U.S.

Foundations became more complex, and were constructed by a greater variety of methods in the 1960's and 1970's. Machine-excavated straight shaft and belled caissons replaced the dangerous hand-excavation methods. Precast-prestressed concrete piles replaced the more costly steel pipe ones, and the advent of soldier pile-tremmied concrete or "slurry wall" excavation support method, arrived in Boston in 1976 (Parkhill, 1998). The downtown development boom in the early 1980's, brought a need for even deeper excavations and foundation systems and these yielded additional insight into the soils and bedrock below the city. The extensive subsurface explorations and innovative construction methods for the nearly $16 billion Central Artery/Tunnel and Deer Island Outfall Tunnel highlighted the value of engineering geology and the high costs incurred when it is lacking. These projects provided a tremendous amount of new data yet to be analyzed for the next round of development.

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