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Natural Resource Stewardship and Science

Saugus Iron Works National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/929

ON THE COVER
Reconstructed forge and rolling-and-slitting mill at Saugus Iron Works National Historic Site. View is from the Saugus River, east of the buildings. Photograph taken in 2006. Photograph available on Wikimedia Commons via Creative Commons Attribution-Share Alike 3.0 Unported license at http://commons.wikimedia.org/wiki/File:Saugus_Iron_Mill.jpg (accessed 21 July 2014).

THIS PAGE
The forge at Saugus Iron Works National Historic Site. The forge was used to remove additional carbon and slag from the pig iron that was cast directly from the furnace. National Park Service photograph available at: http://www.nps.gov/storage/images/sair/Webpages/gallery-01.html (accessed 21 July 2014).

Saugus Iron Works National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/929

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Saugus Iron Works National Historic Site (Massachusetts) on 11 July 2007 and a follow-up conference call on 21 May 2014, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

This Geologic Resources Inventory report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. The report was prepared using available geologic information and the NPS Geologic Resources Division did not conduct any new fieldwork in association with this report. Sections of the report discuss distinctive geologic features and processes within Saugus Iron Works National Historic Site, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geologic map data. A poster (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit. A glossary defines many of the geologic terms used in this text.

Saugus Iron Works operated from 1646 to 1668 and was the first incorporated iron works in North America. Designated a national historic site in 1968, 300 years after its operation, the site preserves the historic setting—a foundation for future iron manufacturing in America. All of the elements necessary to utilize the most advanced iron-making technology of the time—extracting iron by blast furnace—came together at Saugus: bogs rich in iron ore, flux from gabbro obtained near Nahant, upland forests for charcoal, and most importantly, flowing water for power.

The Saugus River flows through a narrow notch over a fall line at the site. Early ironmakers dammed the river and used its energy on waterwheels to power the bellows of the blast furnace, as well as the forge and rolling and slitting mill. The river also provided a transportation corridor to move goods into and products away from the iron works. A natural eddy in the river, known as the Turning Basin, facilitated brisk activity along the site's wharf.

Saugus Iron Works National Historic Site is part of the Avalon terrane of eastern Massachusetts. Terranes are bodies of rock, bounded by faults that are demonstrably different from surrounding rocks and originated elsewhere. The Avalon terrane was once attached to the northwest coast of Africa. It rifted away and accreted onto the eastern edge of North America hundreds of millions of years ago as part of a series of mountain-building orogenies that culminated in the formation of the Appalachian Mountains. The complicated assemblage of rocks in the site area reflects this geologic history. Myriad faults cut through the rocks and movement along these faults juxtaposed different rock types. The rocks are primarily Proterozoic granite, granite gneiss, and metamorphosed volcanic and sedimentary rocks more than 550 million years old; Paleozoic granite more than 370 million years old; and Jurassic diabase dikes that accompanied the rifting associated with the opening of the Atlantic Ocean more than 150 million years ago. A metavolcanic bedrock unit (Lynn Volcanics, geologic map symbol **Zlv**) underlies the site. Pleistocene glaciers and recent earth surface processes left a mantle of surficial deposits over the bedrock in the site area, although they are unmapped.

Noteworthy geologic features and processes include the following:

- Fluvial Features and Processes. The Saugus River and its adjacent riparian zone and floodplain are the primary natural resources at Saugus Iron Works National Historic Site. The river channel includes a flanking brackish water wetland and the Turning Basin. The river meanders across its floodplain and floods seasonally.
- Slope Features and Processes. Slope movements—the downslope transfer of earth materials—occur as small scale slumps and slope creep on the site's steep slopes below the upland bluff areas. The historic slag pile was also a site for slope processes.
- Coastal Resources. The Saugus River is tidal just up to the Turning Basin. Tides are generally less than 2 m (6 ft) but contribute significantly to the hydrologic system and the brackish water estuary and wetland at the site.
- Faults and Folds. Faults, and less commonly folds, are prominent geologic structures surrounding Saugus Iron Works National Historic Site. Faults are fractures in rock along which rocks have moved. The density of faults and the covered bedrock combine to make determining the timing of faulting episodes difficult. Folds are bends in previously flat geologic strata. One convex (anticlinal) fold is mapped northwest of the site.

- Igneous, Volcanic, Metamorphic, and Sedimentary Rocks. Igneous (including volcanic), metamorphic, and sedimentary rocks are included in the GRI geologic map data for Saugus Iron Works National Historic Site. Although the rocks in the site (Lynn Volcanics) are about 600 million years old, they still contain features indicative of their original depositional setting—ejected from a string of ancient volcanoes in a shallow marine basin.
- Glacial Deposits. Glacial and other surficial deposits are not included in the GRI digital geologic map data; however, Pleistocene glaciers flowed over this landscape, scouring and eroding some areas and leaving thick glacial deposits in other areas. Detailed surficial geology information would be a valuable dataset to help determine the glacial history at the site.
- Radiometric Age Dates. The geologic history of this part of Massachusetts is incredibly complex and notoriously difficult to decipher given the surficial cover, urban landscape, concentration of faults, and juxtaposition of terranes. The ages of the geologic map units are therefore critical in deciphering their history. Radiometric age dates included in the GRI geologic map data contribute to understanding the geologic story of New England. The dates range from 600 million to 378 million years ago.
- Paleontological Resources. Fossils have not yet been documented within Saugus Iron Works National Historic Site. The bedrock is either too old or not of the correct type to preserve remains. Pleistocene deposits have, however, yielded fossils in the surrounding areas, so the potential exists for fossil discoveries within the site.

Geologic resource management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- Coastal Vulnerability to Sea-Level Rise and Climate Change. The Saugus River is tidally-influenced up until the Turning Basin at Saugus Iron Works National Historic Site, whose average elevation is 1 m (3 ft). Sea-level rise associated with climate change is a primary resource management concern because much of the cultural resources and vital habitats are within a few meters of the river. Also, due to steep slopes and the location of the riparian corridor in a dense residential setting, there is limited area for upward migration of wetland habitats.
- Flooding and Fluvial Geomorphology of the Saugus River. Similar to sea-level rise, seasonal floods contribute to riverbank erosion and head-cutting erosion within the site and threaten cultural resources and vital habitats within the channel and just adjacent to the river's edge. Siltation and invasive species had clogged and choked the Turning Basin, obscuring the historic setting and threatening the health of the natural ecosystem. In 2007, resource managers at Saugus Iron Works National Historic Site began a multi-year restoration and monitoring project for the Turning Basin. This project restored historic conditions, and improved the habitat for native species.
- Restoring the Turning Basin. Long-term sedimentation clogged the historic Turning Basin obscuring its significance, and allowing the proliferation of invasive wetland species. In 2007, the site began a basin-restoration project to increase the local volume of the river, and change the channel morphology to reflect historic conditions essential to the interpretation of the iron works. This project has involved excavating sediments, removing the Hamilton Street weir, rehabilitating the historic dock and bulkhead structures, and restoring tidal mudflat and marsh habitats. Monitoring is ongoing to study the effects of the restoration on the site's ecosystem.
- Slope Movement Hazards and Risks. Slumping and slope creep are the primary slope movements causing resource management concerns at the site. Trails have been paved to avoid gullying and new drainage systems are being investigated for the parking lot. Currently flow collects in a drainage pipe and flows into the stream while locally eroding the streambank. Monitoring of the historic slag pile to determine if slope processes are changing the historic contours is ongoing.
- Earthquake Hazards and Risks. Saugus Iron Works National Historic Site is not located near a seismic zone; however, the potential for large earthquakes exist. There is a 4% to 6% probability of a magnitude-5.0 or greater earthquake within 100 years. In such an urban setting, should a large earthquake occur, damage to infrastructure would be significant.
- Disturbed Lands and Mineral Extraction. Prehistorically and historically, the Saugus Iron Works National Historic Site area was extensively disturbed to mine Saugus "jasper", iron ore, clay, and flux (gabbro), and to develop and operate the iron works. The site's managers seek to restore and preserve the 17th-century condition of the site. Challenges include adjacent land use, siltation, and erosion.
- Paleontological Resource Inventory, Monitoring, and Protection. All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation. Currently, fossils are not documented within the site although there is some potential for their future discovery.

Products and Acknowledgments

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop Geologic Resources Inventory products. This section describes those products and acknowledges contributors to this report.

GRI Products

The objective of the Geologic Resources Inventory is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for non-geoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" section and Appendix B provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at: http://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

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Geologic Setting and Significance

This section describes the regional geologic setting of Saugus Iron Works National Historic Site, as well as summarizes connections among geologic resources and other site resources and stories.

Site Setting

In 1966, Saugus Iron Works was listed on the National Register and designated a National Historic Landmark. Authorized on 5 April 1968, Saugus Iron Works National Historic Site preserves the place of the first integrated iron works in North America—a critical foundation for the future of iron manufacturing in America. Founded within just a few years of the first permanent English settlement at Massachusetts Bay, this operation functioned from 1646 to 1668. Today, the site includes a slag pile and a restored house from the 1680s, as well as a reconstructed blast furnace, forge, warehouse, wharf, and rolling-and-slitting mill (figs. 1 and 2) (Killion and Foulds 2003).

The site encompasses more than 3 ha (8 ac) on the banks of the Saugus River in Saugus, Massachusetts almost 18 km (12 mi) north of Boston in southern Essex County. If the river channel area is included, the site is about 5.3 ha (13.1 ac) (James-Pirri et al. 2011). Elevation at the town of Saugus, Massachusetts is 6 m (21 ft) above sea level and the average elevation of the Turning Basin is 1 m (3 ft) (James-Pirri et al. 2010). Upland bluffs, steep banks, rolling hills, and level floodplain areas characterize the site's landscape. Because the site is only 5 km (3 mi) inland of the confluence between the Saugus River and Massachusetts Bay, tidal influxes create an estuarine wetland habitat along the Saugus River (Thornberry-Ehrlich 2008).

Geologic Setting

Massachusetts comprises a series of geologic provinces. From west to east they are the Grenville shelf sequence, Grenville belt, Eugeosyncline sequence, Waits River-Gile Mountain, Mesozoic basin, Bronson Hill sequence, New Hampshire-Main sequence, Avalon belt (province), and Narragansett basin (fig. 3) (Zen et al. 1983). Within each province the rocks have a similar age and geologic history. Saugus Iron Works National Historic Site is underlain by the Avalon province.

The rocks of the Avalon province are typically Precambrian granite and granitic gneiss and Precambrian through Ordovician metasedimentary rocks (fig. 4). Ordovician and Devonian granitic plutons intruded the older rocks (Robinson and Kapo 2003). Collectively, these rocks are called a "terrane." A terrane is a body of rock, isolated by faults, with internal compositional continuity, and a uniform metamorphic history. Terranes typically are demonstrably different from surrounding rocks and originated somewhere other than their present location.

Hundreds of millions of years ago, the rocks of the Avalon terrane accreted to the eastern edge of the North American continent along with other terranes during mountain-building events (orogenies), the timing of which is still a subject of much debate (Kopera 2011).

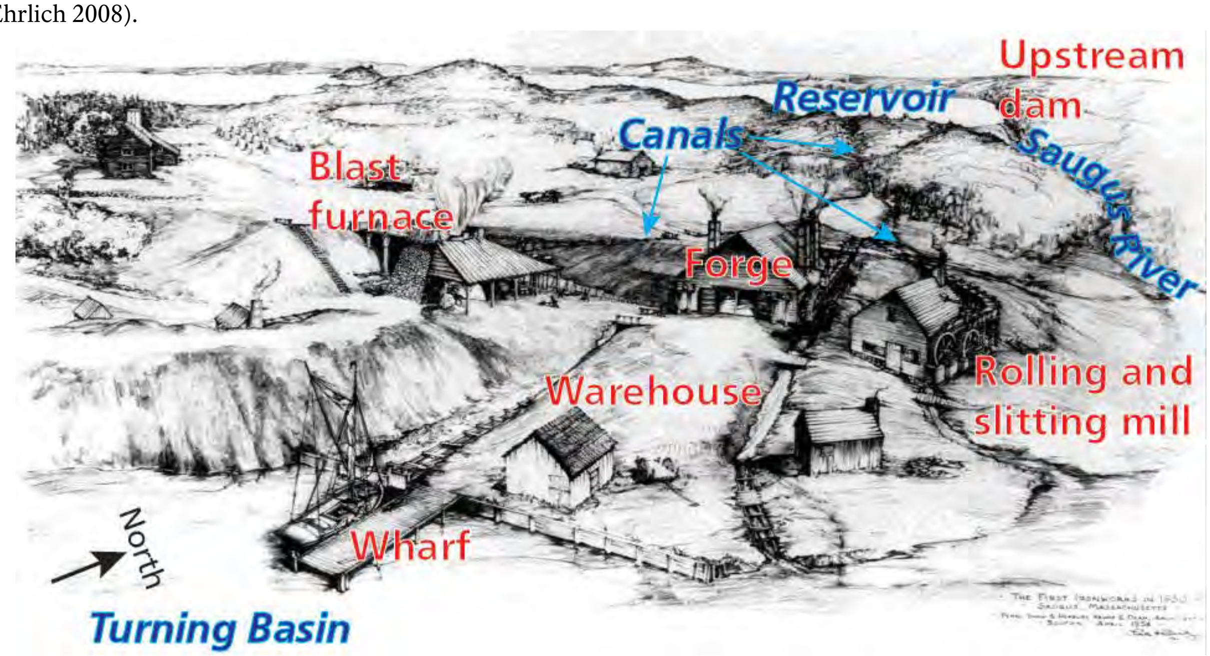


Figure 1. Saugus Iron Works National Historic Site in 1650. This artist's rendition of the site suggests its appearance during iron works operations in the 17th century. Annotation by Trista L. Thornberry-Ehrlich (Colorado State University). Original image is cover art from James-Pirri et al. (2011) attributed to Perry Shaw and Hepburn Kehoe and Dean Architects (1954).

Figure 2. Cultural features within Saugus Iron Works National Historic Site. The red lines denote the boundary of the site. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI World Imagery basemap, accessed 9 May 2014.

In the site area, from west to east, the terranes are called the Merrimack, Nashoba, and Avalon terranes (fig. 5). When the Avalon terrane accreted to North America, the Bloody Bluff fault (named for a historic location in Minute Man National Historical Park) accommodated oblique movement as the Avalon terrane subducted beneath and slid past the Nashoba terrane.

Prior to its accretion to North America, the Avalon terrane experienced a long history of deformation, igneous activity, and sedimentation. The complex geologic history of the Avalon terrane is well represented by the rock assemblage within and surrounding the site (fig. 6). The Neoproterozoic Lynn Volcanics (**Zlv** and **Zlvfb**) underlie the entirety of Saugus Iron Works National Historic Site. These rocks are about 600 million years old. They are in fault contact with adjacent intrusive igneous rocks (e.g., **Zgr**, **Zgrt**, **ZDgdt**, and **Dpgr**) and metamorphic rocks (e.g., **Zvk**) that range from Proterozoic through Devonian in age—or a potential span of more than 250 million years. The youngest geologic map units ("diabase dike with magnetite"—**ZJ[?]db**) may have intruded as recently as 145 million years ago.

The Roxbury Conglomerate and Cambridge Argillite (**ZCrcca** and **ZCrsca**) were deposited in the Boston Basin—formed as a rifted area (nonmarine sedimentary basin) within the Avalon terrane prior to its accretion onto North America (Billings 1976). Saugus Iron Works National Historic Site is located at the southern end of rocky uplands that form the northern border of the Boston Basin, which is a prominent topographic and geologic feature in eastern Massachusetts. East-west trending, north-dipping reverse and thrust faults crisscross the uplands and the Boston Basin. Movement

Figure 3. Geologic provinces of Massachusetts, Rhode Island, and Connecticut. Saugus Iron Works National Historic Site is part of the Avalon belt—a series of accreted terranes added over millions of years to the eastern edge of North America. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after information from Robinson and Kapo (2003). Shaded relief base map by Tom Patterson (National Park Service).

along these faults has forced different rocks to be in contact with one another. These juxtapositions are complex within the Avalon terrane (Kopera 2011).

Earth surface processes of weathering, erosion, and sedimentation have acted on the bedrock landforms for millennia, reworking and depositing unconsolidated surficial materials. Glaciers are agents of great change. During the ice ages of the Pleistocene, glaciers descended repeatedly from the Arctic across New England and caused significant landscape change, eroding some areas and leaving thick glacial deposits in others. As the glaciers melted, glacial lakes filled basins that had been impounded by ridges, ice, and terminal moraines which marked the termination of glacial advance. Following the most recent glacial retreat at the beginning of the Holocene, local streams and rivers such as the Saugus River deeply incised the surficial deposits, reworking them along their channels. Very little of the glacial depositional record remains on the local landscape; the bluffs may be part of a flat-topped sandy glacial delta (Thornberry-Ehrlich 2008). Much of the glacial-era record was eroded away by modern streams and rivers.

Geologic Significance and Connections

The geologic landscape of Saugus Iron Works National Historic Site is related to human history and ecosystem evolution. Originally farm and forest land, the site was chosen for the iron works in 1646 by Richard Leader because of its proximity to the raw materials needed to make iron, its inherent energy source, and its location near a coastal transportation port (Albright et al. 1977; Wall et al. 2004). Although the site has a long history of human disturbance, an important ecosystem thrives there today.

Making Iron by Blast Furnace

By the start of the 16th century, the blast furnace had replaced the “bloom hammering” method as the most technologically-advanced method of producing iron. In a blast furnace (figs. 7 and 8), kiln-dried charcoal, flux

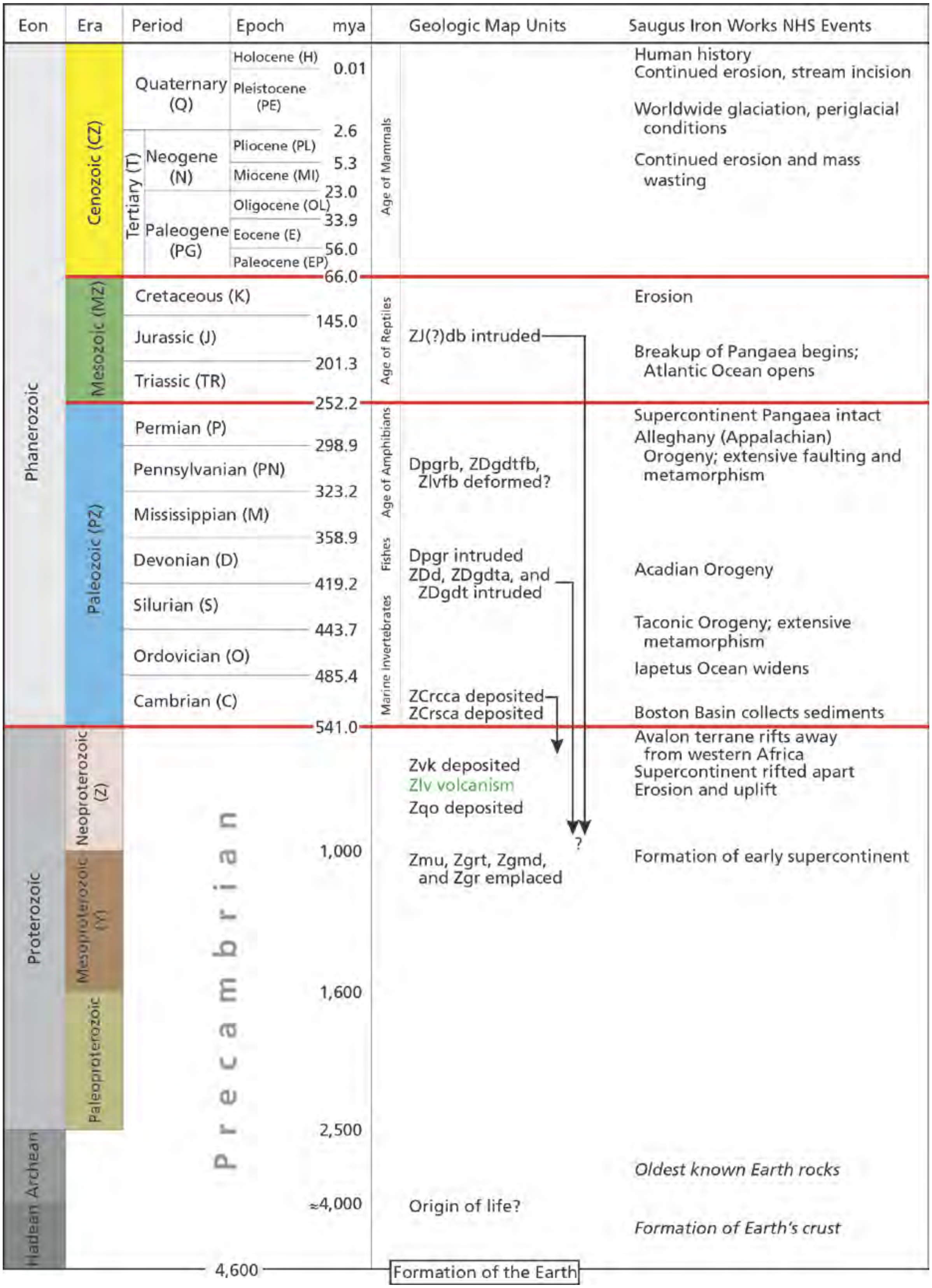


Figure 4. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Green text refers to units that appear within Saugus Iron Works National Historic Site. Arrows indicate a range of ages for the particular unit. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 30 May 2014).

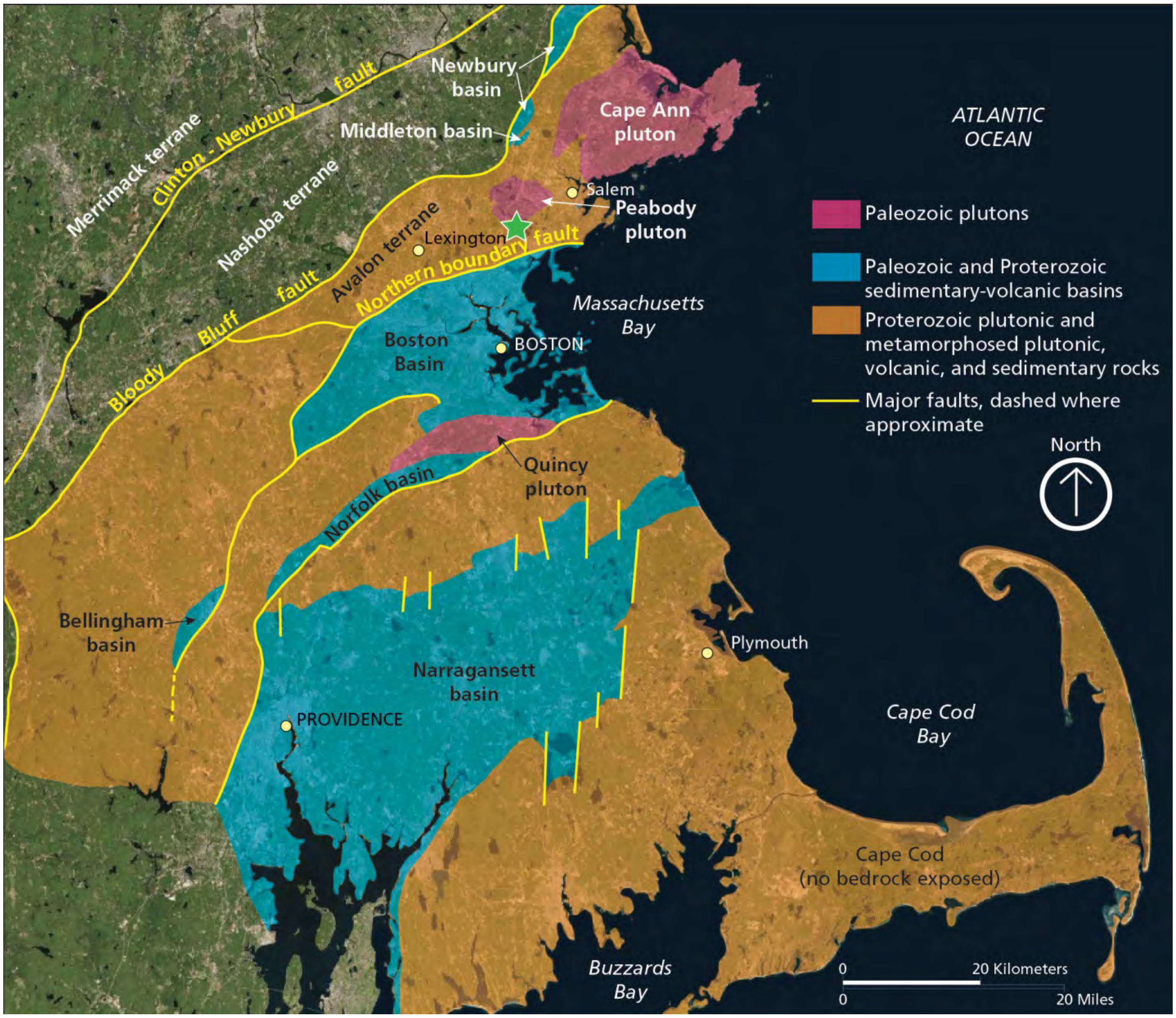
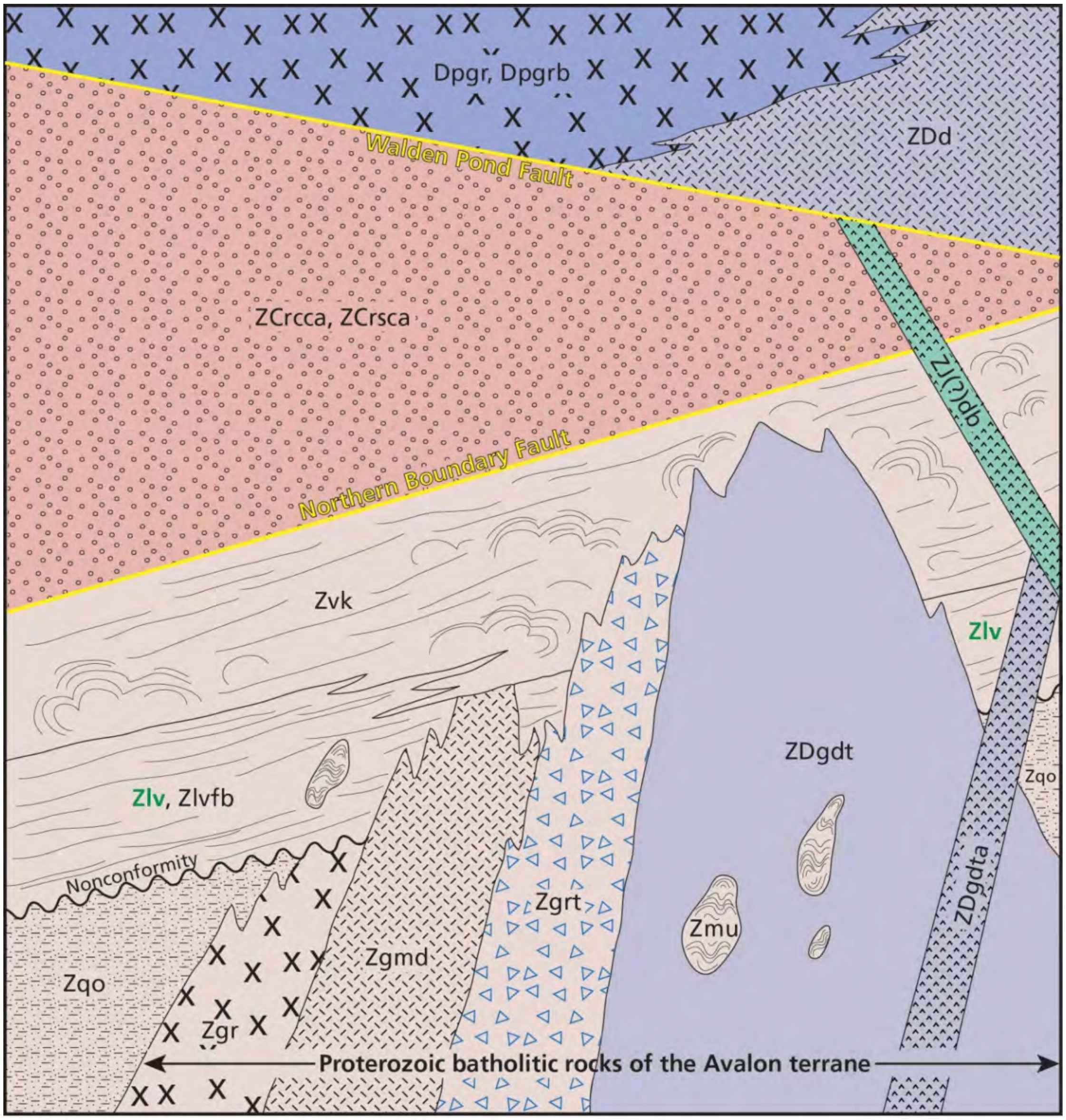


Figure 5. Major geologic features of eastern Massachusetts. Saugus Iron Works National Historic Site (green star) is in the Avalon terrane—one of a series of accreted terranes added over millions of years to the eastern edge of North America. Note the locations of the major faults (bold yellow lines) bounding each terrane and defining the boundaries of the Boston Basin. The Walden Pond Fault (shown on figure 6 separating metasedimentary rocks from igneous plutonic rocks) is not drawn or labeled on this map, but is located just north of Saugus Iron Works National Historic Site and the Northern Boundary Fault within the Avalon terrane. Merrimack and Nashoba terranes are included for reference. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 1 from Goldsmith (1991a) using ESRI World Imagery basemap, accessed 28 April 2014.

(gabbro or limestone), and iron ore were carried over the charging bridge and poured into the furnace top. Waterwheel-powered bellows stoked the fires in the furnace to a temperature of about 1,600°C (3,000°F). The carbon in the charcoal acted as fuel, creating a reducing chemical atmosphere of carbon monoxide. Flux is a substance that was added to promote the fusion of metals and minerals (First Iron Works Association 1952). The flux removed the siliceous (silica-rich) fraction of the iron ore. The chemical bonds within the ore then broke and the ore was reduced to liquid iron and a coating of slag. The slag was continually skimmed from the surface of the molten iron and dumped into the river. The molten iron was removed through sand trenches and the iron was either cast into long bars called "pigs" or other molded products such as pots, stoves, and salt pans (Wall et al 2004).

The iron resulting from this method at Saugus had high carbon content, commonly approaching 4%; therefore, products were brittle. After production, the cast-iron pigs were taken to the forge where a finery hearth was employed to remove the carbon by shaping the pigs under a water-driven, 230-kg (500-lb) hammer into an anchony (resembling a dumbbell). This was then fired again in a chafery forge where it was hammered into plate or bar iron of standard dimensions—"wrought iron." The repeated firing and hammering removed much of the carbon and slag. The waterwheel-powered rolling-and-slitting mill was used to flatten the wrought



Proterozoic? to Jurassic?
ZJ(?)db–Diabase dike with magnetite

Devonian
Dpgr–Peabody Granite
Dpgrb–Peabody Granite, brecciated

Proterozoic to Devonian
ZDd–Quartz-diorite and diorite
ZDgdta–Aplitic granodiorite
ZDgdt–Tonalite to granodiorite

Neoproterozoic to Lower Cambrian
ZCrcca–Roxbury Conglomerate and Cambridge Argillite, undifferentiated
ZCrsca–Argillaceous sandstone and siltstone and Cambridge Argillite, undifferentiated

Neoproterozoic
Zvk–Quartz keratophyre and keratophyre
Zlv–Lynn Volcanics
Zlvfb–Lynn Volcanics, fault breccia

Proterozoic
Zqo–Quartzite and Olistostromal Assemblage
Zmu–Mafic metavolcanic xenoliths of unknown affinity
Zgrt–Trondhjemite
Zgmd–Granodiorte to quartz monzonite
Zgr–Granitoidal rocks, undifferentiated

Figure 6. Schematic rock column. Graphic shows the intrusive nature of the units (e.g., ZDgdt intrudes and postdates Zvk, and is in turn intruded by ZDgdta) and juxtapositions of units across regional faults (e.g., the Northern Boundary and Walden Pond faults bound the ZCrcca and ZCrsca of the Boston Basin). No reference is intended to the land surface (i.e., vertical position) nor geographic locations. Units labelled in green (Zlv) are mapped within Saugus Iron Works National Historic Site. Bold yellow lines are major faults. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. See the Map Unit Properties Table for more detail. Graphic is not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 2 from Kopera (2011), which is modified from Kaye (1980).

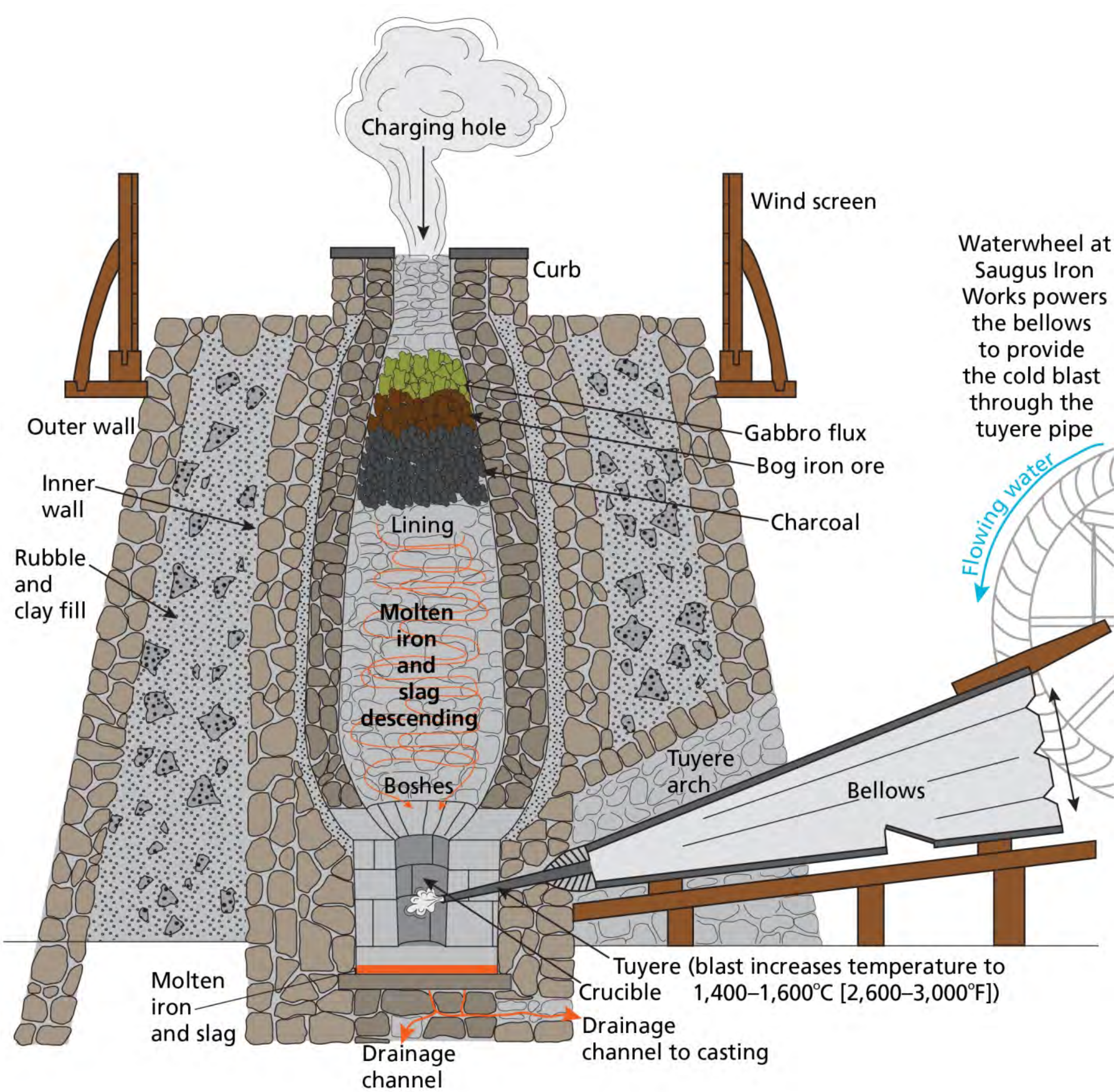


Figure 7. Schematic furnace operation at Saugus Iron Works. Flux material such as gabbro from Nahant, bog iron ore from nearby swamps, and charcoal from wooded uplands were charged into the furnace top. The cold blast of air provided by the Saugus River-driven, waterwheel-powered bellows created temperatures hot enough to extract the molten iron and slag from the charge. The material for the inner and outer walls may have been sourced from local igneous and metamorphic rocks (e.g., Dpgr, ZDgdta, ZDgdt, Zgdm, or Zgr). Local clays (Boston Blue Clay?) provided dense material for the rubble and clay fill. Graphic is not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after a graphic produced in 1951 by Perry Shaw and Hepburn Kehoe and Dean Architects.

iron bars and slice them into thin strips of rod (Hartley 1957; Wall et al. 2004).

Selection of Saugus

The record of human presence extends far beyond the colonial iron works and subsequent agrarian uses. Fossil shell middens and fish-weir archeological sites throughout the greater Boston area record a human presence as much as 12,000 years ago (Johnson 1949; Luedtke and Rosen 1993; Tweet et al. 2010). "Saugus" is an American Indian word meaning "great", "small outlet" or "extended." As evidenced by artifacts, American Indians sought the migratory fish that were funneled through the Saugus River's waterfalls and rapids (Killion and Foulds 2003). American Indians quarried Saugus "jasper" less than 1 km (0.6 mi) downstream from the iron works site on the south side of the river at a quarry source discovered by amateur archaeologist Henry Hayes in 1886. True jasper is a type of quartz. Saugus "jasper" is volcanic rocks, likely a quartz-rich, fine-grained rock known as rhyolite (e.g., part of **Zlv**) (Hollander and Hermes 1999; Kopera 2011).

Figure 8. Furnace at Saugus. The ore, flux, and charcoal were dumped into the furnace over the charging bridge from above. The bellows operation is covered by the wooden roof. Note the paved trail in the foreground and the relatively steep slopes surrounding the operation. Photograph by John Phelan, available on Wikimedia Commons via Creative Commons Attribution 3.0 Unported license at http://commons.wikimedia.org/wiki/File:The_Furnace_at_Saugus_Iron_Works_MA.jpg (accessed 21 July 2014).

Figure 9. Natural resources surrounding Saugus Iron Works. The location of Saugus Iron Works was selected in part because of its proximity to the three components necessary for iron work—fuel (charcoal), iron ore, and flux. National Park Service graphic, available at http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=SAIR (accessed 21 July 2014), modified by Trista L. Thornberry-Ehrlich (Colorado State University).

The reddish, buff-colored stone was extremely fine grained (smooth) and made exceptional tool and projectile point material. The quarry site has been lost to burial or construction (Hollander and Hermes 1999), however, remains from the tool-making activities and other American Indian artifacts may still be present in the sediments flanking the river (Thornberry-Ehrlich 2008).

All of the components necessary for an early iron works operation existed in the Saugus area—energy, flux, and ore (fig. 9). The site's greatest asset, the Saugus River, provided the energy source (Albright et al. 1977). It was the earliest example of major industrial use of a river in North America (Killion and Foulds 2003). Prolific forests were felled to produce the charcoal necessary to heat the ore and extract the iron.

The flux used at Saugus was not the standard for the time. In the mid-17th century, flux sources were typically limestone in the form of imported corals or marine shells. Archeological explorations revealed little evidence of limestone flux at Saugus Iron Works beyond some oyster shells. In the early 1950s, metallurgists H.M. Kraner and R.S.A. Dougherty of Bethlehem Steel analyzed the slag pile and determined that the Saugus ironmasters turned instead to a readily available local material (Marc Albert, Saugus Iron Works NHS and Boston Harbor Islands NRA, natural resource specialist, and Gregg Bailey, Saugus Iron Works NHS, seasonal park ranger, and Janet Regan, Saugus Iron Works NHS, museum curator, email communication, 21 May 2014). Ultramafic gabbro (low-silica, high-iron and magnesium, dark, coarse-grained igneous rocks) from the Nahant Peninsula was used for flux and smelting (First Iron Works Association 1952; Wall et al. 2004). The local gabbro had an iron content of about 11% to 15% and was quarried in Nahant by heating the stone ledges and hammering them until chunks broke away (Wall et al. 2004). The specific type of gabbro used at Saugus Iron Works was first described from Essex County and is thus named Essexite (National Park Service 2014a). Peat bogs and swamp deposits supplied iron ore. The ores were deposited when ferrous iron dissolved in groundwater accumulated as iron oxides on subsurface materials. This occurred at the groundwater/surface water interface at pH ranging from 3.0 to 4.7 (White 1941; Wall et al. 2004). A 60% bog ore and 40% gabbro combination was smelted down with charcoal at Saugus during the bulk of its productive period (First Iron Works Association 1952).

Beyond the raw materials used to produce the iron itself, other geologic materials played a role in the iron works operation at Saugus. Clay, possibly the Boston Blue Clay, is the dominant sediment type at Saugus Iron Works National Historic Site. Glacial and marine clays throughout the area provided material for pottery and bricks, as well as casting material for pots (Wall et al. 2004; Thornberry-Ehrlich 2008). Glacial erratics (rocks carried by glaciers and deposited some distance from their origin) and/or local, granitic bedrock (possibly **Zgr**, **Zgrt**, and **ZDgdt**) make up the foundations and furnaces of the iron works buildings, but the exact provenance of these remains unknown (Thornberry-Ehrlich 2008; Marc Albert and Gregg Bailey, conference call, 21 May 2014).

The founding of the iron works had profound influences on the surrounding settlements. The trade in ores and charcoal made previously inhospitable bogs and stony ground profitable and demand for iron products continued to increase dramatically (Watkins 1968; Wall et al. 2004). Forged iron from Saugus and other trade goods from Salem Village made their way north via ancient American Indian trails; shingles, barrel staves, charcoal, and bog iron ore came back (Killion and Foulds 2003; Wall et al. 2004). Other iron goods were shipped to Boston and, from there, to the rest of the colonies (Killion and Foulds 2003). At its height, the iron works produced about eight tons of cast iron per week (Killion and Foulds 2003). More than 400 bushels of charcoal, three tons of iron ore, and two tons of flux were necessary to produce one ton of iron per day (Marc Albert and Gregg Bailey, conference call, 21 May 2014). The gabbro flux has a very high melting point that likely necessitated more charcoal for the operation (Gregg Bailey, conference call, 21 May 2014). Costs of charcoal and transporting the bulk product were high and profits from the iron works were low causing its short duration of operation (Mulholland 1981).

The blast furnace, fineries, chafery, machine hammer, forge, and slitting mill were all located at the tidal head on the Saugus River (Wall et al. 2004). In addition to furnishing power to the iron works, the Saugus River was a key transportation link throughout the area's history. Unlike the low-lying clay-dominated tide heads of other local rivers, the Saugus River is a steep rocky stream whose course flows through a large north-to-south fracture in the granite and Lynn Volcanics (**Zgr**, **Zgrt**, **ZDgdt**, and **Zlv**) (Kaye 1980). A low-lying fall line occurs just upstream from the iron works. This fall line is the site of rapids and waterfalls. It formed a barrier to transporting goods upstream and helped determine the location of the iron works (Kaye 1980; Wall et al. 2004). The sudden change in bedrock elevation at the fall line provided the hydraulic gradient needed for early industrialization with the waterwheel (Wall et al. 2004). A large, 15-m (50-ft) high stone and earth dam 0.40 km (0.25 mi) upstream on the Saugus River impounded the 3 km^2 (1 mi^2) millpond, which supplied water for the mill. Water flowed through a 500-m (1,600-ft) long canal to a central reservoir whose flow to the forge, furnace, and slitting mill were controlled along wooden flumes (Hartley 1957; Wall et al. 2004). The amphitheater shape of the local bluffs made it possible to set up the three waterwheels and simultaneously provide adequate water power for the iron works and a downward slope to permit the materials to be transported form furnace to forge to slitting mill (Hartley 1957; Killion and Foulds 2003).

After the iron works operations ceased about 1670, the land was largely cleared and farmed, but the Saugus River with its high-energy, steep rocky channel continued to provide energy. It powered several 18th- and 19th-century industrial enterprises including a gristmill, sawmill, chocolate mill, Morocco leather factory, and other cloth works (Albright et al. 1977; Killion and Foulds 2003).

Excavating and Restoring the Iron Works

The story at Saugus Iron Works National Historic Site is still unraveling (Albright et al. 1977; Killion and Foulds 2003). From the 1630s until a land-plot division in 1724, the property retained a roughly 240 ha (600-ac) configuration and was largely farmed after all iron works operations ceased about 1670 (Albright et al. 1977). No domestic buildings dating to the iron working period survived (Albright et al. 1977). Records from 1724 court documents, state the iron works site along the river was "to lie open as a way and for the benefit of creatures to go down to the river as has been usual" (Cummings 1977 p. 381)—an early example of natural resource stewardship (Killion and Foulds 2003). In 1899, the only remaining visible legacy of the 17th-century iron works industrial complex was the 45-m (150-ft) long, 15-m (50-ft) wide, 4-m (12-ft) high slag pile that still exists today (Killion and Foulds 2003).

The Daughters of the American Revolution purchased the former iron works site in 1938 and in 1946, the site was transferred to the First Iron Works Association who began archeological investigations and reconstruction in earnest. In the 1940s, Central Street in Saugus, Massachusetts was rerouted in order to excavate the original foundation of the iron works. In the process, thousands of artifacts from the thick fluvial sediments were exhumed including remnants of the waterwheel (Thornberry-Ehrlich 2008). Archeological excavations in the 1950s at the iron works site revealed the wood supports for the wharf and a corduroy road along the riverbank, as well as remains of the iron works buildings and several waterways. These investigations also uncovered scattered deposits of stored bog iron ore, charcoal, and gabbro—the three primary ingredients used to produce iron. Worked volcanic stones from the Lynn Volcanics are present as artifacts in the fluvial sediments (Killion and Foulds 2003).

As described in the "Flooding and Fluvial Geomorphology of the Saugus River" section, the level of the Saugus River has increased at least 1 m (3 ft) since the 17th-century iron works operations. The reconstructed iron works buildings are essentially sitting over their respective excavation sites. Attempts were made to restore some of the river ravine's natural contours and the slag pile (fig. 10) was recontoured to approximate its historical appearance. In the 1950s reconstruction, a small stone dam with tidal gates (the Hamilton Street weir) was installed downstream to prevent the "unsightly" condition of mud flats at low tide and to

Figure 10. Slag pile and river corridor. The slag pile (foreground) was recontoured to its historic appearance and the corridor was cleared of invasive vegetation. National Park Service photograph courtesy of Marc Albert taken in spring 2013.

maintain a certain water level in the iron works area (Killion and Foulds 2003). The reconstructed blast furnace, forge, rolling-and-slitting mill, wharf and warehouse were completed in 1954 as part of the "First Iron Works" (Killion and Foulds 2003).

During a 1999 survey to locate the source of "Saugus Jasper" (see "Geologic Significance and Connections" section), a new archeological site was discovered adjacent to Saugus Iron Works National Historic Site, paralleling the Saugus River. This site had remnants of the worked volcanic stones from the local Lynn Volcanics (**Zlv**) and some felsite known from locations in Wakefield and Melrose, Massachusetts, some 4 km (2 mi) northwest and 2 km (1 mi) west of Saugus, respectively (Hollander and Hermes 1999). There remains a wide range of known and potential archeological resources throughout Saugus Iron Works National Historic Site, including American Indian materials, possible gravesites, and 18th- through 19th-century agricultural and residential structures. This potential makes the site an area of high archeological sensitivity. Any changes to this landscape must be carefully planned (Killion and Foulds 2003).

The Geoscientists-in-the-Parks program (http://www.nature.nps.gov/geology/gip/) could provide an opportunity to perform research and field study to determine the exact source materials used at the Saugus Iron Works. Massachusetts Geological Survey geologist Joe Kopera also has some insight into potential source areas and could conduct a site visit for assistance.

The Saugus Ecosystem

As part of an ongoing monitoring effort, James-Pirri et al. (2011) provided a comprehensive natural resource condition assessment that should be referenced for more detail about the Saugus Iron Works National Historic Site ecosystem.

Three distinct natural zones make up the site's landscape: a manicured lawn area around the historic iron works and visitor facilities, the Saugus River and floodplain, and a wooded area along the eastern bank of the river (James-Pirri et al. 2011). Within these three zones are fluvial (including riffle [i.e., shallow areas of churned water]; fig. 11), riparian, upland, and tidal-estuarine habitats at Saugus Iron Works National Historic Site. Despite the highly urban landcover of the Saugus River watershed, the site shelters a wide range of flora and fauna for such a small geographic area. Because of the history of land use at the site—the reason the site was created in the first place—anthropogenic disturbance is extensive and determining original, prehistoric conditions is nearly impossible (Agius 2003; Cook et al. 2010).

Cook et al. (2010) reported at least ten species of amphibians and reptiles currently known or potentially present at the site. The principal habitats for these creatures are the Saugus River channel, small seeps on

Figure 11. Saugus River, looking southwest (downstream) from east bank, riffle habitat in foreground. In addition to the tidal estuary areas, the river creates riffle habitat and rapids indicate the high energy setting. National Park Service photograph courtesy of Marc Albert taken in fall 2011.

both sides of the Saugus River, small patches of riparian forest flanking the river, riparian marshes, and fields and lawns of the historic zone. The northern two-lined salamander (*Eurycea bislineata*) spends all life stages (egg, larvae, adult) in the stream habitat at the site. The slag pile and developed uplands provide turtle nesting habitat adjacent to the Saugus River without the need to cross roads, an important and rare habitat in an urban area.

The river is classified as a warm water fishery capable of supporting bass, pickerel, sunfish, and similar aquatic species (Gawley 2013). Since 1989, 25 species of fish have been sampled at Saugus Iron Works National Historic Site, including rainbow smelt (*Osmerus mordax*), American eel (*Anguilla rostrata*), and diadromous alewife (*Alosa pseudoharengus*) (James-Pirri et al. 2011). The high-energy location on a fall line, as well as varied channel deposits (e.g., sand bars or larger cobbles or boulders that act to interrupt streamflow) create vital riffle habitat for rainbow smelt. The Saugus River is one of the few active runs in the Northeast Coastal Basin of Massachusetts (James-Pirri et al. 2011).

At least 160 vascular plants, including 15 non-native, invasive species, were noted during a survey conducted by Clemants (1997). Later surveys identified 11 particularly invasive species and an additional 31 exotic species (Agius 2003). Agius (2003) recommended complete eradication of the site's invasive species and re-introduction of native species to serve as a model for environmental stewardship in the coming decades. Much of this replanting was completed by 2010 as part of the Turning Basin restoration project (see "Turning Basin Restoration" section). The restoration also saw a marked increase in water bird species observed in wetland areas within the site, many of which are listed as Partners in Flight priority species (James-Pirri et al. 2013).

Geologic Features and Processes

This section describes noteworthy geologic features and processes in Saugus Iron Works National Historic Site.

During the 2007 scoping meeting (see Thornberry-Ehrlich 2008) and 2014 conference call, participants (see Appendix A) identified the following geologic features and processes:

- Fluvial Features and Processes
- Slope Features and Processes
- Coastal Resources
- Faults
- Folds
- Igneous Rocks
- Volcanic Rocks
- Metamorphic Rocks
- Sedimentary Rocks
- Glacial Deposits
- Radiometric Age Dates
- Paleontological Resources

Fluvial Features and Processes

The Saugus River and its floodplain compose much of the landscape at Saugus Iron Works National Historic Site. The river meanders across its floodplain below higher bluffs. Because of the site's proximity to the mouth of the Saugus River where it meets the Atlantic Ocean (see "Brackish Estuary" section), the river channel contains submerged bayhead bars at knickpoints (abrupt breaks in slope). These bars are banks of sand and/or gravel deposited across a bay near its head. They mark the part of the bay that lies furthest inland. Bayhead bars often partially confine or impound the water and have a narrow "breach" as an outlet.

As described in the "Geologic Significance and Connections" section, the Saugus River flows across a fall line (through **Zlv**), creating an area of high energy. This energy is the reason the Saugus River has been used by humans for more than 300 years. Dams and mills altered flow, diverting water and powering waterwheels (James-Pirri et al. 2011). Upstream of the iron works site, the slope near the bridge causes high-energy flow of the Saugus River (Marc Albert, Saugus Iron Works NHS and Boston Harbor NRA, natural resource specialist, and Gregg Bailey, Saugus Iron Works NHS, seasonal park ranger, conference call, 21 May 2014). Farther upstream, the Lynn Water and Sewer Commission Diversion Dam controls flow from the upper watershed into the main channel of the Saugus River. Prior to 2006, during summer and autumn low-flow periods, most of the flow was diverted and the river levels were low. The commission now collaborates with conservation organizations to maintain an acceptable continuous flow below the diversion dam (Gomez and Sullivan 2006; James-Pirri et al. 2011).

In addition to the area of high energy, the Saugus River also contained a natural eddy that was likely enhanced to form the Turning Basin, used for turning boats carrying supplies to and goods from the iron works docks. Beyond this point, boats could not easily travel upstream (Marc Albert and Gregg Bailey, conference call, 21 May 2014). Over time, silt and invasive vegetation clogged and obscured the Turning Basin. It has since been restored to historic conditions (see "Restoring the Turning Basin" section).

Brackish Estuary

The Saugus River flows through Saugus Iron Works National Historic Site just 5 km (3 mi) upstream of its confluence with Massachusetts Bay and the Atlantic Ocean. The river is tidal within the park, and tides cyclically raise the river level almost 2 m (6 ft). During incoming tides, saltwater travels along the bottom of the river channel, creating a brackish estuarine environment within the riparian zone. The tidal basin is approximately 2 ha (5 ac) within the site's boundary (CH2M Hill 2004). This environment provides habitat for species such as rainbow smelt and American eel (Thornberry-Ehrlich 2008). The smelt migrate up the river to spawn at the tidal headwaters and just upstream from the iron works site. After spawning, the adult smelt return to the coastal or estuary waters which later also shelter the smelt larvae after they hatch (CH2M Hill 2004).

Slope Features and Processes

Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Soil creep, rockfalls, debris flows, and avalanches are common types of slope movements. These processes and the resultant deposits are also known as "mass wasting" and commonly grouped as "landslides." Slope movements occur on time scales ranging from seconds to years. Refer to figure 12 for schematic illustrations of slope movements. Slope movements create geologic hazards and associated risk in many parks. Hazards and risks associated with slope movements in Saugus Iron Works National Historic Site are described in the "Geologic Resource Management Issues" section.

At Saugus Iron Works National Historic Site, steep slopes, commonly more than 45°, occur between the upland bluffs and the floodplain of the Saugus River. Most of the slopes are vegetated, which enhances their stability. Slumping and slope creep are the primary slope movements associated with these areas (Thornberry-Ehrlich 2008). Evidence of past erosional damage to the slag pile exists near the drainage swale where the western

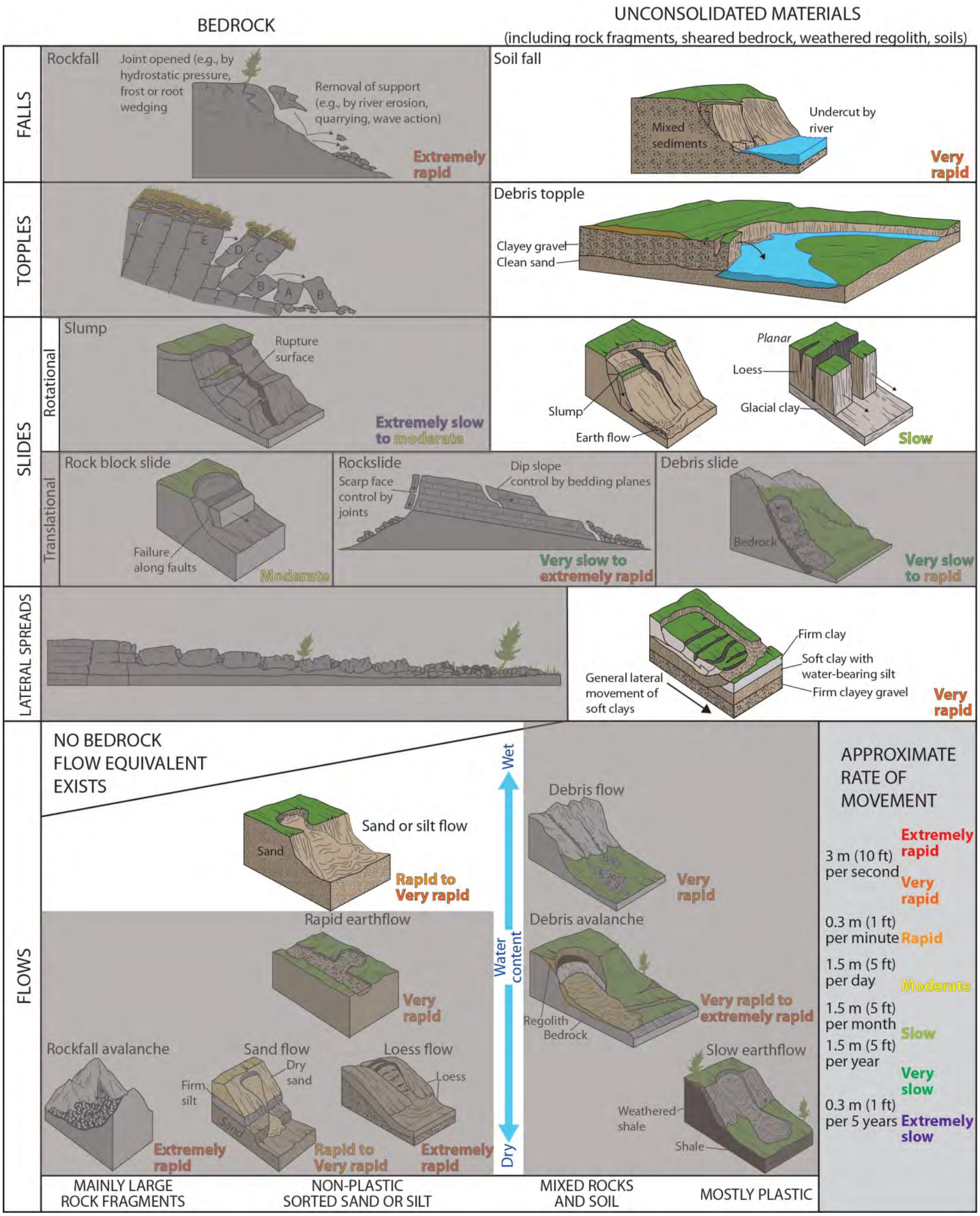


Figure 12. Schematic illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Grayed areas depict mass wasting events that are not likely to occur within Saugus Iron Works National Historic Site. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978).

side of the pile abuts the natural hillslope. The slag pile is generally stable and, as of 2004, appears free from much erosional damage (CH2M Hill 2004). However, disturbances to the vegetative cover may require periodic monitoring as discussed in the "Slope Movement Hazards and Risks" section.

Coastal Resources

Coastal resources are in the transition between terrestrial (on land) and marine (under saltwater) environments. Coastal environments—shaped by waves, tides, and wind—include tidal flats, estuaries, dunes, beaches, and barrier islands (Bush and Young 2009). As of November 2011 (the most recent servicewide statistics), the National Park Service managed 84 ocean, coastal, and Great Lakes parks with more than 18,000 km (11,200 miles) of shoreline (Curdts 2011). Of those, Saugus Iron Works National Historic Site encompasses 1 km (0.6 miles) of shoreline. The NPS Geologic Resources Division Coastal Geology website, http://nature.nps.gov/geology/coastal/index.cfm, provides additional information.

The Saugus River experiences significant tidal fluctuations and regular saltwater incursions contributing to brackish water estuaries within Saugus Iron Works National Historic Site. These tidal wetlands occur primarily downstream of the Turning Basin and were recently restored to their historic appearance (see "Restoring the Turning Basin" section).

Faults

A fault is a fracture in rock along which rocks have moved. Faults are classified based on motion of rocks on either side of the fault plane as described in figure 13. The three primary types of faults are normal faults, reverse (and thrust) faults, and strike-slip faults (fig. 13). Thrust faults are reverse faults with a low angle (<45°) fault plane. Strike-slip, thrust, and reverse faults are all mapped within GRI GIS data, as well as faults of unknown offset. The GRI GIS data include three major, named faults, from north to south: the Walden Pond, Birch Pond, and Northern Boundary faults (Kopera 2011).

East-to-west oriented ("trend"), north-tilted ("dip") reverse and thrust faults are located in the vicinity of Saugus Iron Works National Historic Site. Prominent north-to-south oriented strike-slip faults make up a subset of parallel faults. Faults bound blocks of Proterozoic bedrock throughout the area.

The grinding and breaking of rocks on either side of a fault may create zones of fault breccia—a rock type consisting of broken, angular clasts in a finer-grained matrix. Breccias may or may not be consolidated depending on whether cementation by percolating groundwater took place. Brecciated or highly deformed zones typically border the major local faults. Where these areas are large enough, they are mapped as fault-breccia polygons in the GRI GIS data (e.g., **Zlvfb**, **ZDgdtfb**, and **Dpgrb**).

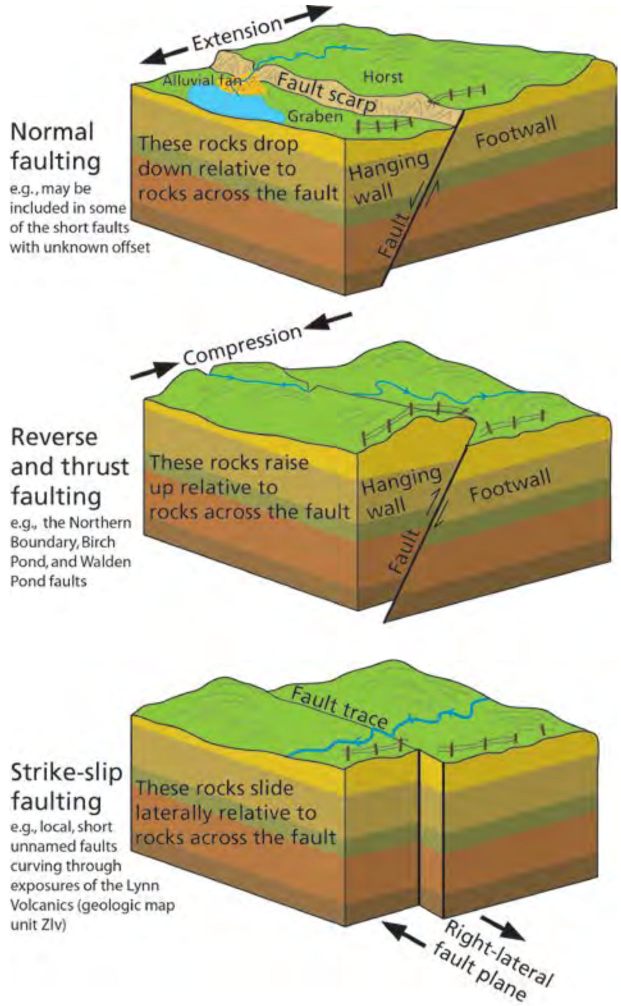


Figure 13. Schematic illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Examples of faults from the site area are included. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

The density of faults, as well as the urban setting and surficial cover which obscure the bedrock, combine to make correlating between rocks on adjacent fault-bounded blocks and determining the timing of faulting episodes difficult for geologists (Goldsmith 1991b; Kopera 2011). The Walden Pond fault cuts through the Devonian Peabody Granite (**Dpgr**) and thus is younger than the granite (fig. 6). The Birch Pond fault cuts through a Proterozoic to Devonian unit (**ZDgdt**). The Northern Boundary fault forms a border between the Proterozoic volcanic rocks (**Zvk** and **Zlv**) and the Boston Bay Group (**Zcr**, **Zcrs**, and **ZCca**). Geologists suspect the reverse faults were reactivated at least once during the series of mountain-building orogenies of the Paleozoic that resulted in the Appalachian Mountains (Kopera 2011). Kaye (1980) mapped the reverse faults cutting the strike-slip faults, but elsewhere, the opposite arrangement occurs with northwest-trending faults cutting the reverse faults (Kopera 2011).

Folds

Folds are curves or bends in originally flat structures, such as rock strata, bedding planes, or foliation. The two primary types of folds are anticlines which are "A-shaped" (convex) and synclines which are "U-shaped" (concave). Both types of folds can be overturned—tilted past vertical—by continued or future tectonic forces. Folds commonly "plunge" meaning the fold axis tilts. As bedrock is compressed, anticlines and synclines form adjacent to each other. One anticlinal structure is identified in the GRI GIS data within geologic map unit **Zqo** (Bailey et al. 1989; Kopera 2011). Folding within the Lynn Volcanics (**Zlv**) underlying Saugus Iron Works National Historic Site is possible, but for reasons explained in the "Faults" section, there is a lack of good exposure to identify fold structures (Kopera 2011).

Igneous Rocks

Igneous rocks are those that formed from molten material. Where molten material cools and solidifies at the Earth's surface, extrusive ("volcanic") igneous rocks form. Where molten material cools beneath the surface, intrusive ("plutonic") igneous rocks form. Igneous rocks are classified by texture (grain size, shape, orientation), as well as the percentage of major minerals (quartz, alkali feldspar, and plagioclase) present in the rock.

The plutonic rocks mapped in the Saugus Iron Works National Historic Site area are classified by geologists based on the percentage of major minerals (quartz, alkali feldspar, and plagioclase) as diabase (**ZJ[?]db**), granite (**Dpgr**), quartz-diorite and diorite (**ZDd**), granodiorite (**ZDgdta**, **ZDgdt**, **Zgdm**), tonalite (**ZDgdt**), trondhjemite (**Zgrt**), and quartz monzonite (**Zgdm**) (fig. 14). Rocks with compositions that are broadly similar to granite can be collectively referred to as "granitoids" (**Zgr**) (Kaye 1980; Kopera 2011). None of these rocks are mapped within the site boundaries, but may have been utilized as building stones. Plutonic ultramafic gabbro from the Nahant Peninsula was used for flux and smelting (First Iron Works Association 1952; Wall et al. 2004). The specific type of gabbro used at Saugus Iron Works is named Essexite from Essex County (National Park Service 2014a). See the "Map Unit Properties Table" for more details.

Volcanic Rocks

Geologists use silica (silicon dioxide, SiO_2) content as a means for classifying volcanic rocks (table 1). The term "mafic" refers to rocks with lesser amounts of silica, such as basalt and basaltic andesite. Mafic refers to the high ***ma***gnesium and iron (***f***err***ic***) content of minerals that characterize those rocks. The term "silicic" refers to rocks with higher amounts of silica, for instance, dacite, rhyodacite, and rhyolite. The percentage of silica influences many properties of magma, including viscosity and explosiveness. In general, lavas with more silica are more viscous and explosive (table 1). With respect to viscosity (internal friction), low-silica basalts form fast-moving, fluid, lava flows that spread out in broad, thin sheets up to several kilometers wide. In contrast, flows of andesite and dacite tend to be thick and sluggish, traveling only short distances from a vent. Dacite and rhyodacite lavas commonly squeeze out of a vent to form irregular mounds or lava domes. In this way, the viscosity of magma determines the type of volcano edifice built by an eruption.

The Lynn Volcanics (**Zlv**) mapped within Saugus Iron Works National Historic Site are a classic example of a rhyolite, or more generally, a felsite. Nineteenth-century geologists used the volcanic rocks at Saugus to define the now-obsolete term "petrosilex"—a siliceous felsite type of rock (Cregger 2012). They described a beautiful, extremely fine-grained, almost glassy rock. As thick, viscous magma is ejected from a volcanic vent, it tends to cool quickly, before large crystals have time to form yielding extremely fine-grained textures. When cooling is very rapid, no crystals are able to grow, and volcanic glass results.

The Lynn Volcanics are predominantly volcanic flows, flows of welded ash, volcanic tuffs, flow breccias, breccia pipes, and extrusion domes; many features indicate an explosive origin (Bell 1977; Kopera 2011). Viscous lava flows and subsequent flows atop the previous flows gave the unit layering. As layers of ash and lava that were ejected from the volcanic vent settled out of the air, the heat retained by these materials combined with the weight of subsequent layers and hot gases caused the particles to weld or fuse together. Welded ash is primarily composed of small, ash-sized particles. Volcanic tuffs are the result of mixtures of ash, irregular shards of volcanic material (lapilli), and other ejecta welding together. Volcanic breccias are jumbled assemblages of angular and broken rock fragments in a finer-grained matrix. A breccia pipe of a cylindrical chimney of breccia, commonly incorporating the country rock (i.e., the rock through which the volcanic vent is erupting). Extrusion domes are piles of lava that build up around the specific erupting vent. These are common for high-viscosity lavas such as rhyolite that do not flow very far from the origin.

Quartz keratophyre and keratophyre (**Zvk**) are mapped with conformable contacts with the Lynn Volcanics. They occur less than 1.5 km (1 mi) southwest of Saugus Iron Works National Historic Site. These are the metamorphosed (see "Metamorphic Rocks" section) equivalent of rocks that form in a submarine volcanic setting with mixtures of marine sediments and pillow lavas.

Metamorphic Rocks

Rocks can be altered—metamorphosed—by high temperature and/or pressure to form metamorphic rocks. Metamorphism can occur in two primary settings: contact or regional. Contact metamorphism is associated

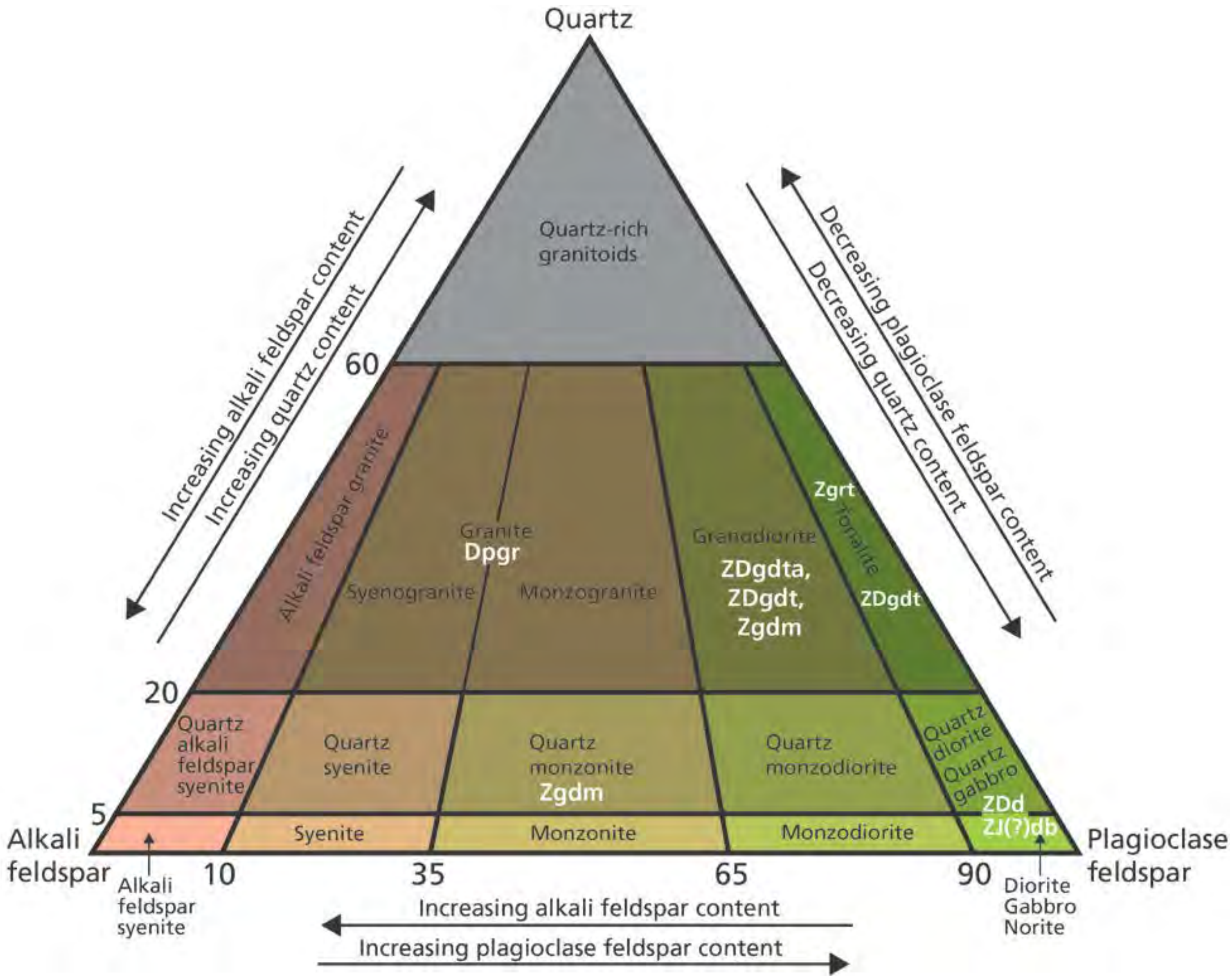


Figure 14. Classification diagram for intrusive igneous rocks. Numbers refer to the percentage of the mineral constituent (quartz, alkali feldspar, or plagioclase feldspar) in the overall composition of the rock. Numbers 5, 20, and 60 refer to the overall quartz component, whereas numbers 10, 35, 65, and 90 refer to the contribution of plagioclase to the overall composition. The corners represent compositions very rich in the corresponding mineral and poor in the two other minerals, but not necessarily other possible component minerals. Bold white text refers to geologic map unit symbols that occur in the Saugus area whose compositions broadly fall within that field. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) following standard IUGS (International Union of Geological Sciences) nomenclature.

Table 1. Volcanic rocks classification and relative characteristics.

Rock Name:	**Rhyolite**	**Rhyodacite**	**Dacite**	**Andesite**	**Basaltic Andesite**	**Basalt**
Silica (SiO_2) content*	≥72%	68%–72%	63%–68%	57%–63%	52%–57%	≤52%
Amount of SiO_2	More					Less
Color	Lighter					Darker
Viscosity of magma	Thick					Fluid
Typical style of eruption	Explosive					Effusive

Note: * from Bacon (2008); Green text denotes the types of volcanic rocks mapped within Saugus Iron Works National Historic Site.

Table 2. Clastic sedimentary rock classification and characteristics.

Rock Name	Clast Size	Depositional Environment
Conglomerate (rounded clasts) or Breccia (angular clasts)	>2 mm (0.08 in) [larger]	Higher Energy
Sandstone	1/16–2 mm (0.0025–0.08 in)	
Siltstone	1/256–1/16 mm (0.00015–0.0025 in)	
Claystone	<1/256 mm (0.00015 in) [smaller]	Lower Energy

Note: Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."

with the intrusion of molten material where rocks adjacent to the intrusion are "baked" by the high temperatures. Regional metamorphism is associated with large-scale tectonic events in the past, such as mountain building orogenies. The two main types of metamorphic rocks are foliated (minerals are aligned in stripe-like layers) and non-foliated. Metamorphic rocks are further classified by degree of foliation, grain size, and parent rock.

Metamorphic foliation occurs within isolated xenoliths of rock (**Zmu**) surrounded by non-foliated rocks (Kopera 2011). Quartz keratophyre and keratophyre (**Zvk**) are metamorphic rocks that typically form from marine sediments and submarine basalts. Despite their tumultuous geologic history within the Avalon terrane, the Lynn Volcanics (**Zlv**, **Zlvfb**) mapped in Saugus Iron Works National Historic Site have generally not undergone metamorphism greater than chlorite grade or greenschist facies—generally temperatures lower than 400°C (Goldsmith 1991b). Secondary mineral such as sericite, chlorite, epidote, and sphene replaced original minerals during this metamorphism (Kopera 2011).

Sedimentary Rocks

Three main types of sedimentary rocks are clastic, chemical, and organic. Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock fragments called "clasts." Clastic sedimentary rocks are named after the size of clasts (table 2). Higher-energy depositional environments, such as fast-moving streams, deposit larger (heavier) clasts while transporting smaller (lighter) clasts. Where water moves slowly or is stagnant, such as in lakes, the water cannot transport even the smallest clasts and they are deposited. Wind also transports and deposits sand-sized or smaller clasts (table 2). Chemical sedimentary rocks form when ions (microscopic particles of rock dissolved during chemical weathering) precipitate out of water. For example, carbonate rocks, such as limestone (calcium) or dolomite (calcium and magnesium) have a carbonate (CO_3^{2-}) ion. Organic sedimentary rocks are composed of organic remains (e.g., coal) or were produced by the physiological activities of an organism (e.g., secretion of calcium carbonate to form limestones of coral reefs).

Although slightly metamorphosed (see "Metamorphic Rocks" section), several map units in the Saugus Iron Works National Historic Site area are of clastic sedimentary origin. The Boston Bay Group (**ZCrcca** and **ZCrsca**) mapped south of the Northern Boundary fault (see "Geologic Structures" section), includes the Roxbury Conglomerate and Cambridge Argillite. These units contain pebble to cobble conglomerate and mudstone, siltstone, and shale (Kopera 2011). The clasts within the fine-grained matrix of the conglomerates were derived from rocks flanking the depositional basin, including volcanic rocks, quartzite, and granite (Kopera 2011). The Boston Bay Group also contains diamictites, which are jumbles of angular and unsorted clasts of varying sizes in a finer-grained matrix. Their origin is enigmatic, but may result from ancient glaciations (e.g., lithified glacial till, see "Glacial Deposits and Erosional Features" section) or landslide deposits.

Quartzite and olistromal assemblage (**Zqo**) are other metasedimentary rocks mapped less than 2 km (1 mi) west of Saugus Iron Works National Historic Site (Kopera 2011). Similar to a diamictite, an olistostrome is a jumbled mix of clast sizes and types in a fine-grained matrix. Their origin is attributed to underwater landslides. Other sedimentary rocks types occurring within **Zqo** are siltstones, mudstones, and very fine-grained sandstones (Kopera 2011).

Glacial Deposits

Repeated glaciations (ice ages) during the Pleistocene (2 million to approximately 20,000 years ago) scoured and reshaped the landscape of the northeastern United States, including Saugus Iron Works National Historic Site, when massive ice sheets advanced from the Arctic (fig. 15). The two major categories of glacial deposits and features are (1) those created or carved by glaciers, (2) those deposited by rivers flowing beneath or out of glaciers ("glaciofluvial") or deposited in lakes near glaciers ("glaciolacustrine"). See figure 16 for schematic illustrations of these deposits and features. Deposits and features associated with glacial ice include till, moraines, drumlins, kettles, grooves, striations, roches moutonnées, and glacial erratics. Glaciofluvial or glaciolacustrine deposits and features include kames, eskers, braided streams, and outwash fans, deltas, or plains.

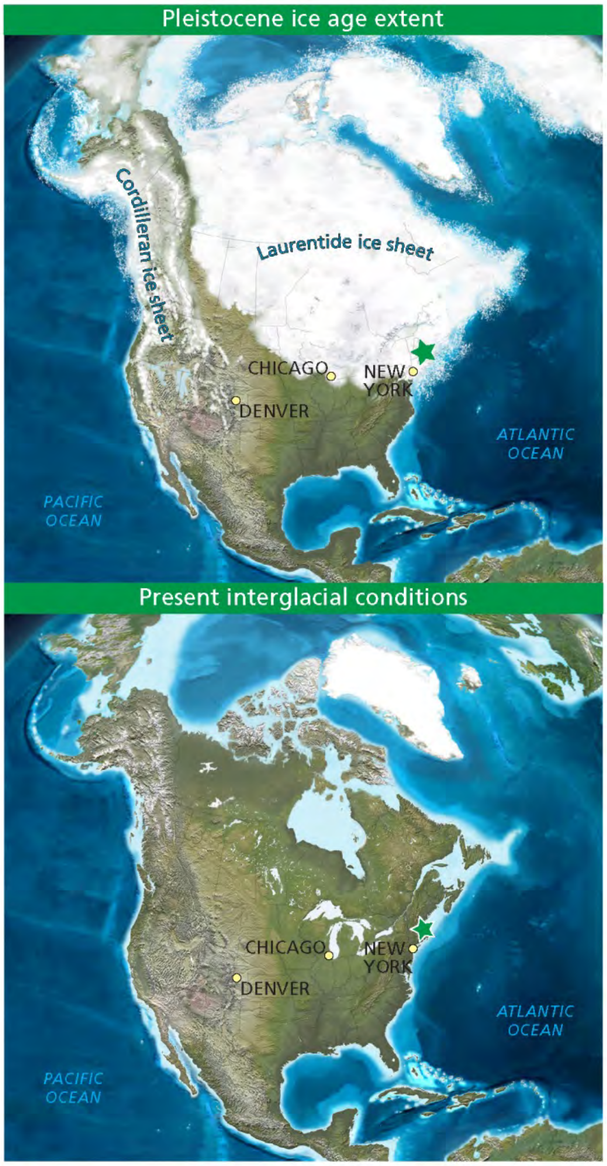


Figure 15. Maps illustrating ice age and interglacial conditions. Nearly half of North America was covered by sheets of ice during the ice age glaciations of the Pleistocene. Relative sea-level drops during glaciations (note the width of Florida). Saugus Iron Works National Historic Site is denoted by a green star. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html (accessed 25 April 2014).

Unconsolidated, surficial geologic map units are not included in the GRI GIS data for Saugus Iron Works National Historic Site. However, mixed glacial, fluvial, and marine sediments underlie most of the land surface at the site. See "Geologic History" section for more information. Detailed surficial geology information would be a valuable dataset to help determine the glacial history at the site.

Radiometric Age Dates

The geologic history of the Avalon terrane and the rest of New England is incredibly complex (see "Geologic History" section). The rocks within Saugus Iron Works National Historic Site and surrounding area are riddled with faults (see "Faults" section). Movement along these faults divides and separates geologic units. Given this complexity, the urban landscape, and general lack of bedrock outcrops, knowing the ages of the geologic map units is critical in deciphering their history. The ages of many rocks within the site area have been determined via radiometric dating techniques. Uranium-lead technique dates range from 600 million to 378 million years ago. Available dates are listed in the "Map Unit Properties Table."

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are non-renewable. Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in National Park Service areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of February 2015, 257 parks had documented paleontological resources in at least one of these contexts. The NPS Geologic Resources Division Paleontology website, http://www.nature.nps.gov/geology/paleontology/index.cfm, provides more information.

Fossils have not yet been documented within the boundaries of Saugus Iron Works National Historic Site. The bedrock units are predominantly volcanic with little to no potential for fossils as they date to a time before the appearance of organisms with hard body parts. However, the Quaternary-age surficial deposits at the site have produced fossils elsewhere and there is potential for fossil discoveries (Tweet et al. 2010). Pleistocene marine fossils occur in clays just north of the site (Thornberry-Ehrlich 2008). Throughout the Saugus region, Pleistocene deposits have yielded foraminifera, diatoms, pollen, mollusks, barnacles, ostracodes, sponges, stony corals, bryozoans, bivalves, gastropods, worm tubes, and crabs (Judson 1949; Kaye 1976; Colgan and Rosen 2001; Tweet et al. 2010). Younger, Holocene deposits include peat deposits from former marshes (Kaye 1982). The peat deposits contain vast records of paleoclimate and environmental factors with remains of swamp plants, tree stumps, and deciduous leaves, as well as beetle fragments (Shimer 1918; Argus and Davis 1962; Tweet et al. 2010). Archeological sites such as shell middens and fishweirs throughout the greater Boston area also contain an abundance of fossil remains in cultural contexts (Johnson 1949; Luedtke and Rosen 1993). Tweet et al. (2010) presented a paleontological resource summary for the NPS Northeast Temperate Inventory and Monitoring Network and is an excellent resource for further detail on the potential for fossil discoveries at Saugus Iron Works National Historic Site.

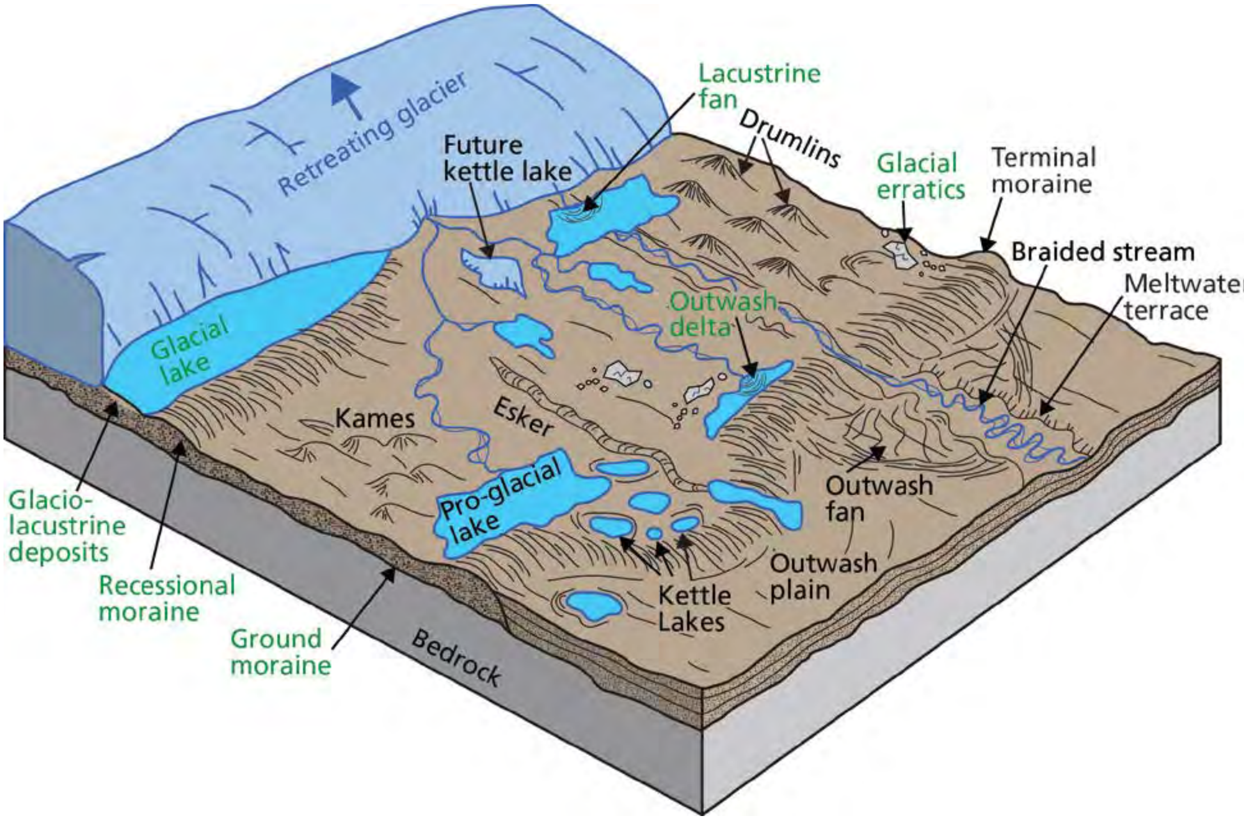


Figure 16. Glacial features and deposits. Surficial geologic units are not mapped in detail at the site. However, given its proximity to open-marine settings glacial features that likely contributed to the site and surrounding area's landscape are labeled in green. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Geologic Resource Management Issues

This section describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Saugus Iron Works National Historic Site. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2007 scoping meeting (see Thornberry-Ehrlich 2008) and 2014 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Coastal Vulnerability to Sea-Level Rise and Climate Change
- Flooding and Fluvial Geomorphology of the Saugus River
- Restoring the Turning Basin
- Slope Movement Hazards and Risks
- Earthquake Hazards and Risks
- Disturbed Lands and Mineral Extraction
- Paleontological Resource Inventory, Monitoring, and Protection

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring.

National Park Service (2002) is the most recent general management plan implemented at Saugus Iron Works National Historic Site. It outlines the existing conditions and management priorities.

Coastal Vulnerability to Sea-Level Rise and Climate Change

Climate change and associated sea-level rise threaten the site's riverine resources and the flora and fauna that thrive there (James-Pirri et al. 2011). Predicting issues with the morphology of the river and head-cutting erosion (see "Flooding and Fluvial Geomorphology of the Saugus River") is the primary resource management concern at Saugus Iron Works National Historic Site. This is particularly the case at the northern edge of the site where the river flows swiftly downslope. The issue is exacerbated by sea-level rise and increases in heavy precipitation events (Marc Albert, Saugus Iron Works NHS and Boston Harbor Islands NRA, natural resource specialist, conference call, 21 May 2014). Davey et al. (2006) identified climate change as a dominant factor driving the physical and ecologic processes affecting the Northeast Temperate Network, including Saugus Iron Works National Historic Site. The current climate-change forecasts predict more frequent extreme events (e.g., flooding and drought) that can negatively affect river hydrology and upset the delicate balance of salinity in the tidal wetlands (James-Pirri et al. 2011).

In general, climate models for the northeastern United States show an increase in climate-related hazards such as heat waves, intense storms, sea-level rise, coastal flooding, and river flooding (Melillo et al. 2014). These hazards will compromise infrastructure and the fisheries and ecosystems at Saugus Iron Works National Historic Site. Temperatures in the northeast increased by nearly 1.1°C (2°F) since 1895. Between 1958 and 2010, the region experienced more than a 70% increase in the amount of precipitation falling in storms. Sea level has risen approximately 0.3 m (1 ft) since 1900 (Melillo et al. 2014). The rate at the Boston tide gauge (the nearest long-term gauge) is 0.26 m/century (0.86 ft/century) (National Oceanic and Atmospheric Administration 2013).

At Saugus Iron Works, increases in temperature would increase the rate of evapotranspiration, which in turn could alter wetland hydrology. This would also affect wetland fauna populations at Saugus Iron Works National Historic Site (Davey et al. 2006). Sea-level rise will inundate the low-lying areas of the site, erode the shoreline, and threaten coastal infrastructure. Because of the adjacent steep slopes and the location of the riparian corridor in a dense residential setting, there is limited area for upward migration of wetland habitats with increasing sea levels (Marc Albert, written communication, 2 December 2014). An increase in the frequency of severe storms would introduce more precipitation, but typically as massive surges that could flood and scour the river channel. See "Flooding and Fluvial Geomorphology of the Saugus River" section for more information about flooding and channel erosion.

More than a third of the area within Saugus Iron Works National Historic Site is wetland and open water only about a meter above sea-level (James-Pirri et al. 2010, 2011). The Saugus River tidal wetlands are vital habitats and were part of an ongoing restoration effort (see "Restoring the Turning Basin" section). Despite the extent and importance of shallow water habitats at Saugus Iron Works National Historic Site, these types of areas in the northeastern United States remain relatively unmapped and poorly inventoried (Hart et al. 2010). Shoreline geomorphology including relative surface elevation in wetlands, shoreline position, and wetland vegetation communities were among the vital signs identified for parks in the Northeast Temperate

Network (NETN) by Mitchell et al. (2006). Of these, only marsh vegetation has been monitored at the site, as part of the Turning Basin project (along with many other biological and physical parameters). Marsh vegetation monitoring is expected to continue as part of long term NETN monitoring after Turning Basin project monitoring finishes in 2016 (Marc Albert, written communication, 2 December 2014).

Coastal Features and Climate Monitoring

Large-scale, surficial geologic data do not exist for Saugus Iron Works National Historic Site. The US Geological Survey is in the process of compiling surficial map coverage for Massachusetts that would cover the Saugus area. Detailed surficial geology including depth to bedrock (**Zlv**) information would be a valuable dataset for modeling the river channel's response to sea-level rise. This mapping would both delineate how the system responded to sea-level fluctuations in the past (throughout the Holocene), and determine the exact composition of the substrate. This would in turn help understand how the surficial sediments may react to factors such as increased erosion, water saturation, and tidal or storm surges. The Geoscientists-in-the-Parks program (http://www.nature.nps.gov/geology/gip/) could be an opportunity to perform detailed surficial geologic mapping within the site. The NPS Geologic Resources Division can also respond to technical assistance requests.

In the *Geological Monitoring* chapter about coastal features and processes, Bush and Young (2009) described the following methods and vital signs for monitoring coastal features and processes: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion. Shallow water mapping techniques outlined by Hart et al. (2010) may help inform resource management of the changes occurring within Saugus Iron Works National Historic Site as a result of relative sea-level rise.

Due to Saugus Iron Works National Historic Site's proximity to the Atlantic Ocean, the Saugus River experiences significant tides and brackish water estuaries occur within site boundaries. Hammar-Klose et al. (2003) completed a coastal vulnerability index (CVI) assessment for Cape Cod National Seashore. CVIs use tidal range, wave height, coastal slope, shoreline change, geomorphology, and historical rate of relative sea-level rise to create a relative measure of the coastal system's vulnerability to the effects of sea-level rise. The CVI provides data for resource management and park facilities plans. The Cape Cod CVI is not designed for tidal rivers and is not applicable to Saugus Iron Works National Historic Site. However, a site-specific CVI for Saugus Iron Works National Historic Site may reveal those areas most at risk for degradation. For more information about CVIs, refer to the US Geological Survey CVI website: http://woodshole.er.usgs.gov/project-pages/nps-cvi/ (accessed 2 February 2015).

Monitoring basic climate patterns will provide a long-term record of the stress associated with climate change (Davey et al. 2006). There is an abundance of National Weather Service Cooperative Observer Program stations in the greater Boston area supplying abundant weather and climate information. Saugus Iron Works National Historic Site is participating in climate change adaptation processes discussions within the National Park Service (Marc Albert, conference call, 21 May 2014). Davey et al. (2006) outlined the status of climate monitoring for Saugus Iron Works National Historic Site and provided recommendations and guidance for monitoring. The Institute of Marine and Coastal Sciences at Rutgers University (http://marine.rutgers.edu/main/ accessed 2 February 2015) is currently studying natural barriers to coastal processes. Melillo et al. (2014) provided a comprehensive summary of climate-change observations, impacts, and predictions for the United States, including chapter on the northeast. They also presented response strategies and guidance for mitigating climate-change impacts.

Flooding and Fluvial Geomorphology of the Saugus River

Fluvial issues at Saugus Iron Works National Historic Site include riverbank and head-cutting erosion, as well as anthropogenic threats to the riverine and wetland resources. Erosion issues are mostly part of a river's natural meander pattern, but can be exacerbated by factors such as anthropogenic landscape disturbances, removal of vegetation, or channel modification. Flooding exacerbates erosion problems with higher flow energy and erosive capacity. Forty-year floods in 2006 caused gravel bars to migrate and some areas of the channel had build-ups of bedload material, particularly in the center of the site, just downstream from the Turning Basin (US Geological Survey 2006; James-Pirri et al. 2010). The shallower areas of the river were scoured, but again, this is a natural process, demonstrating the dynamic nature of rivers where the movement and redistribution of bedload is a natural occurrence (James-Pirri et al. 2010).

Flooding and erosion associated with channel meander threaten cultural resources at Saugus Iron Works National Historic Site. Infrastructure integral to the re-circulation system that powers the waterwheels includes a pump and motor that are located in the warehouse at the site's waterfront dock, just a few feet off the ground. A wooden bulkhead and several stone walls are part of the historic setting, located right at the waterfront and are susceptible to inundation, which could eventually cause damage. The historic slag pile juts into the river channel and has eroded in the past. Erosion of this pile may introduce heavy metals contained within the slag to the river system, and the Massachusetts Department of Environmental Protection has issued an Activity and Use Limitation for the slag pile area to ensure public safety and reduce the likelihood of pollutants entering the river system. Boulders were installed along the high-water line to minimize further erosion of the slag pile (Marc Albert, conference call, 21 May 2014, and written communication, 2 December 2014).

Also, stormflow has the potential to negatively impact many of the values and resources that were a focus of the Turning Basin restoration project. Extremely high stream flows could scour and incise the constructed gravel/cobble berm that was created to separate the active river channel from the still water Turning Basin. Sediments deposited in the basin area would fill in areas excavated during the project, raising the bed surface elevation and recreating the conditions amenable to infilling with vegetation, altering the navigability of the basin, and reducing the tangible connection for visitors between the historic iron works structures and the open river. In addition, if the constructed berm ceased to separate the active channel from the broad basin, the riffle habitat necessary for rainbow smelt spawning would likely be lost, at least temporarily (James-Pirri et al. 2011; Marc Albert, written communication, 2 December 2014). High flows following heavy rainfall can also affect the salinity in the brackish water estuary and Turning Basin. Tides bring in normal influxes of salt water, but these may be counterbalanced by higher freshwater flows or floods following heavy rainfall (James-Pirri et al. 2010).

Up to 56% of the Saugus River watershed is urbanized, and the surrounding landscape and human use of the landscape greatly influence the state of the riverine and wetland resources within the site. Stressors and threats include surface water runoff (increased by impervious surfaces; see "Slope Movement Hazards and Risks" section) contaminated with road salt, non-point source pollution, sewage overflow and infiltration into groundwater, and alteration in river discharge flow rates (James-Pirri et al. 2011). Public water supplies rely heavily on water removed directly from the river or indirectly from groundwater sources and ponds. Such water returns to the system as wastewater treatment discharge (James-Pirri et al. 2011). As described in the "Fluvial Features and Processes" section, the water supply is managed through a cooperative effort with the Lynn Water and Sewer Commission and conservation organizations.

Restoring the Turning Basin

Upon initial settlement, agricultural clearing of forests and plowing fields caused massive sedimentation in local rivers and had profound effects on the channel morphology and aquatic ecosystem. In 1682, the iron works dam was breached by local townspeople possibly because the dam had restricted access to the ocean and reduced migrating fish populations. This breach resulted in a flood and incursion of thick sediment that clogged the river to such an extent that boats could no longer navigate farther than 2 km (1 mi) downstream (Killion and Foulds 2003). In 1957, a failed attempt to dredge gravel and silt from Prankers Pond (north of the iron works site; sometimes called Lily Pond) breached a dam and released silt downstream, filling in most of the 1954-reconstructed wharf area and producing a 2-ha (4-ac) marsh that landlocked the dock (Killion and Foulds 2003; CH2M Hill 2004). The siltation problem was exacerbated by the Hamilton Street weir, which further reduced the flow and the ability of the river to transport sediment (Gregg Bailey, Saugus Iron Works NHS, seasonal park ranger, conference call 21 May 2014). During the 1950s archeological excavations, historic-water-level measurements indicated the river's channel level had risen at least 1 m (3 ft) since the 17th century through aggradation. Aggradation is the building up of a river's channel by sedimentation, in this case of post-agricultural sediments to the river's floodplain (Killion and Foulds 2003; Thornberry-Ehrlich 2008). Local sedimentation also occurs near high use areas such as bridges and trails, and other areas where stabilizing vegetation has been disturbed or destroyed (Thornberry-Ehrlich 2008).

All of this sedimentation filled in much of the Turning Basin—a cultural wetland landscape. Common reeds (*Phragmites australis*, an invasive species, one of 11 identified) clogged the riparian zone, choking out native species (Agius 2003). The infilling sediments also contained industrial contaminants (e.g., hydrocarbons, arsenic, chromium, lead, nickel, and zinc) derived from the surface runoff of the urbanized Saugus River watershed, as well as waste material from the site's own slag pile (CH2M Hill 2004; James-Pirri et al. 2011).

In 2007, NPS staff initiated a project to restore the Turning Basin, increase the local volume of the river, and change the channel morphology to reflect historic conditions essential to the interpretation of the iron works including historic boat routes. Restoring the basin helps interpreters determine how the iron works originally functioned. The project was one of the first tidal freshwater wetland restoration projects in New England, and included areas in the benthic zone, intertidal surface, and floodplain (James-Pirri et al. 2010; Gawley 2013). Specific tasks in the restoration project included excavating sediments, removing the Hamilton Street weir (a few hundred meters downstream from the site), rehabilitating the historic dock and bulkhead structures, and restoring tidal mudflat and marsh habitats (CH2M Hill 2004; Thornberry-Ehrlich 2008; James-Pirri et al. 2011). Between July 2008 and summer 2009, the *Phragmites* reeds, which once dominated 29% of the undeveloped habitat at the site, were removed and 13,000 native marsh plants were planted in the marsh downstream from the opened basin (figs. 17 and 18) (Agius 2003; National Park Service 2014b). The project timing accounted for fish spawning cycles and was designed to avoid contributing excess sediment into the river channel (CH2M Hill 2004). A gravel/cobble berm was included in the restoration to protect riffle habitat for rainbow smelt and to reduce siltation in the open water basin (James-Pirri et al. 2011).

Following this restoration effort, the sediment quality has substantially improved due to a reduction in industrial contaminants (James-Pirri et al. 2010). The restoration likely removed the vast majority of contaminated wetland sediments from within the project area (James-Pirri et al. 2011), however additional contaminated sediments from upstream sources may well be delivered to the river bed in the park on an ongoing basis. Monitoring through 2012 revealed native

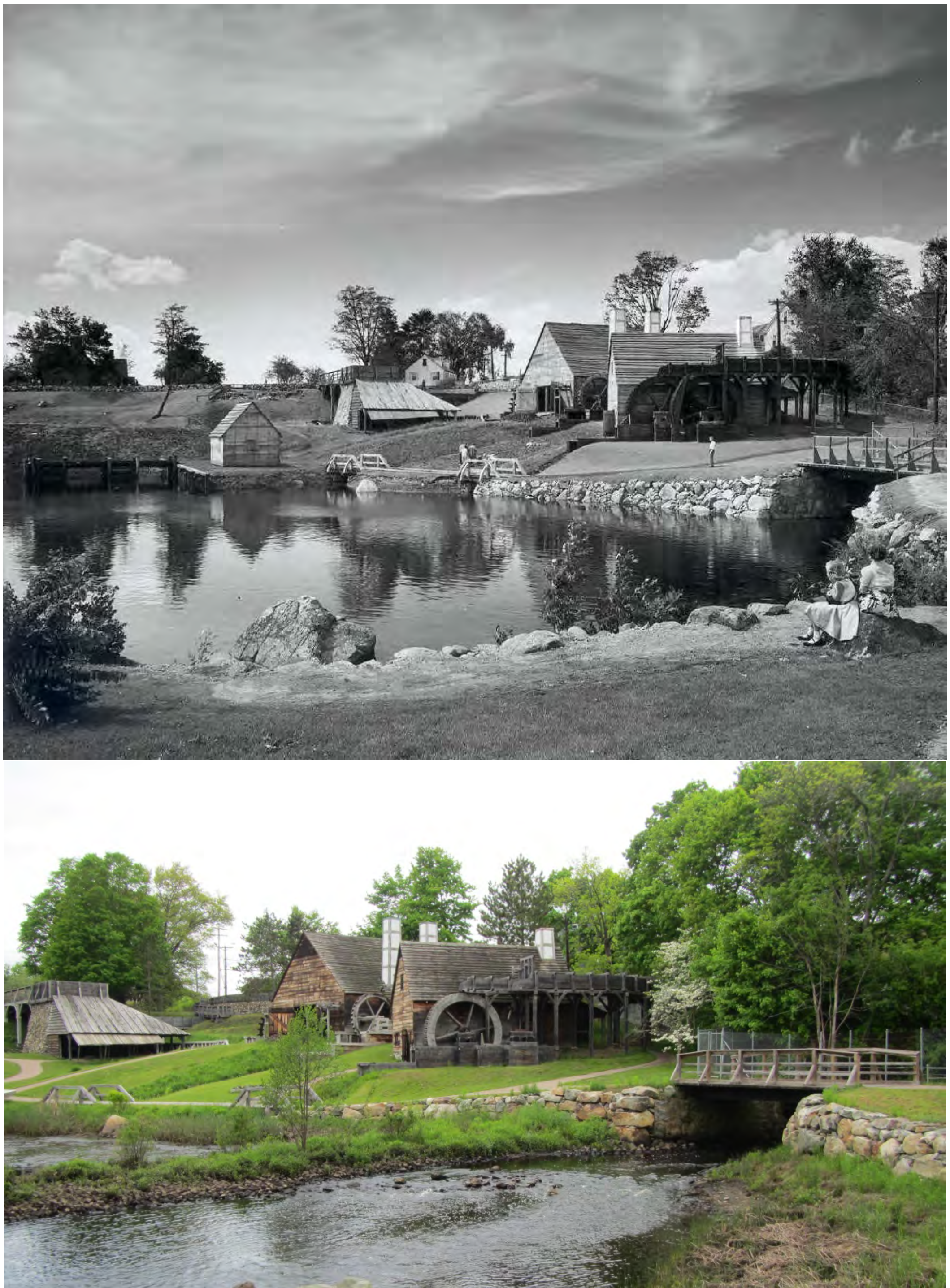


Figure 17. Turning Basin ca. 1954 and ca. 2014. Top photograph was taken just after completion of the reconstruction of the iron works buildings and landscape. Image was taken 3 years before a failed dam washed massive amount of silt into the basin clogging the waterway and leaving the dock stranded in a wetland. Bottom photograph shows a similar perspective after recent restoration projects. National Park Service photographs, bottom courtesy of Mark Albert taken in summer 2014.

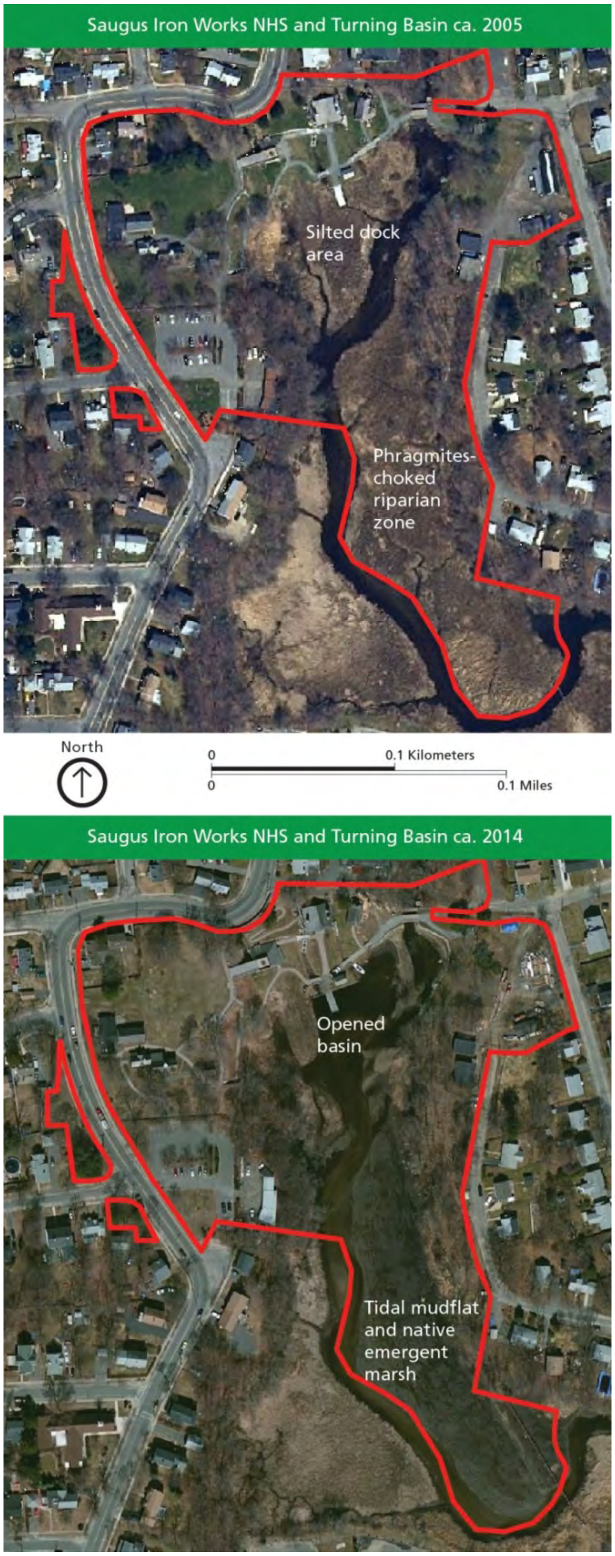


Figure 18. Turning Basin restoration. Pre-restoration conditions (upper image) contrast with post-restoration conditions (lower image). Restoration efforts removed invasive aquatic species and dredged sediments to restore native species and historic settings. The loading dock, once used to transport goods to and from river barges now connects to the Saugus River channel. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) modeled after figure 4 from James-Pirri et al. (2011) and using ESRI World Imagery basemap.

aquatic plant species are colonizing the Turning Basin and several fish species are using the restored basin (James-Pirri 2013). Removal of the Hamilton Street weir restored much of the natural hydrology; however the narrow bridge abutments are still there (Marc Albert and Gregg Bailey, conference call, 21 May 2014). The removal of the rock weir at Hamilton Street in September 2009 could be contributing to the upstream movement of a tidal salt wedge, as higher salinity was recorded in 2012 than in 2004 prior to removal of the weir (CH2MHill 2013)

Fluvial Monitoring and Water Quality

As part of the Turning Basin restoration project, a ten-year monitoring program was initiated to study the effects of the restoration on the site's ecosystem (National Park Service 2014b). James-Pirri et al. (2013) includes data summaries to describe the status of biotic (e.g., vegetation, nekton, avian, and benthic invertebrate communities) and abiotic (e.g., tidal hydrology, river geomorphology, sediment, and water quality) parameters for the first five years after the restoration. Tidal hydrology is a measurement of water-surface elevation and salinity patterns. River geomorphology and sediment composition are monitored via pebble counts, sediment sampling, and cross-sectional channel dimensions along 5 transects (James-Pirri et al. 2013).

As a further resource management reference, in the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile. Hart et al. (2010) outlined survey methods and guidance for shallow water habitat mapping that could be applied to the estuarine habitats at Saugus Iron Works National Historic Site to determine how well the natural system was restored and model sediment movement through the system. Roig and Evans (1993) outlined modeling techniques to simulate surface flows in tidal wetlands and to develop sediment transport and water-quality-modeling tools for coastal wetlands. The Saugus River estuary was one of their case studies.

Detailed water quality discussions are beyond the scope of this report. Contact the NPS Water Resources Division: http://www.nature.nps.gov/water/ for more information and assistance. The Saugus River has been a site of extensive water quality study and monitoring. The Northeast Temperate Network Water Quality Monitoring Program does sampling twice annually at two stream sites (one upstream of the tidal influence and the other at the Turning Basin). They examine the water chemistry, nutrient enrichment, water quantity, and detect invasive plant species (Gawley 2013). Annual results of this monitoring are available online:

http://science.nature.nps.gov/im/units/netn/monitor/programs/lakesPonds/lakesPonds.cfm (accessed 2 February 2015) (National Park Service 2013). The US Geological Survey's National Water Quality Assessment Program for New England provided data for myriad research projects ranging from elevated magnesium concentrations due to the historic brick lining of the Saugus Iron Works furnace (Andronache et al. 2008) to chloride (salt) loading patterns and pathways (see Coefer and Hon 2006; Tedder et al. 2007; Tedder et al. 2008; Sege and Hon 2009; Tedder and Hon 2009; Coefer and Hon 2010; Hon and Tedder 2010; and Coefer et al. 2011). The US Geological Survey data available for Saugus Iron Works are located at: http://waterdata.usgs.gov/ma/nwis/uv?site_no=01102345 (accessed 25 May 2014).

Slope Movement Hazards and Risks

As described in the "Slope Processes" section, slope movements are a common type of geologic hazard—a natural or human-caused condition that may impact site resources, infrastructure, or visitor safety. Risk is the probability of occurrence combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see also Holmes et al. 2013).

At Saugus Iron Works National Historic Site, slumping and slope creep are the primary slope movements causing resource management issues (Thornberry-Ehrlich 2008). The unconsolidated sediments underlying the site can easily erode and fail, particularly where the steeper slopes of the bluffs reach angles of more than 45° and the sediments are saturated. Slope movements are of particular concern where steep slopes intersect site roads or trails. In the 1990s, an unsuitable, loose, dense, silvery trail material called scale (a waste product of local commercial forging operations) was removed after problems with erosion and poor drainage. Then, wood-bordered, crushed-stone paths were installed. Following this work, there remained a significant number of runnels and erosion along the steeper segments (Killion and Foulds 2003). The trails were paved with semi-permeable chip-seal surface subsequent to the 2007 GRI scoping meeting. Paving the trails remediated the trail-erosion issue, but some localized erosion persists on the east banks of the Saugus River at the site. Small rills form along the banks there every spring (Marc Albert, conference call, 21 May 2014.

The slopes on the west side of the site (fig. 19), opposite from site facilities, below the parking lot, are steep and could pose a threat to site operational buildings. Surficial runoff from the parking lot currently flows through a drainage system pipe into a riverside drainage. Erosion is localized below the runoff pipes. This could contribute to slope movements by undercutting slopes. As of 2014, an NPS Northeast Region Office project to replace the

Figure 19. West banks of the Saugus River. Steep slopes, seeps, and runoff drainage below the parking lot could pose slope movement potential and threaten park buildings. National Park Service photograph courtesy of Marc Albert taken in fall 2014.

current parking lot and use ecological techniques (e.g., natural hydrology and gardens) to disperse the runoff and change the current collection of overflow water is currently on hold (Marc Albert, conference call, 21 May 2014).

Prior to the 1954 reconstruction of the iron works buildings and landscape, the slag pile was the sole relatively intact feature directly associated with the 17th-century iron works. As of 2003, this feature had yet to undergo significant archeological description or investigation (Killion and Foulds 2003). The slag pile has been considered an erosion-monitoring target at Saugus Iron Works National Historic Site (Killion and Foulds 2003), and there is some evidence of past erosion on the western side of the slag pile (CH2M Hill 2004); however the park maintains vegetative cover and prohibits public access to the slag pile as per the requirements in the Activity and Use Limitation issued by the Massachusetts Department of Environmental Protection... As part of the Turning Basin restoration (see "Restoring the Turning Basin" section), cross sections of the river at subsequent locations along the channel are surveyed through the year 2016. One of these sections includes the slag pile. There is also ongoing photomonitoring of the pile at least twice per year from multiple angles (Marc Albert, conference call, 21 May 2014).

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), the US Geological Survey landslides website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://www.nature.nps.gov/geology/hazards/index.cfm) and Slope Movement Monitoring (http://www.nature.nps.gov/geology/monitoring/slopes.cfm) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

Earthquake Hazards and Risks

Earthquakes (seismic activity) are ground vibrations—shaking—that occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Earthquake intensity or magnitude ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The "Richter magnitude" is a measure of the energy released by an earthquake. Earthquakes can damage site infrastructure directly, or trigger other hazards such as slope movements on the bluffs above the river that may impact site resources, infrastructure, or visitor safety.

Saugus Iron Works National Historic Site is not located near an active seismic zone. The US Geological Survey's earthquake probability maps (http://geohazards.usgs.gov/eqprob/2009/, accessed 22 April 2014) indicate a 4% to 6% probability of a magnitude-5.0 or greater earthquake within 100 years (fig. 20) (Peterson et al. 2008). Small earthquakes occur occasionally, but most of these events are two minor to be detectable by humans and range in magnitude between 2 and 3. These are typically along northwest trending faults in the Nashoba terrane, west of Saugus.

The potential for large earthquakes exists. Historically, there have been several large earthquakes, including the 1755 earthquake near Cape Anne. This event was approximately 6.4 in magnitude and the shaking was strong enough to ring bells, topple chimneys and weather vanes, and damage stone walls across an area stretching between Portland, Maine to Hartford, Connecticut. If such an even were to occur today, the damages would likely be in the billions of dollars (Thornberry-Ehrlich 2008). The 2011 Virginia earthquake is one example of an earthquake that caused major damage in an area that was similarly considered to be relatively inactive.

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. The nearest seismic station is at the Weston Observatory (http://www.bc.edu/research/westonobservatory/). Braile (2009), the NPS Geologic Resources Division Seismic Monitoring website (http://nature.nps.gov/geology/monitoring/seismic.cfm), and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/) provide more information.

Disturbed Lands and Mineral Extraction

Saugus Iron Works National Historic Site commemorates the legacy of mineral extraction and use by early Americans; the site wishes to restore and preserve the conditions from the height of the iron operations. Prehistorically and historically, the land was extensively disturbed to mine Saugus "jasper", iron ore, clay, and flux (gabbro), and to develop and operate the iron works.

Rebuilding and/or maintaining the historic landscape poses resource management issues including eroding slag piles and artifact protection. As mentioned in the "Geologic Significance and Connections" section, America Indian artifacts such as projectile points may be present in sediments flanking the Saugus River. These river sediments were covered by sediments that had settled behind the dam that failed in 1957 (see "Restoring the Turning Basin" section) or were reworked by high flows stemming from an early breach of the original mill pond dam destroyed in 1682. Some of these artifacts were at risk of exposure during the Turning Basin restoration project, but were carefully avoided during the excavation using topography from 1954 (see

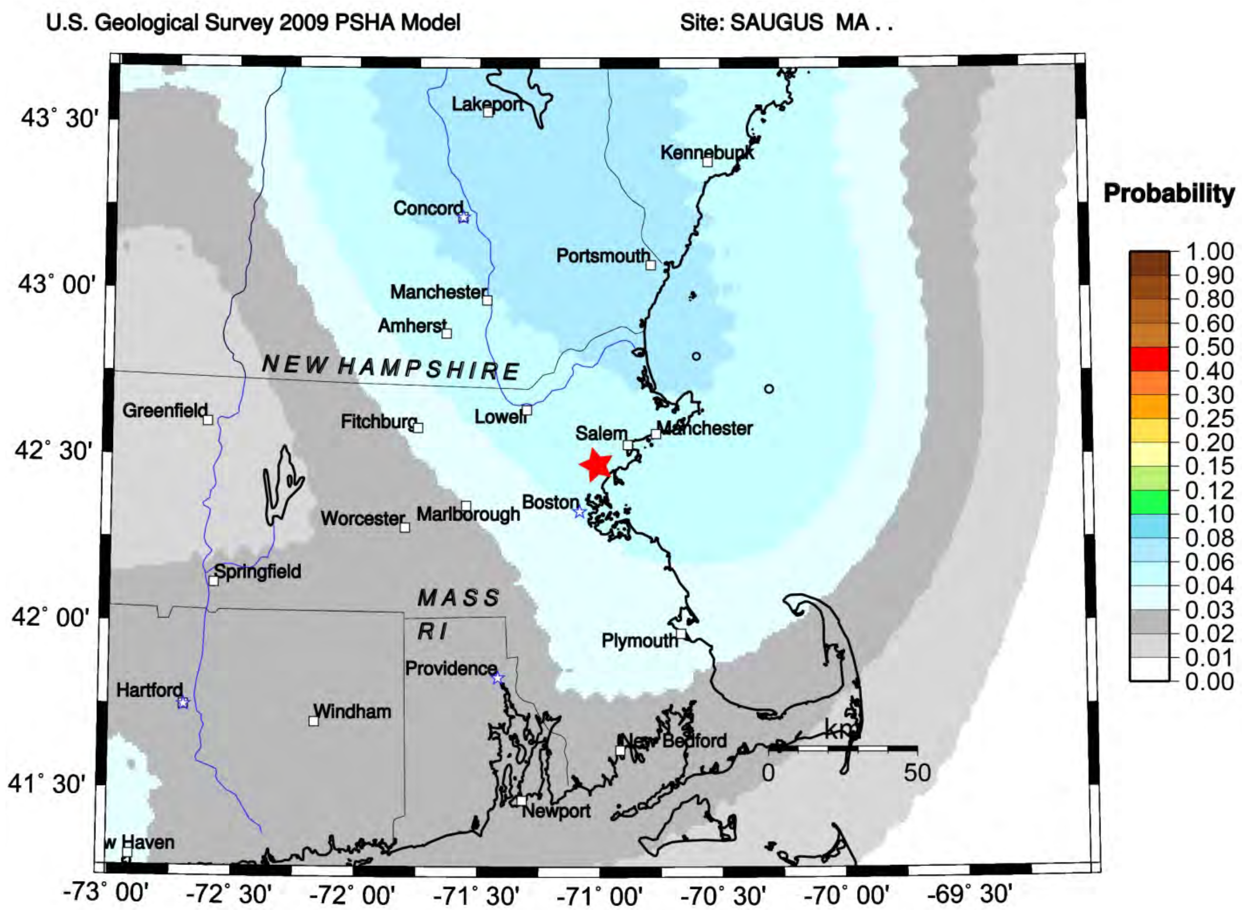


Figure 20. Probability of earthquakes with magnitude greater than 5.0. This probability assumes a 100-year timespan and a 50-km (30-mi) radius around Saugus, Massachusetts (red star). Graphic was generated by the US Geological Survey earthquake probability mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php, accessed 22 April 2014).

"Restoring the Turning Basin" section) (Thornberry-Ehrlich 2008; Marc Albert, conference call, 21 May 2014).

Within site boundaries, erosion could threaten the integrity of the 17th-century slag pile. The pile is located near the original loading dock and is a tangible resource for interpretation. However, the pile contains contaminants that way be released into the Saugus River if eroded (see "Flooding and Fluvial Geomorphology of the Saugus River" for more information) (Thornberry-Ehrlich 2008).

Mineral extraction in the area has continued into modern times. Eleven mine point features are captured in the GRI GIS data for Saugus Iron Works National Historic Site from the US Geological Survey Mineral Resources Data System (http://tin.er.usgs.gov/mrds/). At least half of these are abandoned and/or reclaimed quarries; none are mapped within Saugus Iron Works National Historic Site. The Saugus quarry, operated by Aggregate Industries Northeast, Inc. produces crushed rock from the Lynn Volcanics (**Zlv**) approximately 2.5 km (1.5 mi) southwest of the national historic site (Kopera 2011). Land use was one of the vital signs identified for monitoring for the NPS Northeast Temperate Inventory and Monitoring Network by Mitchell et al. (2006).

Abandoned Mineral Lands

According to the NPS Abandoned Mineral Lands (AML) database (accessed 16 April 2014) and Burghardt et al. (2014), Saugus Iron Works National Historic Site contains no documented AML sites or features. Resource management of any AML features requires an accurate inventory and reporting. All AML features should be recorded in the AML database (the NPS Geologic Resources Division may be able to provide assistance). An accurate inventory can identify human safety hazards, and facilitate closures, reclamation, and restoration of AML features. When appropriate for resource management and visitor safety, AML features can also present opportunities for interpretation as cultural resources. The NPS AML Program website, http://nature.nps.gov/geology/aml/index.cfm, provides further information.

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009

Paleontological Resources Preservation Act (see Appendix B). As of March 2015, Department of the Interior regulations associated with the Act were being developed. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Although a site-specific survey has not yet been completed for Saugus Iron Works National Historic Site, a variety of publications and resources provide site-specific or servicewide information and paleontological resource management guidance. Tweet et al. (2010) summarized known fossil resources from the surrounding area and provide guidance for managing any fossils located within site boundaries. In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Saugus Iron Works National Historic Site.

The mixed assemblage of fault-bounded rocks and unmapped surficial deposits reflect the geologic history in the site and surrounding area: (1) Proterozoic and Neoproterozoic metamorphic and igneous rocks formed and deformed during the early construction of the Avalon terrane, (2) continued igneous and metamorphic rocks formed in the terrane during the Paleozoic, (3) deformation and accretion of the terrane onto North America in the Paleozoic during the formation of the supercontinent, Pangaea, (4) Jurassic igneous rocks intruded the area as Pangaea rifted apart, (5) Pleistocene glaciation and glacial deposits, and (6) Holocene alluvium. The rocks within and around the site span more than 600 million years from the Proterozoic to the present (see fig. 4). The geologic history of Saugus Iron Works National Historic Site involves ancient orogenies; marine deposition; construction of the Appalachian Mountains and Pangaea; the breakup of Pangaea and associated volcanism; followed by millions of years of weathering, erosion, and ice age glaciations (see fig. 15). These events and the resulting rocks formed the geologic landscape that made Saugus an ideal location for a strategic location for the first incorporated iron works of North America.

Proterozoic Eon (2.5 Billion to 541 Million Years Ago): Formation of the Avalon Terrane and its Detachment from Gondwana

Throughout Earth's history, the continental landmasses have drifted, collided, rifted apart, and recombined, culminating in the continents that persist today (figs. 21 and 22). Most of New England is composed of crustal blocks that originated elsewhere and were accreted as exotic terranes onto the continental margin. The origins, formation, and timing of assembly of the individual terranes are a subject of much debate and current research (Skehan 2001). The Avalon terrane—one of a series of landmasses that accreted to the margin of Laurentia (proto-North America) during the Paleozoic Era—formed during the Neoproterozoic Era, more than 590 million years ago. It was originally a collection of igneous (**Zgr**, **Zgdm**, **Zgrt**, **Zmu**, **Zlv**, **Zlvfb**, and **Zvk**) and sedimentary rocks (**Zqo**) in the middle latitudes. These rocks formed in part during the Avalonian Orogeny of the Late Proterozoic Era (Hepburn et al. 1993; Skehan 2001; Tweet et al. 2010). Approximately 610 million years ago, one tectonic plate was overriding another along a subduction zone—a setting similar to the modern Andes Mountains (fig. 23A) (Linnemann et al. 2007). As subduction proceeded, the downthrown plate partially melted providing magma for igneous intrusions into the overlying plate. Today these intrusions (batholitic) rocks of the Avalon Terrane are granite-like rocks mapped as **Zgr**, **Zgdm**, **Zgrt**, and **ZDgdt**. Associated marine basins collected submarine sediments about 600 million years ago, now recorded in the quartzite and olistromal assemblage (**Zqo**). When the magma reached the surface, a series of volcanic eruptions spewed lava and ash across the landscape and atop the intrusives and sedimentary rocks. The Lynn Volcanics and quartz keratophyre and keratophyre (**Zlv**, **Zlvfb**, and **Zvk**, respectively) record these ancient volcanoes in a volcanic arc setting.

The Lynn Volcanics, underlying the entirety of Saugus Iron Works National Historic Site, are composed of silica-rich rhyolites, ash flows, lapilli tuffs, and breccias. These kinds of volcanic features indicate particularly explosive volcanism in contrast with less-explosive, basaltic volcanism such as what occurs at Hawai'i Volcanoes National Park (see GRI report by Thornberry-Ehrlich 2009). As igneous activity waned and the orogeny ended, compression changed to extension and a rift basin opened within the volcanic arc—the Boston Basin (fig. 23B) (Hepburn et al. 1993; Skehan 2001).

The Boston Basin was the center of deposition for the Boston Bay Group (**ZCrcca** and **ZCrsca**). At first, during the Neoproterozoic Era, the basin collected coarse conglomerates including pebbles of volcanic rocks, quartzite, and granites. As sedimentation proceeded, the composition changed to finer-grained argillites dominated by sandstones, quartzites, and siltstones (Kaye 1980; Lenk et al. 1982; Kopera 2011). Deposition in the Boston Basin continued into at least the Early Cambrian Period (Goldsmith 1991a; Kopera 2011).

The Avalon terrane was originally located along the margin of a landmass called Gondwana (Thompson et al. 2007). Gondwana included today's Antarctica, South America, Africa, Madagascar, and Australia. Paleomagnetic signatures in the Avalon terrane indicate the Boston area was attached to, or located near, what is now West Africa (Thompson et al. 2007; Tweet et al. 2010). At this same time, the eastern margin of Laurentia was underwater following the breakup of a supercontinent, called Rodinia. Rifting of this huge landmass culminated in the opening of the Iapetus Ocean—a precursor to the Atlantic Ocean. When the Avalon terrane rifted away from West Africa, beginning about 550 million years ago, a marine basin called the Rheic Ocean formed between the separated landmasses (fig. 23B) (Coleman 2005; Linnemann et al. 2007).

Paleozoic Era (541 Million to 252 Million Years Ago): Mountain Building, Terrane Accretion, and the formation of a Supercontinent

When the Avalon landmass separated from Gondwana, it drifted within the Rheic and Iapetus oceans (separating them) that eventually closed during Appalachian-

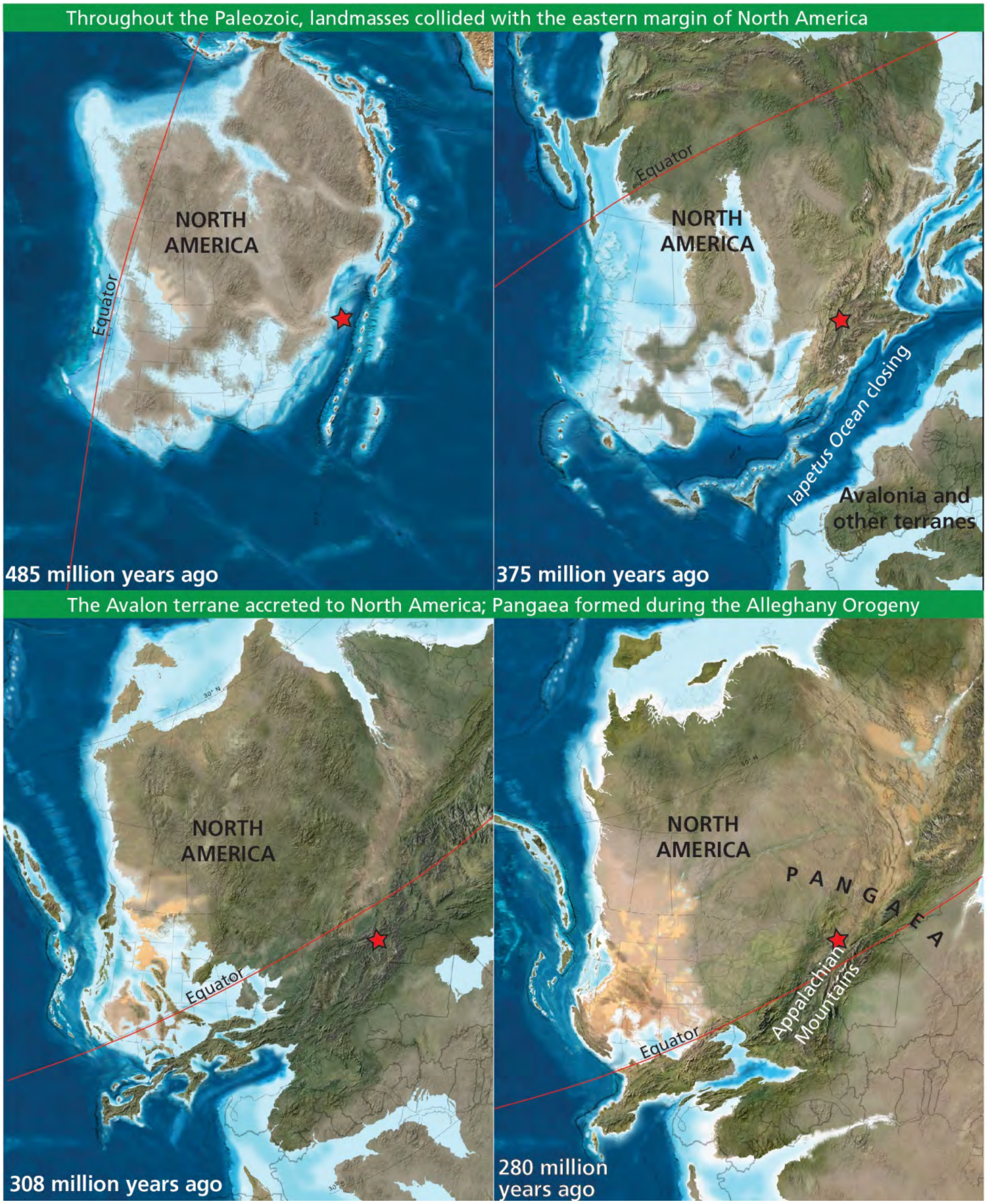


Figure 21. Paleogeographic maps of North America. During the Ordovician, 485 million years ago, the Saugus area was dominated by open marine settings as a volcanic arc was approaching the eastern margin of North America. During the Devonian (375 million years ago), the Iapetus and Rheic oceans were closing as other landmasses collided with North America during the Acadian Orogeny. The Avalon terrane was one of several terranes accreted to the margin of North America during the Paleozoic orogenies. During the Pennsylvanian (308 million years ago), the Alleghany Orogeny formed the Appalachian Mountains. The Appalachian Mountains reached their highest elevation during the Alleghany Orogeny. Red star indicates the location of Saugus Iron Works National Historic Site. Equator locations are the red lines. Paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems; available online: http://cpgeosystems.com/paleomaps.html, accessed 25 April 2014) annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 22. Paleogeographic maps of North America, continued. By the Jurassic (170 million years ago), the supercontinent had broken up and roughly the continents that exist today drifted away from North America as the Atlantic Ocean spread. Throughout the rest of the Mesozoic and into the Cenozoic, the Saugus area was relatively tectonically quiet. Erosion lowered the mountains and built the Coastal Plain toward the widening Atlantic Ocean. Red star indicates the location of Saugus Iron Works National Historic Site. Equator locations are the red lines. Paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems; available online: http://cpgeosystems.com/paleomaps.html, accessed 25 April 2014) annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

Mountain building. The Appalachians formed through a series of orogenies throughout the Paleozoic. In northeastern North America, these were the Taconic, Acadian, and Alleghany orogenies. The Taconic Orogeny began during the Ordovician Period approximately 488 to 440 million years ago (fig. 4). It involved the collision of volcanic island arcs with the eastern margin of what would become North America. Because the Avalon terrane was not part of North America at this time, no trace of this orogeny occurs within the rocks of Saugus Iron Works National Historic Site. By the Middle Devonian Period, about 375 million years ago, landmasses were converging again along the eastern seaboard of ancient North America and the Iapetus oceanic basin continued to shrink as the African continent was approaching. This marked the onset of the Acadian Orogeny, an event focused in New England and recorded by Acadian folds, faults, and igneous intrusions (see fig. 4) (Epstein and Lyttle 2001). Similar to the Taconic Orogeny, the Acadian Orogeny (fig. 23C) involved land mass collision, mountain building, and regional metamorphism (Means 1995). Approximately 325 to 265 million years ago, Gondwana collided with the North American continent during the Alleghany Orogeny (fig. 24D, see fig. 4). This closed the Iapetus and Rheic ocean basins forever and was the last major orogeny to contribute to the Appalachian Mountains formation.

Geologists hypothesize the Avalon terrane accreted to North America during the Acadian Orogeny (e.g., Coleman 2005) or the Alleghany Orogeny (e.g., Skehan 2001) (Tweet et al. 2010; Kopera 2011). The timing of accretion and prior history of the Avalon terrane are still being studied. Within the rocks surrounding Saugus Iron Works National Historic Site are igneous intrusions with inferred ages ranging from Proterozoic Eon to Devonian Period (**ZDgdt**, **ZDgdtfb**, **ZDgdta**, and **ZDd**) (Kaye 1980; Kopera 2011). The Peabody Granite (**Dpgr** and **Dpgrb**) intruded the Avalon terrane during the Devonian Period at least 378 million years ago (fig. 23C) (Kaye 1980; Thompson and Ramezani 2008; Kopera 2011). The many throughgoing faults (see GRI GIS faults data layer and "Faults" section of this report), deformation zones, and the myriad intrusions suggest a long history of internal deformation and change within the terrane prior to its accretion to North America. Regardless of how, or exactly when, it arrived, by some point in the late Paleozoic Era, the Avalon Terrane had collided with the eastern margin of Laurentia as part of the series of orogenies that uplifted the Appalachian Mountains and ultimately sutured Earth's landmasses together into a supercontinent called Pangaea (fig. 24D) (Levin 1999; Skehan 2001; Tweet et al. 2010).

Mesozoic Era (252 Million to 66 Million Years Ago): Pangaea Rifts Apart and Weathering Commences

Pangaea was not to last. During the Triassic and Jurassic periods, rifting pulled what would become Africa and South America apart from North America forming the Atlantic Ocean and Gulf of Mexico (fig. 24E, see fig. 4). Intrusions of molten magma forced upwards through the deformed rocks of the Avalon terrane. Some of these intrusions are the diabase dikes with magnetite (**ZJ[?]db**) that occur throughout the site area (Kaye 1980; Kopera 2011). Continental rifting formed many basins along eastern and southern North America at the base of the Appalachian Mountains. Steeply dipping normal faults formed the boundaries of these basins, which quickly filled with sediment eroded from the surrounding highlands. Great portions of the once Alps-like Appalachian Mountains slowly lowered and were buried by younger sediments of the Coastal Plain derived from the weathering mountains.

Weathering and erosion dominate the relatively quiet geologic history of the Saugus Iron Works area throughout the Mesozoic Era and most of the following Cenozoic Era (see fig. 4). Rivers transported sediments worn from the highlands to build the Coastal Plain towards the Massachusetts Bay and Atlantic Ocean. Because different types of rocks are more or less resistant to erosion, some areas eroded faster than others. The hard granites, quartzites, and metamorphic rocks surrounding the Boston Basin were more resistant to erosion than the sedimentary rocks within the basin and remain as high ground on the basin's rim.

Cenozoic Era (66 Million Years Ago to Present): Ongoing Weathering, Glaciations, and Modern Landform Development

With the exception of recent surficial deposits, any rocks deposited since the breakup of Pangaea are now eroded from the Saugus Iron Works National Historic Site area (fig. 24F) (Masterson et al. 1996).

The Saugus River area was greatly affected by glaciers descending south from the Arctic periodically during the Pleistocene (between 2.59 million and 12,000 years ago) (see figs. 4 and 15). The glacial history of the area is complex. The site area was along a zone where two glacial lobes of a continental ice sheet met—the Narragansett Bay-Buzzards Bay lobe to the west and the Cape Cod Bay lobe to the east (Skehan 2001). Along the edges and between the lobes, relatively scant sediments were deposited. The area was also near the marine shoreline at this time and glaciers and glacial deposits develop differently depending on whether the ice was atop land or water (Kaye 1976; Tweet et al. 2010). During the most recent glacial stage (the Wisconsinan), two prominent tills were deposited; however, these tills are not discernible along the Saugus River. The surficial geology of the site is composed of Pleistocene-age stratified drift (clay and scant sand, gravel, and jumbled till) deposited under marine influence (Kaye 1978; Tweet et al. 2010). The bluffs flanking the floodplains of the Saugus River may be part of a flat-topped sandy glacial delta (Thornberry-Ehrlich 2008).

When the glaciers retreated from the area beginning more than 15,000 years ago, the land surface was depressed from the incredible weight of the former ice sheets causing a local sea-level high, at least 22 m (72 ft) higher than its present elevation. In these submarine settings, glaciomarine clay called the Boston Blue Clay was deposited across the area (Rosen and FitzGerald 2004). Within a thousand years after the ice retreated, the land surface began to rebound and relative sea level lowered. The amount of water contained in continental ice sheets is immense and glaciations coincide with global sea-level lows. When the ice melts, that water is released back into the oceans and sea level rises. By approximately 6,000 years ago, the area was again underwater and collecting marine sediments (Rosen and FitzGerald 2004). Paleoindian sites in and around Boston record human presence by the time sea level was rising (Luedtke and Rosen 1993). The present sea-level of Boston Harbor stabilized around 2,000 years ago (Jones and Fisher 1990).

Throughout the Holocene Epoch, the Saugus River has meandered across its floodplain, reworking glacial and marine sediments and depositing alluvium along its channel and terrace and overbank deposits atop adjacent floodplains. The fertile landscape supported vast forests that contributed charcoal to the iron works at Saugus. The early settlers used the area's geologic resources—ultramafic gabbros for flux from the Nahant Peninsula, and bog iron ore from nearby peat bogs—to start the nation's first incorporated iron works in 1646.

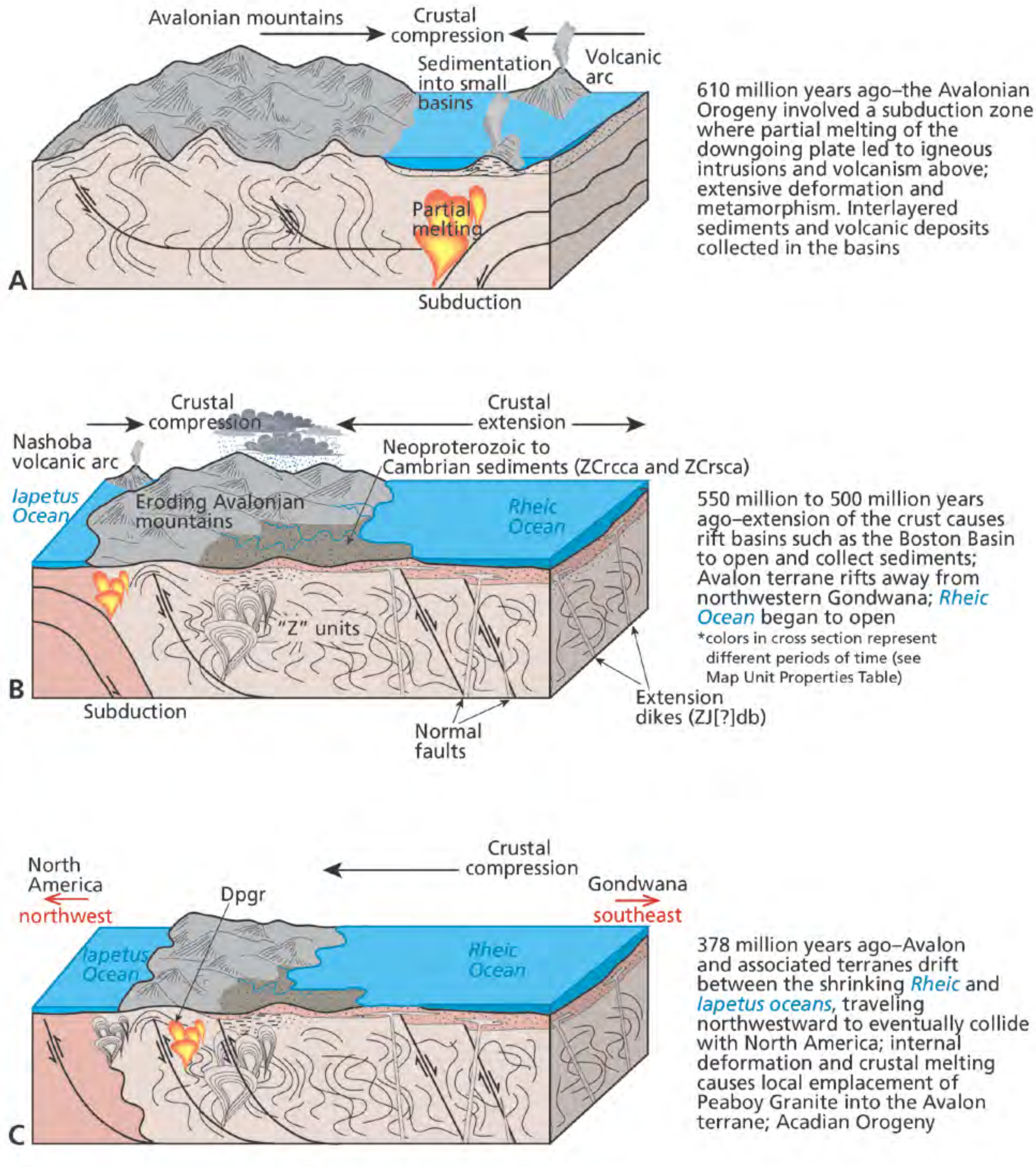


Figure 23. Schematic graphics illustrating the evolution of the Saugus Iron Works National Historic Site landscape. Graphics are not to scale. Graphics by Trista L. Thornberry-Ehrlich, with information from Skehan (2001); Hepburn et al. (1993); Coleman (2005); Linneman et al. (2007); Thompson et al. (2007); and Kopera (2011).

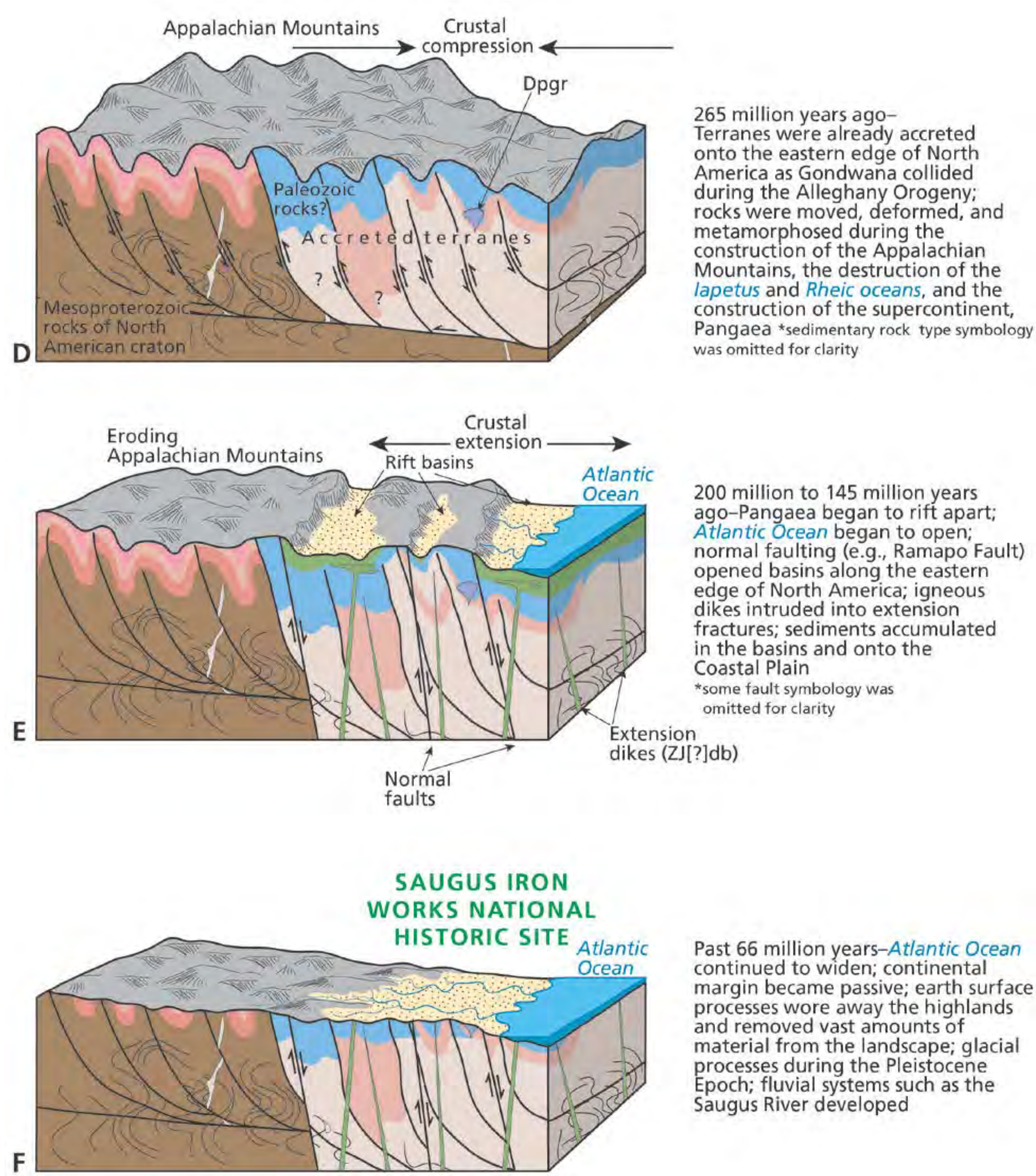


Figure 24. Schematic graphics illustrating the evolution of the Saugus Iron Works National Historic Site landscape, continued. Graphics by Trista L. Thornberry-Ehrlich, with information from Skehan (2001); Hepburn et al. (1993); Coleman (2005); Linneman et al. (2007); Thompson et al. (2007); and Kopera (2011).

Geologic Map Data

This section summarizes the geologic map data available for Saugus Iron Works National Historic Site. A poster (in pocket) displays the map data draped over imagery of the site and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following sources to produce the digital geologic data set for Saugus Iron Works National Historic Site. These sources also provided information for this report.

Kopera, J. P. 2011. Preliminary compilation of bedrock geology in the vicinity of Saugus National Iron Works Historic Site (scale 1:24,000). Massachusetts Geological Survey, University of Massachusetts, Amherst, Massachusetts.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Saugus Iron Works National Historic Site using data model version 2.1. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm, provides more information about GRI map products.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A GIS readme file (PDF) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format
- Layer files with feature symbology (table 3)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- An ancillary map information document PDF) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures.
- An ESRI map document (.mxd) that displays the digital geologic data
- A KML/KMZ version of the data viewable in Google Earth (table 3).

Table 3. Geology data layers in the Saugus Iron Works National Historic Site GIS data.

Data Layer	On Map Poster?	Google Earth Layer?
Geologic Attitude and Observation Localities	No	No
Mine Point Features	No	No
Folds	Yes	Yes
Faults	Yes	Yes
Linear Dikes	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Geologic Map Poster

A poster of the GRI digital geologic data draped over a shaded relief image of the site and surrounding area is included with this report. Not all GIS feature classes may be included on the poster (table 3). Geographic information and selected site features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scale (1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 12 m (40 ft) of their true locations.

Glossary

This section contains brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

accessory mineral. A mineral whose presence in a rock is not essential to the proper classification of the rock.

accretion (structural geology). The addition of island-arc or continental material to a continent via collision, welding, or suturing at a convergent plate boundary.

aggradation. The building up of Earth's surface by depositional processes.

albite. A silicate (silicon + oxygen) mineral of the plagioclase group composed of sodium and aluminum, $NaAlSi_3O_8$.

alkali feldspar. A group of potassium-rich feldspar minerals containing alkali metals.

alluvium. Stream-deposited sediment.

anticline. A fold, generally convex upward ("A"-shaped) whose core contains the stratigraphically older rocks.

apatite. A group of phosphate (phosphorus + oxygen) minerals composed of calcium together with fluorine, chlorine, hydroxyl, or carbonate in varying amounts and having the general formula $Ca_5(F,OH,Cl)(PO_4,CO_3)_3$.

argillaceous. Pertaining to, largely composed of, or containing clay-size particles or clay minerals.

argillite. A weakly metamorphosed rock, derived from mudstone or shale, but more highly indurated; lacks the fissility of shale and the cleavage of slate.

ash. Fine-grained material, less than 2 mm (0.08 in) across, ejected from a volcano.

augen. Describes large lenticular minerals that are eye-shaped in cross section.

augite. A dark-green to black silicate (silicon + oxygen) mineral of the pyroxene group that contains abundant aluminum, iron, and magnesium.

axis. A straight-line approximation of the trend of a fold along the boundary between its two limbs. "Hinge line" is a preferred term.

bank. A submerged ridge of sand in the sea, a lake, or a river, usually exposed during low tide or low water.

basalt. A volcanic rock that is characteristically dark in color (gray to black), contains approximately 53% silica or less, and is rich in iron and magnesium.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger. Also, Earth's crust below sedimentary deposits that extends down to the Mohorovicic discontinuity.

basin (sedimentary). Any depression, from continental to local scale, into which sediments are deposited.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

batholith. A large, generally discordant plutonic body having an aerial extent of 100 km^2 (40 mi^2) or more and no known floor.

bayhead bar. An elongate, offshore ridge or mass, usually of sand, formed a short distance from the shore and across a bay near its head; similar to a bayhead barrier, but smaller and generally submerged.

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated sedimentary deposits and soil.

benthic. Pertaining to the ocean bottom or organisms living on or in substrate; also, referring to that environment.

biotite. A dark-colored, shiny silicate mineral (silicon + oxygen) of the mica group composed of magnesium and/or iron, $K(Mg,Fe)Si_3O_{10}(OH)_2$; characterized by perfect cleavage, readily splitting into thin sheets.

block (fault). A crustal unit bounded completely or partially by faults.

bog iron ore. A soft, spongy, and porous deposit of impure hydrous iron oxide, formed in bogs, marshes, swamps, peat mosses, and shallow lakes by precipitation from iron-bearing waters and by the oxidizing action of algae, iron bacteria, or the atmosphere.

braided stream. A sediment-clogged stream that forms multiple channels that divide and rejoin.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts more than 2 mm (0.08 in) across.

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material.

brecciation. Formation of a breccia, as by crushing or breaking a rock into angular fragments.

brittle. Describes a rock that fractures before sustaining deformation.

calcite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; calcium carbonate. It is the most abundant cave mineral.

carbonate. A mineral group composed of carbon and oxygen plus an element or elements; for example calcite, $CaCO_3$; and dolomite, $CaMg(CO_3)_2$.

cement (sedimentary). Mineral material, usually chemically precipitated, that occurs in the spaces among the individual grains of a sedimentary rock, thus binding the grains together.

cementation. The process by which clastic sediments become lithified or consolidated into hard, compact rocks, usually through deposition or precipitation of minerals in the spaces among the individual grains of the sediment; may occur simultaneously with sedimentation or at a later time.

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition providing more stablity in the current environment.

chert. An extremely hard sedimentary rock with conchoidal fracturing, consisting mostly of interlocking crystals of quartz.

chlorite. A group of silicate (silicon + oxygen) minerals composed of iron, magnesium, and aluminum with the general formula $(Mg,Fe)_6(AlSiO_3)O_{10}(OH)_8$.

clast. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.

clastic. Describes rocks or sediments made of fragments of preexisting rocks.

clay. Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

cleavage. The tendency of a mineral to break along planes of weak bonding.

coarse-grained. Describes a crystalline rock and texture in which the individual minerals are relatively large, specifically an igneous rock whose particles have an average diameter greater than 5 mm (0.2 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are easily seen with the unaided eye, specifically sediment or rock whose particles have an average diameter greater than 2 mm (0.08 in).

coastal plain. Any lowland area bordering a sea or ocean, extending inland to the nearest elevated land, and sloping very gently seaward; may result from the accumulation of material along a coast.

compaction. The process whereby fine-grained sediment is converted to consolidated rock.

compression. A decrease in volume of material (including Earth's crust) as it is pressed or squeezed together.

conformable (igneous). Said of an intrusive igneous contact that has the same attitude as that of the intrusion's internal structures and fabrics.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in) in diameter.

contact metamorphism. One of the principal local processes of thermal metamorphism, genetically related to the intrusion and extrusion of magmas and taking place in rocks at or near their contact with a body of igneous rock. Metamorphic changes are effected by the heat and fluids emanating from the magma and by some deformation connected with the emplacement of the igneous mass.

continental crust. Earth's crust that is rich in silica and aluminum and underlies the continents and the continental shelves; ranges in thickness from about 25 km (15 mi) to more than 70 km (40 mi) under mountain ranges, averaging about 40 km (25 mi) thick.

convergent plate boundary. A boundary between two plates that are moving toward each other. Essentially synonymous with "subduction zone" but used in different contexts.

country rock. The rock surrounding an igneous intrusion or pluton; also, the rock enclosing or traversed by a mineral deposit.

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

cross section. A graphic interpretation of geology, structure, or stratigraphy based on mapped and measured geologic extents and attitudes, depicted in a vertical plane (i.e., a cut or profile view).

crust. Earth's outermost layer or shell.

cryptocrystalline. Describes a rock texture in which individual crystals are too small to be recognized or distinguished with an ordinary microscope.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

dacite. A volcanic rock that is characteristically light in color and contains approximately 63%–68% silica and moderate amounts of sodium and potassium.

debris flow. A moving mass of rock fragments, soil, and mud, with more than half of the particles larger than sand size. Slow debris flows may move less that 1 m (3 ft) per year; rapid ones reach 160 kph (100 mph).

deformation. The process of folding, faulting, shearing, or fabric development in rocks as a result of Earth stresses.

delta. The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area; resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents.

devitrification. Conversion of glass to crystalline material.

diabase. An intrusive igneous rock consisting primarily of the minerals labradorite and pyroxene.

diamictite. Nonsorted or poorly sorted, noncalcareous, terrigenous sedimentary rock that contains a wide range of particle sizes, such as a rock with sand and/or larger particles in a muddy matrix. The term implies no origin.

diamicton. The nonlithified equivalent of diamictite.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

diopside. A silicate (silicon + oxygen) mineral of the pyroxene group; occurs in mafic and ultramafic igneous rocks and some areas of contact metamorphism.

diorite. A coarse-grained, intrusive igneous rock characteristically containing plagioclase, as well as dark-colored amphibole (especially hornblende), pyroxene, and sometimes a small amount of quartz; diorite grades into monzodiorite with the addition of alkali feldspar.

dip. The angle between a bed or other geologic surface and the horizontal plane.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

discharge. The rate of flow of surface water or groundwater at a given moment, expressed as volume per unit of time.

discordant. Describes an igneous intrusion having contacts that are not parallel to foliation or bedding in the country rock.

displacement. The relative movement of the two sides of a fault; also, the specific amount of such movement.

dolomite (mineral). A carbonate (carbon + oxygen) mineral of calcium and magnesium, $CaMg(CO3)2$.

dolomite (rock). A carbonate sedimentary rock containing more than 50% of the mineral dolomite (calcium-magnesium carbonate).

drainage. The manner in which the waters of an area flow off in surface streams or subsurface conduits; also, the processes of surface drainage of water from an area by streamflow and sheet flow, and the removal of excess water from soil by downward flow.

drift. All rock material (clay, silt, sand, gravel, and boulders) transported and deposited by a glacier, or by running water emanating from a glacier.

drumlin. A low, smoothly rounded, elongated oval hill, mound, or ridge of till that formed under the ice margin and was shaped by glacial flow; the long axis is parallel to the direction of ice movement.

epidote. A characteristically green silicate (silicon + oxygen) mineral, commonly occurring as slender, grooved crystals in hand specimens.

erosion. The general process or group of processes that loosen, dissolve, wear away, and simultaneously move from one place to another, the materials of Earth's crust; includes weathering, solution, abrasive actions, and transportation, but usually excludes slope movements.

erratic. A rock fragment carried by glacial ice deposited at some distance from the outcrop from which it was derived, and generally, though not necessarily, resting on bedrock of different lithology.

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix.

extension. Deformation of Earth's crust whereby rocks are pulled apart.

extrusion. The emission of lava onto Earth's surface; also, the rock so formed.

extrusive. Describes an igneous rock that has been erupted onto the surface of the Earth. Extrusive rocks include lava flows and pyroclastic material such as volcanic ash.

fabric. The complete spatial and geometrical configuration of all components that make up a deformed rock, including texture, structure, and preferred orientation.

facies (metamorphic). The pressure and temperature conditions that result in a particular suite of metamorphic minerals.

fault. A break in rock characterized by displacement of one side relative to the other.

feldspar. A group of abundant silicate (silicon + oxygen) minerals, comprising more than 60% of Earth's crust and occurring in all types of rocks.

felsic. Derived from feldspar +silica to describe an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite; also, describes those minerals.

felsite. Any light-colored, fine-grained extrusive igneous or hypabyssal rock composed mostly of quartz and feldspar.

ferric. Of, relating to, or containing iron.

fine-grained. Describes sediment or sedimentary rock and texture in which the individual constituents are too small to distinguish with the unaided eye, specifically sediment or rock whose particles have an average diameter less than 1/16 mm (0.002 in), that is, silt-size particles and smaller. Also, describes a crystalline or glassy rock and texture in which the individual minerals are relatively small, specifically an igneous rock whose particles have an average diameter less than 1 mm (0.04 in).

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

fluvial. Of or pertaining to a river or rivers.

flux. Rock or mineral used in metallurgical processes to lower the fusion temperature of the ore, combine with impurities, and make a fluid slag.

fold. A curve or bend in an originally flat structure, such as a rock stratum, bedding plane, or foliation; usually a product of deformation.

foliation. A preferred arrangement of crystal planes in minerals. Primary foliation develops during the formation of a rock and includes bedding in sedimentary rocks and flow layering in igneous rocks. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas. Secondary foliation develops during deformation and/or metamorphism and includes cleavage, schistosity, and gneissic banding.

footwall. The lower wall of a fault.

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

gabbro. A group of dark-colored, coarse-grained intrusive igneous rocks composed of plagioclase, pyroxene, amphibole, and olivine.

geoarchaeology. The application of concepts and methods of the earth sciences to archaeological problems and vice versa. It provides evidence for the development, preservation, and destruction of archaeological sites, and for regional-scale environmental change and the evolution of the physical landscape, including the impact of human groups.

geodetic surveying. Surveying that takes into account the figure and size of Earth, with corrections made for curvature; used where the areas or distances involved are so great that the desired accuracy and precision cannot be obtained by plane (ordinary field and topographic) surveying.

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

glaciolacustrine. Pertaining to, derived from, or deposited in glacial lakes, especially referring to deposits and landforms composed of suspended material transported by meltwater streams flowing into lakes bordering a glacier.

glaciomarine. Describes the accumulation of glacially eroded, terrestrially derived sediment in a marine environment.

glassy. Describes the texture of certain extrusive igneous rocks that is similar to glass and developed as a result of rapid cooling of the lava, without distinctive crystallization. Synonymous with "vitreous."

gneiss. A foliated metamorphic rock with alternating bands of dark and light minerals. Varieties are distinguished by texture (e.g., augen gneiss), characteristic minerals (e.g., hornblende gneiss), or general composition (e.g., granite gneiss).

Gondwana. The late Paleozoic continent of the Southern Hemisphere and counterpart of Laurasia of the Northern Hemisphere; both were derived from the supercontinent Pangaea.

gradient. A degree of inclination (steepness of slope), or a rate of ascent or descent, of an inclined part of Earth's surface with respect to the horizontal; expressed as a ratio (vertical to horizontal), a fraction (such as m/km or ft/mi), a percentage (of horizontal distance), or an angle (in degrees).

granite. A coarse-grained, intrusive igneous rock in which quartz constitutes 10%–50% of the felsic ("light-colored") components and the alkali feldspar/total feldspar ratio is generally restricted to the range of 65% to 90%; perhaps the best known of all igneous rocks.

granodiorite. A coarse-grained intrusive igneous rock intermediate in composition between quartz diorite and quartz monzonite, containing quartz, plagioclase, and potassium feldspar as the felsic ("light-colored") components, with biotite, hornblende, or, more rarely, pyroxene, as the mafic ("dark-colored") components.

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand; that is, greater than 2 mm (1/12 in) across.

greenschist. A schistose metamorphic rock whose green color is due to the presence of the mineral chlorite, epidote, or actinolite.

groundmass. The finer grained and/or glassy material between the large crystals of an igneous rock. Also, sometimes used for the matrix of a sedimentary rock.

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

hanging wall. The upper wall of a fault.

hematite. An oxide mineral composed of oxygen and iron, Fe_2O_3.

hornblende. A silicate (silicon + oxygen) mineral of sodium, potassium, calcium, magnesium, iron, and aluminum; commonly black and occurring in distinct crystals or in columnar, fibrous, or granular forms in hand specimens.

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks. One of the three main classes or rocks—igneous, metamorphic, and sedimentary.

incision. Downward erosion by a stream, resulting in a deepened channel and commonly a narrow, steep-walled valley.

indurated. Describes a rock or soil hardened or consolidated by pressure, cementation, or heat.

induration. Hardening by heat, pressure, or the introduction of cementing material, especially the process by which relatively consolidated rock is made harder or more compact.

inlet. A small, narrow opening, recess, indentation, or other entrance into a shoreline through which water penetrates into the land; or a waterway entering a sea, lake, or river. Also, a short, narrow waterway between islands, or connecting a bay, lagoon, or similar body of water with a larger body of water.

intertidal. Pertaining to the depth zone between high water and low water; also, pertaining to the organisms of that environment. Synonymous with "littoral."

intrusion. The process of emplacement of magma into preexisting rock. Also, the igneous rock mass formed.

intrusive. Pertaining to intrusion, both the process and the rock body.

island arc. A offshore, generally curved belt of volcanoes above a subduction zone.

isotopic age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products.

jasper. A variety of chert associated with iron ores and containing iron-oxide impurities that give it various colors, especially red.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

kame delta. A flat-topped, steep-sided hill of well-sorted sand and gravel deposited by a meltwater stream flowing into a proglacial or other ice-marginal lake; the proximal margin of the delta was built in contact with a glacier.

keratophyre. A salic extrusive igneous rock formed at shallow depth characterized by the presence of albite or albite-oligoclase and chlorite, epidote, and calcite, all of metamorphic origin.

knickpoint. Any interruption or break in slope.

labradorite. A silicate (silicon + oxygen) mineral of the plagioclase group with the general formula (Ca,Na)(AlSi)4O8.

lacustrine. Describes a process, feature, or organism pertaining to, produced by, or inhabiting a lake.

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

Laurasia. The late Paleozoic continent of the Northern Hemisphere and counterpart of Gonwana of the Southern Hemisphere; both were derived from the supercontinent Pangaea.

lava. Molten or solidified magma that has been extruded though a vent onto Earth's surface.

left-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the left. Synonymous with "sinistral fault."

limb. One side of a structural fold.

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

lithic. Described a medium-grained sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

lithic tuff. A dense deposit of volcanic ash that includes fragments of previously formed rocks that solidified in a vent and were then ejected.

lithification. The conversion of sediment into solid rock.

lithosphere. Earth's relatively rigid outer shell that consists of the entire crust plus the uppermost mantle. It is broken into about 20 plates, and according to the theory of plate tectonics, movement and interaction of these plates is responsible for most geologic activity.

littoral. Pertaining to the depth zone between high water and low water; also, pertaining to the organisms of that environment. Synonymous with "intertidal", but can extend beyond the intertidal.

lodgment till. Successive layers of till plastered beneath a glacier, commonly characterized by a compact fissile structure and stones whose long axes are oriented generally parallel to the direction of ice flow.

mafic. Derived from ***ma***gnesium + ***f***err***ic*** (Fe is the chemical symbol for iron) to describe an igneous rock having abundant dark-colored, magnesium- or iron-rich minerals such as biotite, pyroxene, or olivine; also, describes those minerals.

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

magmatic arc. An arcuate line of plutons, volcanic rocks, or active volcanoes formed at a convergent plate boundary.

magnetite. Iron oxide. An oxide mineral composed of oxygen and iron, Fe_3O_4; commonly contains manganese, nickel, chromium, and titanium. A very common and widely distributed accessory mineral in rocks of all kinds and as a "heavy mineral" in sand.

mantle. The zone of the Earth below the crust and above the core.

marine terrace. A relatively flat-topped, horizontal or gently inclined, surface of marine origin along a coast, commonly veneered by a marine deposit (typically silt, sand, or fine gravel).

mass wasting. Dislodgement and downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity. In contrast to "erosion," the debris removed is not carried within, on, or under another medium. Synonymous with "slope movement."

matrix. The fine-grained material between coarse grains in an igneous or sedimentary rock. Also refers to rock or sediment in which a fossil is embedded.

meander. One of a series of sinuous curves, bends, or turns in the course of a stream, produced by a mature stream swinging from side to side as it flows across its floodplain or shifts its course laterally toward the convex side of an original curve.

mechanical weathering. The physical breakup of rocks without change in composition.

medium-grained. Describes an igneous rock and texture in which the individual crystals have an average diameter in the range of 1 to 5 mm (0.04 to 0.2 in.). Also, describes sediment or sedimentary rock and texture in which the individual particles have an average diameter in the range of 1/16 to 2 mm (0.002 to 0.08 in), that is, sand size.

mélange. A body of jumbled rock that is mappable at a scale of 1:24,000 or smaller and includes fragments and blocks of all sizes embedded in a fragmented and generally sheared matrix.

metamorphic rock. Any rock derived from preexisting rocks that was altered in response to marked changes in temperature, pressure, shearing stress, and chemical environment. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

metamorphism. The mineralogical, chemical, and structural changes of solid rocks, generally imposed at depth below the surface zones of weathering and cementation.

metasedimentary. Describes a sedimentary rock that shows evidence of metamorphism.

metavolcanic. Describes a volcanic rock that shows evidence of metamorphism.

mica. A group of abundant silicate (silicon + oxygen) minerals characterized by perfect cleavage, readily splitting into thin sheets. Examples include "biotite" and "muscovite."

microcrystalline. Describes a rock texture consisting of crystals visible only with a microscope.

mineral. A naturally occurring inorganic crystalline solid with a definite chemical composition or compositional range.

monzonite. An intrusive igneous rock, intermediate in composition between syenite and diorite, containing approximately equal amounts of alkali feldspar and plagioclase and very little quartz. Monzonite contains less quartz and more plagioclase than granite.

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited mostly by direct action of a glacier.

muscovite. A light-colored silicate (silicon + oxygen) mineral of the mica group, $KAl_3Si_3O_{10}(OH)_2$, characterized by perfect cleavage in one direction and the ability to split into thin, clear sheets.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of dip is usually 45°–90°.

obduction. The overriding of oceanic crust onto the leading edge of a continental lithospheric plate.

oblique fault. A fault in which motion includes both dip-slip and strike-slip components.

obsidian. A black or dark-colored volcanic glass, usually of rhyolite composition, characterized by conchoidal fracture.

oceanic crust. Earth's crust that underlies the ocean basins and is rich in iron and magnesium; ranges in thickness from about 5 to 10 km (3 to 6 mi).

olistostrome. A debris-flow deposit consisting of a chaotic mass of intimately mixed heterogeneous materials that accumulated by submarine sliding or slumping in unconsolidated sediments.

olivine. A silicate (silicon + oxygen) mineral of magnesium and iron, $(Mg,Fe)_2SiO_4$; commonly olive-green and an essential mineral in basalt, gabbro, and peridotite.

oligoclase. A silicate (silicon + oxygen) mineral of the plagioclase group, intermediate in chemical composition and crystallographic and physical characteristics between albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$).

orogeny. A mountain-building event.

orthoclase. A colorless, white, cream-yellow, flesh-pink, or gray silicate (silicon + oxygen) mineral of the alkali feldspar group, $KAlSi_3O_8$, characterized by potassium ions in its crystal structure.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

outwash. Glacial sediment transported and deposited by meltwater streams.

overbank deposit. Fine-grained sediment (silt and sand) deposited on a floodplain by floodwaters.

oxidation. The process of combining with oxygen.

oxide. A mineral group composed of oxygen plus an element or elements, for example, iron in hematite, Fe_2O_3; or aluminum in corundum, Al_2O_3.

paleogeography. The study, description, and reconstruction of the physical landscape in past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

Pangaea. A supercontinent that existed from about 300 million to about 200 million years ago and included most of the continental crust of the Earth, from which the present continents were derived by fragmentation and continental drift. During an intermediate stage of the fragmentation—between the existence of Pangaea and that of the present continents—Pangaea split into two large fragments, Laurasia in the Northern Hemisphere and Gondwana in the Southern Hemisphere.

parent material. The unconsolidated organic and mineral material from which soil forms.

parent rock. Rock from which soil, sediment, or other rock is derived.

parting. A plane or surface along which a rock readily separates.

passive margin. A continental plate boundary where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another.

peat. An unconsolidated deposit of semicarbonized plant remains in a water-saturated environment, such as a bog or fen, and of persistently high moisture content (at least 75%). It is an early stage or rank in the development of coal; carbon content is about 60% and oxygen content is about 30% (moisture-free).

pebble. A small rounded rock, especially a waterworn stone, between 4 and 64 mm (0.16 and 2.5 in) across.

pegmatite. An intrusive igneous rock consisting of exceptionally coarse-grained, interlocking crystals, generally granitic in composition and commonly in irregular dikes, lenses, and veins, especially at the margins of batholiths.

plagioclase. A silicate (silicon + oxygen) mineral of the feldspar group that contains both sodium and calcium ions that freely substitute for one another; characterized by striations (parallel lines) in hand specimens.

plastic. Describes a material capable of permanently deforming without rupturing.

plate tectonics. A theory of global tectonics in which the lithosphere is divided into about 20 rigid plates that interact with one another at their boundaries, causing seismic and tectonic activity along these boundaries.

pluton. A deep-seated igneous intrusion.

plutonic. Describes an igneous rock or intrusive body formed at great depth beneath Earth's surface.

potassium feldspar. A feldspar mineral rich in potassium such as orthoclase, microcline, and sanidine.

provenance. A place of origin, specifically the area from which the constituent materials of a sedimentary rock were derived.

pyroclast. An individual particle ejected during a volcanic eruption; usually classified according to size.

pyroxene. A group of silicate (silicon + oxygen) minerals composed of magnesium and iron with the general formula $(Mg,Fe)SiO_3$; characterized by short, stout crystals in hand specimens.

quartz. Silicon dioxide, SiO_2. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen. Synonymous with "crystalline silica."

quartzite. Metamorphosed quartz sandstone. A medium-grained, nonfoliated metamorphic rock composed mostly of quartz.

quartz monzonite. An intrusive igneous rock of granitic composition but with about as much plagioclase as alkali feldspar.

radiometric age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products. The preferred term is "isotopic age."

rebound. Upward flexing of Earth's crust. Synonymous with "upwarping."

regional metamorphism. A type of metamorphism that affects an extensive region, as opposed to local metamorphism that is effective only in a relatively restricted area.

regolith. From the Greek "rhegos" (blanket) + "lithos" (stone), the layer of unconsolidated rock material that forms the surface of the land and overlies or covers bedrock; includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess, and aeolian deposits, vegetal accumulations, and soil.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall.

rhyodacite. A volcanic rock that contains approximately 68%–72% silica and is intermediate in composition between rhyolite and dacite.

rhyolite. A volcanic rock that is characteristically light in color, contains approximately 72% or more of silica, and is rich in potassium and sodium.

riffle. A natural shallows or other expanse of shallow bottom extending across a stream bed over which the water flows swiftly and the water surface is broken into waves by obstructions or a shallow rapids of comparatively little fall.

rift. A region of Earth's crust where extension results in formation of many related normal faults, commonly associated with volcanic activity.

right-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the right.

rill. A very small brook or trickling stream of water usually without any tributaries. Also, the channel formed by such a stream.

roche moutonnée. A glacially sculpted, elongated bedrock knob or hillock.

rock. An aggregate of one or more minerals (e.g., granite), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

rockfall. The most rapid type of slope movement in which a newly detached fragment of bdrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

sandstone. Clastic sedimentary rock composed of predominantly sand-sized grains.

schist. A medium- to coarse-grained, strongly foliated, metamorphic rock with eminently visible mineral grains, particularly mica, which are arranged parallel, imparting a distinctive sheen, or "schistosity," to the rock.

schistosity. The foliation in schist or other coarse-grained, crystalline rock resulting from the parallel alignment of platy mineral grains of mica or inequant crystals of other minerals.

scour. The powerful and concentrated clearing and digging action of flowing water, air, or ice.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

seismic. Pertaining to an earthquake or Earth vibration, including those that are artificially induced.

seismicity. The phenomenon of movements in the Earth's crust. Synonymous with "seismic activity."

sericite. An alteration product of various aluminosilicate minerals—specifically a white, fine-grained potassium mica, usually muscovite or very close to muscovite in composition—occurring as small scales and flakes in metamorphic rocks.

shale. A clastic sedimentary rock made of clay-sized particles and characterized by fissility.

shear. Deformation resulting from stresses that cause contiguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact.

silica. Silicon dioxide, SiO_2, an essential constituent of many minerals, occurring as crystalline quartz, cryptocrystalline chalcedony, and amorphous opal.

silicate. A mineral group composed of silicon (Si) and oxygen (O) plus an element or elements, for example, quartz, SiO_2; olivine, $(Mg, Fe)_2SiO_4$; and pyroxene, $(Mg,Fe)SiO_3$; as well as the amphiboles, micas, and feldspars.

siliciclastic. Describes noncarbonate clastic rocks.

silicic magma. Describes magma that contains more than 65% silica; generally viscous, gas-rich, and tends to erupt explosively.

siliceous. Describes a rock or other substance containing abundant silica.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

slate. A fine-grained, foliated metamorphic rock that easily splits into slabs and thin plates.

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slope movement. The gradual or rapid downslope movement of soil or rock under gravitational stress. Synonymous with "mass wasting."

slump. A generally large, coherent slope movement with a concave failure surface and subsequent backward rotation relative to the slope.

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

sorted. Describes an unconsolidated sediment consisting of particles of essentially uniform size.

sorting. The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation.

sphene. A usually yellow or brown accessory mineral in granitic rocks and in calcium-rich metamorphic rocks; also called titanite.

storm surge. An abnormal, sudden rise of sea level along an open coast during a storm, caused primarily by strong winds offshore, or less frequently, a drop in atmospheric pressure, resulting in water piled up against the coast. It is most severe during high tide.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of stream water.

striation (glacial). One of a series of long, delicate, finely cut, commonly straight and parallel furrows or lines inscribed on a bedrock surface by the rasping and rubbing of rock fragments embedded at the base of a moving glacier, usually oriented in the direction of ice movement; also form on the rock fragments transported by a glacier.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Described as left-lateral (sinistral) when relative motion of the block opposite the observer is to the left, and right-lateral (dextral) when relative motion is to the right.

subduction. The process of one lithospheric plate descending beneath another.

suture. The linear zone where two continental landmasses become joined via obduction.

syncline. A generally concave upward fold of which the core contains the stratigraphically younger rocks.

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

terrace. Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

terrane. A fault-bounded body of rock of regional extent, characterized by a geologic history different from that of contiguous terranes or bounding continents.

thrust fault. A dip-slip fault with a shallowly dipping (less than 45°) fault surface where the hanging wall moves up and over relative to the footwall.

till. Unstratified drift deposited directly by a glacier without reworking by meltwater and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

tonalite. An intrusive igneous rock composed primarily of quartz and plagioclase with 10% or less alkali feldspar.

trace (structural geology). The intersection of a geological surface with another surface, for example, the trace of bedding on a fault surface, or the trace of a fault or outcrop on the ground.

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

trend. The direction or bearing of an outcrop of a geologic feature such as an ore body, fold, or orogenic belt.

tuff. Consolidated or cemented volcanic ash and lapilli.

type locality. The place where a geologic feature such as an ore occurrence, a particular kind of igneous rock, or the type specimen of a fossil species was first recognized and described.

ultramafic. Describes an intrusive igneous rock primarily composed of mafic minerals.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, resulting from either a change that caused deposition to cease for a considerable span of time or erosion with loss of the previously formed record.

undercutting. The removal of material at the base of a steep slope by the erosive action of water (such as a meandering stream), sand-laden wind in a desert, or waves along a coast.

uplift. A structurally high area in Earth's crust produced by movement that raises the rocks.

upwarping. Upward flexing of Earth's crust on a regional scale as a result of the removal of ice, water, sediments, or lava flows.

vent. Any opening at Earth's surface through which magma erupts or volcanic gases are emitted.

vitreous luster. Luster that resembles glass. Synonymous to "glassy."

vitric. Describes pyroclastic material that is characteristically glassy.

volcanic. Pertaining to the activities, structures, or rock types of a volcano. A synonym of extrusive.

volcanic arc. A large-scale (hundreds of kilometers) generally curved belt of volcanoes above a subduction zone.

volcanism. The processes by which magma and its associated gases rise into Earth's crust and are extruded onto the surface and into the atmosphere.

weathering. The physical, chemical, and biological processes by which rock is broken down, particularly at Earth's surface.

welding. Consolidation of sediments under pressure. Also, the diagenetic process whereby discrete crystals and/or grains become attached to each other during compaction

Wisconsinan. Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America, following the Sangamonian interglacial stage and preceding the Holocene Epoch.

xenolith. A rock particle, formed elsewhere, entrained in magma as an inclusion.

zircon. A very durable silicate mineral (silicon + oxygen), $ZrSiO_4$. When cut and polished, the colorless variety provides exceptionally brilliant gemstones.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of January 2015. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm.

NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/

NPS Resource Management Guidance and Documents

1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm

US Global Change Research Program: http://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

Massachusetts Geological Survey: http://www.geo.umass.edu/stategeologist/

US Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geophysical Union: http://sites.agu.org/

American Geosciences Institute: http://www.americangeosciences.org/

Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

National geologic map database (NGMDB): http://ngmdb.usgs.gov/

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”)

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Saugus Iron Works National Historic Site, held on 11 July 2007, or the follow-up report writing conference call, held on 21 May 2014. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2007 Scoping Meeting Participants

Name	Affiliation	Position
Marc Albert	NPS Saugus Iron Works NHS & Boston Harbor Islands NRA	Natural resource specialist
Tim Connors	NPS Geologic Resources Division	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist
Chris Hepburn	Boston College	Geologist
Joe Kopera	University of Massachusetts, Amherst	Geologist
Steve Mabee	University of Massachusetts, Amherst	State Geologist
Brian Mitchell	NPS Northeast Temperate Network	Network Coordinator
Lou Siderus	NPS Minute Man NHS	Planning chief
Meg Thompson	Wellesley College	Geologist
Trista Thornberry-Ehrlich	Colorado State University	Geologist, Report writer
Suzanne Wall	Andover Geologic Consulting	Geologist
Don Wise	University of Massachusetts, Amherst	Geologist

2014 Conference Call Participants

Name	Affiliation	Position
Marc Albert	NPS Saugus Iron Works NHS & Boston Harbor Islands NRA	Natural Resource lead
Gregg Bailey	NPS Saugus Iron Works NHS	Seasonal ranger
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Trista Thornberry-Ehrlich	Colorado State University	Geologist, Writer, Graphic designer

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of January 2015. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC. § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands.	**36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (December 2013).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC. §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and -Only for park administrative uses. -After compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment. -After finding the use is park's most reasonable alternative based on environment and economics. -Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan. -Spoil areas must comply with Part 6 standards -NPS must evaluate use of external quarries. Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director.
Soils	**Soil and Water Resources Conservation Act, 16 USC. §§ 2011 – 2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC. § 4201 *et. seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 C.F.R. Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -Prevent unnatural erosion, removal, and contamination. -Conduct soil surveys. -Minimize unavoidable excavation. -Develop/follow written prescriptions (instructions).

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 16 USC. § 1 *et. seq.*** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC. § 1451 *et. seq.*** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC. § 1342/Rivers and Harbors Act, 33 USC. 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 C.F.R. § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 C.F.R. § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC. § 403** prohibits the construction of any obstruction, on the waters of the united states, not authorized by congress or approved by the USACE. **Clean Water Act 33USC. § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US (including streams)). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also D.O. 77-2) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None Applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

NPS 444/128233, March 2015

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

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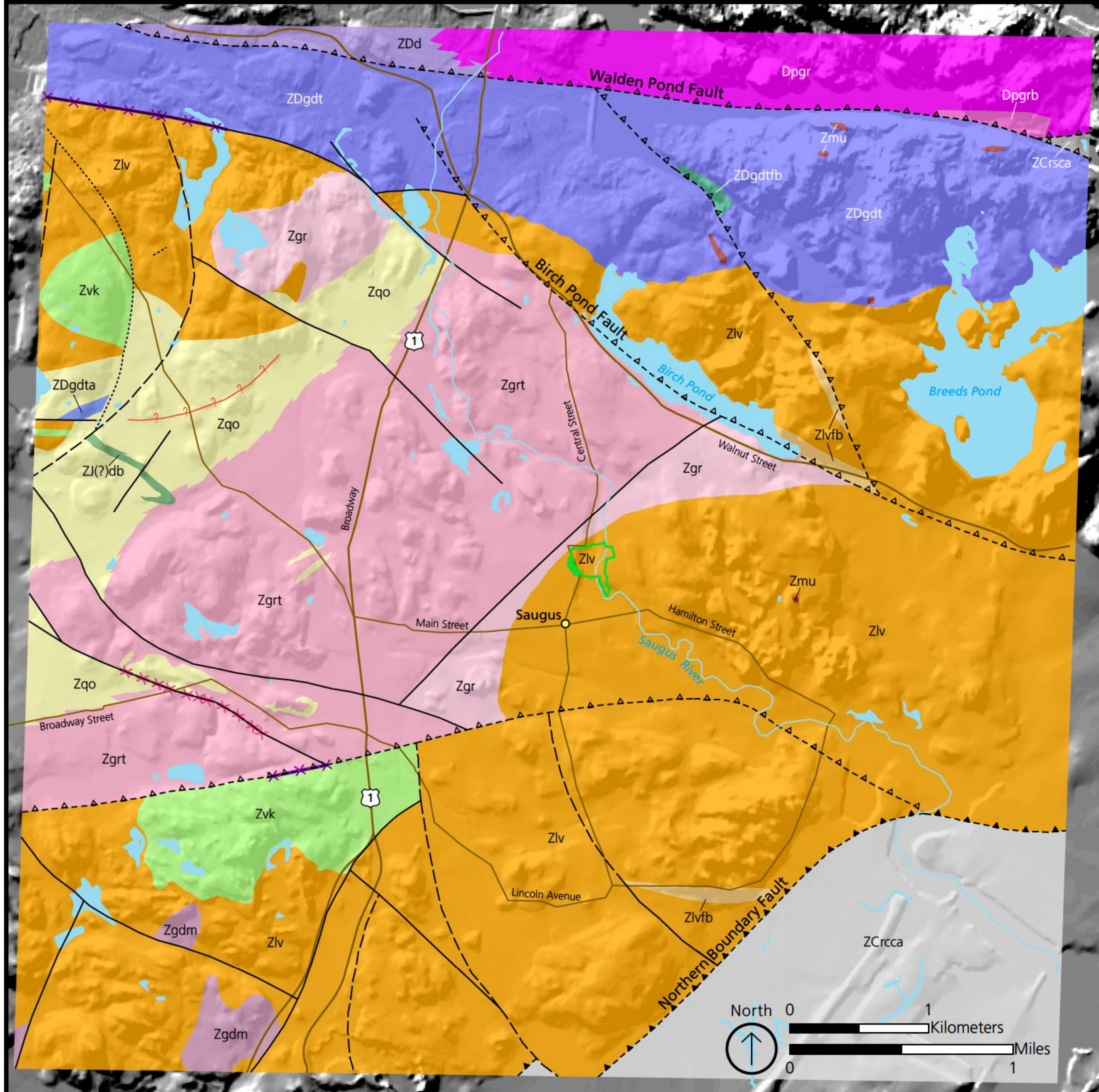
Geologic Map of Saugus Iron Works National Historic Site

Massachusetts

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory



NPS Boundary

Infrastructure
- cities
- roads

Folds
- antiform, queried

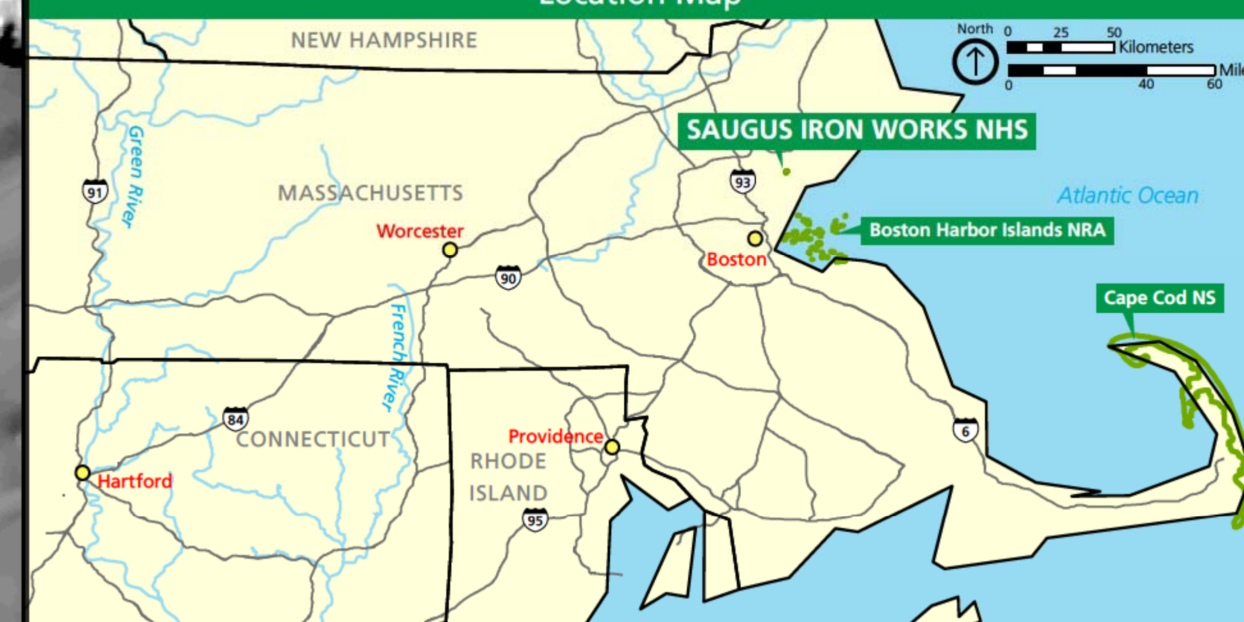
Faults
- thrust fault, inferred
- reverse fault, short dashed where inferred and long dashed where approximate
- right-lateral strike-slip fault, short dashed where inferred and long dashed where approximate
- left-lateral strike-slip fault, approximate
- unknown offset/displacement, solid where known, short dashed where inferred, and long dashed where approximate

Linear Dikes
- unknown unit, known or certain
- unknown unit, approximate

Geologic Units

	water
ZJ(?)db	Diabase dike with magnetite (Proterozoic? to Jurassic?)
Dpgr	Peabody Granite (Devonian)
Dpgrb	Peabody Granite, brecciated (Devonian)
ZDd	Quartz-diorite and diorite (Proterozoic to Devonian)
ZDgdta	Aplitic granodiorite (Proterozoic to Devonian)
ZDgdt	Tonalite to granodiorite (Proterozoic to Devonian)
ZDgdtfb	Tonalite to granodiorite, fault breccia (Proterozoic to Devonian)
ZCrcca	Roxbury Conglomerate and Cambridge Argillite, undifferentiated (Neoproterozoic to Lower Cambrian)
ZCrsca	Argillacious sandstone and siltstone and CambridgeArgillite, undifferentiated (Neoproterozoic to Lower Cambrian)
Zvk	Quartz keratophyre and keratophyre (Neoproterozoic)
Zlv	Lynn Volcanics (Neoproterozoic)
Zlvfb	Lynn Volcanics, fault breccia (Neoproterozoic)
Zqo	Quartzite and Olistostromal Assemblage (Proterozoic)
Zmu	Mafic metavolcanic xenoliths of unknown affinity (Proterozoic)
Zgrt	Trondhjemite (Proterozoic)
Zgdm	Granodiorite to quartz monzonite (Proterozoic)
Zgr	Granitoidal rocks, undifferentiated (Proterozoic)

Location Map



This map was produced by Kari Lanphier (Colorado State University) in February 2014. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source map used in creation of the digital geologic data was:

Kopera, J. P. 2011. Preliminary compilation of bedrock geology in the vicinity of Saugus Iron Works National Historic Site. 1:24,000 scale. Unpublished map and report. Massachusetts Geological Survey, Amherst, Massachusetts.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 12 m (40 ft) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

Map Unit Properties Table: Saugus Iron Works National Historic Site

Colored map units are mapped within Saugus Iron Works National Historic Site. Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PROTEROZOIC? TO JURASSIC?	Diabase dike with magnetite (**ZJ(?)db**)	Diabase is an intrusive igneous rock with a relatively low silica content whose primary mineral constituents are labradorite and pyroxene. In the Saugus Iron Works area, **ZJ(?)db** is fine to medium grained, black to gray, with light brown weathered surfaces. Prominent, scattered magnetite crystals give rock surfaces a sandy texture. Locally, dikes are oriented east to west with some sets trending north to south. Weathered surfaces of **ZJ(?)db** have erratic magnetic polarization, possibly due to modern lightning strikes.	**Igneous Rocks**—**ZJ(?)db** is part of a suite of intrusive igneous dikes in the Saugus area and throughout eastern Massachusetts.	None reported	**Pangaea Rifts Apart and Weathering Commences**—some of **ZJ(?)db** may be associated with the rifting apart of Pangaea during the Mesozoic, but relative age relationships with rocks at some outcrops suggest a Proterozoic age.
DEVONIAN	Peabody Granite (**Dpgr**) Peabody Granite, brecciated (**Dpgrb**)	"Granite" denotes a specific intrusive igneous rock composition characterized by relatively high silica contents, rich in quartz (10 to 50%) and with more alkali feldspars than granodiorite. Other minerals include plagioclase, muscovite, biotite and/or hornblende. In the Saugus Iron Works area, **Dpgr** and **Dpgrb** are coarse grained with a light pinkish gray color. Orthoclase (alkali feldspar) composes up to 55% of the total rock, quartz is between 42% and 53%, with trace amounts of augite and riebecktite minerals. Very few alteration textures seen in **Dpgr**. **Dpgrb** is broken into a chaotic mix of grains surrounded be a fine-grained matrix associated with deformation along local fault zones.	**Faults**—**Dpgrb** is a mappable zone of intensely deformed rocks along major local faults. **Igneous Rocks**—**Dpgr** is a distinctive, discrete member of a suite of intrusive igneous rocks in the Saugus area. **Radiometric Age Dates**—**Dpgr** is 378±0.62 million years old and 395±2 million years old by Uranium-Lead series dating.	None reported	**Mountain Building, Terrane Accretion, and the formation of a Supercontinent**—**Dpgr** may have been emplaced during the continental collisions of the Acadian Orogeny, one of three major orogenies that built the Appalachian Mountains. After its emplacement, zones of **Dpgrb** formed during mountain-building orogenies, most likely the Alleghany Orogeny.
PROTEROZOIC TO DEVNONIAN	Quartz-diorite and diorite (**ZDd**)	Diorite is a relatively silica-poor (mafic) igneous rock with moderate silica content with plagioclase feldspar, hornblende, and biotite with only scant quartz. Locally, **ZDd** is fine to medium grained, dark gray to black with abundant, shiny black biotite crystals. Dark minerals compose about 50% of the total rock. Primary mineral constituents include albite, quartz, orthoclase, biotite, hornblende, diopside, apatite, and ilmenite. Very little secondary alteration occurs in **ZDd**. Injections of red alkali-feldspar granite and pegmatite occurred locally. **ZDd** includes bodies of gabbro. Gabbro was used as a flux agent in the iron works operations at Saugus.	**Radiometric Age Dates**—age dates for **ZDd** include 392±4 million years old, 488.53±0.81 million years old, and 488.48±0.79 million years old (all using Uranium-Lead series dating technique). Additional correlation and dating are necessary to determine the age and relationships among the many diorites and gabbroic intrusive rocks in northeastern Massachusetts.	None reported	**Mountain Building, Terrane Accretion, and the formation of a Supercontinent**—the timing of formation of these units is not well constrained. They are part of a suite of igneous intrusive rocks that compose the Avalon terrane. After emplacement of **ZDgdt**, zones of **ZDgdtfb** formed during mountain-building orogenies.
	Aplitic granodiorite (**ZDgdta**)	"Granodiorite" refers to an igneous intrusive rock that is typically coarse grained and dominated by quartz, plagioclase, and potassium feldspar minerals with some biotite and hornblende as the minor, dark-colored mineral components. The term aplitic refers to the texture of the rock, in this case resembling sugar without significant dark minerals or flaky mica grains. In the Saugus Iron Works area, **ZDgdta** is very fine grained and a light pinkish gray color. It resembles **ZDgdt** in composition, but with a much finer texture.	**Igneous Rocks**—**ZDgdta** is part of a suite of intrusive igneous rocks in the Saugus area.		
	Tonalite to granodiorite (**ZDgdt**) Tonalite to granodiorite, fault breccia (**ZDgdtfb**)	Tonalite is a silica-rich (felsic) intrusive igneous rock with a specific composition rich in plagioclase and quartz, but with little potassium feldspar or mica minerals. Granodiorite is described under **ZDgdta**. In the Saugus Iron Works area, **ZDgdt** is fine grained and light to dark gray with uniformly shaped crystals. Mineral constituents include oligoclase (25–55%), orthoclase or microcline (0–15%), quartz (30–60%), hornblende, and biotite. Many primary minerals are altered and/or strained. **ZDgdtfb** is broken into a chaotic mix of grains surrounded be a fine-grained matrix associated with deformation along local fault zones.	**Faults**—**ZDgdtfb** is a mappable zone of intensely deformed rocks along major local faults. **Igneous Rocks**—**ZDgdt** is part of a suite of intrusive igneous rocks in the Saugus area.		

Colored map units are mapped within Saugus Iron Works National Historic Site. Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
NEOPROTEROZOIC TO LOWER CAMBRIAN	Boston Bay Group: Roxbury Conglomerate and Cambridge Argillite, undifferentiated (**ZCrcca**)	"Argillite" is a general term for a compact rock derived from mudstone, siltstone, and/or shale that has been slightly metamorphosed, but lacks strong cleavage or fissility (propensity to break or splinter along planes). **ZCrcca** and **ZCrsca** are not well exposed in the Saugus Iron Works area. The lowermost members consist of pebble to cobble conglomerate with rare boulders and thick, massive bedding. Clast types include volcanic rocks, quartzite, and granite surrounded by a sandstone to argillite matrix. The conglomerate grades upward into an argillite dominated by gray, buff, to locally purple sandstones, quartzites, and siltstones. Diamictites, or pebbly to conglomeratic mudstones, occur within the argillite. Bedding structures range from laminated to massive.	**Sedimentary Rocks**—flat-lying pebbles indicate the plane of bedding in the conglomerate. Diamictites are terrestrial rocks of mixed size, unrounded, and unsorted clasts with enigmatic origins. Generally, they are rocks whose sediments are derived very closed to their source. They may record deposition of till during an ancient glaciation or landslide deposits. **Radiometric Age Dates**—a volcanic ash bed within the Cambridge Argillite was dated to 570 million years ago using Uranium-Lead series dating of zircons. **Paleontological Resources**—the Cambridge Argillite contains acritarch microfossils common at the end of the Neoproterozoic.	None reported	**Formation of the Avalon Terrane and its Detachment from Gondwana**—The Boston Basin opened as a rift valley when the Proterozoic supercontinent Rodinia broke apart. The lowermost beds of the Boston Bay Group are younger than 593 million years. The Boston Basin collected sediments into the Early Cambrian.
	Boston Bay Group: Argillaceous sandstone and siltstone and Cambridge Argillite, undifferentiated (**ZCrsca**)				
NEOPROTEROZOIC ERA	Quartz keratophyre and keratophyre (**Zvk**)	A keratophyre is a metamorphic rock dominated by sodium-rich feldspar, chlorite, epidote, and calcite. Keratophyres tend to occur in association with marine sediments and submarine basalts. **Zvk** occurs as massive flows, breccias, pillow lavas, and laminated devitrified (crystallized glass) palagonite-tuff. They intergrade with **Zlv** to the east.	**Volcanic Rocks**—**Zvk** contains pillow lavas indicating submarine volcanism.	None reported	**Formation of the Avalon Terrane and its Detachment from Gondwana**—**Zvk** was deposited as a mix of volcanic and marine sedimentary layers atop a subduction zone that also gave rise to many of the intrusive igneous rocks in the area during the time the Avalon terrane was forming on the northwestern edge of Gondwana.
	Lynn Volcanics (**Zlv**)	Rhyolite is an extrusive igneous rock with a mineralogical composition similar to granite. Textures include visible crystals in a glass to cryptocrystalline groundmass. If the alkali feldspar component decreases, rhyolite grades into rhyodacite. **Zlv** comprises rhyolite and rhyodacite flows, welded-ash flows, flow breccias, breccia pipes, extrusion domes, and vitric, lithic, and lapilli tuffs. **Zlv** appears black, red, white, cream, and shades of reddish and greenish gray. Bedding of successive flows is generally massive with some fine flow lamination in welded ash flows. **Zlvfb** consists of areas of **Zlv** which have been extensively faulted into a heterogeneous mix of large clasts in an extremely fine-grained fault gouge matrix. **Zlv** is the only geologic map unit within Saugus Iron Works National Historic Site.	**Fluvial Features and Processes**—**Zlv** forms part of the fall line that causes higher energy flow of the Saugus River. **Faults**—**Zlvfb** is a mappable zone of intensely deformed rocks along major local faults. **Volcanic Rocks**—features such as welded-ash flows, tuffs, flow breccias, and breccia pipes record silica-rich, explosive volcanism. **Radiometric Age Dates**—Uranium-Lead series dating of **Zlv** rhyolite exposed within Aggregate Industries quarry in Saugus indicates an age of 596 million years ago.	**Coastal Vulnerability to Sea-Level Rise and Climate Change**—**Zlv** underlies the entirety of Saugus Iron Works National Historic Site. Surficial geologic map coverage, including the depth to bedrock (**Zlv**) would be a valuable dataset for modeling the river channel's response to sea-level rise. This mapping would both delineate how the system responded to sea level fluctuations in the past, and determine the exact composition of the substrate, which would in turn help understand how it may react to factors such as increased erosion, water saturation, and tidal changes. **Disturbed Lands and Mineral Extraction**—**Zlv** is mined as aggregate material southwest of Saugus Iron Works National Historic Site.	**Formation of the Avalon Terrane and its Detachment from Gondwana**—**Zlv** was deposited by a volcanic arc atop a subduction zone that also gave rise to many of the intrusive igneous rocks in the area during the time the Avalon terrane was forming on the northwestern edge of Gondwana. **Zlv** is locally in fault contact with the Boston Bay Group (**ZCrcca** and **ZCrsca**), but elsewhere show a gradational, conformable relationship. **Zlv** is the extrusive (volcanic) equivalent of granitic-composition rocks emplaced between 625 million and 590 million years ago. **Zlv** lies nonconformably on rocks of **Zgr**, **Zgdm**, **ZDgdt**, and **Zgrt**. After its emplacement, zones of **Zlvfb** formed during mountain-building orogenies.
	Lynn Volcanics, fault breccia (**Zlvfb**)				
PROTEROZOIC EON	Quartzite and Olistostromal Assemblage (**Zqo**)	An olistostrome is the rock resulting from underwater landslides or slumping of unconsolidated sediments characterized by a chaotic mass of intermixed heterogeneous materials. **Zqo** consists of dark, metamorphosed siltstones, mudstones, and very fine-grained sandstones. Parts of Zqo are slump folded and contain irregular masses of meta-quartzarenite (olistostromes). The olistostromes contain massive, moderately to well-sorted, medium-grained, muscovitic (mica-rich) quartzite. Extensive faulting separates **Zqo** into uncorrelatable blocks.	**Sedimentary Rocks**—olistostromes record submarine slope movements. **Radiometric Age Dates**—Uranium-Lead series dating of zircons at the type locality indicates **Zqo** was deposited about 600 million years ago.	None reported	**Formation of the Avalon Terrane and its Detachment from Gondwana**—In the Saugus Iron Works area, **Zqo** is intruded by **Zgr**, **Zgdm**, **ZDgdt**, and **Zgrt (**members of the "Dedham" granite), meaning that **Zqo** is older than those units.

Colored map units are mapped within Saugus Iron Works National Historic Site. Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PROTEROZOIC EON	Mafic metavolcanic xenoliths of unknown affinity (**Zmu**)	A mafic xenolith is a fragment of silica-poor, iron- and magnesium-rich rock within an intrusive igneous rock mass. **Zmu** occurs as mappable blocks within **ZDgdt** and **Zlv**. The xenoliths are characterized by fine-grained, dark gray to greenish gray or black mafic metavolcanic rocks. The major mineral constituents include plagioclase (30–50%), hornblende (50–70%), and opaque minerals that are equigranular or roughly equivalent in size. Irregular clots and veinlets of granite, quartz, and epidote occur throughout the xenoliths.	**Metamorphic Rocks**—**Zmu** exhibits metamorphic foliation (or banding of aligned minerals) that parallels adjacent bedding or layering structures in the surrounding rocks.	None reported	**Formation of the Avalon Terrane and its Detachment from Gondwana**—**Zmu** xenoliths are found within **ZDgdt** and **Zlv** meaning **Zmu** is older than **ZDgdt** or **Zlv**.
	Trondhjemite (**Zgrt**)	Trondhjemite is a light-colored, intrusive igneous rock rich in sodic plagioclase (oligoclase), quartz, sparse biotite, and little to no alkali feldspar. It is named for a city in Norway. In the Saugus Iron Works area, **Zgrt** is coarse grained, light gray with many deformation features. Compositionally, oligoclase is about 50%, orthoclase is less than 10%, and quartz is about 40% of the rock. **Zgrt** is altered with oligoclase becoming sericite, strained quartz, hornblende becoming chlorite, and biotite becoming chlorite.	**Igneous Rocks**—These units are part of a suite of intrusive igneous rocks in the Saugus area.	None reported	**Formation of the Avalon Terrane and its Detachment from Gondwana**—**Zgrt** intrudes the surrounding volcanic rocks meaning that is it younger than those rocks.
	Granodiorite to quartz monzonite (**Zgdm**)	"Monzonite" refers to an intrusive igneous rock composed primarily of equal amounts of alkali feldspar and plagioclase, scant quartz, and augite as the primary dark-colored mineral. Granodiorite is described under **ZDgdta**. Locally, **Zgdm** is fine- to medium-grained light gray to pink and green in color. Approximately 50% of the rock is oligoclase, orthoclase (an alkali feldspar) is 20–40%, quartz is 20–30%. **Zgdm** is highly altered with chlorite, epidote, sericite, and sphene as secondary minerals.			**Formation of the Avalon Terrane and its Detachment from Gondwana**—**Zgdm** intrudes the surrounding volcanic rocks meaning that is it younger than those rocks. In some places, the relationship appears nonconformable and thus the timing of its emplacement relative to **Zlv** is locally unclear.
	Granitoidal rocks, undifferentiated (**Zgr**)	The term "granitoids" refers to general bodies of intrusive igneous rocks dominated by quartz and feldspars. In the Saugus Iron Works area, **Zgr** consists of fine- to coarse-grained, alkali granite to gabbro in colors varying between light and dark. **Zgr** includes bodies of gabbro. Gabbro was used as a flux agent in the iron works operations at Saugus.			**Formation of the Avalon Terrane and its Detachment from Gondwana**—**Zgr** was part of a series of igneous intrusions that formed part of the Avalon Terrane when it was still attached to the northwestern edge of Gondwana during the Proterozoic.