Transfer of blast-furnace finery-forge technology to New England

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ABSTRACT: John Winthrop Jr brought industrial-scale ironmaking to Massachusetts for the London-based Undertakers of Ironworks in New England beginning with a blast furnace blown-in at Braintree in 1645 followed by a nearby finery forge. Within a year a new location for the furnace was sought and the Braintree furnace abandoned for reasons never satisfactorily explained. Archaeological evidence now shows that inadequate, unreliable waterpower caused the failure at Braintree, locates the site of the finery forge, and demonstrates that a blast furnace built near the forge would have succeeded. Winthrop's preoccupation with alchemy and pansophy contributed to the failure of the Braintree furnace. The resulting loss of the Undertakers' capital left the replacement works at Saugus burdened with debt. Winthrop's 1657 second blast-furnace finery-forge project made iron but not profits for the New Haven Colony. Only in the mid-18th century was this technique successfully revived in New England.

Introduction

The Massachusetts Bay Colony prospered through its first decade as new immigrants brought in a steady flow of wealth. When in 1642 civil war in England stopped this flow, the colony's exports of fish and timber no longer balanced the cost of the imports of English manufactured products the colonists relied on. Aware of the scarcity of fuel for ironmaking in England, the Massachusetts legislature decided that export of iron made with the colony's abundant forest resources could be a new source of revenue. To make this happen they turned to their governor's son, John Winthrop Jr, who had a long-standing interest in exploiting New England's natural resources and had been sending mineral samples to European friends for analysis (Woodward 2010, 80). The colony's General Court made Winthrop its agent and in 1641 sent him to England to recruit investors and artisans to transfer industrial-scale ironmaking to Massachusetts. By 1643 he had 24 shareholders organized as the Company of Undertakers of the Ironworks in New England with about £1,000 capital to build a blast furnace, finery forge and slitting mill in Massachusetts. Among the shareholders four, John Becx, Lionel Copley, Thomas Foley, and Joshua Foote owned ironworks in England or Ireland. For the others it was just an investment (Hartley 1957, 69). Winthrop sailed from London in June with a team of experienced artisans to transfer this ironmaking technology (Black 1966, 119).

After a tedious, nearly four-month trans-Atlantic passage Winthrop and his artisans reached Boston in September (Winthrop 1882). Once recovered from the deprivations of the voyage, he with several of his experienced furnace men set about finding a site for the transplanted ironworks, a challenge in lightly explored country. The site had to have access to construction materials, except hearth stones, which were to be brought from England. Wood for coaling was widely available in heavily forested New England. Nearby deposits of ore and flux sufficient for years of production were needed, as was reliable waterpower for the furnace and forge. Accommodation for the ironworks staff had to be built if the works were on common land, or land purchased near established communities. Economically accept-

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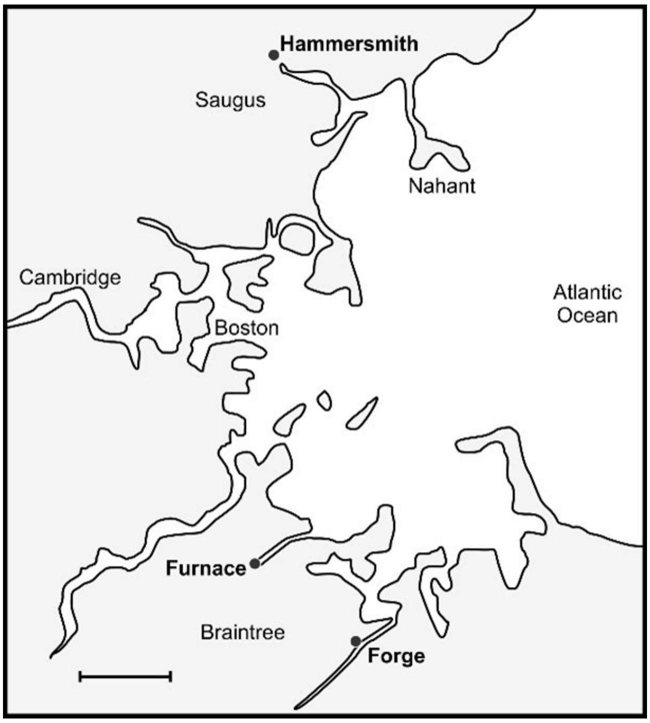

Figure 1: Location map of the area round Boston, Massachusetts showing places mentioned in the text. Scale bar 3 km.

able transportation routes for the natural resources and ironworks products were needed. Balancing these requirements, critical to the success of the enterprise, was a challenge.

Winthrop with his English artisans explored from present-day Maine south toward the Plymouth Colony in their site search. By the spring of 1644 it was time to decide on a location for the blast furnace. When Winthrop found the transition from exploration to decision challenging he drafted his 'Discourse about the fittest place to begin ye ironworks,' (Winthrop R 1892-4, 13-14). The place chosen had to be 'well viewed and considered by the workmen both for the ore & conveniency of waters for the furnace & forge & woods for the supply of coals to both works.' (He did not mention flux for the furnace.) Braintree had been so viewed and considered. But since it was already a settled community there would be expense in acquiring the necessary land, which the Undertakers had not anticipated. So should the works be closer to the unsettled frontier where land was free? He thought not as he made his case: 'If Braintree be thought best, this helps: we shall have workmen of all sorts more plenty and near at hand, teams for carriage may be hired, housing for our workmen near to be hired and wood enough for the present to be procured here by purchase and for the future to belong to the works to be fetched further off.' He had talked himself into the choice of the Braintree site (Fig 1) without mention of waterpower or natural resources other than ore that might be available there. He purchased two hundred acres for the furnace site.

This done, the English ironworkers and local labour completed the furnace and blew it in by May of 1645. Construction of the finery forge, to be located somewhere on the Monatiquot River, 4km from the furnace, might have been started. As expenses at Braintree mounted toward £1500 the General Court granted the Undertakers a monopoly on ironmaking and made an unsuccessful attempt to bring in Massachusetts adventurers, only to find that few colonists would invest in an ironworks they thought others were going to build for them. When the London Undertakers learned that Winthrop needed another £1500 to finish the forge (Pattee 1879, 454) and intended to leave Braintree for New London, they appointed Richard Leader as their agent in his place. Upon arrival in the spring of 1645, just as the blast furnace began making iron, Leader's inspection revealed that the site chosen for it by Winthrop was so unsuitable that he had to find a new location at once. By the end of the year he had secured land on the Saugus River for a new ironworks with a better water supply, that was called 'Hammersmith' when completed (Hartley 1957, 126). The Braintree furnace could then be abandoned.

Braintree archaeology

George C Whitney made the earliest recorded exploration of the Braintree blast-furnace site (Whitney 1827, 50). A 1729 realignment of town lines had placed it in the city of Quincy. Whitney, who apparently had never seen a blast furnace, found what he described as a 'cavern depth about 8 feet, width about 6 feet with an entrance way of 3 feet wide with walls of stone that had been exposed to great heat.' This was a good match to the interior of a typical 17th-century blast furnace (Linsley and Hetherington 1978). The Braintree builders had closely followed established English practice. Whitney also noted a small dam on the stream above the furnace, and that local residents knew ore had once been hauled from a mine 'about a mile' away.

The surviving approximately-2m-high remains of the furnace gradually fell into ruin until construction of a cemetery in 1841 buried them. Reawakened community pride in the 1950s led to competing claims by Massachusetts towns as the site of America's first successful blast furnace. The editor of a Quincy newspaper arranged for Roland Robbins to find the by-then lost furnace site (Edwards 1954, 214). He did, on Furnace Brook, at 42.2458N 71.0010W, where it can be seen now on satellite images.

Robbins used heavy equipment supplied by the city in 1956 to uncover the base of the furnace, its casting bed, and part of the wheelpit and tail race (Linebaugh 2000). The furnace had a 6.7m by 7.3m base, a blowing and a casting arch, and had been about 6m high, as shown by the probable location of the upper end of the charging bridge. Underground drains built beneath the hearth followed established English practice. Robbins uncovered a pig casting bed 4.5m long by 1.2m wide filled with sand about 0.5m deep and, nearby, evidence of cast-ware moulds. He concluded that an overshot wheel about 5m in diameter drove the air-blast bellows. Because the furnace site was then, and still is, closely surrounded by urban and industrial development no trace of the dam Whitney observed in 1827 survived. With this brief excavation completed the city placed fill on the remains leaving only a few courses of the furnace base exposed.

Leader completed the Braintree forge while he was building the entirely new ironworks at Saugus. The existing record of the forge location is John Winthrop's diary entry for 4 December 1645, made after a return journey from Connecticut, 'Passed over the Monotaquid at twilight. Came by the direction of the noise of the falls at the forge' (Winthrop R 1892-4, 12). Removal of dams in the 18th century to facilitate migration of anadromous fish in the Monatiquot followed by urban development destroyed the forge site. Evidence of its location was found a few years before 1898 but, unrecognized for what it was, remained unreported. Workmen digging a well in Quincy had encountered an undisturbed layer of slag and then, a few years later, iron bars at a depth of 1.3m in a trench dug for water-pipes on Adams Street (Bates 1898, 18). Bates thought these features showed the location of the Braintree blast furnace, then in dispute, when in fact they show the forge was located near the intersection of today's Middle and Adams Streets, approximately at 42.224N 70.996W, 3.7km from the furnace (Fig 2).

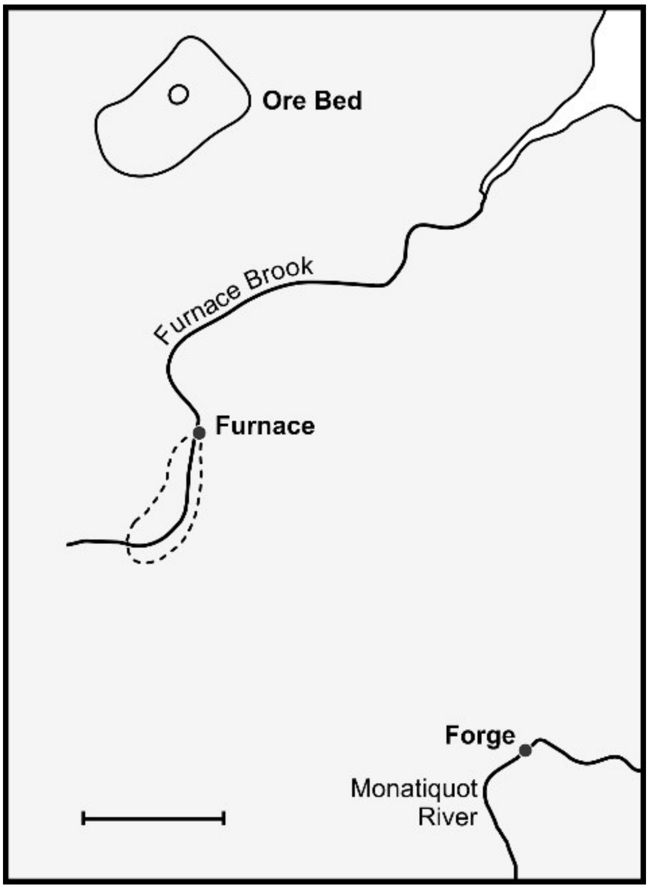

Figure 2: Braintree ironworks locations showing the blast furnace on Furnace Book, the forge on the Monatiquot River, and the probable location of the ore mine. Dashed outline shows the furnace pond that may have existed. Scale bar 1km.

Waterpower at the Braintree furnace and forge

Winthrop built the Braintree furnace on the Mount Wollaston River, later known as Furnace Brook. When E N Hartley visited the furnace site some seventy years ago the small size of the brook led him to question if it could ever have powered a blast furnace (Hartley 1957, 108). To test this we need to know the power a 17th-century furnace required. There are estimates (Tylecote 1976, 82) but quantitative data are lacking. The power to pump air through the furnace depends primarily on furnace burden's resistance to air flow (Rehder 2011, 184). This is sensitive to the size distribution of the fuel and ore lumps, and the presence of fines, for all of which we lack data. An alternative is to use reports by members of the U S Charcoal Ironworkers Association on their visits to charcoal-fired furnaces similar to but larger than the Braintree furnace. At the Beckley furnace in Connecticut they found the blast pressure was 5.2–6.9kPa, the production rate 110tonne/week, and the fuel rate 726kg/tonne of metal (Harris 1885). This made the air requirement 3.9m^3/kg of charcoal burnt, which at the observed production rate meant that the air flow had to be 31m^3/minute. The blowing power calculated from the blast pressure and air flow rate (Rehder 2011, 175) is 4.5 to 6kW. For comparison the power developed by the furnace air pump determined from archaeological data on the furnace's dam and wheel, the hydrology of the riverine water supply, and an efficiency of 60% is 4.5kW.

The iron production rate at the Braintree furnace is not recorded but the archaeological evidence shows its design was close to that of the replacement furnace at Saugus, which made iron at the rate of '8 tun per weeke' according to Governor Winthrop in 1648 (Hartley 1957, 128). Since as early as 1550 English blast furnaces made 7 tonnes of iron weekly, as at the Panningridge furnace (Crossley 1972), and in the 17th century at many others (King 2005), blast-furnace smelting was a well-established, mature technology in 1645. Other than being scaled up in size as at the Beckley furnace it remained much the same thereafter. Based on its production rate, the mechanical power required to blow the Braintree furnace was about 400W. The dimensions of its tail race measured by Robins show a 2.5m fall of water on the furnace wheel. Since the wheel and pump efficiency would not have been higher than about 60% the flow of Furnace Brook had to be at least 78m^3/hour to blow the furnace. The Beckley had less surface area relative to its enclosed volume than the Braintree furnace so the heat loss from its stack would have been relatively smaller, leading to a lower power requirement and possibly an underestimate of the water flow needed at Braintree.

The discharge of Furnace Brook is not gauged. Its flow is found from the size of its drainage basin compared with that of the nearest gauged stream, the Monatiquot River (US Geological Survey 2019). The ratio of drainage basin areas shows that Furnace Brook could provide the flow needed to blow the Braintree furnace during about 60% of the year, or a little over seven months, on average. However, those seven months included December to March, when ice was likely to stop the furnace wheel, while from late March to April snowmelt would raise backwater in the tailrace. Minimum flow followed in late summer and early autumn. Reliable water flow to blow the furnace was thus available during about four months of a year with normal rainfall. That the furnace worked well when the brook had adequate water flow to drive the bellows is shown by analysis of slag collected at the site (Table 1). The composition plotted on the CaO–MgO–SiO_2 phase diagram indicates the hearth temperature reached 1,350°C, sufficient to ensure free-running slag.

In 1827 George Whitney noted that 'The dam which was raised to form a pond for waterworks, is still standing,' and went on to remark that 'by erecting a very small dam, the stream which passes through the meadow, is made to overflow an immense area' (Whitney 1827, 50). A hundred and fifty years of industrial and urban development now covers the dam site and 2km or more of the meadow Whitney saw, making it impossible to reconstruct the size of the pond. Shallow water might have reached as far as today's marshes between granite outcrops within the Blue Hills Reservation. It may have looked like a large pond to the furnace builders in 1645 even though the volume of water it held could blow the furnace only a few days.

Water problems emerged as soon as the Braintree furnace began making iron. The 1645-46 winter was 'the earliest and sharpest we have ever had' according to Governor John Winthrop. The sudden onset of spring brought great floods and high tail water that stopped or reduced the power of the furnace wheel. The 1646-47 winter was mild, allowing iron production to begin early, but was followed by drought so severe that Massachusetts embargoed grain exports until next year's harvest (Kupperman 1984). Pig iron production was necessarily curtailed. Leader solved this problem by placing the Hammersmith blast furnace on the Saugus River, where the drainage basin was 25-times larger than at Braintree.

Since Winthrop chose a site on the Monatiquot River for the forge he must have realized it needed more power than the furnace. On this he was correct. The forge had at a minimum a helve hammer and two or three hearths with air blast provided by water-powered bellows. A finery helve hammer typically had a 200 to 400kg head lifted 0.5 to 0.8m to make about 100 blows a minute (Tylecote 1976, 90). It needed nearly 2kW of water-power. With the power for the air blast at the hearths the river had to deliver about 2.5kW when the forge was in full operation. The Monatiquot River could reliably supply this. The forge operated successfully and carried on after abandonment of the Braintree furnace with pig iron brought from Saugus by water. Accounting in 1653, when Hammersmith entered bankruptcy, showed the forge valued at £666 3s 3d. At that time 2 tonnes of pig iron were on hand ready for fining with 10 tonnes of bar iron completed (Pattee 1879, 460). The forge continued in use through at least 1659 (Hartley 1957, 256).

The river flow data used to evaluate the waterpower at the Braintree furnace and forge are modern while in 1646 New England was still in the last decades of the Little Ice Age. John Winthrop Jr had sent accounts of the

Table 1: Braintree furnace slag composition (wt%).

CaO	MgO	Al_2O_3	MnO	FeO	SiO_2	TiO_2	P	S
11.8	16.5	10.6	1.1	3.6	54.5	2.1	0.16	0.22

Note: Data from Linebaugh 2000.

weather he encountered to friends at the Royal Society but for want of thermometers it was only in the 1720s that quantitative data were recorded. Ezra Stiles made the earliest long-series temperature measurements, from 1778 to1795, with a gap in 1779-80 when his thermometer was broken during an invasion by the British army (Loomis and Newton 1866). By then the transition to a warming climate was underway. Instrumental precipitation records are even scarcer but data from lake-sediment cores show lower precipitation in eastern North America in the 17th century (Gajewski 1988). River flow depends on the balance between rainfall, evaporation and infiltration, all influenced by climate and land use. New England colonists believed that the weather they encountered was providential and therefore could be altered by their behavior, as by subduing the wilderness (Kupperman 1984). In the 19th century most believed that felling the forest diminished river flow. Continued success of water-powered milling shows this was untrue (Eves 1992). Most of the Furnace Brook drainage basin is within the long-established Blue Hills Reservation, still largely free of urbanization. It is unlikely that its discharge was higher in 1645 than it is today.

Alternative explanations for abandonment of the Braintree furnace

No one then or now suggested exhaustion of fuel as the problem at Braintree. Instead want of ore is one explanation offered, perhaps because John Winthrop Jr saw adequate ore the primary requirement in his selection of the furnace site (Winthrop R 1892-4, 13-14). Dr Robert Child, writing to the now-departed Winthrop in March 1647 noted that 'we have cast this winter some tuns of pots, which have proved exceedingly good, likewise mortars, stoves, and skillets. Our potter is molding more at Braintree as yet after another blowing we shall quit, not finding mines there' (Winthrop R 1892-4, 17). Since at this time smelting at the furnace was being closed down, he may have been referring to the stock of ore on hand.

Table 2: Principal slag components (normalized wt%) at the Saugus (S) and Braintree (B) furnaces.

	S (L)	S (L)	S (H)	S (H)	S mean	B (L)
CaO	13.8	13.5	12.3	12.8	13.1	11.8
MgO	17.8	14.4	16.4	7.8	14.1	16.5
Al_2O_3	12.1	13.5	13.6	19.3	14.6	10.6
FeO	2.4	3.1	4.5	6.7	4.2	3.6
SiO_2	53.7	55.5	50.4	52.1	52.9	54.5

Notes: L = data from Linebaugh 2000, H = data from Hallett 1973.

Winthrop found bog ore in Braintree before he left for England in 1641 but did not record where. Evidence now indicates that he supplied the furnace from a bog to the north (Fig 2). Here miners drained a 200ha swamp near the Milton town line, dug ore, and loaded it on carts to take to the furnace (Edwards 1954, 211). It was a 2km haul over easy terrain to Furnace Brook, in accord with Whitney's 1827 account. Even a small area covered with ore 0.1m deep would have contained far more iron than the Braintree furnace ever made, matching the judgement of the experienced furnace men Winthrop brought with him from England that the ore resource was sufficient for at least twenty years of ironmaking (Winthrop R 1892-4, 14). Two or three seasons of blast-furnace smelting are unlikely to have exhausted it.

Unless the ore smelted was self-fluxing, which the bog ore at Braintree was not, flux was the largest material resource needed at the furnace after ore and fuel. Winthrop never mentioned flux in his 'Discourse', curious since the quantity required, while less than the ore needed was still comparable to it. At the replacement Saugus furnace the ore/flux ratio was 60/40 (Thornberry-Ehrlich 2015). The flux, quarried at Nahant, was essexite, an ultramafic gabbro. Comparison of the Saugus and Braintree slag compositions (Table 2) shows that three of the five principal slag constituents at Braintree fall within the range of those at Saugus and two, lime and alumina, are just outside and lower. Essexite could have been the Braintree flux, easily brought from Nahant by boat (Fig 1). The large variation in composition among the Saugus samples reflects variable operation within the furnace, not unexpected, and suggests that adequate sampling of slag should be a concern with data reported for historic blast-furnace sites.

Technical skills, furnace construction, ore, fuel, and flux are not the likely source of failure at Braintree.

Subsequent Developments

Winthrop left the Braintree project unfinished in 1645 for new ventures in New London, where his only known ironmaking was a 1651 bloomery forge in the town's North Parish (Baker 1896, 621). The leaders of the New Haven Colony, in need of an entrepreneur to rescue their faltering economy, enticed him away from New London. During a 1654-5 visit he noted conveniently located bog ore that reawakened his enthusiasm for ironworks. The New Haven town meeting voted a subsidy for a blast-furnace and finery-forge, with a quarter share of the project going to Winthrop for his discovery of the ore and technical assistance. Within a year he had construction underway on the Farm River, between the towns of New Haven and Branford (Black 1966, 174). His participation lapsed after his election as Connecticut's governor in 1657. Expenses mounted, enthusiasm among New Haven voters waned, and construction slowed until Winthrop leased his share to two wealthy Bostonians, William Paine and Thomas Clark, who had gained experience at the Saugus project. By 1663 they had the furnace and forge making iron, but with sparse profits. Among other problems, New Haven, the most strictly puritan town in America, had proved even less welcoming to ironworkers than Massachusetts (Bezís-Selfa 2004, 43).

Some of the bog-ore pits that supplied the New Haven furnace remained visible into the early 20th century, in present-day North Haven (Keith and Harte 1937). A 15km haul over roads, or 36km by waterways, brought ore to the furnace. Since roads in Connecticut were no better than those in Massachusetts bringing ore the 2km to the Braintree furnace in 1645 could not have been onerous. Harte's photographs of the surviving North Haven pits indicate that they were small and shallow. Possibly the quantity of ore Winthrop found was less than he had supposed and led to closure of the New Haven furnace. By 1680 a grist mill had replaced the furnace, and a fulling mill replaced the forge. Early 20th-century highway construction destroyed the ironworks site, leaving little prospect of further archaeological exploration. Absence of slag downstream in the riverbed suggests that total iron production was small.

Winthrop did not repeat one Braintree error; he placed the furnace and forge at the outlet of Lake Saltonstall, so large that it is today a municipal reservoir. By 1655 New England had its own pool of ironmaking skills at Hammersmith. There Winthrop recruited William Osborn and Goodman Pratt to build the New Haven blast-furnace hearth (Woodward 2010, 153). At Braintree no search for hearth stone, the most-critical furnace component, had been needed since it had been brought from England. The New Haven furnace builders had to explore the highlands east of the Connecticut central valley for hearth stone and flux. The completed furnace, not much different from the one at Braintree, cost at least £2,000 (Hartley 1957, 284), double the £1,000 Winthrop had to build the London Undertakers' furnace and forge.

Documentary evidence now reveals a third, previously unknown 17th-century Massachusetts indirect-process ironworks, built on the Monatiquot in present-day Quincy (Pattee 1879, 461). Pattee in common with other 19th-century local-history writers lacked a clear understanding of the difference between a 'forge' and a 'blast furnace' when he wrote his account of the 'forge' John Hubbard of Boston built in 1682-84 on the Monatiquot. He did note that 'The Town of Lynn voted on 13 July 1691, that Mr. Hubbard of Braintree should give three shillings for every ton of rock mine he has from Nahant.' The rock at Nahant was essexite, blast-furnace flux. Hubbard's Monatiquot furnace and finery forge carried on until perhaps 1736, when the town razed the dam providing its waterpower to clear the river for fish passage. Hubbard's success shows that, had Winthrop built the Braintree furnace near the forge, he would have had cast- and bar-iron production underway in 1645. No move to Saugus would then have been needed, and the dissipation of the London Undertakers' capital in a failed furnace avoided.

Discussion

Immigrants in the Massachusetts Bay Colony, where timber was the construction material at hand, immediately needed nails and other bar-iron products. Finds of bloomery slag from contexts preceding 1645 show that small-scale smelting supplied some of this (LaCroix 2016). Cast products required transfer of a blast-furnace, undertaken by Winthrop, but as a component of an industrial-scale ironworks. The site for his furnace had to have building materials, ore, flux, fuel, waterpower and worker accommodation that could be developed with the London Undertakers' £1,000. Winthrop found these (except flux) in Braintree, dispersed over a 6km-wide area (Fig 2). With transportation costs included, site selection became a complicated optimization problem Winthrop found difficult to solve within the time and resources available. Furnace Brook, between the bog-ore mine and the forge, was conveniently at hand. Why he put the furnace there instead of near the forge on the Monatiquot, with its more abundant waterpower, remains unexplained. There is no evidence that he considered the greater expense of hauling ore rather than pig iron the extra distance.

Evaluating waterpower presented difficulties not found among the other natural resources needed for a blast furnace. Timber and essexite were visible and stationary; ore could be sampled by digging test pits. But the flow of Furnace Brook varied, knowable only by observation over a period of years, not possible in recently settled, poorly explored country. No guidance was available from the relation of streamflow to rainfall and evaporation since this was established only in the early 19th century (Dalton 1802). Calculating how long water stored in the probably shallow furnace pond could provide blowing power was a challenge for the furnace builders. Winthrop's commitment to alchemy, pansophy and the transformation of New England into a model of worldwide reform (Woodward 2010, 74) coupled with his commitment to other enterprises, was a distraction from the practical, quantitative decisions needed at Braintree.

Debt, lawsuits, labour and other troubles at Hammersmith soon led Massachusetts towns to turn to local, small-scale, artisanal sources of bar iron. At Millis, recent excavations show that George Fairbanks ran a bloomery so small that he later incorporated it into an addition to his house (LaCroix 2016). By 1652 Taunton citizens had raised money to bring Henry and James Leonard from Hammersmith to build the Raynham forge. While they made bar iron in Taunton the Leonards spread iron-making technique to Concord and other Massachusetts towns including Boxford, where Henry Leonard ran the Rowley Forge in 1672. It is the only 17th-century bloomery-forge site in New England to survive undeveloped, on the National Register of Historic Places (01000201), at 42.6478N 70.9861W.

To supply cast products Massachusetts entrepreneurs built blast furnaces from 1702 onward, always placed at lakes or ponds to assure adequate waterpower (Stott 2007). Joseph Jenks Jr son of the proprietor of the manufacturing forge at Hammersmith, transferred bloom smelting to Pawtucket, Rhode Island, possibly as early as 1688 (Kulik 1980, 38). Only in the mid-18th century did entrepreneurs revive indirect-process ironmaking with furnaces and forges in New England, with their locations then chosen to minimize ore and metal transportation costs (Gordon 1997).

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References

Baker H 1896, *History of Montville, Connecticut, formerly the North Parish of New London, from 1640 to 1896* (Hartford).

Bates A 1898, *The ancient ironworks at Braintree, Mass.* (Quincy).

Bezís-Selfa J 2004, *Forging America, ironworkers, adventurers and the industrious revolution* (Ithaca).

Black R 1966, *The younger John Winthrop* (New York).

Crossley D 1972, 'A sixteenth-century Wealden blast furnace: A report on excavations at Panningridge, Sussex, 1964-1970', *Post-Medieval Archaeology* 6, 42-68.

Dalton J 1802, 'Experiments and observations to determine whether the quantity of rain or dew is equal to the quantity of water carried off by rivers', *Memoires of the Literary and Philosophical Society of Manchester* 5(2), 345-72.

Edwards W 1954, *History of Quincy Massachusetts* (Quincy).

Eves J 1992, 'Shrunk to a comparative rivulet', *Technology and Culture* 33(1), 38-65.

Gajewski K 1988, 'Late Holocene climate change in eastern North America estimated from pollen data', *Quaternary Research* 29, 255-62.

Gordon R 1997 'Choice of method for making wrought iron in the Salisbury district of Connecticut', *Historical Metallurgy* 31(1), 25-31.

Hallett M 1973, 'A note on slag from the first American blast furnace', *Bulletin of the Historical Metallurgy Group* 7(1), 6.

Harris H 1885, 'Charcoal iron manufacture in the Salisbury Region', *Journal of the United States Association of Charcoal Ironworkers* 6, 49-53.

Hartley E 1957, *Ironworks on the Saugus* (Norman).

Keith H and Harte, C 1937, *The early iron industry of Connecticut* (Hartford).

King P 2005, 'The production and consumption of bar iron in early modern England and Wales', *Economic History Review* 58(1), 1-33.

Kulik G 1980, The beginning of the industrial revolution in America: Pawtucket, Rhode Island, 1672-1829, PhD dissertation, Brown University.

Kupperman K 1984, 'Climate and mastery of the wilderness in seventeenth-century New England', in D Hall, D Allen and P Smith (eds), *Seventeenth-Century New England* (Boston), 3-37.

LaCroix P 2016, Bogastow Ironworks, unpublished report.

Linebaugh D 2000, 'Forging a career: Roland W. Robbins and iron industry sites in the northeastern U.S.', *Journal of the Society for Industrial Archeology* 26(1), 5-36.

Linsley S and Hetherington R 1978, 'A seventeenth century blast furnace at Allensford, Northumberland', *Historical Metallurgy* 12(1), 1-11.

Loomis E and Newton H 1866, 'On the mean temperature and fluctuation, of temperature in New Haven Connecticut', *Transactions of the Connecticut Academy of Arts and Sciences* 1(2), 194.

Pattee W 1879, *A History of Old Braintree and Quincy* (Quincy).

Rehder J 2011, *The mastery and use of fire in antiquity* (Montreal).

Stott P 2007, 'Economic and industrial development', in Massachusetts Historical Commission, *Historic and archaeological resources of southeastern Massachusetts: A framework for preservation decisions* (Boston), 187-231.

Thornberry-Ehrlich T 2015, Saugus Ironworks National Historic Site: geologic resources inventory report, NPS/NRSS/GDR/NRR-2015/929.

Tylecote R 1976, *A history of metallurgy* (London).

U.S. Geological Survey Water Year Summary 2019, 01105583 Monatiquot River at East Braintree, MA.

Whitney G 1827, *Some account of the early history and present state of the town of Quincy in the Commonwealth of Massachusetts* (Quincy).

Winthrop J Jr 1882, 'Petition of John Winthrop Jr to houses of Parliament', *Collections of the Massachusetts Historical Society*, 5th series 8, 36-7.

Winthrop R 1892-4, 'October meeting 1892', *Proceedings of the Massachusetts Historical Society*, 2nd series 8, 1-17.

Woodward W 2010, *Prospero's America, John Winthrop, Jr., alchemy, and the creation of New England culture* (Chapel Hill).

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