Ana Crespo Solana
Filipe Castro
Nigel Nayling *Editors*

Heritage and the Sea

Volume 2: Maritime History and Archaeology of the Global Iberian World (15th-18th centuries)

Springer

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Preface

At the core of this book, a collection of chapters from a diverse range of authors, is a desire to draw on a wide array of perspectives and disciplinary approaches to renew our understanding and appreciation of Iberian maritime heritage of the Early Modern Period. Its catalyst is the ForSEAdiscovery Project – a multi-disciplinary endeavour which brought together established and emerging researchers to investigate Iberian shipbuilding and particularly its relationship to forests and timber supply through the lenses of archaeology, history and earth sciences. Many of the chapters draw directly on the project's research results. Other chapters come from collaborations and research associations beyond and encouraged by ForSEAdiscovery.

Our hope is that this collection will be of interest to scientists, academics and students of history and archaeology in the broadest sense, but also accessible to a broad audience seeking a current overview of research into the phenomenon of Iberian seafaring during a period of technological and social transformation. A period in which European horizons expanded to encompass global dimensions through maritime enterprise. Our ambition has been to seek and present new insights and research directions particularly through multi-disciplinary collaboration.

We owe a debt of gratitude to a wider research community than solely the contributors to this collection. To our ForSEAdiscovery family: Aoife Daly, Ute Sass-Klaassen, Jan Willem Veluwenkamp, Ignacio García González, Tomasz Wazny, Garry Momber, Christin Heamagi, Brandon Mason, and so many other members of the ForSEAdiscovery consortium, colleagues and friends who accompanied us in this incessant search for answers in the forest and in the sea of the history of the Iberian empires.

We dedicate this book to our beloved Fadi, lost to us too young, always in our hearts.

Madrid, Spain — Ana Crespo Solana
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Chapter 12
Technology of Iron Anchor-Frame Production in the Age of Exploration

Gregory Votruba

Abstract It is evident that iron anchor-frame sizes and construction undergo considerable changes in the second millennium CE into the Age of Exploration. Their construction changes from baton-assembled or laminated-beam to lone-bar then bundled-bars construction. Although numerous complex factors are involved, it is suggested that the most significant factor was the inclusion of waterpower, and its successive development, for iron production technology. These developments allowed for a dramatic increase in size and weight of anchor frames. This enhancement in nautical technology should be considered a significant factor resulting in the increasing sizes of vessels and unprecedented capacity of nautical activity resulting in and facilitating, globalization.

1 Introduction

Iron-frame wood stock-anchors are among the preindustrial period tools representing the highest level of a society's technical capabilities and economic well-being. The health and efficiency of maritime economies would largely have been based on the function and reliability of their anchors; not least to inhibit shipwreck during storm but for control and comfort of navigation and anchoring generally. It is, therefore, reasonable to suspect that limitations and advances in iron-working and anchor-frame construction could have played an intrinsic role in the nature of a society's nautical culture and the economy generally. For the European continent, the Age of Exploration offers a unique circumstance where an obvious and profound change in nautical culture occurs, the earliest period of repetitive long-distance oceanic navigation and its sustained expansion. Although there were of course certain economic and political drivers, it can be proposed that developments of anchor construction made it possible to now anchor comfortably along the shores of the open oceans, rather than merely the relative calm of Mediterranean and northern European basins.

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The most obvious functional characteristic of iron anchor frames is their size. The relevant treaty authors regularly distinguish stock anchors solely by their weight, with their distinct identification on board (sheet, bower, kedge, etc.) only being a matter of relative weight to others of the complement and size of the ship. Most authorities distinguish ships' anchors' sizes (regularly weight) as relative to a measure of a ship's size (most commonly burden; e.g., de Chaves 1537: 219, Bartolomeo Crescentio 1607: 77–78, and Fournier 1643: 43–44). Work is in progress for synthesizing the modest diachronic and spatial anchor design variations of this period as well as the relationship of ships' sizes to stock-anchor sizes and size variations among ships' complements. Different anchors in a complement would have had the same overall design with Mainwaring most clearly informing, "… for that which in one ship would be called but a kedger, or kedge anchor, in a lesser, would be a sheet anchor" (1644, p. 2). This chapter follows this paradigm *sensu stricto*, focusing solely on the overall anchor-frame dimension and technology of construction.

Early treaty authors all testify that the heavier the anchor, the larger the ship that it can serve. In other words, the heavier the anchor the greater its potential holding resistance. Anchor-frame size is a factor of the availability of iron as well as techniques and tools to enable the construction of a durable product. Provided sufficient iron is available, large anchors can be produced in any period, but technological limitations may result in a product that fractures readily and is therefore impractical. Therefore, in order to investigate anchor-size increase, it is necessary to consider both iron production methods in conjunction with construction techniques.

The scope of this chapter isolates size variation in iron anchor frames in the second millennium centuries preceding and during the Age of Exploration through ca. CE 1650. This can be attempted largely because of the recent commencement of scuba diving and the subsequent development, albeit gradual, of marine archaeological techniques, which has resulted in the publication (of varying quality and preservation) of dozens of relevant anchor frames from tens of datable sites. However, later data seem to be complicated by certain bias. The publication seems to be largely limited to sixteenth-century material and earlier. Perhaps there is a misconception that treaty writing, which first becomes detailed in the seventeenth century, renders seventeenth-century anchor publication redundant. Nevertheless, combining the evidence of published frames (see Catalog and Figs. 12.1, 12.2, and 12.3) with the evidence from the treaties provides an overview of this formative period for general hypothesis building (Table 12.1).

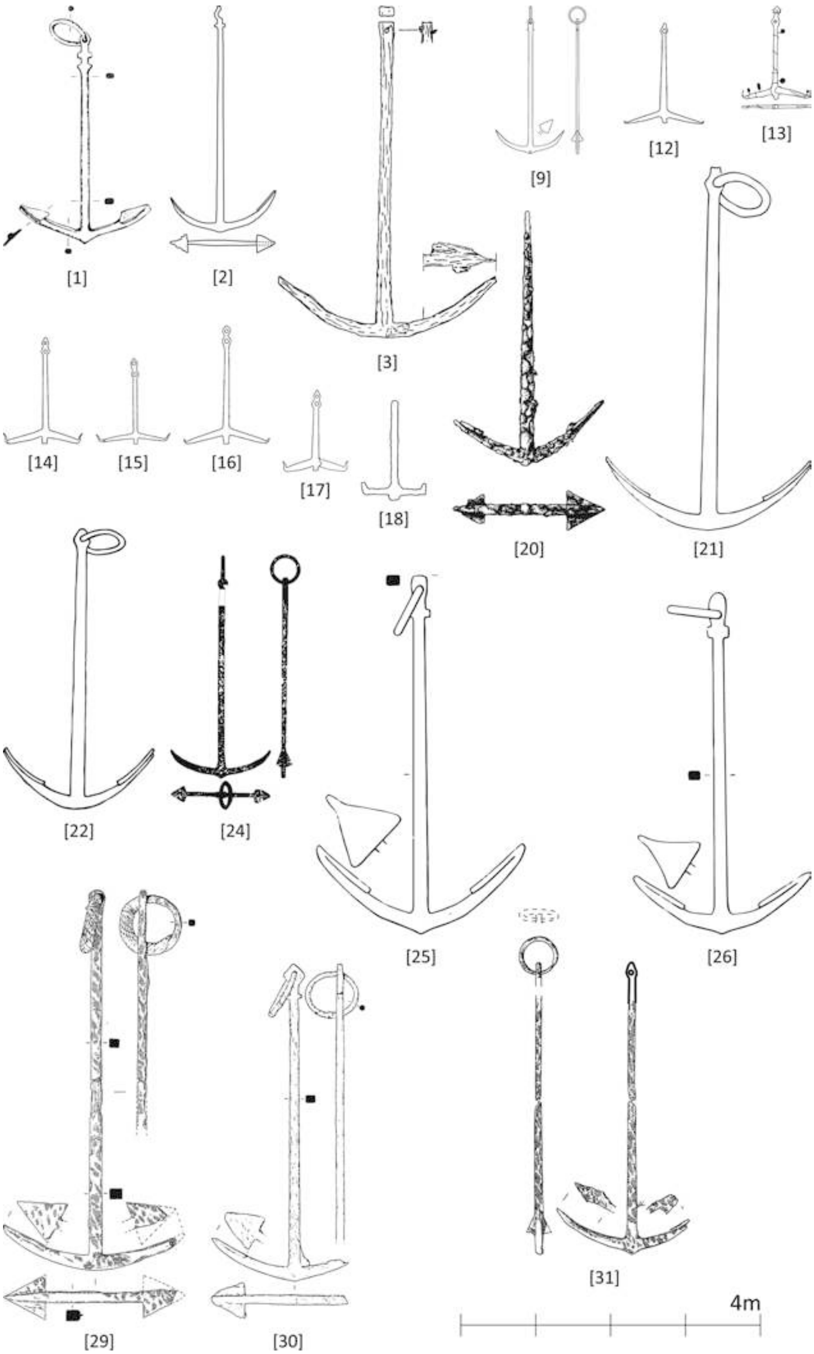


Fig. 12.1 Tracings of iron anchor-frame illustrations. See Catalog for original illustration citations [1–31]

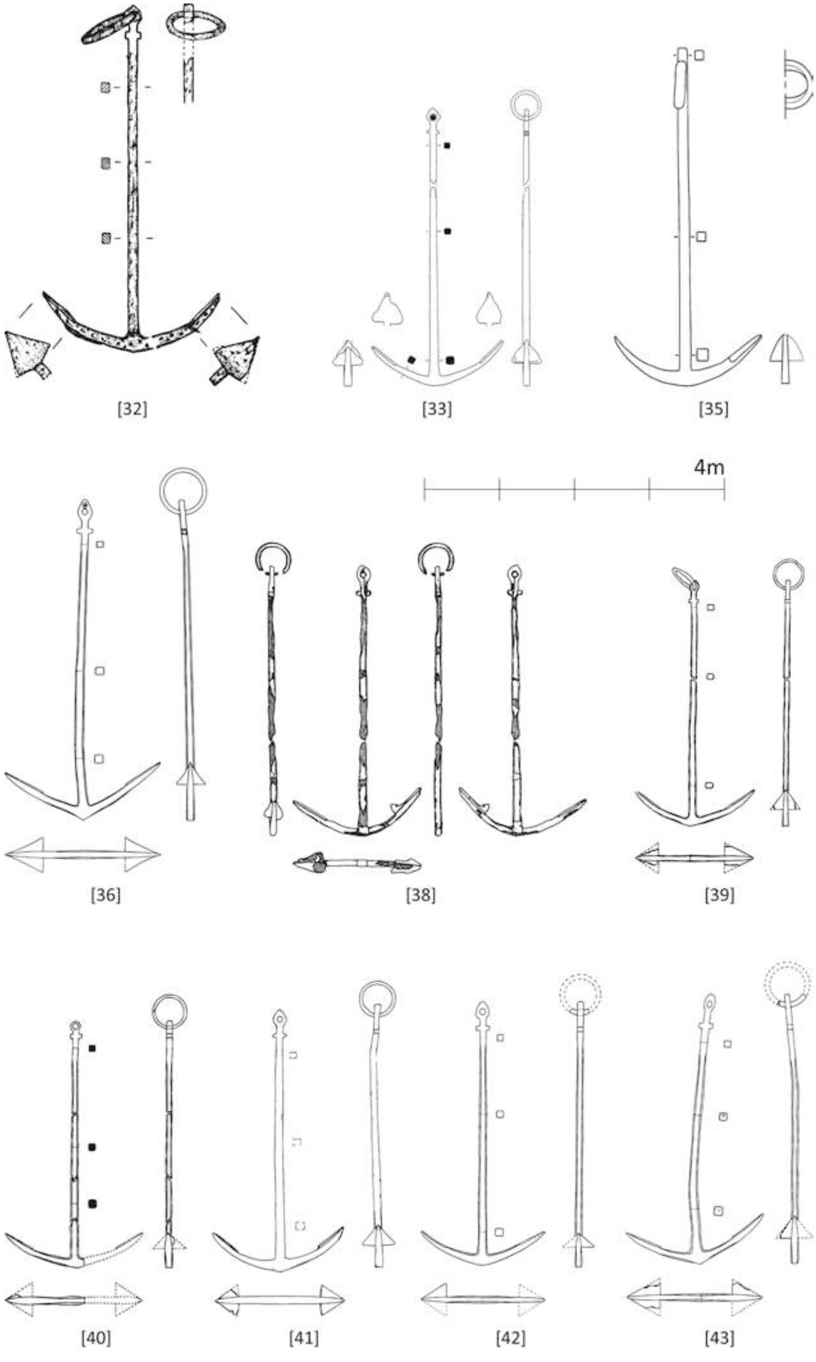


Fig. 12.2 Tracings of iron anchor-frame illustrations. See Catalog for original illustration citations [32–43]

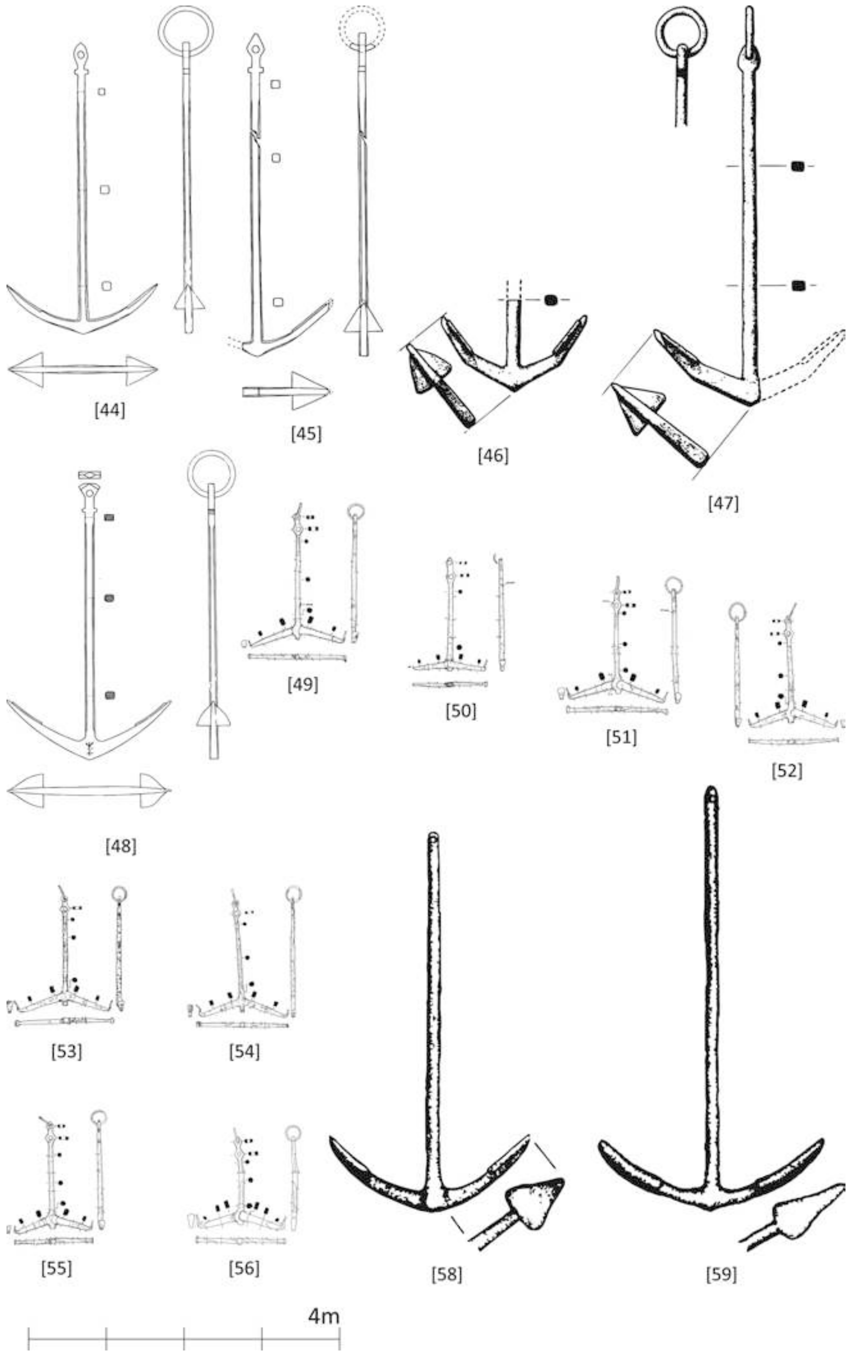


Fig. 12.3 Tracings of iron anchor-frame illustrations. See Catalog for original illustration citations [44–59]

Table 12.1 Catalog of anchor-frame findings cited in the text

Anchor Frame Reference ID	Site Name	Citations	Object Identifier	Traced Line Drawing Citation (Fig. 12.1)
[1]	Atlit Ordnance ship	Galili and Rosen (2014)	N/A	Galili and Rosen (2014, Fig. 5)
[2]	Bahia Mujeres	Keith (Keith 1988a, p. 122 and Fig. 7); Keith (1988b, pp. 56–7 and Fig. 20); Jobling (1993, pp. 56–58 and Fig. 9)	N/A	author reconstruction based on Keith (1988a, Fig. 7)
[3]	*Batavia*	Green (1977a, pp. 51, table 4); Green (1989, pp. 1, 5, 104, 213–5 and Figs.1, 3, 5, 25)	BAT 80311	Green (1989, p. 104 lower)
[4]			Green 1989: Fig. 5, no. 2	N/A
[5]			Green 1989: Fig. 5, no. 3	N/A
[6]			Green 1989: Fig. 5, no. 4	N/A
[7]			Green 1989: Fig. 5, no. 8.	N/A
[8]			Green 1989: Fig. 5, no. 9	N/A
[9]	Bremen Kogge	Lahn and Ellmers (1978, pp. 103, 106–7) Borsig (1981); Ellmers (1988, pp. 157–8)	N/A	Borsig (1981: Fig. 2)
[10]	Çamaltı Burnu 1	Günsenin (Günsenin 2001, 2003, 2005) and Kocabaş (2005 cat. Ç 02, 03, 04, 07, 10, 12, 20, 25 , 2008, 2009)	An Wr 2	N/A
[11]			An Wr 4	N/A
[12]			An 3	Kocabaş (2005: cat. Ç 03 drawing)
[13]			An 4	Kocabaş (2008: Fig. 5)
[14]			An 7	Kocabaş (2005: cat. Ç 07)
[15]			An 10	Kocabaş (2005: cat. Ç 10)
[16]			An 12	Kocabaş (2005: cat. Ç 12)
[17]			An 20	Kocabaş (2005: cat. Ç (20)
[18]			An 25	Kocabaş (2005: cat. Ç 25)
[19]			AN 26	N/A
[20]	Emanuel Point	Smith et al. (pp. 1, 4, 7, 28, 44, 64, 119, 165–8, 174); Burns (1998)	N/A	Burns (1998: Fig. 31)

(continued)

Table 12.1 (continued)

Anchor Frame Reference ID	Site Name	Citations	Object Identifier	Traced Line Drawing Citation (Fig. 12.1)
[21]	Gnalić	Petricioli (1970, p. 9); Martin (1979, p. 32)	Petricioli (1970: Fig. 10, left)	Petricioli (1970: Fig. 10 (left))
[22]			Petricioli (1970: Fig. 10, right)	Petricioli (1970: Fig. 10 (right))
[23]	Highborn Cay	Peterson (1972, Fig. 14, 1974 p.235 and Figs 1, 4, 5); Smith et al. (1985 p.61, 63, 68 and Fig. 4); Keith (1988b, pp. 59–60); Oertling (1989, pp. 235, 241)	N/A	N/A
[24]	Kalmar Harbour, Slottsjarden	Åkerlund (1951, pp. 119–20, 151, 155, Figs. 86 and pl. 1 and 27, d); Lahn and Ellmers (1978, p. 107)	N/A	Akerlund (1951: pl. 27d)
[25]	*La Trinidad Valencera*	Martin (1979, pp. 31 and Figs. 3, 6, 7, 16)	northern	Martin (1979: Fig. 16 (left))
[26]			southern	Martin (1979: Fig. 16 (right))
[27]	Malamocco	Molino et al. (1986)	N/A	N/A
[28]			N/A	N/A
[29]	*Mary Rose*	Rule (1982, pp. 134–5); Marsden (2003, p. 110 and Fig.11.20); McElvogue (2009, pp. 276–81 and Figs. 15.7, 15.9, 15.10)	cat. no. 81A0646	Marsden (2003: Fig. 11.20 (lower))
[30]			cat. no. 82A4078	McElvogue (2009: Fig. 15.7b)
[31]			cat. no. 82A4079	Marsden (2003: Fig. 11.20 (upper))
[32]			cat. no. 05A0104	McElvogue (2009: Fig. 15_7c)
[33]	Molasses Reef wreck	Keith et al. (1984, pp. 45–46, 61 and Fig. 3); Keith and Simmons (1985, pp. 420–3 and Figs. 4, 6, 7, 8); Keith (1986, p. 7); Keith (1987, pp. 235, 242–6 and Fig. 104); Keith (1988a, pp. 118–19 and Fig. 4); Oertling (1989, pp. 230, 235, 240)	N/A	Keith (1987: Fig. 104)

(continued)

Table 12.1 (continued)

Anchor Frame Reference ID	Site Name	Citations	Object Identifier	Traced Line Drawing Citation (Fig. 12.1)
[34]	Mortella II	Cazenave de la Roche (2009, pp. 6–7, 15, 24 28, 44–49 and Figs. 2, 10, 27–30); Cazenave de la Roche (2011, pp. 76–8)	N/A	N/A
[35]	Mortella III	Cazenave de la Roche (2009, pp. 6–7, 15, 24 and Figs. 4, 5, 11, 31–3, 43); Cazenave de la Roche (2011, p. 78)	N/A	Cazenave de la Roche (2009: Fig. 33)
[36]	Padre Island - 1554 salvage vessel (?)	Arnold and Weddle (1978, pp. 212, 224, 230 and Figs. 16, 17)	N/A	Barto Arnold and Weddle (1978: Fig. 16 (right))
[37]	Paphos Airport	Howitt- Marshall et al. (2016, pp. 175, 178–9 and Figs. 1, 2, 3, 6)	N/A	N/A
[38]	Red Bay, Newfoundland	Light (1990, 1992, pp. 249–53); Moore et al. (2007, pp. 76–8 and Fig. 17.4.17)	N/A	Moore et al. (2007: Fig. 17.4.17)
[39]	*San Esteban* (?) - Padre Island	Arnold and Weddle (1978, pp. 88, 224, 230, 224, 230, 296, 302–3 and Figs. 11, 13–16, 21, 70, 74, 75, 77 and tbl. J.1); Keith (1988b: Figs. 8, 9, 10, 11)	cat. no. 157	Arnold and Weddle (1978: Fig. 13 (left))
[40]			cat. no. 161	Arnold and Weddle (1978: Fig. 13 (center))
[41]			cat. no. 80-1	Arnold and Weddle (1978: Fig. 14 (left))
[42]			cat. no. 156-1	Arnold and Weddle (1978: Fig. 14 (center))
[43]			cat. no. 156-2	Arnold and Weddle (1978: Fig. 14 (right))
[44]			cat. no. 159	Arnold and Weddle (1978: Fig. 15 (right))
[45]			cat. no. 81-1	Arnold and Weddle (1978: Fig. 16 (left))
[46]	*San Juan*	Wignall (1973, pp. 468 and Figs. 2a, 3)	N/A	Wignall (1973: Fig. 2a)
[47]	*Santa Maria De La Rosa*	Wignall (1973: 468 and Figs 2b, 4); Wignall (1982, Fig. 2b)	N/A	Wignall (1973: Fig. 2b)

(continued)

Table 12.1 (continued)

Anchor Frame Reference ID	Site Name	Citations	Object Identifier	Traced Line Drawing Citation (Fig. 12.1)
[48]	*Santa Maria De Yciar* (?) - Padre Island	Arnold and Weddle (1978: 212, 224, Figs. 15, 17 and tbl. J.1); Keith (1988b: Fig. 9)	N/A	Arnold and Weddle (1978: Fig. 15 (left))
[49]	Serçe Limanı A	Van Doorninck (Van Doorninck 1988, 2004)	An 1	Van Doorninck (2004: Fig. 12.5)
[50]			An 2	Van Doorninck (2004: Fig. 12.6)
[51]			An 3	Van Doorninck (2004: Fig. 12.7)
[52]			An 4	Van Doorninck (2004: Fig. 12.8)
[53]			An 5	Van Doorninck (2004: Fig. 12.9)
[54]			An 6	Van Doorninck (2004: Fig. 12.10)
[55]			An 7	Van Doorninck (2004: Fig. 12.11)
[56]			An 8	Van Doorninck (2004: Fig. 12.12)
[57]	Tartous	Tanabe et al. (1989, pp. 39 and site plan, C1)	N/A	N/A
[58]	*Trial* (?)	Green (1977a, pp. 1, 42, 50–1, 56 and Figs. 2, 4, 13, 15)	cat. no. A1	Green (1977a, b: Fig. 15, A1)
[59]			cat. no. A6	Green (1977a, b: Fig. 15, A6)
[60]	*Vergulde Draeck*	Green (1977b, pp. 64–5, 72, 90–1, 293 and Figs. 12, 15)	Green et al. (1977a, b: Fig. 15, no. 18 upper)	N/A

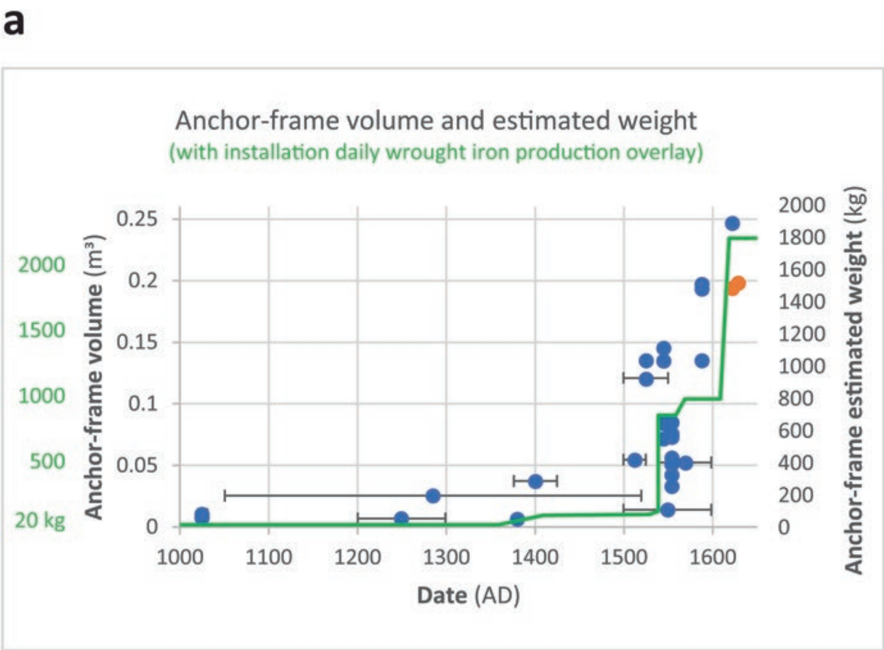
2 Iron Anchor-Frame Size, Beam Construction, and Technology

There is a noticeable increase in the size of anchor frames commencing from the mid-second millennium (Fig. 12.4), a factor based both on construction methodology and architecture of the shank and arm(s)-beams but also accessibility to wrought iron. The iron employed would have been wrought iron since cast iron is inadequately fragile (cf. Duhamel Du Monceau 1764, p. 11). Frames through the first quarter of the second millennium were likely constructed of iron fully manually produced, perhaps limited to itinerate smiths, moving to wherever was the specific need, and therefore there was little permanent infrastructure employed. Permanent furnaces, increasing in efficiency and size, may only have appeared in the thirteenth and fourteenth centuries (Gay 1997, p. 87).

A general understanding of the economics and technology of iron production from the fourteenth into the eighteenth century can be weaned, particularly, from Schubert's synthesis of the increasing daily potential output of iron from individual English installations[1], based on contemporary documents (Fig. 12.4; Schubert 1957: app. 4, cf. Gay 1997: app. 3 and 4). While waterpower had been employed for other purposes previously, Schubert demonstrates that the effect of the adoption of the waterwheel-powered bellows for the iron furnace on production is first recognizable at the beginning of the fifteenth century. Specifically, the potential heat and size of the furnace greatly increased allowing for significantly larger blooms – near 6-fold,

Fig. 12.4 (continued) indication of frame size, but **b** allows for significantly greater sample size since its two basic measurements are more regularly recorded than beam robusticity. The wrought iron maximum daily production from individual installations overlay is primarily based on English historical documents dating from CE 1330 (after Schubert 1957: app.4). Taking into consideration Stech and Maddin's (2004: 193–196) estimate that the limitation was about 25 kg for early simple bloomeries, the earlier limit into the fifteenth century is considered 20 kg, a few kg greater than Schubert's AD 1330–1360 documentation suggests, **a** Chronological scatter graph of an estimation of frames' iron volume, derived from the lengths of the arms and shank multiplied by the central shank section, along with their estimated weight. The data derive from : [1], [2], [9], [13], [24], [25], [26], [29], [30], [31], [32], [33], [34], [35], [36], [38], [39], [40], [41], [42], [43], [44], [45], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], and [58]. The points in orange are frames [3] and [59] which, since they lack document of the central shank section, have been estimated based on the central arm section instead. The estimated weight derives from the volume of the bars multiplied by 7.7 g/cm^3 following Light (1990: n.6). Since the latter bundled-bars tradition constructed frames would not have been entirely solid iron, their weight estimate based on overall dimensions should only be considered a maximum, **b** Chronological scatter graph of frame size based on shank beam length and arms-span determined by calculating the area of an oval defined by arms-span and shank height measurements. The data derive from : [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], and [60].

[1] Technically the data informs of daily output, but Schubert assumes this equated to individual blooms, for which supporting evidence is provided.



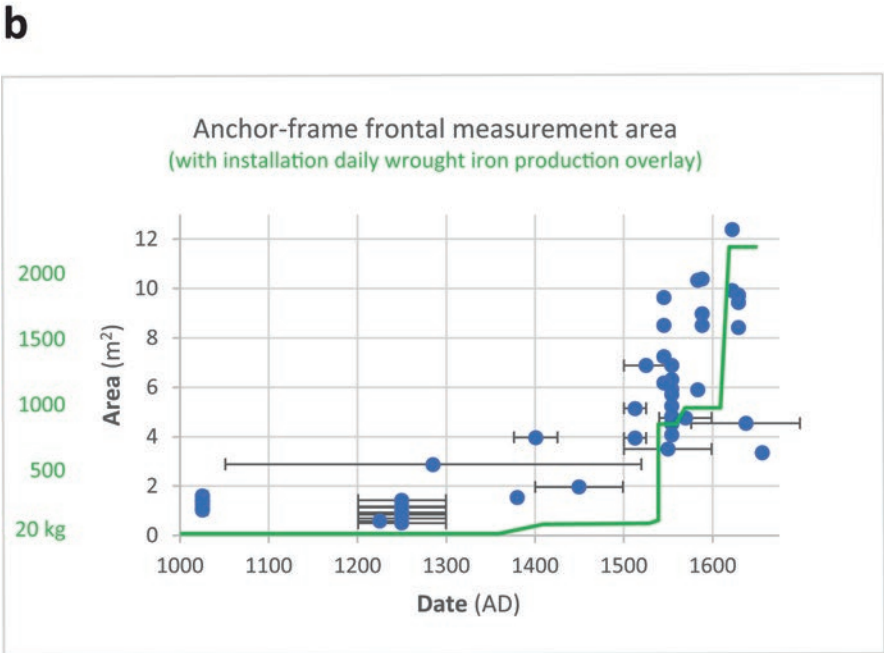


Fig. 12.4 Two calculations of anchor-frame sizes, both overlaid by evidence of iron installation daily wrought iron production. Only frames which have contextual date ranges less than 500 years are included, with the imprecisely dated displaying date-range bars. Chart **a** is a more accurate

from some 16 kg prior to *ca.* 90 kg blooms (Schubert 1957, pp. 139–140). The automated bellows would also allow for more efficient reheating in a chafery for better refinement and workability of the increasingly larger iron masses.

However, a particularly dramatic increase in production commences in the second quarter of the sixteenth century with a further potential 10-fold increase in the size of blooms (Schubert 1957, pp. 148–9). A novel technique of wrought iron production had been imported from northern Europe, perhaps specifically, now, Belgium since it gained the moniker the "Walloon process." This technique is characterized as "indirect" based on the production and subsequent unique refining of cast iron blooms (cf. Gay 1997, pp. 257–60). Essentially, the temperatures that could now be achieved in the furnace were high enough to produce substantial cast iron efficiently. However, the ingots produced (known specifically as "pigs") were too friable, due to high carbon content, to be wrought. Therefore, a discovery was necessary in which by blasting the pig with hot air in a uniquely constructed furnace with incorporated powerful bellows (a "blast furnace"), the blasted air would create a chemical reaction removing the excess carbon and the pig would disintegrate into drops of wrought iron which would coalesce on cooling into a mass called a "loupe." The loupe could be refined and worked as wrought iron blooms had been for two millennia, on reheating under hammer/sledges (Fig. 12.5). With the adoption of this "Walloon process," limits were again surpassed resulting in the great leap in potential iron production observed in the middle of the sixteenth century.

These developments in wrought iron production correspond reasonably well with the pattern of increasing sizes of anchor-frame finds towards the seventeenth century. Examining, specifically, frame size from the commencement of the second millennium (Fig. 12.4), this seems to demonstrate a modest increase by the fifteenth and early sixteenth century, reasonably following the adoption of the water-powered bellows and other furnace related developments in wrought iron production. Subsequently, in the middle of the sixteenth century, a dramatic increase is visible which is contemporary with and can therefore be hypothetically attributed to, the Walloon process. Improvements in the efficiency of machines, architectural furnace and slag extraction adjustments, and other complex factors such as flux additions and fuels, account for the continuing increases in production testified in the latter sixteenth century and beyond, which would, in turn, similarly benefit and enable larger anchor-frame production.

Regarding specific anchor-frame size, at the commencement of the second millennium, frames may have been limited by economic, technical, and cultural factors to those manually maneuverable. Considering also state documentary evidence, between the thirteenth and early sixteenth-century half-ton frames had become feasible. Thirteenth and fifteenth-century Italian documents testify to weights that max out at about 475 kg (Jal 1841; Champollion-Figeac 1843; Long et al. 2009). Significantly greater frames, even weighing over a ton, may first have been economical around the middle of the sixteenth century. An exception is documentation of anchors weighing over 500 kg, even a ton, from 1337 and 1420 English royal inventory records (Friel 1993, pp. 9–10, 1995, pp. 124–5). Following these, Friel suggests that the ability to make massive anchors commenced in the first half of the fourteenth century (1995, p. 127), a century prior to the pattern demonstratable here. The discrepancy between these two datasets is conceivably one between exceptional royal means and ordinary practicality.

Determining the effect of technological developments on anchor-frame architecture remains largely speculative since there have been only limited investigations of the workmanship of shank and arm-beams of finds. For the earliest centuries of the second millennium, we must commence with the better studied Mediterranean evidence. The rounded-shank robust-beam frames of the Serçe Limani and Çamaltı

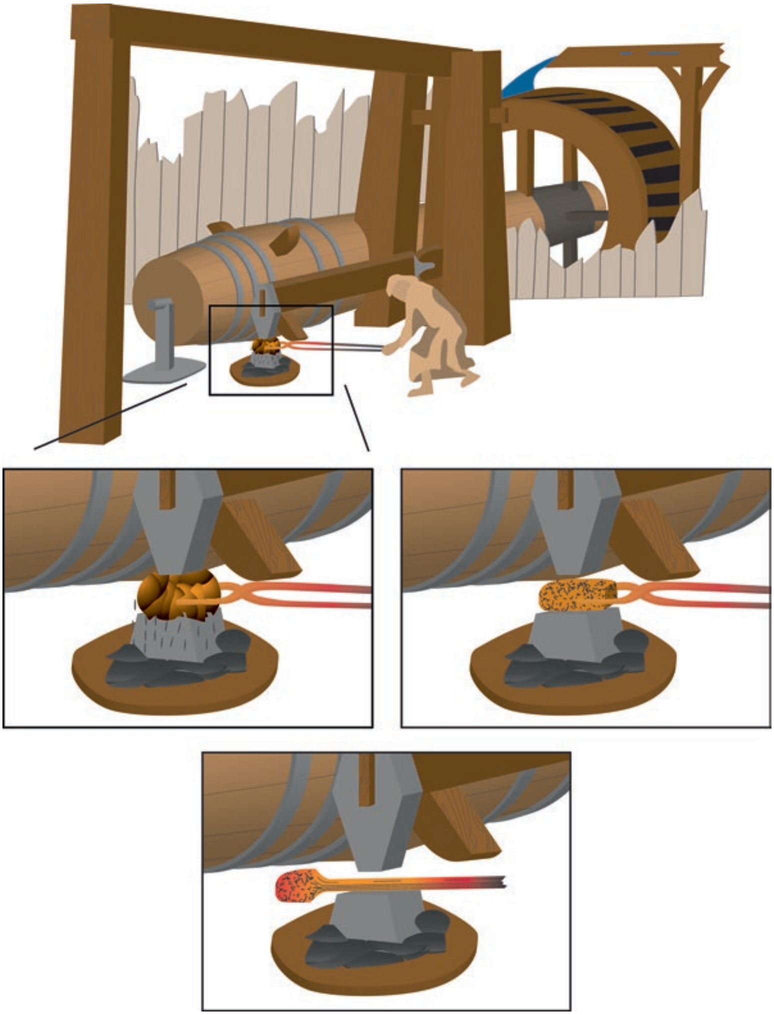


Fig. 12.5 Trace-based illustration of the creation of iron bars from a loupe with a waterwheel-powered mechanical hammer, based on sketches of a François Trésaguet authored 1702 French manuscript. (Archives Nationales AN.M. -D3 31.03/09; cf. Gay 1997: Fig. 101)

Burnu wrecks of the eleventh and thirteenth centuries display multiple weld marks demonstrating that the beams were formed by combining a dozen or so individual iron batons, each weighing around 5–6 kg (Stech and Maddin 2004; Van Doorninck 2004; Kocabaş 2008). Specifically, for the Serçe Limani, the batons are proposed to have been of standard dimension, *ca.* 24 cm x 6 cm diameter. Recognizing that simple furnaces could produce blooms considerably larger than the size of these batons, Stech and Maddin suggest that reheating technology at workshops was relatively simple demanding that the potentially original ca. 20 kg blooms[2] be cut into smaller pieces to enable preconstruction refining at coastal smithy workshops.

Despite the similarity in their date, and while also likely to have been limited to the combining of small iron pieces, we cannot however assume this exact method of construction for Viking frames, examples of which have yet to undergo invasive investigation. Rather, being of a northern European tradition with gracile rectangular shanks, their construction was possibly more similar to the *ca.* 1380 CE Bremen Kogge frame. The construction of its shank and arms-beams[3] are based on the tripartite combining of layers, oriented in the plane perpendicular to the arms, similar to lamination (Börsig 1981). Specifically, two beam-length *ca.* 30 x 20 mm section plates of iron sandwiched an interior section *ca.* 30 x 13 mm. This latter was not a plate but consisted of multiple individually attached pieces of iron which were preworked and welded on in such a way that the internal graining of the middle section ran perpendicular to the beam, opposite the graining of the two outer plates which ran parallel to the beam. The plates also differed from the interior section in having been made of nonphosphoric iron, whereas the middle section was heavily phosphoric. Ultimately, the beams were produced with a hard yet brittle interior but supple iron externally. This may have some similarities to Witsen (1671, p. 144) and Van Yk (1697) who suggest the combining of iron from different sources for anchor frames according to the iron's characteristic and expense. These authors suggest specifically that frames be forged with Spanish iron, which is tough but flexible, in combination with a rigid version, such as that from Sweden.

Most significantly, perhaps, is that the Bremen Kogge frame represents the earliest evidence of the lateral combining of long (beam-length) elements for the architecture of the beams. Its outer plates may be forerunners of subsequent centuries' use of long square-sectioned (previously rough small pieces) or rectangular-sectioned bars, which would become the common form of traded iron (Schubert 1957, pp. 129–30, 143, 151, 160, 162, 169 nn. 3, 172; Gay 1997, p. 260); and the practice of forging anchor frames with them is well supported (cf. Figs. 12.5 and 12.6a). De Reaumur (1764, p. 15) isolates important properties of bars for frames: The act of hammering out a narrow bar shape from the bloom forces much of the slag out, while bars can easily be cut to investigate their interior purity. In addition, producing a bar compacts the iron grains and remaining slag into longitudinal

[2] Stech and Maddin estimate that 25 kg blooms were possible for early installations, while Schubert's documentary evidence explicitly inform ca. 16 kg per day.

[3] Only the shank-beam was intrusively examined, but the arm(s)-beam also superficially demonstrates the same tripartite structure.

graining (cf. Fig. 12.5). For anchor frames, this property acts to strengthen the beam for which the bar is employed since the grains run along the length, whereas any grains running perpendicular to the run of the beam would be a fracture risk. Indeed, this longitudinal graining is apparent with the two Bremen Kogge plates. Concerning its phosphoritic central section, the perpendicularity of the grains and generally greater hardness due to the phosphorus would help fortify the crown-eye and head-eye piercing characteristic of early northern European anchors.

A related but distinct construction method and technique would appear by the sixteenth century. It is best testified by the Red Bay frame as examined and reported by Light (1990, 1992 pp. 249–53). In this case, three bars of similar length and uniform square section (ca. 2 m x 9 cm x 9 cm) were articulated; two for the shank, attached end-on-end with a single scarf, and the remaining bar was used as the arms beam; however, forge-bent headwards. As expected, it is evident that certain care was taken to forge the Red Bay's iron grains to run in the orientation of the bars. Novel, however, is the homogeneity, symmetry, and uniformity of the dimensions of the three bars leading Light to assume that they had been formed in a specialist forge of such bars (1990, p. 307). In order to distinguish this form of architecture from others (i.e., "laminated," "baton assembly," and "bundled-bars"—see below), this technique will be called here as "lone-bar" construction.

Light proposes that the design and feasibility of the Red Bay's bars were the results of efficiency and power resulting from waterwheel-powered heavy hammers. As substantiation for this possibility, in 1497 King Henry VII is documented as having commissioned iron bar stock forged by the *great water hamor* (Schubert 1957, p. 162), the earliest explicit reference to such a hammer. In the early sixteenth century, there is a reference to importing a design for a *martillo de agua* to Spain from Italy that would have also been used for bar production (Fernandez de Pinedo 1988, pp. 7–9). Indeed, the simple linear narrow rectilinear form of such bars would be ideal for refining and forming by the heavy automated hammer. Therefore, it is possible to suspect that the employment of bar stock for lone-bar construction of anchors is in connection with the development of powerful automated hammers. The method of bar construction employing a large waterwheel-powered hammer continued into the eighteenth century when one is sketched in a French document (Fig. 12.5). Conceivably, certain forges had established themselves for the production of bars (for anchor frames or otherwise trade). The produced bar stock would be traded to smiths in coastal cities for assembly and final anchor-frame construction. This said, the efficiency and power of early mechanical hammers were conceivably slight in their early centuries and increased over time. Light (1990, p. 313) suggests that the *ca.* 9 cm x 9 cm section of the Red Bay example was possibly reaching the limits of its forge because slag that had not been worked enough was visible.

Because each bar was limited in dimension by certain factors, such as the size of the bloom produced in the furnace, it was necessary to attach bars end-to-end on the shank to produce the desired shank length. While the Red Bay's arm and crownward-shank bars' length appear to correspond, the headward shank bar was somewhat shorter resulting in the scarf being headward from the center of the shank. This is a

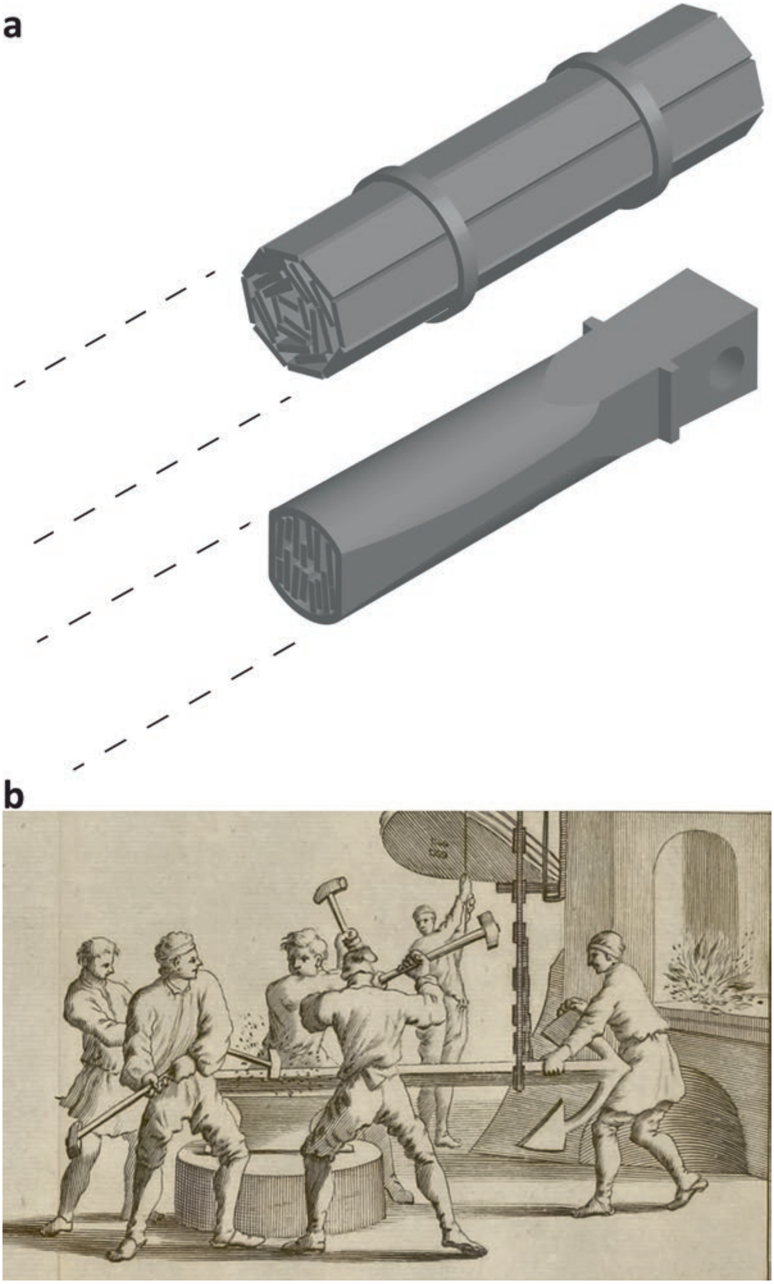


Fig. 12.6 Forging an anchor around 1700 CE, **a** Isometric illustrations of bundled-bar anchor beam construction sections, prior to and after forging. Based on two drawings in a manuscript dating AD 1705 (Gay 1997: 119 and Figs. 97 and 105), **b** A late seventeenth-century illustration of a team of four smiths sledge forging the shank of an anchor frame that is being manipulated with the help of a chain-winch into and out of the furnace by the master smith and another assistant (Van Yk 1697: foldout pg. 178, lower right)

feasibly the result of not only the bending of the headward bar to create the eye but also prior cutting shorter this bar to remove iron material for the ring, lugs, and the two flukes.

Despite only superficial recording, it is possible to propose the lone-bar construction for other frames as well. For the 1545 Mary Rose finds, one carefully illustrated frame ([32]) has scarf weld-like graining in roughly the middle of its shank. Two others are drawn with separations in the middle ([29] and [31]). Mc Elvogue also highlights only a single central shank weld for the *Mary Rose* frames in a generic drawing (2009, Fig. 15.9). Similar separations[4] at the shank are seen with three of the *San Esteban* 1554 wreck attribution ([39], [40], and [45]) and the Molasses Reef wreck finding of the first quarter of the sixteenth century. While it is not specified what caused these separations, it can be proposed that they are due to corrosion/breaking at the weld. A postdepositional slow disintegration of a poorly refined region of iron is identified by Light as the cause for a lower break in the Red Bay shank (1990, p. 313). Light further claims that these ([33], [39], [40], and [45]) and other frames of the 1554 wrecks assemblages ([36], [39], [41], [42], [43], and [44]) were constructed in the same tradition as the Red Bay (1992, pp. 251–2). He highlights that the beam sections are similar and that the head-eyes are designed the same, bent around rather than pierced (the so-called "gothic" finial), which would strongly support the identification of lone-bar architecture. It, therefore, appears that frames were constructed from three or so bars of bar stock, through most of the first half of the sixteenth century at least. That the well-rendered 1468 CE example on the altarpiece of Santa Ursula, Cataluña (cf. Casanovas 1993, photo 11) conspicuously matches with the common even curve bent bar-like arm's profile, symmetrically narrow and long shank known from the early sixteenth-century findings, may permit us to attribute the lone-bar type beam architecture back at least into the third quarter of the fifteenth century.

For the subsequent architectural development, we lack a specifically analyzed frame finding; however, hypotheses can be developed by considering later relevant documents along with consideration of changes in frame beam robusticity. French documents, which are both uniquely detailed and largely synthesized, provide illumination for the common construction of anchor frames around the later seventeenth and early eighteenth centuries (Gay 1997, pp. 115–33 and 131), when technical discussion of construction may be earliest found. One document of 1705 details that bars of 14–16 *lignes* (ca. 3.2–3.6 cm) square, ideally long enough to run the length of the intended beam, are carefully examined for imperfections and subsequently bundled and bound together by iron staple loops (cf. Fig. 12.6a). The bundle is subsequently heated and hammered to form by manual sledges (specifically weighing 12–15 *livres* (5.9–7.3 kg) with four *pieds* (1.3 m) long handles (cf. Figs. 12.6 a below and b). For English construction, there is less specific but complementary discussion (Merriman 1950, pp. 159–63).

[4] [39] and [40] are clearly recorded as fractures occurring prior to the wreck event. Possibly the weld was a relative point of weakness.

When this change occurred, from lone-bar to bundled-bar architecture, requires considerable speculation. Perhaps by the second half of the sixteenth century, the technique of bundling bars together and subsequently working them to create the frames' shank and arm(s)-beams was common since there are two unique form features of frames dating from this period. The first is that some beam finds demonstrate an increase in robusticity to around 250 cm^2, with the Armada wrecks ([25], [46], and [47]) and a first half of the seventeenth century find demonstrating a *ca.* 300 cm^2 section ([58]). Second is that the relative length of the shank conspicuously declines. The decline in shank length can be attributed to the inability to weld two sections of bundled-bars beam together, thus the smiths were limited to extending the bars before bundling them, ultimately resulting in relatively shorter shanks than typical of the first half of the sixteenth century. One possible frame ([48]) might specifically attribute the commencement of the bundled-bars architecture to *ca.* 1550 belonging to the *Santa Maria de Yciar* wreck of 1554. Its form is unique since its beam sections are rectangular rather than square (suggesting two bars bound side by side), the shank is relatively short, and its eye seems to have been punched rather than formed with "gothic" finial bending.

The bundled-bars architecture would be a logical response to the great increase in iron flooding the market as a result of the development of the Walloon process in the middle of the sixteenth century. Perhaps, the mechanical hammer had long reached its technical limits for the construction of bar stock, or feasibly it became impractical for anchor smiths to weld end-to-end a certain thickness of bars produced. The greater availability of wrought iron could not equate to more robust bars or their weldability. However, with the easing of economic factors, thicker beams could be wrought by bundling bars to whatever extent needed. With bundling, iron anchor-frames could now be produced to greater weights than previously and were less likely to suffer bending distortion, which is conspicuous with several sixteenth-century frames of lone-bar architecture ([36], [38] [39], [41], and [43]).

Although rounded, or partially so, shanks would become common later, the informative documentation of sixteenth and seventeenth-century frame findings suggest that they were constructed with at least roughly square (but with beveled edges) sections (cf. Fig. 12.6b). Therefore, we might presume that the bundles of bars would be layered with a similar symmetrical rectilinear section (rather than round) prior to working. Possibly, the ultimate robusticity of the frame would be determined by the width and height of the bar stock layers to be incorporated (3x3, 4x4, 5x5 …).

A Dutch note written in 1622 testifies that Spanish anchors were considered narrow, … *een heel dun Ancker ghelyck een Spaens-Ancker*, … (Van Nouhuys 1928, 1951, p. 44). Perhaps the Spanish were more lethargic in their transition to bundled beams architecture, or possibly the (supposed) suppler nature of Spanish iron was generally less likely to fracture, and their frames could therefore be made with narrower beams. This addressed, finds from the late sixteenth-century Spanish wrecks of *La Trinidad Valencera* ([25] and [26]), *San Juan,* and *Santa Maria de la Rosa* are among the most robust published. Smaller ship's anchor frames may have preserved the simpler lone-bar technique for longer.

How the arms were attached to the shank is also only moderately clarified. The arms of the Yassıada (Van Doorninck 1982) and Serçe Limanı (Van Doorninck 2004) were formed and hammer-welded separately, each to opposite sides of the shank at the crown. However, again, despite the relative chronological propinquity, we cannot assume the same for Viking frames, which have distinct designs. Sølver claims that the Ladby frame (1958, p. 297) was assembled by combining the shank beam with a second beam consisting of both arms, and conspicuously this also seems to be the case with the Bremen Kogge. This latter system was also demonstrated for the sixteenth-century Red Bay frame (Light 1990, 1992), in which the crownward end of the shank-beam was ... portion of the arms-beam (arms beam to shank-beam). The final welding was facilitated by a small enclosing patch placed on the face opposite the thin projection. Since frames built with the lone-bar technique have kept the arms-beam entire, without a scarf, this would be the natural scenario. Alternatively, bundled-bars architecture would have been more difficult to forge bend, which would have encouraged each arm to be constructed separately and individually hammer-welded at the crown (Light 1992, pp. 251–3).

Despite the great thickness that was eventually achieved, the scarce information that we have for the actual forge assembly of iron frames through most of the seventeenth century suggests that it could have been entirely manual. Although Schubert postulates that the water-powered hammer may have remained a novelty in the fifteenth and sixteenth centuries (Schubert 1957, pp. 137–8 and 147–8), this may have continued much longer for anchor assembly smiths. Late seventeenth-century French documents outline that despite considerable inquiry into constructing automated hammers for anchor-frame production in the coastal cities, their use remained limited to a single central region (Nivernais; Gay 1997, pp. 99–120). Automated hammers seem to have demanded a certain high sustained commitment of investment, a unique hydrographic regime, and were insufficiently versatile for anchor-frame construction. Correspondingly, Light notes for the Red Bay frame that it could have been assembled wholly by sledging (Light 1990, p. 309). Van Yk illustrates a large frame being sledged by a team of four smiths who are timing their hits in a continual synchronized manner, guided by a master smith, and maneuvered partially by a crane system with a chain manipulated by a sixth worker (Fig. 12.6b). With bundled-bar construction, manual hammering would ultimately find a complication since the bundles could only be worked to a certain depth resulting in a forged outer shell and unwelded interior bars (cf. Fig. 12.6a) but resulting concern for overly weak beams would only appear in documentation at the end of the seventeenth century.

Regarding the heavy beating necessary for the welding of the individual beams together, we learn of an apparatus used for forging frames as early as the second quarter of the eighteenth century which was an iron mass raised by human power and allowed to drop upon the preheated and placed shank and arm-beams, which would have had a particular benefit in the welding of the beams at the cross. Ultimately, through the seventeenth century, forging frames from standard bar stock may have primarily or entirely utilized a sledging-smith or sledging teams. Therefore, it appears that producing the base bar stock for frames could have been the only use of the water-powered hammer in anchor production, while the frames' final forming and assemblage were manual.

Of course, larger anchors would require greater labor and therefore increased relative cost. Fournier (1643) provides modest evidence stating that the price of *grands ancres* cost 24 *livre* per 100 lbs and 18 *livres* for *petites*. It would go without saying that larger frames, independent of the greater iron and fuel necessary, are more difficult and labor demanding to produce. In this case, it appears that larger frames were considered some 1/3 more expensive to produce than smaller ones. However, subsequently, technological demands on larger anchors may have increased expenditure significantly since late seventeenth-century Dutch (Gay 1997, p. 95) and early eighteenth-century English (Sutherland 1717, p. 141 and 144) documentation give figures around 2/3 to twice more expensive.

The first known experiments in testing the resilience of anchor frames before deployment, particularly relevant considering that interior voids and otherwise imperfections were practically imperceptible, took place by the end of the sixteenth century. A Dutch legal document dating from 1591 quoted by Van Yk (1697) as still valid in his time, states that all frames, independent of size, must be tested for durability before consignment. Specifically, they were suspended crown downward two feet above an iron surface and dropped (Witsen 1671, p. 143). The earliest evidence for such drop-testing in France derives from a 1706 document (Gay 1997, pp. 133–6). However, the drop test would find its end after coming into uncertainty with debates of how high the frames would need to be dropped from and rendered impractical with claims that they are merely damaging to frames that would otherwise be functional. England Royal Navy records of 1703 include the testimony of several smiths that such testing is misleading, they rather suggest that proofing be done by pulling horizontally with a winch (Merriman 1950, p. 163).

3 Conclusions

This investigation allows general hypotheses to be developed regarding important changes in iron anchor-frame production in the second millennium CE through the latter seventeenth century. Wrought iron and iron-anchor production was likely entirely manual through the millennium's earliest centuries, based on traded pieces cut weighing fractions of ca. 20 kg blooms, deriving from installations of ephemeral nature. At this time, at least two techniques of anchor construction were likely employed contemporaneously. In the Mediterranean, several small truncated iron batons were attached to each other end-to-end to produce shank and arm beams. In northern Europe, possibly the tradition was construction with thin and long plates, some with distinct content (e.g., phosphoritic), which were combined in a lamination-like manner.

The earliest significant changes to these traditions, commencing in the late fourteenth or early fifteenth century, were revolutionary. It is likely, primarily, waterpower bellows technology that resulted in some 4–6 times larger blooms, along with the invention of the water-powered hammer. The relevant installations would have been established inland both near where ore was mined, and where there was a uniquely active hydraulic regime (high-flow streams), for channels, or filling artificial ponds that could be emptied through channels, with waterwheels to power the large and sophisticated bellows necessary. Concerning the water-powered hammer, while specific evidence from the crucial fifteenth century is limited to its final decade, we can propose that the water-powered hammer appeared by the middle of this century. The automated hammer would produce stronger and sustained power to convert the increasing in size blooms into standardizing iron bars for cart and riverine transport distribution to workshops on the coast.

It may have been rapidly recognizable that these bars alone, with only minimal additional refining, were suitable for the beams of anchors. Particularly, they may have been better priced, purer, easier to check purity, and arrive with graining running along its length, this latter saving substantial smithing labor. Even when attaching the bars end-on-end for larger anchors, the final beams would contain fewer, for baton assembly architecture much fewer, welds. Manual sledging harbor smith teams now constructing with long standardized and robust premade iron bars, preliminary refined, could more easily, and likely cheaper in materials and labor, produce larger anchor frames in dimension and weight. Such novel changes in anchor-frame construction and size may very well have helped catalyze the novel confidence in sailors to explore uncharted regions that characterizes the end of the fifteenth century.

If a (potential) fifteenth-century appearance of the water-powered hammer resulted in a novel culture of nautical discovery, the second quarter of the sixteenth-century Walloon process ensured its sustainability and expansion to globalization**.** The Walloon process dramatically increased further wrought iron and bar production, and anchor beams could increase in girth (and thus strength) by smiting them with multiple bars prebundled together. The Walloon process may be responsible for the doubling of the practical weight limitations of anchor frames in the latter half of the sixteenth century (i.e., from *ca.* 500 kg to a ton or more).

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