ANCIENT MARITIME TRADE ON BALSA RAFTS
An Engineering Analysis

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By approximately 100 bc Ecuadorian traders had established maritime commercial routes extending from Chile to Colombia. Historical sources indicate that they transported their merchandise in large, ocean-going sailing rafts made of balsa logs. By about ad 700 the data show that Ecuadorian metallurgical technology had reached the west coast of Mexico but remained absent in the region between Guerrero and lower Central America. Archaeologists have argued that this technology was most plausibly transmitted via balsa raft exchange routes. This article uses mathematical simulation of balsa rafts’ mechanical and material characteristics to determine whether these rafts were suitable vessels for long-distance travel. Our analysis shows that these rafts were fully functional sailing vessels that could have navigated between Ecuador and Mexico. This conclusion greatly strengthens the argument that Ecuadorian metallurgical technology and aspects of the metallurgical technologies of adjacent South American regions were transmitted from South America to western Mexico via maritime trade routes.

One key issue in New World Archaeology concerns the extent to which the great civilizations of the Andes and Mesoamerica were in contact with one another prior to the European invasion. Metallurgy, for example, was introduced to western Mexico from the Andean zone around AD 700 (Hosler 1986:546–47, 1988a:832–52, 1994:87–124). Archaeologists have argued that metallurgical knowledge and techniques were most plausibly transmitted via a maritime route (Hosler 1988a:832–33, 841–43, 852; Marcos 1977:102–9; Meighan 1969:11–15), rather than overland, by the sea-going peoples of coastal Ecuador (Hosler 1986:547, 560–64, 1988a:841–43, 1994:87 124). The fact that no metal objects appear in the region between western Mexico and the northern Andean zone during the period under consideration strengthens the argument for a direct maritime transmission of metallurgical technologies from coastal Ecuador to West Mexico.

We know from archaeological data that by approximately 100 bc Ecuadorian traders had established maritime commercial routes extending from Chile to Colombia (Paulsen 1974:602–3; Rostworowski 1970:140). These traders...
transported their merchandise, which included metal ornaments, emeralds, and *Spodium* oyster shells, in large, ocean-going sailing rafts made of balsa logs.' Figure 1 shows a possible maritime transmission route of these trade goods and metallurgical technologies. Ethnographic evidence complements the archaeological findings. Bartolomé Ruíz de Estrada, Francisco Pizarro's chief pilot, captured a sailing balsa raft in 1526 as it sailed northward along the Ecuadorian coast (Sámano-Xerec 1937:65–66). “Ruíz described a raft with 20 men aboard filled with trade goods that included ‘muchas piezas de plata, diademas, coronas, cintos, tenazuelas y cascabeles... todo esto traían para rescatar unas conchas de pescado’ (many silver objects, tiaras, crowns, bands, tweezers and bells, all of this they brought to exchange for some shells)” ( Hosler 1994:103, citing Sámano-Xerec 1937:65–66). Unfortunately, no remains of pre-Columbian rafts have been recovered in Ecuador or elsewhere.

![Figure 1. Possible maritime transmission route of metallurgical technology via balsa raft (dashed line).](image)

The question concerning how metallurgy became established in western Mexico, and whether it was introduced by South Americans sailing north on the balsa rafts depicted in the historical sources, is made particularly compelling because of the highly complex nature of metallurgical technologies. Metallurgy was invented independently in only two areas of the world, in the Near East, from which knowledge was introduced to China and elsewhere (Vincent C. Pigott, Institute of Archaeology, University College London, personal communication 2006), and in the Andean zone of South America (Lechtman 1980:269, 1988:344–50, 2007:323–30). Andean metallurgy dates to as early as 700 BC at Mina Perdida in the Lurin Valley, on the coast of Peru (Burger and Gordon 1998:1108–09).

By AD 400, metallurgy was thriving on the north coast of Peru and Ecuador, as well as in southern Peru, northern Chile, and the adjacent highlands. In the Andean zone, metalworkers handled metal as a solid: they worked cast metal blanks into implements, sheet, and other sumptuary items. They also developed the extractive, smelting, and processing technologies necessary to produce copper-arsenic bronze (in the northern Andes), copper-tin bronze (in the southern Andes), and alloys of copper-gold, copper-silver, copper-silver-gold (Lechtman 1980:270–75, 1988:344–50, 2007:323–30; Hosler 1994:87–101, 105–22), and copper-arsenic-nickel (Lechtman 2003:404–10). To the north, in Colombia, metalworkers managed metal as a liquid, casting thousands of sumptuary and ritual objects from gold and copper-gold alloys using the lost-wax method, open-backed molds, and three-piece molds (Hosler 1994:98–99; Lechtman 1988:344–50). The earliest date for Colombian metalwork is approximately 400 BC (Plazas 1998:43–70). This technology was related to the earlier metallurgy in Peru.

Metal objects appeared in Mesoamerica only after the disintegration of the Classic period states in the Central Highlands, Oaxaca, and the southeastern Lowlands. The earliest metal objects date to around AD 700 and come from sites in the west (Hosler 1986:548–53, 1994:13–17, 45–52). Western Mexico abounds in copper and other metallic ore minerals (Hosler 1986:473–83, 1994:21–31). Hosler’s comprehensive comparative research (regarding fabrication methods, chemistry, and relation of alloy properties to design and function) investigated the origins and florescence of West Mexican metallurgy and demonstrated that the metallurgy of western Mesoamerica was derived from two South American metalworking traditions. One was the lost-wax casting technology of Colombia and the other was the tradition shared in the northern, central, and southern Andes in which objects were shaped from cast metal blanks (Hosler 1988a:835, 1994:52–83, 87–99, 1995:100–15, 1996:1819–24, 2005:45–176).

Even the earliest assemblages of metal objects found in western Mexico (at the Infierillos sites on the Balsas River between Guerrero and Michoacán, at Tomatlan in Jalisco, and at Amapa in Nayarit, all of which antedate AD 1000) demonstrate that these West Mexican metalworkers incorporated elements of both Andean metallurgical traditions (Hosler 1986:548–51, 1994:87–110). Using the lost-wax technique, they cast bells with design characteristics identical to bells recovered in Colombia (Hosler 1988a:550–51, 1994:98–102). They also cold-worked items—for example, copper hand tools and ornaments such as rings, needles, and tweezers—from an original cast blank. These same object classes, made using the same fabrication methods and exhibiting the same design characteristics, appear in great numbers at archaeological sites and in museum collections in Ecuador and northern Peru. In all cases, dates for the Andean material are earlier than those from the West Mexican sites (Hosler 1986:546–64, 1988a:834–38, 1994:103–5).

Figure 2 illustrates perforated-eye needles from Ecuador (a) and West Mexico (b). The earliest Ecuadorian examples of these needles date to 500 BC, and the West Mexican analogues date to AD 800 (Hosler 1988b:207–8). Figure 3a illustrates copper rings, placed on the cranium of a skeleton, excavated from
Ecuadorian burials (Hosler 1988a:835–37). Figure 3b illustrates West Mexican rings identical to those excavated from burials at Tomalían Jalisco, also placed on the skeleton's cranium (Hosler 1988a:836–37). In both cases, these rings encircled a fabric band and functioned as "hair-braid holders" (Hosler 1988a:836–37). In the case of rings and selected other artifact classes, such as axe monies and copper-silver sheet objects (Hosler 1994:122–24), the object, the design characteristics, the fabrication method, and cultural use are identical.

All evidence indicates that West Mexican metalworkers incorporated only certain secular elements of Andean technologies, and they transformed some of these elements for their own cultural ends; for example, they used high-arsenic copper-arsenic bronze for elaborate lost-wax cast bells (Hosler 1988a:832–35, 849–50, 1994:122–24, 227–51). Furthermore, chemical analyses of the metal artifacts clearly show that Ecuadorian merchants did not export either copper ore or metal objects to West Mexico on any significant scale (Hosler 1988a:848–49.

Figure 2. Perforated-eye needles dating to (a) 500 BC in Ecuador and (b) AD 800 in West Mexico (from Hosler 1988b; used by permission). Centimeter scale.

Figure 3. (a) Copper rings, found on the cranium of a skeleton, excavated from Ecuadorian burials. (b) Copper rings excavated from a West Mexican burial.

The design characteristics, fabrication method, and cultural use of these rings are identical to those of their South American counterparts (from Hosler 1988b; used by permission). Scales in centimeters.

Rather, the Andean-style object types recovered in West Mexico seem to be local versions of needles and other items traded by the sea-going merchants for Spondylus or other West Mexican products. What was introduced from the south was knowledge and a few copper artifacts—bells, needles, tweezers, and rings—which later served as prototypes for West Mexican designs (Hosler 1988a:852).

Hosler (1988a:834) has argued that these techniques—smelting, alloying, and fabrication methods such as lost-wax casting and cold work—were transmitted to West Mexican populations by Andean metalworkers who sailed north from coastal Ecuador on balsa rafts. Further, these metalworkers must have lived with peoples in richly mineralized zones of West Mexico for a sufficient amount of time to transmit the critical aspects of this complex technology.

This article assesses the argument for the maritime introduction of metallurgy from coastal Ecuador to West Mexico by modeling the mechanical and material characteristics of balsa rafts to determine whether these rafts were suitable vessels for long-distance trade. Sixteenth- and seventeenth-century European invaders, who were sailors themselves, observed these craft and described them in sufficient detail that we use those descriptions as the data set for our model. To ascertain whether these craft could reliably have carried large quantities of goods between the two regions, we mathematically model four key aspects of their design, evaluating their aerodynamic and hydrodynamic properties, their buoyancy and cargo capacity, their functional lifetime, and the load-bearing capacities of their component materials.

OVERVIEW OF PRIOR RESEARCH

Several contemporary sailors have undertaken voyages attempting either to promulgate a theory of trans-Pacific migration or to recreate the voyages from Ecuador to West Mexico (Haslett 2006:125–31; Heyerdahl 1955:254; Smith 1999:1–3). During the nineteenth century the researchers Thor Heyerdahl and Cameron Smith experimented independently with the sailing abilities of balsa rafts. Heyerdahl sailed the 45-ft balsa raft Kon-Tiki from Callao, Peru, to Polynesia in 1947. The square rig used on Heyerdahl's raft does not accurately replicate the pre-European sail design and, furthermore, was capable only of sailing directly downwind. 2 The fixed square sail he used lacks the maneuverability to sail up or down the coast of Central America (Heyerdahl 1955:255). John Haslett and Cameron Smith attempted several ultimately unsuccessful voyages from Ecuador to West Mexico in the 1990s (Haslett 2006:3–30; Smith 1999:2–4). Their first raft was rigged with a square sail that was very difficult to manipulate (Haslett 2006:53–54), and their subsequent rafts were rigged with European-style lateen sails (Haslett 2006:152–53), which, according to other sources, were not used prior to the Spanish invasion (Johnstone 1980:10–12). In 2006, Thor Heyerdahl's grandson, Olav Heyerdahl, built a balsa raft that successfully recreated the Kon-Tiki voyage across the Pacific (Higraff 2006:1). This raft, the Tangaroa, was rigged with square sails affixed to a yard that could be rotated about the mast. Although one piece of evidence—a 1538 sketch by the sailor Cristóbal Rodríguez (Rostworowski 1970:157–59)—suggests early use of this rigging style, the
bulk of the historical evidence indicates extensive use of crescent-rigged sails (Edwards 1965b:66–71; Zárate 2001:153–56 [1555]; Sámano-Xerez 1937:66–67 [1534]; Estete 1968:66–69 [1555]). These experimental rafts thus featured sail designs largely unsupported by historical evidence. It is therefore difficult and potentially misleading to include these modern facsimiles in the data set used to evaluate ancient rafts’ functionality.

Our assumptions about pre Columbian raft design derive from sixteenth-century first-contact written and pictorial accounts. As we show, sail design is crucial to raft functionality.

THE RAFT MODEL

A raft has to fulfill a specific set of requirements to be considered functional: (a) its components must exhibit the appropriate dimensions and material properties to withstand a given set of external stresses; (b) it must be able to provide sufficient buoyant force to sustain the weight of its cargo and crew; (c) its sail must be able to extract enough power from the wind to overcome the hydrodynamic drag caused by the local water currents; and (d) it must have a service lifetime appropriate to its task. This article uses the historical data set to address each of these requirements in turn.

By evaluating these four functional requirements in the raft model we constructed, we were able to determine the feasibility of long-distance maritime travel between Ecuador and Mexico using balsa-wood sailing rafts. We also determined the rafts’ dimensional limits and, thereby, their potential cargo capacities.

THE DATA: DESCRIPTIONS OF RAFT DESIGN

Sixteenth- and seventeenth-century accounts of raft design provide information regarding the materials used to make balsa rafts, raft dimensions, the types of sails, and the design and dimensions of the steering mechanisms.

Agustín de Zárate, a Spanish chronicler who lived in Pera in 1543 while supporting Gonzalo Pizarro’s rebellion against the king of Spain, describes the base of a balsa raft in his 1555 Historia del descubrimiento y conquista de las provincias del Pera (Zárate 2001:155). He reported that the logs forming the base of the raft “are always of an odd number, commonly five, and sometimes seven or nine” (Zárate 2001:155). His account then says the logs were laid out such that “the middle one is longer than the others, like a wagon tongue, . . . thus the balsa is shaped like an outstretched hand with the fingers diminishing in length” (Zárate 2001:155). Girolamo Benzoni, an Italian trader who encountered balsa rafts in Peru in the 1550s, corroborates this account in his 1565 Historia del Mundo Nuevo (Benzoni 1989:223–24). He says that the rafts are “made of three, five, seven, nine, or eleven very light logs, formed in the shape of a hand, in which the middle one is longer than the others” (Benzoni 1989:223–24).

Francisco de Sámano-Xerez, who traveled with Francisco Pizarro on his second expedition to the west coast of South America, provides additional information about the raft base framework (Sámano-Xerez 1937:66 [1534]). Sámano-Xerez sailed in a ship piloted by Bartolome Ruiz de Estrada, discussed earlier. Off the coast of Ecuador, they encountered a balsa raft “made with crosspieces and underbody of some poles as thick as pillars, lashed together with line made of henequen (Agave sisalana), which is like hemp. The upper works were of other thinner poles, also lashed with line, on which the people and merchandise rode so as not to get wet, since the lower part was awash” (Sámano-Xerez 1937:67).

Agave sisalana, commonly known as sisal, is a fibrous plant still used today to make durable rope that is especially resistant to deterioration in seawater.

Miguel de Estete, who was on the same ship as Ruiz and Sámano-Xerez, described the raft as follows:

these balsas are of some very thick and long wooden logs, which are as soft and light on the water as cork. They lash them very tightly together with a kind of hemp rope, and above them they place a high framework so that the merchandise and things they carry do not get wet. They set a mast in the largest log in the middle, hoist a sail, and navigate all along this coast. They are very safe vessels because they cannot sink or capsize, since the water washes through them everywhere (Estete 1968:66–68).

Figure 4 is a drawing of a balsa raft by the Dutch envoy Joris van Spilbergen, who published an account of his travels, Speculum Orientalis Occidentalis Indiae Navigationem, in 1619. Figure 5 is our model (made using the computer-aided design program SolidWorks) of the base of the raft, based primarily on Spilbergen’s drawing, showing the balsa hull logs, crosspieces, and a set of thinner poles forming a deck, as well as centerboards and two curved masts.

Figure 4, 1619 drawing of balsa raft by Joris Van Spilbergen (from Edwards 1965b), indicating a sailor manipulating a crescent-shaped sail and sailors manipulating centerboards (image courtesy University of California Press).
Emilio Estrada (1955:145) and Clinton Edwards (1965b:74), researchers who experimented extensively with the sailing capacities of balsa rafts, have maintained that the centerboards depicted in the Joris van Spilbergen drawing are a crucial design element. Because balsa rafts have a large area in contact with the water and they present a fairly non-planar profile, it would be impossible to sail one without a stabilizing mechanism below the waterline (Edwards 1965b:73–74). The Spilbergen illustration shows that balsa rafts were steered not with a rudder but with three sets of centerboards: one set in the bow, one set in the stern, and one set in the middle of the boat (Edwards 1965a:351). Figures 4 and 5 show the centerboards’ approximate placement on a balsa raft.

Based on a number of historical sources, both Estrada and Edwards maintain that ocean-going balsa rafts had crescent-shaped sails, with backwards-curving leading and trailing edges (Estrada 1955:146–47; Edwards 1965b:67–69). These highly efficient sails would have given the rafts a considerable amount of maneuverability. As shown in Figure 4, a rope affixed to the top of the masts pulls on and curves the masts downward, giving the sails their characteristic crescent shape. The degree of mast curvature could be adjusted to increase sail efficiency when sailing at different angles to the wind (van Dam 1987:570).

STRESS PATTERNS AND RESULTING CONSTRAINTS IN RAFT COMPONENTS

A functional raft must be able to endure a given set of stresses without breaking or permanently deforming. These stresses, caused by the wind, water, rigging,
The magnitude of the wind force depends on the area of the sail. Assuming a ratio of 2:1 for sail height to sail width, based on historical sources, we obtain a correlation between the height of the mast and the force of the wind (wind load) that the mast would have to sustain. The wind forces on the sail that are transmitted to the mast can be broken down into two perpendicular components, lift force and drag force. Figure 7 shows the direction at which these forces act on the raft. The coefficients describing the lift and drag forces vary according to the point of sail (Larsson and Eliasson 1996:76). The sum of the squares of these coefficients is greatest when a boat's forward velocity is approximately 60 degrees from the apparent wind velocity, according to standard textbooks on yacht design (Larsson and Eliasson 1986:76; Marchaj 1988:45). The force of the wind on the mast is therefore greatest at this point of sail. These forces also depend on the magnitude of the apparent wind velocity. For our calculations, we set the velocity to 9 m per second, which is approximately the highest magnitude the raft would encounter while sailing between Ecuador and Mexico, according to available wind current data (International Research Institute/Lamont-Doherty Earth Observatory [IRI/LDEO] 2006).}

![Diagram](image)

**Figure 7. Components of wind and water forces acting on a raft.**

**Mast Taper Ratio**

The stress profile in the mast is also a function of the mast’s taper ratio (the ratio of the mast’s base diameter to its tip diameter) and the displacement of the tip of the mast, which varies as sailors change the tension on the rope as they pull on it. Increasing the taper ratio decreases the amount of force necessary to displace the tip of the mast by a given distance, but it increases the maximum stress. In particular, it causes a sharp peak in the stress profile in the upper portion of the mast. Decreasing the taper ratio flattens the stress profile and lowers the maximum stress. The mast must have some degree of taper, however, to decrease the amount of force necessary to displace the tip of the mast by a given fraction of its height.

We examined ratios of mast base diameter to mast tip diameter ranging from 1 to 10 in increments of 1, and we examined ratios of tip displacement to mast height from 5% to 50% in increments of 5%. According to this analysis, the maximum ratio of tip displacement to mast height that can be achieved without mast fracture is 20%. This displacement is possible on masts with a base to tip taper ratio of 2. Taper ratios and curvatures greater than these values result in localized stresses with sufficient magnitude to break the mast.

**Safety Factors**

A computer simulation written by L. Dewan in MATLAB (<www.mathworks.com>) determined the stresses along the mast induced by the rope and the wind for a range of mast heights and diameters. Because the maximum wind stress and rope-induced stress do not always occur in the same place, it is necessary to sum the stresses at each point along the mast, then take the maximum of this sum. A mast must be able to withstand the sum of these stresses.

Figure 8 shows a contour plot of the safety factors for feasible mast geometries. The safety factor is defined as the stress at which the mast breaks divided by the maximum stress present in the mast. According to our computer simulation, given the constraints we have described, 1.5 is the largest possible safety factor the mast could sustain. The mast geometries corresponding to this safety factor are encircled by the 1.5 contour line. This safety factor is fairly low by modern standards; it is considered good engineering practice to include a safety factor of at least 2 or 3 for features as critical as a ship’s mast. A safety factor is included because a well-designed mast must be able to withstand unanticipated stresses.

![Contour Plot](image)

**Figure 8. Mast safety factors as a function of mast height and base diameters.**

The mast is modeled as a cantilevered beam (encastred at the raft’s deck) with a 2:1 taper ratio and enduring 9 m/s winds. The dashed line indicates the geometries that require 1,800 newtons of force to displace the mast tip by 20% of the mast’s height.
These stresses would come most likely from unexpected gusts of wind, above and beyond the 9 m per second of wind the mast was designed to tolerate. Table 1 shows the approximate maximum wind gust velocity that the masts could endure, as indexed by their safety factors.

**TABLE 1**

Approximate maximum endurable gust velocity, assuming a mast configuration with a given safety factor.

<table>
<thead>
<tr>
<th>Safety Factor</th>
<th>Maximum Gust Velocity (m/s)</th>
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<tbody>
<tr>
<td>1.0</td>
<td>9</td>
</tr>
<tr>
<td>1.1</td>
<td>10</td>
</tr>
<tr>
<td>1.2</td>
<td>11</td>
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<tr>
<td>1.3</td>
<td>12</td>
</tr>
<tr>
<td>1.4</td>
<td>16</td>
</tr>
<tr>
<td>1.5</td>
<td>18</td>
</tr>
</tbody>
</table>

Masts with a safety factor of about 1.4 could endure gusts up to 16 m per second before lowering their sails. It is highly likely that the Ecuadorian balsa rafts would have encountered unexpected gusts of this magnitude as they sailed, which suggests that the masts almost certainly were built with a safety factor of at least 1.4 (IRI/LDEO 2006).

**Mast Height**

Figure 8 relates a set of feasible mast heights and diameters but places no restriction on the maximum mast height. It is necessary, therefore, to look at another variable to determine the maximum mast height. This factor is the amount of force required to displace the tip of the mast a given distance. It is important to minimize the force required to displace the tip of the mast, because the degree of displacement of a crescent sail must be adjusted frequently to maximize its efficiency when sailing at different angles to the wind. If the necessary rope force is too great, it would be difficult to adjust the sail frequently because that would require more individuals pulling to generate sufficient force. We assumed that three sailors weighing about 60 kg each could apply their combined body weight, approximately 1,800 newtons of force, to a rope tied to the mast tip in order to displace it.

The dashed line in Figure 8 indicates the mast dimensions that require 1,800 newtons of force to displace the mast tip by 20% of its height. Masts below this line require more than 1,800 newtons to generate the displacement and are therefore considered not feasible. The maximum possible mast height occurs near the intersection of the 1,800 newton bending force line and the 1.4 safety factor line. This intersection describes a mast approximately 7.5 m tall and 0.16 m in diameter. Stress analysis does not impose a lower limit on the mast height.

**Sail Area and Raft Length**

The stresses in the mast provide an upper limit on possible mast heights. The mast height limits the maximum sail area, which in turn limits the potential size of the raft. It is necessary to determine the possible sizes of the raft base because these dimensions factor into the raft’s cargo capacity and buoyancy. Capacity and buoyancy are analyzed more explicitly in the following section.

The wind generates lift and drag forces on the sail, as shown in Figure 8. The forces that drive the raft in the desired direction are a function of these lift and drag forces, which are calculated using appropriate lift and drag coefficients. The forward-driving force decreases as the raft sails closer to the wind.

While the wind force drives the raft forward, the hydrodynamic drag force always acts opposite to the raft’s direction of motion. Setting the forward-driving force and the hydrodynamic drag force equal to each other describes a raft that is moving forward at a constant velocity. The resulting equation gives the raft’s maximum wetted area as a function of its sail area. We converted wetted area to arrive at sail length. Assuming that the length of a typical Ecuadorian raft was 1.5 times longer than its width, following Figure 4 (Edwards 1965b:74), a raft with two 7.5-m masts, the tallest possible mast heights given our computations, would be able to propel an 11-m-long raft.

The Centerboards

The raft’s three sets of centerboards are also subject to dimensional constraints. They must withstand the stress generated by forces that push the raft perpendicular to the desired direction of motion. The magnitude of this perpendicular force is a function of the wind lift and drag forces.

Estrada (1955) and Edwards (1965b) built model balsa rafts in the 1950s to test centerboard steering methods. Removing some of the bow centerboards swings the bow away from the wind, as the force of the wind on the sail causes the raft to pivot along the stern centerboards, removing the stern centerboards swings the stern away from the wind (Dewan 2004:1–3; Estrada 1955:143). We also found this to be the case in a 3-m-long model raft we launched in the Charles River in 2004 (Dewan 2004:2).

For a given below-water depth and width, thicker centerboards experience a lower maximum stress. However, the boards must also be thin enough to fit in the gaps between the balsa hull logs. The centerboard geometries tested in our simulations ranged in thickness from 0.01 to 0.10 m, with a below-water depth of 2 m and width of 0.5 m. The maximum stress in the centerboards is on the order of a few hundred kilopascals for all tested geometries. For example, the side force generated by a raft with two 7.5-m masts sailing 60 degrees from the wind would generate a maximum stress of 320 kilopascals in a centerboard with thickness of 0.05 m. The modulus of rupture of native hardwoods is on the order of 100 megapascals (United States Department of Agriculture 1999: Table 4-5); thus there is little chance that this side force could approach a magnitude high enough to snap a centerboard.

In addition to steering the raft, the centerboards also minimize the velocity at which the raft drifts perpendicular to the desired direction of motion. Increasing the below-water centerboard area lowers this perpendicular velocity. However, increasing this area also increases the raft’s hydrodynamic drag.

Setting the perpendicular force on the raft equal to the force the water exerts.
on the centerboards ensures that the raft is not accelerating perpendicular to the
desired direction of motion. This equality describes a relation between the raft’s
forward velocity, its perpendicular velocity, and the centerboard area. The raft’s
sideways velocity should be less than 1/10—an order of magnitude—of its forward
velocity. A raft with two 7.5-m masts would require about 12 m² of centerboards
below the water to maintain this velocity ratio. Our model’s calculations assume
centerboards with below-water depth of 2 m and width of 0.5 m.

By analyzing the stress patterns in the raft’s components we are able to
determine the raft’s size constraints. The mast height limits the raft’s sail area, which
in turn limits the size of the raft base and the necessary number of centerboards.
Knowing the size of the raft’s base allows us to determine its cargo capacity.

RAFT BUOYANCY AND CARGO CAPACITY

Another step in the analysis approximates the cargo mass that a balsa raft could
carry. These calculations assume that the base of the raft is approximately 11
m long by 7 m wide. These dimensions represent the maximum feasible raft
size according to our model. Balsa logs of this length would have a diameter of
approximately 0.9 m when stripped of their bark.

The quantity of goods that the raft could carry is a function of the mass of the
balsa hull logs and deck risers, hardwood crossbeams, decking, mast, and number
of crew members. A raft of this size would need at least six crew members: three
manning the sails and one person on each of the three sets of centerboards.

If the hull logs were 75% submerged, the raft could carry approximately 30
metric tons of goods. This below-water value is a conservative estimate; none of
the relevant historical sources describes the degree to which the logs were
submerged. This calculation assumes that the rafts were built using dried balsa
wood, which has a density of approximately 150 kg per cubic meter, rather
than with green wood. The logs provide less buoyant force the longer they are
in use because of waterlogging, decomposition, and damage by marine borers.
This decomposition is discussed in greater detail in a subsequent section.

RAFT INTERACTIONS WITH VARYING
WIND AND WATER CURRENTS

The wind and ocean currents on the west coasts of South and Central America
vary significantly from month to month, making certain times of year particularly
amenable or inhospitable to sailing either north or south. We investigated the
monthly variation in these conditions and determined at what times of year a
balsa raft would be able to sail north from Ecuador to West Mexico or south for
the return voyage.

The coasts of Ecuador and Central America experience a torrential rainy
season. The severity of these weather patterns would preclude any sailing. The
rainy season in Ecuador lasts from January to early May, and the rainy season
on the Pacific coast of Central America and Mexico occurs from approximately
May to October. A balsa raft would not be able to sail during these times of year.

Likewise, it would have been very difficult to sail during El Niño events, which
manifest off the coast of Ecuador as torrential rains beyond the regular rainy
season. El Niño events, caused by anomalously low pressure differences between
the east and west equatorial Pacific, have occurred approximately once every 2 to
8.5 years since 3000 bc (Mann 2007:111).

We performed analyses to determine the feasible times for sailing during the
dry season. The size of the raft determines the months it can be sailed. Larger rafts
have both larger sails and a larger wetted area. They can therefore extract more
power from the wind but are also subject to a larger drag force from the water. We
first analyzed the aerodynamic and hydrodynamic characteristics of a raft base
that measures 11 m by 7 m with two 7.5-m-tall masts. We modeled the monthly
variations in the raft’s interaction with the changing wind and water currents. This
modeling allows us to determine the times of year at which the raft could be sailed
in a particular direction.

Our analysis was performed using modern wind and ocean current data.
There does exist evidence that the earth’s wind and ocean currents have varied
over time in both magnitude and direction (Aceituno 1988:505; Rodbell et al.
1999:516; Stocker 1999:370). However, this evidence strongly suggests that the
most recent major change in circulation patterns occurred approximately 5,000
years ago (Rodbell et al. 1999:516; Stocker 1999:370). The prevailing currents in
AD 700 would not be significantly different from modern circulation patterns
(Mann 2007:111), and we therefore find it reasonable to use modern data in the
calculations.

Charts showing the monthly averages of ocean surface current velocity in
the year 2000 and charts showing the monthly averages of wind current velocity during
this same time period were obtained from Columbia University’s International
Research Institute/Lamont-Doherty Earth Observatory Climate Data Library
(IRI/LDEO 2006). The ocean surface current charts indicate the highest velocity
water currents that the raft would have to overcome. These currents generate a
hydrodynamic drag force on the raft. The magnitude of the drag force depends
on the apparent velocity of the raft with respect to the surface of the water. The
directions, magnitudes, and locations of the three largest hull drag forces were
recorded for each month.

Using the wind charts and a simulation program written by L. Dewan in
MATLAB, we determined the wind speed and direction in the vicinity of the
largest hydrodynamic drag forces. Estimating the lift and drag coefficients for
the particular point of sail, we calculated the wind driving force pushing the
raft in the desired direction. We then compared this wind driving force with the
hydrodynamic drag opposing the raft’s motion. The raft can overcome an ocean
current at a time of year when the component of the wind force pushing the raft
forward has a greater magnitude than the water drag force opposing its motion.

We then examined the wind current charts separately to determine whether
wind forces alone would be strong enough to prevent the raft from sailing at
certain times of year. Assuming that the raft can sail within 60 degrees of the
wind, there is no time during the year in which the wind currents alone are great
enough to prevent the raft from sailing either north or south. Figure 8 shows the
components of the lift and drag forces, which can be resolved into driving and side forces, that act on the mast and are transmitted to the raft, as well as the water drag that opposes the motion of the base of the raft.

A raft with two 7.5-m masts could sail south to north from September to early January or in June. Sailing in this direction would be easiest in early December. A raft with the same dimensions could sail south to north from January to March or in September. Based on the wind and water currents, sailing from north to south would be easiest in late March.

We performed similar analyses for rafts with different dimensions. Larger rafts have both larger sails and a larger wetted area. They can extract more power from the wind, but they also experience a larger water drag force. In general, the magnitude of the increase in wind force is significantly greater than the increased water drag, so that larger rafts with larger sails have significantly greater leeway in what times of year they can sail. This again is constrained by the torrential rainy seasons that disallow sailing during these periods.

A 6-m-long raft with a single 6-m mast appears to be the smallest that could travel in both the south-north and north-south directions. The corresponding minimum mast height for a two-masted raft is approximately 5 m. These rafts would be able to sail north only in December, and south in late March. Even at those times, the net forward force on the raft is fairly small, so that the raft has very little leeway in navigation. Given our discussion of the time required for Andean metalworkers to introduce metallurgical technologies, our opinion is that South American voyagers most likely remained in Mesoamerica for the duration of the year.

Based on this analysis, it seems likely that the rafts that made the journey had two sails because the additional sail area greatly increases the power the rafts can extract from the wind. The maximum mast height, as determined in the previous section, is 7.5 m, and the minimum mast height for a two-masted raft is 5 m.

**BALSAM WOOD DURABILITY IN A MARINE ENVIRONMENT**

The balsa hull logs are the most important factor limiting the raft’s functional lifetime. Balsa wood decomposes very quickly owing to its low density, and it does not naturally contain chemicals such as siliques that repel microorganisms, insects, or mollusks that would damage it. Like other woods, balsa (which means “raft” in Spanish) decomposes more rapidly in salt water than in freshwater because of the larger numbers of wood-consuming invertebrates that live in salt water. *Teredo navalis*, the common shipworm, causes the most significant damage to a balsa vessel (Lewis and Hall 1983:6). Teredoids, which live throughout the Atlantic and Pacific, are wood-boring mollusks that subsist entirely on cellulose. Although some researchers believe that shipworms were introduced to South America on Spanish ships in the sixteenth century (Kristensen 1979:239), it is possible that the mollusks were native to the region. Because shipworms’ effects on raft viability are so pronounced, we elected to assume that they were extant in South America prior to the Spanish invasion. Some sources argue that balsa logs were likely coated in tar to decrease the extent of shipworm infestation (Haslett 2006:136). Though sources of tar are present on the Ecuadorian coast, there is no archaeological evidence that tar was used in raft building; therefore we do not include it in our calculations.

The evidence describing balsa decomposition in a marine environment comes from a study conducted by Lewis and Hall. Both the balsa blocks in that experiment, which were partially coated with a glass-plastic laminate, and the partially submerged balsa hull logs of an Ecuadorian raft have approximately the same ratio of surface area to volume (Lewis and Hall 1983:2). Since these ratios are the same for both balsa geometries, the balsa blocks and the balsa logs decompose at approximately the same rates. According to Lewis, the blocks lost 16% of their volume over the course of six months. Assuming that the 7,000-km round trip between Ecuador and Mexico takes about four months, a raft would lose about 10% of its balsa wood during each round trip, if it was kept out of the water between the outboard and return trips.

Shipworms caused extensive damage to the rafts Haslett and Smith built for their expeditions in the 1990s, forcing an end to the *Illa-Tiki* Expedition of 1995 and the *Manahu* Expedition of 1998 (Haslett 2006:116, 120; Smith 1999:10–12). Haslett declared the rafts structurally unsound after three and two months at sea, respectively (Haslett 2006:120, 152, 186). He estimates that shipworm infestation ultimately destroyed approximately one third of the wood in the *Illa-Tiki*’s hull logs (Haslett 2006:116). The *Manahu*’s hull logs, although coated with antifouling paint, also suffered significant damage (Haslett 2006:152, 184). This deterioration rate is significantly more rapid than Lewis and Hall’s experiments predict (Lewis and Hall 1983:1).

These two rafts may have experienced such rapid hull log deterioration because they both remained stationary in harbors for several weeks (approximately five weeks for the *Illa-Tiki* and two weeks for the *Manahu*) after they were constructed (Haslett 2006:25 30, 108 12, 153–56). Shipworms thrive in harbors because wooden pilings and ships serve as a plentiful food source (Lewis and Hall 1983:2). Leaving the rafts in harbor for so long likely made the shipworm infestation and consequent damage more severe.

Hull log degradation greatly affects the weight of cargo that the rafts can hold. The shipworms not only decrease the logs’ buoyancy as they destroy the balsa wood, but the wood weight loss also significantly decreases the wood’s modulus of rupture. Though the balsa hull logs are not subjected to significant stresses in calm seas, the waters off the west coast of Central America are frequently and unpredictably very rough. The waves induce the maximum stress in the raft base when the raft is supported by two wave peaks close to the bow and stern. Though water can flow through the raft base, fast-moving waves could temporarily hold the raft in this position.

Undamaged balsa wood with 25% moisture content has a modulus of rupture of about 15 MPa (United States Department of Agriculture 1999: Table 4-5). This value is high enough so that it does not place a realistic upper limit on a raft’s cargo capacity. According to an analysis of the effect of termite damage on wood strength, losing 10% of the wood weight decreases the modulus of rupture by about 75% (DeGroot et al. 1998:27–31). A damaged balsa log with its modulus of
rupture decreased by this amount would not be strong enough to support a large cargo in rough seas.

After four months in the water, the time for one round trip between Ecuador and Mexico, an 11-m-long raft would be able to hold 10 tons of cargo, or one third of the maximum cargo capacity of a new raft. After two round trips the raft could hold only 5 tons. From this analysis, it seems likely that the rafts were not in use in the water for more than eight months. It would be inefficient to send a raft and crew so long a distance with so small a cargo.

CONCLUSIONS

This mechanical and materials engineering analysis shows that prehistoric balsa rafts were fully functional sailing vessels that could have traveled between coastal Ecuador and the west coast of Mexico. Our research demonstrates that these rafts could feasibly measure between 6 and 11 m in length and would require two masts of heights between 5 and 7.5 m. Balsa rafts in this size range had a cargo capacity between 10 and 30 metric tons, which is the same capacity as nineteenth-century Eric Canal barges (Leverett 1966:452). Balsa rafts' remarkable ability to hold and carry large cargoes made them an ideal means of long-distance transport, and would have allowed Ecuadorian traders to avoid a host of difficulties that would have accompanied overland travel. Traveling between Ecuador and West Mexico via an overland route would have necessitated negotiating the complex and varied physical and sociopolitical terrain of the Intermediate Area (notably the Darien region of the Isthmus of Panama) and southern Mesoamerica. A maritime route circumvented these significant logistical and security risks.

Ecuadorian balsa rafts were capable of making at least two round-trip voyages between Ecuador and West Mexico before they became inoperable. Assuming that the raft could sail at 4 knots, and that it traveled about 12 hours per day, it would take between six and eight weeks to complete the 3,000-km voyage between these two regions. Data from our current analyses show that the sea-going traders would most likely have left Ecuador in early December and arrived in Mexico in late January, taking advantage of the favorable wind and water currents. The rafts could travel south again in March, at the earliest, carrying their cargo of Spondylus shells. Leaving Mexico in late March would have allowed the sailors to avoid the rainy season in Ecuador, which ends in early May. It is likely that at least some of the Ecuadorian sailors chose to sail at this time, to deliver their newly acquired trade goods quickly to their home port. However, ethnographic evidence suggests that some sailors elected to remain in West Mexico throughout the Mexican rainy season, or perhaps for even longer stretches of time. In particular, a 1525 document written in Zacatula, Mexico, by the royal accountant Rodrigo de Albornoz describes native accounts of 'Indians from certain islands to the south [who]...brought exquisite things which they would trade for local products... [and] those that had come would stay for five or six months until good weather occurred' (West 1961:133). Leaving in September, which corresponds to a six-month layover, would be feasible according to our analyses, though the wind and water currents would not be as favorable to southerly travel as those present in

late March. It is also possible, though unsupported by available archaeological or ethnohistorical evidence, that some Ecuadorian mariners spent a full year in West Mexico, leaving on another trading vessel sailing south the following March. Hosler has argued elsewhere (1988a:852) that long layovers such as these were necessary for the Andeans to communicate their metallurgical knowledge and techniques—knowledge of ore deposits and smelting regimes, and techniques such as lost-wax casting, cold-working, and others—to their West Mexican trading partners.

The sudden florescence of skilled, complex metallurgy in West Mexico in AD 700, rooted in the metallurgy of two Andean regions, has raised the fundamental issue addressed in this paper: Were balsa sailing rafts—given their design, mechanical, and materials characteristics, and considering Pacific coast weather patterns, ocean currents, and other variables—capable of making a round-trip cargo-carrying voyage between Ecuador and West Mexico? Our study has shown that these rafts were not only capable of making the voyage, but were indeed the optimal solution to these ancient peoples' transport problem. Our work shows that a raft designed to tolerate the wind and water stresses it encountered would have a maximum cargo capacity (30 metric tons) that approximates the weight of the Spondylus shell it could have carried. A maximum Spondylus cargo of 225,000 oysters occupies 40 m² of raft space, thereby precluding shipment of other items. No data exist concerning the quantities of Spondylus traded into the Andean highlands per year, nor how many rafts participated in each voyage. Our calculations raise the possibility that these traders may have voyaged in more than one raft—which is highly likely—and this possibility provokes new questions concerning other items that might have been transported from West Mexico to this Andean region.

NOTES

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1. Spondylus shell was sacred in the Andean region and especially in the Andean highlands, where it was used for rainmaking ceremonies. Because Spondylus requires a warm water habitat, it cannot survive in the waters off the coast of Peru, which are governed by the extremely cold Chile-Peru (Humboldt) current. It thrives, however, in the warm waters from the Gulf of Guayas north to the Gulf of Mexico. The cultural importance of this shell made the acquisition, processing, and exchange of Spondylus a major economic activity in the Andean region.

2. A 1535 sketch by Girolamo Benzoni (1989:223-24) shows fishermen padding a balsa raft rigged with a square fixed sail, like the Kon-Tiki raft. Because prevailing winds never blow directly north from Ecuador to Mexico, this type of craft could not have been used for transport between the two continents.

3. Calculations at the end of this section take into account the larger, unexpected gusts of wind the raft might encounter.
4. Equating the hydrodynamic drag and forward-driving forces acting on a raft gives the following relation between raft base area and sail area:

\[ A_{\text{raft}} = \frac{C_L \rho_{\text{air}} A_{\text{app}} V_{\text{app}}^2 \sin \beta - C_D \rho_{\text{air}} A_{\text{app}} V_{\text{app}}^2 \cos \beta}{\rho_{\text{water}} V_{\text{rms}}^2 C_s} \]

where \( C_L \), \( C_D \), and \( C_s \) are the lift, drag, and friction coefficients, \( \rho_{\text{air}} \) is the density of air, \( \rho_{\text{water}} \) is the density of seawater, \( \beta \) is the angle between the sail and the wind, \( V_{\text{rms}} \) is the raft velocity with respect to the shore, \( V_r \) is the raft's velocity with respect to the water, and \( A_{\text{app}} \) is the area of the raft's sails.

5. The authors gathered data on oyster weight and volume from Wellesley oysters (Crassostrea virginica) consumed at Legal Sea Foods in Cambridge, MA. C. virginica have mass and volume comparable to those of Spondylus oysters. The average weight of two matching oyster shells was 0.13 kg. Assuming a maximum raft cargo capacity of 30 tons, a raft could carry approximately 225,000 Spondylus oysters, which would have a total volume of approximately 40 cubic meters.

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