Ancient Maritime Trade Between Ecuador and Western Mexico on Balsa Rafts: An Engineering Analysis of Balsa Raft Functionality and Design

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Abstract:

By approximately 100 BCE Ecuadorian traders had established extensive maritime commercial routes reaching from Chile to Colombia. Historical sources indicate that they transported their merchandise in large, ocean-going sailing rafts made of balsa logs. By about 700 CE the data show that Ecuadorian metalworking technology had reached the west coast of Mexico but remained absent in the intermediate region of Central America. Archaeologists have argued that this technology was most plausibly transmitted via balsa rafts. However, no remains of pre-Columbian rafts have been found in West Mexico. This paper uses mathematical simulation of balsa rafts' mechanical and material characteristics to determine whether these rafts were suitable vessels for long-distance trade between Ecuador and Mexico. Using historical accounts of the rafts as a data set, we model their aerodynamic and hydrodynamic properties, their buoyancy and cargo capacity, their functional lifetime, and the load-bearing capacities of their components. Our analysis shows that these prehistoric rafts were fully functional sailing vessels that could have navigated between Ecuador and Mexico. This conclusion greatly strengthens the argument that Ecuadorian metallurgical technology was transmitted from South America to Western Mexico via maritime trade routes. Our conclusions, obtained from mechanical and materials engineering analysis, further demonstrate the overall utility of applying engineering methods to archaeological and historical studies.

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 700 CE (1). Archaeologists have argued that metallurgical knowledge and techniques were most plausibly transmitted north via a maritime route with a base in coastal Ecuador (1,2,3). 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 Ecuador to West Mexico.

Archaeological data also attest to the fact that by approximately 100 BCE Ecuadorian traders had established maritime commercial routes reaching from Chile to Colombia (4,5). These traders transported their merchandise, which included metal ornaments, emeralds, and *Spodylus* oyster shells, in large, ocean-going sailing rafts made of balsa logs.[1] Unfortunately, no remains of pre-Columbian rafts have been recovered in West Mexico; however, a sixteenth century document from Zacatula Michoacan does report that large, narrow vessels *(piraguas)* from "islands to the south" arrived at that port bringing rich cargoes to trade (6).

This paper determines whether these Ecuadorian balsa wood rafts were suitable vessels for long-distance trade between Ecuador and Mexico. Sixteenth and seventeenth century European invaders, who were sailors themselves, observed these craft and describe them in sufficient detail that we use those descriptions as the data set for our model. To ascertain whether these craft could have reliably carried large quantities of goods between the two regions, we model four key aspects of their design mathematically . We evaluate their aerodynamic and hydrodynamic properties, their buoyancy and cargo capacity, their functional lifetime, and the load-bearing capacities of their components.

Overview of Past Research

Several contemporary sailors have undertaken voyages attempting either to promulgate a theory of transpacific migration or to recreate the voyages from Ecuador to West Mexico (7,8,9). During the last century the researchers Thor Heyerdahl and Cameron Smith experimented independently with balsa rafts' sailing abilities. Heyerdahl sailed the 45 foot balsa raft Kon-Tiki from Callao, Peru to Polynesia in 1947. The square rig used on Heyerdahl's raft does not replicate the pre-European sail design accurately and furthermore, was only capable of sailing directly downwind. The fixed square sail used on his raft lacks the maneuverability to sail up or down the coast of Central America (7). Cameron Smith attempted several ultimately unsuccessful voyages from Ecuador to West Mexico in the 1990s (8). His rafts were rigged with European-style lateen sails, which according to our sources were not used prior to the Spanish invasion (10). In 2006, Thor Heyerdahl's grandson Olav Heyerdahl built a balsa raft to recreate the Kon-Tiki voyage across the Pacific. His raft, named the Tangaroa, also used a European sail design that did not appear in Ecuador until the eighteenth century.

In all three cases, the design of the sails on these modern facsimiles fail to replicate that of the sixteenth century indigenous rafts. Our assumptions about pre-Columbian raft design derive from first-contact written and pictorial accounts from the sixteenth century. Careful inspection of the sixteenth

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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 Guayaquil 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.

century drawings depict simple crescent-shaped sails, whereas the sails used the other three expeditions are of distinctly European design (11,12). As we show, sail design is crucial to raft functionality.

The Raft Model

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. These accounts are described in detail subsequently.

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

By evaluating these four functional requirements in the model we constructed we determine the feasibility of long-distance maritime trade between Ecuador and Mexico using these balsa-wood sailing rafts. We also determine the rafts' dimensional limits, and thereby determine their potential cargo capacities. Furthermore, comparing balsa rafts' functional characteristics to those of feasible design alternatives allows us to address the social and economic variables that drove the historically documented design choices.

The Data: Descriptions of Raft Design

Agustin de Zarate, a Spanish historian who lived in Peru in 1543 while supporting Gonzalo Pizarro's rebellion against the king of Spain, describes the base of a balsa raft in his *Historia del descubrimiento y conquista de las provincias del Peru* (1555). He reported that the logs forming the base of the raft "are always of an odd number, commonly five, and sometimes seven or nine." 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" (13). Girolamo Benzoni, an Italian trader who encountered balsa rafts in Peru in the 1550s, corroborates this account in his 1565 *Historia del Mondo Nuovo*. 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" (14).

Francisco de 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. De Xerez sailed in a ship captained by Bartolome Ruiz, sent by Pizarro to explore the waterways of northern Peru in 1526. Near Peru's border with Ecuador they encountered a balsa raft "...made with crosspieces and underbody of some poles as thick as pillars, lashed together with line made of hennequen [*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" (15). *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 de 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.” (16)

Figure 1 is a drawing of a balsa raft by the Dutch envoy Joris van Spilbergen, who published an account of his travels called *Speculum Orientalis Occidentalis que Indiae Navigation* in 1619. Figure 2 is a CAD model of the base of the raft, showing the balsa hull logs, crosspieces, and a set of thinner poles forming a deck, as well as centerboards and two curved masts.

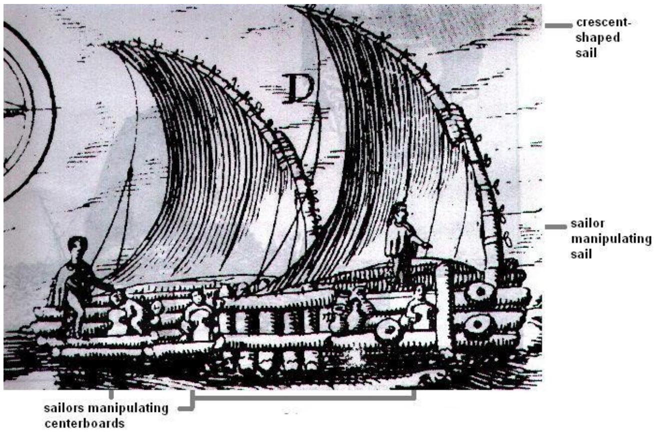

Figure 1. 1619 drawing of balsa raft by Joris Van Spilbergen. *Speculum Orientalis Occidentalis que Indiae Navigation*.

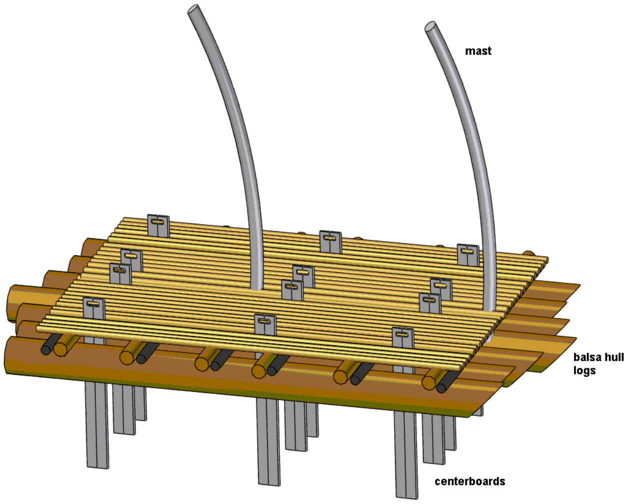

Figure 2. CAD model of raft base.

Emilio Estrada and Clinton Edwards, 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 (17,18). Balsa rafts have a large area in contact with the water and they present a fairly rough profile, so it would be impossible to sail one without a stabilizing mechanism below the waterline (18). The Spilbergen illustration makes clear 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 (18). Figures 1 and 2 show the centerboards' approximate placement on a balsa raft.

Based on a a number of historical sources, Estrada and Edwards maintain that ocean-going balsa rafts had crescent-shaped sails, with backwards-curving leading and trailing edges (17,18). These highly efficient sails would have given the rafts a great deal of maneuverability.[2] As shown in Figure 1, a rope affixed to the top of the masts curves them downwards, giving the sails their characteristic crescent shape. The degree of curvature could be adjusted to increase sail efficiency when sailing at different angles to the wind (19).

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

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[2] A 1535 sketch by Girolamo Benzoni shows fishermen paddling a balsa raft rigged with a fixed square sail. A raft rigged in this style can only sail directly downwind (Romola). Because prevailing winds never blow directly from Ecuador to Mexico, this type of craft could not have been used for transport between the two continents.

deforming. These stresses, caused by the wind, water, rigging, and gravitational forces, limit the feasible dimensions of the raft's components. The stress patterns and resulting dimensional constraints in the raft's mast are examined first.

The Mast

Following the historical record, the mast is modeled as an encastered tapered beam set into the center balsa hull log, perpendicular to the deck (17,18,20). Because the mast cannot rotate in its socket in the balsa hull log, setting it into the deck at an angle would result in a highly turbulent, inefficient sail geometry at all other points of sail (21). Forming a mast out of a curved piece of wood would likewise inhibit sail efficiency and maneuverability. The masts in Figure 1 are each made of two separate pieces of wood (12). Nonetheless, it is appropriate to model each mast as a single beam, under the assumption that there is minimal slip between the two pieces. We assume that the mast's wood has a modulus of elasticity of 10 GPa and a modulus of rupture of 100 MPa, which are approximately average values for hardwoods available in the Ecuadorian region according to the US Forestry Handbook (22). The Kon Tiki and Tangaroa masts were made of mangrove wood, and Smith's rafts had masts made of guayacan wood. Most hardwoods available in Ecuador have moduli of rupture and elasticity similar to these two woods. There is no historical data describing the types of wood used in pre-Columbian masts.

Stress in the mast is due to two independent forces: the force of the wind on the sail, and the force of the rope that gives the tip of mast its required displacement. Figure 3 is a free body diagram of the mast, showing the locations of the wind force (F_{wind}) and the force of the rope displacing the tip of the mast (F_{rope}).

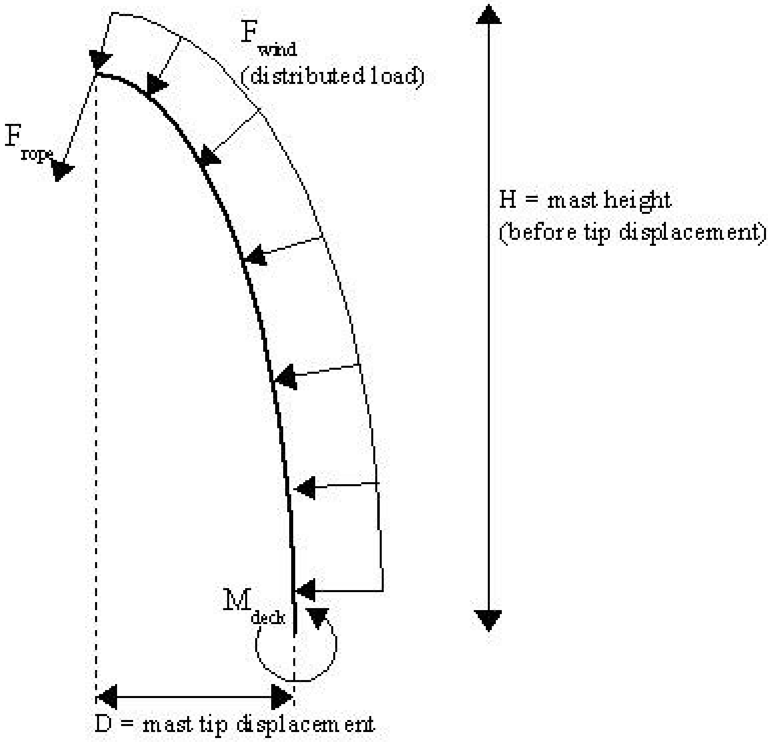

Figure 3. Free body diagram of the forces acting on the raft's mast. The mast is modeled as a tapered cantilevered beam, encastered at the deck end.

The magnitude of the wind force depends on the area of the sail. Assuming a ratio for the sail height to sail width, which is about 2:1 based on historical sources, gives a correlation between mast height and the wind load the mast would have to endure. The wind forces on the sail that are transmitted to the mast can be broken down to two perpendicular components, lift force and drag force. The coefficients describing the lift and drag forces vary according to the point of sail (23). 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 (23,24). 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 these calculations, the velocity was set to 9 m/s, which is approximately the greatest magnitude the raft would encounter while sailing between Ecuador and Mexico, according to available wind current data (25).[3]

The stress profile in the mast is also a function of the mast's taper ratio[4] and the displacement of the tip of the mast. Increasing the taper ratio decreases the amount of force necessary to bend the mast to a certain degree of curvature, 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 bend it a given fraction of its height.

A mast must be able to withstand the sum of these stresses. The computer simulation written by L. Dewan in MATLAB determined the stress induced by rope the wind along the mast 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. These vectors are parallel during some tacking and jibing maneuvers, so the stress magnitudes are summed directly.

We examined ratios of mast base diameter to 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 is 20%, and 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.

Figure 4 shows the feasible mast geometries superimposed on a contour plot of their safety The safety factor is defined as the stress at which the mast breaks divided by the maximum stress present in the mast. According to Figure 4, 1.5 is the largest possible safety factor the mast could have sustained, given the constraints we have described. This number 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. We include this factor because a well-designed mast must be able to withstand unanticipated stresses. These stresses would come most likely from unexpected gusts of wind, above and beyond the 9 m/s 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.

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[3] Calculations at the end of this section take into account the larger, unexpected gusts of wind the raft might encounter.

[4] The taper ratio is defined here as the ratio of the mast's base diameter to the mast's tip diameter.

Table 1. Approximate maximum endurable gust velocity, assuming a mast configuration of a given safety factor.

Safety Factor	Maximum Gust Velocity (m/s)
1.0	9
1.1	10
1.2	11
1.3	12
1.4	16
1.5	16

Masts with a safety factor of about 1.4 could endure gusts up to 16 m/s before lowering their sails. It is highly likely that the rafts would have encountered unexpected gusts of this magnitude as they sailed, which suggests that the masts almost certainly had a safety factor of at least 1.4 (25).

Figure 4 shows a set of feasible mast heights and diameters, but place 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 for required to displace the tip of the mast because the degree of displacement a crescent sail must be adjusted frequently to maximize its efficiency when sailing at different angles to the wind. If the necessary bending 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 approximately 1800 N of force—that is, their combined body weight—to a rope tied to the mast tip in order to bend it.

The thick line in Figure 4 indicates the mast dimensions that require 1800 N of force to displace the mast tip by 20% of its height. Masts below this line require more than 1800 N to generate the displacement and are therefore considered unfeasible. The maximum possible mast height occurs near the intersection of the 1800 N bending force line and the 1.4 safety factor line. This intersection describes a mast approximately 7 meters tall and 0.16 meters in diameter. Stress analysis does not impose a lower limit on the mast height.

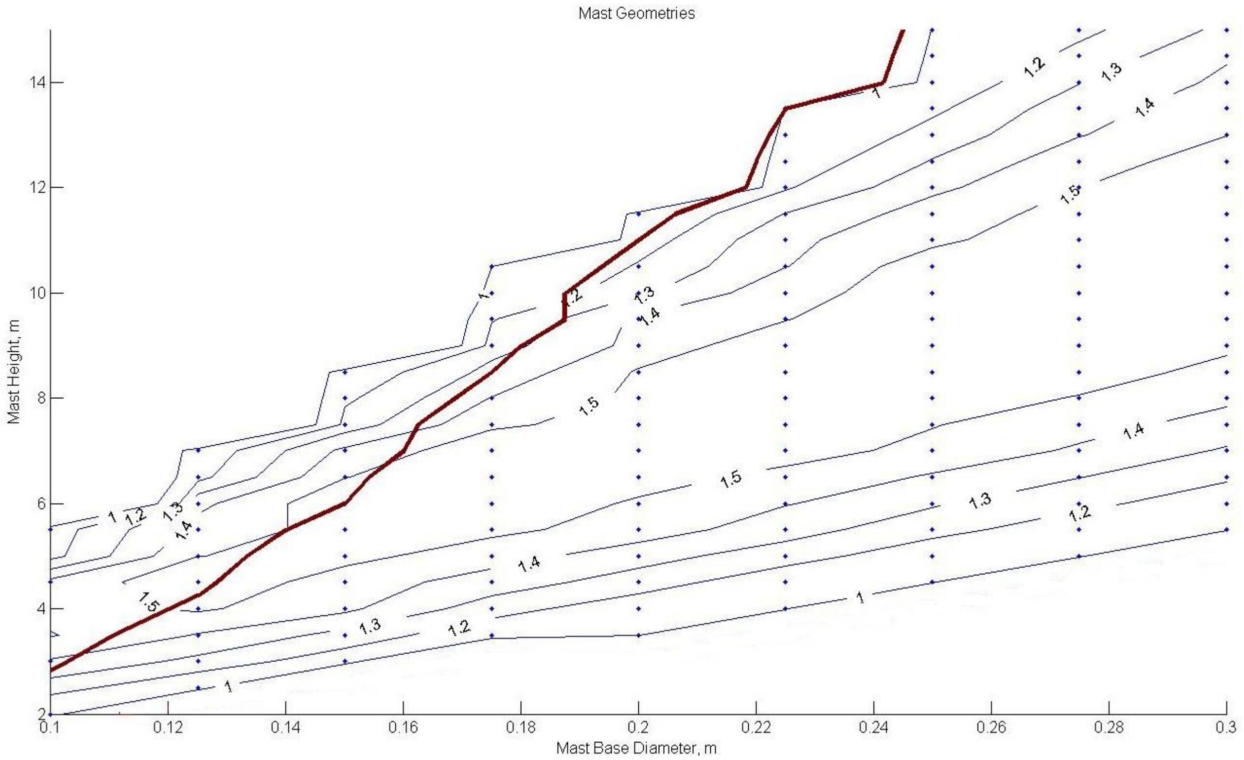

Figure 4. Mast safety factors and 1800 N force line

The Sail and Raft Length

The stresses in the mast provide an upper limit on the 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. 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 then converted wetted area to raft length by assuming that the raft's length was 1.5 times longer than its width, following Figure 1 (18). A raft with two seven meter masts, which are the tallest possible mast heights given our computations, would be able to propel an 11 meter 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 and Edwards 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 forces the raft to pivot along the stern boards; removing the stern centerboards swings the stern away from the wind (17, 26). We also found this to be the case in a 3 meter long model raft we launched in the Charles River in 2004 (26).

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 meters, with a below-water depth of 2 meters and width of 0.5 meters. The maximum stress in the centerboards is on the order of a few hundred kPa for all tested geometries. For example, the side force generated by a raft with two 7 meter masts sailing 60 degrees from the wind would generate a maximum stress of 320 kPa in a centerboard with thickness of 0.05 meters. The modulus of rupture of native hardwoods is on the order of 100 MPa (22), 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 of its forward velocity. A raft with two 7 meter masts would require about 12 square meters of centerboards below the water to maintain this velocity ratio. These calculations assume centerboards with below-water depth of 2 meters and width of 0.5 meters.

By analyzing the stress patterns in the raft's components we are able to determine the raft's size limitations. 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 of the analysis approximates the cargo mass that a balsa raft could carry. These calculations assume that the base of the raft is approximately 11 meters long by 7 meters wide. These dimensions represent the maximum raft size calculated in the previous sections of this paper. Balsa logs of this length would have a diameter of approximately 0.9 meters 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. It is certain that the logs must have been partially above water. 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 following section.

Raft Interactions with Varying Wind and Water Currents

The wind and ocean currents on the west coast 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 Mexico or south for the return voyage.

The west coast of South and Central America experiences a torrential rainy season. The severity of these weather patterns would preclude any sailing. The rainy season in Ecuador is from January to April, and the rainy season on the Pacific coast of central America and Mexico occurs from approximately May to October. A raft would not be able to sail in the vicinity of these countries during their rainy seasons.

We performed analyses to determine the feasible times for sailing during the dry season. The size of the raft limits 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 an 11 meter by 7 meter raft with two 7 meter 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.

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 IRI/LDEO Climate Data Library (25).

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, 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 to the hydrodynamic drag opposing the raft's motion. The raft can overcome an ocean current if the component of the wind force pushing the raft forward has a greater magnitude than the water drag force opposing its motion.

We then looked at the wind current charts separately to determine whether wind forces alone would be 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 5 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.

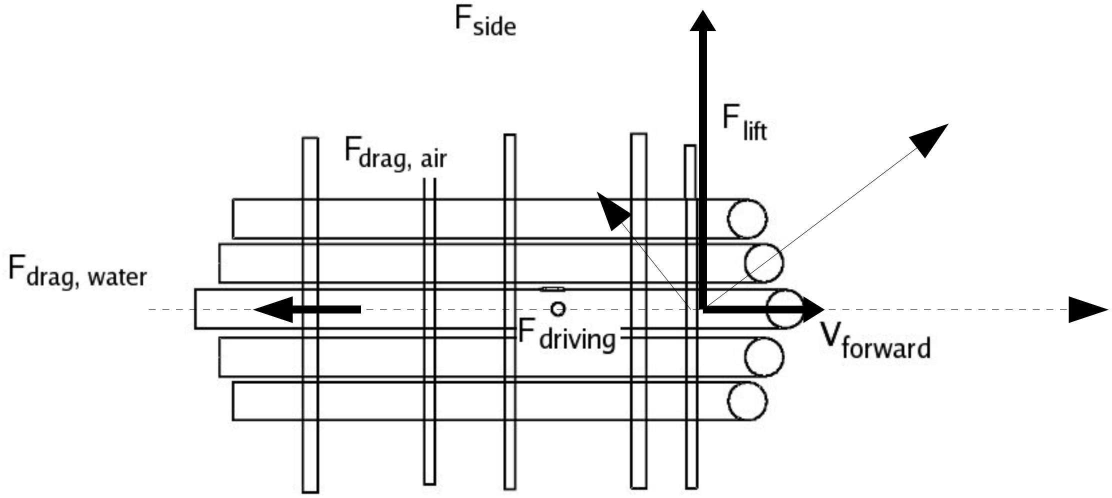

Figure 5. Wind and water forces on raft.

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

After completing this step, we performed a similar analysis 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 larger rafts with larger sails have significantly greater leeway in what times of year they can sail.

A 6 meter long raft with a single 6 meter 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 meters. These rafts would be able to sail north only in January-December, and south in early April. Even at those times, the net forward force on the raft is fairly small, so the raft has very little leeway in navigation.

Based on this analysis, it seems likely that the rafts that made this 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 meters, and the minimum mast height for a two-masted raft is 5 meters.

Balsa 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 due to its low density, and it does not naturally contain chemicals such as silicates that repel microorganisms, insects, or mollusks that would damage it. Balsa, like other woods, decomposes faster in salt water than in freshwater because of the generally larger numbers of wood-consuming invertebrates that live in salt water. *Teredo navilis*, the common shipworm, causes the most significant damage to the balsa raft (27). Teredinids, which live throughout the Atlantic and

Pacific, are wood-boring mollusks that subsist entirely on cellulose. While some researchers believe that shipworms were introduced to South America on Spanish ships in the sixteenth century, 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.

The data describing balsa decomposition in a marine environment comes from the study *Fouling and Boring of Glass Coated Plastic Balsa Blocks* conducted by J.A. Lewis in 1983. Both the balsa blocks in Lewis' 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. Since these ratios are the same for both balsa geometries, the balsa blocks and the balsa logs have approximately the same decomposition rates. According to Lewis, the blocks lost 16% of their volume over the course of six months. Assuming that the 7000 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 outbound and return trips.

This hull log degradation greatly affects the weight of cargo 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 (20). This value is large enough so that it does not place a 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% (28). 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, which represents one round trip between Ecuador and Mexico, an 11m raft would be able to hold 10 tons of cargo, which is 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 for more than eight months. It would be inefficient to send a raft and crew so long a distance with so small a cargo.

Long-Distance Trade Feasibility

A balsa raft between 6 and 11 meters in length, equipped with two masts of heights between 5 and 7 meters would be able to sail nonstop between Ecuador and Mesoamerica. Rafts in this size range have a cargo capacity of between 10 and 30 metric tons.

Assuming that the raft could sail at 4 kts, a moderately slow walking pace, and that it traveled about 12 hours per day, it would take between six and eight weeks to complete the 3000 km voyage between Ecuador and Mesoamerica. The 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. Leaving in late March would have allowed the sailors to avoid the rainy season in Ecuador, which ends in April.

Our analysis shows that these prehistoric rafts were fully functional sailing vessels and could have been sailed between Ecuador and the west coast of Mexico. Our study greatly strengthens the argument that maritime trade transmitted Ecuadorian metallurgical technology from South America to

Western Mexico. We also know that that the sailing vessels were capable of at least two round trip voyages between the two regions. This is a critical element in the argument because balsa wood is unavailable in western Mexico, the craft needed to be seaworthy for the return trip. This also suggests that the voyages were probably also undertaken by two or more rafts, one perhaps carrying balsa logs for replacements.

This conclusion adds weight to the argument that metallurgy and other South American cultural elements were introduced to western Mexico via a maritime route. Apart from these data our study demonstrates that information obtained from mechanical and materials engineering analysis can be useful in archaeological and historical studies.

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