

An Analysis of Pre-Columbian Balsa Raft Design
to Determine the Suitability of Such Rafts
for Ancient Maritime Trade Between Ecuador and Mexico

by

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Submitted to the Department of Mechanical
Engineering in Partial
Fulfillment of the Requirements for the
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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 maritime routes. However, no remains of pre-Columbian rafts have been found in West Mexico. This thesis uses mechanical and materials engineering analysis to determine whether these craft could have sailed from Ecuador to Mexico. Using historical accounts of the rafts as a data set, this thesis models their aerodynamic and hydrodynamic properties, their buoyancy and cargo capacity, their functional lifetime, and the load-bearing capacities of their components. The analysis shows that these prehistoric rafts were fully functional sailing vessels and could have been sailed between Ecuador and Mexico. This study greatly strengthens the argument that maritime trade transmitted Ecuadorian metallurgical technology from South America to Western Mexico.

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Contents

Introduction.....	4
Overview of Past Research.....	4
The Data: Descriptions of Raft Design.....	5
Raft Base.....	5
Centerboards.....	6
Sail Design.....	6
Methods.....	7
Stress Patterns and Consequent Size Limitations.....	7
Buoyancy and Cargo Capacity.....	8
Aerodynamic and Hydrodynamic Characteristics.....	8
Functional Lifetime.....	8
Results and Analysis.....	9
Stress Patterns and Consequent Size Limitations.....	9
Stress Patterns in Mast.....	9
Correlation Between Mast Height and Raft Length.....	11
Stress Patterns in Centerboards.....	12
Buoyancy and Cargo Capacity.....	13
Aerodynamic and Hydrodynamic Characteristics.....	14
Functional Lifetime.....	14
Conclusions Regarding Long-Distance Trade Feasibility.....	15
References.....	17
Appendix A: Mast Stress Analysis.....	19
Appendix B: Maximum Raft Length as a Function of Mast Height.....	23
Appendix C: Correlation Between Mast Height and Centerboard Area.....	25
Appendix D: Cargo Capacity of 11 m Balsa Raft.....	27

Introduction

Long-distance maritime trade routes linked the Andean culture area to surrounding regions starting around the year 100 BCE (Paulsen 1974). Traders living on the coast of Ecuador during this time period constructed large balsa sailing rafts to reliably transport cargoes of metal ornaments, pearls, and *Spondylus* oyster shells (West 1961, Edwards 1965, Hosler 1988). Hosler demonstrated that metallurgy was introduced to West Mexico from Ecuador by about 700 CE, and she argued that this transmission was most likely via a maritime route (Hosler 1988). Other authors have likewise posited the existence of extensive maritime trade along the Pacific coast of the Americas (Marcos 1977, Meighan 1969).

This thesis determines whether Ecuadorian balsa wood rafts were suitable vessels for long-distance trade between Ecuador and Mexico. 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 sufficiently long functional lifetime. This thesis uses the historical data set to address each of these requirements in turn.

Overview of Past Research

During the last century the researchers Thor Heyerdahl and Cameron Smith independently experimented with balsa rafts' sailing abilities (T Heyerdahl 1947, Smith 1999, H Lechtman personal communication 2006). Heyerdahl sailed the 45 foot balsa raft Kon-Tiki from Callao, Peru to Polynesia in 1947. The square rig in Heyerdahl's raft was only capable of sailing directly downwind (T Heyerdahl 1947). Cameron Smith attempted several voyages from Ecuador to West Mexico in the 1990s (Smith 1999). His rafts, however, were rigged with European-style lateen sails, which were not used prior to the Spanish invasion (Johnstone 1980). 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 in these modern facsimiles fail to replicate that of the sixteenth century indigenous rafts. This thesis' assumptions about ancient Ecuadorian raft design derive from writing and drawings by sixteenth and seventeenth century Spanish, Italian, and Dutch explorers. Careful inspection of the sixteenth century drawings depict simple crescent-shaped sails, whereas the sails used the other three expeditions are of distinctly European design (Madox 1582 and Spilbergen 1619, from Edwards 1965). As this thesis demonstrates, sail design is crucial to raft functionality.

The Data: Descriptions of Raft Design

Raft Base

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 1555 *Historia del descubrimiento y conquista de las provincias del Peru*. He reported that the logs forming the raft base "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" (de Zarate 1555, rpt 2001). 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" (Benzoni 1565, from Edwards 1965).

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" (de Xerez 1526, rpt 1985). *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 (Herbert 1954).

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.

(de Estete, *Noticia del Peru* 1535)

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.

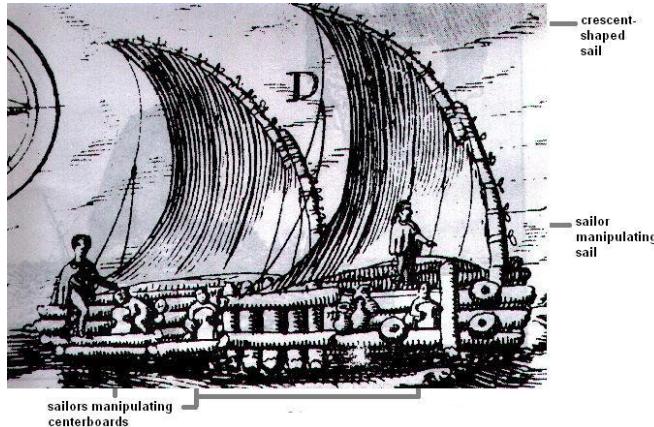


Figure 1. 1619 drawing of balsa raft by Joris Van Spilbergen, showing three sets of centerboards and crescent-shaped sails. (Edwards 1965)

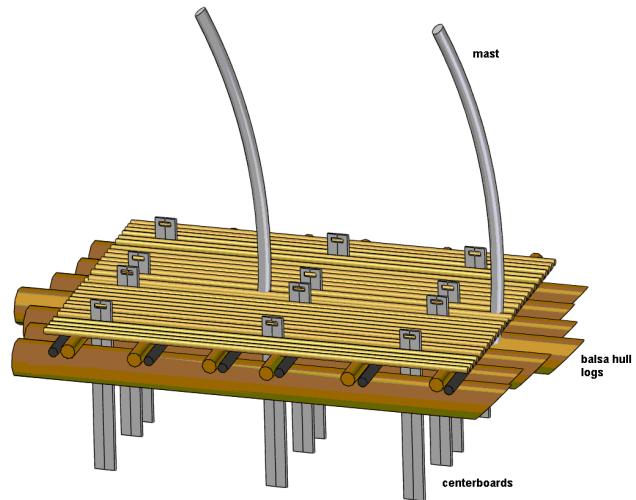


Figure 2. CAD model of raft base, showing centerboards and curved masts.

Centerboards

Emilio Estrada and Clinton Edwards, researchers who experimented extensively with balsa raft sailing, have maintained that the centerboards depicted in the Joris van Spilbergen drawing are a crucial design element (Edwards 1965, Estrada 1955). 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 (Estrada 1955). The historical illustrations make clear that balsa rafts were steered with three sets of centerboards: one in the bow, one in the stern, and one in the middle of the boat (Spilbergen 1619, from Edwards 1965). Figures 1 and 2 show the centerboards' approximate placement on a balsa raft.

Sail Design

Ocean-going balsa rafts had crescent-shaped sails, with backwards-curving leading and trailing edges (Estrada 1955, Edwards 1965). These highly efficient sails would have given the rafts a great deal of maneuverability.¹ As shown in Figure 1, a rope affixed to the top of the masts curved them downwards, giving them their characteristic crescent shape. The degree of curvature could be

1. 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. 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.

adjusted to increase sail efficiency when sailing at different angles to the wind (van Dam 1987).

Methods

The historical accounts and illustrations provide the data set for analyzing the feasibility of using these rafts for long-distance trade between Ecuador and Mexico. This analysis requires examination of four distinct criteria—stress patterns in the raft's components and consequent size limitations, buoyancy and cargo capacity, aerodynamic and hydrodynamic characteristics, and functional lifetime.

Stress Patterns and Consequent Size Limitations

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, and gravitational forces, limit the feasible dimensions of the raft's components. Two MATLAB programs were created to determine the stresses and consequent size limitations in the raft's components. Specifically, these programs evaluated the stresses induced in the mast and centerboards. The range of feasible raft sizes was then extrapolated from the ranges of feasible component dimensions.

Following the historical record, the mast was modeled as an encastered tapered beam set into the center balsa hull log, perpendicular to the deck (Estrada 1955, Edwards 1965). 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 very turbulent, inefficient sail geometry at all other points of sail (White 2003). 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 (Spilbergen 1619, from Edwards 1965). Nonetheless, it is appropriate to model each mast as a single beam, under the assumption that there is minimal slip between the two pieces. It is assumed 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 Forest Product Laboratory's Wood Handbook (US Department of Agriculture 1999). The Kon Tiki and Tangaroa had masts made of mangrove wood, and Smith's rafts has masts made of cocobolo wood (Smith 1999). Most hardwoods available in Ecuador have moduli of rupture and elasticity similar to these two woods. Researchers have not yet recovered any historical data describing the types of wood used in ancient rafts' 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 mast its required curvature. A mast must be able to withstand the sum of these stresses. A MATLAB program determined the bending and wind stress along the mast for a range of mast heights and widths, as well as the force necessary to bend the mast a given fraction of its height. The MATLAB code for this program can be seen in Appendix A. Because the maximum bending stress and wind stress do not always occur in the same place, it was 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 were summed directly.

Buoyancy and Cargo Capacity

After determining the viable raft dimensions, the mass of cargo that the balsa rafts could carry was approximated. The quantity of goods 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. The MATLAB code used to perform these capacity calculations for a range of raft dimensions can be seen in Appendix C.

Aerodynamic and Hydrodynamic Characteristics

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. Additionally, the size of the raft limits the months it could 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.

Charts of the monthly averages of ocean surface currents, obtained from Columbia University's IRI/LDEO (International Research Institute / Lamont-Doherty Earth Observatory) Climate Data Library, were used to determine the highest velocity water currents that the raft would have to overcome when sailing from Ecuador to Mexico. The directions, magnitudes, and locations of the largest three hull drag forces were recorded for each month. Using charts of the monthly wind speed averages, also obtained from the IRI/LDEO Library, the wind speed and direction in the vicinity of the largest hydrodynamic drag forces was determined. After estimating the raft's point of sail to determine the correct lift and drag coefficients, the corresponding wind driving force pushing the raft in the desired direction was calculated. This wind driving force was then compared 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 larger magnitude than the water drag force opposing its motion. The wind current charts were then evaluated separately to establish whether adverse winds alone would be enough to prevent the raft from sailing in certain months. This modeling makes it possible to determine the times of year at which the raft could be sailed in a particular direction, either north to Mexico or south to Ecuador.

Functional Lifetime

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 (Lewis 1983). Shipworms, which are extant throughout the Atlantic and Pacific, are wood-boring mollusks that subsist entirely on cellulose.

The 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. By determining the rate of decay of balsa wood in a marine environment and evaluating how this decay affects the wood's material properties, it was possible to approximate a service lifetime for the raft.

Results and Analysis

Stress Patterns and Consequent Size Limitations

i. Stress Patterns in Mast

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. 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 (Larsson 1996). 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 (IRI/LDEO 2006).²

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

According to this analysis, the ratio of mast base diameter to tip diameter must be approximately 2, and ratio of tip displacement to mast height had to be less than 20%. Taper ratios and curvatures greater than these values result in localized stresses with sufficient magnitude to break the mast.

Figure 3 shows the feasible mast geometries superimposed on a contour plot of their safety factors. The MATLAB code used to generate Figure 3 can be found in Appendix A. 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 3, 1.5 is the largest possible safety factor the mast could have sustained, given the described constraints. 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. This factor is included because a well-designed mast must be able to withstand unanticipated stresses. These stresses would most likely come 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.

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

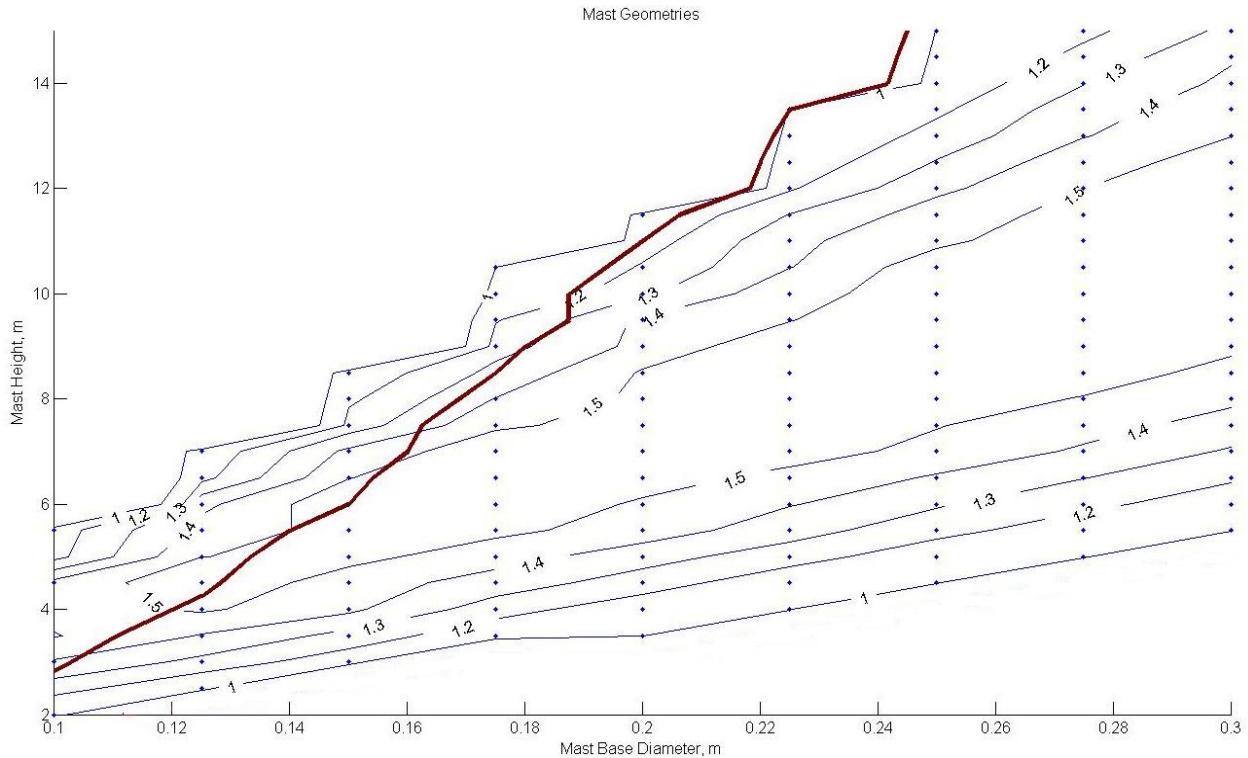


Figure 3. Mast safety factors and 1800 N force line.

Masts with a safety factor of about 1.4 could endure gusts up to 16 m/s before lowering their sails. It is very likely that the rafts would encounter unexpected gusts of this magnitude as they sailed, so the masts almost certainly had a safety factor of at least 1.4 (IRI/LDEO 2006).

Figure 3 shows 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 required bending force because the degree of bending in 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 frequently adjust the sail because it would require more individuals pulling to generate enough force. It was 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.

The thick line in Figure 3 indicates the masts that require 1800 N of force to displace their tip by 20% of their 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.

Table 1. Approximate maximum endurable gust velocity.

Safety Factor	Maximum Gust Velocity (m/s)	Maximum Gust Velocity (kts/s)
1.0	9	17.5
1.1	10	19.4
1.2	11	21.4
1.3	12	23.3
1.4	16	31
1.5	16	31

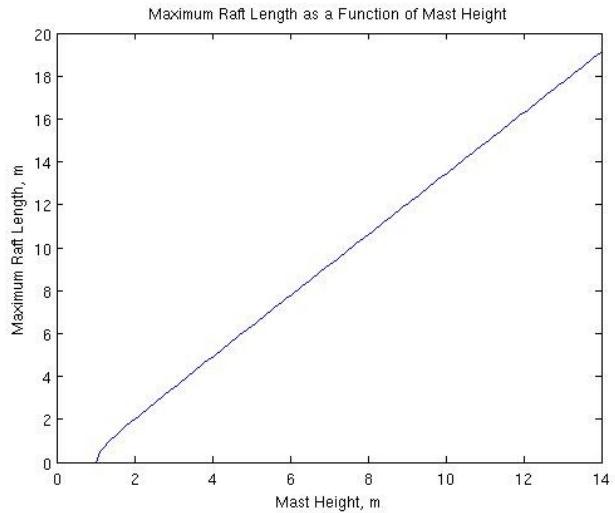


Figure 4. Maximum raft length as a function of mast height, two sails.

ii. Correlation between Mast Height 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. 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.

While the wind force drives the raft forward, the hydrodynamic drag force always acts opposite 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. Wetted area is then converted to raft length by assuming that the raft's length was 1.5 times longer than its width, following Figure 1 (Edwards 1965). A raft with two seven meter masts, which are the tallest possible mast heights given my computations, would be able to propel an 11 meter long raft. Figure 4 shows the correlation between mast height and maximum raft length for rafts with two sails. The MATLAB code used to generate Figure 4 can be found in Appendix B.

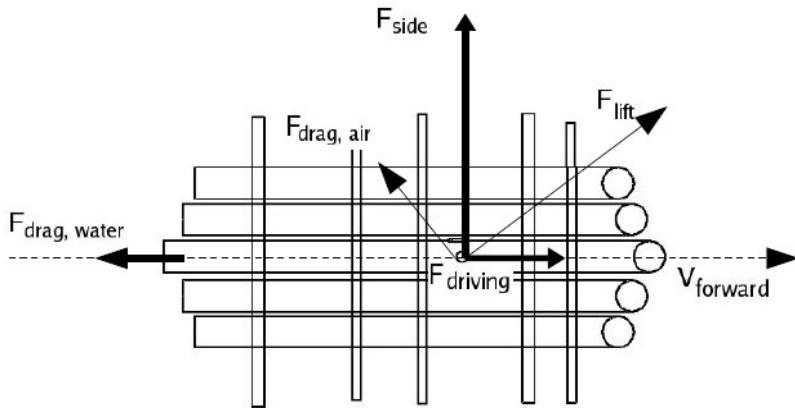


Figure 5. Wind and water forces on raft.

iii. Stress Patterns in 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 (Estrada 1955, Edwards 1965). This steering mechanism was also successful for a 3 meter long model raft launched in the Charles River in 2004 (Dewan 2004).

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 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 (US Department of Agriculture 1999), so there is little chance that this side force could ever be large 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 gives 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. Figure 6 shows the correlation between mast height and the below-water centerboard area necessary to keep the perpendicular velocity less than one tenth of the forward velocity. The MATLAB code used to generate Figure 6 can be found in Appendix C.

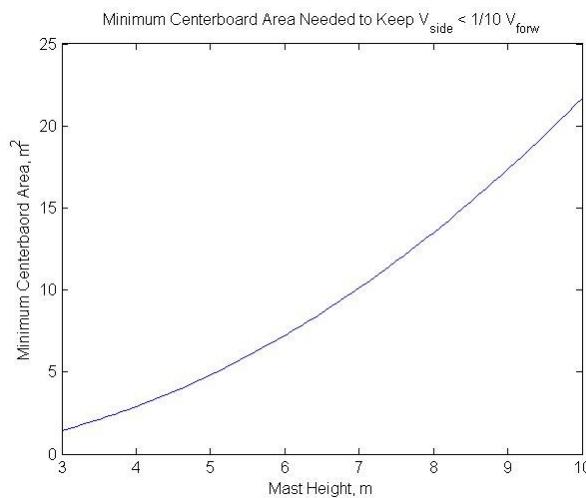


Figure 6. Correlation between mast height and balsa raft centerboard area.

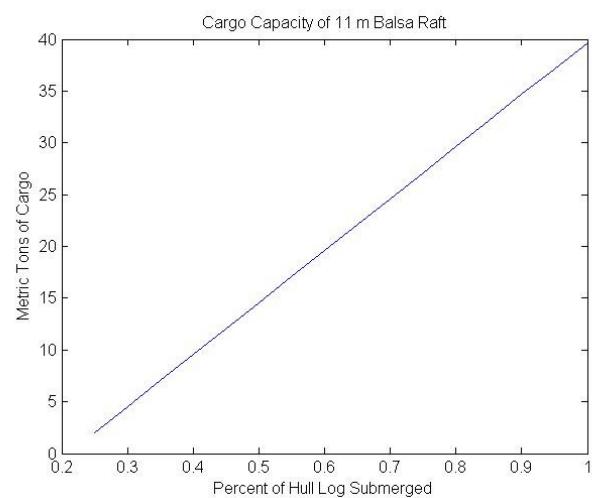


Figure 7. Cargo Capacity of 11 m

Thus by analyzing the stress patterns in the raft's components it is possible 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 one to determine its cargo capacity.

Buoyancy and Cargo Capacity

These calculations assume that the the base of the raft is approximately 11 meters long by 7 meters wide. These dimensions are the maximum raft size as calculated in the previous sections of this thesis. Balsa logs of this length would have a diameter of approximately 0.9 meters when stripped of their bark (Dinwoodie 1981).

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 percentage is a conservative estimate; none of the relevant historical sources describe the degree to which the logs were submerged. Figure 7 plots balsa rafts' cargo capacity as a function of hull log submersion. The MATLAB code used to generate Figure 7 can be found in Appendix D. 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.

Aerodynamic and Hydrodynamic Characteristics

The west coast of South America, Central America, and Mexico 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. Additional analysis determined the feasible times for sailing during the dry season.

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 late March or early April.

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 two-masted raft is approximately 5 meters. These rafts would only be able to sail north 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.

Functional Lifetime

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. 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 both have approximately the same surface area to volume ratio. 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 (Lewis 1983). Assuming the 7000 kilometer 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 (US Department of Agriculture 1999). This value is large enough so that it does not place a limit on the rafts 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% (De Groot 1998). 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, the raft would be able to hold 10 tons of cargo. 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.

Conclusions Regarding Long-Distance Trade Feasibility

A balsa raft between 6 and 11 meters in length, equipped with two masts with heights between 5 and 7 meters would be able to sail nonstop between Ecuador and Western Mexico. Rafts in this size range have a cargo capacity 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. The traders would most likely leave Ecuador in early December and arrive 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 allow the sailors to avoid the rainy season in Ecuador, which ends in April.

This analysis shows that these prehistoric rafts were fully functional sailing vessels and could have been sailed between Ecuador and the west coast of Mexico. Additionally, this study greatly strengthens the argument that metallurgy and other South American cultural elements were

introduced to western Mexico via a maritime route. Apart from these data, this study demonstrates that information obtained from mechanical and materials engineering analysis can be useful in archaeological and historical studies.

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Appendix A: Mast Stress Analysis

```

clear all
close all

% This m.file determines a band of feasible geometries for the mast of an
% Ecuadorian balsa raft. It determines the stress profile in the mast due
% to tip bending and wind stress, then sums the stresses and selects the
% maximum. If the maximum stress is less than the wood's modulus of
% rupture, the geometry is plotted on a chart. This program then
% determines the maximum force required to bend the tip of the mast.
% points that require less than 1600 N to bend are plotted in blue,
% indicating that this bending could be performed by not more than two
% people.

% Created by Leslie Dewan, June 2006

hold on
rangemastheight = [2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 11
11.5 12 12.5 13 13.5 14 14.5 15]; % testing these mast heights
rangeb = 0.5*[0.1 0.125 0.15 0.175 0.2 0.225 0.25 0.275 0.30];
%testing these mast base radii

possiblecombinations = zeros(length(rangemastheight)*length(rangeb),4);
% preallocating matrix with zeros
goodcombinations = zeros(length(rangemastheight)*length(rangeb),4); %
preallocating other matrix with zeros

testnum = 1;
% what number test is this, so you'll know where to put the numbers in the %
possiblecombinations matrix

for m = 1:length(rangemastheight) % cycling through range of mastheights
    for n = 1:length(rangeb) %cycling through range of base diameters

        %Constants
        global E mastheight a b P

        E = 10*10^9; % average MOE of dry hardwood
        mastheight = rangemastheight(m); %height of mast, in meters
        b = rangeb(n); % radius of base of mast, in meters
        a = b/2; % radius of tip of mast, in meters
        P = 500; % initial guess for force on the tip of the mast, in newtons.
        %start off with a fairly low force
        xspan = [0 mastheight];

        %boundary conditions for ode
        v0 = [0 ; 0];
        % at the surface of the deck (x = 0) the mast has no displacement and no slope

        %now use ode45
    end
end

```

```

%using large bending approximation (though probably not entirely
%necessary for ~20% bending)
[x,v] = ode45('bending', xspan, v0);
displacement = v(:,1);
slope = v(:,2);
%run ode45 once to get initial value for displacement. then run
%the ode again in the while loop,
%changing the force applied until there is enough dispalcement

while max(displacement) < 0.20*mastheight
    P = P + 250; % incrementing force on the tip of the mast
    [x,v] = ode45('bending', xspan, v0);
    displacement = v(:,1);
    slope = v(:,2);
end
max(slope)

Mb = P*(mastheight-x);
% approximation of bending moment in the mast. This is sufficiently accurate.
r = b - (b-a)*x/mastheight;
%radius of the mast, in meters, as a function of the distance from the deck
I = pi*r.^4/4;
% area moment of inertia of the mast, as a function of the distance from the
deck

bstress = (Mb.*r./I)*10^-6;
%computes stress in MPa as a function of distance along the mast
maxbstress = max(bstress);

%now determine the wind stress
%%%%%%%%%%%%%
sailarea = 0.5*mastheight.^2;
% for sails with base~=height, based on Spilbergen and Madox figures
% force on the mast comes from two sources: lift and drag force on
% the sail
Cl = 1.2; % lift coefficient
Cd = 0.7; % drag coefficient
rhoair = 1.225; % density of air in kg/m3
vapp = 9;
% raft's apparent velocity; this is for the raft starting to accelerate in the
%
% fastest winds it will encounter
liftforce = 0.5*Cl*rhoair*sailarea*vapp^2; %calculating lift force
dragforce = 0.5*Cd*rhoair*sailarea*vapp^2; %calculating drag force
totalwindforce = sqrt(liftforce.^2 + dragforce.^2);
totalwindpressure = totalwindforce/sailarea;

FR = totalwindforce; % this is true by force balance. FR is the
restoring % force provides by a rope (NOT the bending rope) on the tip of the
mast

mastlineforce = totalwindforce./mastheight; %line of force on the mast

```

```

Mw = -FR*(mastheight-x) + 0.5*(mastheight-x).^2*mastlineforce;
% moment caused by the wind force

wstress = (-Mw.*r./I)*10^-6;
%computes stress in MPa as a function of distance along the mast
maxwstress = max(wstress);
%%%%%%%%%%%%%%%
totalstress = bstress + wstress;
%summing the two, because will be in same direction at some points of sail, or
%during some maneuvers
maxstress = max(totalstress) % selecting the maximum stress along the
mast

%put four variables in possible combinations matrix
possiblecombinations(testnum,1) = b;
possiblecombinations(testnum,2) = mastheight;
possiblecombinations(testnum,3) = P;
possiblecombinations(testnum,4) = maxstress;

testnum = testnum+1; %incrementing testnum
end
end

possiblecombinations
%NOW pick out the good combinations (with maximum stress less than 100
%MPa) and plot mastheight versus base diameter
testnum = testnum-1;

for k=1:testnum
    if possiblecombinations(k,4)< 100
%if the maximum TOTAL stress in that particular possible combination is less
than %100 MPa
        goodcombinations(k,1) = possiblecombinations(k,1);
%first column of goodcombinations is b
        goodcombinations(k,2) = possiblecombinations(k,2);
%second column of goodcombinations is mast height
        goodcombinations(k,3) = possiblecombinations(k,3);
%third column of goodcombinations is force applied to top of mast
        goodcombinations(k,4) = possiblecombinations(k,4);
%fourth column of goodcombinations is maxstress
    end
end
goodcombinationsb = goodcombinations(:,1)
goodcombinationsh = goodcombinations(:,2)
goodcombinationsp = goodcombinations(:,3)
heavycombinations = goodcombinations;
%initializing this
%here's a way to separate out the ones that are too heavy, will later plot
%them a different color
for i = 1:testnum

```

```
if goodcombinations(i,3)<=1600
    heavycombinations(i,1) = 0; %removing it from heavy combinations if
it's not too heavy
    heavycombinations(i,2) = 0;
    heavycombinations(i,3) = 0;
    heavycombinations(i,4) = 0;
end
end

figure(1)
plot(2*goodcombinations(:,1),goodcombinations(:,2),'bo',
2*heavycombinations(:,1),heavycombinations(:,2),'ro')
xlabel('Mast Base Diameter, m');
ylabel('Mast Height, m');
title('Good Combinations, a=b/2 sigmax=100MPa E = 10GPa 20% curvature');
```

Appendix B: Maximum Raft Length as a Function of Mast Height

```

function mastheighttoraftlength()
% Input a range of mast heights, determines sail area, then outputs the
maximum
% raft length that could reasonably be driven by that sail
% assuming two sails, each with b/h = 1
% Created by Leslie Dewan, July 2006

mastheight = [1:0.1:14]; % range of mast heights
sailarea = 2*(0.5*mastheight.^2); % for two sails with b/h ~= 1, taking into
%account 1 meter of clearance from the deck

% First calculate the driving force
beta = pi/3;
% angle between the raft's forward velocity and the apparent wind velocity
Cl = 1.1; % lift coefficient for beta = 60
Cd = 0.4; % drag coefficient for beta = 60
rhoair = 1.225; % density of air in kg/m3
vapp = 2; % wind's apparent velocity; equal to the actual velocity when the
raft %first starts moving
liftforce = 0.5*Cl*rhoair*sailarea*vapp^2;
dragforce = 0.5*Cd*rhoair*sailarea*vapp^2;

drivingforce = liftforce*sin(beta) - dragforce*cos(beta);
%forward driving force on the raft

fdrag = drivingforce; % force from wind on sail must be at least equal to the
drag %force if the boat is going to go forward at a reasonable velocity

rhowater = 1025; % density of seawater at 20 C
muwater = 1.2*10^-6; % kinematic viscosity of saltwater at 20 C
width = 10; % first approximation for waterlinelength, necessary for
evaluating %reynold's number. doesn't matter much, because rho/mu is in the
same equation
vforward = 1; %want it to go at least 1 m/s (2 kts) in a 1.5 m/s wind (3 kts)

reynolds = (rhowater*width*vforward)/muwater; % determining Reynolds number of
flow
cf = 0.075/((log10(reynolds) - 2)^2) % determining friction coefficient of
flow

raftarea = 2*fdrag/(rhowater*(vforward^2)*cf); % determining raft's wetted
area

%assume that the raft's footprint has an aspect ratio of 3:2 (this aspect
%ratio is based on the diameter vs length curves I made for the logs, assuming
that %the logs are lined up as close together as possible, allowing some space
for rope %in between them)
raftlength = sqrt(1.5*raftarea);

```

```
plot(mastheight,raftlength)
title('Maximum Raft Length as a Function of Mast Height')
xlabel('Mast Height, m')
ylabel('Maximum Raft Length, m')
```

Appendix C: Correlation Between Mast Height and Centerboard Area

```

function centerboardanalysis
% determines sail area for a range of mast heights, then determines the
% minimum centerboard area needed to keep the raft's sideways velocity less
% than 1/10 of its forward velocity
% Created by Leslie Dewan, July 2006

E = 10*10^9; %modulus of elasticity
MR = 100*10^6; %modulus of rupture

length = 2; %below-water depth
width = 0.5; % centerboard width
t = 0.05; % centerboard thickness

I = (1/12)*width*t^3; % moment of inertia
mastheight = [3:0.1:10]; % range of mast heights
sailarea = 2*(0.5*mastheight.*((mastheight-1)));
%calculate the side force on the raft
beta = pi/3; % angle between the raft's forward velocity and the apparent wind
velocity
C1 = 1.1; % lift coefficient for beta = 60
Cd = 0.4; % drag coefficient for beta = 60
rhoair = 1.225; % density of air in kg/m3
vapp = 1.5; % wind's apparent velocity
vforw = 1; %raft's forward velocity
liftforce = 0.5*C1*rhoair*sailarea*vapp^2;
dragforce = 0.5*Cd*rhoair*sailarea*vapp^2;

sideforce = liftforce*cos(beta) + dragforce*sin(beta); % side force on the
raft

sidelineforce = sideforce/length; %approximate side force as a uniform line of
force

%model centerboard as cantilever beam, encastered at deck
%maximum moment, and therefore maximum stress, is where the board
%intersects with the deck
maxmoment = 0.5*sidelineforce*length^2;
maxstress = maxmoment*(t/2)/I % no problems with exceeding maximum allowable
stress

fdrag = sideforce; %assume the raft is not accelerating to the side
rhowater = 1025; % density of seawater at 20 C
%muwater = 10^-6; % kinematic viscosity of saltwater at 20 C
%width = 5; % first approximation for ship width, necessary for evaluating
reynold's number. doesn't matter much, because rho/mu is in the same equation
vside = 0.1*vforw; % sideways velocity should be 1/10 of forward velocity

cf = 1; % for this geometry. Not sure of this is accurate

```

```
boardarea = 2*fdrag/(rhowater*(vside^2)*cf); % determining raft's wetted area
numboards = boardarea/(width*length);

plot(mastheight,numboards)
title('Minimum Centerboard Area Needed to Keep V_{side} < 1/10 V_{forw}')
xlabel('Mast Height, m')
ylabel('Minimum Centerbaord Area, m^2')
```

Appendix D: Cargo Capacity of 11 m Balsa Raft

```

function balsabuoyancy

lengthb = 11; %length of the balsa logs
db = 0.9; %diameter of the balsa logs
rb = db/2; %radius of the balsa logs
numlogsb = 7; %number of balsa logs in the raft

rhobalsa = 150;
rhohw = 1100; % approximate density of hardwood used for some components
rhobamboo = 200; %average density of vegetable matting
rhow = 1025;
g = 9.8;

subfr = [0.25:0.05:1.0];
vsub = numlogsb*subfr*pi*rb^2*lengthb
freaten = 0.40; %fraction of the hull logs eaten by shipworms
fbuo = (1-freaten)*rhow*g*vsub

% weight of balsa hull logs
fbalsa = rhobalsa*numlogsb*pi*rb^2*lengthb*g

% weight of crossbeams
lengthc = 8;
dc = 0.2;
rc = dc/2;
numc = 7;
rhoc = 1100;
fc = rhohw*numc*pi*rc^2*lengthc*g

% weight of deckrisers
ddr = .3; % diameter of deck risers
rdr = ddr/2;
Ldr = 7; % length of deck risers
Vdr = (rdr^2)*pi*Ldr; % volume of one deck riser
numdr = 8;
fdr = Vdr*numdr*rhobalsa*g; % weight of the deck risers

% weight of deck planking
ddp = .08; % diameter of vegetable matting forming deck
rdp = ddp/2;
lengthdp = 12;
% length of deck planking, in meters (will be approximately same length as
% hull logs)
numdp = ddp/lengthdp; % number of pieces of deck planking
fdp = g*rdp^2*pi*lengthdp*rhobamboo*numdp; % mass of deck planking

%weight of mast
dmast = .2; % diameter of mast, in meters
rmast = dmast/2;

```

```
lengthmast = 8; %length of mast, in meters
fmast = g*(rmast^2)*pi*lengthmast*rhohw;

numcrew = 5;
masscrew = 75*g;
fcrew = numcrew*masscrew;

fcargo = fbuo - (fbalsa + fc + fdr + fdp + fmast + fcrew)
mcargo = fcargo/g

plot(subfr,mcargo/1000)
xlabel('Percent of Hull Log Submerged')
ylabel('Metric Tons of Cargo')
title('Cargo Capacity of 11 m Balsa Raft')
```