An analysis of log raft open water performance and crew capability to move megaliths Pre-classic Olmec used for Colossal Head sculptures.

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Abstract

In Mesoamerica, Preclassic Olmec society used large stones for monumental head sculptures, some weighing over twenty tonnes. These megaliths were retrieved from the Tuxtla Mountains and transported a distance of at least 80 kilometres to their principal centre at San Lorenzo. The methods and routes used are uncertain, but water- based routes using rafts were considered the more likely method. Of two watercraft types proposed, a log raft configuration has been more favoured. This raft is examined, considering structural viability and, as the primary motive force, human physiological capabilities. Analyses were undertaken of both raft and crew and their combined performance under these loads. Maritime and meteorological elements found in the Gulf of Mexico, were applied to technological parameters. These analyses show that a log raft configuration would not be a viable means to move such highly valued stones upstream on rivers, nor over open waters.

Keywords: Olmec; megaliths; log rafts; analysis; transport

INTRODUCTION:

Mesoamerican archaeologists have long debated how stones used for iconic sculptures known as *Cabezas Colosales*, or Colossal Heads, were transported by Preclassic Olmec. Contributing to this debate are the long distances involved, large stones used and challenging terrain over which to move the stones.

These stones, many weighing over twenty tonnes, were moved from the Tuxtla Mountains (Williams and Heizer, 1965), to the major Olmec centre at San Lorenzo /Tenochtitlan between 1200- 900BC, and later to La Venta, on the Isthmus of Tehuantepec in Mexico. The direct land route distance is some 80 kilometres, with many swamps, floodplains and fast -flowing rivers that must be crossed, imposing logistical, technical and time frame constraints on their transportation. On open water routes, seasonal conditions also impose similar constraints, but more particularly on crews and watercraft. This route option has a minimum transportation distance of between 120 –150 kilometres (75- 94 miles) and is endorsed by a stone sculpture depicting rope bound in such a way as to suggest hauling (Diehl, 2004:118). Although there is evidence the Olmec had knowledge of the wheel, this evidence postdates the probable age of the heads (Lopez, 2004:110). In any case, the Olmec did not have suitable domesticated draught animals.

The man power commitment to land transport would have been considerable. Land transport implies track preparation, timing and diverting available manpower from agricultural pursuits to be employed over long periods to suit seasonal conditions. Nevertheless, without confirmatory evidence, the presence of the Olmec Colossal Heads at San Lorenzo and at La Venta continues to challenge researchers to explain their retrieval.

With early research favouring water routes over land routes (Coe, 2000:68) questions and contradictions still exist with a water based route. For example, such a route is a considerable distance from a stone working workshop at Llano Del Jicaro (Borstein, 2001, Gillespie, 1994). Preclassic Olmec knowledge of watercraft is unclear, and there is little direct evidence available. Water transport theories are only based on modern watercraft or Middle Formative period jade celts, similar in profile to canoes (Benson and de la Fuente, 1996). A comprehensive hypotheses adopted the more likely log raft configuration (Velson and Clark, 1975) analysed in this paper.

To examine Olmec megalith transport, known log rafts and performance characteristics associated with these are analysed and the preferred water route option tested. This is done in conjunction with oceanographic, meteorological and riverine data applied as parameters. These can establish the viability of using log rafts along the Gulf of Mexico coast and rivers associated with San Lorenzo and its Preclassic Olmec hierarchical society.

The Olmec 'heartland' and San Lorenzo

When introducing or writing of the Olmec, researchers often refer to the Olmec as the "mother culture" and the area associated with this society as their 'heartland' (Benson, 1981, Coe, 2000, Diehl, 2004) . This sphere of political and economic influence was approximately 200km long by 80km wide (125 x 50 miles) with its political centre of San Lorenzo, as its heart. Situated some 60 km (38 miles) from the Gulf of Mexico on a ridge, San Lorenzo overlooks extensive floodplains and swamplands, characteristic of the Rio Coatzacoalcos basin. Its position and elevation make the plateau a dominant feature over this area, underwritten by the productive floodplains. These supported a population in the thousands, with those residing on the plateau being artisans as well as, political and religious hierarchy members (Diehl, 2004:29). From this site, centralised authority initiated the manufacture of cultural icons, including the Colossal Heads, supported by a favourable economic situation that allowed for manpower resources required to transport and carve the Colossal Heads.

Colossal Heads

Of seventeen known Colossal Heads, ten were found at San Lorenzo and these weigh between six and twenty five tonnes (Clewlow, et al., 1967:85). The heads have distinctive individual features, suggesting they represent different rulers during the florescence of San Lorenzo. A common feature is their flattened backs and small base. Large stones were typically used for altars or thrones in San Lorenzo, and it has been argued that one may have been reused for a Colossal Head (Porter, 1989), perhaps indicating both the difficulties of acquiring large stones and their value. This dual purpose suggests stone blanks would be larger and heavier than the weight adopted in previous transportation calculations (Velson and Clark, 1975:32-34).

The stone for Olmec sculpture was not quarried, but obtained from alluvial deltas in the vicinity of Cerro Cintepec in the Tuxtla Mountains (Williams and Heizer, 1965). To move the stone blanks to their final resting place, or to stone working workshops, such as Llano del Jicaro,(Porter, 1989) indicates that large numbers of men were used in the process. Manpower would be needed for pathway preparation as well as stone moving. In the case of water transport, manpower numbers to build, then power, the adopted watercraft are also significant.

With these inconsistencies, limited evidence and updated data, along with the ability to initiate a new investigation, made clear that the need to establish a practical and testable analytical framework was pivotal. The protocol adopted is similar to that utilised for other maritime transport research (Hazell, 2001, Hazell, 2003a, Hazell and Fitzpatrick, 2005).

Theoretical research framework

Initially, replication experimentation was considered for this investigation, but discounted, as difficulties were anticipated in faithfully replicating log raft construction with current fiscal and logistical constraints. Enacting the transportation would have been similarly constrained. These limitations made compromise inevitable endorsing a theoretical framework option able to adopt and apply appropriate replication data while still providing useful outcomes. This method is able to apply maritime conditions, meteorological and environmental data as parameters to define human performance and power capability for transport. Specific data such as ocean surface currents and wave forces establish viability of the transport method. For these elements meteorological and oceanographic data is sourced from various maritime institutions (Collier, 1964, Escoto, 1964, Gatty, 1944, Jenkins, 1973, Myres, 1993, Navy, 1995). Recent data related to sea level, coastline changes, river flow velocity and human physiological data, are also incorporated.

Estuarine and riverine environments include tidal flows that meet outgoing river flows and shifting sandbars. In this situation flow velocity makes upstream propulsion important for steerage to avoid and overcome these obstacles. As with open sea propulsion, determining human physiological power capability for upstream river travel is drawn from replication experimentation, in addition to ethnographic and ethnohistoric observations (Bechol, 1972, Doran, 1971, Haddon and Hornell, 1936-38, Hornell, 1931, Horvath and Finney, 1976, Lane-Poole, 1940, Ling, 1970, Morton, 1975).

Structural viability, stability capability and propulsion needs, associated with open waters and using a log raft direct focus on its open sea handling expectations. Viability of these elements is determined by winds, waves and currents in open water. Upstream to San Lorenzo from the Rio Coatzacoalcos estuary, viability analysis is dominated by propulsion capability using flow velocity and river bed conditions.

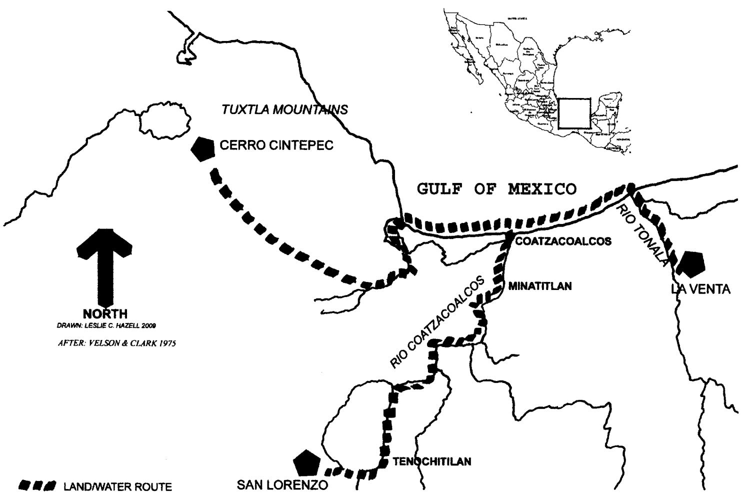

Figure 1 Theoretical water routes to San Lorenzo and La Venta (after Velson & Clark 1975)

ANALYSIS OF LOG RAFT PERFORMANCE:

Theoretical water routes (Figure one) were deemed to offer the most likely chance of success. This route option begins by travelling downstream to the coast from the Cerro Cintepec area of the Tuxtla Mountains, then hugging the Gulf of Mexico coast towards the Rio Coatzacoalcos estuary. After negotiating the estuary, the raft would travel upstream along the Rio

Coatzacoalcos for some 35 kilometres or more to the San Lorenzo Plateau possibly via the Rio Chiquito, which passes close to the plateau.

A log raft, as suggested by Velson & Clark (Velson and Clark, 1975), was adopted as the model for this analysis. Their hypothesis of water routes and log rafts is plausible, as this is theirs has a basic configuration requiring limited skill to operate and with a suitable timber (mahogany) being readily available (Coe, 2000, Stuart, 1993). Although a dense timber, this species would provide sufficient buoyancy and structural strength (Knutson and Moore, 1952) for carrying twenty tonne loads.

Log raft structure

The Velson & Clark hypothesis used a log raft constructed from *Ceiba sauraum.* Its size, based on specific gravity properties of *Ceiba*, would need to be 25ft x 27ft x 4.2ft or 7.6m x 8.2m X 1.25m. This would support around 38 tons (Velson and Clark, 1975) on the assumption that *Ceiba* has a “specific gravity of 0.089 (dry) with a weight of 23 pounds per cu ft” (Velson and Clark, 1975). The draft also allows for one foot (or 30cm) of freeboard. This expectation would change in saltwater compared to freshwater due to variable density values (Pond and Pickard, 1993 : 8-9). Nevertheless, even though the hypothetical route encompasses both density values, with this type of configuration (being a non-displacement hull), the freeboard variation expected is not significant.

Logs would be laid in two layers “at right angles to each other”, notched for secure fixing and fixed with vines common to the region. Although these are not specified (Velson and Clark, 1975) using vegetable fibre bindings is the likely method for connecting the logs. Possible fibres include *Agave lechugilla*, *Avage sisalana* (sisal) (Dewan and Hosler, 2008) and *Gossypium hirsutum* (cotton) as these were used in Preconquest Mexico (Cortes, 1977) and are depicted in sculptural examples (Coe and Diehl, 1980a). The design suggested differs from early Spanish reports of known rafts from South American cultures in which rafts consisted of odd log numbers with a longer central log (Dewan and Hosler, 2008). This format is a rudimentary hydrodynamic shape that may have reduced resistance and so assisted the propulsive effort. Importantly for viability, minimizing hull area in contact with water surface limits frictional resistance. Watercraft behaviour and buoyancy through hull/water contact (Kent, 1958:193), will also depend on the prevailing seascape and so determine the ability of the raft structure to maintain its load carrying capacity.

Winds, waves and log raft structure

Critical to megalith transport viability is structural integrity and stability, with both established by buoyancy, structural connections and their combined reaction to the dynamic force of wind, waves and currents. These actions also influence the crew's ability to manage the craft. The following analysis examines those forces and the impact they would have on a log raft in the Gulf of Mexico.

As a dynamic force, wind velocity is not constant, nor are the waves it produces, giving rise to an uneven pattern of waves known as *windsea* (Bird, 1984, Butt and Russell, 2004, Minikin, 1950, Sanderson, 1982). Uneven wave patterns test stability in open waters by applying uneven forces. Wind blowing for a period of twelve hours, at a constant speed and direction, at a typical twelve knots (22 kmh) with a fetch,(distance the winds act upon the sea surface), of 150 km (94 miles), will give a probable wave height of one metre (three feet) (Sanderson, 1982).

The values cited are typical of the Gulf of Mexico for at least half of the year (Myres, 1993, Navy, 1995). Generally, waves in the area created by prevailing winds of 5-6 knots (9 kmh or 5.6mph), will be at least 0.5- 1m and usually onshore or at right angles to the required travel direction (Myres, 1993, Navy, 1995) of a megalith carrying raft. Waves generated from or over a long distance characteristically have longer wave interval or length, greater speed and overall size. The combination of wave direction, length and size, load the raft with changing forces to different sections of its structure (see Figures 2 & 3).

Local prevailing winds would generate quartering waves, or waves across the projected line of travel, moving at a speed of 4-5 knots (6 kmh or 3.7mph). Winter winds are also predominately east to northeast onshore to the Veracruz coast, making this season the more favourable period in the Gulf of Mexico. Wind data for the months of January, July and October indicate only a 2% chance of hitting 2 on the Beaufort scale (Myres, 1993). April has similar wind force and frequency of winds, while having only a 1% chance of calms (Myres, 1993). Closer to the shoreline these waves are modified by sea - bed proximity, its type and gradient, thus intensifying wave shape and steepness (Haslett, 2009: 25). In doing so wave energy is compressed to the point where the wave becomes unstable. This gives rise to the familiar shore - breaking wave (Butt and Russell, 2004, Minikin, 1950). These waves have a greater impact on watercraft stability making this coastal zone a hazardous area for viable waterborne megalith transport. Therefore, even if the major part of the journey was outside the shore break, the raft and load must still cross this turbulent area to access open waters or to travel back upstream.

Although the cargo may be stable on still waters, this situation will likely change in open water. Constant wave movement induces a continual change in the direction of force relative to wave action, causing a rolling or pitching motion (Figure 2). Superstructure loads, such as people, deck structures or large stones, add force as leverage to the rolling motion. As the wave passes, the point within the raft where this force is acting, changes. If the weight/leverage ratio thus created exceeds the necessary righting moment geometry, the craft will not overcome the load applied and capsize or the load will slip and be lost overboard (Kent, 1958).

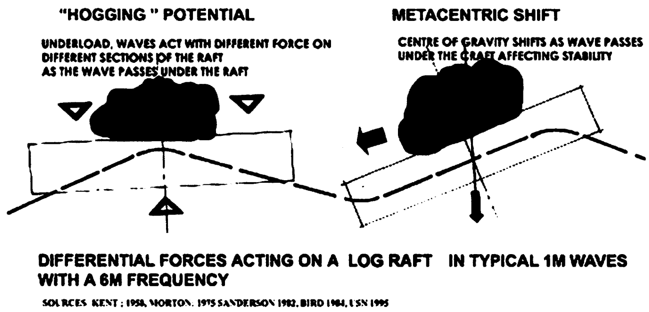

Figure 2: Raft behaviour and differential loading with wave action

The dynamics of a marine environment require a load be stable and not able to move from a set position for stability. Outlining the conditions in the Gulf of Mexico illustrate this need. In January N-NE winds develop from a dominant high pressure system, centred beyond Florida. The size and beat of waves generated by this wind are derived from a typical velocity of only 10 knots. Assuming this wind is coming from the same direction for 24 hours with a fetch of around 900kms, gives a beat of around 6-7m, with the wave travelling at 15 km/h and generating a wave height of about 2m (Bird, 1984, Sanderson, 1982). These waves increase the angle at which the force is applied to the craft, changing the theoretical stability point, known as the metacentric point (Figure 3). A rounded boulder moves in sympathy with movement and angle compared to one whose bottom surface is flattened. Chocking a rounded boulder shape requires structures that add to the top-heavy weight, so raising the metacentric point while increasing instability and resistance as more log surface is in contact with water.

This behaviour and changed metacentric point influence also changes with buoyancy. For adequate buoyancy, the hypothetical raft size required was 7.6m x 8.2m (Velson and Clark, 1975). These dimensions nearly match the calculated distance between wave crests. Therefore, as they pass under and through the craft at right angles, waves will exert upwards pressure on both sides of the raft, then its centre. As hull sections are therefore flexing, connection wearing occurs. The degree to which this will occur before failure is variable. This is a common problem with raft construction (Alsar, 1973) as demonstrated with failures in trans-Pacific voyages (Heyerdahl, 1982, Heyerdahl, 1973). Unlike modern inorganic roping, vegetable binding is subject to swelling and decay in a wet and salty situation. To maintain these connections while underway would require dedicated crew, with a working knowledge of fibres and cording (Follensbee, 2008).

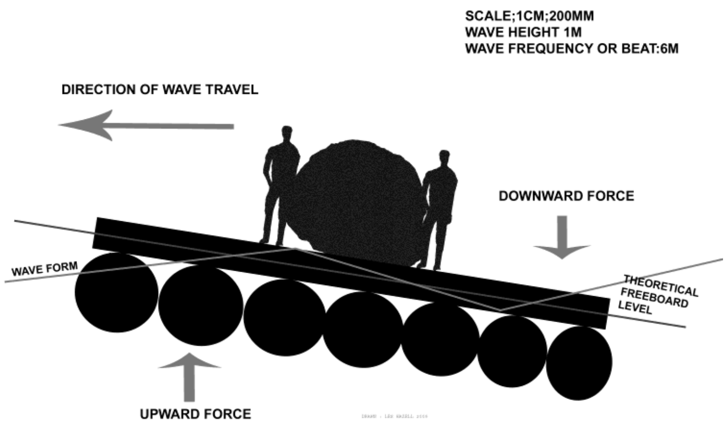

Figure 3: Megalith hogging force on raft

Passing waves have another effect on a log raft, they do not wholly lift the raft, and this affects its buoyancy. Wave surges flow over and pass between the logs, as replication voyages have shown (Alsar, 1973, Heyerdahl, 1973, Severin, 1995). As a log raft dips, the water flowing over the logs will add weight to the raft forcing those portions affected by this surge, to be pushed down. Log buoyancy must overcome this force, or it will tip with its load and capsize (Figure 3). This dynamic weight was not included in previous research for determining buoyancy requirements - and as weight means resistance, then propulsion is also affected.

OCEAN SURFACE CURRENTS AND RAFT PROPULSION

Passing waves modify or even prevent the application of stroke power as the raft rises and falls. While this is hard to quantify, paddling mechanics and propulsion capability can however, be examined. Velson and Clark calculated ten paddlers were needed to propel the Olmec log raft, whose total weight was 75.3 tons (150,662lbs or 68340kgs) (Velson and Clark, 1975). When applied to sea surface current flow velocities this weight/propulsion equation can be examined with data cited from contemporary pilot charts (Myres, 1993) and other sources (Gatty, 1944, Jenkins, 1973). Surface currents in the Gulf of

Mexico flow clockwise at a constant rate of ½-1½ knots (or 1-2 km/h) year round which is counter to the obvious direction of travel along the Gulf coast (UK National Hydrographer, 2002, UK National Hydrographer, 1981, UK National Hydrographer, 2003).

For analysis, a minimum ocean surface current velocity of 1.8 km/h was adopted as a benchmark. This velocity can be compared to paddling capability using ethnographic and experimental examples of canoe paddling. It is noteworthy these canoes would offer less passage resistance than log rafts, thus offering a more optimistic speed. The first example involves a measured test conducted using a racing canoe weighing about 6000 lbs (2727kg), which attained a speed of six knots (nearly 11 km/h) (Finney, 1967). For the test, eight paddlers "in excellent paddling condition" with two relief paddlers and two steersmen (Horvath and Finney, 1976) were used, although critically, this rate could only be maintained "for a few minutes at a time" (Horvath and Finney, 1976). Importantly, this test was undertaken in calm water with a sustainable (over several days) pace anticipated to be around 3 knots (5.6 km/h) (Horvath and Finney, 1976). However, the Olmec load of over 63000 kg is many times the racing canoe weight. A speed of four kilometres per hour based on sustained paddling data, is therefore assumed here, being estimated on its load and resistance applied by the log raft configuration (Finney, 1967, Holmes, 1993, Horvath and Finney, 1976, Smith, 2000).

The assumption is underwritten by personal experience with an Australian surfboat. This craft has a hull weight of 200 kg and is rowed by 4 oarsmen with another steering (sweep oarsman) giving a combined weight of 625 kg, assuming 85 kg per rower. A typical training session covers 42-49 kilometres in open bay waters, a similar distance to that required in the Olmec task. A sustained speed of 1100 m/seven minutes (Smith, 2000) is achieved, which translates into 3.43m - ¹ or 12.34kmh. The theoretical Olmec log raft is approximately 120 times heavier, with only twice the number of paddlers. The Olmec crew must make at least 2 km/h to match the opposing surface current, but, in addition, would need at least another 2 km/h for steerage and control. This is unlikely, but a theoretical comparison can be made with calculations that account for differences in resistance and wetted surface and comparative power possibility.

Calculating power to overcome drag is given by:

$$P= \frac{pAC_p v^3}{2}$$

Where P is power (watt), p is the density of the fluid (kg/m^3), A is the cross sectional area of the object experiencing the drag (m^2), Cp is a coefficient of pressure (depends on the shape of the object) and *v* is the velocity of the fluid past the object (m/s).

Nine kilometres per hour is approximately 2.5 m/s, the density of water is 1000 kg/m^3 and a formed hull has a coefficient of drag of about 0.04. Assume that a surfboat's wetted area is no more than 2 m^2. Substituting these values yields the total power used to push the surfboat.

$$P= \frac{1000 \times 2 \times 0.04 \times 2.5^3}{2}$$

= 625 watt

Dividing this total between the five crew members, the average power per crewmember is 125 watts.

The wetted cross section of the raft would be 7.6 m by 0.95 m, or 7.22 m^2. The total available power for crew (based entirely on the previous calculation for the surf boat) would be 1,250 watt. The pressure coefficient for a rectangle is approximately 2.0.

Therefore using:

$$V= \sqrt[3]{\frac{2P}{PAC_p}}$$

$$V = \sqrt[3]{\frac{2 \times 1250}{1000 \times 7.22\ 2.0}} = 0.6 \text{ m/s}$$

0.6 m/s is about 2 km/h.

These calculation figures are based on a mechanical advantage of oars rather than paddles. They suggest a log raft would not be viable when propelled with the crew numbers suggested by Velson and Clark (Velson and Clark, 1975), especially when using paddles providing less mechanical advantage than oars.

RESISTANCE, STABILITY AND PROPULSION

Arguably, using modern crew aerobic capacity data is inappropriate to examine propulsion needs and capacity. Research however, has shown modern human physiology is similar to that of ancient societies (Cordain, et al., 1998). Modern examples may overstate propulsion expectations, but ancient societies developed a lifelong hardiness in contrast to our modern, often sedentary, lifestyle. Other factors though affect analytical examination of Olmec speed capability. Minimal hydrodynamic resistance due to shape and material finishing favours the modern example. Log components in contact with water create laminar resistance, developing multiple vortices established by a roughened log surface. Therefore with more surface area in contact with water, greater resistance to propulsive force is the result. The log raft would have a wetted area of approximately 94 m^2 (log areas can be assumed to vary over their length and diameter) compared to approximately 2 m^2 of the surf boat.

Based on this comparison, it is unlikely that 10 paddlers could paddle a hydro-dynamically inefficient log raft, whose displacement weight is 75.3 tons, at 4 km/h to produce a true speed of 2 km/h. An increase in paddler numbers would not be viable, as this option is limited by the rule of “specific tractive force” (Langbein, 1962 : 13), where increasing power is offset by the weight added and added resistance thus applied. This limitation would apply to the use of oars, by adding weight for additional deck area to properly exercise the mechanical advantage. Compounding this, any increase in deck area must be proportional to maintain stability. Therefore its beam must also be increased, adding weight and so creating more resistance.

A further propulsion option is wind power. Inconclusive evidence of sail configurations suitable for Gulf of Mexico conditions excludes specific analysis of this option (Callaghan, 2003, Dewan and Hosler, 2008), although a key point can be made regarding sail. Harnessing the prevailing onshore winds requires specific technology to allow this. The sail must be capable of pivoting on the mast at an angle to effectively harness the available wind in order to maintain speed in the desired direction. The known triangular sails are described as efficient (Dewan and Hosler, 2008), yet we have no evidence the Olmec had this technology (Callaghan, 2003), nor the crucial centreboard needed for maximising sail power and control (Dewan and Hosler, 2008).

UPSTREAM TO SAN LORENZO

Limitations identified to this point are applicable to open sea travel, yet upstream travel also imposes constraints as the following analysis demonstrates.

Modern pilot sources (Myres, 1993, Robinson, 1993) and an estuary map (UK National Hydrographer, 2003) are utilized in addition to a Spanish explorer's notes (Cortes, 1977).

At the time of the Spanish conquest, the shallowest depth at the mouth or estuary of the Rio Coatzacoalcos noted by Cortes, was 2-2.5 fathoms or 3.6 – 4.5m, and "the greatest depth they found was five or six fathoms (9-11m) ... and judged this to be about the depth for thirty leagues (144km) from its mouth" (Cortes, 1977). Tidal flows affect the lower reaches of the Rio Coatzacoalcos: the adverse outgoing current is between 5 and 5.5 knots (9 - 9.7 km/h) two hours after high water. If timed correctly, the incoming tidal flow would assist upstream travel. This flow averages 2.5 to 3 knots (4 -5.6 km/h) (Myres, 1993). However, this assistance is limited to sections influenced by incoming tidal flows and these do not extend past Minatitlan. This town is around 25 kilometres upstream from where the modern port of Coatzacoalcos now stands, although sand bars and shoals are present beyond this area (Myres, 1993). The Olmec centres of Tenochtitlan and the San Lorenzo plateau are still 36 kilometres further upstream.

With an ebbing or outgoing tide cycle of twelve hours, flow velocity as noted (without considering seasonal flood flow velocity before dams controlled flows), would be in excess of the raft crew's capability to make headway against it. The river flow also sets up counter flows up to a cable, or over 200 m from the entrance, that would draw and then sweep, any craft caught out to sea into faster counter-clockwise ocean surface currents. As a common estuary phenomenon (Bird, 1984: 201), this was probably present in prehistoric times and emphasizes the need to make headway and steerage way, particularly when flow velocity and patterns are compounded by upstream riverbed profiles.

These profiles require changes of direction compounded by currents which form a channel or channels, none of which are straight nor static in position and usually only visible at low water levels. These elements provide constant challenges to navigation. Deeper channel formations typically sweep from side to side in a typical, ‘s’ path as Figure 4 shows on a small scale.

Goulburn River in Eildon Lake bed, Victoria, Australia, Photo: Les Hazell, 2006

Between channels are shallow banks deflecting current flows, increasing flow velocity and inducing counter flows. Combining these constraints with river depths of 9m (27 feet) (Cortes, 1977) and in shore ocean depths (3-4m or 10-12 feet) makes the use of poles for propulsion and basic handling or steering ineffective. This limitation is compounded by weight and leverage force restrictions against the calculated flow velocity.

A further haulage option that could be considered is hauling the craft upstream using ropes. Examples in Indonesia (Dillon, 2004) and RapaNui (Heyerdahl, 1958), and replication experiments (Richards and Whitby, 1997), demonstrate this strategy was not a practical option. In the first instance, as worker numbers increase coordination is required to effectively apply power. The examples show this is difficult to achieve. A further limitation is the hauling rope, which must possess sufficient strength to meet the load applied by the raft and be constructed in lengths to suit the width of likely rivers found in the area. Using a vegetable fibre rope, the only material available, would require a circumference too difficult to weave in such lengths (in excess of 100metres) and still able to be gripped by haulers. A useful comparison is that of a 75mm modern sisal rope which has a breaking strength of some 7200 pounds [3 tons] or 3266 kg, while manila rope has a breaking strain of 9000 pounds [4 tons] or 4082 kg. The combined deadweight of log raft and twenty tonne load is over 70 tonnes. The largest woven cords found in the Tehuacan Valley were approximately 15 mm (MacNeish, et al., 1967), suggesting this hauling method would not be used.

Eliminating this method and other propulsion options reinforces the use of paddles.

Upstream paddling analysis

To test paddling, upstream flow velocity beyond any tidal influence is determined with assumptions made for the Río Coatzacoalcos profile. The mean depth of 9 m cited by Cortes for the Río Coatzacoalcos is adopted, together with a width of 320 m as the average width of the river. Its gradient and width are derived from survey map interpretation using two sources ((Coe and Diehl, 1980a : Map 1) and also (INEGI, 1985, INEGI, 1999)).

For simplicity, the shape of the riverbed was assumed to have a clear unimpeded parabolic shape and using monthly peaks, with a mean flow of 374.6 m^3/s. were used in the following calculation.

Flow in an open channel is given by:

Q= v x A

Here Q is the flow in m3/s and *v* is the mean velocity in m/s., rearranging this gives the mean velocity in the channel as:

$$v = \frac{Q}{A}$$

Substituting for A in this equation yields:

$$v = \frac{3Q}{2W \times d}$$

$$v = \frac{3 \times 374.6}{2 \times 320 \times 9} \approx 0.2 \text{ m/s}$$ Average velocity of the cross section river

However, water velocity near the bottom is almost zero, while the water velocity at the surface is up to 1.5 or 1.75 times the average velocity. Assuming the higher of these multiplying factors, the water velocity at the surface is; v = 0.2x 1.75 ≈ 0.35 m/s. This is assumed to be mean velocity at the surface of the river all year around. During periods of lower flow, velocity will be less, greater flow increasing velocity.

From these calculations the following points using the mean velocity on the river surface of 0.35 m/sec, can be made:

- This velocity translates into 1.26 km/h. I assume from speed data analysis, the maximum the crews could paddle would be 2-3 km/h.
- Mean flow figures from Las Perlas station, show that for 5 months, flows exceed the calculated mean by up to twice the velocity and so would be well above the capacity of crews to move and control the rafts upstream.
- Of the remaining 7 months, flow levels and thus river levels would be too low for over 4 months to give adequate draft even though velocity could be matched by crew power capacity.

- During the other 3 months when river depths are more practical, power would be equal to river velocity.
- However, in this period across the width of the river, velocity will vary, so in slower areas the sediment that is dropped as a consequence, forms shallow bars which would ground the raft (steering speed needed). In the deeper channels with adequate draft, velocity exceeds minimal calculated mean and this would still exceed crew power capacity. River velocity/ crew power capacity is too closely matched for reliability.
- Velson and Clark suggest 72 men could move a canoe raft at 1.5 knots, which is 2.7 km/h (Velson and Clark, 1975 : 21). Riverbed profile and bank formation would make this speed unlikely, as flow velocity varies (Gierke, 2002) across the width of a winding river of this type (Lancaster and Bras, 2001).
- Wash material is held by water flow river current and as this slows, this material is deposited changing river depths. In addition, the position of shallow bars will change from season to season. Numerous ox-bow lakes and lagoons indicate changes have occurred to river positions (INEGI, 1985).

DISCUSSION

Early hypotheses suggested water routes using river and open sea passages were most likely (Coe, 2000). The analytical methodology described indicates such a presumption is not viable when based on the mean maritime conditions cited, less so when it is likely adverse conditions will be in excess of the mean (Myres, 1993). Human power capability, structural integrity and stability demonstrated by the analyses, suggest open sea travel is not compatible with the reliability required for valuable stones portage. The maritime conditions described, with their difficulties of propulsion and stability, make log rafts and open sea stages impractical, compared to land routes.

A winding river course makes navigation unpredictable with steering to avoid sandbars dependent on adequate speed, which the calculations indicate is unlikely. Crew power capacity ratio is inadequate with craft size and weight ratios unlikely to overcome the deficiencies. Constant changes of direction to follow the deeper water would be necessary on the floodplain reaches of the Rio Coatzacoalcos. Towing a log raft with canoes is deemed impractical for the same reason when compared to flexibility of terrain and seasonal conditions. Waiting for flooding tides to assist upstream movement is plausible. However, tidal influences do not extend the full distance between river mouth and the nearest point to the San Lorenzo Plateau. Without this assistance normal downstream flow velocity would be in excess of propulsion capacity beyond Minatitlan. Using sails in rivers is unlikely and along the Gulf coast of Veracruz, prevailing winds are either onshore or against the direction of travel throughout the year.

CONCLUDING REMARKS

By adopting environmental data in conjunction with known human physiology capacity, this analysis has allowed some conclusions to be drawn. Although this is a theoretical approach, it is a useful framework for investigation. The analyses show Olmec megalith water transport by open water involves many structural and crew elements. These must function as a working combination to achieve success. Critical points raised by this type of analysis identified vulnerability at odds with the value placed on the stones. As water transport is deemed not feasible, land transport routes and methods need to be reconsidered.

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