HYPOTHETICAL RECONSTRUCTION OF AN ANCIENT EGYPTIAN SEA-GOING VESSEL FROM THE REIGN OF HATSHEPSUT, 1500BCE

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SUMMARY

Archaeological evidence, including excavated ships' timbers, ancient ship models, excavated river-going vessels and iconic bas-relief depictions, has been used to design and build a hypothetical reconstruction of an Ancient Egyptian sea-going vessel from the reign of Hatshepsut (approximately 1500BCE). Following in the footsteps of Hatshepsut's fabled voyage to the land of Punt, the ship was built on the Nile and then transported overland to the Red Sea where it successfully completed a 120 mile southward journey towards Sudan.

In this paper we focus on some of the design challenges faced as well as the construction techniques used to build the vessel. Also presented are findings and comments on the vessel performance under sail over a two-week period on the Red Sea, where a wide variety of sea and wind conditions were encountered. Qualitative comparisons are made with predicted sailing performance. Difficulties encountered and the resolutions found are also examined.

NOMENCLATURE

AVS	Angle of vanishing stability
BCE	Before current era
Ca	Ship/Model correlation allowance
Cd	Drag coefficient
Cf	Skin friction coefficient: ITTC'57
Ct	Total resistance coefficient
Cw	Wave resistance coefficient
DEI	Deck edge immersion angle
DWL	Design waterline
GMt	Transverse metacentric height
S	Surface area [m^2]
STIX	ISO Stability index
v	Velocity [m/s]
VCG	Vertical centre of gravity
VCB	Vertical centre of buoyancy
?$_{air}$	Density of air [1.293 kg/m^3]
?$_{sea}$	Density of sea water [1025 kg/m^3]

1. INTRODUCTION

For the making of a documentary film '*Quand les Égyptiens naviguaient sur la Mer Rouge*' (When the Egyptians sailed the Red Sea) investigating the Eighteenth Dynasty Female King Hatshepsut's fabled voyage to Punt, French film production house, Sombrero & Co. decided to raise funds for the design and construction of an Ancient Egyptian sea-going vessel.

Two registers at Hatshepsut's funerary monument at Deir el Bahari, dating from 1482BCE, depict five vessels arriving and departing from a location called *Punt* – god's land. Since first substantial publications of these reliefs [1], there has been widespread speculation as to the purpose of the voyage, the location of Punt and the types of vessel used; indeed whether the voyage was even possible. Most Egyptologists agree that Punt was on the African coast of the southern Red Sea near modern Eritrea or Somalia or possibly on the Arabian coast near modern Yemen. The likely location of Punt can be determined from the description and depiction of various plants and animals being carried by the vessels: frankincense, myrrh, gold, ivory, leopard skins, giraffe tails, baboons and other exotica. It is thought that Hatshepsut undertook such a voyage in order to bring back these exotic trade items which would strengthen her position as a king with the powerful priests. It is documented that the Egyptians traded with Punt from as early as the Fifth Dynasty (2498 – 2345BCE) and that sporadic trade continued into the start of the 20th Dynasty (1190 – 1077BCE), a period of approximately 1500 years [2]. Hatshepsut's voyage to Punt is perhaps one of the best known. She had a fleet of five vessels, each of over 20m in length, constructed; and these vessels sailed to Punt to bring back its treasures to Egypt.

Figure 1: Deir el Bahari

It is well documented that the Egyptians were accomplished mariners on the Nile, but there is debate as to whether they were also able to build vessels which could safely navigate open water. For Sombrero's documentary, a hypothetical reconstruction of an Egyptian vessel from 3500 years ago was required to demonstrate whether it would have, at least, been possible for the ancient Egyptians to undertake such a voyage. In addition to the sailing voyage on the Red Sea, the lack of any infrastructure on the shores of the Red Sea, in ancient times, required that the vessels be constructed on the Nile, disassembled and then taken overland, across the desert to the Red Sea where they were reassembled and put to sea.

2. EVIDENCE

Until relatively recent finds of ships' timbers, ropes and other nautical equipment, along with cargo inscribed "the treasures of Punt", in caves on the banks of the Red Sea near Wadi Gawasis [3], there was no direct physical evidence on which to base the design of a sea-going ancient Egyptian vessel. However, the finds at Wadi Gawasis, together with the relief images from Deir el Bahari and the remains of river-going vessels, have provided sufficient evidence to develop a plausible hypothetical reconstruction.

The relief images of Hatshepsut's memorial at Deir el Bahari show profile depictions of five vessels. They show the rigging and steering oar arrangement in some considerable detail as well as depicting the use of oars for manoeuvring. Unfortunately the underwater part of the hull is not shown.

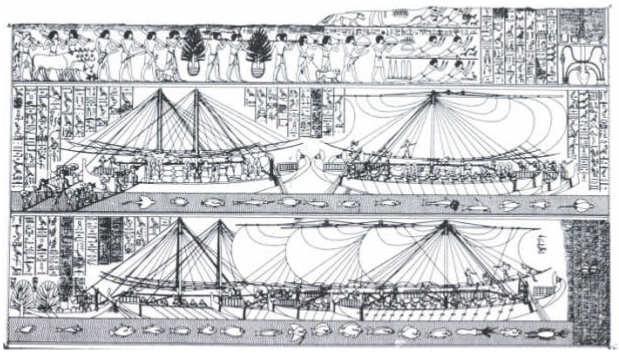

Figure 2: Drawing of bas reliefs at Deir el Bahari

Timbers found at Wadi Gawasis and Ayn Sokhna [4] show traces of attack by marine life indicating that they had been immersed in sea water for some time and are undoubtedly ships' timbers. Identification of key timbers such as steering oar blades has helped to determine that the relief drawings are drawn to a reasonable degree of accuracy in terms of scale related to the human figures depicted. This has enabled key vessel dimensions such as length, mast height, etc. to be estimated.

The final pieces of the design puzzle came from the numerous models and several full-size vessels which have been excavated. River-going vessels such as the Khufu ship c2500BCE discovered by Kamal el-Mallakh in 1950 near the Great Pyramid and particularly the Dashur boats c1850BCE [5] have been used as a basis for the body plan of the reconstructed vessel. A more complete description of the archaeological evidence used may be found in [6].

The vessel was named *Min of the Desert* after the Ancient Egyptian god of the Eastern Desert who is repeatedly praised and illustrated in inscriptions from Wadi Gawaisis.

Figure 3: Ships' timbers found at Wadi Gawasis

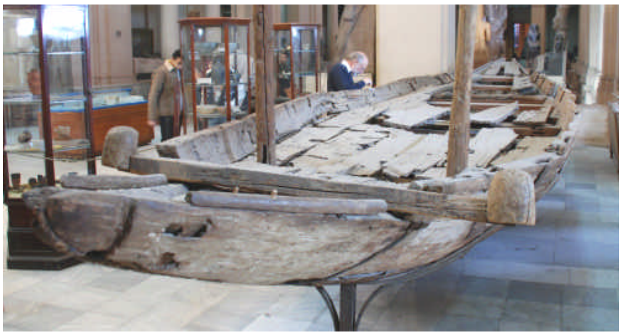

Figure 4: Dashur boat, Cairo Museum.

3. DESIGN

The design was developed in the naval architecture software package *Maxsurf* where the ability to use digital images of the bas-reliefs and paper-based linesplans as background images was invaluable. Hydrostatic analysis to verify the vessel's static stability was performed in *Hydromax*; *Hullpseed* was used to estimate the vessel's resistance.

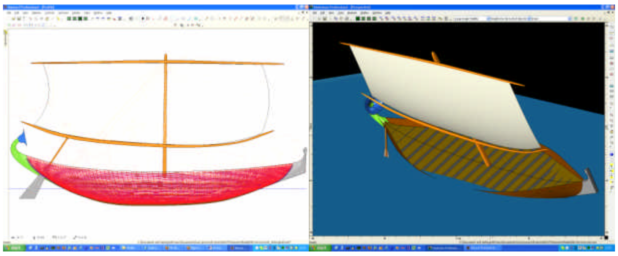

Figure 5: Hull modelling in *Maxsurf* and analysis *Hydromax*

From measurements of excavated timbers and dimensions scaled from the bas-relief images, it was determined that *Min* should have the following approximate principal dimensions:

Table 1: Primary dimensions of *Min*

Length overall	20.3m
Length of main hull	18.3m
Beam on shear	4.9m

3.1 HULL

The team's very early attempts to obtain a suitable hullform solely from the profile drawings of the bas reliefs generated a hullform with unrealistic underwater shape. This is because the drawings showed only the above-water part of the vessel and the underwater shape had to be extrapolated from the above-water portions of the keel line (as seen below, Figure 6).

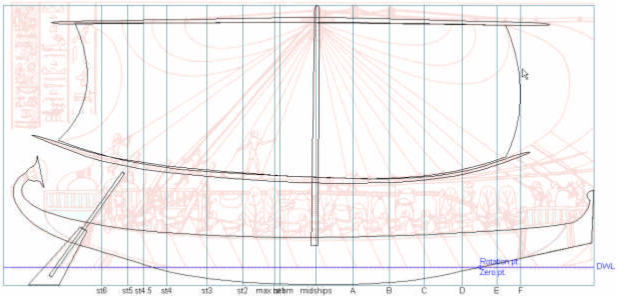

Figure 6: Extrapolated profile indicates very shallow draught and low displaced volume.

3.1 (a) Basis hullform: Dashur boat 3D model

Thus, it was decided to use the physical remains of the Dashur boat, documented by Ward [5], as the basis hullform. The original linesplan taken from a reconstruction of the excavated timbers (pink) in Figure 7 to Figure 9 was used to generate a faired and consistent 3D model (green). Using the bas-relief images as a basis, the design waterline (DWL) – waterline shown in the images – was estimated to be about 36% of the overall depth of the hull.

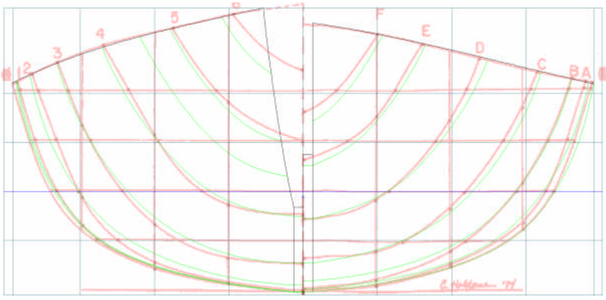

Figure 7: Dashur model: body plan

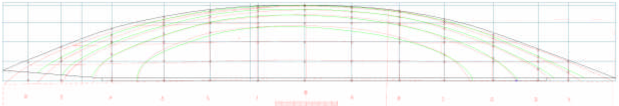

Figure 8: Dashur model: plan (bow on right)

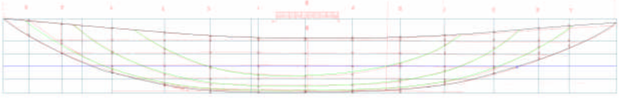

Figure 9: Dashur model: profile (bow on right)

3.1 (b) Hullform modifications for a sea-going vessel

It should be remembered that the Dashur boat was designed to navigate the relatively calm waters of the Nile. Hatshepsut's vessels, designed to sail on the Red Sea, would have required a modified hullform with improved stability and sailing characteristics. For these reasons, the effect of reducing the breadth:draft ratio and also increasing the freeboard were examined. The main motivation for doing this was to improve the range of stability and also to try and improve the angle of deck edge immersion. As a result of these changes, the vertical centre of gravity (VCG) was also lowered, resulting in improved stability characteristics. It was noted that raising the freeboard would make the vessel harder to row, but it was expected that the vessel's primary propulsion would be the sails. Oars would only be used when manoeuvring and rowing would be done in a standing, rather than seated position, in accordance with the evidence from the reliefs.

The evolution of the parent Dashur model to the final *Min* vessel is shown in Figure 10 below. The Parent hullform (Grey) was derived from the Dashur model by linear scaling to the required length (whilst maintaining the original Dashur boat length:breadth and breadth:draft ratios). This hullform was then adjusted to fit the profile shape as shown in the bas-relief drawings – Proto. (Green). The final hullform *Min* (Red) was achieved by increasing the depth (whilst maintaining constant breadth) and making the keel timbers more prominent.

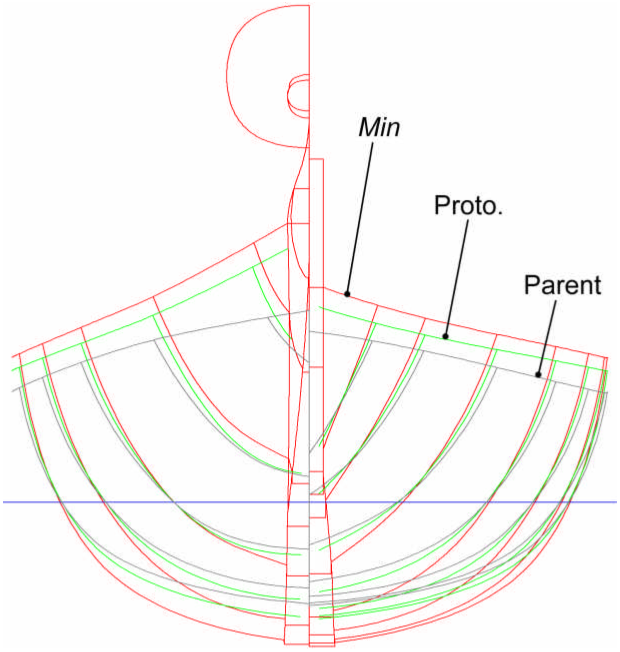

Figure 10: *Min* – Parent and modified hullforms:
Grey: linear scaling of Dashur model (Parent).
Green: Profile adjusted to fit relief images (Proto).
Red: Final hullform with increased depth (*Min*).

3.1 (c) Effect of hullform on stability

The main dimensions of the three vessels are given in Table 2, with some key stability measures given in Table 3.

The adjustments made to the Proto. model were to try to improve the seaworthiness of the vessel; of some concern was the low angle of vanishing stability and deck edge immersion angle, as shown in Table 3. The STIX Stability index [7] provides an overall assessment of the stability properties of a sailing monohull: the greater the value, the safer the vessel. Although STIX is designed for assessing the stability of modern sailing yachts, we can use it as a useful comparator for the design variants. *Min* has a value of 23.7 which is a Design Category C rating (STIX = 23):

> “Waves up to 2.0m significant height and a typical steady wind force of Beaufort Force 6 or less. Such conditions may be encountered on exposed inland waters, in estuaries, and in coastal waters in moderate weather conditions. Winds are assumed to gust to 17m/s.”

The Parent and Proto. vessels have lower values which correspond to a Design Category D rating (STIX = 14):

> “Waves of 0.5m significant height and a typical steady wind force of Beaufort force 4 or less. Such conditions may be encountered on sheltered inland waters, and in coastal waters in fine weather. Winds are assumed to gust to 13m/s.”

This increase in STIX index gives an indication that the changes that have been made to the hullform should provide additional safety when sailing in open water. It should be noted that downflooding through the deck was not considered for the STIX indices quoted.

Table 2: Primary dimensions of evolved design

	Min	Proto.	Parent
Length WL [m]	14.064	13.311	13.311
Beam WL [m]	4.282	4.255	4.262
Draught [m]	1.183	0.948	0.849
Disp. [tonne]	29974	24090	21130
Ballast [tonne]	7777	2264	488
VCG above DWL [m]	0.394	0.603	0.625

Table 3: Some key stability measures

	Min	Proto.	Parent
Area 0-30 [m.rad]	0.0969	0.1196	0.1509
Area 0-DEI [m.rad]	0.0878	0.0950	0.0892
Area 0-AVS [m.rad]	0.4219	0.3848	0.4068
DEI [deg]	28.6	26.6	22.6
AVS [deg]	90.0	78.6	74.5
max.GZ angle [deg]	43.2	37.7	33.2
GMt upright [m]	0.695	0.907	1.195
STIX value	23.7	20.3	19.3

Figure 11 shows the static stability (GZ) curves for the three vessels. The error bars show the effect of raising or lowering the vertical centre of gravity (VCG) by 0.1m.

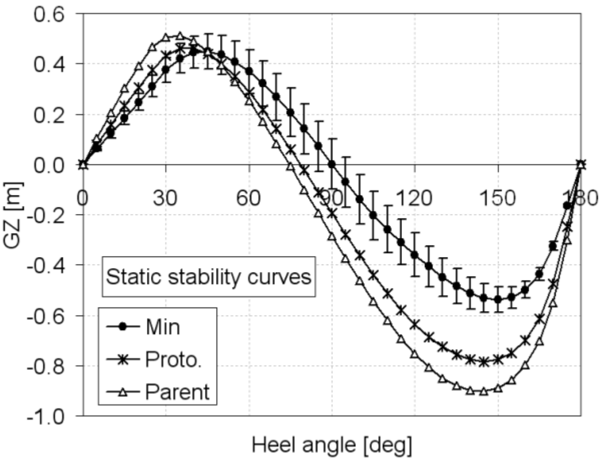

Figure 11: Static stability curves

Much of the increased range of stability for *Min* (compared with the parent vessel) is due to the increased ballast that can be carried. Adding ballast low in the vessel results in a lower VCG and hence increased stability. However, reducing the breadth:draft ratio improves the vessel’s stability at higher angles of heel (above the angle at which maximum GZ occurs) but at the cost of reduced initial GMt. It is perhaps of interest to look at Figure 12 which shows the stability curves for the vessels with the VCG assumed at the centre of buoyancy of the upright vessel floating at the DWL (if the hull sections were completely semi-circular, the GZ would be zero for all angles of heel). Thus these curves show the effect of hullform on stability (rather than the combined effect of hullform and lowered centre of gravity as in Figure 11).

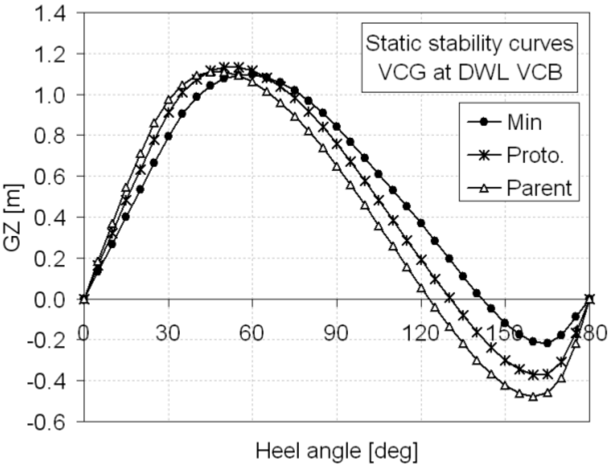

Figure 12: Static stability curves

Looking at the comparative differences between the stability curves of the different vessels in Figure 11 and Figure 12, it can be seen that the hullform changes have a significant effect on the stability; particularly between the Proto. version and *Min*.

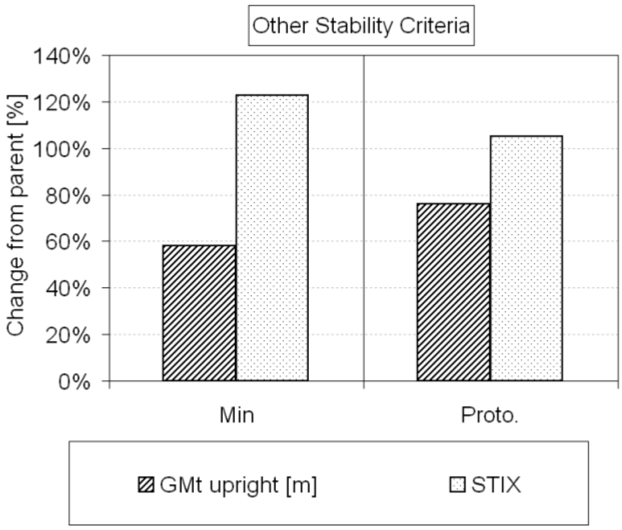

Figure 13: Relative changes of GMt and STIX criteria due to hullform modifications

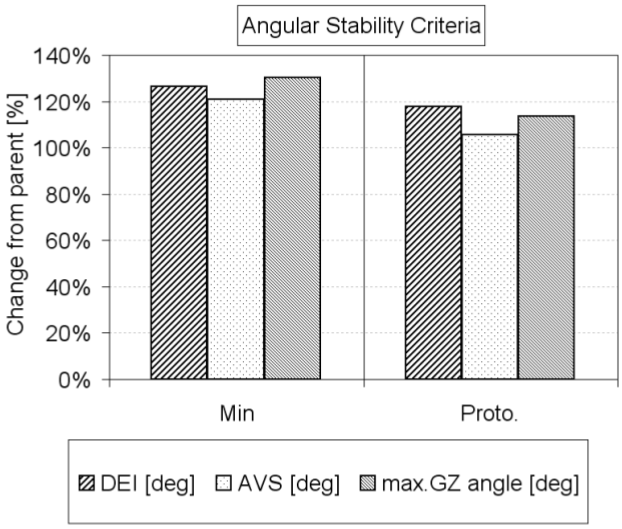

Figure 14: Relative changes of angular stability criteria due to hullform modifications

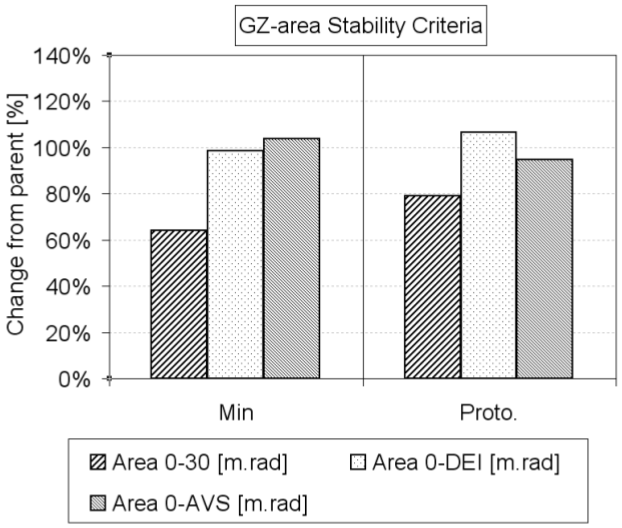

Figure 15: Relative changes of GZ-area stability criteria due to hullform modifications

The effects of the changes in the GZ curves can be characterised by certain stability measures. The relative changes from the Parent are shown in Figure 13 to Figure 15. Although initial stability (GMt) is reduced (Figure 13), it is still adequate and the overall stability as measured by the STIX index is significantly increased. This is primarily due to the increase of some key angles: deck edge immersion (DEI), angle of vanishing stability (AVS) and angle at which the maximum value of GZ occurs – Figure 14. Measures of so-called dynamic stability (area under the GZ curve) are reduced or largely unchanged when compared with the parent (Figure 15).

3.1 (d) Summary of Hullform modifications and stability benefits

Ideally the vessel should have angle of vanishing stability of well over 90deg. By increasing the depth of the vessel, the hullform produces more righting moment at higher angles of heel. Also, the vessel is able to carry more ballast, further extending the range of positive stability. The result of these changes is that *Min* has an AVS of 90deg, whereas the Parent has an AVS of less than 75deg. The freeboard also increases, which increases the angle of deck edge immersion. At just under 29deg, this value, although better than the Parent, is still sufficiently low to cause some concern.

There is a small loss in initial stability, particularly GMt, but the values attained are well within acceptable limits. There is also a hidden benefit in reducing GMt: GMt is the only stability measurement that can be "felt" by the crew (without heeling the vessel to large angles and taking measurements). GMt is felt as the stiffness of the vessel. A vessel with high initial GMt may feel stiff and give the crew a feeling of security – this is often a false sense of security, because high initial GMt typically gives rise to low angles of maximum GZ and vanishing stability (catamarans are an extreme case of this). Finally since the vessel is only intended to sail down wind, a high righting moment at low angles of heel is not required.

3.2 PLANKING LAYOUT

One of the key features of the vessel's hull was that it was to be constructed shell first, without any framing. Only one main floor timber was used to help support the mast at its base. The hull was constructed of extremely thick (up to 22.5cm) planks held together by paired, unpinned mortise and tenon joints, Figure 16. These planks had to interlock to prevent movement and to match the archaeological remains that had been found. A three-dimensional foam model was milled using a CNC multi-axis router. This was then used to help determine the planking arrangement – a sort of three-dimensional jigsaw puzzle of interlocking pieces.

Figure 16: Mortise and tenon joints near keel plank

3.3 SPARS

3.3 (a) Mast

Min was to have a single main mast with an upper and lower yard which would support a single rectangular sail. The principal dimensions of the rig are given in Table 4. The rig, as built, is shown in Figure 17.

The mast was stepped on the main keel beam and passed through the deck where it was braced against substantial transverse deck timbers. The spars were made of Douglas fir, sails of 800g/cm cotton and cordage of hemp. Two halyards were used to hoist each yard; these passed through fairleads, without sheaves, at the top of the mast. Archimedes (287-212BCE) is credited with having designed the pulley block and it was certainly not in use at the time of Hatshepsut.

Table 4: Key rig dimensions

Mast tip above deck	8.3m
Lower yard above deck	2.0m
Upper yard above deck	7.7m
Length of sail along lower yard	14.5m
Length of sail along upper yard	14.3m
Length of lower yard	16.7m
Length of upper yard	15.7m
Sail area	80.9m^2

Figure 17 a: Rigging and sail arrangement

Figure 17 b: Rigging arrangement

The mast was designed as an un-stayed mast using the vessel's transverse righting moment as a guide to the bending moment that the mast should be able to support. For modern sailing vessels, the largest sail forces are (normally) experienced when sailing upwind. In this case the heeling moment from the rig is mostly transverse, so basing the design on the vessel's transverse righting moment makes sense. *Min* would not be capable of sailing upwind, and, when sailed downwind, the rig moment would be mainly in the longitudinal direction. Since the longitudinal righting moment is considerably greater than that in the transverse direction, it would be possible to apply greater loads to the rig under this condition. However, a design of the mast based on the lower (transverse righting moment) is justifiable because it would be quite unsafe to sail the vessel in a condition where a broach would cause it to capsize. (A large sail force acting longitudinally could be supported by the vessel, but if the same force were applied transversely, due to a change of course or wind direction, the much smaller transverse righting moment would be insufficient to prevent capsize.)

The mast diameter was calculated using two methods. The first, being based on a wind pressure on the sail as proposed by Skene [8], suggested a mast diameter at the deck of 28.5cm for a design wind speed of 17kts. This increased to a diameter of 39.5cm when the design wind speed was increased to 27.5kts. The second method followed the design guidelines proposed by Bureau Veritas [9] and was based on the vessel's righting moment (essentially a calculation of required section modulus based on the bending moment of a cantilevered beam under a point load with a safety factor of 1.8.) A design righting moment of approximately 182kNm was used; this included the effect of 30 crew members increasing the righting moment by being on the windward side of the vessel. These calculations gave a diameter of 43cm at the deck, tapering to 25cm at the mast tip. The actual mast, as constructed, had a diameter of 45cm at the base tapering to 24cm at the base of the yard lift fairleads and to 14cm at the top of the halyard fairleads.

Finally some simple beam bending calculations were carried out for different loading distributions between the upper and lower yards generating a constant heeling moment. As might be expected, this illustrated that the mast-tip deflections were quite dependent on the rigidity and moment transfer of the through-deck fixing: increasing the rigidity at this point reduced the mast tip deflections but substantially increased the loads that had to be withstood at the deck.

3.3 (b) Yards

The yards were considered as cantilevered beams with a uniformly distributed load due to the wind pressure on the sail. In practice some of the weight of the lower yard was taken by standing rigging. Three loading conditions were used; the first two being the extreme conditions where the entire load was taken on either the upper or lower yard alone and the third where the load was equally shared between the two. In all cases the load was derived from the vessel righting moment. The self-weight of the yards was not considered. The extreme conditions suggested spar diameters of 26cm for the upper yard and 38cm for the lower yard whilst the more realistic condition with the load shared between the two spars gave diameters of 24cm for both.

The yards were originally built with a diameter of 24cm at the middle, tapering to 14cm at the ends. They were built in two halves joined by a lashed scarf joint. The total weight of the full-length yard was 250kg. During initial trials it was found to be impossible to hoist the upper yard more than a couple of metres above the deck, even without the sail attached. This was due to a number of factors: the shear weight of the yard, the lack of pulleys and the angle of the halyards to the vertical which reduced as the yard was hoisted up the mast – see Figure 17. For this reason it was decided to reduce the diameter by approximately 33%, reducing the weight to a more manageable 110kg; these reduced dimensions were also more in accord with ancient representations.

4. CONSTRUCTION

The vessel was built at a shipyard in Rashid (Rosetta), a port city near the mouth of the Nile, in Egypt. The timber used for the construction was Douglas fir – similar in physical properties (density, modulus and grain structure) to, but more readily available than, Lebanon cedar (the timber which would, most likely, have been used in the original vessel). Timber from trees over 150 years old were sourced from plantations near Lyon in France. The tenons were made from acacia, as would have been the originals, since this is still readily available in the dimensions required. To validate that construction using the tools and techniques of the ancients was viable, the craftsmen shaped the thick timbers by hand using traditional hand tools (adze, etc.), though these were made of iron rather than hammered copper. However, due to the extremely short construction schedule, it was necessary to utilise electric routers and planers to finish the vessel topsides. *Min's* hull was built in six months.

Figure 18: *Min* at various stages of construction

The hull was initially constructed with no caulking between the planks, instead relying on the quality of the craftsmanship and expansion of the timbers when wet to ensure that the vessel was watertight. Unfortunately after the vessel was launched, it became apparent that the planks were not going to swell sufficiently to effectively seal the joints. It is not clear exactly what the cause of this problem was. It may have been that the edges of planks in the lower part of the hull were not sufficiently well matched so as to form a watertight seam or it may have been the case that, despite lack of remaining archaeological evidence, some sort of caulking had been used by the ancients. Since the vessel could not be sailed in this condition, the decision was made to caulk the joints using linen fibres and bees' wax (materials that would have been available to Hatshepsut and still in use today for this purpose). It was found that this caulking was very effective, with the hull only taking on an estimated 2-3 litres of water per hour.

The successful completion of *Min* verified that a shell-first construction technique using traditional tools was technically realisable and effective. This supported the interpretations of the archaeological and iconographic evidence that had been made.

5. PERFORMANCE

With a tight filming schedule there was limited time available for trials. Initial trials were performed in late November 2008 on the Nile. A second set of trials were undertaken on the Red Sea over a 14-day period in December of the same year.

5.1 VESSEL MASS AND CENTRE OF GRAVITY

Unfortunately time and equipment were very limited and as a result a full lightship survey and inclining experiment were not possible.

5.1 (a) Lightship mass

In the lightship condition, without rigging or ballast, the fore and aft drafts were recorded as 0.729m and 0.978m respectively. (These values were derived by measuring the vertical distance to the waterline, port and starboard, along the length of the vessel.) This gave a displacement of 17.1t (assumed water density 1010kg/m^3) and a trim by the stern of a little over 1deg. The weight of the ship in the same condition, as estimated during the design phase, was 17.07t with a trim of about 0.5deg by the stern. The immersion at this draught was 340kg/cm; thus, with inaccuracies in draught measurement and building, there could easily be an error of the order of 1t in the measured displacement. However, despite the possible errors, these measurements gave some confidence in the mass and centre of gravity that had been estimated for the vessel. (It had been hoped that the vessel could be weighed when it was loaded by crane onto a lorry for transportation to the Red Sea, but unfortunately this was not possible.)

Similar draught and mass calculations were planned after ballasting the vessel with approximately three tonnes of sand. Attempts to do this within the limited time available were thwarted by too much wind, making it impossible to measure the water position with any degree of accuracy. However, as expected, once the ballast was loaded, the vessel felt significantly stiffer due to the VCG being lowered.

5.1 (b) Inclining

A detailed inclining experiment was not possible, but it was planned to try to measure the roll period of the vessel. The vessel was anchored whilst a line was tied to the top of the mast and taken ashore. The plan was to have about 20-30 men pull the vessel over and then release it (with the aid of a quick-release knot). However it was not possible to incline the vessel sufficiently before the anchors started to drag, so the results of these tests were inconclusive.

5.2 MANOEUVRABILITY

5.2 (a) Effectiveness of steering oars

Initial trials of the vessel were carried out on the Nile River towing the vessel behind a motor launch. The twin steering oars, or quarter rudders, provided a sufficient moment to steer the vessel with or without tension in the tow cable. Since it was a little difficult to co-ordinate the same rudder angle between two helmsmen (one being required for each oar), small modifications to the vessel's course were best achieved by manipulating a single oar – the other one being left amidships; this prevented the situation where both helmsmen were trying to steer the vessel in different directions. For abrupt changes in course, co-ordinated movement of the oars was most effective. To achieve the tightest turn possible, the rudder angle had to be applied progressively to prevent separation on the suction side of the oar: putting the rudder over to a moderate angle to initiate the turn and then increasing the rudder angle as the vessel started to turn and the stern started to swing out.

The steering was found to be quite heavy with the ship under sail. Another problem was that the steering oars were only held in place by lashings. Devising a lashing technique which prevented the oars from dropping too low in the water, whilst still being relatively free to rotate, was quite challenging. Possibly the situation would have been improved by having a greater immersed volume of the oar blade (hence greater buoyancy) and/or longer loom. In fact the vessel was slightly under ballasted, requiring an additional three tonnes of ballast to bring it to the DWL. This would have increased the steering oar immersion as well as improved the vessel's directional stability by increasing the waterline length.

5.2 (b) Rowing

Rowing with 13 oarsmen on each side was quite crowded, but possible. It was also found that rowing from a standing position facing backwards to the direction of travel to be most effective.

During the initial trials with only eight rowers (four on each side), it was possible to make some progress into a 10-15kt headwind. After more practise (during the voyage on the Red Sea) it was possible to reach a speed of 2.5 knots using 14 rowers. During sail hoisting manoeuvres, six rowers, stationed forward in the vessel, kept the bow pointing downwind.

5.3 SAILING PERFORMANCE

Sailing trials were conducted over a 14-day period including a 7-day voyage on the Red Sea starting at Safaga and heading south towards Sudan. A wide variety of wind and sea conditions were encountered, including rolling swells of 2-3m significant wave height (crew observations) and winds speeds of up to 25kts, as measured by a hand-held anemometer. Two sails were used during the voyage, a large sail of 77.5m^2 measuring 14.35m wide by 5.4m tall and a smaller sail of 20.7m^2 measuring 6.9m wide by 3m tall.

A crew of 20 including five Egyptian sailors from Lake Borolos were able to handle the vessel; though hoisting the sail still remained a laborious task, requiring a team of six men on each halyard. The steering oars proved to be effective, though heavy to use, especially in heavy weather and were buffeted by the waves.

During the reasonably heavy seas that *Min* encountered, she felt seaworthy despite quite acute roll motions. The plank seams held fast despite being towed through some quite large waves.

Although there was not sufficient time to perform extensive sailing tests, records were made of apparent wind speed and sailing speed (over the ground using a GPS). Some tests were carried out in order to estimate the true wind heading on which the vessel could sail. It was found that *Min* could sail a course on a broad-reach, up to approximately 110deg off the wind; leeway angles were not accurately measured but judging from the wake, leeway angles were not excessive and in fact much less than anticipated, probably no more than 15deg. As has been mentioned earlier, the vessel was under ballasted. Increasing the draft would probably have further improved the sailing performance (increasing pointing ability and speed and reducing leeway) due to: increased waterline length, immersion of steering oars, and underwater lateral projected area and reduced topsides windage area.

5.3 (a) Sailing performance predictions

Some simple sailing performance predictions were made for the downwind sailing condition. A slender body method [10, 11] was used to predict the wave pattern drag with a form factor derived from Holtrop's [12] formulation of 1.348; a correlation coefficient of 0.0004 was used. The various resistance components are given in Figure 19. It is likely that the peaks and troughs, caused by wave interaction, are somewhat exaggerated but these results can be used as a reasonable first approximation to the vessel resistance.

The total resistance coefficient, Ct, is given by Equation 1; with Cf calculated from the ITTC'57 model-ship Correlation Line, using a kinematic viscosity of 1.19×10^{-6} m^2/s and a nominal waterline length of 14.062m.

$$Ct = Cw + (1+k)\ Cf + Ca \qquad (1)$$

Assuming that the vessel is travelling dead downwind and that the sail is acting only as a drag device, with a typical drag coefficient, Cd = 1.5, the force on the sail is given by Equation 2, where v is the apparent wind speed (true wind speed less ship speed).

$$F = 0.5\ ?_{air}\ S\ v^2\ Cd \qquad (2)$$

Equating this to the hull resistance and solving for v, one may estimate the apparent wind speed needed to propel the vessel at a given speed: Equations 3 and 4.

$$R = F = 0.5\ ?_{air}\ S\ v^2\ Cd \qquad (3)$$

Rearranging:

$$v = v\ \{2\ R\ /\ (\ ?_{air}\ \ S\ Cd)\ \} \qquad (4)$$

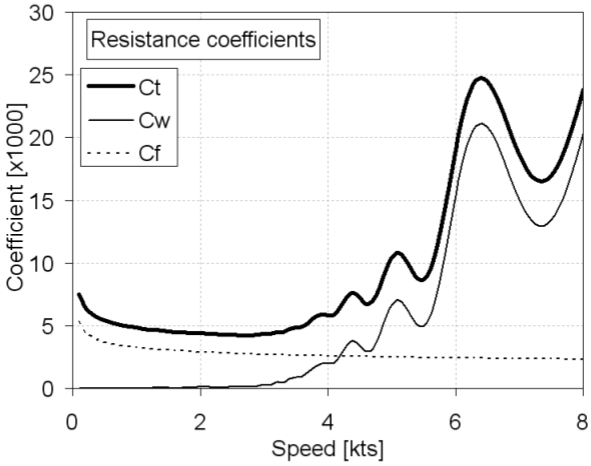

Figure 19: Predicted resistance coefficients, using the slender body method for wave resistance.

Calculations using the method described above have been compared with the trials observations and are shown in Figure 20. The dots represent observations of ship speed and apparent wind speed; black dots being for observations when the large sail was in use and grey dots for the small sail. The thick solid lines are the predictions assuming Cd = 1.5, a typical value for such a low aspect ratio sail (Fujiwara et al [13]). Again black for the large sail and grey for the small sail. The thinner dashed lines show the relatively small effect of changing the Cd values (1.7 and 1.3).

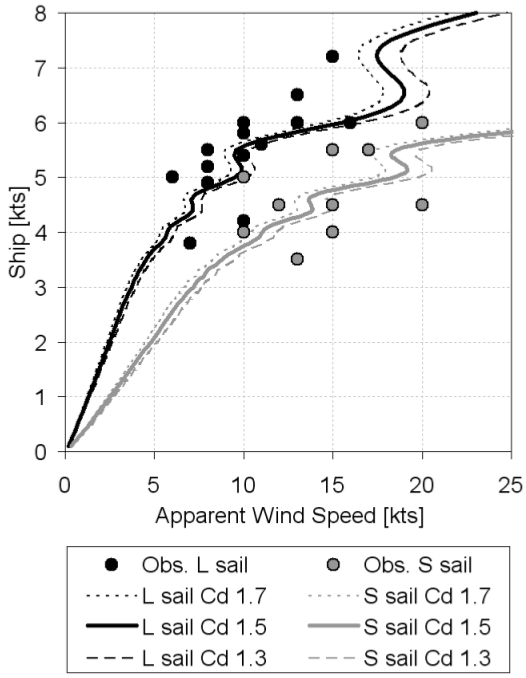

Figure 20: Ship speed vs Apparent wind speed: Correlation between observations and predicted results.

5.3 (b) Objective sailing performance observations

The following are a number of comments that were made by crew members relating to the sailing performance of *Min*.

> "The crew were worried that the ship would not be able to withstand the strong sea waves, particularly since it was held together by wooden joints alone, as was ancient Egyptian practice. However, even in swells of up to three metres, the ship handled well, corkscrewing through the waves smoothly and taking only one small splash of a wave over the rail even when the wind was blowing at 25kts."

> "Although it took brute strength to haul up the sail and to row the ship, once the sail was set all of us remarked on the efficiency and simplicity of the ship when manoeuvring and steering, and on its responsiveness."

> "We did not have any particular problems with the navigation. In fact, the ship was easy to sail. We did not practise anchoring, though it would have been possible to do that, but our intention was not to imitate the voyage entirely."

The overall sailing performance is perhaps best summed up by skipper David Vann's comments:

> "We had to learn about the sail, also. We discovered that it was better to not raise the upper yard all the way, for instance. It was better to lower it just a bit and let the sail billow, like in the reliefs. I was amazed at how easy the boat was to sail. We could sail anywhere from straight downwind to 90deg off either side, and there was no risk at all. We didn't have to fear small wind shifts. Everything was smooth, and we had all the time in the world to make any changes. Those thick lower sheets began to make tremendous sense. We changed our tack simply by letting one out a bit and pulling the other one in. We led the upwind sheet across the deck for better leverage when we were higher on the wind. And we were sailing at 7kts, about as fast as a modern cruising sailboat with the same waterline and conditions.
>
> We did have one thing break. We tried initially to use the upper sheets to help adjust the sail, and we put too much pressure on one and snapped the upper yard. We had tried to lead the sheet forward, a departure from the reliefs, a practice you'd use on a modern boat. But after the accident, we went back to the reliefs, led those sheets aft and kept them fairly loose. We used them only to shape the sail. One brilliance of the ship's rig design is that all of the heavy loads are taken by the mast rather than the sheets. On a modern boat, the sheets have the highest loads on the boat and are frightening. But on Min, the lower yard is bound to the mast, so the sheets handle only the side to side adjustments, not the primary driving load. I was able to adjust the sail myself, with no one else's help, if I first loosened one line and then tightened the other, though usually we had two people on each line. But I was amazed that one person without a winch could do this, and I could do it up until about 12-15kts of wind, when a second person was required."

6. CONCLUSIONS

Min outperformed our expectations in terms of sailing and seakeeping performance. The structural integrity remained sound demonstrating the reliability of the paired, unpinned, mortise and tenon fastening system. Some questions still remain unanswered as to how to make the joints watertight without resorting to caulking (the excavated planks had clean edges with tool-marks still visible).

The rig was efficient at propelling the vessel, not only downwind but also across the wind up to an angle of about 100deg off the wind. It was also reasonably easy to manoeuvre the sail (if not to hoist it). The steering oars were effective though maybe the fastening system could have been improved, and the vessel could be manoeuvred by six to 14 oarsmen depending on the weather conditions and manoeuvre to be achieved.

The completed ship confirms the most recent hypothesis on the construction of the ships of ancient Egypt. *Min of the Desert* is the only experimental reconstruction of a ship from the ancient Egyptian period that has been constructed based on scientifically validated archaeological evidence. Along with the archaeological evidence of timbers with significant shipworm damage, the experiment described in this paper demonstrates, beyond reasonable doubt, that the Ancient Egyptians independently developed sea-going sailing vessels.

Those who worked on and sailed *Min* were generally full of praise for the technology of the ancient Egyptians.

> "At first, it seemed to me to be a crazy project, but then I grew to respect the technology and to have faith in the ship, and I was with them every minute of the voyage."

– Mahrous Lahma, Chief shipwright at Chantier Ebad El-Rahman

Min of the Desert is now a permanent exhibit at the Museum of Suez in Egypt.

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The greatest thanks must go to the shipwrights of Chantier Ebad El-Rahman, Rashid, Egypt and the sailors from Lake Borolos who formed the core of the crew, without whom construction and sailing of this vessel would not have been possible. We also thank our all-volunteer crew and especially our captain, David Vann, for his steadfast performance in an untried, experimental vessel.

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Figure 21: *Min* sailing on the Red Sea.
Fluctuat nec mergitur: It is tossed by the waves but it does not sink – Paris motto.