# 7. From the Golden Horn to Heraclea: duration of the passage in calm weather

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## 1. Summary

One of the pieces of evidence of the speed of an ancient Greek trireme under oar is a statement by Xenophon (*Anabasis* 6.4.2) that for a trireme the passage from Byzantium to Heraclea entailed "a long day under oar". One version makes it "a very long day". The implied speed sets a standard by which any reconstruction of an ancient Greek trireme's hull and oarsystem must be judged.

In this paper data from British Admiralty charts and British Admiralty Sailing Directions (the Black Sea Pilot) are used to assess how long the passage would take in calm weather during the ancient sailing season at cruising speeds 7, 7½ and 8 knots relative to the water. It is assumed that today's conditions are close to those that obtained in antiquity.

Skilful helmsmanship and local knowledge would be required in order to avoid adverse currents wherever possible and to exploit favourable eddies.

The main conclusion is that sustained cruising speeds in the range 7–8 knots are compatible with the statement made by Xenophon and with the calculated performance of a moderately good crew (say at 7½ knots relative to the water) and of an outstandingly good one (nearly 8 knots). The passage would occupy from about 15 to about 17 hours not including any mid-day stoppage. An outstandingly good crew could accomplish more than 90% of the distance in daylight at midsummer, but if a cooler season were essential or the crew slower some part of the voyage would have to be conducted in twilight and/or by moonlight.

## *2. Discussion*

### *2.1. How long was "a long day"?*

Morrison has pointed to Herodotus' use of the word *makremeria* ('long days') and gives reason for thinking that for Herodotus 'a long day' meant the period between sunrise and sunset in summertime (Morrison 1991). Morrison has quoted Brown's Nautical Almanack to show that at the beginning of April and the beginning of September in the latitude of the southern Black Sea the sun is above the horizon for about 12 hours and 40 minutes (in modern hours and minutes) and at midsummer for 15 hours, but that if the hours of twilight before sunrise and after sunset are included, making perhaps "a very long day" the durations extend to 14 hours and 40 minutes in early April and early September and to 17½ hours in midsummer. Of course twilight shades off into darkness in which coastwise navigation would be hazardous. I therefore propose that a little more than half the nominal duration of twilight be added, making "very long days" vary from about 14 hours up to 16½ hours in the absence of help from the moon. On cloudless nights when the moon was full or nearly so, it would have shone brightly all night. That might suggest that "a very long day" could have extended to 24 modern hours or even more. But then we might expect Xenophon to have written not "a (? very) long day" but "a day and a night". What he did write, coupled with the data given above, does not rule out that part of the voyage was sometimes conducted by the light of the moon but does appear to me to rule out a 24 hour "long day". In what follows I seek to show that a moderately good crew in a suitable ship could accomplish the voyage in about 18 hours including an hour's rest at mid-day, and that an exceptionally good one could accomplish it without stopping in 15 hours. I think it is reasonable to conclude that that these durations are consistent with Xenophon's text and with the data from the almanack. The mean speeds while the ship was under way would have been in the range 7 to 8 knots relative to the water.

### *2.2. Ascent of the Bosporus in normal charted conditions*

The information given here is derived from Admiralty Chart No. 1198 and from the *Black Sea Pilot: Admiralty Sailing Directions*. The course is assumed to start at the modern bridge near the mouth of the Golden Horn and to end on the eastern side of the northern exit into the

*Table 7.1. Currents and counter currents (eddies) encountered during the preferred course; durations if the ship's speed is 7.5 knots relative to the water.*

| *Nautical Miles* | *Remarks* | *Duration in minutes (to nearest 0.5)* |
|---|---|---|
| 0–5.3 | Helpful countercurrent Averaging 0.5 knot | 40 |
| 5.3–5.7 | Adverse current of 1.5–2 knots on the port bow during the crossing | 4*–4.5* |
| 5.7–6.2 | Some help, up to 0.25 knot | 4 |
| 6.2–8.6 | Adverse current of 1.5–2 knots | 24–26 |
| 8.6–9.9 | Helpful eddy of 0.5 knot | 10 |
| 9.9–10.7 | Adverse current of 1–1.5 knots | 7.5–8 |
| 10.7–11.1 | Helpful eddy of 0.25 knot | 3 |
| 11.1–12.1 | Adverse current of 1.5–2 knots | 10–11 |
| 12.1–12.5 | Helpful eddy of 0.25 knot | 3 |
| 12.5–13.6 | Adverse current of 1.5–2 knots | 11–12 |
| 13.6–14.4 | Helpful eddy of 0.25 knot | 6 |
| 14.4–16.4 | Adverse current of 0.5–1 knot | 17–18.5 |

* Allowing for leeway during the crossing

Black Sea. It is described in tabular form. Distances in nautical miles (n.m.) are relative to the land. During the first 5.3 n.m. the recommended course is close to the west bank. It then crosses over and stays near to the east bank as far as the northern exit. I have assumed that during the crossing the ship's heading is at 45 degrees to the adverse stream. The course made good is then at 54.2 degrees to the stream if the adverse current is 1½ knots, or at 57.9 degrees to it if the adverse current is 2 knots. Apparently the stream in the narrows at the crossing can reach 7 knots but presumably not during the sailing season. Exceptionally, the flow may cease. The variations quoted below are presumed to be normal, but wider ones must occur from time to time.

At about 6.75 n.m. the adverse current in the centre of the narrow channel is charted as 1.5–2 knots, increasing to 2–3 knots at about 7.5 n.m. where the strait is wider. This may be an effect of the changing depth. As the ship's course at these points is near the east bank I have felt justified in proposing an adverse current of 1.5–2 knots throughout the stretch from 6.2 to 8.6 n.m. where the ship enters a helpful eddy (Table 7.1).

The total duration is in the range 2 hours 20 minutes to 2 hours 26 minutes depending on the currents encountered.

If the ship's speed through the water is 7 knots the total duration for the 16.4 n.m. is in the range 2 hours 31 minutes to 2 hours 38 minutes; if the speed through the water is 8 knots the range is from 2 hours 10 minutes to 2 hours 16 minutes.

### *2.3. Conditions of navigation in the southern Black Sea*

Here is a summary of the statements in The *Black Sea Pilot* referring to the wind, waves, currents, temperatures and humidities.

*The prevailing wind* all the year is from the NE but there is a significant proportion of days in which the wind blows from the NW to the SW quarter. Near the coast the wind direction tends to be modified by the land and sea breezes that are well marked in summer. The onshore wind develops in mid-morning. By mid-afternoon it may reach Force 3 to 4 (*i.e.* 7 to 16 knots): it fades soon after dusk. The land breeze is usually weaker and blows offshore from late evening till shortly after sunrise.

*On waves* the information is limited but shows that slight seas with waves of 0.5 m or less (implying slight winds; see my paper on pp. 68–75 below on 'The performance of ancient triremes in wind and waves') are reported in over 50% of observations in spring and autumn. Waves exceeding 2.5 m are reported in fewer than 10% of observations, though waves of up to 13 m have been reported. In summer, very rough seas do occur, but are unusual, and slight seas with waves 0.5 m or less are reported on over 64% of observations.

*Swells* are mostly from the NW and NE. In summer they are generally low. Heights of 1 m or less are recorded in about 50% of observations. Swells exceeding 4 m in height are unusual, though in autumn swells up to 15 m can occur in the E (presumably beyond the region of interest here).

*There is an anticlockwise current* in the Black Sea. According to the *Black Sea Pilot* its velocity along the western part of the southern coast is 0.25 to 0.75 knots in general. It is greatest after the melting of the snows in late spring and early summer. The latest edition of the *Encyclopaedia Britannica* (referring I think to the Black Sea as a whole) gives 40–60 cm/sec (0.78–1.17 knots) as the velocity of circulation near to the shore, but less further out. *The Black Sea Pilot* says the circulation is "weak and inconstant ... Countercurrents ... occur between the main current and the shore in many places."

*Humidity*: in summer in the S and SE coasts the relative humidity is around 85% in the early morning falling to about 70% in the afternoon.

*Table 7.2.*

| **Istanbul** | *April* | *May* | *June* | *July* | *August* | *September* |
|---|---|---|---|---|---|---|
| Temp. C | 7–16 | 12–21 | 16–26 | 18–28 | 18–29 | 15–25 |
| R.H. | 81–61 | 81–60 | 77–56 | 77–52 | 80–51 | 84–57 |
| Wind, knots | 4–8 | 4–7 | 4–8 | 5–10 | 4–10 | 3–9 |
| m/s | 2–4 | 2–3½ | 2–4 | 2½–5 | 2–5 | 1½–4½ |
| **Zonguldak** | *April* | *May* | *June* | *July* | *August* | *September* |
| Temp. C | 7–14 | 12–19 | 15–23 | 17–25 | 18–25 | 15–22 |
| R.H. | 76–72 | 77–74 | 76–73 | 75–73 | 75–71 | 77–70 |
| Wind, knots | 3–5 | 3–5 | 2–6 | 2–6 | 3–6 | 3–6 |
| m/s | 1½–2½ | 1½–2½ | 1–3 | 1–3 | 1½–3 | 1½–3 |

*Table 7.3. Times under oar, Bosporus exit to Heraclea, 210 km with helpful current of 0.5 m/s (1 knot):*

| Speeds relative to the water, knots | 7.0 | 7.5 | 8.0 |
|---|---|---|---|
| Duration of rowing, hours and minutes | 14h 10m | 13h 20m | 12h 35m |

*Table 7.4. Total journey time, Golden Horn to Heraclea*

| Ship's speed relative to the water | 7 knots | 7.5 knots | 8 knots |
|---|---|---|---|
| *Duration, hours and minutes* | | | |
| At weaker Bosporus current | 17h 41m | 16h 40m | 15h 45m |
| At stronger Bosporus current | 17h 48m | 16h 46m | 15h 51m |

*Temperature*: in July and August, the air temperature reaches its maximum, and mean daily temperatures range between maxima of 25–30 °C and minima of 17–19 °C. The extreme highest temperatures recorded in coastal districts are generally around 38–41 °C but over the open sea the extreme maxima are generally around 27–32 °C.

The ranges of temperature, relative humidity and windspeed at Istanbul and Zonguldak (east of Heraclea/Eregli) for the months April–September are given in Table 7.2.

In each case the first-given temperature is the mean daily minimum for the month and the other is the mean daily maximum.

Extremes sometimes well beyond these can occur. The first-given R.H. is the average humidity at 0700 and the other is at 1400. The first-given wind is the mean at 0700 and the other is at 1400. Zonguldak is on the south coast further east than Heraclea.

I assume that an ancient trireme would have been steered close enough to the shore to benefit from the faster current there, whose magnitude I take to be 0.5 m/s, the middle of the range given by *Encyclopaedia Britannica.*

The data on the temperature and humidity confirm the importance of ventilating the ship to cool the oarsmen.

The windspeeds confirm that very light winds predominate during the ancient "sailing" season, and bearing in mind the information to be given in my paper on 'The performance of ancient triremes in wind and waves' below it is not surprising that on the whole the waves are low.

## *2.4. Duration of the voyage after leaving the Bosporus, and total duration*

We may take the distance from the northern end of the Bosporus to Heraclea as 113 n.m. (say 210 km). The times taken by the ship to cover this distance at steady speeds of 7, 7.5 and 8 knots relative to the water, given a helpful current of 0.5 m/s (about 1 knot) are given in Table 7.3.

These durations exclude any time spent resting at mid-day.

Adding together the times spent rowing up the Bosporus and in the Black Sea and allowing an hour's rest at mid-day, about half-way into the journey, ignoring any progress that might be made during that rest by virtue of the current and recalling that calm weather is assumed, I obtain the durations given in Table 7.4 for the total journey time:

Say 17h 50m, 16h 50m and 15h 50m respectively.

If there were after all a slight tail wind or onshore wind, not strong enough to raise hampering waves, say a true wind of 4 m/s or 8 knots, it would give virtually no help when the ship was under oar (and if it were from astern it could well cause the men to overheat while they were rowing) but it could drive the ship on at about 4 knots during the hour's rest. This would gain 4 n.m. or about 7.5 km, about 3% of the total distance, reducing the total durations given above by about half an hour. The current of about 1 knot on its own would gain about 1 n.m. worth about 8 minutes.

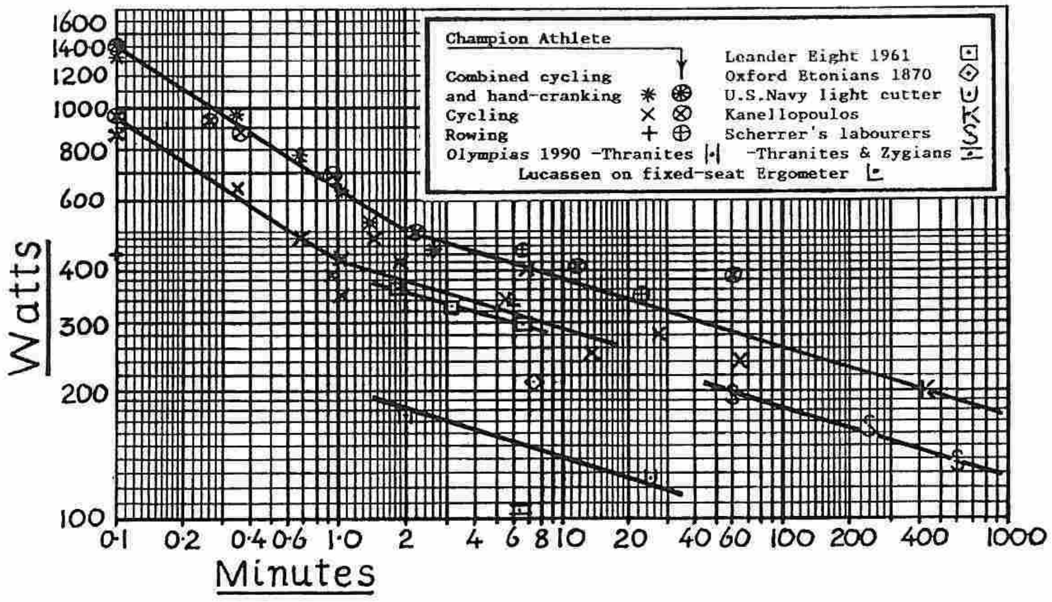

*Figure 7.1. The gross mechanical power of athletes of various kinds in relation to the duration of their efforts (from Shaw 1993b, 65, fig. 10.4).*

***2.5. Power required***

The power required by *Olympias* at various speeds was deduced by Grekoussis and Loukakis from tank tests of a bare hulled model and their results were reproduced by Lowry and Squire in the form of a graph (Grekoussis and Loukakis 1985; Lowry and Squire 1988). By examining this graph I have found that the power consumption of *Olympias* with rudders partly raised to reduce their resistance can be expressed by the formula:

$$\text{Power in watts} = 155V^3 + 4.13V^5$$

Where V is the speed in m/s.

I suggest that the power required by a Mark II trireme reconstruction would be about 8% more than this because of her probably greater length and displacement. If the whole oarcrew were in action the effective power per man would be 1/170 of this larger quantity but of course each man must do still more because of the inefficiency of the oars and their inertia which both absorb power unavoidably. The man must develop much more power than is absorbed by the ship. If I assign a mean ideal efficiency of 0.78 to the oars (see my paper 'Towards a revised design of a Greek trireme' on pp. 76–81 below) and adopt the formula

$$\text{power in watts absorbed by the trireme oar} = 0.96r + 0.016r^2$$

where r is the rate of striking (Shaw 1993a; for the method of calculating the rates of striking which follow, see the Appendix to this Paper and pp. 76–81 below)

and if I take
$r = 25.5$ when speed = 7 knots
$r = 28.8$ when speed = 7.5 knots, and
$r = 32.3$ when speed = 8 knots

then I find that to the nearest 5 W the gross power to be exerted per oarsman is

rendement 50%

115 W at 7 knots
145 W at 7.5 knots, and
180 W at 8 knots

The graph of power a man can exert continuously against the duration of the exercise shows that hardened manual labourers, if kept cool and given adequate sustenance in the form of easily digestible food and drink, could exert 180 watts for just under two hours, 145 watts for about 7½ hours and (if the straight line can be extrapolated) 115 watts for as long as 30 hours (based on the study by Scherrer *et al.* 1981 of sugar-cane cutters in Queensland, Australia; see Shaw 1993b, 65, fig. 10.4 (reproduced here as Fig. 7.1) and the paper by Coates on 'Human mechanical power' on pp. 161–4 below); whereas men of the ability of Kanellos Kanellopoulos, (who in 1988 flew under his own power from Crete to Santorini) could sustain 180 watts for about 13 hours, 170 watts for about 16½ hours (Nadel and Bussolari 1988) (Fig. 7.1). (It is hoped that further information on stamina will become available in the future.)

I retabulate here the duration of the voyage at the three speeds, and at the stronger of the Bosporus currents assumed earlier:

| | |
|---|---|
| At 7 knots | 17 hours 50 min. including an hour's rest |
| At 7.5 knots | 16 hours 50 min. including an hour's rest |
| At 8 knots | 15 hours 50 min. including an hour's rest |

From these data it follows that a crew consisting of men whose power and stamina equalled that of modern manual labourers could probably sustain a speed above 7 knots but not as much as 7.5 knots, *i.e.* they could row from Byzantium to Heraclea in a time of about 18 hours (including an hour's stoppage at mid-day). This would involve rowing by the light of the moon for part of the way. A crew of clones of Kanellopoulos could perhaps forgo the mid-day rest and if they did so they might complete the voyage in as little as 15 hours. Such a voyage could be about 90% completed while the sun was up during a few weeks either side of midsummer but at other times the help of the moon would be required.

## 3. Conclusion

It looks as though a moderately good trireme crew capable of cruising at about 7¼ knots relative to the water, if given appropriate nutrition, a fast and well-ventilated ship, a good set of oars and calm weather, could complete the passage between Byzantium (say the Golden Horn) and Heraclea (modern Eregli) in about 18 hours if they rested for an hour in mid-voyage. (They would probably need to do that.) If they started out at 0400 they would reach their destination at about 2200. An elite crew cruising at nearly 8 knots might not need to stop half way and might then complete the passage in about 15 hours.

It seems reasonable to regard these durations as consistent with Xenophon's "long day". If we are to believe Xenophon (and why not: he had no reason to lie) it follows that the ability to cruise at 7–8 knots (depending on the standard of the oarcrew) is one of the most important criteria by which any ship claiming to be a reconstruction of an ancient Greek fast trireme should be judged.

## Appendix

*Calculation of rates of striking* (See also my paper on 'Towards a revised design of a Greek trireme' below.)

$$\mathrm{nPrLE}/60 = 1.08 \times (155V^3 + 4.13V^5)$$

$$V \text{ is in m/s; } 1 \text{ knot} = 0.5148 \text{ m/s}$$

$$n = 170,\ P = 7{,}43r,\ L = 0.99 \text{ m},\ E = 0.78$$

The equation shows that:

When $V = 7$ knots r is 25.47 say 25.5 spm
$V = 7.5$ knots r is 28.77 say 28.8 spm
$V = 8$ knots r is 32.32 say 32.3 spm.

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# 8. The Performance of Ancient Triremes in Wind and Waves

*Timothy Shaw*

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## 1. Summary

This note argues that ancient triremes did not need help from the sails when they made the fast passage between Byzantium and Heraclea referred to by Xenophon as being achievable in "a long day under oar". Nor would a wind strong enough to offer useful propulsive force all the way in the Black Sea have been helpful in fact: in such a long passage it would have eventually have raised waves high enough to negate the benefit. The main reason for this is the ship's high speed of 7 to 8 knots.

## 2. Introduction

It is acknowledged that *Olympias* is incapable of cruising all day at 7–8 knots under oar. Her cramped stateroom has been blamed, an explanation that is supported by physiological studies including The Trireme Trust's in 1990 and 1994. These data when coupled with the known resistance/speed curve of *Olympias* confirm that a carefully-selected and well-trained all-male oarcrew whose stature is similar to that attributed to ancient Greek men ought to have enough power and endurance to match the ancient performance with no help from the sails provided that the men have enough stateroom to row at full length. I have argued that a suitably lengthened stateroom can be provided within an *interscalmium* of 0.98 m (two cubits) by strongly 'skewing' the layout of the seats and stretchers (Shaw 1994). This concept has been given detailed expression in Plan 201–12 (Fig. 8.1) which closely resembles Plan 8 (*Olympias*) (Fig. 8.2) apart from the three main changes: the skewed oar-rig, an increase in the height of the *zyga* and a 10% increase in the *interscalmium*.

However, and perhaps not surprisingly, it has been suggested elsewhere that (a) the passage referred to by Xenophon must have been sail-assisted and/or (b) an ancient trireme was not like *Olympias* at all.

As regards (b), I will not go beyond stating that there is massive evidence unrelated to the present discussion that an ancient trireme's hull and main principles of her oarsystem were very like those of *Olympias* and Plan 201–12.

Here, I am concerned with the impact of (a) given that the ship is as shown in Plan 201–12. The question is important, for if (a) were correct, we should no longer be able to insist on a high cruising speed for a trireme under oar, and the case for improving important details of the design would therefore be based on rather weaker evidence than would exist if Xenophon's statement were accepted. We should find ourselves relying not on verifiable or potentially verifiable figures but on a mere opinion that ancient ship designers would not deliberately restrict a crew's length of stroke if they could help it.

This document shows that (a) cannot be true if an ancient trireme was like that depicted in Plan 201–12. As I show in what follows, any tailwind strong enough to offer a useful thrust via the sails at a ship's speed as high as 7 to 8 knots would after blowing for a few hours across a 'fetch' of some scores of kilometres raise waves high enough to hinder the oarsmen, or worse, and so negate the benefit. A passage at that speed under sail alone is ruled out by the fact that if the ship were no more seaworthy than the *Olympias* was for good reasons designed to be, she would be obliged by the waves to seek shelter before reaching Heraclea. A wind on the beam is no help either.

If I am right, it would follow that where the wind, if any, had a long 'fetch', the fastest passages by the triremes were made under oar, and in calm weather, and that when Xenophon said or wrote "under oar" he meant precisely that, not "under sail and oar" and not "under sail". This does not rule out that slower passages by triremes between Byzantium and Heraclea were conducted under sail or under sail and oar in light winds.

## 3. Discussion

First I discuss the propulsive effect of the wind via the sails, making use of our experiences in *Olympias*. Then I give the effect of the wind on the waves. Then I go into the effect of the waves on the ship and on the rowing, again making use of experience in *Olympias*. I mention the importance of ventilating the ship. The conclusions follow.

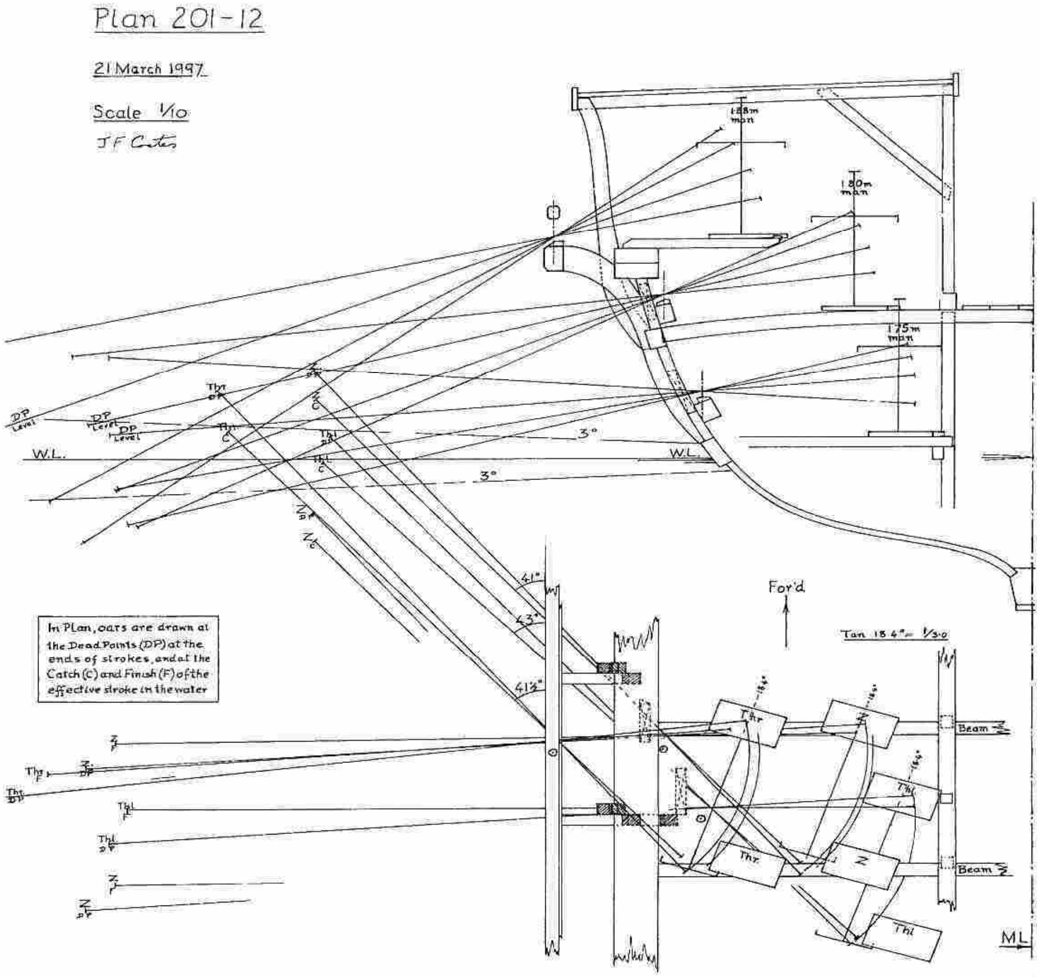

*Figure 8.1. Proposed modification to* Olympias *oar-rig, with interscalmium of 0.98 m and skewed layout of seats and stretchers (Plan 201–12) (Drawing: John Coates).*

### *3.1. The propulsive effect of the wind*

In my paper 'From the Golden Horn to Heraclea' above, I show that in order to complete the passage between Byzantium and Heraclea in "a long day" a trireme must sustain a speed of between 7 and 8 knots (3.6 to 4.1 m/s) through the water. Here, in order to minimise the number of tables, I deal with the mean of these namely 7½ knots or say 3.9 m/s. While in the Black Sea the ship would be assisted, according to the *Black Sea Pilot*, by an anticlockwise current of ¼ to ¾ knots (13–39 cm/sec), the higher values occurring in spring and early summer. The latest *Encyclopaedia Britannica* says the current amounts to 40–60 cm/sec near the shore but less farther out. I shall assume the ship steers near enough the shore to benefit from a current of 0.5 m/s (1 knot).

Our experiments on sailing *Olympias* have shown that her speed in still water is at best rather less than half the true wind speed, whether the wind is astern or on the beam. A tailwind needs to blow at about 8.5 m/s (16.5 knots, which is Force 4 bordering on 5) if it is to propel the ship under full sail through still water at the postulated 3.9 m/s (7.5 knots) with no help from the oars. A wind on the beam needs a velocity of about 9.8 m/s (19 knots, which is Force 5). The error of the ship's log has been taken into account.

It has long been suggested that the sails could safely be enlarged (Coates, Platis and Shaw 1990, 36). This could reduce the required windspeed by a few percent. On the other hand the proposed improved version of *Olympias* given in Plan 201–12 will probably have a little more resistance, tending to restore the original relationship. In what follows I assume that a tailwind of 8.5 m/s (16.5 knots) or a beam wind of 9.8 m/s (19 knots) will still be required to drive a Mark II trireme through still water at 3.9 m/s (7.5 knots) under sail.

To obtain the propulsive force of gentler winds, such as might, with the help of the oars, enable the ship to continue at 3.9 m/s (7.5 knots), consider the following.

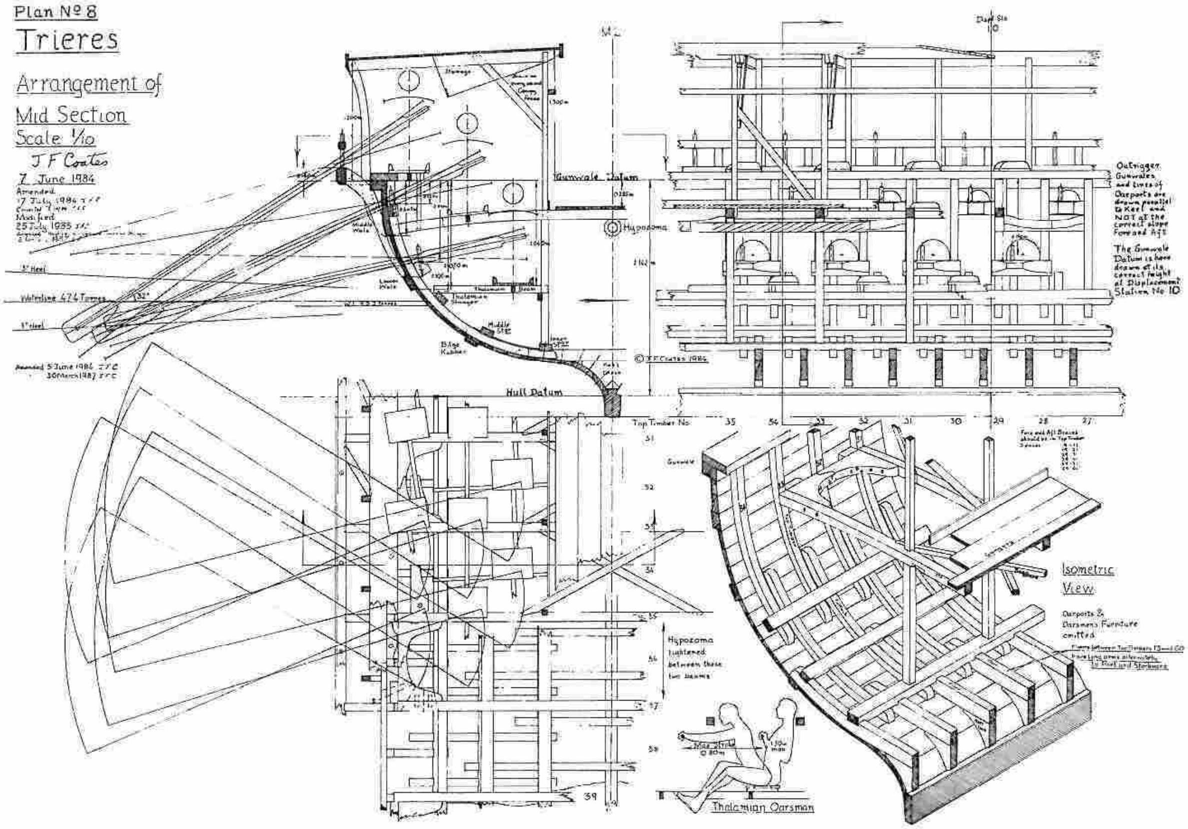

*Figure 8.2: Existing arrangement of mid-section in* Olympias *(Plan 8) (Drawing: John Coates).*

Take the case of a wind from astern. We may assume that the usual square law of air resistance applies to the sails in this case, and that the same sail area is used irrespective of the strength of the wind as no very strong winds are being considered. Then we have that:

Resistance of the ship at 3.9 m/s (7.5 knots) in still water = propulsive force of an 8.5 m/s (16.5 knots) true wind from astern which is a 4.6 m/s (8.9 knots) wind relative to the ship.

Since the ship must continue to move at 3.9 m/s (7.5 knots) through the water which is itself moving in the same direction at 0.5 m/s (1 knot), a true windspeed of V m/s coming from astern implies a relative wind of (V – 3.9 – 0.5) m/s and a propulsive force proportional to that quantity squared. (The coefficient of proportionality is a constant if the sail area is unchanged.) It follows that when the ship is in the Black Sea the propulsive force of the wind of true speed V is a percentage X of that of a relative wind of 4.6 m/s (8.9 knots) where:

$$X = 100\,[(V - 3.9 - 0.5)/4.6]^2$$

Table 8.1 shows, for example, that when the true wind speed is 5 m/s (9.7 knots) the speed of the relative wind pressing on the sails is only 0.6 m/s (1.2 knots) and this reduces the oarsmen's burden by only about 2%. The table suggests that higher windspeeds would be much more helpful but this will be true only if the wind has had insufficient time and 'fetch' to raise waves high enough to hamper the oarsmen. Details of the average roughness of the sea caused by steady winds of true velocities 5, 5.5 and 6 m/s (9.7, 10.7 and 11.7 knots) are given in the next section.

I now consider the case of a wind on the beam. To give enough propulsive force to drive the ship at 3.9 m/s (7.5 knots) through the water without help from the oars a beam wind has to be fairly strong. It is perhaps worth re-emphasising the point that it is because the ship's speed is high, *i.e.* about 4.4 m/s (8.5 knots) past the land, that the wind is unhelpful. Suppose the wind's true direction is at 90 degrees to the ship's course. Then the angle by which the direction of the apparent wind differs from the ship's course is that whose tangent is the true wind speed divided by the ship's speed past the land. Table 8.2 gives examples.

To find the wind direction in degrees from the ship's heading a leeway angle of say 7 degrees needs to be subtracted from the tabulated angles. Table 8.2 shows that the ship has to be sailed more and more close-hauled as the

*Table 8.1.*

| *True speed of tailwind m/s* | *Relative speed of tailwind m/s* | *Propulsive force of the sails as a percentage of that required to maintain the ship's speed at 7.5 knots (3.9m/s)* | *Balance to be provided by the oars percent* |
|---|---|---|---|
| 5 | 0.6 | 2 | 98 |
| 5.5 | 1.1 | 6 | 94 |
| 6 | 1.6 | 12 | 88 |
| 7 | 2.6 | 32 | 68 |
| 8 | 3.6 | 61 | 39 |
| 9 | 4.6 | 100 | nil |

*Table 8.2.*

| *True wind speed, m/s* | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| *Apparent wind direction, degrees from the ship's course* | 53.7 | 57.8 | 61.2 | 63.9 | 66.3 |

wind drops. Owain Roberts has written that "*Olympias* will sail well up to 60 degrees off the apparent wind making no more than 7 degrees leeway" (Shaw 1993b, 37). This I take to mean that her course may come as close as 67 degrees from the direction of the apparent wind. According to Table 8.2 this calls for a true windspeed of more than 10 m/s (19.4 knots) if the true wind is at 90 degrees to the course made good. (This exceeds the quantity of 9.8 m/s (19 knots) assumed earlier because the ship's speed is 4.4 m/s (8..5 knots) not 3.9 m/s (7.5 knots)). Dr Basil Greenhill and Peter Allington, have explained that that the use of auxiliary power enables a sailing ship rigged as a schooner to point higher than normal (Greenhill and Allington 1993). On reading that, we might guess that under oar plus sail a trireme could point as much as 5 degrees higher than stated by Roberts. On their next page however, Greenhill and Allington say that "a square-rigged vessel's lack of weatherliness effectively meant that she could not motor-sail to windward." Even if we ignore that, and accept a 5 degree improvement, the windspeed is still required to be as much as 8.3 m/s (16 knots). This windspeed should keep the oarsmen cool but it would also be incompatible with fast rowing, indeed it may prevent all rowing as the ship would heel and probably also roll because of the waves created, even if the wind itself were steady. Coates and Morrison wrote in the first edition of *The Athenian Trireme* that a steady beam wind of 14 knots [which is only 7.2 m/s] would cause [the then unbuilt] *Olympias* to heel about 8 degrees under the action of both sails, or 7 degrees without the boat sail (Morrison and Coates 1986, 223). This would put the thalamian oarports very near the water on the lee side (Coates, Platis and Shaw 1990, 35, fig. 19 gives a good impression of the situation).

If we reduce the windspeed to a level at which the angle of the heel is small enough and the waves low enough to permit hard rowing we find from Table 8.2 that if the ship's speed is somehow maintained at 4.4 m/s (8.5 knots) the apparent wind is too near the ship's head and its propulsive effect will be nil.

There are a few more points. Suppose the ship steers fairly near the shore and makes use of an offshore (*i.e.* a southerly) wind which has only a short fetch and duration of action on the water. Such a wind however will not arise till the late evening, will blow during the night, and die out soon after sunrise. And even if part of the passage were made by moonlight (which I show above in my paper 'From the Golden Horn to Heraclea' was probably sometimes the case in antiquity) the night would not be long enough for the offshore wind to take the ship very far. An onshore wind, on the other hand, arising about mid-morning and continuing until evening may raise fairly high waves.

### 3.2. *The effect of the wind on the waves*

I am indebted to Mr D. J. T. Carter, sometime of the institute of Oceanographic Sciences, Wormley, Surrey, and now of Satellite Observation Services, Godalming, for the information that has enabled me to give the wave heights and other wave data in what follows. His equations are given in his 1982 paper 'Prediction of Wave Height and Period for a Constant Wind Velocity using the JONSWAP Results'. They express and summarise the findings of the Joint North Sea Wave Project of 1969 and they are considered to be applicable to conditions in the south-western part of the Black Sea. They refer to winds measured at a height of 10 m above the mean sea surface, acting for various durations and over various lengths of fetch, over water that is deep enough that the sea floor does not influence the waves, and in the absence of swell. Carter has kindly supplemented this information by means of a personal communication.

*Table 8.3. An asterisk means that the sea has reached its full development at the given windspeed, duration and fetch. The wave velocity C is measured with respect to the water which is itself moving at 0.5 m/s (1 knot). A wave having C above 3.9 m/s (7.5 knots) will overtake the ship.*

| *Fetch* | *Duration* | *W = 4.5 m/s* | | | *W = 5.0 m/s* | | | *W = 5.5 m/s* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *km* | *hours* | *H* | L | *C* | *H* | L | *C* | *H* | L | *C* |
| 50 | 3.2 | 0.23 | 4.1 | 2.5 | 0.27 | 4.7 | 2.7 | 0.30 | 5.2 | 2.9 |
| 100 | 6.3 | 0.38 | 7.4 | 3.4 | 0.43 | 8.3 | 3.6 | 0.49 | 9.3 | 3.8 |
| 150 | 9.5 | 0.49* | 10.1 | 4.0 | 0.58 | 11.9 | 4.3 | 0.65 | 13.2 | 4.5 |
| 200 | 12.6 | 0.49* | 10.1 | 4.0 | 0.60* | 12.5 | 4.4 | 0.73* | 15.1 | 4.9 |

In reality of course the wind does not have a constant velocity but we may still draw valid conclusions from the equations.

I should mention that Carter's equations are not the only ones one might use. Others give somewhat different answers but they are thought to be more appropriate for large oceans such as the North Atlantic than for the limited fetch of westerly winds in the south-western Black Sea.

Carter's equations give us H, the so-called 'significant height' of the waves measured from crest to trough, and the time T that elapses (on average) between successive occasions on which the sea surface rises above its mean level. I have obtained the wavelength L from the formula $L = 1.56\ T^2$ and the wave velocity C from the formula $C = 1.56\ T$. The coefficient 1.56 applies when L is in metres, C is in metres/second and T is in seconds.

The significant height H of the waves is a measure of the average roughness of the sea, and I should make it clear that the quantities given as T, L and C are also averages masking considerable variation. For statisticians it may be mentioned that to a good approximation the elevation of the sea's surface has a Gaussian distribution. The significant wave height is defined as four times the standard deviation of that elevation, *i.e.* at any given location that elevation fluctuates by up to two standard deviations above and two below its mean level for about 95% of the time. If the distribution were truly Gaussian the surface would be found at 2 or more standard deviations away from the mean about 4.6% of the time, 2½ or more standard deviations away about 1.2% of the time, 3 or more standard deviations away about 0.27% of the time and 4 or more standard deviations away only about 0.006% of the time. This means, for example, that if the significant wave height of a fully-developed sea is 0.50 m and the period is 2.58 seconds, then in a time-span of 8 hours, about 7.63 hours will see the passage of about 10,650 waves of up to 0.50 m, but the remaining 22 minutes will see higher waves (distributed at random throughout the whole 8 hours): there will be about 16 minutes' worth of waves between 0.50 and 0.625 m, about 4½ minutes' worth of waves between 0.625 and 0.75 m, and about 1¼ minutes' worth of waves between 0.75 and 1.00 m. A wave of height greater than 1.00 m is unlikely to occur in eight hours if the significant height is 0.50 m, but it is found that every interval of 3 hours is likely to see a wave whose height is as much as 0.9 m, i.e. 1.8 times the significant height for the given duration or fetch, and windspeed.

We are considering a passage in an easterly direction from the northern exit of the Bosporus along the southern coast of the Black Sea where the 'fetch' of westerly winds increases as the ship proceeds. Since Heraclea is about 113 nautical miles (say 210 km) from the Bosporus, this is the greatest 'fetch' that concerns us if the wind is from the west. I shall present the significant wave heights at 50, 100, 150 and 200 km of fetch, corresponding (by an argument explained below) to durations of about 3.2, 6.3, 9.5, and 12.6 hours respectively. The greatest fetch in the JONSWAP work was 160 km so in quoting for 200 km I am guilty of a slight extrapolation.

To avoid exaggerating the waves I shall discuss a simple case in which the sea is calm initially; but early in the morning as the ship emerges from the Bosporus the wind springs up uniformly all along the course and blows steadily thereafter.

As the ship is to cruise at 3.9 m/s (7.5 knots) through the water its overall speed is 4.4 m/s (8.5 knots) and so it takes 3.2 hours to cover 50 km, 6.3 hours to cover 100 km, 9.5 hours to cover 150 km and 12.6 hours to cover 200 km. Hence in the postulated conditions, by the time the ship reaches the 50 km point the wind will have been blowing for 3.2 hours; when the ship reaches the 100 km point the wind will have been blowing for 6.3 hours, and so on. The propulsive action of the wind will be uniform the whole way. As the durations are fairly short, the waves mostly do not reach their full potential development: the sea is still growing. I have omitted the duration of the mid-day rest the crew may have taken.

As I have assumed a favourable current of 0.5 m/s (1 knot), the windspeeds in relation to the water are reduced by that amount in Table 8.3 which gives the significant wave height H, the mean wavelength L (both in metres) and the mean wave velocity C in m/s. W is the windspeed in m/s relative to the water.

From Carter's formulae I have obtained the data shown in Table 8.3.

I should add that the significant height of waves generated by an 8.5 m/s (16.5 knots) wind relative to the water – one strong enough to propel the ship at 3.9 m/s (7.5 knots) through the water via the sails only – would, at 200 km and 12.6 hours, be about 1.4 m, with a wavelength of about 28 m.

*Table 8.4. Height,* etc., *of the "Three-hour" wave, m. An asterisk means the sea is fully developed. H. L, C and W have the same meanings as in Table 8.3.*

| **Fetch km** | **Duration hours** | ***W = 4.5 m/s*** | | | ***W = 5.0 m/s*** | | | ***W = 5.5 m/s*** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *H* | *L* | *C* | *H* | *L* | *C* | *H* | *L* | *C* |
| 50 | 3.2 | 0.42 | 5.0 | 2.8 | 0.48 | 5.7 | 3.0 | 0.54 | 6.3 | 3.1 |
| 100 | 6.3 | 0.68 | 9.0 | 3.7 | 0.78 | 10.1 | 4.0 | 0.88 | 11.3 | 4.2 |
| 150 | 9.5 | 0.87* | 12.2 | 4.4 | 1.04 | 14.4 | 4.7 | 1.17 | 16.0 | 5.0 |
| 200 | 12.6 | 0.87* | 12.2 | 4.4 | 1.08* | 15.1 | 4.9 | 1.31* | 18.3 | 5.3 |

As I have explained, some waves must exceed the significant height. The "3 hour" heights are given in Table 8.4. That for an 8.5 m/s (16.5 knot) wind at 200 km, 12.6 hours is 2.5 m. Its wavelength would be about 34 m.

In Table 8.4 the heights H, lengths L and velocities C are 1.8 times, 1.2 times, and 1.1 times those given in Table 8.3 for the same fetch, duration and windspeed. For these factors I am indebted to Carter.

### *3.3. The effect of the waves on the ship*

For reasons explained in *The Trireme Project*, *Olympias* was designed and built to withstand a wave of height 0.8 m and wavelength equal to the waterline length of the ship, about 33 m. Such a wave would not strain the hull. The scantlings of the principal timbers were made the same as those measured by Miss H. Frost at the wreck of a Punic 'long' ship off Marsala. A trireme built in accordance with Plan 201–12 would observe the same criterion. The sills of her thalamian oarports (closed by the *askomata*) would be about 0.3 m above the calm waterline (so that a wave of height 0.6 m would wet them) and those of the zygians about 1.0 m above it. It is believed that ancient Greek triremes were no more seaworthy than this.

Of course the 3-hour wave 2.5 m high and 34 m long for a windspeed of 8.5 m/s (16.5 knots) at a fetch of 200 km and a duration of 12.6 hours would severely strain the ship. Waves of the significant height for those conditions, about 1.4 m, would also strain and damage the hull structure if their heading were similar to that of the ship, as their wavelength, about 28 m, appears long enough that the hull would at times be supported on only one crest. If the hull remained intact and upright such waves would not swamp the ship but they would make rowing impossible.

In the less severe conditions associated with a windspeed of 5.5 m/s (10.7 knots) some waves will eventually rise to a height of about 1.3 m but the wavelength of about 18 m should ensure that the hull is always supported on at least two crests. The ship may therefore survive but as shown below, rowing will still be impossible.

### *3.4. The effect of the waves on the rowing*

Here I should explain that the style of rowing I advocate to enable a fast trireme to attain the highest possible cruising speed in smooth and slight seas is not that of Burlet and Zysberg in which the stroke is short and the depth of immersion of the oarblade is much greater at midstroke than at the catch and finish (Burlet and Zysberg, 1986; cf. Burlet *et al.* 1986; Bondioli *et al.* 1995). The style of Burlet and Zysberg would have to be adopted in rough water but it would not yield the highest speed in smooth and slight seas. For that, one needs a long stroke. The blade is fully immersed as quickly as possible at the catch, thereafter remaining at more-or-less constant depth (if the water is flat) until it is cleanly extracted at the finish. This entails that to a good approximation any given point on the oar moves from catch to finish in a horizontal, circular arc in relation to the ship. The more skilful the oarsmanship, the closer the approximation although a slight increase in depth of immersion towards midstroke does no harm provided that the instantaneous turning point of the oar in relation to undisturbed water is not immersed.

Smooth swells of great height may be compatible with such a style of rowing if the wavelength is so great that the ship rises to them. Such waves certainly occur from time to time in the Black Sea but in the conditions considered here they will be overlain by the short waves whose data has been tabulated.

In what follows I draw on experience gained during the sea trials of *Olympias*. Although she cannot be cruised at 3.9 m/s (7.5 knots) experience in her is instructive and relevant. It indicates that if a trireme remains on a even keel without significant pitching, good progress under oar can be maintained for 3 or 4 hours in short waves of height up to about 0.30 m (the crests rising about 0.15m up the ship's side): in a ship built in accordance with Plan 201–12 a well-trained and determined crew should be able to row strongly and at full length in waves of this height although we have yet to demonstrate that such an effort could be sustained all day in such waves. Waves 0.3 m high would have a wavelength of about 5 m. The ship would overtake them at a relative speed of about 1 m/s (2 knots). There could be about 7 crests in the wetted length of the ship.

From Table 8.3 it appears that a trireme could maintain reasonably good progress under oar for at least the first 50 km and 3.2 hours in a tailwind of up to 5.5 m/s (10.7 knots) relative to the water, the wind arising as the ship leaves the Bosporus, as the significant height of the waves does not exceed 0.3 m. The rowing would occasionally be rendered more difficult by larger waves of heights up to those of the 3-hour waves of Table IV at the given fetch and duration. But the assistance afforded by the wind via the sails would be slight, only 12 percent of the total thrust as shown for a true wind of 6 m/s (11.7 knots) in Table 8.1.

At longer distances and durations the picture looks less rosy. The crew of a ship built in accordance with Plan 201–12 would not be able to maintain their long stroke in waves more than about 0.5 m in height (the crests then giving about the same effect, at the blade tips, as a heel of 3 degrees) because they would have to adjust the heights of their blades to the crests and troughs. With increasing wave height, oarsmen would have to adopt progressively shorter but less powerful strokes so that their rowing would become more like that employed in later galleys as described by Burlet and Zysberg and as used in oared seaboats generally (though not in Cornish racing gigs).

Most waves of height 0.5 m would keep pace with the ship; higher ones would overtake her. Because of the fore-and-aft oscillation of the water the men whose blades were in the crests would have to pull much harder than those whose blades were in the troughs (assuming the latter could reach the water) impairing uniformity and making timekeeping difficult.

I conclude that it is not possible to continue rowing powerfully enough to sustain a cruising speed of 7.5 knots in a trireme when the significant height of the waves exceeds about 0.5 m. Even in a wind as light as one of 5.5 m/s (10.7 knots) relative to the water these conditions would arise well before 150 km and 9.5 hours, and difficulties caused by waves greater than the significant height would become more serious than they would be in the first 50 km.

Further effects of waves higher than 0.5 m are considered below.

As mentioned earlier, the leather seals of the thalamian oarports would begin to be wetted when the water came up to about 0.3 m, implying a wave height of 0.6 m if their were no rolling, pitching or heaving. Possibly the thalamian oars could still be used but their power would be small. If the water came up 0.4 m (wave height about 0.8m) the thalamian oars would have to be drawn in and the power of the other oars would be severely reduced. (Of the three levels of oarsmen the thalamians are put out of action first, reducing the already limited oarpower by a third.)

As the waves rise they make it progressively harder for the blades to reach the water in the troughs and to be recovered when buried in the crests. Certain photographs of the *Olympias* in a swell, when compared with an elevation drawing of the ship, show that waves rising no more than about 0.4 m above the calm waterline were more than high enough to have this effect; the thalamian oars were out of action. Furthermore the wave height was less than twice this figure because the height to which some of the crests rose in relation to the ship was enhanced by the pitching and heaving of the ship. These measurements discredit a statement reported on p. 40 of *The Trireme Trials 1988* that the whole crew had rowed (admittedly only a short distance) in waves of up to 1.2 m. The whole crew did row but the height of the waves was overestimated. According to a statement on p. 45 of *The Trireme Trials 1988* waves 1.0 m in height caused problems to some oarsmen (they were thranites and zygians, the thalamian oars having been drawn in). The report goes on to describe the conditions as "very difficult…when three big waves came together they seriously disrupted the stroke and it appeared that these conditions were about on the limit for rowing at two levels". The occasion was that on which the photographs referred to were taken and it would seem that the wave height given in that report was an overestimate.

According to Table 8.3 the significant height of the waves raised by a 5.5 m/s (10.7 knot) wind relative to the water would reach 0.65 m at 150 km and 9.5 hours; and I propose that this rules out any hope of a strong rowing performance in such a wind beyond this distance and duration. Table 8.4 shows that occasional disruption of the rowing by such waves would set in much sooner and of course it would become much more frequent and more severe as the voyage progressed and the waves grew higher.

As already mentioned, the 3-hour wave raised by a 5.5 m/s (10.7 knot) wind relative to the water at 200 km and 12.6 hours has a height of about 1.3 m. It would overtake the ship at a relative speed of about 1.4 m/s. Rowing would become impossible. The thalamians, of course, would be completely out of action. Although the sills of the zygian oarports are 1.0 m above the mean water level, and so a wave of height 1.3 m rising 0.65 above the calm waterline would not reach them if the ship remained on a even keel and did not heave or pitch severely, such a wave would make it very difficult for the zygian and thranite oarsmen to reach the water in the troughs and impossible for them to recover their blades if they were buried in the crests. The reason for this is that although the thranites, zygians and thalamians sit at different heights the height above calm water to which they can lift their blades is little if any higher for the upper two levels than it is for the thalamians. This is because they all have to reach calm water with their blades without raising their hands too high and therefore they all have about the same scope for lowering their oarlooms to their thighs at the recovery. Finally, a pitch amplitude of 1 degree either side of the horizontal would alternately raise and lower the foremost and sternmost zygian oarports by about 0.22 m.

In practice the waves will not be regular; also the ship will probably roll, pitch and heave. And of course, oarsmen who become seasick will contribute little propulsive power.

Tables 8.3 and 8.4 show that even in a wind for which W is only 4.5 m/s (8.7 knots) and V = 5.0 m/s (9.7 knots) affording, as shown in Table 8.1, very little thrust from the sails, the significant wave height of the fully-developed sea is 0.49 m and there will be a number of waves between this height and 0.87 m, the height of the "3-hour" wave.

There is a further point. Oarsmen cannot give of their best if they are overheated. During the "sailing" season of antiquity the climate in the Black Sea was probably as hot as it is now. That means the ship would have to be well-ventilated in order that the men's sweat could cool them by evaporating. Otherwise it would drip off uselessly. A tailwind of only 1.6 m/s (3.1 knots) relative to the ship (true wind, 6.0 m/s (11.7 knots)) would scarcely be enough, but a stronger one would certainly make the sea too rough for fast rowing. In a calm, the ship would be ventilated by her own motion through the air at 4.4 m/s (8.5 knots).

Commonsense suggests that assistance from the wind would have been accepted if it blew at a suitable velocity for a fairly short time, not long enough to raise hampering waves, and if on the quarter, not strongly enough to cause excessive heel. But it would be absurd to assume that any ancient trierarch or *kubernetes* would have set out knowing that he needed to rely on such an unpredictable phenomenon. If the wind continued to blow, the oarsmen would eventually have to give up and perhaps the ship would have to find shelter.

I mentioned in the Introduction that quite apart from the arguments presented here, there is good reason to think that assistance from the wind was unnecessary. This does not exclude the possibility of sail assistance in places where the fetch or duration of the wind were short enough to preclude the generation of hampering waves or where low speed was acceptable. But I regard it as certain that ancient Greek oarsmen making fast passages in their triremes between Byzantium and Heraclea did so under oar in smooth seas, or seas in the lower range of "slight" *i.e.* waves no higher than 0.3 m. They needed no help from the sails and they expected none.

It appears from the *Black Sea Pilot* that at the present time there are days with suitably calm weather particularly during the spring and autumn. The prevailing wind, however, is from the north-east, as was probably the case in antiquity.

A trireme was unsafe in even moderately heavy weather. No wonder that larger ships with longer oars permitting higher freeboard and higher oarports were eventually developed, though at a cost in speed and agility under oar.

## 4. Conclusion

Given all the foregoing, it seems necessary to believe that when Xenophon said "under oar" that was precisely what he meant. The high cruising speed implied by his account is the reason why a wind gentle enough not to hamper the oarsmen by raising waves or heeling the ship would also give hardly any propulsion, and why the oarsmen would overheat. Stronger winds would be objectionable unless the wind blew for only a short time. While sail-assistance during a short-lived blow was acceptable, a good oarcrew in a fast ship neither needed nor expected it. In the Black Sea the fastest passages were made under oar in calm weather.

## Acknowledgements

I am much indebted to D. J. T. Carter who read and commented on an earlier draft of this paper. Any errors, however, are entirely my responsibility.

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