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Mappings of Potential Sailing Mobility in the Mediterranean During Antiquity

D. Gal[1] · H. Saaroni[2] · D. Cvikel[1]

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Abstract
A comprehensive mapping of potential sailing mobility was performed for the eastern and central Mediterranean basins. The mapping is based on newly developed methods for measuring potential sailing mobility of merchant ships with a loose-footed square sail in antiquity, both for direct passages and for coastal sailing. The metrics of the measured direct and coastal sailing passages generate new measures of potential sailing mobility that provide new insights into the functioning of maritime links. The study also applies the measurements to several case studies in historical context including mapping of potential sailing mobility for the grain shipments from Egypt to Rome and the potential sailing mobility of Phoenician maritime links between the Levant and colonies to the west. The mappings reveal the bottlenecks for westward sailing from the Levant in the summer months. The mappings also highlight the bi-directional sailing links that could be maintained throughout the summer season despite the prevailing Etesian winds. The mappings contribute to deeper understanding of seafaring options and challenges during Antiquity.

Keywords Ancient sailing routes · Experimental archaeology · Maritime connectivity · Mediterranean · Seafaring

Introduction

In spite of ample evidence of the existence of maritime links in the Mediterranean during antiquity, there is very little archaeological evidence, and only fragmentary documentary evidence, of how these links functioned. Scholarship has attempted to derive measures and understandings of sailing mobility from the factors that

✉ D. Gal
dgal11@campus.haifa.ac.il

1 Department of Maritime Civilizations and the Leon Recanati Institute for Maritime Studies, University of Haifa, 3498838 Haifa, Israel

2 Department of Geography and the Human Environment, Porter School of the Environment and Earth Sciences, Tel Aviv University, Ramat Aviv, 6997801 Tel Aviv, Israel

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determine sailing ship mobility: (a) the wind, (b) the ships' sailing performance envelope, and (c) the mariners' preferences and limitations. Qualitative works suggesting ancient sailing routes have referred to the limited available documentary evidence in support of their derived understandings (Arnaud, 2005; McGrail, 2004; Pryor, 1988). Scholars have also suggested coastal sailing, exploiting land and sea breezes, as an alternative or supplementary method of advance when passages encountered contrary prevailing winds (Casson, 1950, p. 46; McGrail, 2004, p. 94; Morton, 2001, p. 145; Murray, 1993, p. 40; Pryor, 1988, pp. 13–15, 89–90).

It follows that quantitative mappings of potential ancient sailing mobility may be an alternative approach to obtain understandings of available sailing routes, seasonal sailing possibilities, trade-offs between coastal sailing (cabotage) and direct point-to-point sailing passages, and the sailing environment and characteristics of ancient seafaring as they relate to specific historical contexts. Mapping can generate the relative costs of maintaining maritime links in support of network analyses.

In the past decade, several works have attempted to use quantitative methods to map potential ancient sailing mobility. ORBIS, the Stanford geospatial network model of the Roman world, provides an interactive model to determine transportation costs and time in a multimodal environment (Scheidel et al., 2012). Leidwanger suggested and demonstrated the use of Geographic Information System (GIS) cost surface analysis to model distance with time in ancient Mediterranean seafaring (2013). TRANSIT, an openly accessible GIS toolbox for estimating the duration of ancient sail-powered navigation, offers a similar GIS cost surface analysis solution to model ancient sailing durations (Alberti, 2018). Safadi and Sturt also use GIS cost surface analysis to demonstrate the expression of sailing duration in non-linear Cartesian form (i.e., destinations with fast passages are shown to be physically closer to the departure point) (2019). A recent study by Trapero Fernández and Aragón also employs GIS cost surface analysis to model late Iron Age sailing along coasts in the western Mediterranean (2022).

Warnking was the first to take a dynamic model approach to mapping ancient sailing mobility using wind data with high spatio-temporal resolution and weather-routing software, recognizing that averaged wind conditions are not valid for calculating sailing, and that dynamic[1] factual wind conditions are needed (2016, p. 50). A study by Perttola introduces dynamic wind input to a GIS cost surface analysis with repetitive sequential runs (2021).

This paper presents a comprehensive measuring of potential sailing mobility, and applies the measures of sailing mobility to the mapping of several Mediterranean case studies of merchant ships. The mapping is relevant for the technological period of Mediterranean merchant ships rigged with a single loose-footed square sail (also known as the brailed sail). This period extends from the Late Bronze Age to the Islamic period (ca. 1300 BCE–ca. 700 CE) (thereafter 'the period') (Casson, 1995; McGrail, 2004; Wachsmann, 1998; Whitewright, 2018). The mapping was performed by applying results of the method for measuring potential sailing mobility both on direct sailing passages (Gal et al., 2021a) and

[1] Wind data changes as the simulated/calculated passage progresses.

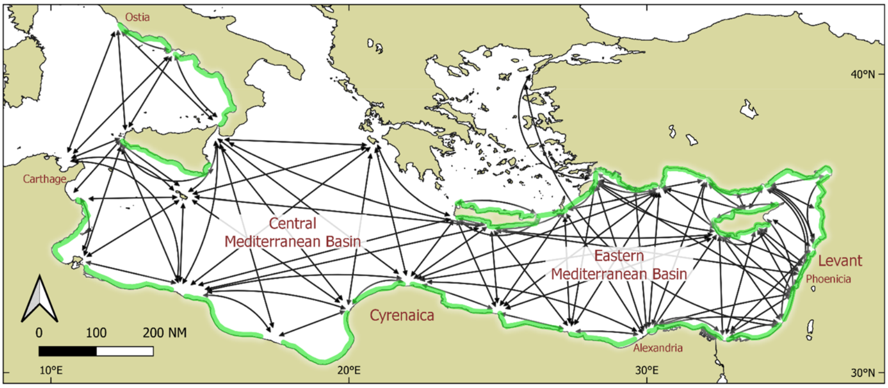

Fig. 1 Scope of the mobility measurements. Black lines indicate bidirectional links, and green shading indicates the coastal sections measured for coastal sailing (D. Gal)

on coastal breeze-driven sailing passages (Gal et al., 2021b). Examination of both modes of sailing illuminated cases where coastal sailing might have been preferred as an alternative to direct passages. Both methods used weather-routing software to simulate sailing on the basis of dynamic wind and current data at high spatio-temporal resolution.

The geographical extent of the measured direct links and coastal sections includes the central and eastern basins of the Mediterranean, excluding the Aegean and Adriatic Seas, with Carthage and Ostia being the westernmost links (Fig. 1).

Mappings of four case studies were performed, based on the measurement results. These were selected to demonstrate the contribution of mapping to adding insight to ancient seafaring and the conduct of maritime links.

The first case study focuses on a known continuing expedition and examined the potential routes taken by Alexandrian grain ships to the port of Ostia. There is literary evidence of two Alexandrian grain ships sailing via the coast of Lycia: the *Isis* (Casson, 1950) and the grain ship that St. Paul joined at Myra (Acts 27, 28), but we have no evidence on why or when this route might have been advantageous. This case study offers detailed seasonal routing options, and enhances understanding of the number of possible annual grain transport cycles.

The second case study examined mobility on a regional scale looking at the seasonal options of exiting the Levant westward, and in a wider context exiting the eastern Mediterranean basin. The Levant is the ‘end of the road’ when sailing downwind with the prevailing winds, and the return possibilities, contrary to the prevailing wind, have been of concern to scholars (McGrail, 2004, p. 94; Pryor, 1988, p. 90).

The third case study concerns mobility in a cultural phase and examined potential routes used by the Phoenicians between the Phoenician cities in Lebanon and their colonies in the eastern and central Mediterranean basins and Carthage.

The fourth case study investigated the potential of eastern Mediterranean intra-regional bi-directional maritime links suggesting intra eastern Mediterranean networks that could have been maintained during the summer months, despite the limits of the seasonal prevailing north-westerly winds.

Methods

Methodology Overview

The mapping of potential sailing mobility described in this study has two components: (a) measurements of potential sailing mobility on direct sailing passages and (b) measurements of mobility for breeze-driven coastal sailing runs. These two methods are described in detail in two previous publications (Gal et al., 2021a, 2021b). Although each set of measurements is derived separately, the parallel examination of both modes of sailing exposes cases where a potential preference of one mode over the other might have existed, and it supports a comprehensive analysis of Mediterranean sailing mobility and seafaring of the period. Both methods follow the premise that due to the limited upwind sailing capability of period ships, a key factor of sailing mobility in the Mediterranean is attributed to the variabilities of the Mediterranean winds, especially when sailing passages lie contrary to prevailing winds. The premise is based on the fact that these variabilities, and the winds in general have not changed in the last 3000 years, allowing the use of modern meteorological data to represent wind conditions in the period of the study (Gal et al., 2021a; Murray, 1987). A 15-year sample (2004–2018) of meteorological data was used to ensure, at least partial, inclusion of climatic variability including possible effects of the El-Niño Sothern Oscillation.

The core process of the mapping methods used was to extract measures of potential sailing mobility from a large set of meteorological data at high spatial–temporal resolutions. This was achieved by simulating sailings throughout the dataset, exposing the variabilities of the wind and their contribution to the construction of sailing passages. The meteorological data, in the order of billions of records of sailing passages, was reduced to the order of millions of records by the sailing simulations. The resulting sailing data was then further reduced by statistical methods to obtain measures of potential sailing mobility with a broad set of sailing metrics.

The characteristics of the simulated ship were derived from the experimental sailings of the *Ma 'agan Mikhael II* replica ship as described in the published method for direct sailing passages (Gal et al., 2021a). For the current study, an additional bias for marginally better upwind capability was defined, to allow the simulated ship to make good a course of 78° to the true wind in all sea conditions. This, for example, would typically occur in 10 knots true wind, when a heading of 55° is maintained to the apparent wind, and after accounting for the difference between true and apparent[2] winds, and accounting for leeway.[3]

The inclusion of the human element, as defined by a set of criteria (Table 1), provides metrics of potential sailing mobility beyond the single speed-related measure of passage sailing duration. The monthly division and distribution of the sets of

[2] Apparent wind is the wind measured or sensed on board a moving ship. It includes the vector of the wind induced by the ship's movement.

[3] Leeway is the sideways drift of a sailing vessel induced to counter the sideways force exerted by the wind.

Table 1 Criteria for reasonable passages

No	Parameter	Value	Description
1	Min. passage velocity made good (VMG)	1.0 knots	Effective passage speed based on shortest possible sailing path divided by passage duration
2	Max. passage distance ratio	1.5	Ratio between actual distance sailed and shortest possible sailing path
3	Max. tacking ratio	1.0	Number of tacks performed by the simulator per nautical mile (nm) of shortest sailing path
4	Max. % destination in no-sail sector	25%	Percent of time that the destination was in the simulated ship's no-sail sector (upwind)
5	Max. true wind speed (TWS)	31 knots	Maximum true wind speed encountered on passage
6	Max. waves	2.75 m	Maximum significant height of waves encountered on passage

reasonable and unreasonable passages based on these criteria reflect the windows of opportunity for exploiting favourable winds to allow successful sailing passages. This provides a coefficient of mobility (i.e., the proportion of the month allowing a successful passage), and also the ability to measure time spent waiting to sail.

Measuring Potential Sailing Mobility on Direct Sailing Passages

Sailing simulations were performed on 224 individual passages (112 bi-directional maritime links). A list of the passages with an index map appears in Appendix 1. Passages were chosen to provide a comprehensive mapping of potential sailing mobility in the eastern and central basins of the Mediterranean, and to support the investigation of several historical contexts of maritime links. The scope of work and limits of computing capacity did not allow the simulation of every possible maritime link. Some of the names given to the nodes may not be relevant to the entire period of the study, and the more commonly known place names were arbitrarily used. A general outline of the method (detailed in Gal et al., 2021a) follows.

A simulated sailing departed on each passage every day at 03:00 UTC during the 15 years of data (2004–2018), providing 5479 simulated sailing summaries for each passage, totalling 1.2 million recorded sailings. The source of atmospheric data and significant wave height was the ERA5 Reanalysis database. The spatial resolution of this data was 0.25° (ca 27 km), and the temporal resolution was 1 h (Hersbach et al., 2020). Sea current data for the simulations was sourced from Copernicus Monitoring Environment Marine Service (CMEMS) (Simoncelli et al., 2019). The sailing simulator considered dynamic wind and current data in space and time as the simulated passage advanced. A sub-hourly log book for each sailing was summarized as a single record for each of the simulated passages. The final analysis of the sailings for each passage was summarized in a data sheet of the potential sailing metrics for the passage (Example sheets in Appendix 3).

The practicality of each simulated passage was determined by applying a set of hypothetical criteria to distinguish between passage sailings deemed reasonable for a human crew to conduct and those deemed unreasonable. The criteria are listed in Table 1, and these suggest the mariners' limits in relation to contrary wind passages and to stormy weather. A passage is considered unreasonable if the value of any of its parameters is beyond its set limit. The criteria settings have been drawn from extensive sailing of the *Ma 'agan Mikhael II* replica ship and reflect more than 100 years of cumulative experience in sailing crossings throughout the Mediterranean by the replica ship's three skippers. Moreover, sensitivity checks conducted over $\pm$ 1.5 standard deviations for each of the parameters indicated that more prudent mariner criteria or more risk inclined mariner criteria have only a marginal effect on mobility measures.

Measuring Potential Sailing Mobility for Coastal Sailing

The 26 stretches of coast that were measured for potential breeze-driven sailing mobility are listed in Appendix 2. Coastal stretches lying in a generally east to

Table 2 Criteria for a reasonable coastal run attempt

No	Parameter	Value	Description
1	Max. changes of tack	5	Number of tacks/wears performed by the simulator. A value above 5 indicates contrary wind
2	Max. % destination in no-sail sector	25%	Percent of time that the destination was in the simulated ship's no-sail sector (upwind)
3	Max. true wind speed (TWS)	31 knots	Maximum true wind speed encountered on passage
4	Max. waves	2.75 m	Maximum significant height of waves encountered on passage

west direction, such as those on the south coast of Asia Minor and the North African coasts, were examined only for westward sailing (contrary to the prevailing winds). The Levant coastal stretches, which lie generally perpendicular to the prevailing winds, were examined in both northbound and southbound directions. A general outline of the method of measuring potential sailing mobility for breeze-driven coastal sailing (detailed in Gal et al., 2021b) follows.

Sailing simulations for breeze-driven coastal sailing required wind data input at high spatial–temporal resolution to enable resolving the mesoscale local breeze events. This required a dataset at 3-km spatial and 1-h temporal resolutions. Such a data set covering the coastal stretches of most of the studied region did not exist. This dictated the prerequisite generation of a new reanalysis database, which was accomplished by downscaling the ERA5 Reanalysis database with the numeric weather prediction model WRF (Skamarock et al., 2021). The resulting 3-year data set (2018–2020) provided the mesoscale data needed to resolve breeze events.

Each stretch of coast was marked with points, 5 nautical miles (NM) apart, averaging about 31 points per stretch. Potential sailing mobility was measured by simulated sailing runs from every defined coastal point to the following three points for each day. Fifteen hourly departures were simulated to ensure temporal bracketing of the breeze events. This amounts to more than 47 million simulated sailing records for all coastal stretches. For coastal sailing with land to the left, the departure bracket began at 09:00 solar time, with the objective of covering the afternoon sea breeze. For sailing with land to the right, the departure bracket began at 21:00 solar time, to allow the bracket to cover the night/morning land breeze.

A coastal run was considered successful if four consecutive run attempts were reasonable. This would indicate evidence of at least a 3-h favourable breeze. A reasonable attempt was determined by the criteria listed in Table 2.

Two checks were performed to indicate whether a coastal sailing run was propelled by a breeze or by dominant synoptic-scale winds. If the true wind speed was 13 knots or less, and if the number of reasonable attempts, out of the 15, was 8 or less, then the propelling wind was considered as a breeze; otherwise, it was considered a dominant synoptic wind.

Following the establishment of measures of sailing mobility from each point, coastal voyages were integrated between the first and last points of each coastal stretch. A single daily departure provided a data set of 1096 coastal voyages for each coastal stretch, including measures of mobility and waiting time.

Applying Measures of Sailing Mobility to the Mapping of Case Studies

The initial task of selecting candidate passages to be examined for their mobility was a largely manual one of picking the sets of passages that, with basic seafaring considerations, could logically be connected to create several options of constructing an entire composite route (e.g., Alexandria to Ostia). Choices of the northern Mediterranean coast, southern Mediterranean coast, and central routes were considered as well as potential crossing passages between routes. Literary evidence on possible route segments was also considered (e.g., evidence of grain ships in Chelidonian Islands or Myra). Choice of segments also included stretches of coastal sailing that could be advantageous, and might be included as hybrid segments in the voyage. The selected segments were examined separately for each of the months. The monthly coefficient of mobility indicated the relative difficulty of conducting passages. The examination exposed the effective voyage durations driven by the individual passage durations and time spent waiting. The results indicated the mariners' likely routing preferences.

To assist in visualizing case studies, a GIS model was created using the Quantum GIS (QGIS) package (QGIS Development Team, 2009). Maps created in the GIS were used in the case study sections. The passage segments in the GIS map contain three attributes based on the mapping results: (a) the coefficient of mobility, (b) the passage duration, and (c) a representative waiting time in days, which is calculated as half the maximum consecutive waiting time for the passage. The latter calculation reflects the randomness of when the next window of opportunity for a departure might have appeared between zero days and the maximum measured consecutive wait. The passage segments were conditionally coloured in the GIS map according to the mobility coefficient. A coefficient of 0.4–1.0 was considered as reasonable to sail (green), a coefficient of 0.2–0.4 was considered borderline (orange), and a value of 0–0.2 was considered not reasonable (red). Coastal points were similarly coloured according to their mobility coefficient.

Measurement Outputs

The results of the sailing simulations are summarized in data sheets. These are openly available at https://doi.org/10.17632/hzbg2wyjxb.1. Each of the 224 direct sailing passages (listed in Appendix 1) has a corresponding data sheet detailing the measures of sailing the passage in each month of the year. Each of the 26 coastal stretches (listed in Appendix 2) is also summarized in a data sheet showing mobility measures for each month of the year. The data sheets and following sections of this paper include nautical and sailing terms that may not be clear to all readers. Appendix 4 includes a glossary of nautical terms used in this study.

Outputs for Direct Sailing Passages

Three examples of data sheets for passages with different angles to the prevailing winds are shown in Online Resources 1–3. The data produced from mapping a direct sailing passage includes (a) a set of metrics relating to potential mobility, (b) metrics related to points-of-sail and upwind sailing, and (c) metrics describing the environment encountered on the simulated passages.

Potential mobility measures include the following metrics, each provided with values for average, standard deviation, and quartiles:

1. Coefficient of mobility (0–1), which represents the proportion of the month that a daily sailing departure would culminate in a successful passage. The number is normalized to a maximum of 1.
2. Total number of days spent waiting to sail in a month. This corresponds to the inverse of the coefficient of mobility.
3. Maximum consecutive waiting days per month. Combined with the coefficient of mobility for the month, it gives an indication of the number and frequency of windows of opportunity for favourable winds.
4. Duration of the sailing passage expressed in decimal days. This does not include waiting time; it is the net time spent sailing on the passage.
5. Passage velocity made good (VMG) in knots. This is the effective speed for the passage, and is calculated from the shortest sailing distance possible divided by the duration.

Metrics related to point-of-sail and upwind sailing are provided for both the set of reasonable passages and the set of unreasonable passages ('Methodology Overview'). The latter provides insight into the characteristics of the set of unreasonable passages. The measures include the following:

1. Percentage of the passage duration spent beating (78–108° to the true wind).
2. Percentage of the passage duration spent reaching (108–160° to the true wind).
3. Percentage of the passage duration spent on a downwind run (160–180° to the true wind).
4. Percentage of the passage duration that the target destination was in the no-sail sector (i.e., upwind from a close-hauled course and requiring tacking).
5. The ratio between the shortest possible sailing distance for the passage and the actual distance sailed. This gives an indication of the relative difficulty of sailing directly to the target.
6. The ratio between the number of tacks performed by the simulator and the shortest sailing distance for the passage. This is a relative indicator reflecting the degree to which the destination was in the no-sail-sector.
7. Average ship speed on the passage in knots. This also provides a relative indication on point-of-sail as the ship's speed is higher when running downwind, and approximately half of that speed when close-hauled.

Environmental metrics are provided for sets of reasonable and unreasonable passages, and all passages grouped by months. The measures include the following:

1. Average true wind speed (TWS) for sailings on the passage.
2. Maximum TWS encountered during sailings on the passage.
3. Maximum significant wave height[4] encountered during sailings on the passage.
4. Average cloud cover for sailings on the passage.

Coastal Sailing Runs

Two sample coastal-stretch data sheets are provided in the supplementary data. The first sheet, for the section between Ermoupolis and Kriou (the southern coast of Crete) (Online Resource 4), exemplifies westbound coastal sailing contrary to prevailing winds. The second sheet, Ashkelon to Byblos (Online Resource 5), exemplifies coastal sailing perpendicular to the prevailing winds. The data sheets comprise the following:

1. Monthly summary of passage durations for the entire coastal stretch, indicating both the count of days spent waiting and the count of days in which an advance with a coastal run was achieved.
2. Set of monthly charts indicating the coefficient of mobility for each coastal point in the coastal stretch, also showing the proportion of breeze-driven mobility to mobility resulting from synoptic wind.
3. Set of monthly charts indicating, for each point in the coastal stretch: (a) the average number of days spent waiting during the month, (b) the maximum count of consecutive waiting days experienced, and (c) the average consecutive days spent waiting.

Computing Requirements

This research required one storage-oriented server to store input and output data. Three computing-oriented servers running the WRF numeric weather prediction model were needed to produce a downscaled reanalysis database for input to the coastal sailing simulations, requiring 8 months of continuous runs. Four high-end (gaming) workstations were needed to run the weather-routing software, producing 1.2 million direct passage simulations and 47 million coastal run simulations. Sailing data production required about 6 months of continuous runs.

[4] The significant wave height is the average height of the highest one-third of all waves measured.

Application of Mobility Measurements in Case Studies

Roman Grain Routes from Alexandria to Ostia

The first case study focused on the potential routing options for grain shipments departing from Alexandria with Ostia as the destination on a monthly basis. The routing options for this case were the outcome of the measures of potential sailing mobility for each direct passage relevant to the case, and from the mobility measures of relevant coastal sailing stretches (summarized in Table 3). The results indicate the elements of the voyage duration, i.e., the potential number of days spent sailing, the potential number of days spent waiting for suitable sailing winds, and the suggested total routing duration, as specified below. To account for the random time between the mariners' intention to sail and the appearance of the next window of opportunity for favourable winds, the days spent waiting were calculated as half the monthly maximum consecutive waiting period encountered averaged over the 15 years of data.

March and April

Measures of potential sailing mobility for candidate passages for this case study during March and April were very similar, and suggest similar routings (exemplified in Fig. 2 for April). All candidate passages and relevant coastal stretches offered high values of potential sailing mobility, allowing construction of almost direct routes. The two suggested options were (a) a southerly route via Cyrenaica (Apollonia) and (b) a northerly route via Crete (Kommos). The Cyrenaica routing would have been Alexandria, Apollonia, Leptis Magna, Motya (western tip of Sicily), and then Ostia. An alternative routing via Cyrenaica would have been Alexandria, Apollonia, Messina, and Ostia. The option via Crete would have been Alexandria, Marsa Matrouh, Kommos, Messina, and Ostia. It can be seen in Table 3 that the total duration on all options for both March and April was similar, at about a total of 30 days. The prevalence of passages with high coefficients of mobility in April is an indication that prevailing west and northwest winds have not yet set in. The actual passage through the Strait of Messina was not simulated and not accounted for. It would be prudent to consider 1–2 days extra waiting for a favourable combination of wind and currents to negotiate the Strait.

May

The mapping results for May, shown in Fig. 3 and detailed in Table 3, indicate that it was a transition month, beginning to exhibit lower measures of mobility for westbound sailing, in both the eastern basin and the northern part of the central basin. However, there was still a potential for direct passages, albeit with slightly longer durations, as shown in Table 3. The best option in May, for a

Table 3 Monthly routing options and voyage durations for grain ships sailing from Alexandria to Ostia. Waiting days are calculated as half the maximum measured consecutive waiting times. Durations in the table have been rounded to the nearest day

Month	Route options	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
January	Via Crete	Marsa Matrouh, Kommos, Messina, Ostia	17	20	37
February	Via Cyrenaica	Apollonia, Leptis Magna, Motya, Ostia	19	20	38
	or	Apollonia, Messina, Ostia	17	16	32
March	Via Cyrenaica	Apollonia, Leptis Magna, Motya, Ostia	19	14	33
	or	Apollonia, Messina, Ostia	18	11	28
	Via Crete	Marsa Matrouh, Kommos, Messina, Ostia	18	14	32
April	Via Cyrenaica	Apollonia, Leptis Magna, Motya, Ostia	19	11	30
	or	Apollonia, Messina, Ostia	17	11	28
	Via Crete	Marsa Matrouh, Kommos, Messina, Ostia	17	13	30
May	Via Cyrenaica	Apollonia, Leptis Magna, Motya, Ostia	20	13	33
	or	Apollonia, Messina, Ostia	19	17	36
	Via Crete	Marsa Matrouh, Kommos, Messina, Ostia	20	20	40
June	Via Rhodes	Marsa Matrouh, Rhodes, Karpathos, Kommos, Leptis Magna, Motya, Ostia	28	30	58
July	Via Gelidonya	Gelidonya, Rhodes (coastal), Karpathos, Kommos, Leptis Magna, Motya, Ostia	29	19	48
		Gelidonya to Rhodes coastal section duration	11	8	19
		Total for hybrid voyage	40	27	67
August	Via Gelidonya	Gelidonya, Rhodes (coastal), Karpathos, Kommos, Leptis Magna, Motya, Ostia	28	18	46
		Gelidonya to Rhodes coastal section duration	11	14	25
		Total for hybrid voyage	39	32	71
September	Via Crete	Marsa Matrouh, Menelaus, Kommos, Messina, Ostia	22	31	53
	or	Marsa Matrouh, Menelaus, Kommos, Leptis Magna, Motya, Ostia	24	28	52

Table 3 (continued)

Month	Route options	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
October	Via Cyrenaica	Apollonia, Leptis Magna, Motya, Ostia	19	9	28
	or	Apollonia, Messina, Ostia	18	9	26
	Via Crete	Marsa Matrouh, Kommos, Messina, Ostia	18	13	31
November	Via Cyrenaica	Apollonia, Leptis Magna, Motya, Ostia	19	16	35
	or	Apollonia, Messina, Ostia	17	13	30
	Via Crete	Marsa Matrouh, Kommos, Messina, Ostia	17	13	30
December	Via Cyrenaica	Apollonia, Leptis Magna, Motya, Ostia	19	25	44
	or	Apollonia, Messina, Ostia	17	19	36
	Via Crete	Marsa Matrouh, Kommos, Messina, Ostia	17	20	37

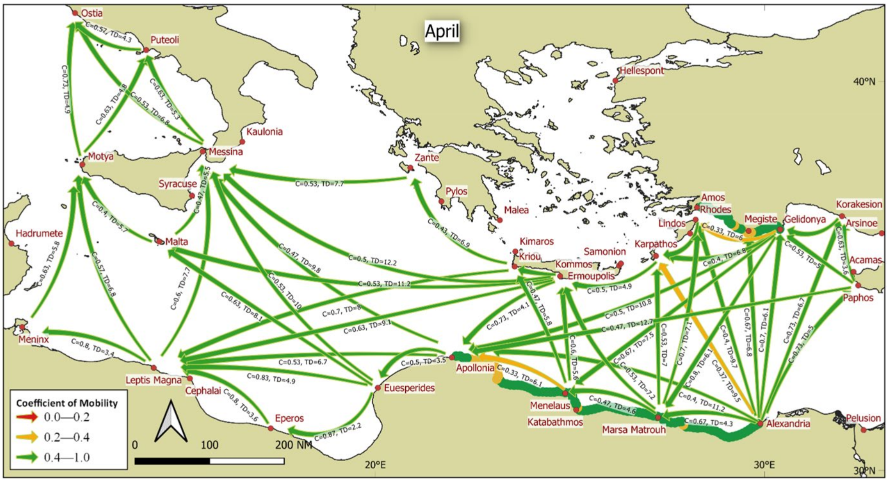

Fig. 2 Mobility measures for candidate passages in routings between Alexandria and Ostia in April. N.B. In this and all following figures, *C* is the coefficient of mobility and TD is the total duration of passage (number of days, including waiting time) (D. Gal)

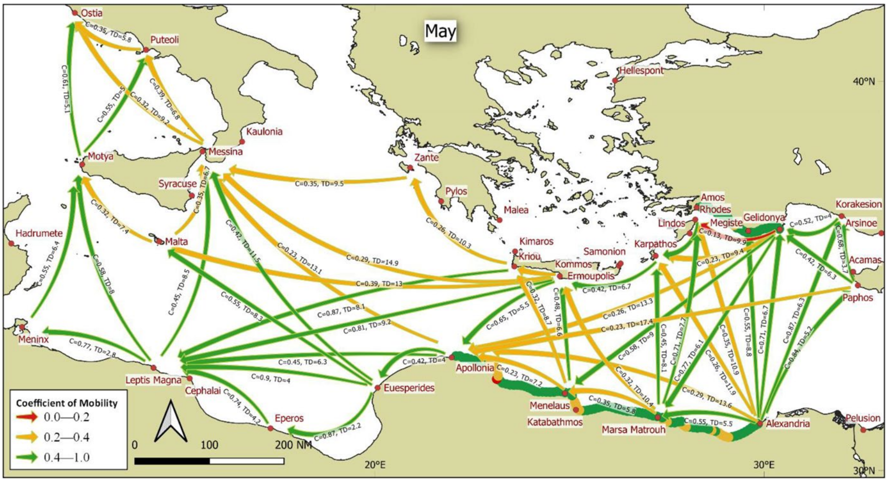

Fig. 3 Mobility measures for candidate passages in routings between Alexandria and Ostia in May (D. Gal)

33-day routing, was via Cyrenaica, choosing to pass south of Sicily to the west, rather than through the Strait of Messina. The Crete option would potentially have been the least attractive, with a total duration of 40 days.

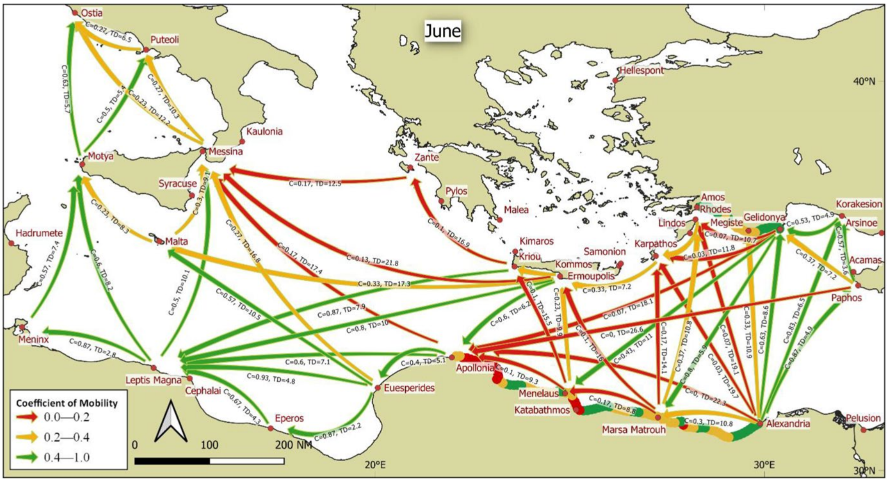

Fig. 4 Mobility measures for candidate passages in routings between Alexandria and Ostia in June (D. Gal)

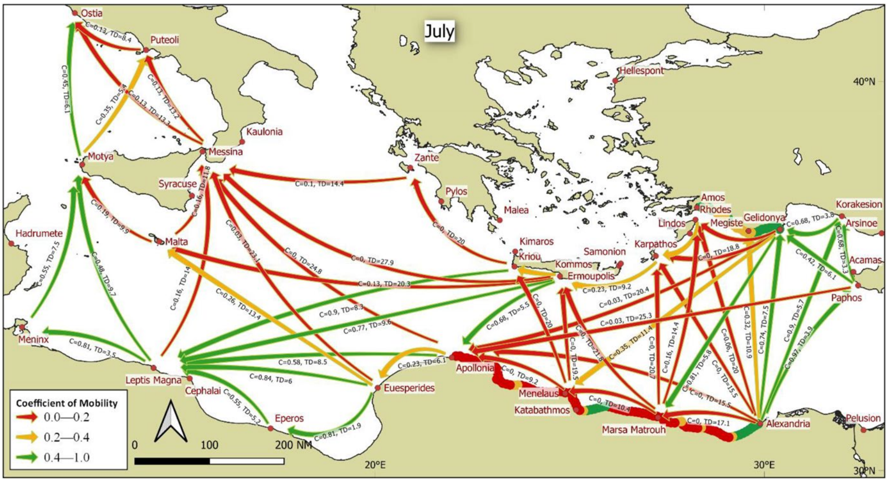

Fig. 5 Mobility measures for candidate passages in routings between Alexandria and Ostia in July (D. Gal)

Summer — June, July, and August

The mapping results for June suggest the development of two bottlenecks associated with westward sailing from the eastern Mediterranean basin (Fig. 4; Table 3). Red coloured passages indicate very low coefficients of mobility, suggesting that westward sailing between Alexandria and Cyrenaica was no longer reasonable beyond Marsa Matrouh onward to Apollonia, either by direct passages or by coastal sailing (see Fig. 4). The second bottleneck appears on the south coast of Asia Minor. This

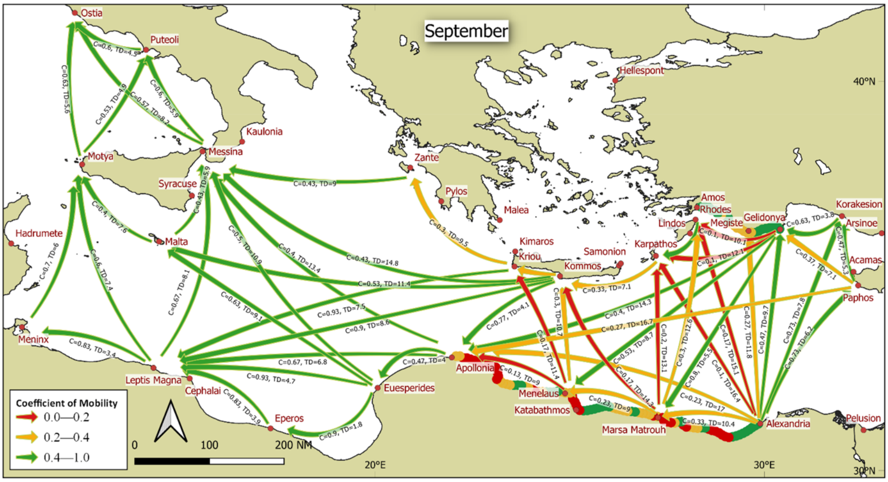

Fig. 6 Mobility measures for candidate passages in routings between Alexandria and Ostia in September (D. Gal)

is due to the difficulty in crossing from Alexandria to the north Mediterranean coast and making a landfall west of Gelidonya. In addition, the potential for direct sailing passages between Gelidonya and Megiste to Rhodes is extremely low. Coastal sailing measures suggest that coastal sailing westward along this coast was an alternative to direct passages, albeit at a significant cost in time.

The single suggested routing for June exploits the potential remaining ability to cross northward from Marsa Matrouh to Rhodes and then to advance via Karpathos, Kommos in Crete to Leptis Magna, Motya in west Sicily, onward to Ostia. Total duration for this routing would have been 58 days, with a few more days spent waiting for favourable winds than days spent sailing.

The mobility measurement results for candidate passage segments in July and August are very similar, and are presented for July in Fig. 5. They indicate that the North African bottleneck between Egypt and Cyrenaica was at its peak. Even coastal sailing potential mobility measures indicate that it would not have been a feasible alternative. West of Crete and Cyrenaica passage mobility measures show potentially good possibilities to reach Ostia via the western side of Sicily. The only suggested routing alternative for the midsummer months (July and August) would have been to cross to the northern coast of the Mediterranean from Alexandria, with a likely landfall at Gelidonya (Chelidonian Islands); then to hug the Lycian coast, advancing by breeze-driven coastal sailing to Rhodes; and to continue with the appearance of suitable winds via Karpathos to Kommos in Crete. From Kommos potential mobility improves with the passage via Leptis Magna and Motya to Ostia. Total potential voyage duration for such a routing would have been 67 days, including 19 days spent coastal sailing in adverse conditions along the Lycian coast.

As stated above, the measurement results for August are quite similar to those described for July. The routing via Gelidonya would have been the only option, as suggested in the previous paragraph. The Lycian coastal sailing section was

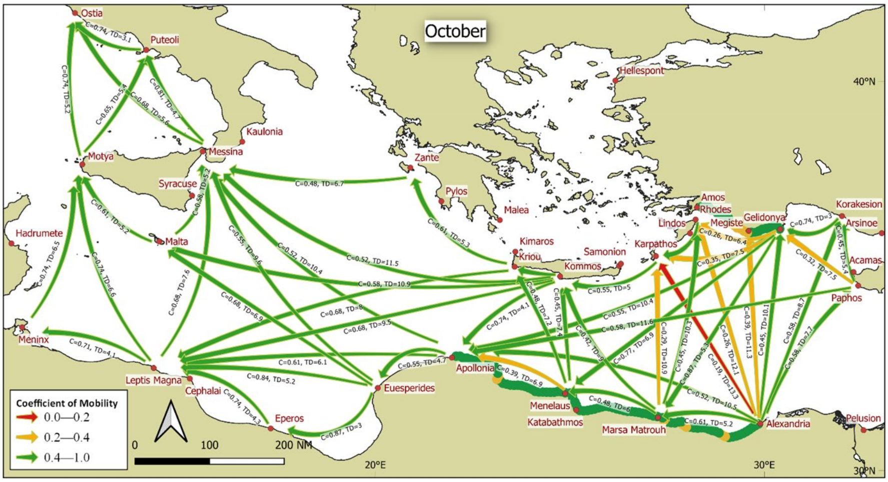

Fig. 7 Mobility measures for candidate passages in routings between Alexandria and Ostia in October (D. Gal)

measured to be slower in August, taking 25 days, resulting in a total voyage duration of 71 days. This is the slowest voyage time emerging from the mappings.

September

The results of mobility measurements for September are shown in Fig. 6 and Table 3. September is characterized by the initial opening of the summer month bottlenecks, and the possibility of sailing to Ostia via Messina. It was now possible to cross to the northern Mediterranean coast at Crete, and the crossing to Gelidonya further to the east was no longer required.

The optimum routing was to depart Alexandria westward as far as possible, i.e., to Menelaus, and then to cross to Kommos, continuing to Messina and Ostia. This potentially took 53 days in total. It was also feasible to continue from Kommos to Leptis Magna, Motya, and Ostia, suggested to have taken 52 days. The resulting total voyage times for September were still relatively high, but they nevertheless indicate improving sailing conditions.

October and November

The potential sailing mobility measurements for October and November are very similar, indicating months that have exceptionally good mobility (Table 3; Fig. 7). The direct routing options for these 2 months are similar to those in March and April. Possible routings were via Apollonia in Cyrenaica or Kommos in Crete, continuing either directly via Messina or via Motya to Ostia. Total sailing durations were potentially around 30 days (Table 3).

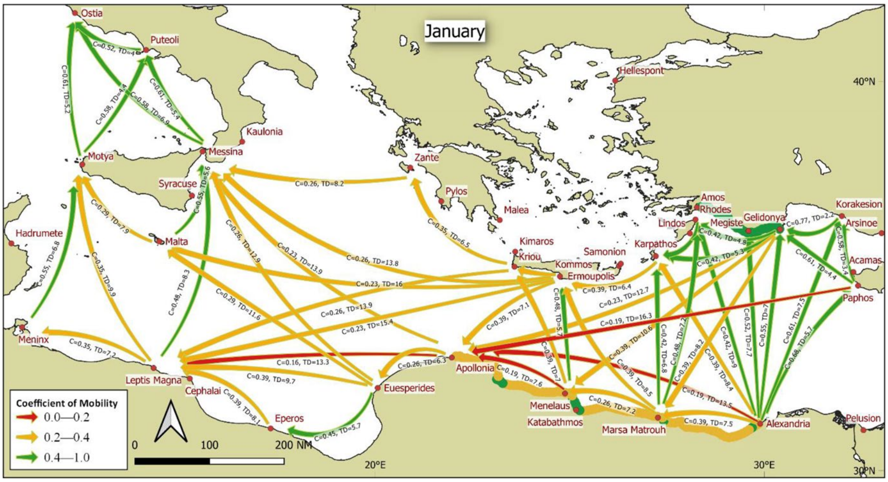

Fig. 8 Winter mobility measures for candidate passages in routings between Alexandria and Ostia (shown for January) (D. Gal)

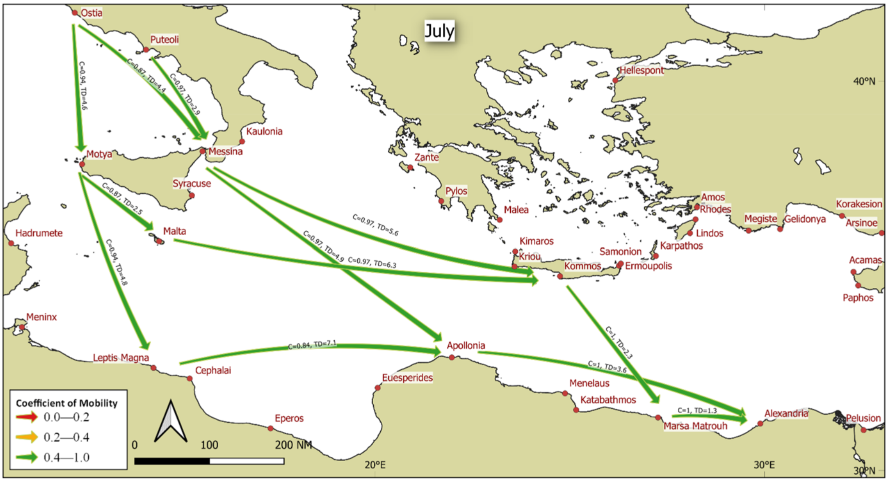

Fig. 9 Mobility measures for candidate passages for return voyages to Alexandria. The map is for July, but the routing segment options are valid for all other months (D. Gal)

Winter months — December, January, and February

Mapping results for the winter months (Fig. 8; Table 3) indicate that the central Mediterranean basin exhibits significantly lower values of potential sailing mobility, as exemplified in the map for January (Fig. 8). This stands in contrast to the high wintertime mobility measures typical of the eastern Mediterranean basin detailed in the next section. This can be attributed mainly to the higher probability of meeting stormy weather during the longer sailing passages, typical of the central basin,

Table 4 Monthly routing options and voyage durations for grain ships sailing the return route from Ostia to Alexandria. Waiting days are calculated as half the maximum measured consecutive waiting times. Durations in the table have been rounded to the nearest day

Month	Route options	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
January	Via Cyrenaica	Messina, Apollonia, Alexandria	12	9	21
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	13	11	24
February	Via Cyrenaica	Messina, Apollonia, Alexandria	13	8	21
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	14	9	23
March	Via Cyrenaica	Messina, Apollonia, Alexandria	14	7	21
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	14	8	22
April	Via Cyrenaica	Messina, Apollonia, Alexandria	14	6	20
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	15	7	22
May	Via Cyrenaica	Messina, Apollonia, Alexandria	14	3	16
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	14	5	19
June	Via Cyrenaica	Messina, Apollonia, Alexandria	14	2	15
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	14	2	16
July	Via Cyrenaica	Messina, Apollonia, Alexandria	12	1	13
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	13	1	14
August	Via Cyrenaica	Messina, Apollonia, Alexandria	13	1	14
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	14	2	15
September	Via Cyrenaica	Messina, Apollonia, Alexandria	14	4	18
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	15	5	19
October	Via Cyrenaica	Messina, Apollonia, Alexandria	16	7	23
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	17	8	24
November	Via Cyrenaica	Messina, Apollonia, Alexandria	15	8	23
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	15	10	25

Table 4 (continued)

Month	Route options	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
December	Via Cyrenaica	Messina, Apollonia, Alexandria	13	9	22
	Via Crete	Messina, Kommos, Marsa Matrouh, Alexandria	14	10	24

rather than to contrary winds. Grain shipment routings for this period were therefore less likely.

Return Routes from Ostia to Alexandria

The sailing mobility measurement results for passages in potential return routes from Ostia to Alexandria depict a completely different set of sailing measures, as these return routings were conducted with prevailing winds and not contrary to them, as exemplified for July in Fig. 9. The same segments support return routes in all other months of the year, including the winter months. The durations of the return voyages are detailed in Table 4. The fastest voyages are in July and August, averaging about 14 days, including time spent waiting. The slowest return voyages were measured for March, April, October, and November, averaging about 23 days. The net time spent sailing is almost the same throughout all months. The winter months of December, January, and February also exhibit high coefficients of mobility, but longer waiting periods are evident, resulting in total durations of 21–24 days.

Routes Exiting the Levant

This case study examined the opportunities for exiting the Levant through the eastern Mediterranean basin in the direction of the Aegean or Ionian seas via Rhodes or Crete. The need to examine such routes arises from the difficulties of sailing westward against the prevailing north-westerly winds. An additional potential exit route westward from the Levant via the North African coast and Cyrenaica is examined in the following case study, concerning maritime links between Phoenicia and its colonies. The results are detailed in Table 5.

Spring Months of March, April, and May

March and April are characterized by high measures of potential sailing mobility. This is evident in the number of direct sailing opportunities to exit the Levant. The options were for direct sailing passages to Rhodes, passages with a stop at Paphos in Cyprus, passages via the Anatolian coast, via Alexandria, and a direct passage to Kommos in Crete. These are shown in Fig. 10 and detailed in Table 5, where total voyage durations including waiting time were in the order of 2 to 2.5 weeks.

Measures of sailing mobility for May reflect the increasing prevalence of the contrary north-westerly winds (Fig. 11). The only options for direct sailing passages in May were via Alexandria to Rhodes, and via Alexandria and Marsa Matrouh to Kommos. A passage via Cyprus required segments of coastal sailing, as did the passage via the Anatolian coast. Potential mobility measures associated with coastal sailing were such that total voyage duration between the Levant and Rhodes was in the order of 5 to 6 weeks when no direct passages were possible. The fastest option was for direct sailing passages via Alexandria with total voyage duration of 19 days, of which 8 days were spent waiting for favourable sailing winds.

Table 5 Routing options for voyages exiting the Levant. Waiting days are calculated as half the maximum measured consecutive waiting times. Durations in the table have been rounded to the nearest day

Month	Route option	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
January	Direct to Rhodes	Caesarea, Rhodes	6	5	10
	Via Cyprus	Dor, Paphos, Rhodes	6	7	12
	Via Alexandria	Dor, Alexandria, Rhodes	8	10	18
	Via Anatolia	Dor, Holmoi, Korakesion, Gelidonya, Rhodes	7	9	16
	Via Crete	Tyre, Kommos	8	5	13
February	Direct to Rhodes	Caesarea, Rhodes	6	4	10
	Via Cyprus	Dor, Paphos, Rhodes	6	7	12
	Via Alexandria	Dor, Alexandria, Rhodes	8	7	15
	Via Anatolia	Dor, Holmoi, Korakesion, Gelidonya, Rhodes	7	9	16
	Via Crete	Tyre, Kommos	8	5	13
March	Direct to Rhodes	Caesarea, Rhodes	6	6	12
	Via Cyprus	Dor, Paphos, Rhodes	6	8	14
	Via Alexandria	Dor, Alexandria, Rhodes	9	8	17
	Via Anatolia	Dor, Holmoi, Korakesion, Gelidonya, Rhodes	8	12	20
	Via Crete	Tyre, Kommos	9	6	15
April	Direct to Rhodes	Caesarea, Rhodes	7	7	14
	Via Cyprus	Dor, Paphos, Rhodes	8	9	17
	Via Alexandria	Dor, Alexandria, Rhodes	9	7	16
	Via Anatolia	Dor, Holmoi, Korakesion, Gelidonya, Rhodes	10	12	22
	Via Crete	Tyre, Kommos	10	4	13

Table 5 (continued)

Month	Route option	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
May	Via Cyprus	Dor, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	6	5	11
		Kition to Paphos coastal section duration	6	3	9
		Gelidonya to Rhodes coastal section duration	11	8	18
		Total for hybrid voyage	22	16	38
	Via Alexandria	Dor, Alexandria, Rhodes	11	8	19
	Via Anatolia	Dor, Holmoi, Korakesion (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	7	4	10
		Holmoi to Korakesion coastal section duration	9	7	17
		Gelidonya to Rhodes coastal section duration	11	8	18
		Total for hybrid voyage	26	19	45
	Via Crete	Dor, Alexandria, Marsa Matrouh, Kommos	11	13	24

Table 5 (continued)

Month	Route option	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
June	Via Cyprus	Dor, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	6	5	11
		Kition to Paphos coastal section duration	7	14	20
		Gelidonya to Rhodes coastal section duration	11	9	20
		Total for hybrid voyage	24	27	51
	Via Anatolia	Dor, Holmoi, Korakesion (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	6	4	10
		Holmoi to Korakesion coastal section duration	10	11	20
		Gelidonya to Rhodes coastal section duration	11	9	20
		Total for hybrid voyage	26	23	50
July	Via Cyprus	Dor, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	4	3	7
		Kition to Paphos coastal section duration	7	14	21
		Gelidonya to Rhodes coastal section duration	11	8	19
		Total for hybrid voyage	22	25	47
	Via Anatolia	Dor, Holmoi, Korakesion (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	5	3	8
		Holmoi to Korakesion coastal section duration	9	12	21
		Gelidonya to Rhodes coastal section duration	11	8	19
		Total for hybrid voyage	25	22	47

Table 5 (continued)

Month	Route option	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
August	Via Cyprus	Dor, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	6	5	11
		Kition to Paphos coastal section duration	6	7	13
		Gelidonya to Rhodes coastal section duration	11	14	25
		Total for hybrid voyage	23	26	49
	Via Anatolia	Dor, Holmoi, Korakesion (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	5	3	8
		Holmoi to Korakesion coastal section duration	10	19	29
		Gelidonya to Rhodes coastal section duration	11	14	25
		Total for hybrid voyage	26	35	62

Table 5 (continued)

Month	Route option	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
September	Via Cyprus	Dor, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	6	7	13
		Kition to Paphos coastal section duration	6	5	11
		Gelidonya to Rhodes coastal section duration	11	7	18
		Total for hybrid voyage	23	19	42
	Via Alexandria	Dor, Alexandria, Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	12	8	19
		Gelidonya to Rhodes coastal section duration	11	7	18
		Total for hybrid voyage	22	15	37
	Via Anatolia	Dor, Holmoi, Korakesion (coastal sailing), Gelidonya, Rhodes (coastal sailing)			
		Sum of direct sailing passages	6	4	10
		Holmoi to Korakesion coastal section duration	10	8	18
		Gelidonya to Rhodes coastal section duration	11	7	18
		Total for hybrid voyage	26	19	45
	Via Crete	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	13	27	40

Table 5 (continued)

Month	Route option	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
October	Direct to Rhodes	Caesarea, Rhodes	8	7	15
	Via Cyprus	Dor, Paphos, Rhodes	8	12	20
	Via Alexandria	Dor, Alexandria, Rhodes	10	8	18
	Via Anatolia	Dor, Holmoi, Korakesion, Gelidonya, Rhodes	10	14	24
	Via Crete	Tyre, Kommos	10	5	15
November	Direct to Rhodes	Caesarea, Rhodes	6	4	10
	Via Cyprus	Dor, Paphos, Rhodes	7	6	13
	Via Alexandria	Dor, Alexandria, Rhodes	9	7	16
	Via Anatolia	Dor, Holmoi, Korakesion, Gelidonya, Rhodes	9	10	19
	Via Crete	Tyre, Kommos	9	3	12
December	Direct to Rhodes	Caesarea, Rhodes	6	4	10
	Via Cyprus	Dor, Paphos, Rhodes	6	7	13
	Via Alexandria	Dor, Alexandria, Rhodes	8	11	19
	Via Anatolia	Dor, Holmoi, Korakesion, Gelidonya, Rhodes	8	10	17
	Via Crete	Tyre, Kommos	8	6	14

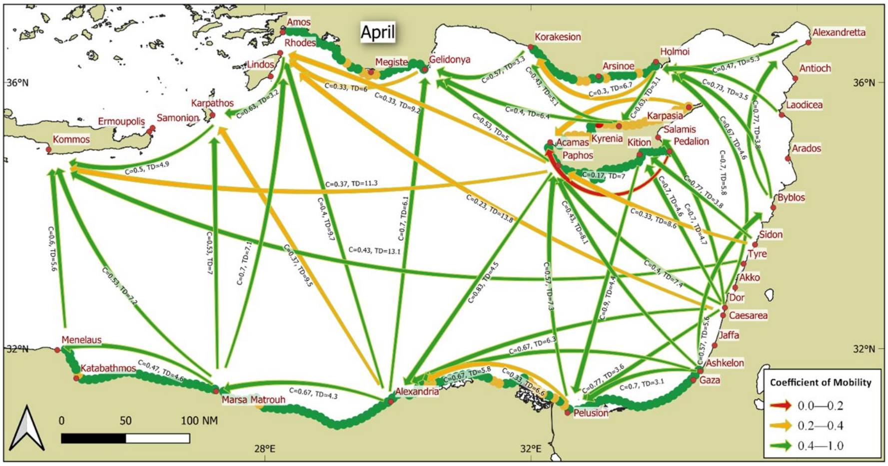

Fig. 10 Mobility measures for routings exiting the Levant in April (D. Gal)

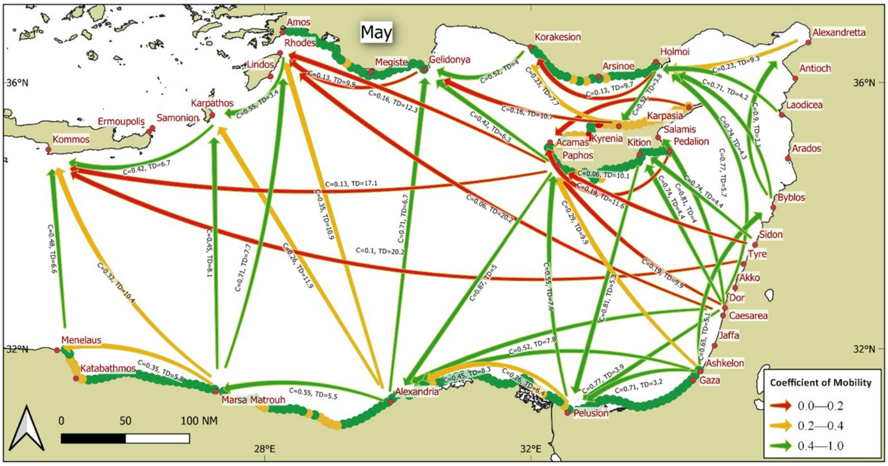

Fig. 11 Mobility measures for routings exiting the Levant in May (D. Gal)

Summer Months of June, July, and August

The mapping results indicate that the three summer months of June to August had very low measures of sailing mobility for any direct passages out of the Levant through the eastern Mediterranean basins. The evident bottlenecks were as follows: (a) the inability to sail westward along the North African coast, including by coastal sailing; (b) westward sailing past Cyprus was limited to slow and difficult coastal sailing along the southern coast; and (c) westward sailing along the southern coast of Asia Minor required slow and difficult coastal sailing along the Cilician and Lycian coasts. These are detailed in Table 5 and shown in Fig. 12.

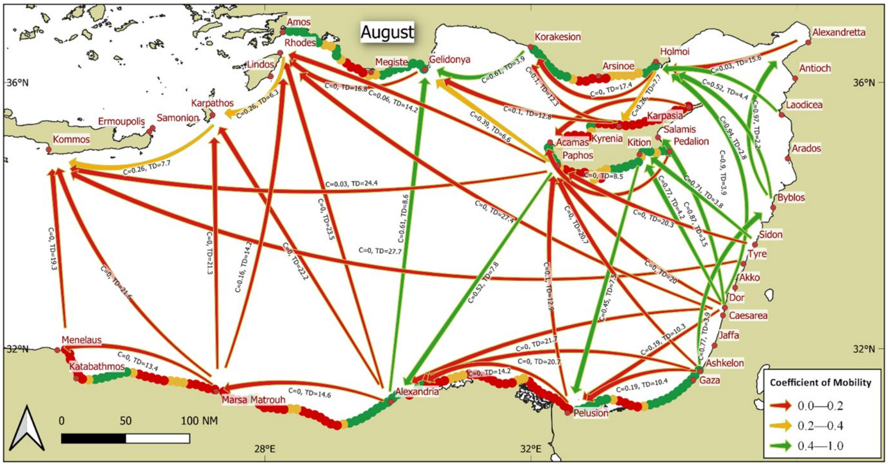

Fig. 12 Mobility measures for routings exiting the Levant in August, and also representative of June and July (D. Gal)

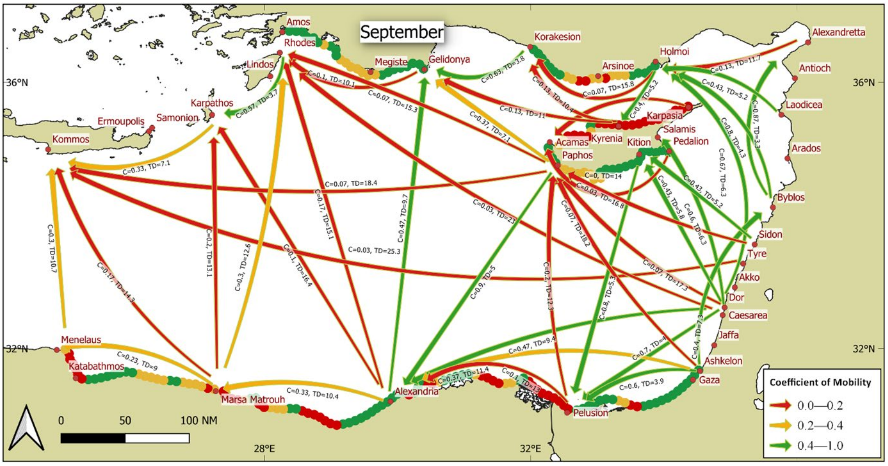

Fig. 13 Mobility measures for routings exiting the Levant in September (D. Gal)

The shortest potential voyages to Rhodes would have required about 7 weeks in this season.

Autumn Months of September, October and November

Mapping results for September indicate that this was a transition month with an indication of improving measures of potential sailing mobility. Examination of Table 5 and Fig. 13 reveals that there was the possibility of a single direct sailing route via Alexandria, Marsa Matrouh, and Menelaus to reach Kommos in Crete.

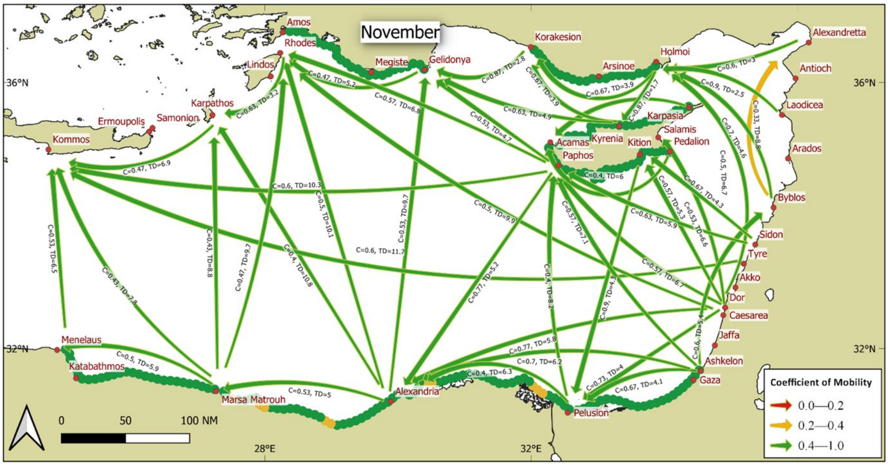

Fig. 14 Mobility measures for routings exiting the Levant in November (D. Gal)

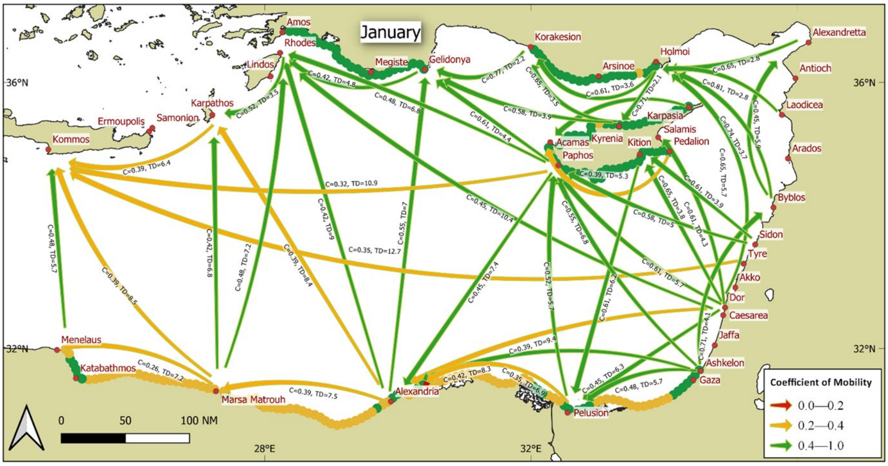

Fig. 15 Mobility measures for routings exiting the Levant in January which is also representative of the mobility for December and February (D. Gal)

Routes to Rhodes still required segments of coastal sailing. Total voyage times to Rhodes were 5.5 to 6 weeks, shorter than in the midsummer months.

The results of the mapping indicate that potential sailing mobility during October and November is most similar to that measured for March and April, with November exhibiting the highest values of mobility coefficient (Table 5; Fig. 14). There is no need for coastal sailing on routings to Rhodes or Kommos in either month. Direct sailings between Caesarea and Rhodes were possible with 10 to 14 days' total voyage duration, including waiting time.

Winter Months of December, January, and February

All three winter months exhibit high measures of mobility coefficient, as shown in Fig. 15 for January, which closely resembles the mappings for December and February. The sailing and waiting durations for the winter months are also quite similar to those of March, April, October, and November (Table 5).

Phoenician Routes Between Phoenicia and Colonies

Phoenician maritime links between the Levant and Carthage involve the crossing of both the eastern and the central Mediterranean basins, each exhibiting different characteristics of potential sailing mobility. Considering this, the mapping results are presented in two sections, individually for each of the basins, first from Phoenicia to Crete, and then from Crete onwards to Carthage. For each section, the possible routing options are detailed for each month of the year. The entire voyage durations need to be summed from the selected section totals (specified in Table 6).

Routings from Phoenicia to Carthage

The mapping results, together with the data specified in Table 6, indicate that there were three distinct periods for sailing from the Levant to Carthage. The best times were March and April (Fig. 16), early in the year, and also after the summer, during October and November (Fig. 17). In these months with high mobility coefficients, total voyage times were in the order of 30–35 days, including waiting time. These months exhibit the feasibility of exiting the eastern Mediterranean basin without the necessity of coastal sailing, and they also exhibit good measures of sailing mobility in the central basin.

The second distinct period was that of the winter months, December, January, and February. In these months, the mapping results for the eastern section of the voyages between the Levant and Crete indicated similar passage times to those presented for spring and autumn. Total passage durations to Crete remained in the order of 2 weeks. However, the continuation passages to Carthage reflected lower measures of potential sailing mobility in the central Mediterranean basin in winter months. Noticeable in the results (Table 6; Fig. 18, exemplified for February) is that the time spent sailing the leg from Crete to Carthage during the mid-winter months does not differ substantially from the spring and autumn months. However, the waiting time was significantly longer, with total passage durations of 3 to 3.5 weeks for this section.

The third distinct period was that of the warm period, from May to September (Fig. 19, exemplified for August). The mapping results for these months reflected the difficulty of exiting the eastern Mediterranean basin (see ‘Routes Exiting the Levant’). Total voyage times between the Levant and Carthage were in the order

Table 6 Routing options and durations for Phoenician links to Carthage. Waiting days are calculated as half the maximum measured consecutive waiting times. Durations in the table have been rounded to the nearest day

Month	Route	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
January	Phoenicia to Crete	Tyre, Kommos	8	5	13
	or	Sidon, Paphos, Kommos	9	7	16
	or	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	10	20	30
	Crete to Carthage	Kommos, Malta, Carthage	11	16	26
	or	Kommos, Leptis Magna, Carthage	13	14	27
February	Phoenicia to Crete	Tyre, Kommos	8	5	13
	or	Sidon, Paphos, Kommos	9	7	15
	or	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	10	14	24
	Crete to Carthage	Kommos, Leptis Magna, Carthage	13	11	24
March	Phoenicia to Crete	Tyre, Kommos	9	6	15
	or	Sidon, Paphos, Kommos	10	8	17
	or	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	10	11	21
	Crete to Carthage	Kommos, Malta, Carthage	11	10	20
	or	Kommos, Leptis Magna, Carthage	12	9	20
April	Phoenicia to Crete	Tyre, Kommos	10	4	13
	or	Sidon, Paphos, Kommos	10	10	20
	or	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	10	11	21
	Crete to Carthage	Kommos, Malta, Carthage	10	7	17
	or	Kommos, Leptis Magna, Carthage	12	4	16
May	Phoenicia to Crete	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	12	14	26
	or	Tyre, Kition, Paphos (coastal sailing), Gelidonya, Karpathos, Kommos	17	18	35
	Crete to Carthage	Kommos, Malta, Carthage	11	9	20
	or	Kommos, Leptis Magna, Carthage	13	4	17

Table 6 (continued)

Month	Route	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
June	Phoenicia to Crete	Tyre, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing), Karpathos, Kommos	27	36	63
	Crete to Carthage	Kommos, Malta, Carthage	13	12	25
	or	Kommos, Leptis Magna, Carthage	14	4	18
July	Phoenicia to Crete	Tyre, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing), Karpathos, Kommos	28	37	64
	Crete to Carthage	Kommos, Leptis Magna, Carthage	15	4	19
August	Phoenicia to Crete	Tyre, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing), Karpathos, Kommos	27	35	62
	Crete to Carthage	Kommos, Malta, Carthage	14	10	23
	or	Kommos, Leptis Magna, Carthage	14	3	17
September	Phoenicia to Crete	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	13	27	40
	or	Tyre, Kition, Paphos (coastal sailing), Gelidonya, Rhodes (coastal sailing), Karpathos, Kommos	26	26	53
	Crete to Carthage	Kommos, Malta, Carthage	12	7	19
	or	Kommos, Leptis Magna, Carthage	13	3	16
October	Phoenicia to Crete	Tyre, Kommos	10	5	15
	or	Sidon, Paphos, Kommos	11	8	19
	or	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	12	13	25
	Crete to Carthage	Kommos, Malta, Carthage	10	7	17
	or	Kommos, Leptis Magna, Carthage	12	5	17

Table 6 (continued)

Month	Route	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
November	Phoenicia to Crete	Tyre, Kommos	9	3	12
	or	Sidon, Paphos, Kommos	10	7	16
	or	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	10	13	23
	Crete to Carthage	Kommos, Malta, Carthage	10	9	19
	or	Kommos, Leptis Magna, Carthage	13	9	22
December	Phoenicia to Crete	Tyre, Kommos	8	6	14
	or	Sidon, Paphos, Kommos	9	8	16
	or	Dor, Alexandria, Marsa Matrouh, Menelaus, Kommos	10	20	30
	Crete to Carthage	Kommos, Malta, Carthage	11	14	25
	or	Kommos, Leptis Magna, Carthage	13	15	28

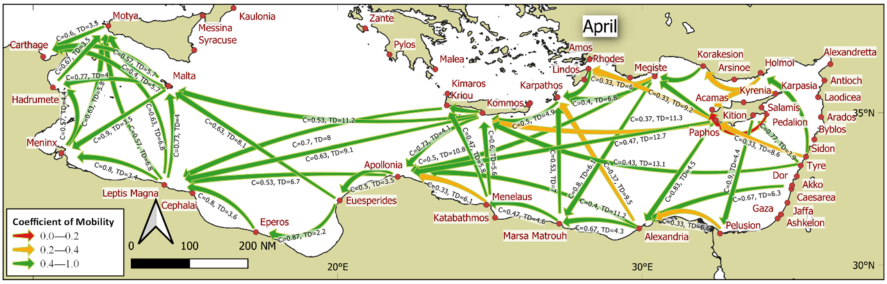

Fig. 16 Mobility measures for Phoenician routes between the Levant and Carthage for April (D. Gal)

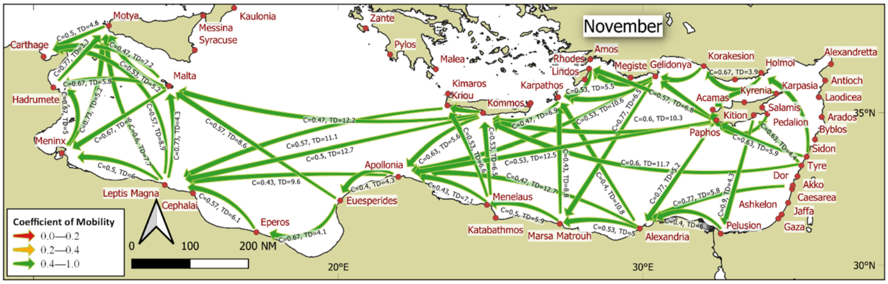

Fig. 17 Mobility measures for Phoenician routes between the Levant and Carthage for November (D. Gal)

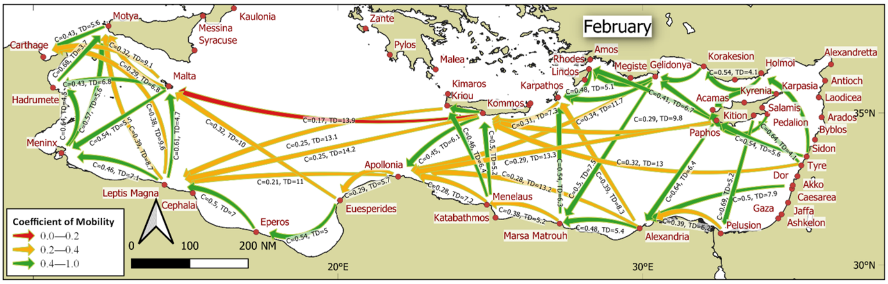

Fig. 18 Mobility measures for Phoenician routes between the Levant and Carthage for February (D. Gal)

of 80 days in the midsummer months and about 60 days in the transition months of May and September (Table 6).

Eastward Return Routings to Phoenicia

The return route options from Carthage to the Levant are shown for July in Fig. 20, and detailed in Table 7 for the entire year. Mapping results indicate that total return voyage durations were between 15 and 28 days, with the fastest voyages occurring in

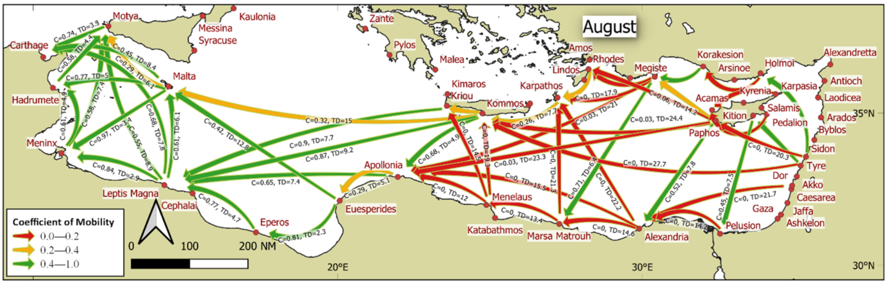

Fig. 19 Mobility measures for Phoenician routes between the Levant and Carthage for August (D. Gal)

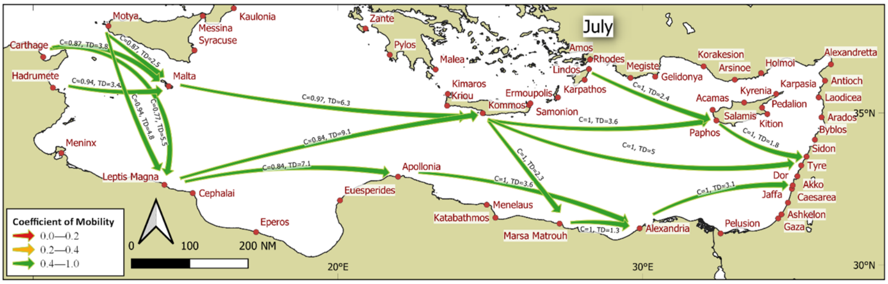

Fig. 20 Mobility measures for Phoenician return routes from Carthage to the Levant for July (D. Gal)

the midsummer months. The winter months exhibit similar sailing durations to the summer months, but significantly longer waiting durations of 8–11 days, compared to 2–3 waiting days in the midsummer months.

Eastern Mediterranean Intra-regional Sailing Mobility

The previous case studies (‘Roman Grain Routes from Alexandria to Ostia’ to ‘Phoenician routes between Phoenicia and colonies’) examined potential inter-regional sailing mobility in the Mediterranean. In all cases, sailing mobility was hindered by the prevailing north-westerly summer winds in the eastern Mediterranean basin. These prevailing winds rendered many bi-directional maritime links impossible during this season. These difficulties raised the inevitable research question: which sailing links were viable during the summer months in this region? This case study attempts to answer this question and identify the potential bi-directional sailing links in the eastern Mediterranean despite the summer prevailing winds. Figure 21 shows mapped passages for all bi-directional links in the eastern Mediterranean with no filtering. The many red-coloured links in bi-directional pairs indicate very low coefficients of mobility and the impracticability of maintaining maritime links in both directions during the warm season.

Table 7 Routing options and durations for Phoenician return voyages from colonies. Waiting days are calculated as half the maximum measured consecutive waiting times. Durations in the table have been rounded to the nearest day

Month	Route options	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
January	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	15	11	26
	Via Crete	Carthage, Malta, Kommos, Phoenicia	14	9	22
February	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	15	11	26
	Via Crete	Carthage, Malta, Kommos, Phoenicia	13	8	21
March	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	16	9	25
	Via Crete	Carthage, Malta, Kommos, Phoenicia	14	9	22
April	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	17	8	25
	Via Crete	Carthage, Malta, Kommos, Phoenicia	14	6	20
May	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	18	7	25
	Via Crete	Carthage, Malta, Kommos, Phoenicia	15	4	19
June	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	18	5	22
	Via Crete	Carthage, Malta, Kommos, Phoenicia	14	2	16
July	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	17	2	19
	Via Crete	Carthage, Malta, Kommos, Phoenicia	14	2	15
August	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	18	3	21
	Via Crete	Carthage, Malta, Kommos, Phoenicia	14	2	16
September	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	18	5	23
	Via Crete	Carthage, Malta, Kommos, Phoenicia	14	3	17
October	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	20	9	28
	Via Crete	Carthage, Malta, Kommos, Phoenicia	17	7	24
November	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	18	9	27
	Via Crete	Carthage, Malta, Kommos, Phoenicia	16	8	24

Table 7 (continued)

Month	Route options	Segments	Sailing (Days)	Waiting (Days)	Total duration (Days)
December	Via Cyrenaica	Carthage, Leptis Magna, Apollonia, Alexandria, Phoenicia	15	10	25
	Via Crete	Carthage, Malta, Kommos, Phoenicia	14	9	23

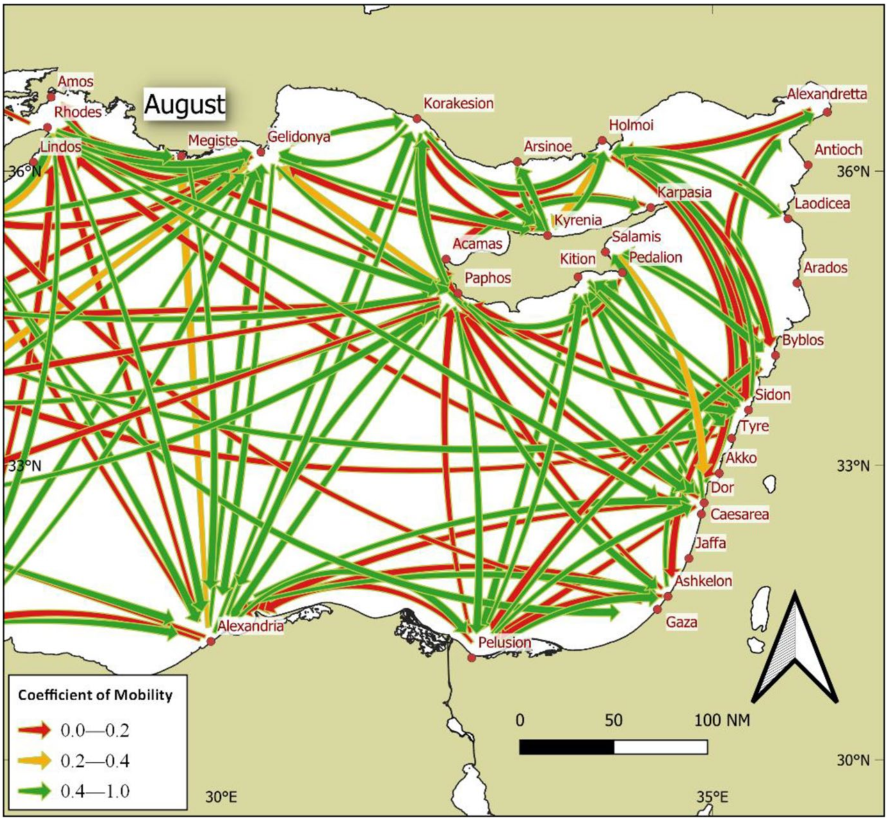

Fig. 21 All mapped passages in the eastern Mediterranean basin for August. Red links in a bi-directional pair indicate very low coefficients of mobility (D. Gal)

A filter was then applied to display only bi-directional links where both sailing directions exhibited a coefficient of mobility of 0.2 and above during all of the five months of May to September, which represent the season of the Etesian winds. The results of this filtering are the three distinct networks of potential sailing links in Fig. 22, shown in the dashed ellipses. These links are as follows: (a) between western Cyprus, Lycia (between Korakesion and Megiste), and the west side of the Nile Delta (Alexandria); (b) between eastern Cyprus, the middle Levant coast (between Dor and Byblos), and the east side of the Nile Delta (Pelusion); and (c) between the northern coast of Cyprus, points on the Cilician coast and Laodicea on the Syrian coast. These networks comprise internal bi-directional links with high coefficients of mobility, mostly above 0.4. Also, noticeable is the lack of bi-directional links connecting the networks to each other.

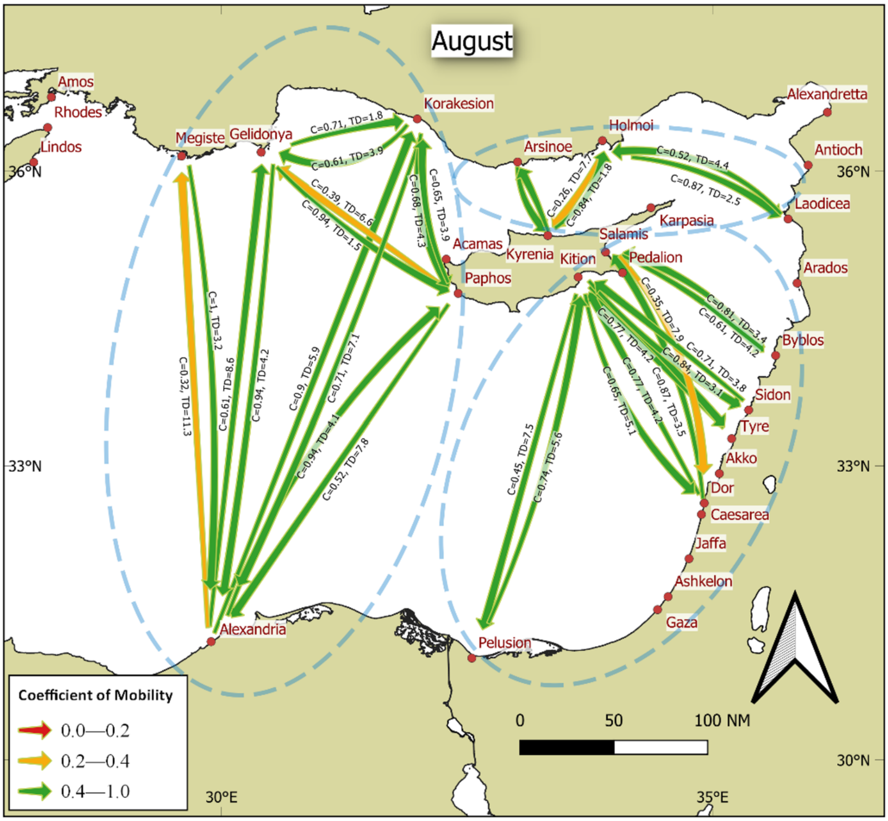

Fig. 22 Mapping sustainable bi-directional links in the eastern Mediterranean, showing only passages exhibiting a coefficient of mobility of 0.2 or more for all five warm season months of May to September. The three distinct networks of potential maritime links are outlined with dashed ellipses. The map shown is for August (D. Gal)

Summary and Discussion

The results of the measurements of potential sailing mobility and other sailing parameters, exemplified by the sample data sheets (see Appendix 3) and presented in 'Measurement outputs', provide new metrics enabling assessments of mobility in direct sailing passages and for coastal breeze-assisted sailing. Additional metrics and resulting measures have enabled insight into the functioning of period seafaring, allowing the analysis of sailing characteristics, the relationship between the three main factors of sailing mobility: the ships, the mariners, and the wind. Application of the measured sailing mobility to the case studies has resulted in new quantified insights into the functioning and mapping of potential period Mediterranean maritime links, unavailable in previous studies.

Metrics of Potential Sailing Mobility

This study allows expressing measures of potential sailing mobility, primarily in terms of a coefficient indicating the probability of sailing a passage in a given month, and in terms of time spent waiting for the weather conditions to execute a passage. The study also shows that sailing speed and resulting time spent sailing are only secondary measures of sailing mobility, dwarfed by the probability of executing a successful passage and the expected consecutive waiting time that might have been experienced. For example, a month in which a given passage offers an opportunity of a slow 4-day passage on 80% of the month's days with a maximum consecutive waiting time of 2 days, clearly has better sailing mobility than a month in which an opportunity to sail the same passage at double the speed, i.e., in 2 days, occurs on 10% of the days, with a maximum consecutive waiting time of 20 days.

These new metrics of potential sailing mobility are an expression of practical sailing mobility, reflecting the fact that the mariners would have carefully chosen the conditions in which they ventured to sail. It is practical mobility that is of interest, and not only the technological capabilities of the ships. The method of criteria based differentiating between the sets of reasonable and unreasonable passages reflect the human factor in sailing mobility (Table 1).

The data for coastal breeze-driven sailing ('Coastal Sailing Runs') determine the possibility of exploiting the coastal breeze cycle for individual sections of longer coastal stretches. The measures of coastal sailing performed in this study indicate substantial differences in mobility between coastal sailing contrary to prevailing synoptic winds and coastal sailing across the prevailing synoptic winds. Also apparent in the measurement datasheets is the observation that coastal points exhibit differing mobility coefficients, and that mobility is not necessarily homogeneous in a coastal stretch for a given month. This leads to insights regarding specific coastal areas that period mariners would have probably avoided at particular times. From the pure perspective of potential sailing mobility, measured results show that coastal sailing does not provide an effective alternative to advancing contrary to prevailing winds in months when direct passages are limited. In the months when coastal sailing exhibits higher mobility, the option of direct passages is also high, and there is no need for coastal breeze-assisted propulsion.

Previous quantitative studies have only attempted to represent sailing mobility in terms of sailing duration based on calculations of effective sailing speed (Alberti, 2018; Arcenas, 2012; Leidwanger, 2013; Safadi & Sturt, 2019; Trapero Fernández & Aragón, 2022; Warnking, 2016). These studies have addressed measures of ships' technological mobility, but they have not expressed quantitative measures of practical mobility. Moreover, none of these quantitative studies provide measures of period breeze-driven coastal sailing mobility. The title of a recent study by Trapero Fernández and Aragón implies modelling of coastal sailing, but it only refers to regional sailing in sight of and along coasts as coastal sailing, without attempting to model the breeze cycle. (2022) The present study, on the contrary, defines coastal sailing as a mode of propulsion following scholars cited in 'Introduction' (e.g. Casson, 1950, p. 46; McGrail, 2004, p. 94; Morton, 2001, p. 145; Murray, 1993, p. 40; Pryor, 1988, pp. 13–15, 89–90), and considers sailing passages adjacent to coastal sections to be in the set of direct sailing passages driven primarily by synoptic winds.

Table 8 Averaged wind values encountered during 1.2 million simulated sailings in eastern and central Mediterranean basins. Based on 15 years (2004–2018) of hourly ERA5 wind data

Month	Average passage TWS (knots)	Average of maximum encountered TWS (knots)	Maximum encountered TWS (knots)
January	12.2	21.2	45.3
February	12.0	20.9	41.7
March	11.2	19.7	38.8
April	10.1	18.1	43.6
May	9.1	16.7	43.6
June	8.9	15.8	35.5
July	9.1	15.7	30.9
August	8.9	15.5	36.6
September	9.0	16.2	42.1
October	9.1	16.8	39.2
November	10.1	18.2	40.8
December	11.5	20.2	42.6

Insights to Period Seafaring

Additional measured parameters obtained from the simulation of direct passages provided the ability to reflect on the relationship between the ship and the wind (points-of-sail) during the passages, and on the environment encountered during the passages (detailed in 'Outputs for Direct Sailing Passages'). These metrics and their fine detail are unique to this work, and have not been shown by previous quantitative works on Mediterranean sailing. Close examination of these sailing parameters helps in understanding the virtual border area between reasonable and unreasonable passages, and the possible effects of variations in wind direction, ship technology and mariners' limits in this border area. With the wind being the dominant factor, it becomes clear that this set of sailing metrics can provide quantifiable insights to the ancient term 'favourable wind'.

The environmental metrics also provide insights into ancient seafaring by revealing measures encountered in the passage segments for both reasonable and unreasonable passages. An interesting example is that of the averaged and maximum wind speeds encountered in all the 1.2 million simulated sailings in the central and eastern Mediterranean basins (shown in Table 8). It is evident that, on average, sailing in this area encounters relatively benign wind conditions. This reflects on the average sailing speeds achieved in this area. The measure of cloud cover provides indication of the possibility of conducting stellar navigation for a particular passage and month. None of the previous quantitative studies have provided this level of detail for the sailing environment.

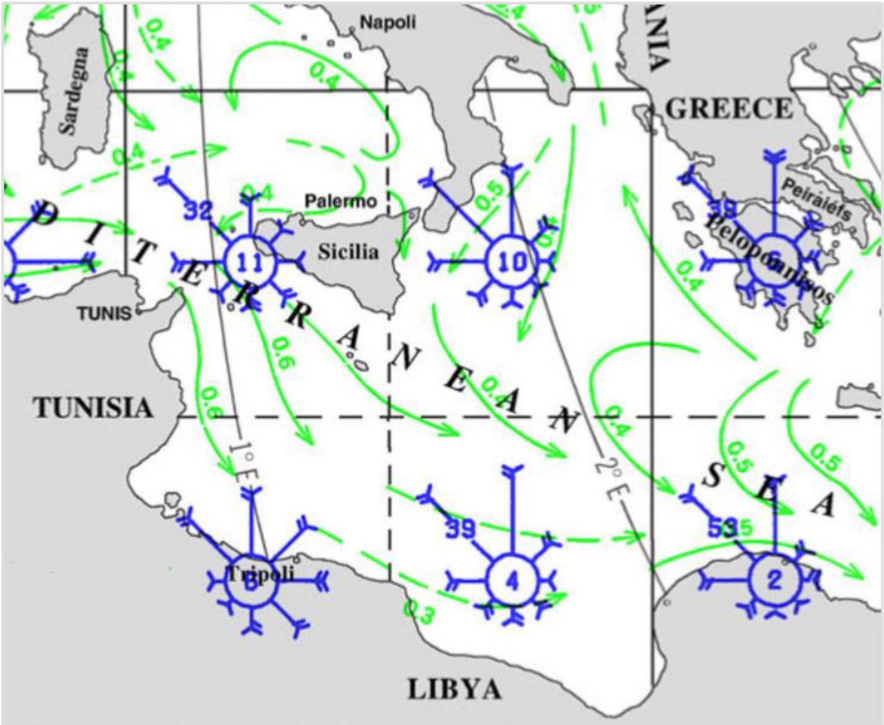

Fig. 23 Wind roses and surface currents for July in the Gulf of Sidra (US National Geospatial-Intelligence Agency, Atlas of Pilot Charts)

Results of Case Study Mappings

The studies of the Roman grain shipments, the Phoenician links between the Levant and colonies, and exiting the Levant, highlight the common difficulty of westbound sailing in general, and specifically during the extended hot season of May to September. There are however significant differences between the eastern and central Mediterranean basins. The eastern basin develops distinct summertime bottlenecks to westward sailing on both its southern and northern shores. During June to August, it is practically impossible to sail from the Nile Delta to Cyrenaica, either by direct sailing passages or by coastal breeze-driven sailing. During the same months, on the northern shores, direct sailing between eastern and western Cyprus is also not practical. On the south coast of Asia Minor, direct sailing passages westward are also not practical on the Cilician coast north of Cyprus, and along the Lycian coast between Gelidonya and Rhodes. On these northern routings, coastal sailing does offer limited possibilities to advance westward, albeit at a high cost of time spent waiting for coastal breeze-driven runs.

The two gateways westward to the central Mediterranean basin are via Cyrenaica or via Crete. Once either of these two locations is reached, sailing westward is assured, even at the peak of the summer. The central basin also exhibits two general sailing options, the northern option, from Crete to Messina, and then onward to the western basin; and via the Gulf of Sidra, continuing to the west of Sicily and onward. The northern option is not viable in the summer months of June to August, whereas the southern option remains open, with relatively high measures of mobility. These high westbound coefficients of mobility in the Gulf of Sidra appear in both the study of grain shipments to Rome and in the examination of Phoenician links with Carthage. These findings stand in apparent contradiction to the wind roses for this area (Fig. 23) which indicate prevailing north-westerly winds over the central Mediterranean. Examination of the raw high-resolution wind data used in the simulations revealed that the appearance of meso-scale highs (anticyclones), which tend to develop in the Gulf of Sidra several times a month bringing easterly wind vectors, support sailing parallel to the coast and out to the western basin. The incidence of easterly winds is partially evident in the wind rose for Tripoli (Fig. 23). This phenomenon, typical of the Gulf of Sidra in summer, is described by Hatzaki et al., (2014, Figs. 7, 8), and serves well as an example of the significant impact of meso-scale variabilities in the wind patterns on sailing mobility.

The option of coastal sailing was introduced to the case studies. In general, results indicate very little contribution of coastal sailing to the contexts examined, due to significantly longer voyage times needed for coastal sailing. Results have shown that when contrary prevailing winds caused direct passages to be impractical, they also suppressed the coastal breeze cycle, as exemplified in the Adriatic Sea (Klaic et al., 2009) and in the Gulf of Eilat (Saaroni et al., 2004). Accordingly, when coastal sailing was possible, it was not really needed, as direct sailing passages could be conducted. This is clearly evident in the case study of exiting the Levant during the extended hot season of May to September, when direct sailing passages were not practical, and coastal sailing was required to bypass the westward summer bottlenecks on the coasts of Cyprus and Anatolia. Results show that traversing these bottlenecks by breeze-driven coastal sailing would have been very costly in terms of time, and they suggest that mariners would have preferred to exit the Levant before or after the hot season. These results challenge Pryor's suggestion that counter-clockwise breeze-driven coastal sailing constituted the 'trunk routes' exiting the Levant (1988, pp. 13–15, 89–90).

The examination of potential routes used by the Alexandrian grain ships clearly revealed four distinct sailing periods during the year. In the spring and autumn months, direct sailing was possible, and the gateways to the central basin, i.e., Crete or Cyrenaica, were easily achievable. The durations between Alexandria and Ostia were about 1 month on the average, with 1 to 2 weeks more in May and September. The grain shipments during summer months of June to August encountered the bottlenecks for exiting the eastern basin, and ships would have needed to cross to the northern Mediterranean shores to eventually reach Crete. The Lycian coast would have required costly coastal sailing. Summer grain voyages would have taken 60 to 70 days. Accounting for 3 weeks turnaround time, it is suggested that a grain ship that wintered in Alexandria might be able to make three voyages, and then spend the next winter in Ostia. A ship departing Ostia to Alexandria at the beginning of March would most likely be able to run only two deliveries.

The route via the Lycian coast is identified with Alexandrian grain shipments to Italy (Lucian, *Navigium*; *Acts* 27), but it is suggested that this was not a preferred route, but rather a last resort option for ships leaving Alexandria in July or the beginning of August. A ship ready to depart in mid-August might have well have waited for the direct passages to open in September. The winter period exhibited lower potential mobility in the central basin, due to higher probability of encountering strong winter depressions with longer passages than in the eastern basin (Nissen et al., 2010).

The case study of intra-regional maritime links is a good example indicating that the mapping of multiple direct passages serves not only to examine composite routes between regions, such as the grain routes to Ostia, but also enables identification of potential maritime links within a region despite dominant prevailing winds. It is suggested that the bi-directional links occur when they lie perpendicular to the prevailing wind.

Conclusions

The data science methodology of using a large input of high spatio-temporal resolution environmental data enables simulation of a large sample of individual sailings applied to a large set of passage segments. The comprehensive methodology and analysis (a) expose the meso-scale variabilities of the wind, proving that they are a key to sailing mobility; (b) introduce the human factor in sailing mobility, enabling the measurement of practical sailing mobility, including measures of probability of conducting a successful passage and expected waiting time for suitable winds; (c) support new insights into period seafaring, using the high-level details of measured sailing parameters; and (d) the computing resources required to perform such a study were not prohibitive.

The mapping of the case studies in this research provides new insights into the potential envelope of sailing mobility in their historical contexts. These mappings are free of external influences; however, they delineate the limits in which political, commercial, or security (e.g. piracy) considerations may be applied. The examination of coastal breeze-driven sailing in the mapped case studies suggests that coastal sailing is a time-consuming and inferior alternative to direct sailing when contrary winds prevail.

The study outputs of measures of potential sailing mobility for passage segments are provided in usable form to support wider research into the functioning of maritime links. The authors of this research hope to continue measuring and mapping potential sailing mobility by extending the scope to the western Mediterranean basin, the Red Sea, and the Adriatic. The library of data sheets will be subsequently updated with every new measured passage.

Research Data

All data sheets produced in this research are accessible as an open data resource at Mendeley Data https://doi.org/10.17632/hzbg2wyjxb.1 (Gal et al., 2022), in the hope of contributing to a wider research of maritime links.

Appendix 1 List of direct sailing passages

An index map of all bi-directional direct sailing passages is shown in Fig. 24 followed by a listing of the individual passages. Datasheets for each passage are part of the research data for this study and can be found at https://doi.org/10.17632/hzbg2wyjxb.1.

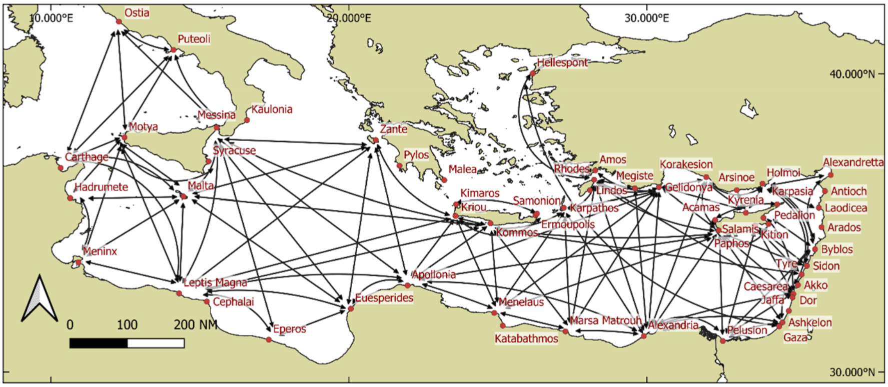

Fig. 24 Direct bi-directional passages (D. Gal).

1 Acamas-Karpasia
2 Acamas-Pedalion
3 Alexandretta-Byblos
4 Alexandretta-Holmoi
5 Alexandria-Apollonia
6 Alexandria-Ashkelon
7 Alexandria-Dor
8 Alexandria-Gelidonya
9 Alexandria-Karpathos
10 Alexandria-Korakesion
11 Alexandria-Marsa Matrouh
12 Alexandria-Megiste
13 Alexandria-Paphos
14 Alexandria-Pelusion
15 Alexandria-Rhodes
16 Amos-Gelidonya
76 Holmoi-Byblos
77 Holmoi-Dor
78 Holmoi-Korakesion
79 Holmoi-Kyrenia
80 Holmoi-Laodicea
81 Holmoi-Sidon
82 Karpasia-Acamas
83 Karpathos-Alexandria
84 Karpathos-Gelidonya
85 Karpathos-Kommos
86 Karpathos-Marsa Matrouh
87 Karpathos-Menelaus
88 Karpathos-Rhodes
89 Kimaros-Samonion
90 Kition-Dor
91 Kition-Pelusion
151 Menelaus-Kommos
152 Menelaus-Kriou
153 Menelaus-Marsa Matrouh
154 Menelaus-Paphos
155 Meninx-Hadrumete
156 Meninx-Leptis Magna
157 Meninx-Malta
158 Meninx-Motya
159 Messina-Apollonia
160 Messina-Eperos
161 Messina-Euesperides
162 Messina-Kommos
163 Messina-Leptis Magna
164 Messina-Malta
165 Messina-Ostia
166 Messina-Puteoli

17 Apollonia-Alexandria
18 Apollonia-Euesperides
19 Apollonia-Gelidonya
20 Apollonia-Kommos
21 Apollonia-Kriou
22 Apollonia-Leptis Magna
23 Apollonia-Menelaus
24 Apollonia-Messina
25 Apollonia-Paphos
26 Apollonia-Zante
27 Arsinoe-Kyrenia
28 Ashkelon-Alexandria
29 Ashkelon-Byblos
30 Ashkelon-Paphos
31 Ashkelon-Pelusion
32 Byblos-Alexandretta
33 Byblos-Ashkelon
34 Byblos-Holmoi
35 Byblos-Pelusion
36 Byblos-Salamis
37 Caesarea-Rhodes
38 Carthage-Leptis Magna
39 Carthage-Malta
40 Carthage-Motya
41 Carthage-Ostia
42 Carthage-Puteoli
43 Dor-Alexandria
44 Dor-Holmoi
45 Dor-Kition
46 Dor-Paphos
47 Dor-Pelusion
48 Dor-Salamis
49 Eperos-Euesperides
50 Eperos-Leptis Magna
51 Eperos-Messina
52 Ermoupolis-Kriou
53 Euesperides-Apollonia
54 Euesperides-Eperos
55 Euesperides-Leptis Magna
56 Euesperides-Malta
57 Euesperides-Messina
58 Euesperides-Zante
59 Gaza-Hellespont
60 Gelidonya-Alexandria
61 Gelidonya-Amos
92 Kition-Sidon
93 Kition-Tyre
94 Kommos-Apollonia
95 Kommos-Karpathos
96 Kommos-Kriou
97 Kommos-Leptis Magna
98 Kommos-Malta
99 Kommos-Marsa Matrouh
100 Kommos-Menelaus
101 Kommos-Messina
102 Kommos-Paphos
103 Kommos-Tyre
104 Korakesion-Alexandria
105 Korakesion-Gelidonya
106 Korakesion-Holmoi
107 Korakesion-Kyrenia
108 Korakesion-Paphos
109 Kriou-Apollonia
110 Kriou-Ermoupolis
111 Kriou-Kommos
112 Kriou-Leptis Magna
113 Kriou-Menelaus
114 Kriou-Zante
115 Kyrenia-Arsinoe
116 Kyrenia-Gelidonya
117 Kyrenia-Holmoi
118 Kyrenia-Korakesion
119 Laodicea-Holmoi
120 Leptis Magna-Apollonia
121 Leptis Magna-Carthage
122 Leptis Magna-Eperos
123 Leptis Magna-Euesperides
124 Leptis Magna-Kommos
125 Leptis Magna-Kriou
126 Leptis Magna-Malta
127 Leptis Magna-Meninx
128 Leptis Magna-Messina
129 Leptis Magna-Motya
130 Leptis Magna-Zante
131 Malta-Carthage
132 Malta-Euesperides
133 Malta-Hadrumete
134 Malta-Kommos
135 Malta-Leptis Magna
136 Malta-Meninx
167 Messina-Zante
168 Motya-Carthage
169 Motya-Hadrumete
170 Motya-Leptis Magna
171 Motya-Malta
172 Motya-Meninx
173 Motya-Ostia
174 Motya-Puteoli
175 Motya-Syracuse
176 Ostia-Carthage
177 Ostia-Messina
178 Ostia-Motya
179 Ostia-Puteoli
180 Paphos-Alexandria
181 Paphos-Apollonia
182 Paphos-Ashkelon
183 Paphos-Dor
184 Paphos-Gelidonya
185 Paphos-Kommos
186 Paphos-Korakesion
187 Paphos-Menelaus
188 Paphos-Pelusion
189 Paphos-Rhodes
190 Paphos-Sidon
191 Pedalion-Acamas
192 Pelusion-Alexandria
193 Pelusion-Ashkelon
194 Pelusion-Byblos
195 Pelusion-Dor
196 Pelusion-Kition
197 Pelusion-Paphos
198 Puteoli-Carthage
199 Puteoli-Messina
200 Puteoli-Motya
201 Puteoli-Ostia
202 Rhodes-Alexandria
203 Rhodes-Caesarea
204 Rhodes-Gelidonya
205 Rhodes-Hellespont
206 Rhodes-Karpathos
207 Rhodes-Marsa Matrouh
208 Rhodes-Megiste
209 Rhodes-Paphos
210 Salamis-Byblos
211 Salamis-Dor

62 Gelidonya-Apollonia	137 Malta-Messina	212 Samonion-Kimaros
63 Gelidonya-Karpathos	138 Malta-Motya	213 Sidon-Holmoi
64 Gelidonya-Korakesion	139 Malta-Zante	214 Sidon-Kition
65 Gelidonya-Kyrenia	140 Marsa Matrouh-Alexandria	215 Sidon-Paphos
66 Gelidonya-Marsa Matrouh	141 Marsa Matrouh-Gelidonya	216 Syracuse-Motya
67 Gelidonya-Menelaus	142 Marsa Matrouh-Karpathos	217 Tyre-Kition
68 Gelidonya-Paphos	143 Marsa Matrouh-Kommos	218 Tyre-Kommos
69 Gelidonya-Rhodes	144 Marsa Matrouh-Menelaus	219 Zante-Apollonia
70 Hadrumete-Malta	145 Marsa Matrouh-Rhodes	220 Zante-Euesperides
71 Hadrumete-Meninx	146 Megiste-Alexandria	221 Zante-Kriou
72 Hadrumete-Motya	147 Megiste-Rhodes	222 Zante-Leptis Magna
73 Hellespont-Gaza	148 Menelaus-Apollonia	223 Zante-Malta
74 Hellespont-Rhodes	149 Menelaus-Gelidonya	224 Zante-Messina
75 Holmoi-Alexandretta	150 Menelaus-Karpathos	

Appendix 2 List of coastal sailing stretches

An index map of all coastal sailing stretches is shown in Fig. 25, followed by a listing of the coastal stretches measured for potential sailing mobility. Datasheets for each coastal stretch are part of the research data for this study and can be found at https://doi.org/10.17632/hzbg2wyjxb.1.

Fig. 25 Coastal sections mapped for coastal sailing mobility (D. Gal).

1. Alexandretta to Byblos
2. Alexandretta to Holmoi
3. Alexandria to Marsa Matrouh
4. Amos to Ermoupolis

14. Holmoi to Korakesion
15. Korakesion to Gelidonya
16. Karpasia to Acamas
17. Leptis Magna to Meninx

5. Apollonia to Euesperides
6. Ashkelon to Byblos
7. Ashkelon to Pelusion
8. Byblos to Alexandretta
9. Byblos to Ashkelon
10. Eperos to Leptis Magna
11. Ermoupolis to Kriou
12. Euesperides to Eperos
13. Gelidonya to Amos
18. Messina to Puteoli
19. Menelaus to Apollonia
20. Meninx to Hadrumete
21. Marsa Matrouh to Menelaus
22. Pedalion to Acamas
23. Pelusion to Alexandria
24. Puteoli to Ostia
25. Samonion to Kimaros
26. Syracuse to Motya

Appendix 3 Example data sheets

Data sheets for direct passages

Three datasheets are suggested as examples for potential sailing mobility in relation to the prevailing winds. The passage from Paphos to Rhodes (Online Resource 1) is an example of a contrary wind passage. The passage from Rhodes to Paphos (Online Resource 2) represents passages with following prevailing winds. The passage from Alexandria to Paphos (Online Resource 3) is representative of cross-wind passages.

Coastal sailing datasheets

A coastal sailing datasheet for the south coast of Crete between Ermoupolis and Kriou (Online Resource 4) is suggested as a sample of a coastal sailing contrary to prevailing winds. A second sheet for the coastal stretch between Ashkelon and Byblos (Online Resource 5) is representative of a coastal sailing stretch that lies perpendicular to prevailing winds.

All of the above suggested datasheets can also be found in the published research data.

Appendix 4 Glossary of nautical terms

Beating	See points of sail
Coastal sailing	The mode of sailing short daily runs along a coastal section exploiting the daily breeze cycle
Direct passages	The mode of continuous open water sailing between departure and destination points
Distance ratio	The ratio between the distance sailed and the navigation distance. Higher ratio values indicate upwind sailing and increasing difficulties in navigating

Beating	See points of sail
Distance sailed	The actual distance over ground sailed between the departure and destination points. This is usually more that the navigation distance
Downwind	See points of sail
Duration	The time spent sailing the passage expressed in decimal days
Implausible passages	The subset of simulated passages that do not meet one or more of the hypothetical criteria defining the mariners' limits of reasonability and safety
Mobility coefficient	A measure of potential sailing mobility representing the proportion of the number of days per month in which a sailing departure would complete as a plausible passage. This is normalized to a maximum value of 1 for all months of the year. The inverse of the coefficient (1 minus the coefficient) represents the proportion of the month potentially spent waiting for an opportunity to sail
Navigation distance	The shortest possible distance to sail between departure and destination points. In cases where the orthodromic distance line does not cross land the navigation distance and the orthodromic distances are equal
No sail sector	See points of sail
Orthodromic distance	The shortest possible distance between the departure and destination points of the passage. This line may cross land and therefore it may be less than the navigation distance (i.e., the shortest distance possible to sail). Also known as the great circle distance
Passage VMG (velocity made good)	The effective speed of the passage based on passage duration and the shorted possible sailing distance (navigation distance) for the passage
Plausible passages	The subset of simulated passages meeting the hypothetical criteria defining the ancient mariners' limits of reasonability and safety
Points of sail	Description of the sailing limits and characteristics in relation to the true wind angle (TWA). Following are the points of sail for a ship with a single loose footed square sail, provided by the simulator: -No sail sector defines the sector in which sailing is not possible – 0 to 77° TWA -Beating is between 77 and 107° TWA which is the sector in which the sail configuration is for close hauled sailing -Reaching is between 107 and 160° TWA which is the sector with wind on a rear quarter -Downwind is between 160 and 180° which is the sectors in which the sail configuration is for running before the wind
Reaching	See points of sail
Ship speed (Avg./max.)	Average or maximum speed of the ship over ground (SOG) throughout the passage. This will normally be greater than the passage VMG due to the distance sailed being more than the navigation distance
Tacking ratio	The ratio between the numbers of simulated tacks performed during the passage and the navigation distance. The ratio represents the number of tacks per nautical mile. This measure is an indicator to the degree of upwind sailing
True wind angle (TWA)	The angle between a ship's bow and the true wind

Beating	See points of sail
True wind speed (TWS)	The speed of the true wind encountered during the simulated passage as might be measured by a stationary observer
Velocity made good (VMG)	See passage VMG or windward VMG
Waiting (Days)	Days spent waiting for favourable wind. These are the days in which a simulated departure would have culminated in a implausible passage. Statistics are shown for both total monthly waiting days and maximum consecutive waiting days
Windward VMG	The effective velocity of the ship achieved by tacking to advance in the direction of the wind

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