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– ARTICLE –

Experimental Voyages by Real and Virtual Traditional Canoes of the Kula Area, Papua New Guinea, Provide Insights into Ancient Sailing Technology of the Pacific Ocean and for the Settlement of Polynesia

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ABSTRACT

The sailing performance of traditional and ancient Pacific canoes has been a subject of on-going study and debate. In 2002 the anthropologist, Frederick Damon made a voyage across the Massim, Papua New Guinea, in a traditional Kula canoe, and recorded the journey (Damon 2017). This provided an opportunity to test whether theoretical modelling of canoe sailing performance can be realistic. The voyage of the real canoe has been closely matched by the simulated voyage of a virtual canoe of similar design in the same recorded weather. The experiment shows that the science of sailing can be applied to archaeological canoe remains and, with this possibility in mind, the design of the virtual canoe incorporated technical features of hulls and sails found in pre-European Polynesia. The experiment supports the identification of three technological innovations that enabled colonising canoes to sail upwind to East Polynesia. Two innovations already known were the Oceanic spritsail and the double canoe (Blust 1997, Di Piazza 2015). We propose that the third was a hull with a V-shaped underwater profile that generated hydrodynamic lift to windward. These innovations could have had separate origins but were integrated as a package prior to the discovery of East Polynesia. Such canoes could make return voyages to and from known destinations. The Damon voyage also demonstrates difficulties and hazards of voyaging directly downwind.

Keywords: voyaging canoes, sailing capability, simulation, migration, East Polynesia

INTRODUCTION

The colonisation of East Polynesia was the last remarkable episode of maritime migration in the remote islands of the Pacific Ocean but the sailing technology involved has not been well understood (Irwin 1992). Previously there was a longstanding navigational debate about how indigenous ocean sailors could find their way at sea without instruments, chronometers or maps, but this was solved by experimental voyaging by scholars and sailors in the late 20th century (Finney 1994, Gladwin 1970, Lewis 1972). Currently, there is another issue concerning the sailing capability of the canoes that is still to be resolved (Thomas 2021). Two currently debated propositions are (1) whether migration canoes could sail to windward, and (2) the speed at which they could make passages over long distances at sea (Anderson 2017, Irwin and Flay 2015). This issue affects our understanding of migration insofar as canoes capable of sailing upwind could have made return voyages of exploration followed by planned migration (Irwin 1992), whereas those constrained to downwind sailing (Goodwin *et al.* 2014) would have made risky one-way voyages into the unknown.

The debate has been in stalemate due to the lack of material remains of boats, but some recent archaeological discoveries in New Zealand including the Anaweka *waka* (canoe), which dates from the late 14th century (Johns *et al.* 2014), provide a window into early East Polynesian technology. This elite canoe reconstructs as a sophisticated composite planked canoe at least 14 metres long (Irwin *et al.* 2017), and it has a carved image of sea turtle that evokes the rich cultural symbolism of tropical Polynesia. There are no remains of ancient sails, but the diverse sails of East Polynesia described by early European sailors and a few from the late 18th century held in museum collections (Hiquilly *et al.* 2009) represent the late pre-European period, and their shared technology implies a common ancestry, which is supported by historical linguistics (Di Piazza 2015).

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To investigate the nature of early migration the sailing performance of traditional and ancient Pacific canoes has been a subject of on-going study in archaeology and engineering at the University of Auckland (Jackson and Bailey 1999, Irwin and Flay 2015, Jacobs 2003). The research involves testing sails in a wind tunnel and testing hulls by computational fluid dynamics and in towing tanks, and the results used as input to a velocity prediction program, VPP (Boeck 2012, Dudley 2020, Flay *et al.* 2008, 2019, Murano 2016).

An opportunity arose to test the realism of the VPP methodology for a traditional Kula outrigger canoe of indigenous design and construction. In 2002 the anthropologist Frederick Damon took an open sea voyage of 225 km between Koyagaugau (Dawson) and Muyuw (Woodlark) Islands in the Massim region of Papua New Guinea, made in three stages during July 4–15, 2002 (Figure 1). The voyage was in an 11 metre traditional canoe essentially the same as used in the Kula Ring at the time of Malinowski's famous book *Argonauts of the Western Pacific* (1922). The same voyage was simulated in 2020 in the same recorded weather, in a virtual canoe of comparable type (Dudley 2020). The capability of the two canoes was closely matched and the comparison showed theoretical modelling of sailing performance was realistic in this case. On this voyage the canoes sailed against the wind, across the wind and downwind between 75°–180° to the true wind angle making average speeds for the different legs between 4.5 to 5.5 knots (8.3–10.2 km/hr).

The virtual canoe included design elements derived from East Polynesia which inform us about the sailing technology involved in the colonisation of East Polynesia. The hull was modelled on the early Anaweka canoe, and wind tunnel testing shows that a late pre-European Māori sail collected in New Zealand during the Cook voyages and held in the British Museum, Oc NZ, 147.7, (Hiquilly *et al.* 2009) was similar and aerodynamically more powerful than the Massim lugsail. Finally, the real canoe experienced problems that demonstrate the difficulty and hazards of sailing directly downwind in such craft.

SEAFARING IN THE MASSIM AND THE KULA RING

The Massim comprises the islands at the eastern end of New Guinea plus the adjacent mainland coast and was recognised as a culture area by social anthropologists around the turn of the 20th century (Haddon 1894, Seligman 1910). The Kula was a vast cultural and maritime institution lo-

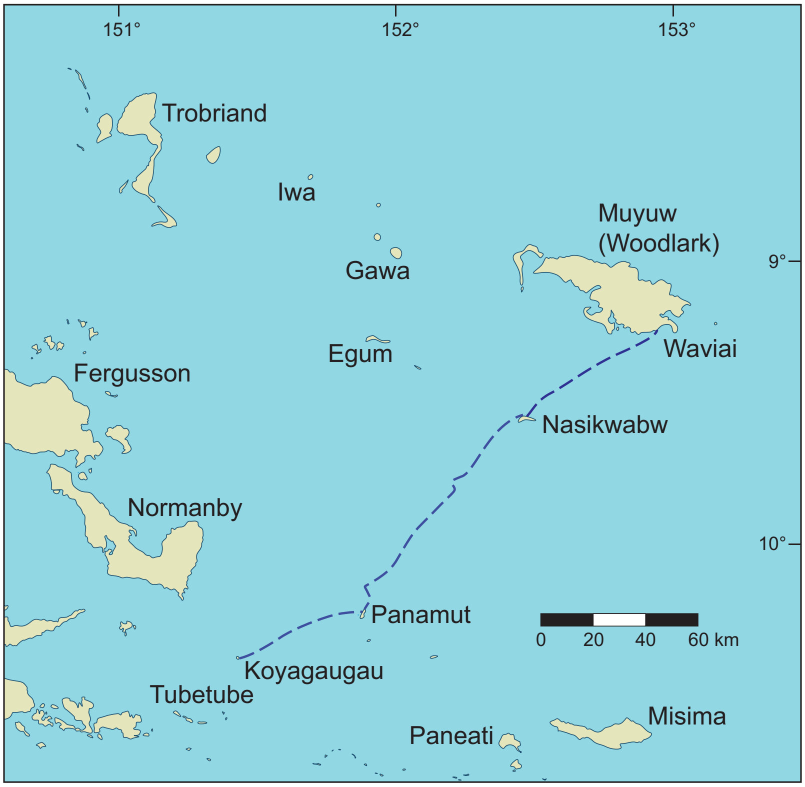

Figure 1. Two voyages are compared when sailing from Koyagaugau to Muyuw (dotted line on map) in the Massim area at the eastern end of mainland Papua New Guinea. The distance of 225 km was covered in three legs. One voyage, in July 2002, was undertaken in a traditional Kula canoe and recorded by the anthropologist Frederick Damon. The other voyage was a computer simulation made by a virtual canoe in the same weather in 2020. The design of the virtual canoe provides information about ancient Polynesian voyaging.

cated in the Massim and its most striking element was the exchange of shell valuables – armshells and necklaces – which circulated against each other (Malinowski 1922, Young 1983). The small island of Tubetube, with its near neighbour Koyagaugau, developed as a central node in the southern Kula in late prehistory (Irwin *et al.* 2019,). The people were expert sailors and transported obsidian from Fergusson Island and stone adzes from Muyuw (Woodlark) to the southern Massim and the Papuan coast (Irwin *et al.* 2019, Macintyre 1983, Shaw *et al.* 2021). Tubetube canoes sailed further than any others to articulate trade in the Massim, and the people were described as 'merchant venturers … laden for trade … but armed for combat' (Seligman and Strong 1906: 240).

Winds in the Massim are seasonal and so was inter-island voyaging. The southeast trade wind blows steadily from April to November and for the rest of the year the northwest monsoon prevails, but it is intermittent and brings gales. During the southeast season the breeze is fresh and becomes a near-gale a few days each month, so voyages in both seasons were often delayed (Lauer 1970). Commentators all describe sailing in the Massim as strategically downwind (from east to west) in the southeast, and back again with the change of season (Damon 2017, Malinowski 1922, Lepowski 1991). However, given its location, the canoes of Tubetube could sail across the wind to and from Muyuw, in both seasons.

Malinowski (1922) described two kinds of canoe in the Massim, *masawa* and *nagega* with different rigs and performance. *Masawa* were *inshore* canoes used on shorter voyages in sheltered waters around the Trobriand, Fergusson and Nomanby Islands lasting a few days with overnight stops (Lauer 1970). Elsewhere, the larger and distinctively carved and decorated *nagega* were used for longer voyages in the open sea and can be characterised as *offshore* canoes. Voyages from Tubetube to Muyuw used Egum and Nasikwabw (Alcestor) as stepping stones, also taking several days. Navigation was demanding and dangerous, as can be inferred from its associated magic and myth (Malinowski 1922). In modern times *nagega* were replaced on Tubetube by small diesel launches, but they survived longer on neighbouring Koyagaugau. It transpires that the canoe on which Damon sailed to Muyuw in 2002, was the last time that voyage was made by a canoe with a sail constructed of traditional materials (Damon 2017).

CONVENTIONAL POINTS (ANGLES) OF SAIL

No boat can sail directly into the wind and no informed scholar has suggested prehistoric Pacific voyaging canoes could sail at sea closer than 75° from the wind, so that zone is shown as *no-go* in Figure 2. When a boat is heading above 90°, it is in an *upwind* mode (going against the wind); but when it is heading from 90° to 180° it is going *downwind.* When the wind is coming from the side a boat is *beam reaching* (although in the diagram between 80° and 75°it is really *close reaching*). A *broad reach* has wind coming from aft of the beam but, beyond approximately 150°, a boat is said to be *running* with the wind from behind. The cut-off between reaching and running is at around 150° because that is where speed reduces and other circumstances arise (below).

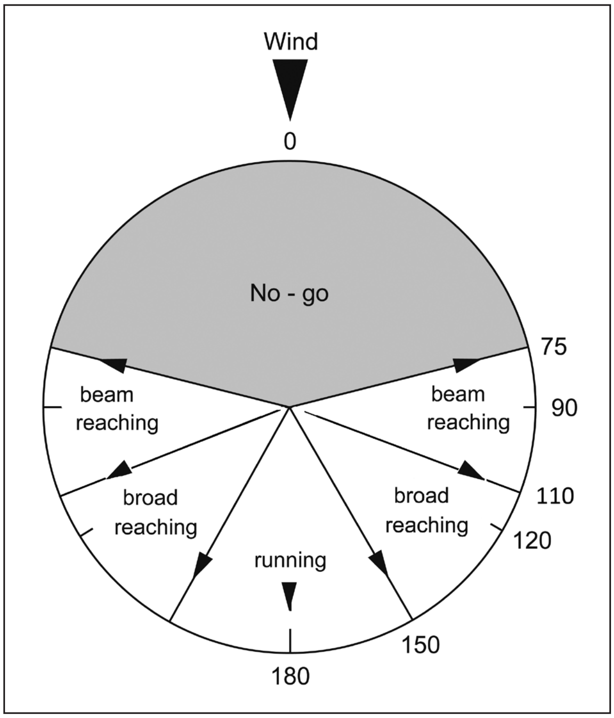

Figure 2. Conventional points of sail for traditional Pacific sailing canoes. Wind angles indicate the direction in which a canoe is heading in relation to the true wind direction. Note that, in sailing, the *true wind* is the speed and direction of wind observed by a stationary wind instrument (anemometer) while the *apparent wind* is the wind observed on a moving craft, which is composed of the combined speeds and directions of the craft and the true wind.

THE KOYAGAU NAGEGA CANOE USED IN THE 2002 VOYAGE

Nagega were observed on Tubetube by G. Irwin in 1980 and described in detail by Damon (2017) on Muyuw where they are known as *anageg*. They had a moderate V-shaped hull comprising a low dugout underbody with raised planks and carved prow boards at both ends, and an outrigger about the same length as the hull (Figures 3–6). They had a rectangular lugsail of intricate wooden and fibre construction that was hoisted up a mast. The outrigger was always kept to windward when sailing and the canoe *shunted* (reversed direction, exchanging bow for stern), when changing direction relative to the wind direction. The dimensions of the *Lavanay*, owned by a Koyagaugau man named Duweyala on which Damon sailed, are shown in Table 1.

Table 1. *Dimensions of the outrigger canoe Lavanay*

***Lavanay* measurements, 2002**	
Keel length, stright, end for end	10.7 m
Keel length, following the arc	11.85 m
Distance between two prow boards	8.37 m
Length of sail	8.5 m
Estimated width of sail	2.8 m
Mast length	8.74 m
Outrigger float length	11.32 m

Figure 3. The nagega *Lavanay* with a young man, Onosimo, at Ole, Koyagaugau, in July 2002. Photograph by F. Damon.

Figure 4. *Lavanay* at Panumut, a stepping-stone island on the 2002 voyage to Muyuw. Photograph by F. Damon.

Figure 5. Side view of a Koyagaugau *nagega* of similar dimensions to *Lavanay*, at Tubetube in 1980. Photograph by G. Irwin.

Figure 6. The Koyagaugau *nagega* under sail at Tubetube in 1980. Photograph by G. Irwin.

THE METHOD FOR MODELLING THEORETICAL CANOE SAILING PERFORMANCE USED IN THE 2002 VOYAGE

Sails

In 2008 an initial model canoe designed from ethnographic and historical sources by Irwin and Flay (2015) measuring 2.8 m long with a sail 2.0 m high, was built by R. May (2008) for wind tunnel testing (Fig. 7). This was a 1/5th scale model of a 14 m canoe, 1.2 m wide with a modest sail area of 18.5 m^2 sail reaching 10 m above sea level, that could be set up as either as a double canoe or with a single outrigger. The sail was designed as a generic, hypothetically "ancestral", Oceanic spritsail. It followed the triangular form of a late pre-European Maori sail collected by James Cook held in the British Museum (Oc, NZ 147), but curvature was added to the trailing edge, as seen elsewhere in Polynesia. Measurements were taken of the driving force coefficient, *Cdf*, as a function of the apparent wind angle, AWA, the side force coefficient, *Cs* (which affects leeway), and the rolling (or overturning) moment coefficient, *Crm*, (which affects stability), as functions of the apparent wind angle, AWA.

In 2016 F. Munaro (2016) tested five further models of Pacific sail shapes including a Massim lugsail, a 'crab-claw' lateen sail as used on the Papuan coast and Santa Cruz, and three different East Polynesian sails held by the British Museum and believed to be of late 18th century age. The model sails tested were all of the same height, ~2.0 m, but they were of different shapes and sail areas. To achieve a valid comparison of their performance, the mast heights and sail areas of full-size sails were scaled to share the same value of the rolling (overturning) coefficient, *Crm* (Dudley 2020), so that they would all have similar risk of capsize.

The aerodynamic properties of the Massim lugsail are shown in Figure 8 in graphs of the driving force coefficient, *Cdf*, the side force coefficient, *Cs*, and the rolling moment coefficient, *Crm*, all as functions of the apparent wind angle, AWA. The driving force coefficient is also shown for the Māori sail probably collected during the Cook voyages and now held by the British Museum. This late pre-European Polynesian sail was similar but more powerful than the Massim one.

Hulls

The hydrodynamic properties of three representative traditional canoe hull forms 12.0 m long (Fig. 9) were analysed by computational fluid dynamics, CFD (Boeck *et al.* 2012), and 1/10th scale models of these were tested by Flay in a towing tank at the University of Newcastle in 2013. The results were in close agreement and it was found that canoe hulls with V-shaped underwater cross-sections were more capable of sailing upwind that U-shaped ones (Flay *et al.* 2019). The variability in hull performance was greater than in sail performance.

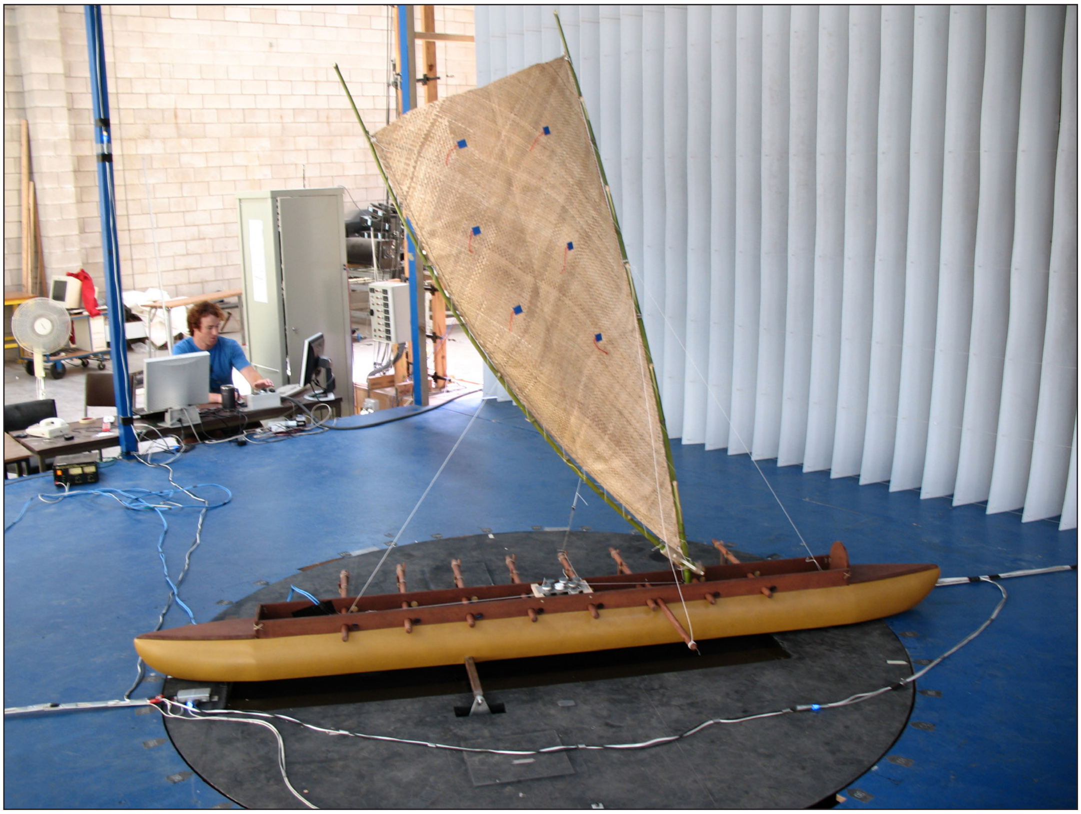

Figure 7. An Oceanic spritsail of a generalised East Polynesian form was tested at the Yacht Research Unit at the University of Auckland. It was mounted on a balance embedded in a turntable in the Twisted Flow Wind Tunnel. The model was tested at angles to the wind between 30°and 180°, at 10° intervals. The trim was adjusted by small electric winches on the model using tell-tails on the sail to get the trim resulting in the largest driving force. The sail was made of finely-woven pandanus and the spars were bamboo.

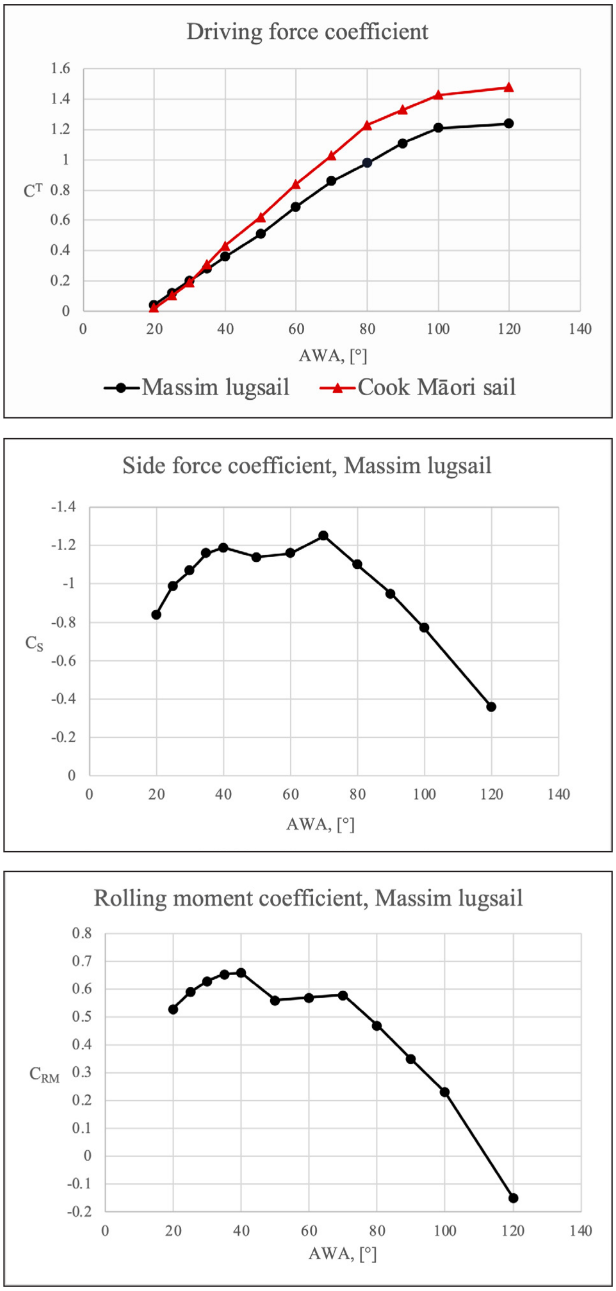

Figure 8. Graphs showing the driving force coefficient, *Cdf*, the side force coefficient, *Cs*, and the rolling moment coefficient, *Crm*, all as functions of the apparent wind angle, AWA, for a 2.0 m high model Massim lugsail mounted on a 2.8 m hull. The driving force coefficient is also shown for the Māori sail in the British Museum probably collected during the Cook voyages.

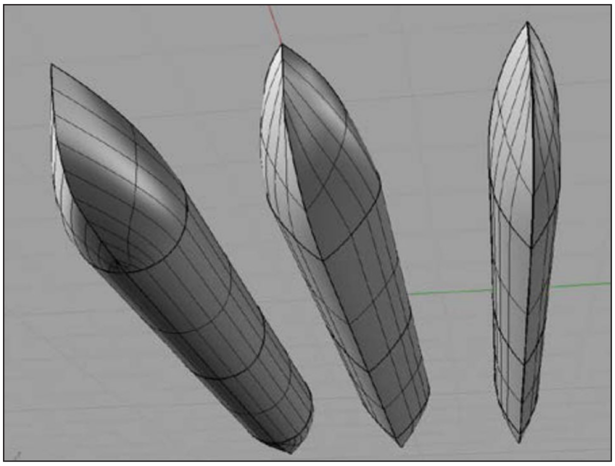

Figure 9. Three reconstructed hull shapes, U, V1 and V2, which represent a range of forms known among both ethnographic and archaeological Pacific canoes. The V1 form was 12.0 m long with a beam of 1.20 m at the waterline. From Boeck *et al.* 2012.

A suitable hull for the virtual canoe, which extended the comparison to East Polynesia, was a 14 m version of the Anaweka canoe. A large plank of this canoe was found in New Zealand and dated to the 14th century AD (Johns *et al.* 2014). The hull form was reconstructed by computer aided design, CAD, and found to be of a moderate underwater V-shaped section similar to the V1 form in Figure 9 (Irwin *et al.* 2017). To match the Kula canoe we attached an outrigger with a round cross section of similar shape to the U form in Figure 9 designed by scaling the 14 m-long U-shaped hull to 90% of its length and 30% of the cross-section. This produced the canoe design shown in Figure 10A.

Figure 10B shows the plan of the 1/5th scale model of the Tubetube lugsail tested in the wind tunnel by Munaro (2016). It could be expected that the extra length of the virtual canoe (14.0 m as opposed to 10.7 m) could result in a small speed advantage in hull speed of up to a knot. However, this advantage is negated by the smaller sail area of the virtual canoe. The ratio of length to width of *nagega* sails at 3:1 gives an area of approximately 23.8 m^2 for the *Lavanay*, based on the sail length of 8.50 m (Table 1). But the virtual canoe has a smaller sail area of 16.5 m^2 (Dudley 2020), which is a conservative calculation that derives from using the same maximum rolling coefficient, *Crm*, for all of the sails types tested.

Velocity prediction program, VPP

VPPs are a conventional mode of performance analysis in yacht design which incorporate aerodynamic and hydrodynamic data and predict the speed of vessels in different wind speeds and at different wind angles. In the course of our research, VPPs have been calculated for a range of outrigger and double-hulled canoes of various shapes and sizes in combination with a range of different sails (Dudley 2020). The VPP for the virtual 14 m outrigger canoe used in the 2002 Kula voyage shows predicted boat speed, by wind speed, by true wind angle, TWA, including leeway (Figure 11). To take one example of the use of this chart, it can be seen that in a wind speed of 19.4 knots (10 metres/second)

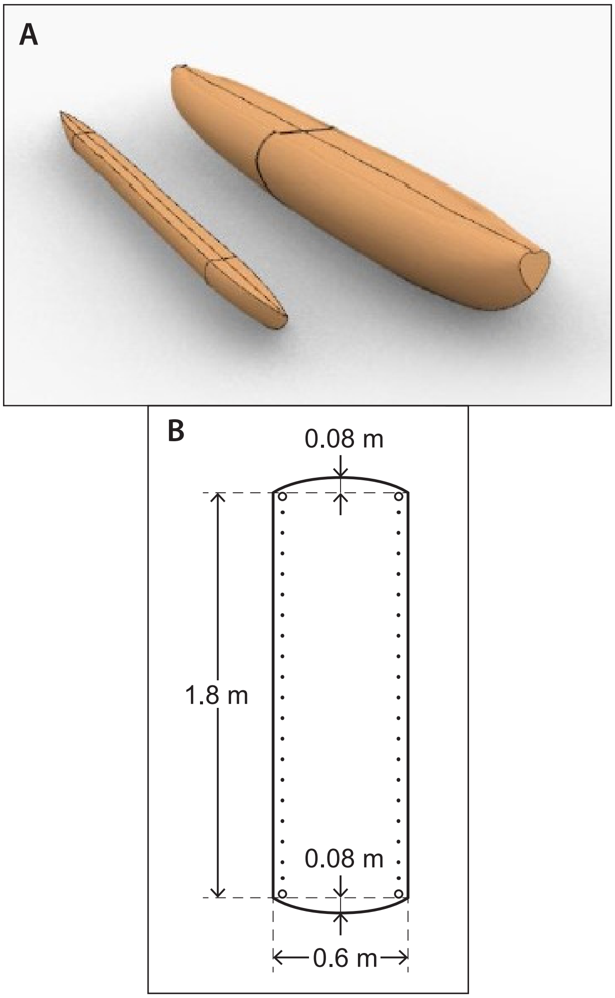

Figure 10. A: The virtual canoe had a moderate V-shaped underwater hull profile and a single U-shaped outrigger 90% of the length of the hull and 30% of its beam, set with its centreline 1.5 m from the main hull. B: The plan of a model sail 2.0 m high made of pandanus, that was tested in the wind tunnel on a hull 2.80 m long, and scaled to match the full-size virtual canoe.

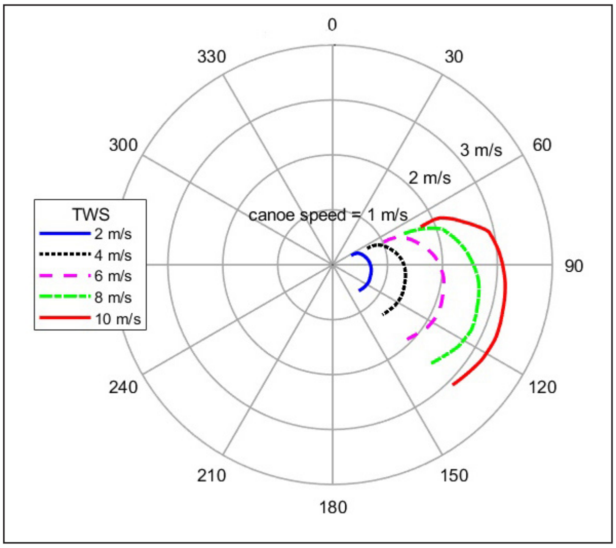

Figure 11. Polar plots of the speed of the virtual canoe as a function of true wind angle,TWA, including leeway, for true wind speeds, TWS, of 2, 4, 6, 8 and 10 m/s (metres per second). 1 m/s = 1.94 knots = 3.6 km per hour. To take one example of the use of this chart, it can be seen that in a wind speed of 19.4 knots (10 m/s) at a true wind angle, TWA, of 90° the canoe is sailing at 6 knots; in 15 knots (8 m/s) of wind at 75° TWA, the speed is 4.3 knots (2.3 m/s).

at a true wind angle, TWA, of 90° the canoe is sailing at 6 knots, which is a close match of the actual voyage (below). This canoe has the theoretical capability to sail upwind at a TWA of 75°, which it did on Leg 3 of the voyage.

Weather

The weather data used in this simulation was downloaded from the Copernicus Programme, Climate Data Store (CDS), which stores worldwide weather data since 1979. More specifically, the data used are hourly values derived from ERA5 near-surface wind speed. (Copernicus, 2020). The cell-size for the observations is 0.25 x 0.25 in degrees, which corresponds to about 28 km². The weather in this cell was generalised, and localised squalls that occurred were not apparent in the data. Waves and sea currents were not included.

Routing software

The track of the simulated canoe was directed by the *qtVlm* routing software developed by Meltemus (2020a, 2020b). This software is designed for sailing vessels and is able to calculate and optimise the best route to follow at sea towards a designated target using meteorological data. Normally this software is used by sailing vessels to find the optimal routes through changing weather patterns during voyages lasting weeks, rather than days; however, it served the purpose of our experiment. The simulation parameters in *qtVlm* were set to maximum accuracy since the voyages were short. The wind patterns used were the same wind patterns as encountered by Damon, sampled at intervals of one hour.

THE 2002 VOYAGE

On board the *Lavanay* there were skilled sailors. Damon (2017:11) admits to having had little sailing experience but he was committed to the voyage and well equipped with a camera, watch, magnetic compass and GPS receiver, with which he recorded his position at frequent intervals as the voyage proceeded. He could not record the wind direction or velocity or the angle of the boat to the wind. However, we can estimate these from meteorological records of weather from the time of his voyage and by comparison with data from the virtual canoe.

By contrast, on board the virtual canoe there was no human intelligence. On each leg of the voyage it set off for the designated target at its maximum calculated speed determined by the VPP, steering the optimal course through the weather as programmed by the routing software. It paid no heed to daylight or darkness or to the sea conditions or to shallow water or reefs encountered along the way.

By sailing a *nagega* together with a virtual canoe of a comparable type on the same voyage we were able to test the realism of the methodology and measure canoe performance.

Leg 1

From the islet of Ole, Koyagaugua, Leg 1 to Panamut was sailed under clear skies in a moderate breeze (13–18 knots on the Beaufort Scale) (Fig. 12). Only one steering oar was required. This passage was mostly sailed by reaching downwind at a true wind angle, TWA, of 110–120°, so the velocity made good, VMG, was reached when sailing straight to the destination for both vessels. The maximum speed reached by the Kula canoe was 6.5 knots (12.0 km/hr) (Damon 2017:10). The average speed of the virtual canoe was 5.6 knots (10.4 km/hr) over a distance of about 50 km. The passage was mainly uneventful although the record for the 12.18 pm GPS position of the Kula canoe probably has an error for longitude. On arriving at Panamut, the Kula canoe slowed down to pass through the fringing reef, whereas the virtual canoe naively arrived at full speed, five minutes earlier. The actual performance of the *nagega* was remarkably similar to the predicted performance of the virtual canoe.

Leg 2

July 6, 2002 was a windy and cloudy day, and the Kula canoe needed to use a second steering paddle, one in front of the other at the stern, to hold a steady course. The distance was 96 km (52 nautical miles) and the course required to clear the western end of Nasikwabw was around 035° (True) (Fig. 13). The canoes left at 4.40 am, before dawn, and much of Leg 2 was out of sight of land and steering was by the direction of the waves, wind and sun, although Damon had a magnetic compass on board. In the confusion of getting under way from the island in the dark, the GPS was misread at 5.43 am but probably correctly at 6.22 am after the canoe had been heading north and sailing

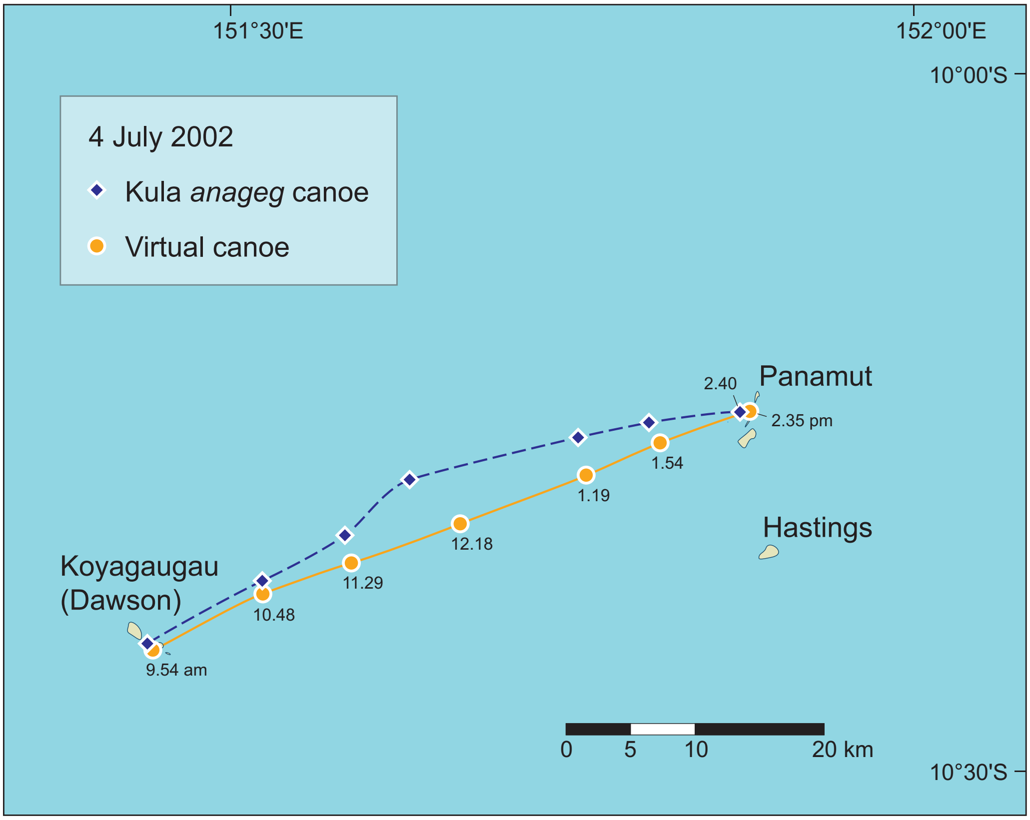

Figure 12. Leg 1, a distance of about 50 km, was sailed at a true wind angle of 110°–120° at an average speed of approximately 5.6 knots (10.4 km/hour). The actual performance of the *nagega* was remarkably similar to the predicted performance of the virtual canoe.

Figure 13. Leg 2 was a distance of 96 km. The wind direction shifted from 170° to 190° during the day (180° is from due south), and the average wind speed increased from 19 to 22 knots (35 to 41 km/hour). There were gusts and squalls. The virtual canoe travelled around 54 sea miles at an average speed of approximately 5.6 knots (10.4 km/hr) at a true wind angle (TWA) of around 135°. The *nagega* sailed nearly directly downwind in the early morning and at around 160° TWA between 7.00 and 9.00 am. It experienced some dangerous mishaps during the voyage.

directly downwind. Then it settled down on course for Nasikwabw. Thereafter the two canoes tracked at much the same speed.

We know from the Copernicus CDS records that the wind shifted from 170° to 190° in direction during the day (180° is due south), and increased from an average speed of 19 to 22 knots (about 35 to 41 km/hr), and there were gusts and squalls through the day, when the wind speed abruptly increased. The normal long south-easterly swell persisted through the day, and there would have been shorter waves caused by the southerly wind, and these waves would have been crossed by the faster-travelling swells.

Leg 2 involved broad reaching and periods when the *nagega* sailed further downwind and throughout the morning the tracks of the two canoes diverged. The simulated canoe was technically unable to sail directly downwind to match the course of the real canoe because the wind tunnel data only went to an apparent wind angle, AWA, of 120°, true wind angle, TWA, around 135° (Figure 11). In the meantime the real canoe was sometimes running downwind at more than 150° TWA with the wind behind. However, the canoes had similar speeds and at 10.59 am after six hours sailing they were about two km apart. The higher sailing angle of the virtual canoe meant it would have passed to the east of Nasikwabw, missing the island, so at 10.00 am the routing software initiated a dog-leg in the course until it could lay (access) the target island again sailing at 120° AWA from the wind.

From around 9.00 am the *nagega* was hard-pressed by rising wind and waves and began to experience difficulties. It did not reduce sail, but had the sail set as low as possible on the mast for stability and to reduce the angle of heel (Figure 14). The average speed of the real canoe is calculated as 6.8 knots between 8.42 and 9.30 am and recorded compass courses suggest it sometimes veered off course. At 9.30 am the *nagega* was overpowered by a gust or squall. Damon (2017: 13) reports yelling on board, '… the mast and sail was radically changed, and we seemed to head into the waves close to a 120° direction' [magnetic compass direction]. The canoe had evidently *rounded up* into the wind (see below). After about 10 minutes the crew was back in control, but just before 11.00 am, '… there was another episode like this, heading off at 60–70°. Right after we returned to our course the mast snapped' (Damon 2017: 13). The canoe drifted north for about an hour while the crew rigged up a new mast to support the sail and it was under way again by 12.15 pm. The *nagega* continued under jury rig to Nasikwabw.

Leg 3

There was a delay of more than a week on Nasikwabw while a replacement mast was made (Fig. 15). Leg 3 of 60 km was sailed on 15th July 2002, mostly beam reaching at around 90°–100° in a moderate breeze, but at different times both canoes were sailing upwind at higher angles and at slightly slower speeds as predicted by the VPP. The canoes departed at 9.37 am and the virtual canoe, as programmed, took off at full speed and sailed upwind at an angle of around 75° until 10.35 and then headed straight towards Waviai on the south coast of Muyuw. But the real canoe was slow to get under way. It took a more northerly course and fell behind so by 10.35 it was about 5 km (2.7 nautical miles) west and downwind from the virtual canoe. From 10.35 until 15.43 the canoes followed generally similar tracks beam reaching at much the same speed. But from 15.43 the real canoe sailed the rest of the leg at an upwind angle of around 75° at a slightly slower speed while it made up the lost ground and negotiated the coral reefs along the exposed south coast of Muyuw. Damon writes (2017: 14): '… as we veered towards our destination, the wind came increasingly from our front …. I began to think we were sailing much closer to the wind than Finney [1994] thought Oceanic craft were capable'. After its slow start the real canoe arrived at Waviai an hour and a quarter after the virtual one, but their performance was very comparable. The real canoe sailed at speeds close to those predicted by the VPP, at an average speed of 4.7 knots while beam reaching in a wind speed of around 15 knots (~8 m/s), and at around 4.0 knots at a higher upwind angle at the end of the journey.

Figure 14. 'The sail is very low on the mast. This is shortly before the mast snaps' (Damon pers. comm 2021).

DISCUSSION

Two propositions currently under debate are whether migration canoes could sail upwind and make fast passages over long distances at sea (Anderson 2017: 224).

Upwind sailing

In order to sail upwind, a sail must develop sufficient driving force in the desired direction, but the aerodynamic side force which comes with the driving force and causes

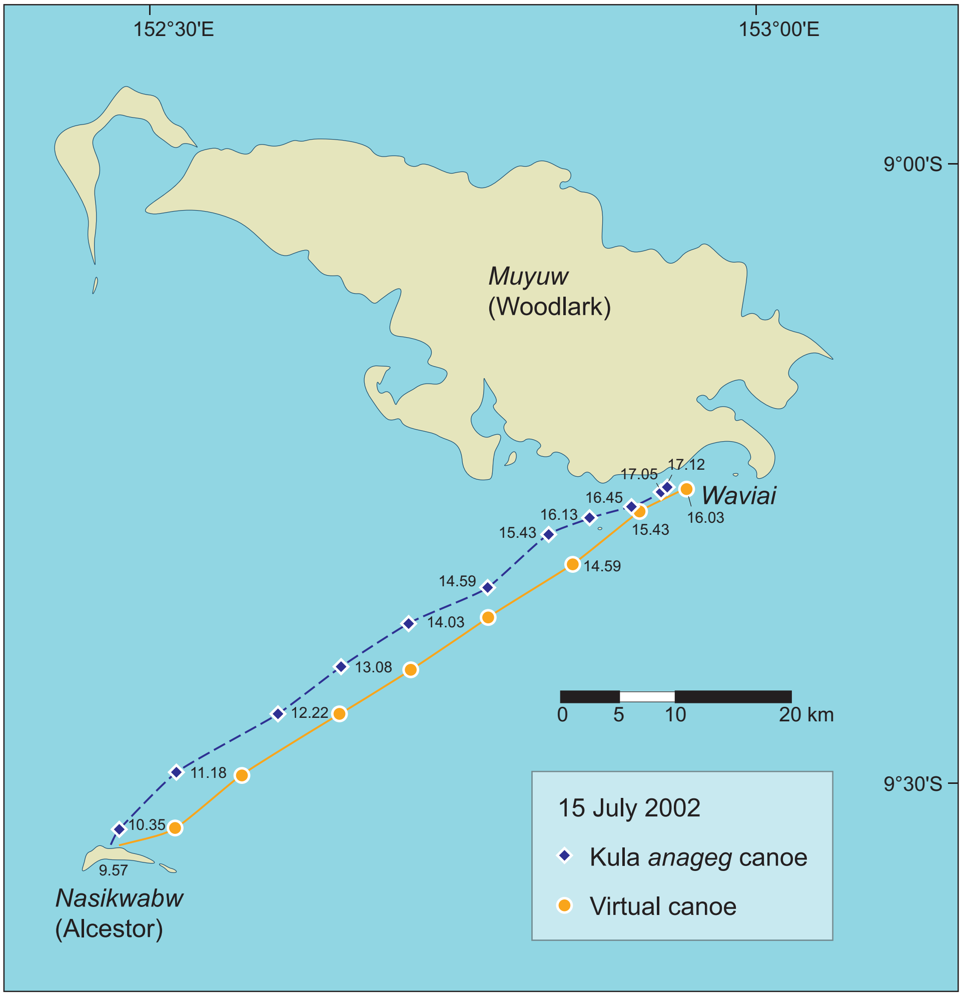

Figure 15. Leg 3, a distance of 60 km, was a beam reach at true wind angles of around 90° for much of the way, but both canoes sailed upwind at different stages of the journey. The average speed of the real canoe was 4.5 knots (8.3 km/hr); however, it was slow to get underway from Nasikwabw and fell behind and to leeward of the virtual canoe, but they sailed at similar speed in open sea. From 15.43 the real canoe finished the trip to Waviai sailing upwind at around 75° to make up the lost ground as it negotiated the reefs along the exposed coast of Muyuw, arriving one and a quarter hours later.

leeway, has to be balanced by the hydrodynamic side force (lift) generated by the canoe hull. As described above, computational fluid dynamics, and towing tank tests show that V-shaped canoe hulls are better able to generate lift than U-shaped ones (Boeck *et al.* 2012, Flay *et al.* 2019). Both of the canoes in this study had hulls with a moderate V-shape and for periods on Leg 3 they both sailed upwind at 75°.

The result is pertinent to East Polynesia because the hull of the virtual canoe was based on a moderate V-shaped reconstruction of the late 14th century Anaweka canoe from New Zealand (Irwin *et al.* 2017, Johns *et al.* 2014). Voyaging canoes with similar hulls recorded on Cook's first and third voyages included a *pahi* in Tahiti and a *tongiaki* in Tonga (Haddon and Hornell 1997).

We also found that the driving force of the Māori sail is slightly better than the Massim lugsail. (Figure 8). There are no known ancient sails, but the diverse shapes seen by early Europeans in the different islands of East Polynesia, shared the same basic technology and had fairly similar performance in the wind tunnel (Munaro 2016), which adds weight to the suggestion that they shared a common ancestry (Irwin and Flay 2015).

With regard to speed, the three legs of the Kula voyage were made in a range of conditions at average speeds for the legs between 4.5 to 5.5 nautical miles per hour. These figures match the earlier estimates of Lewis (1972) and Finney (1977) for Pacific voyaging canoes in general.

Downwind sailing

Kula *nagega* were seaworthy sailing vessels well suited to making open sea passages in the Massim lasting a few days in predictable seasonal conditions, but they were not large enough to carry a migrant group with its cargo on ocean passages of several weeks with occasional severe weather. However, their sailing capability is comparable to larger vessels and the events of Damon's voyage provide an opportunity to discuss problems shared by larger canoes on longer voyages. During Leg 2 when the *nagega* was running downwind it was heading into trouble of a kind well known among sailing vessels that would have been an issue in pre-European times (Anderson 1996). With the wind and waves coming from behind on at least two occasions during gusts or squalls the canoe *rounded up* into the wind or *broached*. Essentially, the canoe veered across the leading face of a wave and turned to lie broadside to the waves and facing more into the wind. Fortunately, the waves were not breaking so the canoe did not swamp, but eventually the mast broke.

Rounding up and broaching happens to sailing boats of almost any size, given the conditions, and it often results from the loss of directional control when the side force on the sail and hull overpower the force provided by the rudder. In a gust, the wind force on the sails can increase with the square of the velocity, but the counteracting force from the velocity of water over the rudder does not increase because, at that moment, the boat speed has not yet increased.

There are issues caused by waves. Damon (2017: 13) says of Leg 2: '… the wind remained strong the whole way; as we got closer to Nasikwabw, waves towered over us as they came almost from our rear'. Waves are caused by local winds whereas swells are the product of wider seasonal weather patterns. Swells are longer and move faster than shorter local waves and when the peaks of the waves and swells cross each other it creates a confused sea which can create problems for steering. Also, more subtly, water rotating in the crest of waves moves in the same direction as the rudder of a boat travelling downwind, and reduces the directional force of the rudder as the crest of the wave passes due to the reduction in the relative velocity of the water onto the rudder (Fig. 16).

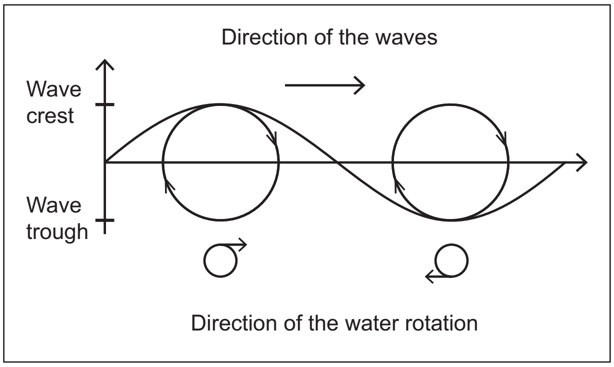

Figure 16. Waves are created by transfer of energy from wind to water. Water does not move as a wave passes unless it breaks, but in open sea there is an orbital movement of water in a wave close to the surface. The size of the circular orbit decreases rapidly with depth and is gone at about half a wavelength below the surface. The rotation can reduce the effectiveness of the rudder of a boat accelerating down the face of a wave.

Broad reaching obliquely across the waves and wind is faster, safer and more comfortable than running with them. In daylight it is usually possible to steer away from breaking waves in windy conditions, however, it is more dangerous to sail downwind at night when one cannot see what is coming from behind. Goodwin *et al.* (2014) have proposed a theory of early East Polynesian colonisation by downwind voyages during periods when there were climatic shifts in the patterns of prevailing winds. Insofar as this invokes broad reaching or with running more directly downwind in good weather, we have no issue. However, experienced early navigators would have been wary of having to run directly downwind in bad weather.

CONCLUSIONS

We measured the sailing performance of a traditional offshore canoe of the Massim, and the closely-matched performance of the virtual canoe shows that theoretical modelling of sailing technology can be realistic.

We applied the results of the experiment to early migration voyages in East Polynesia by using the archaeological remains of the 14th century AD Anaweka canoe as a model for the hull of the virtual canoe and also by showing that the driving force of a Māori sail was better than the Massim lugsail (Fig. 8). The Massim canoe could sail at angles between 75°–180° to the true wind angle making average speeds for different legs between 4.5 to 5.5 knots (8.3 to 10.2 km/hr), and it follows that an East Polynesian canoe could do the same. This matches the earlier estimates of Finney (1977, 1994) and Lewis (1972) based on their experimental voyages.

The need for an upwind sailing capability was foreshadowed by simulated voyaging from West to East Polynesia by Di Piazza *et al.* (2007), who found wind patterns from Samoa to the Cooks became much more difficult to traverse than earlier voyages in Lapita times from Vanuatu to Fiji. Montenegro *et al.* (2014, 2017) concluded that advances in sailing technology were necessary for such voyages to occur and are explicit that intentional voyages from West to East Polynesia would be viable '… when undertaken with vessels capable of sailing efficiently against the wind' (Montenegro *et al.* 2014: 242).

The predictions of these simulations are consistent with the capability of canoes in this study and with a range of relevant additional canoe hulls and sails described elsewhere (Dudley 2020, Irwin *et al.* in prep). We are now working on the theory that the colonisation of East Polynesia was based on the prior coming together of three technological innovations into a new voyaging package. The first of these was the Oceanic spritsail, already identified on technological and linguistic evidence by Di Piazza (2015: 446) as an innovation by Proto-Oceanic (POC) speakers, and '… probably the vehicle used for the settlement of East Polynesia, some 800 years ago'. Wind tunnel tests show this type of sail was able to generate sufficient driving force to sail upwind (Figure 8). The second, probably more crucial, innovation was a hull with a moderately V-shaped underwater profile with enough hydrodynamic lift to sail upwind, as typified by the 14th century AD Anaweka canoe, which had a planked hull on a dugout timber underbody. The third innovation was the double canoe, as suggested linguistically by Blust (1997). Its extra load-carrying capacity for the long voyages of East Polynesia is often remarked, but VPPs also show that two V-shaped hulls generate more lift to windward than a single V-shaped hull with an outrigger (Dudley 2020). These innovations could have had separate origins but were integrated as a package prior to the discovery of East Polynesia. Moreover, canoes with the capability to reach central East Polynesia were able to reach all of the marginal islands (Dudley 2020).

By contrast, the canoes associated with the earlier spread of Lapita sites across Island Melanesia to West Polynesia probably had more limited capability. There are no archaeological remains of hulls of this age but the sail has been thought to be some kind of Oceanic lateen because of its wide distribution (Di Piazza 2015, Kirch 2000). The results of further testing of simpler canoes are presented elsewhere (Irwin *et al.* in prep) and it can be argued that Lapita canoes were able to negotiate the seasonal alternation of monsoonal and trade winds of the western Pacific but it became more difficult to sail beyond.

A final conclusion refers to the theory of colonisation by downwind voyaging during times of climate change when there were shifts in the patterns of the prevailing winds (Goodwin *et al.* 2014). Our view is that downwind migration in Polynesia was certainly possible but was unnecessary in terms of our results. One-way voyages by canoes that could not return were always dangerous (Irwin 1992). The settlement of New Zealand is one case where archaeological and genomic evidence support a major migration of the ancestors of the Maori to a known destination (Walter *et al.* 2017).

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