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– ARTICLE –

Three Late 18th Century CE East Polynesian Sails in the British Museum Collected from New Zealand, Tahiti and Hawaii (or the Marquesas) Reveal Regional Adaptations in Sailing Technology, and Insights for Early Voyaging

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Abstract

Three unique sails in the British Museum provide valuable information about sailing technology and practice in the late 18th century, CE, and insights into early East Polynesian migration. The sails were collected from New Zealand, Tahiti, and the third most probably from Hawaii or the Marquesas. Tacking double canoes were used in the settlement of East Polynesia, in combination with the Oceanic spritsail, and the sails reveal different adaptations that match patterns of interaction and isolation among the island groups as indicated by the movement of industrial stone. The Māori and Hawaiian/Marquesan sails were furthest apart geographically but remained the most similar in the isolated margins of East Polynesia, and both adapted to an increase in paddling and downwind sailing. The Tahitian canoe, located in central East Polynesia, remained better adapted for ocean voyaging, and shared structural elements with West Polynesia, potentially through the Cooks Islands. The paper describes sail forms, examines selected early historical drawings to see how they were used in the late 18th century and uses methods of wind engineering to estimate their sailing performance. The paper finds evidence for adaptive variation and change between sails with shared ancestry.

***Keywords*:** East Polynesia; Oceanic spritsail; Sailing technology; Pacific voyaging

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1. Introduction

The "Long pause" between the settlement of West and East Polynesia ended late in the first millennium CE with a burst of maritime migration through East Polynesia. In this region ocean area increases and land area decreases by orders of magnitude, and there are more contrary winds (Irwin 2008). Computer simulation has indicated that intentional voyages would be viable when undertaken with vessels capable of sailing efficiently against the wind (Montenegro, Callaghan, and Fitzpatrick 2014, 242). Indeed, this episode of ocean voyaging was characterised by a new kind of two-spar sail usually called the Oceanic spritsail, and double-hulled canoes were now involved as well as single canoes with outriggers.

In the centuries following the migrations, voyaging and interisland exchange continued in some regions, but diminished and stopped altogether in remote parts of East Polynesia. Coastal seafaring continued, but sailing technology and practice diverged in separate island groups. The three unique late 18th century CE British Museum (BM) sails have shared origins and illustrate regional adaptations.

The exact provenance of the sails has been lost, but the origins of two are not in doubt. The Māori sail was probably from the Cook collection (Starzecka, Neich, and Pendergrast 2010) and is made of New Zealand flax (Phormium tenax). The second sail has the distinctive form of the Society Islands and parchment labels attribute it to Tahiti. The third sail is an East Polynesian type most like early drawings from Hawaii or the Marquesas (Haddon and Hornell 1997). The Hawaiian/Marquesan (HA/MQA) sail and the Māori sail are most similar structurally, but furthest apart geographically, and they evidently retained more of their ancestral form in the isolated margins of East Polynesia (Burrows 1938). By contrast, in Central East Polynesia, the Tahitian rig diverged more from the original and shared some technical attributes with West Polynesia, which accords with evidence for interaction between the regions (Finney 2006).

2. East Polynesian Canoes

There are no archaeological remains of Lapita canoes but linguistic reconstructions of the names for parts of boats suggest a single hull with an outrigger (Pawley and Pawley 1994). There is divided opinion about whether it had a three-spar lateen sail or lugsail, which could be presumed from their later wide distribution (Di Piazza, Pearthree, and Paillé 2014; Kirch 2017), or whether it had a simpler two-spar rig (Doran 1981; Anderson 2000). Whatever the case, computer simulation has shown that an efficient sail was required to negotiate the seasonal monsoon and trade winds of the Lapita seascape (Irwin et al. 2024).

The later settlement of East Polynesia was achieved with improved voyaging canoes. There were now tacking double canoes as well as outriggers, both matched with two-spar Oceanic spritsails (Doran 1981; Haddon and Hornell 1997). Blust (1999) believes double canoes were developed after Fiji and West Polynesia were settled, and Di Piazza (2015) considers the Oceanic spritsail was a West Polynesian innovation used in the settlement of East Polynesia, although not all agree (see below). The three BM sails, plus contemporary records of European sailors, show that Oceanic spritsails diverged in form on different island groups, but the basic technology remained the same (Irwin and Flay 2015).

East Polynesian canoes were distinctive in several ways:

- They changed direction by tacking (passing the bow into and through the wind), and they had a distinct bow and stern which could each be optimised for performance, the bow for entry into the waves and the stern for safety when sailing downwind while being overtaken by following seas (Dudley et al. 2021).
- The two-spar Oceanic spritsail was well suited to the tacking manoeuvre and also for depowering (reefing) in heavy weather (see below).
- Double canoes had improved sailing and seakeeping capability to negotiate the vast eastern Pacific Ocean with greater buoyancy, stability, load-carrying capacity and range.
- Wind tunnel tests show that two hulls together sail closer to the true wind angle than one hull with an outrigger (Irwin et al. 2023), and towing tank tests show canoes with V-shaped underwater profiles sail upwind better than U-shaped ones (Flay et al. 2019).

The earliest archaeological canoe in Polynesia, found at Anaweka, New Zealand, dates from the late 14th century CE (Johns, Irwin, and Sung 2014). It consists of a complete large plank from the hull of a sophisticated ocean-going canoe with an upwards-curving stern suitable for downwind sailing, together with a moderately V-shaped hull section suitable for sailing upwind.

At the end of the 18th century CE, some Tahitian canoes were still capable of sailing offshore and, according to Joseph Banks, could "… lay very near the wind [sail upwind]" (Beaglehole 1962:161). However, he described Māori as expert in paddling, but not in sailing "… we very seldom saw them make use of Sails and indeed never unless they were to go right before the wind (Beaglehole 1962 II:23-24). By Cook's time, double canoes were giving way to single ones without outrigger, especially in the North Island (Haddon and Hornell 1997, 200). For Hawaii, (Kāne 1998, 1) writes: "As long-distance voyaging declined, the need shifted from voyaging canoes to large canoes for chiefly visits and warfare within the Hawaiian Islands, resulting in changes in canoe design. For these short coastal and inter-island trips, paddling replaced sailing as the dominant power mode". In both New Zealand and Hawaii large canoes became craft for combined paddling and sailing, and sails and hulls adapted in form to their changing use.

The general shapes of Oceanic spritsails recorded in East Polynesia by Cook's artists before 1780 are shown in Figure 1. They were fore-and-aft sails that could take the wind from either side. The leading edge was attached to a forward spar stepped on the canoe, which transferred wind forces from rig to hull, and the spar at the trailing edge of the sail was attached to the bottom of the mast for trimming to the wind (although this has been in debate for New Zealand). The Tahitian rig was unusual for East Polynesia in having a standing mast, but the other rigs were raised and lowered, all as one.

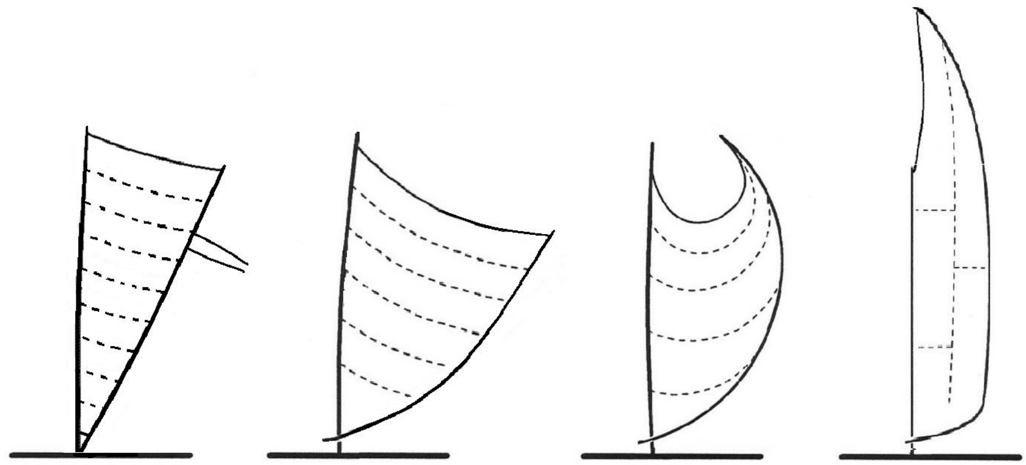

Figure 1: East Polynesian sails retained the same two-spar technology but diverged considerably in form. Māori sails were drawn by Spöring and Parkinson in 1769, the Marquesan sail by Hodges in 1774, the Tahitian by Parkinson in 1769 and Webber 1778, and the Hawaiian by Webber also in 1778. Hawaiian and Marquesan sails were almost identical, triangular with apex down, and the difference between them in the figure is due to a cord drawing the top of the two spars of the Hawaiian sail together (Haddon and Hornell 1997:35). The evidence for the mode of attachment of the spars to the hull of the Māori sail in 1769 is unclear.

3. The British Museum (BM) Māori Sail (Rā), BM OC 1999, Q147

We describe sail form in general terms, but it has been investigated in detail by a Marsden project led by C. Smith and D. Campbell, Whakaarahia anō te rā kaihau! - Raise up the billowing sail! In addition, an expert weaving collective led by Maureen Lander, Te Rā Ringa Raupā, has recreated a duplicate of the original, which is currently on a multi-year visit to its New Zealand homeland. Photographs in Figure 2 show it is of fine and intricate manufacture with an elongated, inverted triangular form. It measures around 4.40m high, 1.90m wide at the top, and there is a flat facet at the foot 0.34m wide. There are 13 horizontal plaited panels of woven flax (Phormium tenax), and the top is trimmed with feathers. A pennant attached to one edge served as both a decoration and a “tell-tale” to indicate the wind direction. Zig-zag bands of openwork plaiting up the sail were mainly decorative.

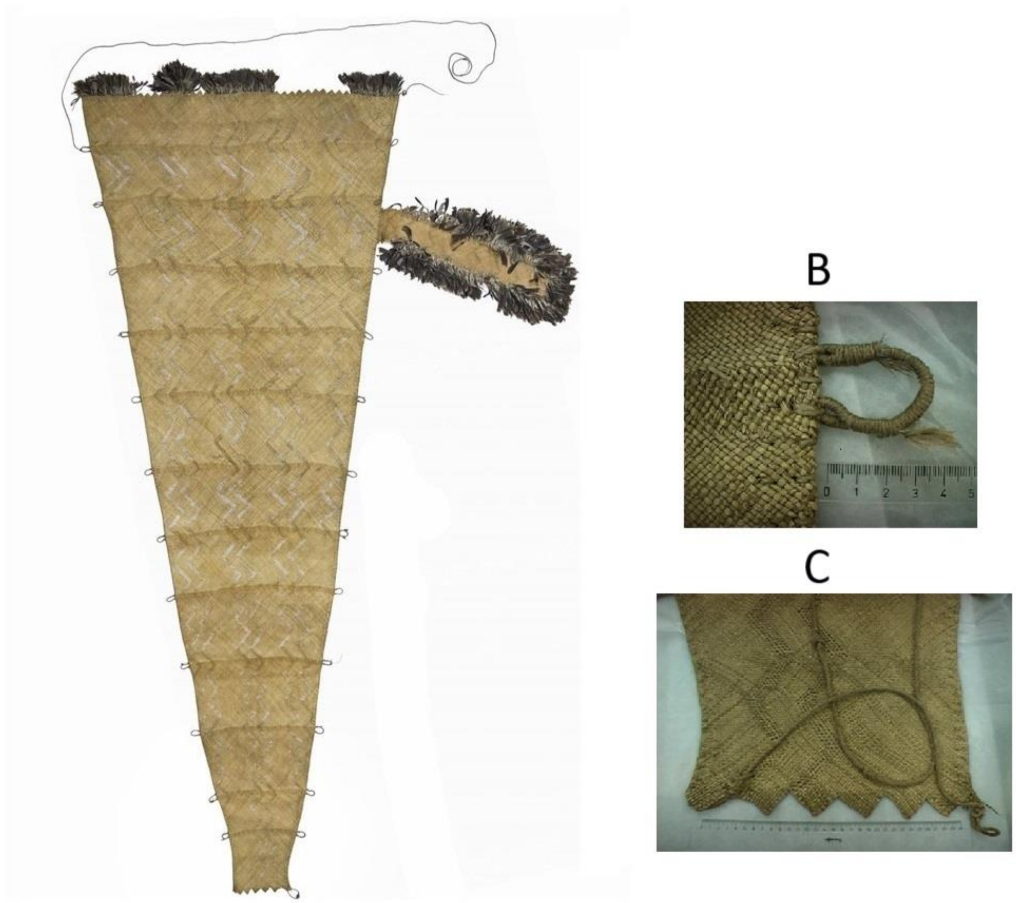

Figure 2: Photographs of the Māori sail, showing a fibre loop (Figure 2B), and zig-zag decoration found on bottom and top edges (Figure 2C). The loop of line attached to the bottom two corners could have been used as a downhaul (Figure 2C).

For our purposes we note that it is a light, strong, and powerful sail, often described as triangular, but the short flat base could be either functional or could simply reflect the method of manufacture. It has leading and trailing edges with the pennant trailing from the back edge, and there are minor details of asymmetry as in the pattern of the open-weave decoration. Fibre loops for attachment to the spars are located at strong points where the panels overlap and join. A replica sail on display at Auckland Museum is currently set up with the spars inside the loops which prevent the sail from setting smoothly and based on comparisons with HA/MQA and Tahitian rigs (below), we think the spars were usually laced outside the loops or connected with short ties. A long line attached to the second-highest loop on the leading edge reaches beyond the bottom of the sail and could have been for lacing. The loops spread the weight of wind along the spars and based on wood technology preserved at the 17^{th} century wetland archaeological site of

Kohika, we think spars would have been smooth poles split from the heartwood of trunks rather than just suitably sized branches (Wallace and Irwin 2004).

3.1. Drawings of Māori sails by Cook's artists 1769-70

We focus on drawings made during Cook's first visit because sails drawn after 1800 CE could have been influenced by European contact, and the first detailed naval architectural drawing of a Māori canoe with an Oceanic spritsail was made by Admiral Paris, nearly 60 years later.

Figure 3 is a detailed drawing made by Herman Spöring, on 2nd November 1769, of the first Māori canoe seen under sail by those on the Endeavour. The large double canoe had been seen on the previous day near Moutohorā (Whale Island) in the Bay of Plenty and next day the canoe, with more than 50 people on board ready for a confrontation, sailed alongside the Endeavour for about an hour (Beaglehole 1995:190). Coincidentally, within a few hours travel of this encounter, up the nearby combined estuary of the Rangitaiki and Tarawera rivers, the 17th century wetland archaeology site of Kohika contains a huge inventory of canoe-related wooden and fibre artefacts that provide relevant information about contemporary marine technology (Wallace and Irwin 2004).

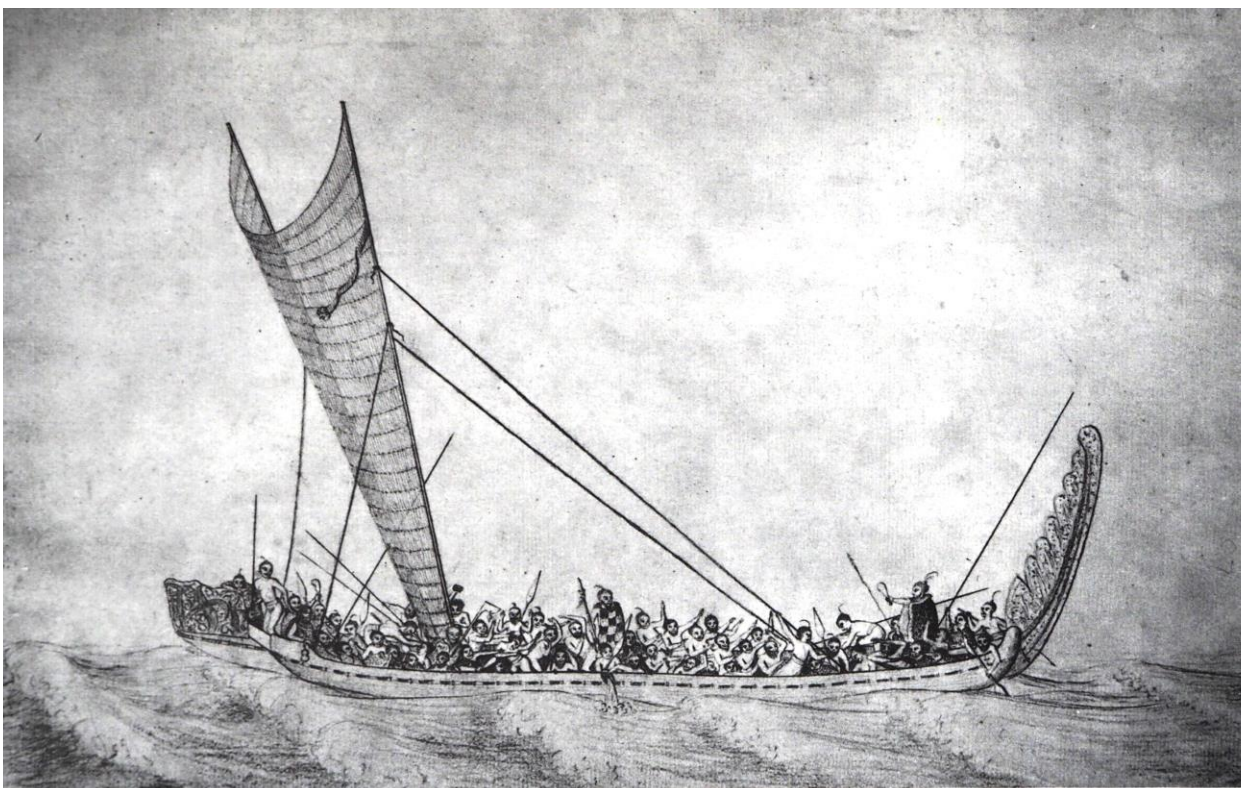

Figure 3: Herman Spöring's drawing of the Motouhorā double canoe, 1769, British Library, London: Add.Ms.23920 f.48. The canoe is sailing downwind with the sail trimmed to keep pace with the slower *Endeavour*. The longer hull is on the right-hand side of the canoe facing forward (starboard) and the shorter hull is on the left (port). The sail is approximately twice the height of the BM sail with 25 visible panels, compared with the BM's 13 plaited flax panels.

- The canoe is sailing downwind and being overtaken by waves generated by a wind of around 12 knots (22km), with half-metre waves just beginning to break.
- The wind is coming, not from directly astern but from over the starboard side. The canoe is thus on the starboard tack, and a steering paddle is on the port side, aft.
- The starboard spar is the leading spar and is acting as the mast. It is to windward and ahead of the port spar, which trails to leeward, and a pennant similar to the one on the BM sail streams forward from the trailing edge.
- The two spars are of similar height and the sail has the same triangular shape as the one in the BM. The bottoms of the spars are obscured.
- The spars are leaning (raked) forward. There are no lines holding the spars apart, so the sail bellies forward with the weight of wind. In fact, the sail is spilling wind from the top of the sail to slow the canoe. Clearly it was faster than the Endeavour in the conditions and deliberately slowed to hold station.
- The sail has no permanent (standing) rigging and on this occasion the running rigging consisted of four lines. Two lines led aft, one from each spar. The line from the starboard spar (which can be seen passing behind the sail), was acting as a backstay to hold up the sail against the force of the wind. The port line served partly as another backstay, but also as a sheet to trim the sail to the angle of the wind, and it can be seen leading aft to the port hull. The two ropes leading forward were acting as forestays, steadying the rig as the canoe ran downwind. At times the starboard forestay would have been quite heavily loaded to resist the lateral load from the sail on to the starboard spar which would be pulling in the port direction.

There are no side stays (shrouds) to be seen attached to the sides of the canoe near the mast, so the rig would have had little lateral support. If the canoe had turned to starboard (right), away from the Endeavour to reach across the wind, the sail would have collapsed to leeward. Clearly, with the running rigging so deployed there was no intention to sail in any other direction, and when the canoe broke away it pulled the sail down (Parkinson 1984:102). With 50 or more people on board it would have been much faster for them to paddle against the wind than to tack against it. A canoe sailing at 75˚ to the true wind must tack almost four miles back and forth to gain one mile directly into the wind.

Both the actual BM sail and the one in Spöring's drawing of the Motouhorā canoe are powerful sails with much of the wind force in their wide inverted triangular tops. The BM sail is small but would be able to propel a fairly large single canoe downwind in a moderate or fresh breeze. The Motouhorā sail is twice the height, around 9.2 metres according to Anderson's (Anderson 2022, 57) calculation, and it is approximately 80% of the waterline length of the canoe. This sail would be hard to manage in a fresh breeze (17–21 knots [29–38 km/h]) and would be overpowered in anything stronger (see below).

Figure 4 is a more stylised and less reliable drawing by Sidney Parkinson. It may not be a drawing of any particular canoe (Anderson 2022), but there are several similarities with the basic structure of the canoe in Spöring's drawing, which Parkinson could have seen. Once again, the bottom of the sail is obscured, so it is unclear whether the spars were connected to each other or separately to the canoe. However, one interesting point of difference between the drawings is that the Parkinson canoe has a side-stay or shroud, which would provide lateral support for the rig to reach across the wind.

Figure 4. A drawing of a double canoe by Sydney Parkinson, 1770, British Library, London: Add.Ms.23920 f.49. Here the starboard spar has more support from lines attached about two-thirds of the way up. However, the port (adjustable) spar is forward of the starboard spar for this point of sail.

3.2. The double spritsail

There is a possible discrepancy between Spöring's drawing and a written description of the same sail (Anderson 2022; Irwin and Flay 2015). James Magra, a midshipman on the Endeavour, in his published account of the voyage (Magra 1771) described the sail as triangular "… ending at a point in the bottom. One of its angles was marled to the mast, and another to a spar with which they altered its position according to the direction of the wind, by changing it from side to side" (Magra 1771: 82). These are features of an Oceanic spritsail. However, Anderson (2022) interprets the drawing as having both spars attached directly and separately to the canoe, as distinct from an Oceanic spritsail, and suggests it was a different type of sail which he calls a double spritsail. Brief contemporary written descriptions of Māori sails by James Cook (Beaglehole 1955: 284), and Joseph Banks (Beaglehole 1962: II: 23–24), do not settle the question because neither of them specified whether the two spars were connected to each other at the bottom, or separately to the canoe.

The different views about the sail type may or may not be significant. On one hand there could be a culture historical implication because Anderson (2022) contends that the Māori sail was a double spritsail which reached New Zealand before the Oceanic spritsail and regards it as a sail unable to sail upwind. However, on the other hand, the sails are very similar in shape and it is possible that connecting the bottoms of the spars separately to the canoe was simply a local adaptation of the Oceanic spritsail and the sails do not represent different chronological types. We use wind tunnel tests to investigate this possibility, below.

4. The Hawaiian/Marquesan (HA/MQA) Sail, BM OC 1999, Q140

This is a finely plaited pandanus sail consisting of horizontal panels (Figure 5). It measures 5.15m long and 3.66m wide at the top. The leading edge is fairly straight but the lower half of the trailing edge curves to meet the leading edge at the bottom. There are loops for attachment of the spars on both sides. The sail is decorated with several lines of closely spaced holes and has a zig-zag pattern along the top. There are no old labels indicating the source, but it is clearly a two-spar Oceanic spritsail which closely matches early European drawings of sails from Hawaii and the Marquesas. Acquisition notes suggest the sail probably reached the British Museum in the late 18th or early 19th century. It was conserved in 2009 and examined at the time by G. Irwin.

Figure 5: Photographs of the HA/MQA sail taken during conservation at the British Museum in 2009.

4.1. Drawings of HA/MQA sails

Figure 6 is an engraving of a drawing by Webber. It is of a small to medium-sized coastal double canoe travelling fairly fast downwind under both paddle and sail. There are 10 people aboard, nine of them paddling. The sail is of modest size for a boat of this length but very capable of driving it forward. It is constructed in horizontal panels like the BM sail. The mast is stepped on the port hull (left side facing forwards), which is larger than the starboard hull although of similar length, and the spars are laced or tied outside the edges of the sail. The ropes supporting the rig include a backstay, double side-stays (shrouds) on both sides attached to the outsides of a crossbeam connecting the two hulls. The spar at the back of the sail is controlled by a sheet leading aft and has been allowed to extend ahead of the mast. If the engraving of the original drawing is correct, for the sail to fill with wind at this angle, the wind must be coming from aft of the beam on the starboard side, and the sail is in downwind mode.

Figure 6: A Hawaiian canoe with a masked crew. Engraving after Webber by Grignion. The line lifting the boom and pulling the tops of the spars together creates the illusion of a crab-claw shape. This line was used for depowering (reefing) the top of the sail by forming a funnel from which air could escape.

Figure 7 is a watercolour painting of a larger canoe with a relatively larger sail, sailing at a similar angle to the wind as the canoe in Figure 6, but on the opposite (port) tack. The bottom of the sail is obscured, but we can safely assume it is an Oceanic spritsail. There is a large crew on board and, as with the Māori canoe in Figure 3, it would have been much quicker for this canoe to paddle directly upwind than to tack back and forth laboriously under sail.

Figure 7: Canoes bringing presents to Captain Cook, Hawaii, January 27, 1779. Watercolour by Webber. One would expect to see a line from part-way up the curved spar to the stern of the port hull to take the sail load, but such a line is not evident in the painting.

Figure 8. A Hawaiian tacking outrigger canoe off Ni'ihau Island. Ink and watercolour by Webber, 1778. Interestingly, the front vessel has turned away downwind, and the sail has been eased out compared with the vessel in the foreground.

Another drawing by Webber (Figure 8) shows a canoe sailing at a different angle to the wind. The line between the tops of the spars is absent or eased, and the tops of the spars are further apart. With running rigging deployed in this manner the canoe is reaching across the wind, rather than going downwind like the canoes in Figures 6 and 7. The difference between the sail shapes is simply due to the angle to the wind at which these Hawaiian canoes were sailing when drawn.

The presence or absence of the line joining the tops of the spars seems to be the main difference between early artists' drawings of Hawaiian and Marquesas sails. We note that a 1774 drawing of a Marquesan sail by Hodges is similar in shape to the Hawaiian sail in Figure 8 and is also trimmed for reaching, with running rigging comprising stays (shrouds) on both sides, plus a forestay, and a sheet attached to the outer end of the trailing spar (Haddon and Hornell 1997:40).

4.2. The Māori and HA/MQA sails compared

Of the three BM sails, the Māori and HA/MQ are most alike, and they share so many detailed similarities there can be no doubt that they have an historical connection. There are no known direct pre-European connections between these island groups in the northern and southern hemispheres, so it follows the connection could date from the migration period. The HA/MQA sail is generally classified as an Oceanic spritsail like the Māori sail.

- Both sails have distinct front edges attached to the spars which served as masts. The back edge of the Māori sail is straight and has a trailing pennant and the HA/MQA has a curved trailing edge and a fuller more cambered sail.
- Both sails are made up of horizontal panels, 13 in the Māori sail averaging 338mm in width, and 16 panels in the larger HA/MQA, averaging 322mm wide.
- In both sails the bias of the plaited panels is set diagonally to hold the shape of the fabric when in use.
- The fibre loops along the sides for attachment of the spars are placed at the panel joints in the Māori sail, and in most cases in the HA/MQA.
- The tops of both sails have a very similar zig-zag decorative form.
- Both sails have ropes for attachment to spars at the top and bottom.
- The main difference between Māori and HA/MQA sails is that the HA/MQA is wider in relation to its height.

5. The Tahitian Sail, BM OC 1999, Q139

This sail has the distinctive form of the Society Islands, as confirmed by two labels of parchment-type paper with "Tahiti" handwritten in black ink. It measures 9.68m x 1.53m with a straight leading edge, a curved lower trailing edge and a tapering upper trailing edge (Figure 9). According to Joseph Bank's estimated ratio of sail height to boat length (Beaglehole 1962:160), this sail would have been from a canoe approximately 12.5 metres long.

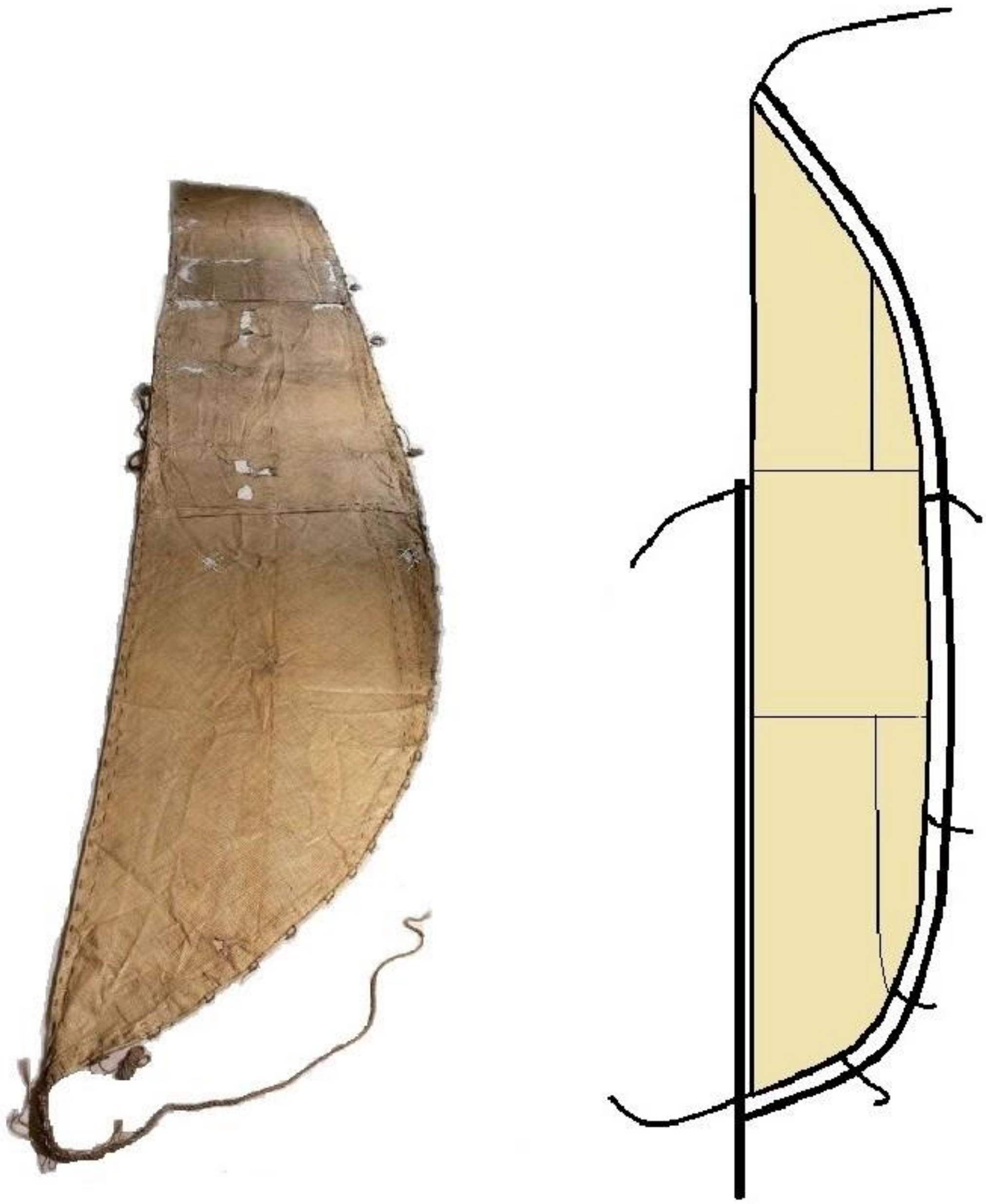

Figure 9. A photograph and a schematic plan of the Tahitian sail. Note that the photograph gives an oblique view, and the plan is not exactly to scale. Adapted from Hiquilly et al. (2009).

This sail differs from the previous two.

- It has a standing mast which provides greater stability.
- The sail is narrower in relation to its height and curves inwards both at the top and bottom.
- The trailing spar is longer than the mast and the leading edge of the sail extends well above the mast.

- The sail is made up of three large mats of plaited pandanus plus smaller pieces of different size and shape, rather than in horizontal panels.

Notwithstanding the differences of the BM Tahitian sail from the other two, it shares other features consistent with its East Polynesian origins.

- It is an asymmetric two-spar Oceanic spritsail rig with leading and trailing edges.
- It has a curved trailing edge like the HA/MQA sail.
- There are closely spaced loops for the attachment of spars for the height of the mast and the length of the J-shaped trailing spar. The upper part of the leading edge above the mast had no loop fasteners but was strengthened with a cord and extra stitching.
- Ropes at the bottom and about two thirds of the way up the sail were for attachment to the mast, and a rope at the top of the sail was evidently for a trailing a decorated pennant and tell-tale.
- The bias of the weave is set diagonally in the sail, as in the other two.

Unlike Māori and Hawaiian canoes, Tahitian ones sailed upwind. Banks wrote "… with these sails their Canoes go at a very good rate and lay very near the wind" (Beaglehole 1962:161). The navigator/priest Tupaia told Cook that Tahitian canoes had gone back and forth to islands 15 sailing days to the west, and they waited for spells of westerly winds in summer to work their way home again against the easterly trade winds (Finney 2006:138).

5.1. Drawings of the Tahitian sail

Historical drawings and engravings of Tahitian canoes are generally consistent with the BM sail. The tall rig was supported by widely spaced side-stays (shrouds) fixed to the end of a crossbeam extending beyond the sides of the canoe. A similar arrangement was also seen on some West Polynesian canoes and is thought to relate to contact between central East Polynesia and West Polynesia in the late pre-European period. Figure 10 shows a fairly typical small Tahitian outrigger canoe with a standing mast supported by shrouds from the crossbeam, and also by forestays and backstays. The sail is made of plaited mats and appears to be in reaching mode.

Another tipaerua design canoe in Figure 11 shows the spars tied or laced outside the loops on the edges of the sail and a ladder giving access up the mast. The sail sheet attaches at the point where the horizontal boom at the foot of the sail meets the vertical boom-sprit (Hiquilly et al. 2009). It has been suggested that many of the canoes that voyaged to New Zealand were tipaerua, as many Māori canoes likewise had a low bow and high upturned stern (Finney 2006: 129).

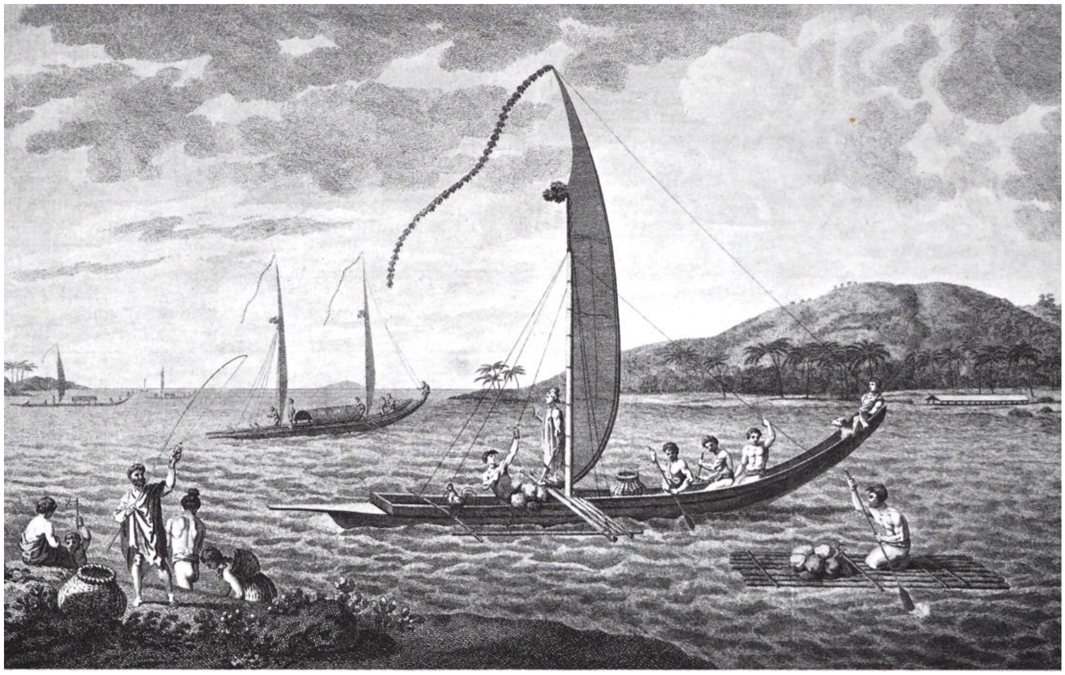

Figure 10. A Tahitian outrigger canoe of *tipaerua* form, with a low bow and high stern. Engraving by Rooker after Parkinson, 1769.

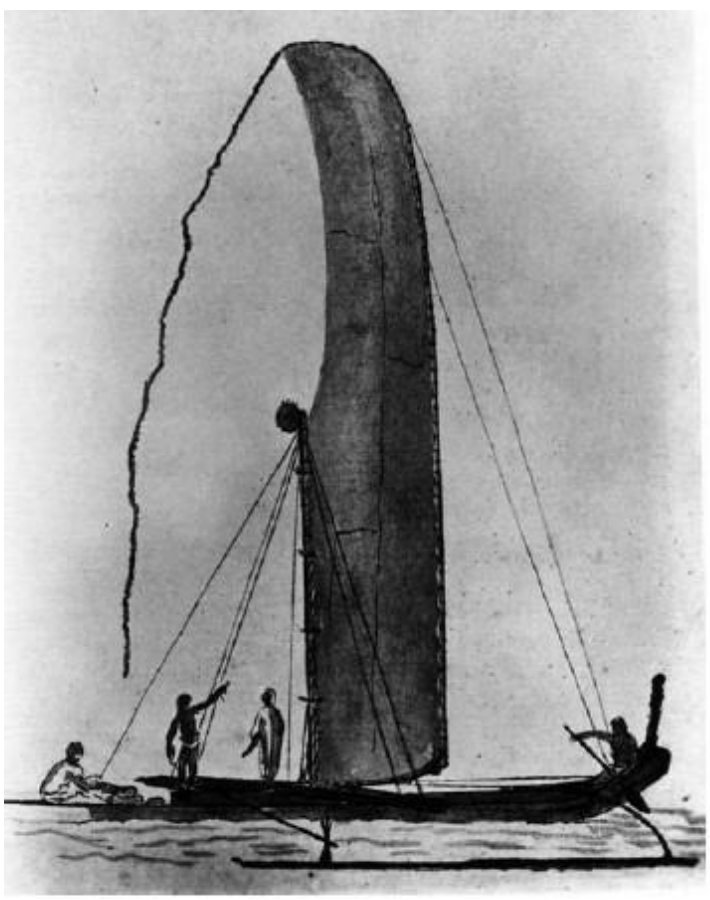

Figure 11. Pen and wash drawing by George Tobin, Tahiti, 1792, adapted from I. Lee, Captain Bligh's second voyage to the South Sea, Longmans Green and Co., London (1920).

6. Wind tunnel testing and results

C.A. Marchaj was a pioneer in the study of the aerodynamics and hydrodynamics of sailing boats which he described in a number of landmark publications (e.g., Marchaj 1979, 1996). He made extensive use of wind tunnels and test tanks in his research and compared different rigs from around the world. He made the surprising discovery that the "crab claw" sail (a generalised West Polynesian type) was superior to the Bermudan rig (a standard western type) when sailing at all angles both against and with the wind (Marchaj 1987). The Yacht Research Unit at the University of Auckland was established in 1987, and in 1992 a model of a 12-metre flying proa based on the description of one drawn and described by Anson on a visit to Guam in 1742 was wind tunnel tested and its theoretical performance predicted (Jackson and Bailey 1996). This current project began in 2008 and G Irwin viewed the HA/MQA sail in 2009 when it was being conserved at the British Museum (Irwin 2010, Irwin and Flay 2015). In 2014 Di Piazza et al. (2014) published the results of wind tunnel testing in France of small models made of epoxy-fibreglass of 10 traditional rig types known across the Pacific.

For this study, two-metre-high models of the three BM sails were made of finely plaited pandanus matting and tested in the Twisted Flow wind tunnel at the Yacht Research Unit, University of Auckland (Irwin et al. 2023). Their aerodynamic properties reflect their shared technology and regional divergence.

- We measured four variables, the driving force, the side force, the rolling (or overturning) moment and the pitching moment.
- We tested the Māori double spritsail set at the same height as the Māori Oceanic spritsail and also when lowered down to the gunwales (sides) of the canoe, as depicted in the Spöring drawing of the Motouhorā canoe in Figure 3, above.

6.1. Driving force

To sail across the wind, or upwind, sails must develop enough driving force in the desired direction (generally perpendicular to the wind direction), and Figure 12 compares the BM sails in terms of their driving force coefficient (Cdf). With both versions of the Māori sail at the same height, the driving force of all four sails was much the same across a range of wind angles from 30˚-120˚. There was a lot of power high in the inverted triangular sails, and they were efficient at turning wind into driving force. All of them could reach across the wind on multihull canoes with lateral stability, and when combined with moderately V-shaped hulls, they could sail upwind as well (Irwin et al. 2023). We conclude that these simple two-spar sails are similar in performance and form and are all Oceanic spritsails.

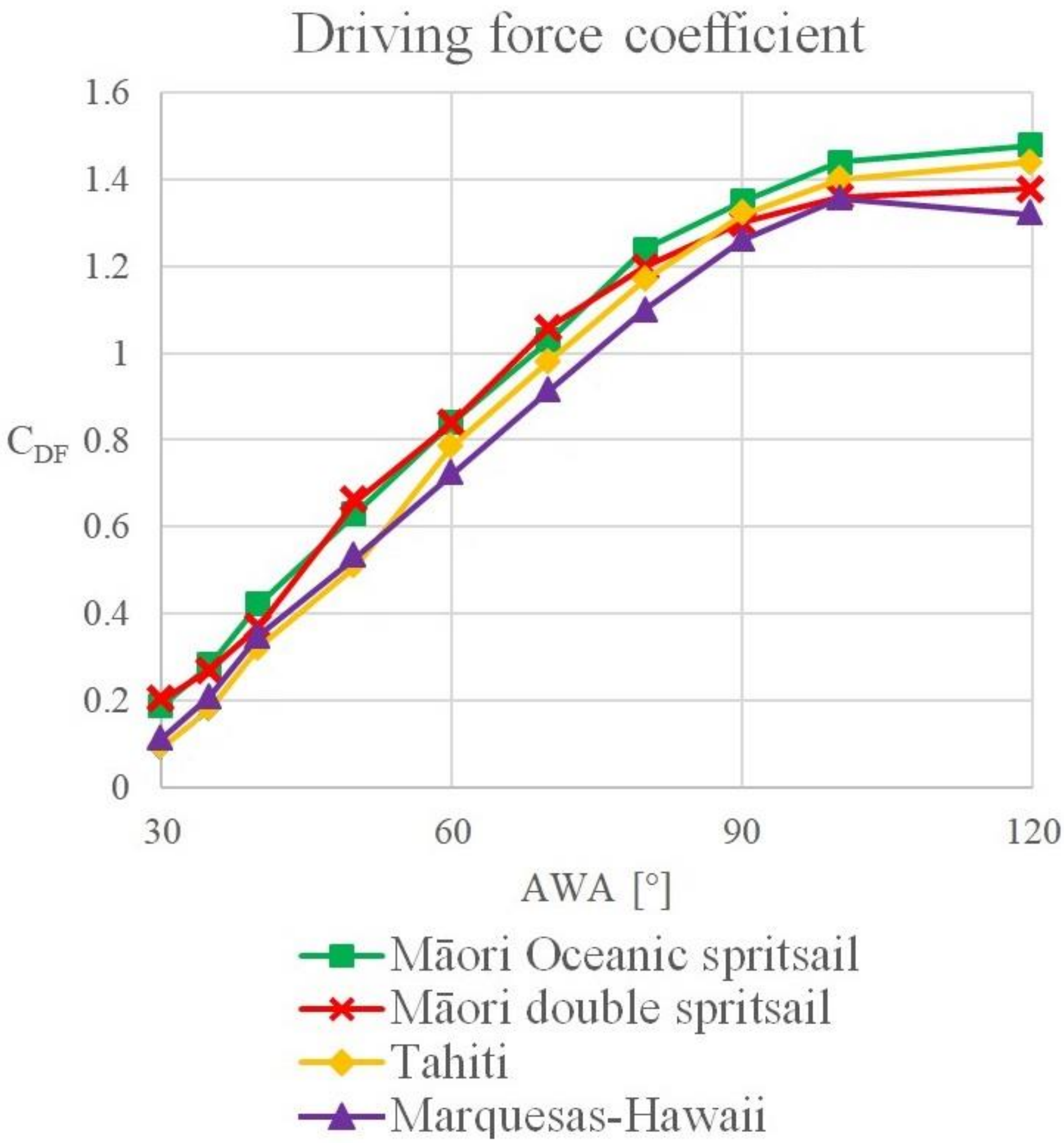

Figure 12. Driving force coefficient vs apparent wind angle, showing that the driving force of the three BM sails is similar, with the Māori sail set both ways. The apparent wind direction (AWA), is the direction of the wind, as observed from the moving vessel.

6.2. Rolling (overturning) moment

However, when reaching across the wind the aerodynamic side force normal to the vessel direction generates a rolling (or overturning) moment shown in Figure 13, which must be balanced by the righting moment of the hull and/or the weight of the crew or cargo located on the windward side of the vessel. Figure

14 compares the stability of the four sails and significant differences were found. The Māori sail rigged as a double spritsail was the least stable because the two independent spars provided no support for each other and were hard to control, as observed in the wind tunnel tests. Also, when reaching, this sail twisted between the two corners of the base attached to separate spars set sideways across the canoe. Similarly, in a sea trial of a double spritsail rig, Anderson and Boon (2011:110) also found that a fold developed diagonally in the sail, and it did not set well. We conclude that the Māori double spritsail was a variant of an Oceanic spritsail suitable only for sailing downwind.

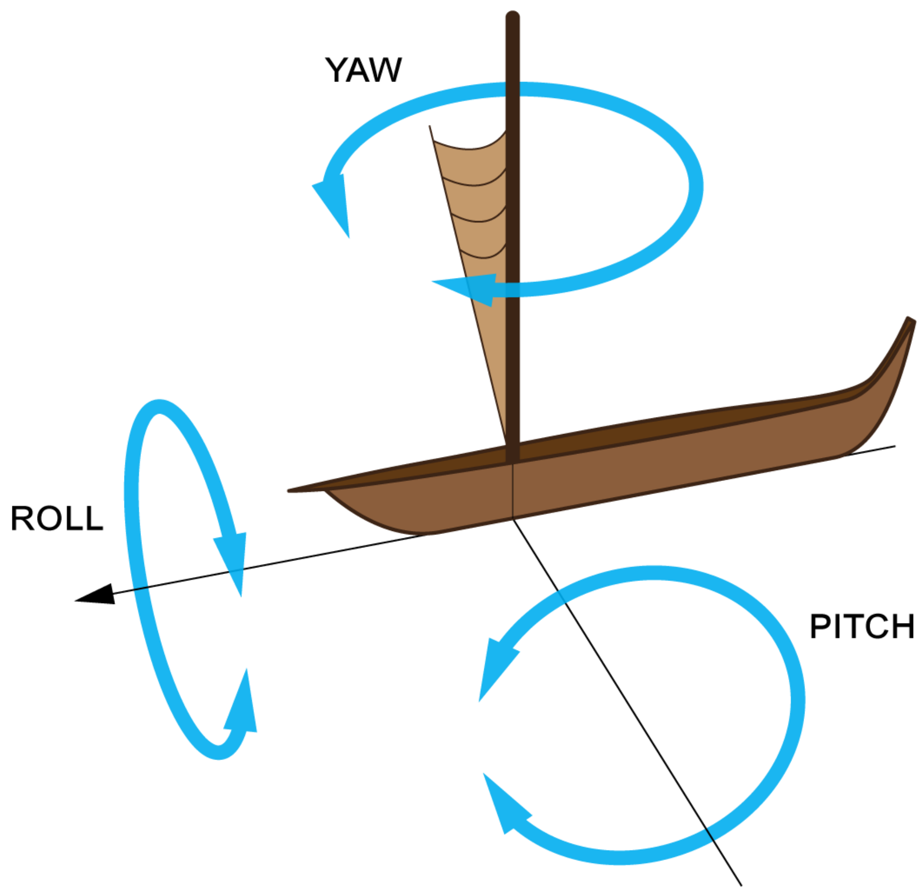

Figure 13. An illustration of the rolling moment which causes a canoe to roll from side to side, the yawing moment which moves the bow sideways from the direction of travel, and the pitching moment which causes the bow to lift in the waves. The Māori sail lacks the curved trailing edges of the Tahitian and HA/MQA sails and the fullness of the HA/MQA. Its bilaterally symmetrical shape would reduce the rolling and yawing moments of a single canoe with no outrigger and is a possible adaptation to changes in canoe types.

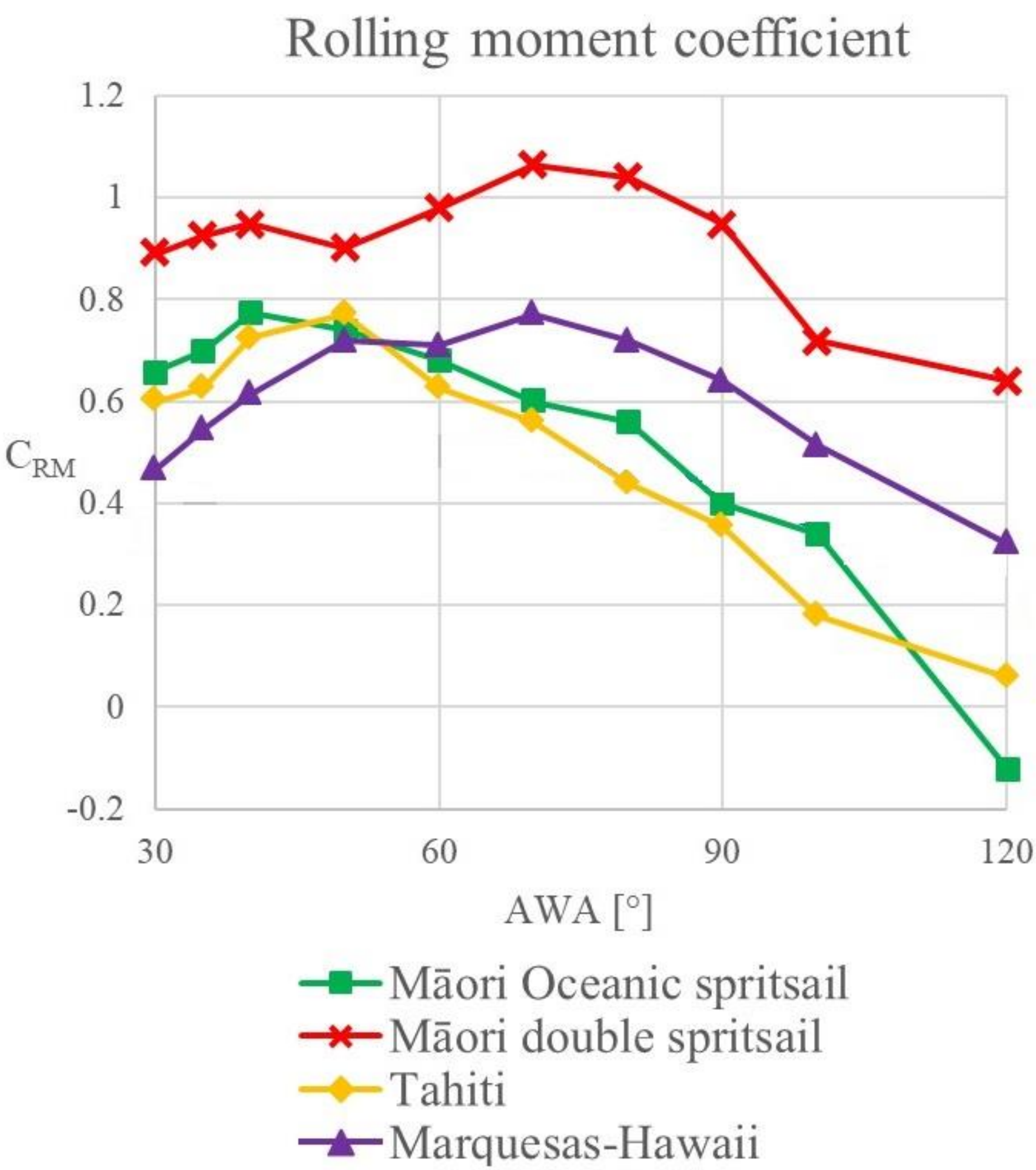

Figure 14 shows that the Māori sail, when set as a double spritsail, was the least stable. The Tahitian sail, although tallest, had the lowest rolling moment due to its design (below).

6.3. Depowering (reefing) the Oceanic spritsail

Voyaging canoes in East Polynesia sometimes had to cope with heavy weather. As one example, during a voyage by the Hawaiian double canoe Hokule'a, from Rarotonga to Tahiti in 1986, the canoe was struck by 57 squalls and had to lower sails, masts and spars to the deck (Finney 2006:142). This voyage was a test of a strategy for sailing east from Samoa to the Cook and Society islands during the southern winter, when there are fairly regular interruptions to the prevailing easterly winds, by westerly winds associated with the passage of fronts extending north from easterly-moving low pressure systems further south. For a few days on these occasions, westerlies can be used for sailing east, but the weather can be squally with poor visibility.

The three types of BM sail found different solutions to the need to reduce sail in stronger winds or, when necessary, to drop them altogether. The Hawaiian sail was routinely depowered by the line drawing the tops of the two spars together as in Figures 6 and 7, which had the effect of forming a funnel at the top of the sail from which air could escape.

The Tahitian sail sometimes had a ladder arrangement up the mast so the sail could be lowered. The finer trailing spar was much longer than the mast at the leading edge, so that in stronger winds and gusts the flexible top of this tall thin sail could bend and spill wind. This was a unique and sophisticated adaptation for an ocean voyaging canoe. The narrow sail could also be trimmed with just the leech (trailing edge) drawing and could "feather" its way upwind.

Joseph Banks said the Tahitian sail "… had no contrivance of reefing or furling" (Beaglehole 1962:161), but William Wilson, first mate on the missionary ship Duff during its voyage to the Pacific in 1796-1798 wrote:

> "As they have no method of reducing their sail at the head, being only able to cast it off at the foot and roll up a part, they are driven to the greatest inconvenience when overtaken by bad weather.… When a squall comes, they luff the head of the sail to it; and if she is likely to fall off, they jump overboard and hold her head to windward until the gust of wind is passed". (Wilson 1799:401)

This jumping overboard manoeuvre would only work for small coastal outrigger canoes, which often capsized and could be righted, but not for large double canoes. However, this account raises the possibility that sails were rolled up at the bottom.

In the case of the Māori canoe drawn by Spöring in Figure 3 above, the sail is raked forward and spilling wind over the top to slow down to keep pace with the Endeavour. It is also set right down close to the gunwales, reducing power in the top of the sail. Figure 15 shows the results of a wind tunnel test which compared the Māori sail set (1) as an Oceanic spritsail, (2) as a double spritsail set at the same height, and (3) as a double spritsail set as low as possible. It was found that lowering the double spritsail reduced the overturning moment, which increased the stability of the vessel when the wind was fresh or the canoe heavily laden as in the drawing. This result provides a rationale for using the sail with the spars set apart at the base as suggested by Anderson and Boon (2011), and if correct we would interpret it as a local adaptation of the Māori sail for sailing downwind. In this configuration a sail could be set on shorter spars and reefed by rolling up at the bottom as reported by Wilson for the Tahitian sail. Unfortunately, the bottom of the sail in Spöring's drawing is obscured and the details of its attachment are unknown.

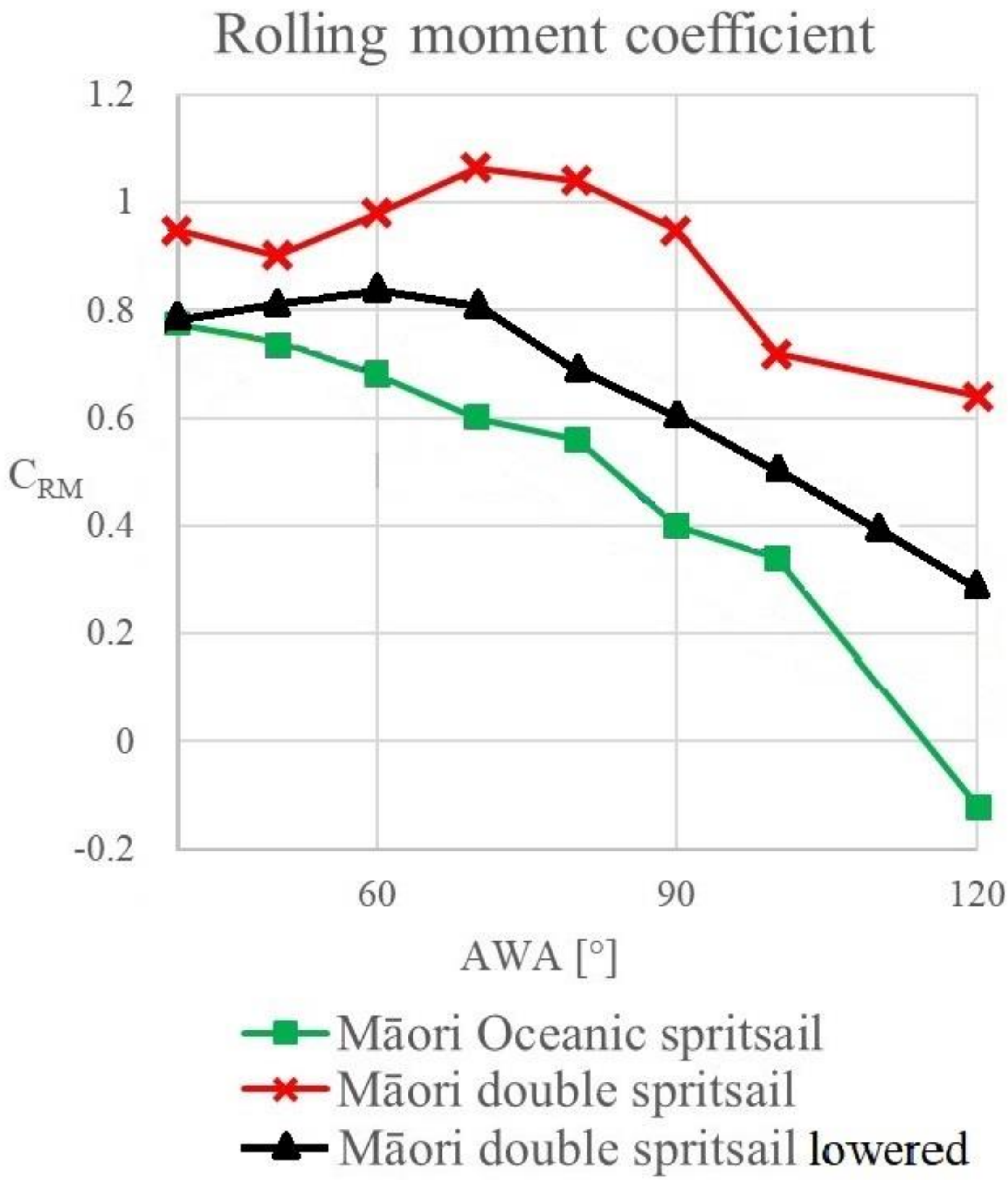

Figure 15. Lowering the Māori double spritsail to the gunwales reduced the rolling moment (*Crm*), but this rig was only suitable for sailing downwind.

Both the HA/MQA and Tahitian sails are asymmetrical in shape and have curved trailing edges but the Māori sail is bilaterally symmetrical with straight edges. Such a shape reduces both the rolling and yawing moments shown in Figure 13 and we think that a change of shape would have been a useful and plausible adaptation to the increasing use of Māori single canoes which lack the lateral stability of double canoes.

We also think it very possible that original early East Polynesian Oceanic spritsails had a simpler conventional way of depowering in strong winds, which would be to rake the mast backwards, to reduce the power in the top of the sail. The results of a wind tunnel test in Figure 16 show that a 30˚ rake of a generic Oceanic spritsail considerably reduced the rolling moment coefficient (Crm), which would allow a reaching canoe to sail with greater safety and comfort.

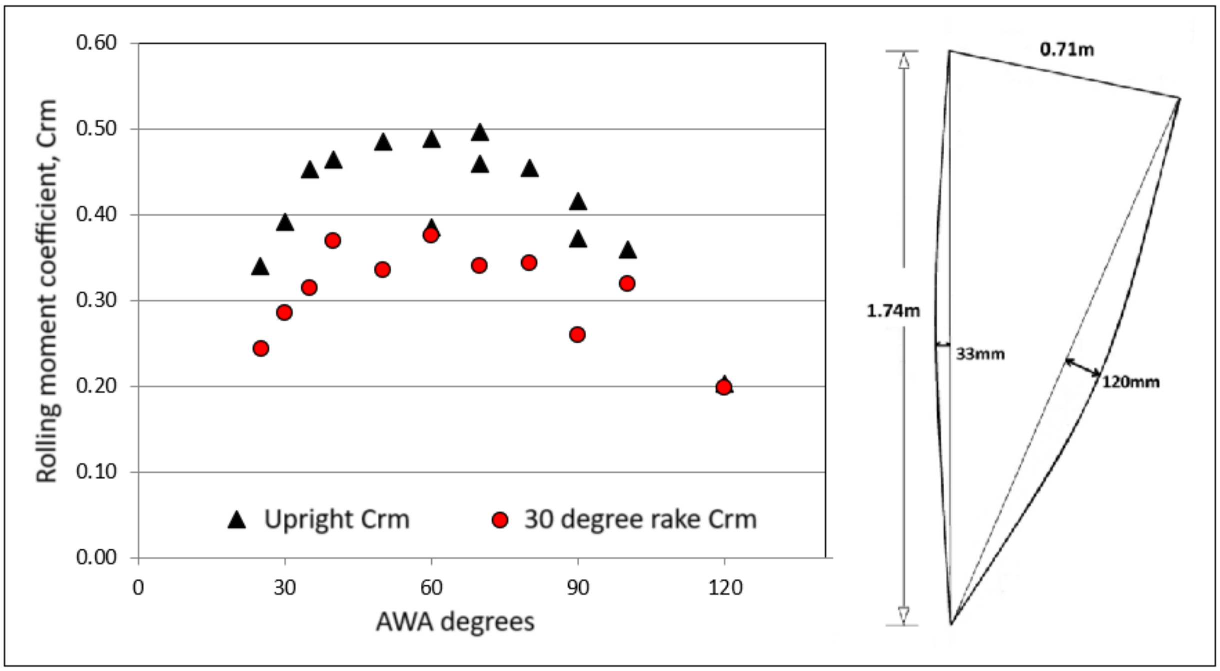

Figure 16. A wind tunnel test of a generic Oceanic spritsail made of finely woven pandanus shows that a 30˚ backwards rake considerably reduces the rolling moment coefficient (*Crm*), allowing a canoe to sail with greater safety and comfort in stronger winds. The model sail is an iscosceles triangle, similar to the Māori sail with additional material at the leading edge to allow for mast bend, and with the addition of a curved trailing edge as found elsewhere in East Polynesia. It is shown in upright mode.

7. Interaction and isolation in East Polynesia: evidence of transport of adze rock

A context for the diversification of the sails is provided by evidence of interaction and isolation of the island groups concerned. Direct physical evidence of movement between islands and archipelagos in Polynesia is best provided by tracing the origins of transported rock used in the manufacture of adzes. In the last 40 years considerable progress has been made in the geochemical sourcing of lithic material excavated from archaeological sites in the Pacific (Best et al. 1992; Weisler 1993; Weisler 2016; Best 1984). Such data allows us to document prehistoric voyaging and shed light on patterns of interaction and isolation (Figure 17). Adzes were required in wood working of all kinds but crucial for the building of large voyaging canoes (Turner 2000). The distribution of adze stone reflects patterns of interaction but also the quality of stone resources needed for adze production. The high islands of Polynesia generally provide suitable igneous rock for adze production although quality may vary considerably with sources of very high-quality stone few in number. All igneous rock found in atoll sites is foreign and demand would have been on-going, although shell from large shellfish can provide the material necessary for production of most adze forms, albeit possibly not completely replacing the effectiveness of stone (Clem 2017; Szabó 2016).

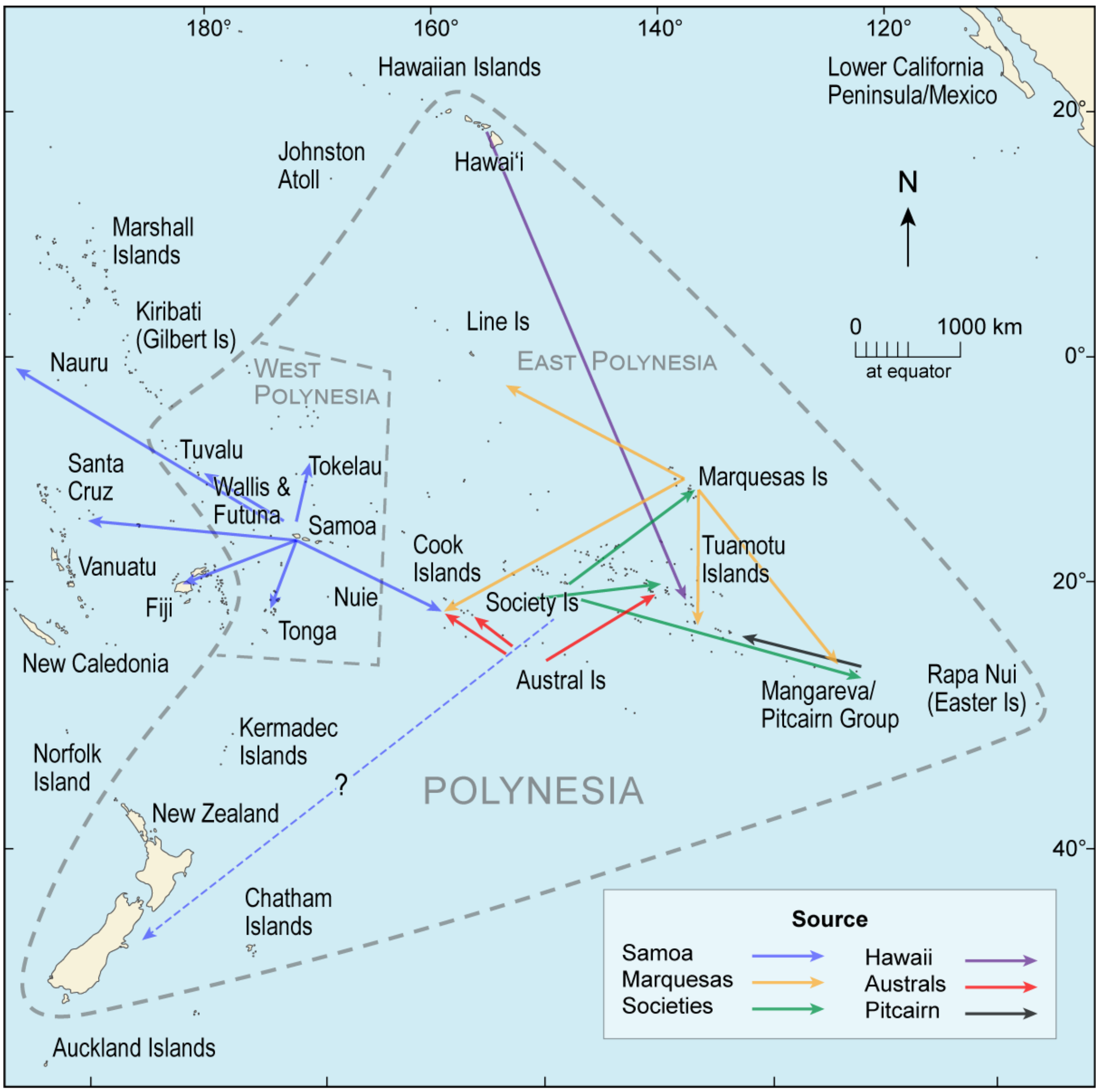

Figure 17. The pre-European movements of industrial stone provide an index for the decline in ocean voyaging and the relative isolation of island groups.

The geochemical sourcing of adze rock in the Pacific began with a study of material from Samoa. Earlier petrographic study had indicated that this was a source of material moving, very early, west into the Polynesian Outliers of the Solomon Islands (Leach and Davidson 2008; Best et al. 1992; Sheppard 2022), often agreeing with oral tradition. Subsequent study has shown that high-quality material from the large Tutuila adze quarry of Tatagamatau (currently the only quarry showing extraction pits in the tropical Pacific (Weisler and Walter 2017)) and a variety of other Samoan sources, moved at the time of the settlement of East Polynesia into a very large number of islands (Best et al. 1992). Clark et al. (2014) summarize data from Tutuila sources as reaching 27 locations: to the west (San Cristobal [Makira], Taumako, Nupani, Tikopia, Rotuma, Uvea, Cikobia, Taveuni, Vanuabalavu, Lakeba, Waqava, Moce, Totoya, Kabara, Namuka, Ogea, Fulanga, Vatoa); to the North (Phonpei, Tuvalu, Manra, Tokelau, Pukapuka) and to the south (Tonga, Rarotonga, Mangaia, Mauke). This is the most extensive distribution of material in the Pacific often dating at it earliest from the time of the settlement of East Polynesia and continuing, in the case of Tonga, into late prehistory and the time of the Tongan maritime expansion. To date there is no evidence of movement of Samoan adze rock further east beyond the Southern Cooks into either central East Polynesia or further east.

The distribution of Samoan basalt in the Southern Cooks is comparatively unique, for it would appear that all the earliest settlement sites in the Southern Cooks have quantities of Samoan stone greater than that found elsewhere (Walter and Sheppard 1996; Sheppard, Walter, and Parker 1997; Weisler, Kirch, and Endicott 1994; Weisler et al. 2016; Allen and Johnson 1997). The basalts of the Southern Cooks are generally low silica 'softer' stone of poor flaking quality (with the exception of the poorly known Mata'are source on Mangaia (Weisler, Endicott, and Kirch 1994)), unlike the Samoan material, and more suitable for pecking and grinding to produce thick cross-section fully ground adzes of the Duff type 3 form (Sheppard, Sand, and Parker 2001). Movement to this adze form allowed the adoption of a wide range of locally available stone (Sheppard, Walter, and Parker 1997), after the movement away from early flaked quadrilateral forms. Connections east into central east Polynesia are evidenced by the appearance in the Cooks of very small amounts of stone from the Australs, possibly the Societies and from as far east as the Marquesas (1 adze) (Weisler and Walter 2016; McAlister, Sheppard, and Allen 2013; Allen and Johnson 1997; Rolett et al. 2015), all probably in the first few centuries after settlement. Study of considerable amounts of foreign stone at the early site of Tangatatau on Mangaia indicates a sharp falloff in extra-archipelago contacts after 1600 AD (Weisler et al. 2016: Fig. 3).

Directly east of the Southern Cooks lie the Austral Islands. The larger high islands in this group generally have igneous rock suitable for adze manufacture, however higher quality stone is found at the Vitaria quarry on Rurutu (Rolett et al. 2015) and the Tanataetea complex on Tubuai (Hermann 2013). A small number of adzes sourced to Vitaria have moved east into the Tuamotus and probably west into the Southern Cooks (Rolett et al. 2015: Fig. 8), with one adze from the Eiao quarry in the Marquesas found on Tubuai and dated to the second half of the 14th century CE (Hermann et al. 2017).

Six hundred kilometres directly north of the Australs lie the high Society Islands which have abundant resources of suitable adze stone (Kahn 2009; Kahn et al. 2013), which would have created little local demand for external material. There are limited sourcing studies of adze collections from this region, however a study of a large (47) excavated collection from the 'Opunohu Valley on Mo'orea (Kahn et al. 2013) showed considerable intra-archipelago movement of adze stone but no movement beyond, leading the authors to conclude that post 1350 CE 'Opunohu was not involved in the extra-archipelago importation of adze rock. An earlier study by Weisler (1998) had sourced one adze from 'Opunohu to Eiao in the Marquesas dating circa 1173–1406 CE at two sigma. However, as discussed below the Societies have been an important source of stone for the resource poor Tuamotus and at least one adze was transported 1600 km southeast to Mangareva at the end of the Tuamotu chain (Green and Weisler 2003; Weisler and Green 2001).

To the east of the Australs lie the Tuamotus, a broad chain of atolls and uplifted limestones which begin just east of the Society Islands then trend ~1500 kms southeast to Mangareva and are completely devoid of igneous rock (Weisler and Walter 2017). Manufacture or use of stone adzes required access to material from outside the archipelago, although shell adzes were commonly made locally (Clem 2017; Emory 1975). A considerable number of stone adzes in the Tuamotus have been sourced (Collerson and Weisler 2007) to the Society Islands (14), the Eiao source in the Marquesas (1), Rurutu and Rapa in the Australs (2) and Pitcairn (1) , with one Hawai'ian adze coming from Kaho'olawe.

Some 900 kilometres northeast of the Tuamotus lies the Marquesas archipelago. Considerable sourcing research (McAlister and Allen 2017; McAlister 2011) in this region has shown that the high-quality basalt from the Eiao Island quarry has been widely distributed in small amounts back into East Polynesia, much in character like the extensive distribution from the Tatagamatau quarry west from Samoa. A geochemical study of 278 adze samples from sites in Nuka Hiva (McAlister and Allen 2017) demonstrated considerable intra-archipelago movement of stone from a number of sources but did not identify any material from outside the group. Distribution out from the archipelago, from the Eiao quarry, does include specimens found in the Southern Cooks (McAlister, Sheppard, and Allen 2013), Society Islands (Weisler 1998), Tuamotus (Collerson and Weisler 2007), Mangareva and the Line Islands (Piazza and Pearthree 2001) where it is found in early contexts. The distribution of Eiao stone would appear to contract after 1450 CE (Rolett 2002)

The distant archipelagos of marginal East Polynesia all show very early discovery of local sources of suitable adze rock, but sourcing studies have arguably failed to identify any stone from outside, even in sites identified as dating from very early settlement. In Hawai'i there is considerable intra-island movement of adze rock including from the large high-quality Mauna Kea source (Kirch et al. 2012; Jennings, Weisler, and Walter 2023; Mills et al. 2022; Lass 1994), but very little evidence of inter-island movement within the archipelago, and there is just the one case of Hawai'ian stone moving out from the archipelago (Collerson and Weisler 2007). In the Pitcairn group early movement from the very high-quality sources on Pitcairn Island only extends to neighbouring islands and in the early period to Mangareva with a decline after 1450 CE (Weisler and Walter 2017). On Easter Island colonists rapidly found and exploited a variety of stone sources for adze manufacture, however there is no evidence for movement of stone into or out of the island (Simpson Jr and Dussubieux 2018). In the continental island of New Zealand Māori very early identified many high quality sources of adze stone scattered across the islands (Weisler and Walter 2017; Jennings, Weisler, and Walter 2023) which were widely distributed and used in the sites of earliest occupation (Walter et al. 2017). This early long-distance movement has been described as a 'coloniser' form of exchange which declined sharply after a few generations followed in late prehistory in a 'trader' form of distribution of greenstone (nephrite jade) from the South to North Island (Walter, Jacomb, and Bowron-Muth 2010). To date there is only one surface-collected adze of characteristic central East Polynesian form found in New Zealand; however its age is unknown and it is very difficult to exclude the possibility that it was made in New Zealand, based on petrography and geochemistry (Leach, Sheppard, and Parker 2017). The other possible import is three scoria blocks in the South Island which have been sourced to the Society Islands (Ramsay et al. 2021; but see Anderson 2022).

Throughout East Polynesia there is evidence from industrial stone distribution of long-distance voyaging continuing in the early period of settlement followed by decline after some generations, often with the development of simpler adze forms which could be made from stone with more limited flaking qualities which was locally available (Walter, Jacomb, and Bowron-Muth 2010; Jennings, Weisler, and Walter 2023; Weisler et al. 2016). As noted by Weisler and Walter (2017) a general overview of long distant movement of stone in East Polynesia, as evidence of connectivity, indicates earliest movement from Samoa and West Polynesia into the Southern Cook Islands which then formed a bridge east into central and marginal East Polynesia.

8. Conclusion

The evidence for the movement of industrial stone shows that contact between both Hawaii and New Zealand with central East Polynesia was minimal, and the evidence for contacts with the Marquesas appears to be early. We also find that the 18th century sails from these isolated and widely separated island groups in marginal East Polynesia were more similar to each other than to the Tahitian sail in central East Polynesia, which was accessible to external contact and influence. We also conclude that the 18th century HA/MQA and Māori sails described in this paper retained more of the form and structure of the Oceanic spritsails of the migration period.

Approximately a thousand years ago the vast eastern Pacific Ocean with its small, scattered islands and contrary winds was being settled by tacking canoes with Oceanic spritsails. Double canoes had greater capacity, range and upwind capability than single canoes, although some made the journey, and tacking canoes had differently designed ends with improved seakeeping ability. The Oceanic spritsail remained the basic sail of East Polynesia. Wind tunnel testing has not shown it was better than the three-spar lugsails, lateens and crab-claw rigs found in other parts of Oceania, but these were mostly associated with shunting canoes with reversible and similarly shaped bows and sterns. We conclude that the East Polynesian two-spar rig was well-suited to the tacking manoeuvre and convenient for reefing.

East Polynesian sails diversified after the migrations and the Tahitian rig acquired a standing mast with a very tall narrow and flat sail capable of sailing upwind as required. Hawaiian and Marquesan sails remained asymmetric like the Tahitian with a curved trailing edge but became fuller-bellied and squat for paddle-assisted sailing downwind. The Māori sail probably became bilaterally symmetrical in shape and better balanced as it adapted to sailing downwind in large-bodied single canoes. All three sails developed ways to manage gusts and stronger winds. Uniquely, the Tahitian sail with its shorter mast and longer flexible trailing spar could bend at the top and spill wind, the Hawaiian sail had a line to draw the tops of the spars closer together creating a funnel for wind to escape, and the Māori sail could be lowered and reefed at the bottom when going downwind.

The marine technology of early migrations allowed deliberate and purposeful voyaging, including upwind sailing when required. The pre-European transport of industrial stone provides an index for the decline in ocean voyaging and the relative isolation of island groups. Māori, Hawaiian and Marquesan sails remained structurally most alike in marginal East Polynesia, but in central East Polynesia long-distance voyaging lasted longest and the Tahitian sail shows West Polynesian influence, probably via the Southern Cooks.

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Data sharing not applicable – no new data generated.

Partnerships

This research did not use any primary data from Indigenous contexts.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization, G.I., P.S., R.G.J.F.. methodology, G.I., P.S., R.G.J.F.; investigation, G.I., P.S., R.G.J.F.; writing—original draft preparation, G.I., P.S.; writing—review and editing, G.I., P.S.

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