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The maritime transport of prehistoric megaliths in Micronesia

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Abstract

This paper examines Micronesian examples of megalithic transport, focusing particularly on the ocean transport of the famous stone money disks quarried in Palau by Yapese Islanders and moved back to Yap prior to European contact. Using a combination of climatic, oceanographic, ethnohistorical, ethnographic, and archaeological data, we examine the maritime technologies that the Yapese could have used to transport stone money across several hundred kilometres of open-ocean and offer hypotheses to show how this might have been accomplished using bamboo rafts, canoes and rafts towed by fishing canoes.

Introduction

Large stones or 'megaliths' many weighing in excess of 1000kg, were some of the most socially important and archaeologically visible resources used in the Pacific Islands. The largest and most famous examples of megaliths in Oceania are the moai statues of Rapa Nui (Bahn and Flenley, 1992; Burley, 1993; Mulloy, 1970; Rainbird, 2002; Van Tilburg, 1995). Other well-known examples in the region are beachrock or limestone slabs used for chiefly backrests, fortifications, and tomb enclosures in Tonga (Burley, 1993; Burley, 1998; Kirch, 2000; McKern, 1929), the stone faces of Palau (Osborne 1979:161; 174–176), latte stones in the Marianas (Russell 1998), basalt columns and boulders in both Pohnpei (Ayres and Scheller 2001) and Kosrae (Athens, 1990; Athens, 1995; Rainbird, 1995), and the stone money disks of Yap (Fitzpatrick, 2002, 2003a; Fitzpatrick and Diveley, 2004).

Ethnographic, ethnohistorical, and archaeological research demonstrates the importance that megaliths had to societies in the Pacific and the roles they played in spiritual and economic development and the rise of sociopolitical complexity. Despite megaliths having been found throughout the Pacific, however, the methods used for quarrying and transporting them are processes still not fully understood. Archaeological investigations (Ayres and Scheller 2001; Fitzpatrick and Diveley 2004), and aerial photography (Lipo and Hunt 2005) have shown that megaliths were moved from their quarries to other locations. Modern experiments dedicated to investigating the process of moving stones in Indonesia (Heizer 1966), Rapa Nui (Mulloy 1970; Van Tilburg 1995), and Pohnpei (Ayres and Scheller 2001), illustrate some of the difficulties in moving megaliths over land, and in the latter case, across shallow lagoons. Little research has been conducted, however, on how megaliths in Oceania could be transported over open water and the technologies possibly used to accomplish this task.

That megaliths were transported between islands testifies to the willingness of native Pacific Islanders to exploit distant resources and in the process, risk their lives to acquire socially and economically important stone, similar to other parts of the world. Micronesia, a region that comprises the northwestern part of the Pacific, is especially well suited for analysing megalithic production and transport because numerous examples exist whereby indigenous groups exploited and shaped stone and then transported them to different locations.

In an effort to better understand the engineering and labour requirements needed to transport megaliths of varying size, we examine the overseas transport of some of the most well known megaliths in Micronesia – Yapese stone money disks. These disks were quarried from limestone in Palau by Yapese Islanders and moved over 400 km back to Yap prior to and after European contact.

We recognize that not all disks were created equal. These megaliths come in varying shapes and sizes that changed through time in concert with available (and continually improved) technologies. The size of stones moved in prehistoric times probably did not exceed 2 m in diameter 'as the largest canoes were unable to carry more than one piece of this dimension' (de Beauclair, 1963). A disk of 2.0 m in diameter and about 30 cm thick would weigh around 2.76 tonnes. Although the weight of an individual disk would certainly vary due to the size of the perforation and edge thickness, we conservatively adopt 2000 kg as a benchmark weight in our analysis of watercraft buoyancy for overseas transport.

We begin by describing what is currently known archaeologically and historically about stone money to

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illustrate the importance these objects had to Yapese society. We then review the predominant annual winds and currents present in western Micronesia to provide a framework for analysing seafaring. Finally, we discuss the handling characteristics of specific watercraft types known to be in use historically in Micronesia that would or could have been used to transport stone money. For our research we use various watercraft configurations including bamboo rafts, single outrigger canoes, and a towed raft combination as suggested by Yapese oral traditions (de Beauclair, 1963; Müller, 1917). By combining the anemological (wind), oceanographic (currents), and ethnohistorical data with what we know about seafaring technologies, we can then develop hypotheses on the most viable and reliable configurations potentially used for transporting stone money and the time it took for the trip from Palau back to Yap.

Prehistoric megaliths in Micronesia: the case of stone money

In western Micronesia, Yap islanders carved disks in Palau of limestone (more specifically calcite; Fitzpatrick 2003c) known as *rai*, also commonly referred to as 'stone money' in Palau (Figure 1).

The quarrying and transport process, with 'several tens of men', could take years and when brought back to Yap, disks became important symbols of wealth, status, and power. Stone money disks are prominent features of Yapese culture and can be found today along village pathways, in front of private residences, and symbolized on government issued license plates.

Rai were used in a variety of social transactions such as gifts for marriage or payment of debts (Berg, 1992; de Beauclair, 1963; Fitzpatrick, 2003a). Their value was dependent on the size, shape, quality, and history of each disk. Yap has no indigenous limestone (Gifford, 1959) and so the Yapese negotiated with Palauan clans or villages to gain access to this exotic resource. The disks found at quarry sites are typically circular to ovoid in shape and range in size from 30 cm up to 330 cm in diameter. Completed disks have a central hole that was apparently made with a reef stone 'used as a fire drill' (de Beauclair, 1963).

Figure 1. Stone money disk on Orrak Island. (Scott Fitzpatrick)

According to Yapese oral traditions, those stones made and transported using traditional tools, as opposed to those manufactured historically with the help of European technologies, were the most highly valued. Only a few are thought to exist today (de Beauclair, 1963). Disks in the upper size range found in Yap, and representing the largest *rai* known, weigh in excess of nine tonnes and were quarried during historic times using metal tools and transported on European ships. Most *rai* are known to have come from the Rock Islands of Palau, although some were also apparently quarried in Guam (Berg 1992).

Archaeological and ethnohistorical research suggests that quarrying stone money may have begun as early as 600 years ago (Fitzpatrick, 2003a), although most evidence indicates that intensive *rai* production took place during the 18th and 19th centuries when Europeans arrived and became involved in this indigenous exchange system. In the process, traditional methods for carving and transporting stone money were transformed with the introduction of iron tools and the use of larger ships to transport disks back to Yap (Fitzpatrick 2003a, 2004; Fitzpatrick *et al.* in press). The most notable participant in this trade was Captain David Dean O'Keefe, an Irish-American who arrived in Yap after becoming shipwrecked in the late 19th century. Captain O'Keefe negotiated with the Yapese to bring labourers to Palau and *rai* back to Yap in exchange for copra (dried coconut meat). In 1872, the Yapese began travelling to Palau on O'Keefe's ship and the arrangement became a thriving business. He would sell copra and other goods in Asian markets, return to Palau to load the stone money cargo, and bring the disks back to Yap. Historical records indicate that he brought thousands of stone money pieces from Palau (Fitzpatrick 2003a) and by the late 1800s, Yap was inundated with stone money. O'Keefe was later forced off of Yap by German administrators and a ban was placed on inter-island voyaging near the turn of the 20th century. This effectively collapsed the lucrative transport of stone money between Palau and Yap.

In the 1930s, over 13 000 stone money disks were recorded by the Japanese (de Beauclair, 1963; Fitzpatrick, 2003a), although it is unclear how many of these were carved prior to European contact using traditional methods. Nonetheless, the sheer number of rai suggests that there was a considerable human investment in the quarrying and transport of these disks from Palau back to Yap over a period of several hundred years.

In their desire to obtain stone money, the Yapese faced many obstacles in their desire to obtain stone money, only a few of which can be seen archaeologically. The known archaeological record reveals little about the negotiating process with Palauans for limestone access or the transporting of workers to Palau and back, locating and carving the often brittle limestone and moving *rai* over the jagged karst terrain of the Rock Islands (Fitzpatrick 2003c; Fitzpatrick and Diveley 2004). It is clear, however, that the loads would need to be manoeuvred through the complex coral reef systems to an adequately wide and deep channel. Only after these difficult social and physical engagements would the Yapese have begun their long journal back home across open ocean.

Environmental background to stone transport

Geography

Micronesia is a region of the Pacific made up of approximately 3000 islands and reef islets (Figure 2). The total land area is approximately 2700 km^2 in an area of ocean around 7.4 million km^2 in size (Craib 1983). The colonization of many of these islands during the last two millennia (even the smaller coral atolls which have relatively fewer resources than higher volcanic islands), is a testament to the extensive navigational and sailing knowledge of Micronesians.

Yap and Palau are remnants of the highest peaks of the Kyushu Range that stretch from Japan to New Guinea. The islands lie west of the Andesite Line and are characterized by submerged continental rocks containing both volcanic (e.g. andesite) and metamorphic rocks (e.g. slate, schist). Palau consists of several hundred islands.

Yap, (see Figure 2B) consists of four main islands (Yap, Gagil-Tomil, Map, and Rumung) separated by narrow water passages and surrounded by a fringing reef. The Yap island group is situated at about 9° 30' north and is approximately 400 km northwest of Palau.

In addition to analysing local geography and reef passages (see Fitzpatrick and Diveley, 2004), climatic and oceanographic factors are integral parts of examining the

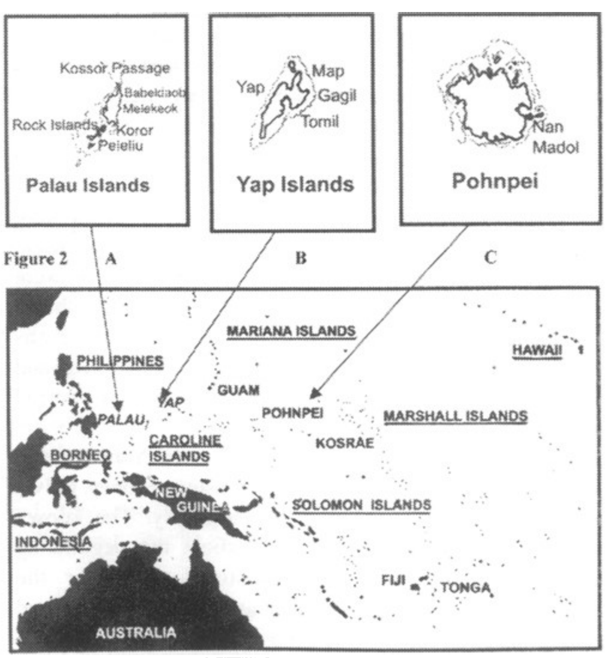

Figure 2. Oceania region. (Drawn by L. Hazell)

processes surrounding megalithic transport in Micronesia. For ancient mariners determining the seasonal patterns of winds and ocean currents is critical to avoid adverse wind directions and velocity, factors which directly influence the safety of the crews and the successful transport of heavy cargo (even though it was probably common for lives to be 'lost on strange islands or at sea …' (de Beauclair, 1963).

It is of course impossible to exactly replicate past weather conditions and fluctuations in winds and ocean currents affecting travel between Yap and Palau. However, modern data collected from a number of sources can be used as a benchmark for analysis (Falanruw, 1994; Gatty, 1944; Heyen, 1972; Jenkins, 1973; Johannes, 1992; Morris, 1988; USN, 1995) and has been applied in the Pacific and other parts of the world for estimating hypothetical routes of migration during different times of the year (e.g. Callaghan 1999, 2001).

Anemological (wind) data below demonstrate the effects that wind velocity and direction on the ocean surface would have on waveform, size, and speed. In addition, the direction and velocity of ocean currents all must be considered as affecting the buoyancy and handling of watercraft.

Having consistent airflow for sailing power and navigation, and favourable currents when crossing long stretches of open ocean, are important factors for open ocean sailing. As such, these elements can be used as analytical parameters in a research framework to determine likely seasons and sailing directions as well as the capabilities of craft and crews under such conditions.

Anemological (wind) patterns

The main climatic feature in western Micronesia is the equatorial trough of low pressure that induces an airflow known as the Northeast Trades (see Figure 3A). These occur throughout the winter and spring from October to May (Morris, 1988) and are fairly consistent winds with a mean speed of around 10 knots (18 km/h) throughout the winter and spring that would allow for 24 hour sailing.

During most of each day, the trades come from the northeast. But at midday, when the winds have reached their maximum velocity, the prevailing direction is from the east. With decreasing northeast trade winds in the month of April, the east winds are more frequent and become dominant in the region. On average, the mean wind velocity decreases from 10.5 km/h per hour in January to 5.8 km/h per hour in June. This is primarily due to the development of the Australian anticyclone that dramatically shifts the prevailing winds (Corwin *et al.* 1956). From July through October, winds are comparatively light with the mean monthly velocity around Koror ranging between 0.5 and 1.5 km/h per hour. In September, the zone of convergence begins to move southward and is again centred over the Palau Islands in October (Siedler, 1951; Rapaport, 1999). Finney (1988) and Hogg (1966) do note, however, some exceptions to both velocity and direction that would affect a laden craft.

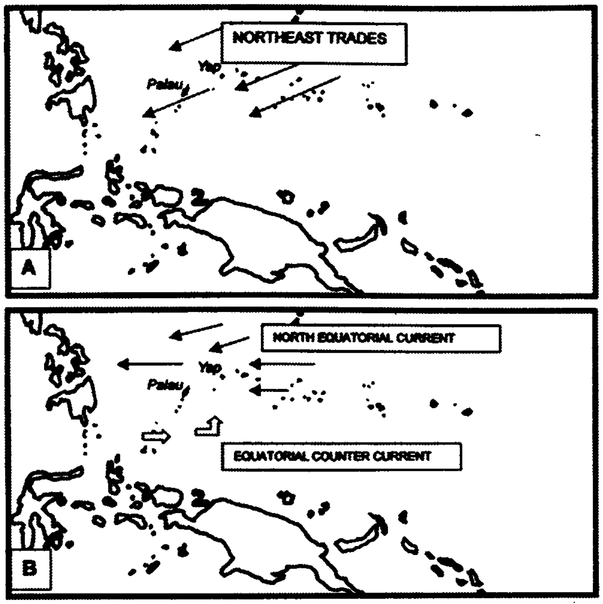

Figure 3. A: Prevailing winds, October–May; B: Ocean surface currents, June–December. (Drawn by L. Hazell)

Although the prevailing direction varies between east and northeast by about 45 degrees, this is still within the sailing beat or tacking capability of local sailing craft, critical to making progress against the wind. Tacking, and a local variation described as shunting (Doran, 1981), allows a sailing craft to sail into the wind by changing the angle of the sail to push the craft along. The tacking angle limitation of craft and sail is referred to as sailing 'close to the wind' where the craft sails as directly into the wind as sail, design and hull configuration will allow. Pacific watercraft are recognised for their ability to sail close to the wind, particularly when compared to early European square-rigger sailing ships (Bechol, 1972; Doran, 1976, 1978, 1981; Finney, 1988; Golson, 1972; Grimble, 1924; Haddon and Hornell, 1936–38; Hornell, 1946; Levison *et al.*, 1973; Morton, 1975; Parsonson, 1972).

Outside of the Northeast Trades, the highest number of days for winds originating from any given direction occurs in September. These 4–7 knot (7.2–12.6 km/h) winds come from the southwest for about seven days (Morris, 1988; USN, 1995). Calms (or low wind velocity) are reported for a similar number of days.

During September, surface currents can have a northwest to southwest set with only one or two days of suitable conditions for laden craft, particularly paddled rafts. The variable winds and surface currents also make this and other months with similar conditions difficult periods for sailing, and would have provided fewer chances for successful megalith transport. For example, the chance of having favourable southwest winds for travel from Palau to Yap would be between 41–60% in July, a rate that is reduced to 21–40% in October with a similar percentage for potentially opposing winds in October (Morris, 1988).

The Northeast Trades offer a comparatively consistent velocity and wind direction. This has two advantages for sailing: a constant wind direction that aids navigation on the open sea and a constant southeast or northeast ocean swell (depending on the month). Changes in the basic features of the waves such as shape, frequency, and size alert the navigators to the proximity of land (Gatty, 1944; Golson, 1972; Heyen, 1972). The second advantage allows the sailing capabilities of outrigger canoes to make full use of a constant or known wind velocity as a power source for sailing between the two island groups (Golson, 1972; Heyen, 1972; Lewis, 1978).

However, because it is necessary to tack against these consistent winds and currents, the extra distance travelled adds significantly to voyage length and travel time. Compare, for example, a square-rigger sailing clipper that can sail a maximum of 67° into the wind or a modern sailing yacht which can sail at an angle of 45°. A typical Pacific canoe can manage 60° (Doran, 1981). By translating these performances into distance travelled, we can see that in order to effectively travel against the wind, the Pacific canoe would need to travel twice the given straight line unit of distance, the square rigger 2.6 times, and the modern yacht only 1.4 (Doran, 1981; Finney, 1988; Morton, 1975).

The optimum sailing efficiency (or capability) as described above, determines both time and distance. For our research, this capability must be factored into regional wind conditions and direction to allow the crews viable travel periods within a reasonable amount of time. Hence, predictable and consistent winds such as the Northeast Trades would offer the best chance for successful sailing transport, particularly when 1.3 km/h drift currents flowing east to west are against the general direction of travel. The current is constant and paddling either a canoe or raft continuously would require a sustained peak effort to overcome its velocity. Even with small disks, this would be impractical and unsustainable using a paddled raft as we argue below. It is important to note that light or variable winds will limit airflow as an effective force for outrigger canoes, particularly with ocean surface currents that may not be moving in the same direction.

Currents

Palau is located at the junction of three major ocean currents – the North Equatorial Current (NEC), Equatorial Counter Current (ECC), and South Equatorial Current (SEC). The formation of these can produce considerable seasonal current pattern changes in the region (Irwin, 1992; Rapaport, 1999).

Between Yap and Palau, ocean currents are fairly consistent for most of the year, with only minor local variations in and around the various islands and reef systems that would 'not affect off shore passages' (Heyen, 1972). The currents flow east to west at around 0.75 to 1.25 knots (2.5 km/h) except through August and October when a variable, weaker NE set or direction occurs; a rate of 3 knots has been reported, however (Morris, 1988). The dominant ocean current that Yapese navigators would have encountered is the North Equatorial Current (NEC; (Figure 3B; Gatty, 1944; Jenkins, 1973; Morris, 1988; USN, 1995).

It is unlikely that paddlers could continuously propel the craft against even the lower velocity, as later discussion and examples will illustrate. If consistent ocean currents are against the direction of travel, and light variable winds are inadequate for viable navigation with sailing craft, it is reasonable to suggest that the most likely time of the year for sailing would be when there are consistent winds.

Sailing strategies and human endurance

Studies have shown that even well-conditioned athletes succumb to overexertion and must limit themselves to maintaining a certain pace to achieve satisfactory results. The same rules apply to prehistoric paddlers who must consume energy, resist overexertion, and constantly adjust their manoeuvres in response to anemological, oceanographic, and weather conditions (Baumeister, 1967; Cordain *et al.*, 1998; Henderson *et al.*, 1925; Horvath and Finney, 1976). By examining these issues in studies of prehistoric megalithic transport, we can more accurately determine what particular water transport methods could be used against or with the prevailing climatic and oceanographic conditions. These are used in conjunction with information gathered from oral traditions, historically known technologies, and archaeological investigation. Although the present study is limited in its ability to fully demonstrate how stone money manufacture and transport would be affected by human endurance factors, determining the viable water and associated land transport methods through cost benefit analysis and human energetics can lend some insight into the socio-economic costs associated with megalith production. Typically, the quarrying of disks took 'many months' before they could be moved from their quarry down to the water's edge for eventual transport (de Beauclair, 1963), and these efforts should be considered in stone money manufacturing and movement processes.

In general, experiments and personal experience (Baumeister, 1967; Cordain *et al.*, 1998; Hazell, 2001; Hazell, 2003; Henderson *et al.*, 1925; Horvath and Finney, 1976; Michael *et al.*, 1961; Severin, 1987) show that humans are limited in the duration of maximum effort (which for our research, is paddling at peak capacity). Strenuous exercise such as paddling imposes an aerobic cost. This ability, or lack thereof, determines the duration of sustained peak physical capacity. The capability of an individual to take up oxygen is the limiting factor for sustained physical effort (Åstrand, 1960). Even sustained peak capacity is still less than the sustained effort required to paddle a laden craft for hours against prevailing ocean currents (Counsilman, 1977; Severin, 1987).

As an example, a modern surfboat under maximum effort by a crew and a 200 kg displacement can produce around 6–7 km/h (Hazell, 2001). By comparison, a craft with around 1000 kg net displacement weight carrying around 2000 kg will have a probable speed of around 1–1.5 km/h due to resistance and handling factors, particularly in the open sea with the same number of paddlers. Increasing the number of paddlers will increase endurance rather than overall speed. But, necessary resting periods for paddlers would still result in the laden craft and its crew making little true headway when this pattern needs to be maintained over several hundred kilometres to offset the influence of the prevailing surface currents.

For megalith transport to be successful, a sustained means of propulsion would be necessary for extended periods of time. Sailing craft could provide the most reliable (repeatable) and viable (sustainable) means to do so. But this advantage is still subject to performance and load-carrying capability of the watercraft based on construction strength and integrity of the materials used.

Wind-generated waves will affect both the craft's structure and performance. Waves generated by 4–7 knot winds can reach up to 1 m high depending on reach or the distance and time the wind acts upon the surface of the sea from a particular direction (Bird, 1984; Kent, 1958; Sanderson, 1982). There is also a relationship between the height and beat, or wave interval. For the prevailing winds of this area, a 6 m beat and a wave speed of 7–10 km/h can be expected at the optimum time for transport (Kent, 1958; Sanderson, 1982).

The effect of these conditions can be illustrated by using a typical raft or canoe for this region which has an approximate beam of 7 m (Doran, 1981; Haddon and Hornell, 1936–38). By taking this wave beat and height beam-on (at right angles to the direction of travel), different sections of the raft or single outrigger will have a variable load applied to them. As the craft pitches or rises to a wave, the metacentric point (or centre of gravity) shifts, affecting buoyancy and stability by forcing lower parts of the raft to take on more of the load (Kent, 1958). Fastenings and cross-members of a bamboo raft would chafe and loosen as the applied pressure increased or decreased at varying points (Severin, 1995). Constant repairs are difficult to achieve with limited manpower, especially when sail adjustments for tacking and steering are needed to maintain the basic action of the craft. For a sailing canoe, each tacking manoeuvre, when the craft changes direction across these waves, will force the laden craft into a position of instability due to the metacentric shift. In addition, with a low freeboard or positive buoyancy, normally around 40 cm, water will inevitably fill or even swamp the canoe without constant bailing. However, while a steady ocean swell is expected in western Micronesia, relatively minor variations in wind velocity and direction will form an intermediate random pattern of waves of varying heights and frequency (Sanderson, 1982). The laden canoe will be slow to rise or respond to this uneven pattern and again be under threat of capsizing, so water must be bailed constantly.

From these observations and analysis, we now examine the performance of Yapese watercraft documented from ethnohistorical and ethnographic sources. These accounts provide several examples of the types of watercraft that may have been used in transporting stone money and how they each would be affected by ocean conditions during different times of the year (Bechol, 1972; Callaghan, 1999; Doran, 1976, 1981; Golson, 1972; Haddon and Hornell, 1936-38; Hornell, 1946; Langdon, 2001; Levison *et al.*, 1973; Morton, 1975). We analyse the load perfor-mance and load bearing capabilities of bamboo rafts and outrigger canoes, both of which are known to have been used by the Yapese (Doran, 1981; Haddon and Hornell, 1936–38; Hornell, 1946; Ling, 1970).

Yapese watercraft: analysis and performance for megalithic transport

Bamboo rafts

Yapese oral traditions describe the use of bamboo rafts and workers loading and setting them adrift with stone money which would then be caught up with several days later and towed back to Yap (de Beauclair, 1963; Fitzpatrick and Diveley, 2004). Large quantities of bamboo were available for constructing rafts and replication experiments provide some basic data for determining buoyancy requirements for this material in stone transport.

Ethnographic observations of sailing rafts indicate that they were in widespread use in the Pacific, yet archaeological evidence is limited (Blaxland, 1840; Bowen Jr., 1953; Doran, 1978; Haddon and Hornell, 1936–38; Hornell, 1946; Langdon, 2001; Ling, 1956; Ling, 1970; Morton, 1975). These are not compelling grounds, however, to exclude them from consideration since very few cases exist anywhere in the world of prehistoric watercraft being preserved in the archaeological record (McGrail 2003), especially in tropical regions where the preservation of organic materials is generally poor.

Robert Bednarik (pers. comm. 2004) found, 'a raft of high quality bamboo could carry 52% of its own weight before submerging', which means 17–18 tonnes of bamboo could effectively carry 7–8 tonnes. This estimate is based on bamboo raft construction tested by Bednarik (1997, 1998, 1999) in replication voyaging experiments. This estimate is borne out in other replication studies.

For example, Severin (1995) used a raft 60 feet (18.3 m) long with a beam of 15 feet (4.6 m) and a draught of only 1 ft. 6 in. (0.41 m) to carry seven tons of food, equipment, and crew of seven across the Pacific. Along the Ya River in China, a typical 80 foot (24.4 m) craft having a beam of 12 ft. 6 in. (3.8 m) could carry seven tons (7.8 tonnes) of cargo while having a maximum draught of 6 in. (16 cm; Worchester, 1983).

In these two cases, the raft was lengthened to provide the required buoyancy using three layers of bamboo. Selection and cutting of suitable varieties of bamboo for rafts at the right time of the year was critical. During the drier seasons, sap content is minimal, which maximises buoyancy (Severin, 1995; Worchester, 1983). The draught, or amount of freeboard, however, is ambiguous due to the nature of their construction. Waves, rather than passing ***under*** the raft, really pass ***through*** the layers, so the raft remains semi-submerged, but buoyant nonetheless (Severin, 1995). It should be noted that the dimensions cited by Severin (1995) and Worchester (1983) are not seen in the available evidence for Yapese rafts (Hernsheim, 1880; Loutz, 1910).

Having good buoyancy, bamboo rafts could have carried even the largest disks (Figure 4). Ayres and Scheller (2001) demonstrated this using similar materials and construction techniques for a raft that measured 7–9 m long and about 80 cm wide which supported a stone weighing 422 kg. Therefore, while buoyancy is not an issue for 2000 kg stones moved by islanders prehistorically, the effort needed to paddle the rafts and keep them afloat under load while going against the prevailing currents, is a difficult, if not unsustainable undertaking (Henderson *et al.*, 1925; Horvath and Finney, 1976; Michael *et al.*, 1961).

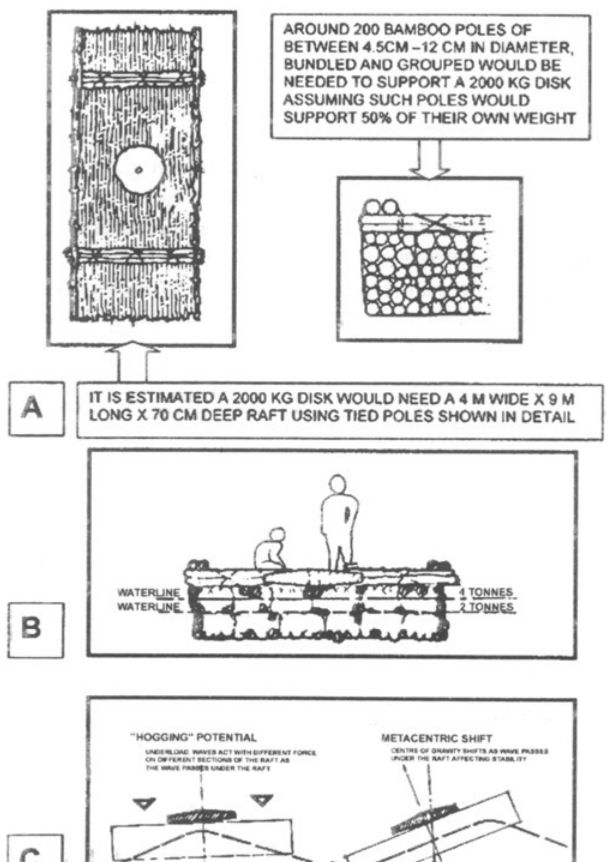

Figure 4. A: Bamboo raft construction and load/size relationship; B: Schematic cross-section – relative positive buoyancy or freeboard under 2000 kg load; C: shifting forces acting on a 4 m bamboo raft in 1 m waves. (All drawn by L. Hazell)

When not in use and without maintenance, bamboo rafts have an effective life of as little as six to ten months (Doran, 1978), suggesting that a new raft would be needed after nearly every retrieval voyage. Raft connections and structural poles would be weakened by prolonged exposure to salt water and subjected to teredo borer attack unless specially treated (Severin, 1995). The teredo is a bivalve mollusc (also known as a shipworm), the larva of which are planktonic and attracted to wood. This vulnerability, in addition to the need for constant on-going repairs, applies equally to both bamboo and other rafts as experimental voyages have shown (Heyerdahl, 1990). Under load, the effects of raft degradation would be amplified.

Some observations provide performance data of value for investigating how well bamboo rafts would function when transporting megaliths. Doran (1978) cited eyewitness accounts from sailors, along with experimental raft data, to illustrate that a straight-line distance of 33 km would in reality be 95 km after tacking legs to suit headwind sailing limitations. If these figures are applied to the approximate 400 km distance between Yap and Palau, the total distance travelled while tacking is 1110 km. Different sources report variations in speed to provide a time frame for covering this distance over open-ocean.

Levison *et al.* (1973), for example, used 5 knots (9 km/h) as a benchmark for simulation modelling and Doran used (1978) used 10 knots (18 km/h). After allowing for surface currents, a speed of 5 knots would give a corrected voyage duration of around 6–7 days to make the one way trip from Palau to Yap.

These figures are assumed to be with unladen rafts and certainly not with a cargo of stone, so true speed would be considerably less. Therefore, a corrected speed of 2 knots (3.6 km/h) is a reasonable assumption, giving a voyage time of around 13–14 days between the two island groups.

As noted previously, the Northeast Trades provide the most consistent period (~6 months) in which to travel if a sailing raft is used. Ethnographic reports (Edwards, 1960, 1965; Morrell, 1832), note how Peruvian balsa sailing rafts could do 5 knots 'on a wind'. However, these times are more likely to be achieved when there are ideal sailing conditions and by using a jagger board (also known as a dagger, centre, or *guara* board), a feature not known to have been used in Micronesia. This device allows a craft to sail closer to the wind than would normally be possible when using a single position steering rudder. Nonetheless, the critical positioning of the sail mast and changing jagger board position while tacking (shunting) would limit the size of the stone carried.

Single outrigger canoes

The second option for the Yapese transporting stone money is a single outrigger canoe. These perform similarly to rafts, but have a lesser load capability (Levison *et al.*, 1973). The Yapese used two types of canoes – the distinctive *tsukupin* (Figure 5), which is primarily a fishing vessel, and an

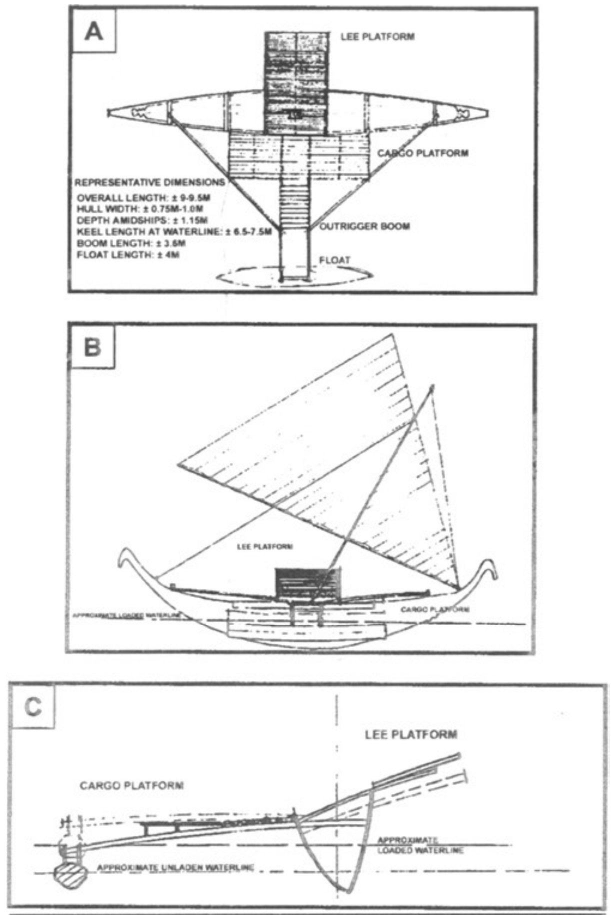

Figure 5. Tskupin configuration variant schematics. A: plan; B: side view; C: cross section detail. (All drawn by L. Hazell)

outrigger canoe known as a *popo* which has similar dimensions (Haddon and Hornell, 1936–38). Müller (1917; in Haddon and Hornell 1936–38:382) described the *popo* as having an overall length of 9.4 m with a keel length of 7 m. Depth amidships (the centre of the craft across the beam) was 1.15 m and the outrigger floats of 4 m attached to a boom of 3.6 m (Haddon and Hornell, 1936–38). Unlike the *popo*, the *tsukupin* possessed both lee and cargo platforms and was used primarily during the fishing season. It would be a very likely choice for stone money transport because of its cargo platform. But, there is a potential for instability when making shunting or tacking manoeuvres (see below).

The volume (displacement) weight of the *tsukupin* is 12 m^3 or 2005 kg (4422 lbs; Doran, 1981). The total weight, including 800 kg for the crew and 2000 kg of stone, is 10 560 lbs or around 4805 kg. The craft has an estimated safe positive buoyancy of 6350 kg (14,000 lbs) assuming an unladen freeboard of 40 cm. This freeboard is reduced under load by over half, even with wave heights under 1 m while tacking or shunting. Cargo weight influences the speed and stability of the outrigger and it is especially vulnerable to capsizing when on a shunting (tacking) leg. While some watercraft configurations improve their sailing stability when under load, single outriggers do not (Doran, 1981).

The shunting manoeuvre is similar in principal to European tacking. In this instance, however, the craft does not come around to point the bow of the craft in the new direction, but simply reverses direction to allow the outrigger to remain on the windward side at all times, rather than alternating between lee and windward legs. The hull, being symmetrical bow to stern, can be reversed, with rudder position and sail positions changed to suit the altered orientation.

The canoe will lose speed, or way, at a greater rate than would normally be the case with an unladen canoe. In doing so, the craft will move beam-on to the waves, a problem aggravated by uneven wave trains (James, 1983). While a steady ocean swell is expected, relatively minor variations in wind velocity and direction will form an intermediate random pattern of waves of varying heights and frequency depending on their duration and intensity (Sanderson, 1982). The laden canoe, in comparison to one unladen, will be slow to respond to this uneven pattern and come under threat of swamping.

Cargo weight will also increase friction, or resistance, by increasing the wetted surface. This influences the ability to either cut through or rise to oncoming waves (Doran, 1981; Kent, 1958; Seaton, 1909; Walton, 1921). A slow response to waves bow-on under load is also increased when sailing close to the wind. Retaining positive buoyancy, with frequent water coming onboard under these conditions, casts doubt on the viability of the *tsukupin* for transporting all but the smaller pieces of stone money.

The downwind (sailing with the wind) performance of a single outrigger requires a higher wind velocity than when sailing close to (against) the wind. It also requires a larger sail-handling capacity and so the potential for capsizing increases (see Doran [1981:68–69] who discusses the issue in more detail in relation to this type of craft). In general, the decreased downwind sailing performance is less of an issue as the craft would be unladen. It is during the return trip where accurate assessments of load and craft/crew capability will determine the success size of the stone disks transported. This requires that shipbuilders, ship-handlers, and navigators be cognizant of the canoe's anticipated performance when tacking and encountering variable wave patterns.

Traditional displacement watercraft in Oceania used two strategies to sail closer to the wind – one is structural in nature and the other is the shunting or tacking manoeuvre. The former is a transverse asymmetrical hull shape, not to be confused with the longitudinally symmetrical hull mentioned previously, and a windward outrigger float (Doran, 1976; Haddon and Hornell, 1936–38). The asymmetrical hull shape exerts differential pressure, similar in effect to an airplane wing, which creates high pressure under the wing and lower pressure above. Complementing handling behaviour, watercraft in Micronesia and the Pacific in general have a characteristic beam ratio equal to half the overall length, a ratio that usually gives a higher level of stability when unladen (Doran, 1981; Haddon and Hornell, 1936–38).

Close wind sailing capability is a factor for successful stone retrieval as much as stability and structural integrity of the craft. Another factor to consider is the likelihood of adverse conditions arising during extended voyaging. On average, 10 typhoons occur annually in the Pacific and there is a 20–40% chance of contrary winds (Morris, 1988) which would affect the success of a megalith carrying voyage.

Continuous sailing performance and speed will be determined largely by the navigator's skill, craft performance, and wind direction and speed. Outrigger speeds, such as those reported by Morton (1975), indicate that they could travel 'twenty-four miles an hour' (38.4 km/h) and 'he [*Anson from the Centuriaon*] thought they would do twenty knots' (36 km/h); these figures can serve as a general guide. In addition, 'A French officer ... estimated a speed of 10 knots ...' and 'been told they occasionally could reach fifteen' (knots or 27 km/h; Morton, 1975).

The variations and uncertainty of these outrigger performance figures suggest that using average or continuous speed is more appropriate for assessing possible successful transport methods; this is often less than noted by other researchers (Doran, 1976, 1978, 1981; Haddon and Hornell, 1936-38; Horvath and Finney, 1976; Levison *et al.*, 1973; Parsonson, 1972). The *tsukupin* is reputed to have covered 470 km in five days, equalling an average speed of 2.0 knots (3.7 km/h; de Beauclair, 1963), but it is unknown whether the craft was carrying cargo. Anderson (1967) noted Tongan double canoes could do seven knots 'in a gentle breeze'. This rate is also noted by Cook (Beaglehole, 1967) who while 'riding on a Tongan canoe, found it did seven knots by the log ... in a gentle gale'. Heyen (1972) noted modern Gilbertese canoes 'in racing trim' timed at over twenty knots'. Another example cited is a return trip of 500 miles (800 km) from Satawal to Saipan which took 10 hours for the first leg of 52 miles (83.2 km) while the remaining legs over 422 miles (675.2 km) took four days, giving an average speed of 8 km/h, or around 4 knots if we assume 4 x 24 hour days of sailing (Levison *et al.*, 1973). Whether cargo was being carried is not known, nor is the specific wind speed stated. The calculated average speed is similar to that noted by McCoy who states 'that such a canoe close-hauled can maintain a steady speed of approximately 5 knots under normal conditions' (Levison *et al.*, 1973)

Assuming that speeds from longer trips are affected by probable variations in wind velocity and surface currents, it is appropriate to use these speeds as a more conservative estimate. But variations in speed due to differing resistance from heavier loads further clouds the performance data. The duration of the voyages affected by these variables will be similar to those of a sailing raft, but with a higher risk of instability and greater buoyancy limitations.

Analysis of watercraft types

While a raft is probably not a viable option due to the unlikely possibility of crews being able to propel it against the prevailing currents, the sailing raft, because of mast restrictions and possible issues with structural integrity, is also inadequate for all but the smaller stone disks, as is the outrigger canoe albeit for buoyancy reasons. However, this is not to say that either or both of these were not used – firsthand observations would seem to suggest otherwise (de Beauclair, 1963). As oral traditions indicate, the loss of life may have influenced the value of *rai*, suggesting that not all Yapese stone money trips were successful, nor were they all expected to be.

Yapese oral traditions and historical paintings (e.g. Hernsheim 1880) describe or depict workers setting bamboo rafts adrift from Palau after being loaded with stone disks.

> '. . . a method was devised whereby the stones were singly allowed to drift on large bamboo rafts in the southwest wind; then after several days the men sailed after them in faster boats and tried to find them again so as to tow them toward Yap, no longer so far distant' (Müller, 1917).

This strategy would enable the Yapese to overcome the buoyancy limitations of sailing outriggers and take advantage of their close sailing capabilities. This would also avoid the need for paddling a raft against surface currents – instead they could be towed. Cheyne (1852) reported seeing Yapese canoes waiting along northern Babeldaob for passage back to Yap, but it is unclear whether they were carrying disks themselves, towing them behind rafts, or if this represented a change in transport behaviour post-European contact. If the strategy was to set the cargo adrift, a canoe typically travelling at 2–3 knots (around 5.4 km/h) with surface currents would take around 21–24 hours to catch the raft after several days of drifting. Visibility near sea level is less than 6 km, so time would also be needed to search for the raft. It is possible that the search time could be diminished if a signal mast or other device were placed on the raft so that it was visible from a further distance away.

Nevertheless, with a possible 128 km daily drift, the time required for retrieval would probably take 70–80 hours. As the drift of 1.2–1.8 km/h is southwards away from Palau, retrieval would take 3–4 more days to simply retrace the trip. This would be necessary as the prevailing ocean currents flow east to west for most of the year except between March and May when there is a 50% probability of a constant northeast current flow (Morris, 1988). The 'southwest wind' stated by Müller occurs mainly between July and October. Thus, the rafts are more likely to be taken away by ocean currents than driven northward by the wind. True speed against this current is 5.4 km/h, less surface current velocity, giving a corrected speed of 3.6 km/h.

As a result, a retrieval mission to catch and tow the rafts after leaving Palau and returning back to Yap would take around 21 days. This estimate is made up of three days at around 70 km/day with the current to catch the rafts. Shunting legs on this stage would be minimal because of sailing with both the wind and current. By taking the raft in tow and sailing against the current at a true speed of 3.6 km/h, a distance of 770 km is covered with shunting legs to retrace their passage back to Palau. This is then added to the 740 km covered in shunting legs between Palau and Yap against the prevailing wind. The total time taken at a speed of 3.6 km/h gives the estimated total of 21 days for the return trip.

It is important to note that inter-island transport is only one of many steps in the process of manufacturing and exchanging stone money. There are also various critical pre-departure activities. Time would be needed for negotiating with Palauans for limestone access, finding suitable speleoethems for carving *rai*, building a stone infrastructure

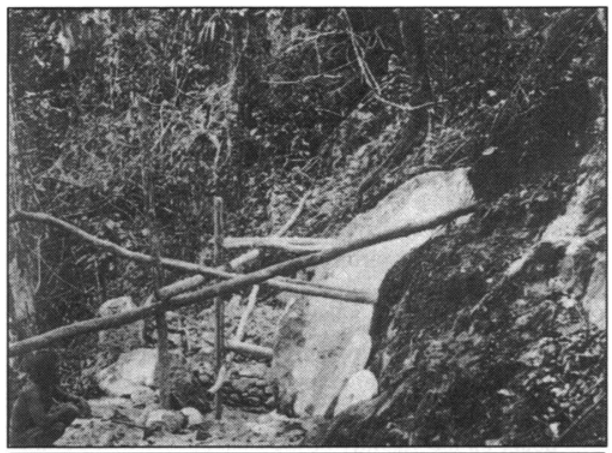

Figure 6. Timbers being used for support and/or scaffolding at a stone money quarry; note Yapese man in bottom left corner and stone wall/alignment bottom/centre. (From Müller 1917:132)

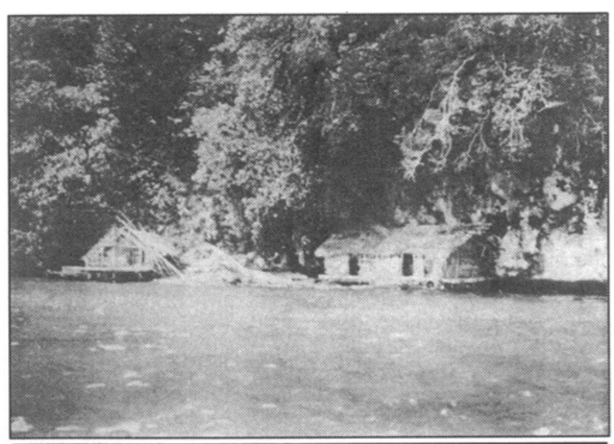

Figure 7. Residential, dock, and/or canoe house structures constructed on an island's edge near a stone money quarry, possibly the Metuker ra Bisech site. (From Müller 1917:128)

system of walls, docks, pathways, and foundations (see Fitzpatrick 2003; Fitzpatrick and Diveley 2004) (Figures 6 and 7), carving *rai*, subsistence activities during their stay, and the loading and unloading of these megaliths in Palau and Yap.

Nor does the timeframe include the building or replacing of degraded rafts and/or canoes. A similar single outrigger canoe in the Gilbert Islands (Kiribati) took about four months of steady construction by skilled craftsmen to complete (Grimble, 1924). Bamboo rafts would take considerably less time by comparison and less skill to build. However, the raft's vulnerability to decay in salt water and teredo borer attack means that it would need to be replaced at least annually. Altogether, this provides a comparative estimate of several months of activities prior to, during, and after *rai* production. This suggests the Yapese would need, and were willing to expend, a comparatively large amount of their available time and labour for a resource whose value was, in part, determined by factors associated with its retrieval.

Discussion and conclusions

Experimental studies involving stone transport have shed light on the effort and time required to move megaliths. Lehmann (in Heizer 1966) reported the movement of a one ton stone sculpture in Colombia over 7 km of rough terrain that required 35 men over a seven day period. Another experiment in Indonesia (Heizer 1966:827) involved the moving of an 11 tonne tomb capstone dragged on a sledge for two days by 525 men. Using these figures to estimate a person/weight ratio for carrying stone, it was postulated that it would take around 150 people to move stones in the seven tonne range found at some Palauan quarry sites (Fitzpatrick 2003), even with metal tools and other European technologies.

It is likely, as Ayres and Scheller (2002) suggested, that depending on the shape of the stone, once a weight of five tons is approached, it is easier to drag than lift. However, because stone money (albeit, probably smaller ones) were also transported over open-ocean prehistorically using rafts and/or canoes, it is critical to determine how this was done to provide a truer estimate of the labour and social costs involved.

Overall, the evidence cited above indicates that there were several options available for the Yapese to move megaliths – rafts, outriggers, or rafts towed by another craft.

As noted previously, Müller (1917) described the towing of laden rafts back to Yap. Our analysis suggests that this strategy would have been the most successful, if not the only way, the Yapese could have retrieved and transported the larger (2–3+ tonne) stone disks. Using the single outrigger to transport smaller stones either singly or in groups would have been a practical alternative. In enclosed waters, a paddled bamboo raft for transporting disks was possible, but not in the open sea.

Drift rates against the return leg direction, being in excess of sustainable paddling, would prevent the use of a paddled bamboo raft, notwithstanding its obvious buoyancy properties (deficiencies). Buoyancy limitations of *tsukupin* single outrigger canoes would exclude them from transporting the larger stones (those in excess of 2 tonnes). Therefore, the combination of using rafts towed by a single outrigger canoe would seem to provide a safer and more reliable option to transport the larger megaliths. Yet towing would not be without risk as resistance from a raft under seagoing conditions could damage the towing craft. Modern attempts to tow boats or cargo behind smaller watercraft illustrate the inherent dangers involved with such a task, suggesting that this method may too have been impractical or even impossible. The reliability of such a technique requires further study and experimentation to more fully examine the intricacies of megalithic transport on open water.

It is clear that all options for transporting megaliths across open ocean would have imposed a cost in human terms due to the vulnerability of the craft when under load. And it is important to note that although some of these options may be theoretically possible, even minor climatic or load changes could easily turn these return voyages into failed ventures.

As a displacement hull, the single outrigger depends on shifting its weight in water by volume to maintain buoyancy. The overtopping of its positive buoyancy reserve or the safety margin before water will flow into the craft is critical, and correctly assessing viable loads for safe displacement capacity could mean the difference between success and catastrophic failure. This risk is increased with load and the craft's slower response to meet uneven wave patterns typical of the open sea. The unladen single outrigger canoe has admirable sailing capabilities as witnesses note. The bamboo raft, presumably custom built in Palau to suit the size and number of stones carried, would not be as restricted by buoyancy limitations. Not having a displacement hull, the buoyancy of a bamboo raft is not overtly affected by uneven wave patterns and overtopping waves, but is vulnerable to structural failure unless constant repairs are made.

In addition, a raft is limited in speed when paddled against prevailing surface currents that are encountered on the homeward leg back to Yap. The raft's structural integrity also has a higher potential for failure when confronted with uneven wave trains, saltwater damage, and teredo borers. A sailing raft is less capable of harnessing the wind and manoeuvring over open-ocean than the outrigger, especially under load. The central mast positioning needed for a typical sail format would also determine the number and/or size of stones to be carried. Typical multi-layer construction of the sailing raft, while providing stability, is inefficient hydrodynamically. Diminished speed and handling against currents and winds as a consequence make this a less reliable and viable option in comparison to a single outrigger canoe.

The strategy of towing a raft with a single outrigger was the most flexible in terms of the load it could carry despite potentially being set adrift and increasing the time needed to find, secure, and tow the floating cargo. By exploiting the relatively constant Northeast Trade winds, the sailing outrigger could handle the various load and oceanographic changes. In addition, by towing a raft behind an outrigger, the time needed to transport the stones, although potentially longer, would probably not have been as life threatening. If problems arose such as a storm, the raft could simply be cut loose and potentially picked up later.

The risks of towing, as noted earlier, cast doubt on the viability of this method. It is important to note that all of the strategies we describe carry considerable risk, which apparently was recognised by the Yapese. As a result of these factors, values of *rai* may have increased as a consequence of risk and human life lost during carving and/or retrieval. Later, when Europeans became involved in *rai* production, a decrease in value occurred when comparatively more reliable and safer European ships were used for transporting labour and larger pieces of stone money (de Beauclair, 1963; Fitzpatrick, 2004). Our analysis suggests that none of the options for stone money transport – bamboo rafts, outrigger canoes, or towing – could have been successful in moving disks larger than two metric tonnes or so, supporting the hypothesis that larger *rai* could have only been transported on European ships.

As we have shown, determining the most successful watercraft that could be used in stone money transport is aided by examining anemological and oceanographic data. These are elements that also help explain the time required to bring *rai* from Palau back to Yap and highlight the potential risks and complexities involved with megalithic production and transport by traditional Micronesian societies.

Our analysis demonstrates that the Yapese could have moved megaliths around two metric tonnes across open ocean using traditional watercraft. It may be useful to explore maritime strategies as a possible means for moving megaliths in other parts of the Pacific, or even worldwide, when resource availability (e.g. timber, bamboo), complex topography, and distance from quarries to destination suggest that this may be a viable transport option compared to terrestrial ones.

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