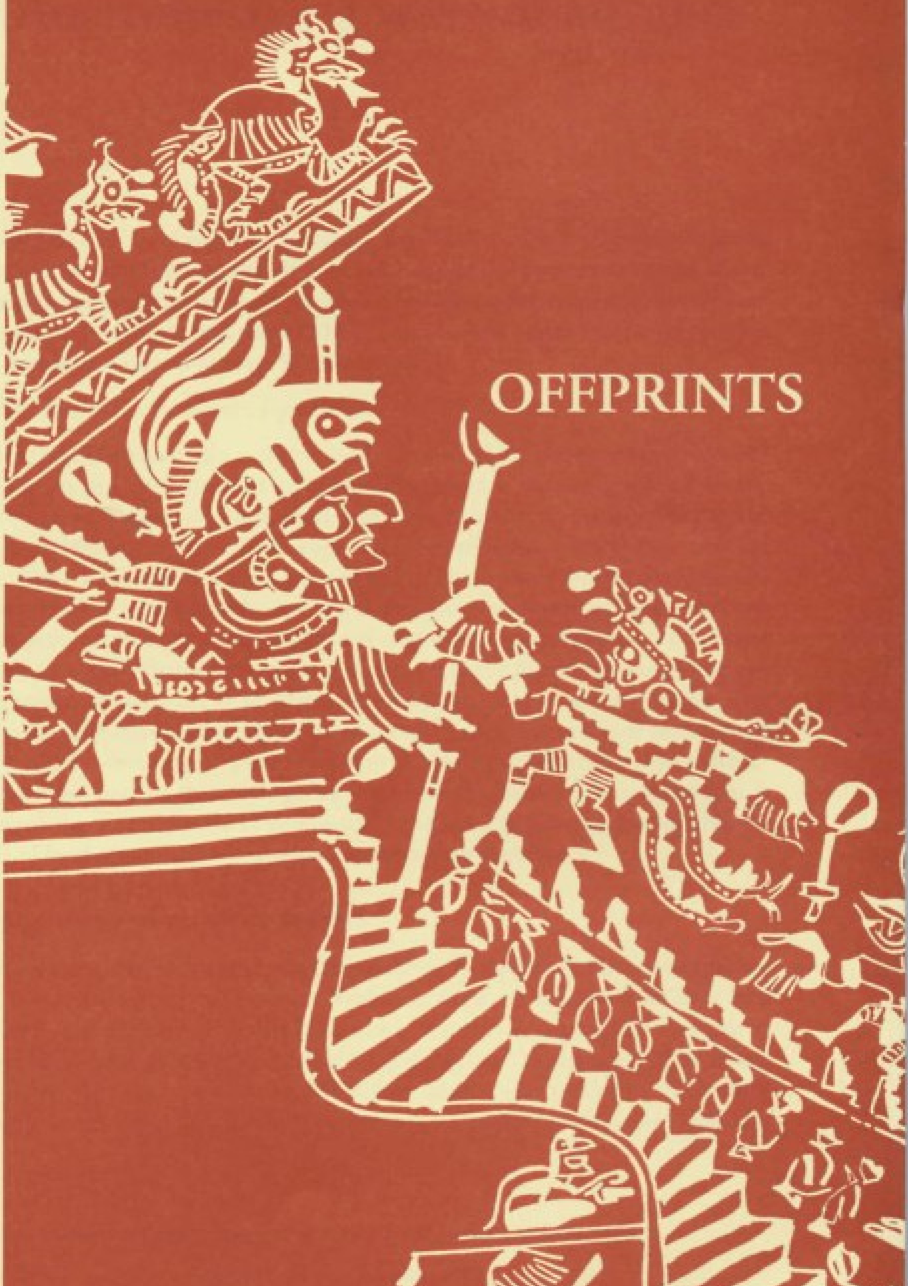
ANTIQUITY

Volume 77 Number 297 September 2003

A Quarterly Review of Archaeology
Edited by Martin Carver



OFFPRINTS

ISSN 0003 598X

Population expansion in the western Pacific (Austronesia): a wave of advance model

Joaquim Fort[1]

The author reconsiders the 'wave of advance model' used to describe (and partly explain) the rate at which people adopted farming. It is usually applied to large open areas, where one population group can easily see or meet another – but the populations considered here live on islands. Joaquim Fort finds that the 5000 km extent of the South Pacific was settled in the Neolithic period at a rate of at least 8 km per year.

Keywords: Neolithic, Pacific Ocean, demic, population.

The wave of advance model is based on a mathematical formula, which was originally proposed by Fisher (1937) to explain the spread of advantageous genes. It has been applied to the expansion of agriculture in Neolithic Europe, leading to the conclusion that farming originated in the Near East, from where it spread over Europe at a speed of about 1 km/yr (Ammerman & Cavalli-Sforza 1984). Subsequent studies have set out to investigate whether the spread of agriculture was mainly a *demic* process (physical diffusion of human populations), as opposed to a purely *cultural* process (diffusion of ideas between neighboring populations) (see Gkiasta *et al.* 2003). The present paper further investigates the way that the model reports changes in culture and population, by applying it to island communities in the western Pacific. The investigation concerns the Neolithic expansion in western Oceania (Austronesia) as indicated by Lapita pottery and its derivatives. This expansion is also equated to the expansion of population and farming, and in this case, given the distances involved, the expansion is certainly demic, involving the movement of people across the sea. The fact that the populations must farm islands of land separated by sea poses an interesting problem.

Character of the wave of advance model

The intuitive basis for the wave of advance model is as follows. To understand the development of agriculture in the place where a population lives, one needs to take into account two factors: mobility and reproduction. If individuals move, the area occupied will increase in time, and if a population reproduces very quickly its geographical expansion will be faster, because there are more individuals to disperse. Mobility is usually represented by the symbol *m*, whereas reproduction is taken into account by means of a parameter with the symbol *a*.

---

[1] Departament de Física, Universitat de Girona, Campus de Montilivi, 17071 Girona, Catalonia, Spain

Received: 27 September 2001 Revised: 11 November 2002 Accepted: November 2002

These symbols will be explained in more detail below.

The wave of advance model has been recently refined (Fort & Méndez 1999a; 1999b) by taking into account (i) that it is currently applied to two-dimensional population expansions, and (ii) the effect of the diffusive delay due to the mean generation time τ. The predicted speed is (Fort & Méndez 1999a)

$$v = \frac{\sqrt{am}}{1 + \frac{a\tau}{2}} \tag{1}$$

where the reproductive parameter a is usually called the initial growth rate of the population the mobility m is the mean square displacement per generation, and τ is the mean generation time (mean age difference between parents and their progeny). The reason why τ appears in Equation (1) is that usually sons have to grow before they leave their parents. Note that if this point were neglected (i.e., if τ were assumed so small that it can be approximately set equal to zero), then Equation (1) would become $v = \sqrt{am}$. This is almost the formula used by Ammerman and Cavalli-Sforza (1984: 68), namely $v = 2\sqrt{am}$. The only additional difference is the factor 2, and is due to the following point. It has been shown (Fort & Méndez 1999a) $v = \sqrt{am}$ that holds in two dimensions (e.g. the Earth's surface), whereas Fisher's result $v = 2\sqrt{am}$ can be used for populations dispersing in one dimension (e.g. along a coast). When applied to the European Neolithic, Equation (1) leads to a speed of 1 km/yr, which agrees with the value observed from archaeological data (Fort & Méndez 1999a).

The theory which leads to Equation (1) is a straightforward extension of the classical model due to Fisher (1937) and widely used in ecology (Shigesada & Kawasaki 1997; Turchin 1998; Williamson 1996). In both cases, one assumes a *tabula rasa*, or level playing field, in the sense that all areas of two-dimensional space are assumed equally suitable in principle for the settlement of human populations. This provides a macro-model, an approximation to a large-scale, space-averaged description of the observed clustered distribution of sites (Ammerman 2001). At a small scale, the habitat will not be homogenous, and we need to take account of the inevitable local ecological variation which is almost universal and affects specific local choices. Such 'micromodels' propose movement between one acceptable niche and another, as in the 'saltatory jumps' of Van Andel & Runnels (1995), or the 'leapfroggings' of later authors. As far as this author knows, no micromodel has yet offered quantitative, numerical predictions for the speed v in km/yr. As Bar Joseph (2001) clearly states, 'The two models have a common denominator and are essentially the same. The 'wave of advance' draws the large picture and the average rate of movement while the 'saltatory jumps' deals with the detailed reality'.

For mainland expansions, the first attempts to predict the expansion speed were based on discrete models (Birdsell 1957). In this context, *discrete* means that one distinguishes between suitable and unsuitable areas for settlement. But in such models one needs to assume specific numerical values for the number and size of the 'colonising' groups, the critical population density among which some individuals leave the territory in search of virgin lands, etc. (Birdsell 1957). Therefore, although discrete models are more detailed, they have the very important drawback that many parameter values are needed, which are very difficult to estimate in practice (Birdsell 1957).

The macromodel provided by Equation 1 is thus more practical, and, in the case of the spread of farming in Europe, it yields good agreement to the speed inferred from the dating of archaeological sites (Fort & Méndez 1999a; Ammerman 2001). The model enshrined in equation 1 was successfully applied very recently to explain the expansion of a completely different kind of biological population, namely T7 viruses in a medium composed of agar and *e. coli* cells (Fort & Méndez 2002). For a wide range of cell concentrations, the wave-of-advance speed predicted by such a continuous model was in agreement to that observed in laboratory experiments. This gives additional support to the approach we shall apply below.

Application to island populations

Since macro-models incorporate and average out the many jumps involved, it is reasonable to apply the same equation to island expansions, such as that in western Oceanic region (Figure 1). In the case of island expansions, settlements cluster on islands with large areas of sea between them (see Figure 2). This is analogous in practice to mainland expansions, where settlements are clustered near aquifer resources, while large forest areas remain unsettled (Ammerman 2001). The problems of applying the refined Equation 1 to island communities are therefore to some extent already present in mainland areas.

Although in Figure 2 we have only drawn long jumps for the sake of clarity, equation (1) was derived by considering an arbitrary distribution of jumps (i.e., travel distances; Fort & Méndez 1999a). There is no need to assume that all jumps are of equal length. Indeed, it would be questionable to do so, since often children stay at home with their parents, so that the jump length of some 'jumps' vanishes, whereas the mean or average length does not. Therefore, the model also allows for jumps inside an island ('terrestrial spread') in addition to inter-island, 'sea jumps' (such as that drawn in Figure 2). The mobility parameter m takes care of all such jumps in an averaged, macroscopic way (Fort & Méndez 1999a).

We believe that the archaeological data for the Neolithic expansion in western Oceania are already sufficiently numerous and accurate to calculate an order of magnitude for the speed of population expansion. We will try to answer the following questions: (i) What do archaeological data tell us about the speed of this process? and (ii) Can we explain why the speed has the value thus determined, instead of a different one? We will use anthropological data to suggest that there was a higher mobility among Oceanic than among than European Neolithic populations, and we will conclude that the speed of advance was consequently higher.

In order to use Equation (1) for the Neolithic expansion in Oceania, we need to evaluate the parameters a, τ and m.

Let us first discuss the initial growth rate a. It is very interesting that almost exactly the same growth curve has been obtained for two human populations which settled in empty space (Birdsell 1957). One of these sets of data refers to the Oceanic island of Pitcairn, and the other one to the Bass Strait Islands (between Tasmania and Australia). The agreement of both curves (Birdsell 1957: Figure 1) is remarkable if we take into account that these geographical areas are separated by some 10,000 km, and that there is a time interval of about 100 years between the periods during which both data sets were recorded. This leads to the value 0.032 ± 0.003 yr^{-1}, which has been used and discussed in more detail elsewhere

(Birdsell 1957; Ammerman & Cavalli-Sforza 1984: 71; Fort & Méndez 1999a).

Next we turn to the value of the generation time τ, i.e. the mean time between the birth date of a person and that of one of her/his daughters or sons. Values of τ in the range from 25 to 30 years have been often used for Neolithic populations (Ammerman & Cavalli-Sforza 1984: 155–156; Fort & Méndez 1999a). However, some authors have proposed $\tau = 20$ yr for Oceanic pre-industrial populations (see Kaeppler (1978: 248); Kirch (2000: 96)). Although such a low value seems unlikely, for our purposes we do not need a very narrow range of values for τ. Therefore, we will allow for the range $\tau = 25 \pm 5$ yr in our estimations below.

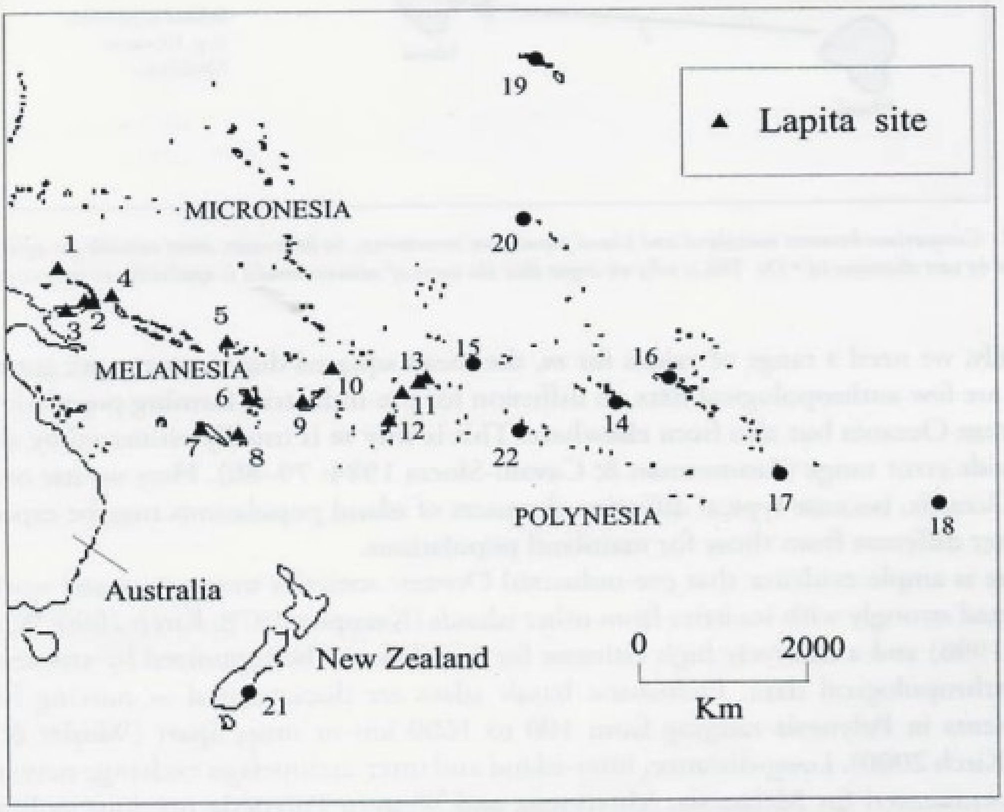


Figure 1. Map of Oceania. Triangles denote Lapita and related archaeological sites. Circles are sites corresponding to the expansion of Austronesian speakers beyond Samoa and Tonga. The geographical position and settlement dates of these sites have been used in Figure 2 for the computation of the speed of the wave of advance. The additional, non-Lapita Micronesian expansion is not included because it was apparently delayed (for explanations based on environmental factors, see Kirch (2000: 174) and Irwin (1992: 99)). Similarly, linguistics points to a previous expansion from mainland China, across Taiwan and the Phillipines (Bellwood 1997; Gibbons 2001; Gray & Jordan 2000), but it is not included because the corresponding archaeological settlement dates are not numerous and accurate enough at present and because their relationship with the Lapita culture is not well-established (Gibbons 2001). Also, Genetics has arisen some debates on the reality of this earlier expansion (Oppenheimer & Richards 2000; Diamond 2000; Gibbons 2001). The references where radiocarbon dates were reported can be found in Table 1. Some nearby sites appear under a single number (numbers 2 and 13 in the figure), but are considered separately in Figure 2. Distances inferred from this map are only approximate because of the Earth's curvature; we have computed the precise distances corresponding to great circle routes and used them in Figure 2. 1. Mussau; 2. Duke of York, Watom; 3. New Britain; 4. Nissan; 5. Santa Cruz; 6. Vanuatu; 7. New Caledonia; 8. Loyalty; 9. Fiji; 10. Futuna; 11. Ha'apaii; 12. Tonga; 13. Samoa, Niuatoputapu; 14. Societies; 15. Pukapuka (Cooks); 16. Marquesas; 17. Pitcairn; 18. Easter; 19. Hawaiian Islands; 20. Fanning; 21. New Zealand.

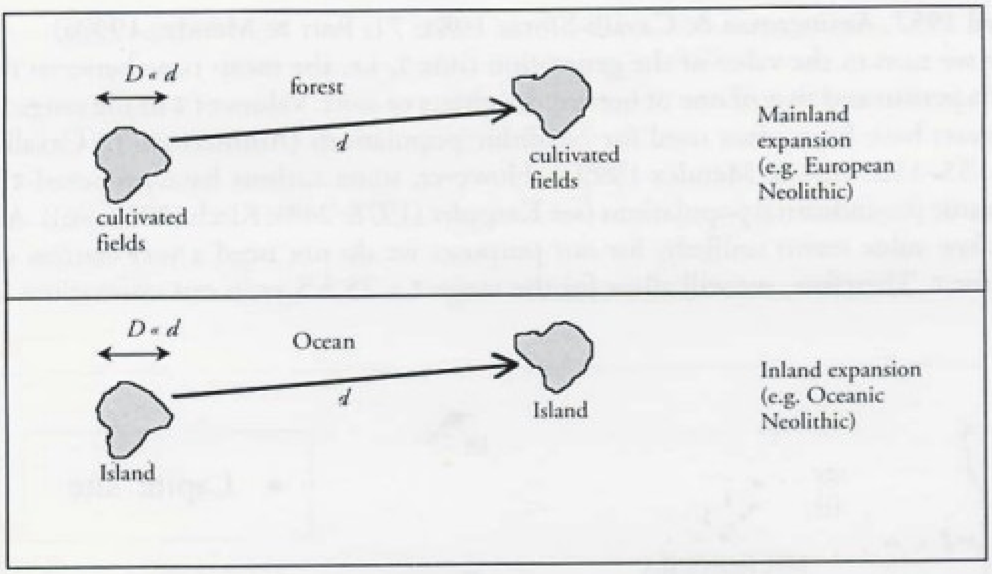


Figure 2. Comparison between mainland and island population movements. In both cases, areas suitable for agriculture are separated by vast distances (d ª D). This is why we argue that the wave of advance model is applicable to both cases.

Finally, we need a range of values for *m*, the mean squared displacement per generation. There are few anthropological data on diffusion for pre-industrial farming populations, not only from Oceania but also from elsewhere. This is why *m* is usually estimated by allowing for a wide error range (Ammerman & Cavalli-Sforza 1984: 79–80). Here we use only data from Oceania, because typical diffusion distances of island populations may be expected to be rather different from those for mainland populations.

There is ample evidence that pre-industrial Oceanic societies were not closed worlds but interacted strongly with societies from other islands (Kaeppler 1978; Kirch 2000; Weisler & Kirch 1996) and a relatively high estimate for mobility can be supported by archaeological and anthropological data. Prehistoric basalt adzes are documented as moving between settlements in Polynesia ranging from 100 to 1600 km or more apart (Weisler & Kirch 1996; Kirch 2000). Long-distance, inter-island and inter-archipelago exchange networks are well-documented for Melanesia, Micronesia and Western Polynesia previous to European contact (Kaeppler 1978; Malinowski 1922; Weisler & Kirch 1996). Ethnographic studies suggest an order of magnitude of about $d \approx 100$ km for inter-island diffusion (Mead 1930; Weisler & Kirch 1996). Malinowski (1922) reported migrations from the Trobriand islands to Dobu near Eastern New Guinea (with distances *d* of up to 150 km), as well as frequent migrations within the Trobriands ($d \leq 60$ km) and from the Marshall-Bennets into the Trobriands ($d \approx 100$ km). Parkinson (1986) described the immigration of about 110 people into Ontong Java (in the border between Melanesia and Micronesia) in the period 1880–1885 from about 500 km away. When combined with the population of Ontong Java at the time of European contact (Roscoe 1987), this yields an estimate of 550 km for the mean distance. This is much higher than the distances reported by Malinowski, which is no surprise because in that case the mean distance from any of the islands considered to the nearest one is much lower than in the case described by Parkinson. Multiple contact between populations in different archipelagoes, with an order of magnitude of 1000 km, have also been proposed on the basic of genetic studies of animals that accompanied the ancestral human migrants (Matisoo-Smith *et al.* 1998). The possibility of long-distance travel has been assessed by means of computer simulations in which wind and current forces are taken into account (Irwin 1992) and sailing trials with reconstructed antique canoes have shown that such journeys were indeed technically possible (Irwin 1992; Finney 1977). It has been argued that after colonization of new islands and archipelagoes, daughter communities would not tend to break away but to maintain linkages with their homelands (Kirch 2000).

Since we are interested in analyzing a population dispersal that swept over a distance of more than 10 000 km (see Figure 1) with islands of varying degree of isolation, it does not seem realistic to try to determine a very precise, homogeneous value for the mean migration distance. Therefore, from the anthropological observations above, we will allow for a mean migration distance in the range from 60 to 550 km/generation. Then, since the mobility m is defined as the mean square displacement per generation, it may be estimated as $m \approx d^2$, which yields values for m between 3.6×10^3 km and 3.0×10^5 km^2/generation. In comparison, the corresponding estimations for m in mainland populations are from 3.0×10^2 to 2.0×10^3 km^2/generation (Ammerman & Cavalli-Sforza 1984). All of these considerations are consistent with the fact that the range of values for m, as estimated above, is higher than the corresponding range for mainland populations.

Results

Using the values $a = 0.032$ yr^{-1} and $\tau = 25$ yr into equation (1), we predict a speed v in the range from 1.5 to 14 km/yr (obtained for $m = 3.6 \times 10^3$ and 3.0×10^5 km^2/generation, respectively).

Figure 3 shows the archaeological data in comparison to our theoretical prediction. Distances will not be exact because the actual routes may have been chosen on the basis of winds, currents and seasons. For the Lapita sites (triangles in Figure 3), distance is computed from the oldest site so far known (Mussau). For the subsequent expansion (circles in Figure 3), one may similarly determine distances from the earliest site (Northern Cooks) or, alternatively, from the Eastern Lapita site (Samoa). We follow the later procedure, since Austronesian populations east of Samoa necessarily came from the west. Let us mention, however, that we have checked that both procedures give essentially the same plot, and exactly the same conclusions. Figure 3 includes some broken lines, which are an attempt to represent the overall process. After an initial expansion, the Lapita culture (triangles) experiences a standstill of about 1700 years (Kirch 2000; Cann 2000). This was followed by a second expansion (circles). From the data available at present, we see that the observed speed for the first expansion is difficult to determine, because it relies heavily on the date of Mussau (the oldest site, at the lower left in Figure 3). However, note that we can safely infer a lower limit for this speed, namely 8 km/yr. The thinner broken line in the lower left of Figure 3 has a speed of 29 km/yr. At first sight, one might be tempted to call this the upper limit for the speed. However, such a conclusion seems questionable since, if the date of Mussau were in substantial error, even a horizontal line would be consistent with the other data (implying a very rapid process). Therefore, we have included the thinner line with speed 29 km/yr in Figure 3 only as a guide to the eye. What we can infer from this figure is that the speed of the Lapita expansion was *at least* of 8 km/yr. This observed lower boundary of 8 km/yr agrees, as far as the order of magnitude is concerned, with the theoretical speed found above (1.5 to 14 km/yr). We can see that the total distance involved was higher for the Lapita (about 5000 km, from the triangles in Figure 3) than for the European Neolithic (3000 km), but the time spent was much shorter for the Lapita (some 500 years or less, see Figure 3) than for the Europeans (3000 yr, from Ammerman & Cavalli-Sforza 1984). This difference in the time elapsed is the source not only of the differences in speed, but also in the error in determining them,

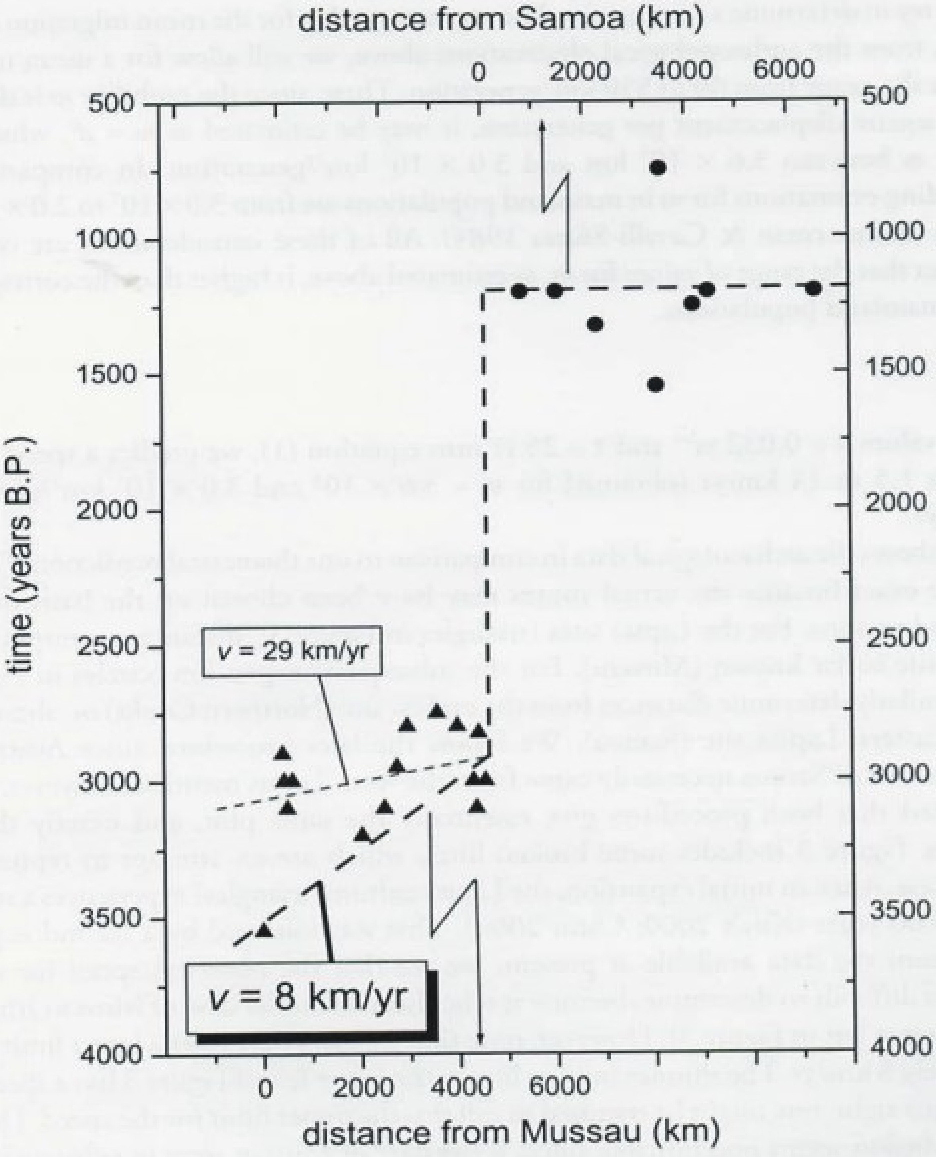


Figure 3. Estimation of the speed of the Austronesian expansion from the archaeological observations (dates in years before present). Triangles denote Lapita sites. Circles correspond to sites for the subsequent, Eastern expansion (see Figure 1). For the Lapita expansion (lower left), we infer a speed of at least 8 km/yr.

which is higher in the case of the Lapita. Indeed, the time interval corresponding to the triangles in Figure 3 is so low that a regression analysis yields a very high error (and a very low correlation coefficient). This is why we have presented only an estimation for the lower bound of the speed. The new result of $v > 8$ km/yr is interesting, however, because it shows a major difference with the European Neolithic and also because it is consistent with the predicted range for the speed (1.5 to 14 km/yr).

The dates of the second expansion (circles in Figure 3) fall in a narrow range (150-yr width), except for the Marquesas and New Zealand (the latter was probably colonised after some delay: this is not surprising since it involves a major jump, see Figure 1). Therefore, this second expansion seems extremely fast. But on the other hand, the two data outside the 150-yr range are in the middle of the others. In contrast with the Lapita expansion (triangles), it does not seem possible at present to determine a numerical bound for the speed of the second expansion, because of the relative positions and high dispersion of the circles in Figure 3.

Table 1. Dates, distances and sources of the sites used in Figures 1 & 3.

LAPITA	Number in Figure 1	km from Mussau	yr BP	Sources
Mussau	1	0	3550	Kirch (2000)
Watom	2	416	2900	Kirch (2000)
New Britain	3	512	3100	Kirch (2000)
Duke of York	2	442	3000	Kirch (2000)
Nissan	4	616	3000	Kirch (2000)
Santa Cruz	5	2029	3200	Kirch (2000)
Vanuatu	6	2490	3100	Kirch (2000)
Loyalty	8	2958	2800	Sand (1997)
New Caledonia	7	2745	2950	Sand (1997)
Fiji	9	3570	2750	Anderson & Clark (1999)
Tonga	12	4368	3100	Kirch (2000)
Futuna	10	3981	2800	Kirch (2000)
Ha'apai	11	4416	2825	Burley *et al.* (1999)
Samoa	13	4553	3000	Kirch (2000)
Niuatoputapu	13	4306	3000	Kirch (2000)

NON-LAPITA	Number in Figure 1	Km from Samoa	yr BP	Sources
Rakahanga (N.Cooks)	15	760	1200	Spriggs & Anderson (1993)
Aitutaki (S. Cooks)	22	1460	1200	Spriggs & Anderson (1993)
Societies	14	2247	1325	Spriggs & Anderson (1993)
Marquesas	16	3424	1550	Spriggs & Anderson (1993)
Pitcairn	17	4445	1200	Green (2000)
Easter	18	6530	1200	Spriggs & Anderson (1993)
Hawaiian Is.	19	4148	1250	Spriggs & Anderson (1993)
New Zealand	21	3507	750	Anderson (1991)

Critique

More precise determinations of the speeds may become possible after more accurate and numerous archaeological data become available. It would also be interesting to make further refinements of our theoretical computations for the speed by measuring dispersal distance distributions for pre-industrial agriculturalists in islands of varying sizes and isolations. This point deserves an additional comment. Here, we have estimated the numerical value of m by means of the approximation $m \approx d^2$, and used for d typical values for the distance per generation. More precise determinations would be based on averaging, i.e. using $m = f_1 d_1^2 + f_2 d_2^2 + \ldots$, where f_1 is the frequency of distance d_1 per generation, etc. (f_1 is the number of observations of d_1, divided by the total number of observations). This procedure has been used for mainland pre-industrial farmers (Ammerman & Cavalli-Sforza 1984: 155). So far, I have not been able to find such detailed data for *island* pre-industrial farmers, thus I have had to approximate $m \approx d^2$. For all these reasons, this paper should be regarded only as a first step, which outlines the methodology that can be used in future studies if more detailed diffusion data become available. Indeed, I would like to stress that the diffusion parameter m is not expected to be homogeneous because the mean island size and degree of isolation is not the same throughout the Pacific. This will lead to different values for the predicted speed at different geographic areas (e.g. for a faster speed for the circles than for the triangles in Figure 2).

The arrival of people in the model is based on the appearance of pottery (Lapita) associated with farming. However, genetic evidence points to the mixing of the Neolithic populations with pre-existing hunter-gatherers populations in Melanesia (Oppenheimer & Richards 2000; Gibbons 2001). In Western Oceania too the interaction with hunter-gatherers may be important (Bellwood 2000). Although models exist (Rendine, Piazza & Cavalli-Sforza 1986; Méndez, Fort & Farjas 1999, Sec. V), the estimation of a parameter or set of parameters characterizing the degree of interaction between farmers and hunter-gatherers remains unclear (for recent work see Gkiasta *et al.* 2003; Bentley *et al.* 2003). At present, we can only say that a varying degree of mixing may lead to local perturbations to the rate of spread. This point is only relevant for that region that had earlier populations, so that in the present case it would not apply beyond the Solomons (Bellwood 2000). Therefore, beyond number 4 in Figure 1, we would not need to consider any interaction between farmers and hunter-gatherers (as has been assumed overall in this paper).

Conclusion

It may be concluded that the wave-of-advance model is suitable not only to describe and explain the observed speed of the expansion of European farming (Ammerman & Cavalli-Sforza 1984; Fort & Méndez 1999a; 1999 b) but also that of the Austronesian population expansion. The present treatment shows that a continuous demic diffusion model can cover also models of 'saltatory jumps' and 'leapfrogging' suggested by other authors (above). In the case of the spread of farming between islands, we can be sure that the mechanism was demic, rather than cultural. In view of the uncertainties explained above, the order-of-magnitude agreement between the theoretical speed range (1.5 to 14 km/yr) and the observed lower bound ($v > 8$ km/yr, from Figure 3) is rather satisfactory. Changing the values of a and τ above yields essentially the same predictions (Tables 2 and 3). The refined equation (1)

Table 2. Effect of the population initial growth rate a on the prediction for the speed ν of the Austronesian expansion (generation time $\tau = 25$ yr).

	$a = 0.029\ \mathrm{yr}^{-1}$	$a = 0.035\ \mathrm{yr}^{-1}$
$m = 3.6 \times 10^3\ \mathrm{km}^2/\mathrm{generation}$	$\nu = 1.5$ km/yr	$\nu = 1.6$ km/yr
$m = 3.0 \times 10^5\ \mathrm{km}^2/\mathrm{generation}$	$\nu = 13.7$ km/yr	$\nu = 14.3$ km/yr

Table 3. Effect of the mean generation time τ on the prediction for the speed ν of the Austronesian expansion (initial growth rate $a = 0.032\ \mathrm{yr}^{-1}$).

	$\tau = 20$ yr	$\tau = 30$ yr
$m = 3.6 \times 10^3\ \mathrm{km}^2/\mathrm{generation}$	$\nu = 1.8$ km/yr	$\nu = 1.3$ km/yr
$m = 3.0 \times 10^5\ \mathrm{km}^2/\mathrm{generation}$	$\nu = 16.6$ km/yr	$\nu = 12.1$ km/yr

seems to serve an *island* expansion as well as a *mainland* expansion, and shows that the former was much faster. This may be explained by a much higher mobility, as suggested by anthropological data.

Acknowledgements

The author is extremely grateful to Profs. Luca Cavalli-Sforza and Peter Bellwood for very useful advice and discussions, and to Prof. Aurora González for providing access to the Human Relation Area Files and for discussions. Computing equipment was funded in part by the Generalitat de Catalunya under grant SGR-2001-00186 and by the Ministry of Science and Technology under grants BFM2000-0351 and REN2000-1621 CLI..

References

Ammerman, A. 2001. Agriculture: Spread of agriculture, in *Oxford Encyclopaedia of Evolution* (in press).

Ammerman, A. & L. L. Cavalli-Sforza. 1984. *The Neolithic transition and the genetics of populations in Europe.* Princeton: Princeton University Press. For computer simulations and the role of the interaction between farmers and hunter-gatherers, see Rendine, Piazza & Cavalli-Sforza (1986).

Anderson, A. 1991. The chronology of colonization in New Zealand. *Antiquity* 65: 767–95.

Anderson, A. & G. Clark. 1999. The age of Lapita settlement in Fiji. *Archaeol. Oceania* 34: 31–39.

Bar-Yoseph, O. 2001. Natufian through Early Neolithic: Economic and Demographic Trends in Southwestern Asia, in *Examining the Farming/Language Dispersal Hypothesis.* MacDonald Institute for Archeological Research, University of Cambridge, 24–27 Aug. 2001.

Bellwood, P. 1997. *Prehistory of the Indo-Malaysian Archipelago.* Honolulu: University of Hawai'i Press.

Bellwood, P. 2000. *Polynesian prehistory and the rest of mankind.* Proc. Pacific 2000 Conference (Easter Island Foundation, Hawaii, 2002).

Bentley, R.A., L. Chikhi & T.D. Price. 2003. The Neolithic Transition in Europe: the radiocarbon record revisted. *Antiquity* 77: 63–67.

Birdsell, J.P. 1957. Some population problems involving Pleistocene Man. *Cold Spring Harbor Symposium in Quantitative Biology* 22: 47–69.

Burley, D.V., D.E. Nelson, & R. Shulter Jr. 1999. *Archaeol. Oceania* 34: 59–70.

Cann, R.L. 2000. Talking trees tell tales. *Nature* 405: 1008–09.

Diamond, N. 2000. Reply to Oppenheimer and Richards, 'Slow boat to Polynesia?' *Nature* 410: 167.

Finney, B.R. 1977. Voyaging canoes and the settlement of Polynesia. *Science* 196: 1277–85.

Fisher, R.A. 1937. The wave of advance of advantageous genes. *Annals of Eugenics (London)* 7: 355–69.

Fort, J. & V. Méndez. 1999a. Time-delayed theory of the Neolithic transition in Europe, *Physical Review Letters* 82: 867–71 (1999). For computer simulations and the role of the interaction between farmers and hunter-gatherers, see Méndez, Fort and Farjas (1999), Sec. V.

–1999b. Reaction-diffusion waves of advance in the transition to agricultural economics. *Physical Review E* 60: 5894–5901.

–2002. Time-delayed spread of viruses in a growing plaque. *Physical Review Letters* 89, 178101.

Gibbons, A. 2001. The peopling of the Pacific. *Science* 291: 1735–37.

Gkiasta, M., T. Russell, S. Shennan & J. Steele. 'Neolithic transition in Europe: the radiocarbon record revisited' *Antiquity* 77: 45–62.

Gray, R.D. & F.M. Jordan. 2000. Language trees support the express-train sequence of Austronesian expansion. *Nature* 405: 1052–55.

Green, R.C. 2000. Religious structures of Southeastern Polynesia. In *Essays in honour of Arne Skjolsvld 75 years.* P. Wallin & H. Martinsson-Wallin, eds. Oslo: Kon-Tili Museum, pp. 83–100.

Irwin, G. 1992. *The prehistoric exploration and colonization of the Pacific.* Cambridge: Cambridge University Press.

Kaeppler, A.L. 1978. Exchange patterns in goods and spouses: Fiji, Tonga and Samoa. *Mankind* 11: 246–52.

Kirch, P. 1986. Rethinking Polynesian prehistory. *J. Polynesian Soc.* 95: 9–40.

Kirch, P.V. 2000, *On the road of the winds. An archaeological history of the Pacific Islands before European contact.* Berkeley: University of California Press.

Malinowski, B. 1922. *Argonauts of the Western Pacific.* London: Routledge and Kegan Paul, specially Chap. XI, Sec. IV.

Matisoo-Smith, E., R.M. Roberts, G.J. Irwin, J.S. Allen, S. Penny & D.M. Lambert. 1998. Patterns of prehistoric human mobility in Polynesia indicated by the mtDNA from the Pacific rat. *Proc. Nat. Acad. Sci. USA* 95: 15145–50.

Mead, M. 1930. *Social organization of Manua.* Bishop Museum Bull. 76. Honolulu: Bishop Museum.

Méndez, V., J. Fort & J. Farjas. 1999. Speed of wavefront solutions to hyperbolic reaction-diffusion equations. *Physical Review E* 60: 5231–43.

Oppenheimer, S.J. & M. Richards. 2000. Slow boat to Melanesia? *Nature* 410: 166–167.

Parkinson, R. 1986. Ethnography of Ontong Java and Tasman Island with remarks. *Pacific studies* 9: No. 3, 1–31.

Rendine, S., A. Piazza, & L.L. Cavalli-Sforza. 1986. Simulation and separation by principal components of multiple demic expansions in Europe. *American Naturalist* 128: 681–705.

Roscoe, P.B. 1987. Of canoes and castaways: reassessing the population of Tongavera (Penrhyn Island) at contact. *Pacific Studies* Vol. 11, No. 1, 43–61, specially note 5 and the population model in p. 50.

Sokal, R.R. & F.J. Rohlf. 1981. *Biometry,* 2nd ed. San Francisco: Freeman.

Sand, C. 1997, The chronology of Lapita ware in New Caledonia. *Antiquity* 71: 539–47.

Shigesada, N. & K. Kawasaki. 1997. *Biological invasions: theory and practice.* Oxford: Oxford University Press.

Spriggs, M. & A. Anderson. 1993. Late colonization of East Polynesia. *Antiquity* 67: 200–217.

Turchin, P. 1998. *Quantitative analysis of movement. Measuring and modelling population redistribution in animals and plants.* Sunderland: Sinauer Associates, Inc.

Van Andel, T.H. & C.N. Runnels. 1995. The earliest farmers in Europe, *Antiquity* 69: 481–500.

Weisler, M.I. & P.V. Kirch. 1996. Interisland and interarchipelago transfer of stone tools in prehistoric Polynesia. *Proc. Nat. Acad. Sci. USA* 93: 1381–1385.

Williamson, M. 1996. *Biological invasions.* London: Chapman & Hall.