the highest concentration of NH_4^+ typically found in the Potomac (~ 1.5 mg liter^{-1}). Growth is limited therefore by substrate [NH_4^+], and the equations reduce to Eqs. 3 and 4. The behavior of NH_4^+ in the Potomac and Delaware rivers implies that microbial populations move with river flow, whereas in shallow streams nitrifying activity occurs at the bottom [T. J. Tuffey, J. V. Hunter, V. A. Matulewich, *Water Res. Bull.* **10**, 555 (1974)].

13. The validity of Eq. 5 was verified by detailed analysis with a complete hydraulic and kinetic model.
14. The value $\alpha = 0.1$ gave the best fit for 1977 and 1978; 0.05 is optimal for 1979.
15. The number of active nitrifying bacteria should be measurable in principle, but existing methods (most probable number) appear unreliable. Numbers of nitrifying bacteria predicted here are comparable to values determined by E. J. C. Curtis, K. Durrant, and M. M. I. Karman [*Water Res.* **9**, 255 (1975)] for polluted estuaries in England.
16. D. E. Hammond and C. Fuller [*Eos* **61**, 1003 (1980)] estimated τ in the range 4.5 to 7 days by using radon deficit measurements. The engineering formula $\tau = (d^3/(Dv))^{1/2}$ gives a similar value, $\tau = 5.7$ days, with depth $d = 450$ cm, tidal velocity $v = 15$ cm sec^{-1}, and diffusion coefficient $D = 2.5 \times 10^{-5}$ cm^2 sec^{-1} (*1*).
17. Small quantities of N_2O are formed during chlorination of sewage—typically ~ 10 percent of the source from nitrification (0.06 g sec^{-1} compared to 0.5 g sec^{-1} from nitrification). Slightly larger quantities of N_2O (0.2 g sec^{-1}) were produced as a result of heavy chlorination in 1979 [R. J. Cicerone, J. D. Shetter, S. C. Liu, *Geophys. Res. Lett.* **5**, 173 (1978); W. A. Kaplan, J. W. Elkins, C. E. Kolb, M. B. McElroy, S. C. Wofsy, A. P. Duran, *Pure Appl. Geophys.* **116**, 423 (1978)].
18. Yields of N_2O from nitrification in the Potomac were estimated also by observing the time courses of N_2O, O_2, NH_4^+, NO_2^-, and NO_3^- in water samples placed in sealed vessels. Observations at 0, 7, 24, and 48 hours showed parallel increases in N_2O and ($NO_2^- + NO_3^-$), with N_2O yields between 3.0×10^{-3} and 3.7×10^{-3} mole of nitrogen per mole of NO_2^- on 5 August 1979 and between 1.8×10^{-3} and 4×10^{-3} on 17 August 1980.
19. The concentration of ($NO_2^- + NO_3^-$) increases downstream of sewage plants as NH_4^+ is oxidized. On average, the peak concentration of ($NO_2^- + NO_3^-$) accounts for 54 ± 14 percent of the total nitrogen source. However, a much higher fraction of NH_4^+ may be removed by reaction 1, since oxidized species (NO_2^- and NO_3^-) are rapidly consumed in the estuary (*9*).

20. We are indebted to T. Flaherty for invaluable discussions and to C. Spivakovsky, W. Kaplan, L. Hashimoto, A. Duran, C. Kolb, T. Goreau, G. Soffen, J. Ledwell, P. Tolbert, A. Appiah, S. Troian, S. Frankel, and K. Buttleman for help in sampling and analysis. Supported by NSF grant DEB79-20292, EPA grant R807081010, and NASA grant NASW 2952 to Harvard University.

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Lapita Colonization of the Admiralty Islands?

Abstract. *Archeological research in the Admiralty Islands provides evidence of occupation by 3500 years ago and suggests settlement by obsidian-using maritime colonists, whose Lapita pottery style underwent gradual modification within the Admiralties.*

Excavations at Kohin Cave (*1*), Admiralty Islands, Manus Province, Papua New Guinea, have produced pottery and Lou Island obsidian throughout well-stratified deposits. Four sherds from lower stratigraphic layers are decorated with dentate-stamped impressions, distinctive of the Lapita style (*2, 3*). Lou Island, in the Admiralties, is one source of obsidian found in Lapita sites further east (*4, 5*). The dentate-stamped sherds from Kohin Cave are the first evidence of a cultural association between the Lapita complex and an assemblage of comparable age from the Admiralty Islands. The sherds are in a secure stratigraphic context, from layers bracketed by carbon-14 dates. The evidence from Kohin Cave suggests that these sherds and others from the lower layers represent an early phase in a local developmental sequence, beginning with the settlement of the Admiralties by seagoing colonists whose pottery was in the Lapita style.

Table 1. Carbon-14 (half-life 5570 ± 30 years) dates from Kohin Cave. The age of sample ANU-2248 is corrected to the equivalent charcoal age (*15*).

Number	Sample	Layer	Age (years)
ANU-2089	Charcoal	4	2070 ± 120
ANU-2215	Charcoal	4	1910 ± 90
ANU-2212	Charcoal	5	2310 ± 120
ANU-2248	Shell	10	3450 ± 100

Two excavations of Kohin Cave, on the southeast coast of Manus Island, in 1978 (*1*) and 1979 covered 11 m^2. Excavation followed depositional strata, and disturbances and discontinuous lenses were isolated. The stratigraphy of the two excavations correlates well. Most layers, although varying in thickness, are continuous throughout. Excavation techniques and layer correlations allow the provenance of cultured materials and their association with dated samples to be stated with confidence.

The deposits, in ten major layers, all contain cultural material and are built up on a bedrock base at an average depth of 1 m below the surface. Two layers have special significance. Layer 4, continuous throughout the excavated area, has a surface defined by several hearths and scattered ash and charcoal, indicating a period of occupation. Layer 10, a shell midden, is built up on bare rock. Carbon-14 dates have established the chronology (Table 1). The layer 4 samples are from opposite ends of the 1978 excavation and date cultural features in that layer. The charcoal of the layer 5 sample is not as clearly the product of human action as are other samples but is stratigraphically associated with cultural material. The layer 10 sample (from a small species of *Tridacna*) dates the surface of that layer; stratigraphic evidence indicates that layer 10 was deposited rapidly. There is no evidence to suggest a chronological hiatus between layer 10 and those above it.

Sherds and obsidian flakes and spalls occur throughout the layers, but there were no other significant artifacts. The obsidian derives from several sources on Lou Island (*6*). Neither pot forms nor fabric types can be satisfactorily distinguished from the sherds, which are mostly very small and eroded or chemically altered (Table 2). In layer 10, sherds are rare, even taking into account the much smaller volume excavated; however, that layer may have been deposited virtually during a single cultural event.

Distinctive sherds (rims and decorated pieces) provide a basic ceramic sequence, of which the salient features are as follows: (i) there is overall continuity of rim forms and decoration; (ii) several new rim forms and elaborations of decoration appear in layer 4; (iii) the four dentate-stamped sherds derive from layers 7, 8, and 9; and (iv) the layer 10 sherds are not distinctive. Figure 1 shows typical decorated sherds, including all the decorated body sherds from layers 7 through 9. Because of fragmentation and chemical alteration, the four dentate-stamped sherds cannot be clearly associated with others from the same layers on the basis of either formal or fabric identity. Each sherd seems to bear a different motif, each executed with a tool of different dimensions. The other four decorated body sherds and decorated rims from layers 7 through 9 have shell impressions or linear incisions. Such decoration is not inconsistent with the Lapita style (*2, 3, 7*), but it is not itself distinctive and occurs throughout the Kohin sequence. From stratigraphic associations and position in the ceramic

Table 2. Numbers and types of sherds in various stratigraphic layers of Kohin Cave. Totals include all sherds, and rims include both plain and decorated sherds; decorated refers to body sherds only. Approximate densities were derived from the area excavated and the estimated average thickness of the layer.

Layer	Sherd count			Density (m^3)
	Rims	Decorated	Total	
1 to 3	30	17	826	376
4	27	23	591	358
5 and 6	9	1	259	173
7 to 9	28	8	883	370
10	0	0	8	24

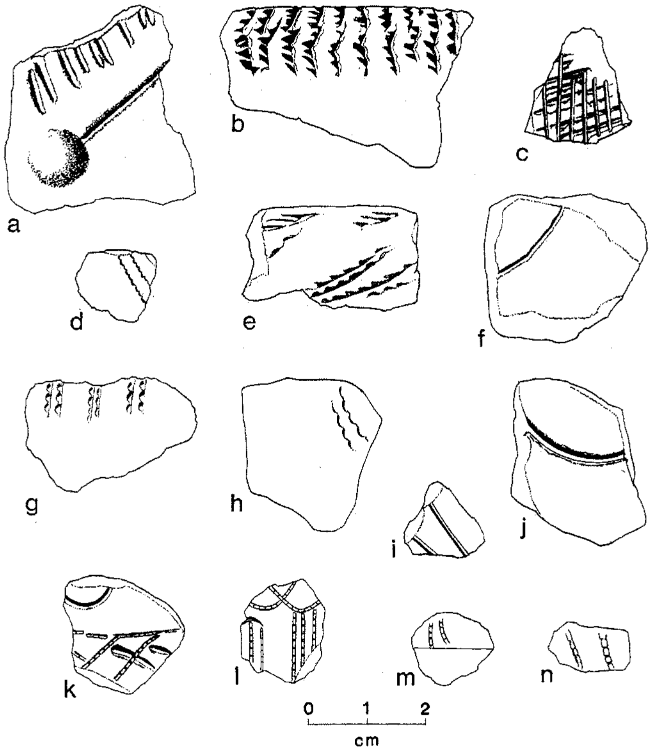

Fig. 1. Decorated sherds from Kohin Cave: (a to d) layer 4, (e to f) layers 5 and 6, (g to n) layers 7 through 9; (a, c, f, i, and j) incised; (b, d, e, g, and h) shell-impressed; (k to n) dentate-stamped; (b and e) rims.

sequence, however, the dentate-stamped sherds and other sherds from layers 7 to 10 belong together.

The quantity and disposition of cultural material throughout the sequence is consistent with short-term visits by small groups of people. Such occupation might not necessarily reflect the routine of the population at large, but only more transitory episodes such as visits by people seeking refuge or shelter.

The basal Kohin date is the earliest yet from the Admiralty Islands. Sherds from site surveys (*1*), sorted on the basis of the Kohin ceramic sequence, suggest that most sites are chronological equivalents of layer 4 (about 2000 years old) or are younger. Most older surface material comes from Lou Island, from exposures of a soil mantled by up to 3 m of ash and pumice deposited about 2000 years ago (*6*).

Lapita sites are distributed from the St. Matthias Islands (*5, 7*) to Tonga and Samoa (*3*). Lapita pottery characterizes the earliest sites known in Tonga and Samoa. These sites represent the only known major colonization of these islands and are therefore ancestral to the islands' Polynesian cultures (*3, 8, 9*). Thus, the nature of the Lapita complex is crucial to the question of Polynesian origins. White and Allen (*10*) suggested that the spread of the Lapita complex might be due to either a rapid movement of maritime colonists or a network of specialized long-distance traders. They favor the first possibility and point out that the second depends on the existence of established populations with which to trade and predicts that Lapita sites would occur in areas from which resources found in Lapita contexts are derived. Their argument against trade referred to a preceramic occupation of Kohin Cave and to the absence of Lapita pottery in the Admiralties. The Kohin evidence refutes both these points, but preceramic occupation elsewhere in the Admiralties is still a possibility. The trader hypothesis is weak because of the absence of evidence of preceramic occupation and of a two-way flow of goods. The colonization hypothesis invites questions about the source, direction, and nature of movements and is strongest where there is evidence that primary Lapita settlement resulted in an adaptation to local conditions and subsequent internal development, as there is for Tonga, Samoa, and probably for Fiji (*3*). Further west, from the New Hebrides to the large islands of the Bismarck Archipelago, where there is evidence of a more complex suite of ceramics (*11*) and of preceramic settlement, in New Ireland at least (*12, 13*), the chronological and cultural relationships of Lapita sites are less clear. Lapita origins in the Bismarck Archipelago are attributed either to a population movement from island Southeast Asia (*5, 9*) or to primarily local development (*10, 13*). The Bismarck Archipelago has been proposed as the immediate source of the Lapita complex in areas to the east (*3, 10, 14*).

The Kohin ceramic sequence suggests cultural continuity within the Admiralties from 3500 years ago. The presence at the beginning of the Kohin sequence of obsidian from several Lou Island sources and in the closest Lapita site, in the St. Matthias Islands, dated at 3900 years old (*5*), demonstrates that detailed knowledge of this resource was already available, implying settlement in the Admiralties earlier than 3500 years ago. The appearance, later in the Kohin sequence, of obsidian from additional Lou Island sources (*6*) shows that local supply, once established, was maintained across a difficult open-sea passage. However, there is as yet no evidence to show whether distribution was effected by trade or direct access, either within the Admiralties or beyond. Although the Kohin evidence favors primary Lapita colonization, it does not rule out participation of the population in networks of internal or external trade and exchange.

Kohin Cave is not a typical Lapita site, and its only direct connection with such sites is the presence of four small sherds. Nonetheless, the Kohin evidence suggests the possibility that the Admiralty Islands were colonized by makers of Lapita pottery. There is no evidence for subsequent major internal cultural discontinuities nor for the source of the colonizing movement. Archeological distributions of related material are clearest to the east of the Admiralties, where the local development (not necessarily in total isolation) of the Lapita cultural complex, including the skilled navigation techniques necessary to carry a population to the Admiralties, may have occurred.

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References and Notes

1. J. Kennedy, *Mankind* **12**, 72 (1979); *Res. Melanesia* **4** (Nos. 1 and 2), 25 (1979).
2. J. Golson, *Pac. Anthropol. Rec.* **12**, 67 (1971).
3. R. C. Green, in *The Prehistory of Polynesia*, J. D. Jennings, Ed. (Australian National Univ. Press, Canberra, 1979), pp. 27–60.
4. W. R. Ambrose, in *Ancient Chinese Bronzes and Southeast Asian Metal and Other Archaeological Artifacts*, N. Barnard, Ed. (National Gallery of Victoria, Melbourne, 1976), pp. 351–378; *Mankind* **11**, 326 (1978).
5. F. Bafmatuk, B. Egloff, R. Kaiku, *Hemisphere* **25**, 77 (1980).
6. W. R. Ambrose, J. R. Bird, P. Duerden, *Br. Archaeol. Rep. Int. Ser.*, in press.
7. B. J. Egloff, *Rec. Papua New Guinea Public Mus. Art Gallery* 5 (1975).
8. J. M. Davidson, in *The Prehistory of Polynesia*, J. D. Jennings, Ed. (Australian National Univ. Press, Canberra, 1979), pp. 82–109.
9. P. Bellwood, *Man's Conquest of the Pacific* (Collins, Auckland, 1978); in *The Prehistory of Polynesia*, J. D. Jennings, Ed. (Australian National Univ. Press, Canberra, 1979), pp. 6–26; R. Shutler, Jr., and J. C. Marck, *Archaeol. Phys. Anthropol. Oceania* **10**, 81 (1975).

10. J. P. White and J. Allen, *Science* **207**, 728 (1980).
11. J. Garanger, *Pac. Anthropol. Rec.* **12**, 53 (1971); *Pub. Soc. Océan. 30* (1972); J. Specht, thesis, Australian National University (1969); *Mankind* **8**, 310 (1972).
12. J. E. Downie and J. P. White, *Rec. Aust. Mus.* **37**, 762 (1978).
13. J. P. White, J. E. Downie, W. R. Ambrose, *Science* **199**, 877 (1978).
14. R. C. Green, *R. Soc. N.Z. Bull.* **11**, 245 (1976).
15. R. Gillespie and H. A. Polach, in *Radiocarbon Dating: Proceedings of the Ninth International Conference on Radiocarbon Dating*, R. Berger and H. Suess, Eds. (Univ. of California Press, Los Angeles, 1979), pp. 404–421. I have discarded four other charcoal dates (ANU-2211, ANU-2213, ANU-2214, and ANU-2249) because of probable in situ humic acid contamination.
16. I thank the Australian National University for research funds; the University of Papua New Guinea for affiliation in Papua New Guinea; J. Allen, W. Ambrose, P. Kennedy, C. Matthews, the Manus Provincial Government, and the Mbunai community for field assistance; A. Blackwell, P. Hughes, and B. Jacobs for research assistance; M. J. Head and H. Polach for advice on carbon-14 dating; W. Mumford for drawings; and J. Allen, W. Ambrose, J. Golson, M. Spriggs, J. P. White, and D. Yen for discussions.

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Elastic Arteries in Invertebrates: Mechanics of the Octopus Aorta

Abstract. *The aorta of the octopus,* Octopus dofleini, *is a highly distensible, elastic tube. The circumferential elastic modulus increases with inflation in the physiological range from about* 10^4 *to* 10^5 *newtons per square meter. Rubber-like fibers have been isolated, apparently for the first time, from the aorta of an invertebrate. These fibers have an elastic modulus, like elastin, of about* 4×10^5 *newtons per square meter and are present in sufficient quantity to account for the elastic properties of the intact vessel under physiological conditions. Thus the circulatory system of an invertebrate animal provides an "elastic reservoir" (much like that of the vertebrate system), which increases the efficiency of the circulation.*

The passive elasticity of blood vessels is a fundamental feature of the vertebrate circulatory system. Major arteries provide an elastic reservoir, which is distended during cardiac systole and maintains positive blood flow to the peripheral vessels while the heart refills (*1*). The pulsatile flow of blood from the heart is thus transformed into a steady flow through the capillaries, thereby increasing the efficiency of the circulation (*1*). In the vertebrates, the rubber-like protein elastin is responsible for the high extensibility and elasticity of the artery wall under physiological pressures (*2*). Elastin, however, has been found exclusively in the vertebrates, and its appearance coincides with the evolution of the advanced circulatory systems in these animals (*3*). The inherent advantages of elastic reservoirs has led us to suspect that elastic arteries also exist in many invertebrates. If this is so, then the elasticity must be based on a material that is different from elastin. Histological studies have suggested that "elastic fibers" occur in the blood vessels of many invertebrates (*4*). However, there are no reports on the mechanical properties of any invertebrate blood vessel, nor have the presumptive elastic fibers ever been isolated and tested mechanically.

From observations on the blood pressure of the cephalopod *Octopus dofleini*, Johansen and Martin (*5*) concluded that the circulatory system contained an elastic component. We, therefore, investigated the mechanical properties of the aorta of this invertebrate by in vitro inflations of arterial segments and found that the aorta is indeed a highly extensible elastic tube. Pressure-radius data gathered from these tests were used to construct a circumferential stress-extension curve for the artery wall [Fig. 1a, (i)]. Like most soft biological tissues the artery wall of the octopus exhibits a nonlinear (J-shaped) stress-extension curve, in which the incremental elastic modulus (*2*), that is, the stiffness, increases continuously with extension ratio (λ, where λ is the ratio between the extended length L and the starting length L_0), particularly in the physiological range of stress [Fig. 1a, (i)]. J-shaped stress-extension curves are found for all vertebrate arteries [for example, see Fig. 1a, (ii)]; this appears to be a design feature of highly extensible pressure vessels that prevents rupture (*6*). In vertebrate arteries, the low modulus region of the stress-extension curve is dominated by elastin (*7*). Similarly, we suspected, in the octopus, that an undescribed elastic protein might be present to provide the low modulus region of the stress-extension curve seen in Fig. 1a, (i). We have subsequently isolated and performed direct mechanical tests on an extracellular, rubber-like protein that we believe is responsible for the elasticity of the octopus aorta under physiological pressures.

Examination of the aorta of *O. dofleini* by light and electron microscopy revealed several tissue layers: an inner layer of circular muscles, a central layer of longitudinal muscle, and, outermost, a loose collagenous sheath. In addition, a layer of presumptive elastic fibers (5 to 7 μm in diameter) lines the vessel lumen and is called the internal elastica (IE)

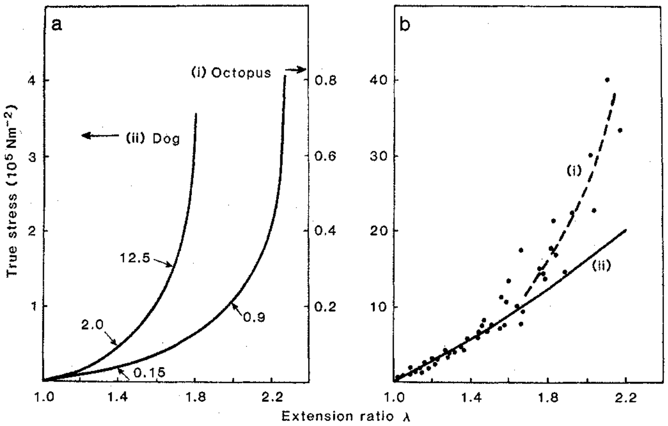

Fig. 1. Plots of true stress (force per cross-sectional area) against extension ratio (λ, ratio of extended length to starting length). (a) Comparisons of in vitro inflations of whole artery segments from (i) *Octopus dofleini* with (ii) the dog carotid, a typical vertebrate artery (*14*). The stress axis is on the right side for the octopus and on the left side for the dog. In both cases the stress and extension ratio are calculated for the circumferential direction. Both curves are nonlinear and the incremental elastic modulus [as defined by Bergel (*2*)] increases continuously with λ. The upper and lower limits of extension under average physiological pressures (18 to 40 mmHg in the octopus, 60 to 120 mmHg in the dog) are indicated by the arrows on the curves along with the corresponding values of the incremental elastic modulus at these extensions; this modulus has the units of stress (10^5 Nm^{-2}). The lower values of stress and modulus in the octopus aorta compared to those in the dog artery reflect the difference in pressures that are normally experienced by these two animals. (b) Results from force-extension tests on native elastic fibers taken from the internal elastica (IE) of the octopus aorta (i). These tests were performed on force transducers similar to that shown in Fig. 2b (*8*). Up to 60 percent extension ($\lambda = 1.6$) the data fit the predicted curve for an ideal Gaussian rubber (ii) plotted from the equation stress $= G(\lambda^2 - \lambda^{-1})$, where G, the elastic modulus, is equal to 4.6×10^5 Nm^{-2}. At extensions above 60 percent, the data diverge from the ideal case as the elastic fibers begin to exhibit non-Gaussian behavior that is typical of natural rubbers when stretched to large extensions. The octopus elastic fibers have the extensibility and modulus of a rubber-like material.