

Origins of Agriculture at Kuk Swamp in the Highlands of New Guinea

T. P. Denham,^{1*} S. G. Haberle,² C. Lentfer,³ R. Fullagar,⁴ J. Field,⁴ M. Therin,⁴ N. Porch,⁵ B. Winsborough⁶

Multidisciplinary investigations at Kuk Swamp in the Highlands of Papua New Guinea show that agriculture arose independently in New Guinea by at least 6950 to 6440 calibrated years before the present (cal yr B.P.). Plant exploitation and some cultivation occurred on the wetland margin at 10,220 to 9910 cal yr B.P. (phase 1), mounding cultivation began by 6950 to 6440 cal yr B.P. (phase 2), and ditched cultivation began by 4350 to 3980 cal yr B.P. (phase 3). Clearance of lower montane rainforests began in the early Holocene, with modification to grassland at 6950 to 6440 cal yr B.P. Taro (*Colocasia esculenta*) was utilized in the early Holocene, and bananas (*Musa* spp.) were intensively cultivated by at least 6950 to 6440 cal yr B.P.

Investigations into the antiquity of agriculture began in the Highlands of Papua New Guinea in 1966, with subsequent excavations in the 1970s at Kuk Swamp in the Wahgi Valley. The finds from Kuk were the oldest and most comprehensive of any wetland archaeological site in the interior (1, 2) and were claimed to represent the independent origins of agriculture in New Guinea during the early Holocene (3). These claims were, however, largely unsubstantiated. Archaeological remains of former cultivation dating back to the early Holocene at Kuk were reported but never fully published (1, 2). Previous researchers noted an association between *Musa* spp. phytoliths and archaeological phases (4) and documented the presence of numerous edible plants throughout the Holocene (5). The mechanisms of dispersal and anthropogenic associations of these plant remains were uncertain. Erosion rates in the catchment (6) and palynology at several sites in the Highlands (7, 8) were suggestive of accelerated forest clearance beginning in the early Holocene, but the timing and nature of initial clearance were un-

known. Given these problems, the notion of early independent agricultural development in New Guinea has been questioned (9, 10).

Here we present multidisciplinary data from renewed investigations at Kuk that show that agriculture arose independently in New Guinea by at least 6950 to 6440 calibrated years before the present (cal yr B.P.). We conducted new archaeological investigations and used radiocarbon dating, stratigraphic analyses, and a suite of archaeobotanical and paleoecological analyses (including diatom, insect, phytolith, pollen, and starch grain analyses). These findings contribute to our knowledge of agricultural origins across the globe and have broader implications for understanding the development of human societies.

Site and stratigraphy. Kuk Swamp is located in a large intermontane valley in the interior of New Guinea at 1560 m above mean sea level (AMSL) (Fig. 1). The Wahgi Valley has a slightly seasonal lower montane humid climate with a mean annual temperature of ~19°C and mean annual rainfall of ~2700 mm. The Kuk site is situated on a wetland margin comprising a low-gradient alluvial fan deposited after the Last Glacial Maximum (LGM) at 21,500 cal yr B.P. (6). These alluvial deposits overlay lacustrine and paludal peats that accumulated during the last glacial period.

The early to mid-Holocene stratigraphy represents immature paleosol profiles, which are characteristic of periodically waterlogged environments (Fig. 2A). Despite this pedogenesis, biostratigraphic signatures, as indicated by distinctive phytolith and pollen assemblages, are retained between and within individual units. These biostratigraphic signatures are corroborated by synchronous samples collected from deeper, well-

preserved, and largely unaltered fills of ditches and paleochannels.

Paleoecological evidence. Paleoecological records from several sites in New Guinea show that from 17,500 cal yr B.P. to the end of the last glacial period, open grasslands between 1200 and 2000 m AMSL were completely replaced by forests dominated by *Nothofagus* (11). The altitudinal expansion of forests was caused by warming climates, increased precipitation, and less frequent fires (12). In the absence of anthropogenic disturbance, the upland valleys during the Holocene would be expected to support montane rainforest on dry slopes and vegetation ranging from seral swamp forest to open grass and/or sedge in wetlands (11). The first signs of human impact are recognized as a reduction or change in the forest composition, followed by the expansion of open herbaceous vegetation and, in many cases, increased concentrations of charcoal in sediments (13, 14). Today, upland valleys are dominated by anthropogenic grasslands frequently burned by people. The timing of the earliest anthropogenic impacts on upland landscapes is variable and occurs as early as 7800 cal yr B.P. in the Baliem Valley of the Indonesian province of Papua (8) and as late as 1700 cal yr B.P. in the Tari Basin of Papua New Guinea (11).

To investigate the nature and timing of the transition from forest to grassland in the Wahgi Valley, we took 24 sediment samples from overlapping monoliths containing 1.3 m of continuous Holocene strata and Pleistocene peat (Fig. 2A). Samples from this section were augmented with 14 samples selected from the fills of prehistoric agricultural features excavated at proximal locations at the site. A minimum of 300 pollen grains and 200 phytoliths were counted for each sample. We obtained radiocarbon dates on paired and other organic material collected during excavation.

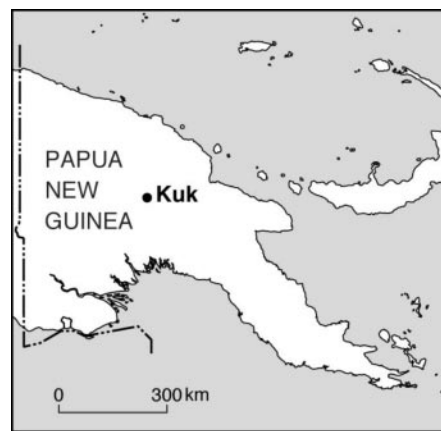


Fig. 1. Site location map.

¹School of Archaeology and Anthropology, Australian National University, Canberra ACT 0200, Australia.

²Resource Management in Asia-Pacific Program, Research School of Pacific and Asian Studies, Australian National University, Canberra, ACT 0200, Australia.

³School of Environmental Science and Management, Southern Cross University, P.O. Box 157, Lismore, New South Wales 2480, Australia. ⁴Department of Archaeology, University of Sydney, Sydney, New South Wales 2006, Australia. ⁵School of Geography and Environmental Science, Monash University, PO Box 11A, Clayton, Victoria 3800, Australia. ⁶Winsborough Consulting, 23606 Round Mountain Circle, Leander, TX 78641, USA.

*To whom correspondence should be addressed at Department of Archaeology, Flinders University, GPO Box 2100, Adelaide, South Australia 5100, Australia.

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The paleoecological data from Kuk Swamp indicate that, like other areas of the Highlands, a mosaic of cold-adapted grasslands and montane forest persisted across the valley floor before the Holocene (Fig. 3). Unlike other valleys in the uplands, the grasslands within the Kuk Swamp catchment did not succumb to forest advance at the onset of the Holocene. Instead, the grasslands and fern flora increased at the expense of forest between 10,200 and 7400 cal yr B.P. under the influence of periodic fire episodes and probably anthropogenic clearance. At the same time, forest composition in the catchment changed from a dominance of montane canopy taxa such as *Nothofagus*, *Castanopsis*, and gymnosperms to a predominance of subcanopy taxa, particularly *Pandanus*, Zingiberaceae, and Musaceae sect. *Eumusa*. At 6950 to 6440 cal yr B.P., the data imply that forest declined abruptly as burning increased within the catchment and an open grass-seed swamp-land became established. Musaceae phytoliths reach a maximum of 15% of total phytolith counts in this period (Fig. 3), which we inter-

pret to be derived from bananas (including Musaceae sect. *Eumusa*) growing locally within an open grassland environment.

Archaeological evidence. The archaeological remains at Kuk have been divided into six phases of wetland use (1–3). The earliest three phases are relevant to the origins of agriculture in New Guinea, because they pre-date known Southeast Asian influence on the island at ~3500 cal yr B.P. at the earliest (15) (Table 1).

The oldest archaeological features at Kuk (phase 1) are pits, stakeholes, postholes, and runnels that are restricted to slightly elevated and better-drained levées of a paleochannel (Fig. 2B). These features are consistent with planting, digging, and tethering of plants and localized drainage in a cultivated plot and are interpreted to represent a single period of shifting cultivation on the wetland edge. The paleochannel is dated to 10,220 to 9910 cal yr B.P. (tables S1 and S2), and two dates from a feature on an adjacent surface are slightly earlier and later than this date, respectively. Based on func-

tional associations among these features and their ages, we interpret them to be contemporaneous. The use of the wetland margin at this time was not specialized and represents the spatial extension of shifting cultivation practices (that is, dryland practices) onto the wetland margin during a drier period.

The phase 2 palaeosurface consists of the preserved circular and subcircular bases of regularly distributed mounds, as well as less organized features (Fig. 2C). The paleosurface is dated to 6950 to 6440 cal yr B.P., which accords with the date of an overlying and infilling deposit, R+W ash, at 6440 to 5990 cal yr B.P. (tables S1 and S2). Regular morphologies of features, numerous stake- and postholes, and heterogeneous feature fills with elevated charcoal frequencies are all consistent with a cultivated paleosurface. The mounds created better-aerated soils along the moist, poorly drained wetland margin. The innovation of mounded cultivation indicates greater reliance on the wetland for subsistence in a resource-poor grassland landscape.

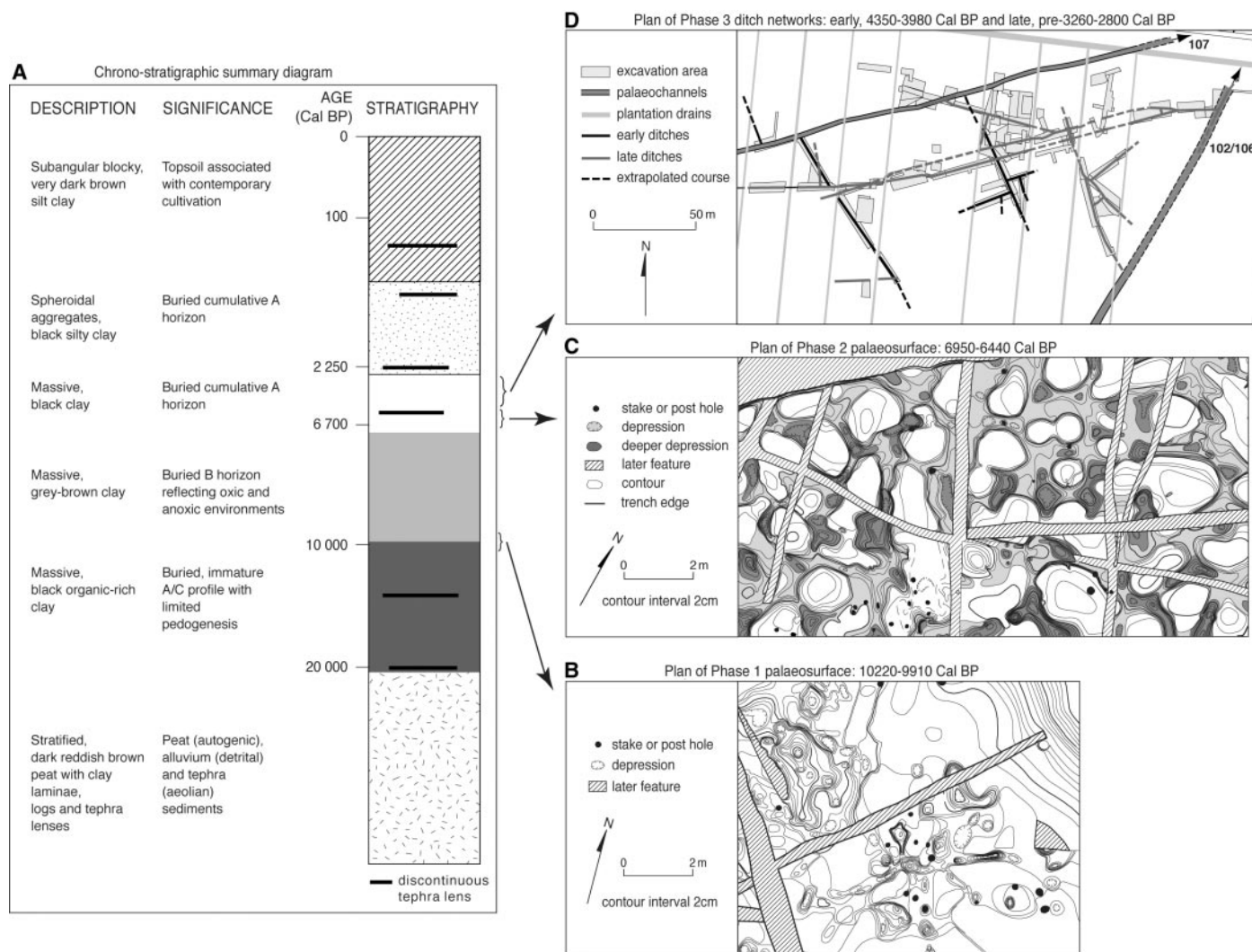


Fig. 2. Archaeostratigraphic representation of phases 1, 2, and 3.

Phase 3 is composed of sequential ditch networks that articulate with major drainage channels, and an earlier curvilinear feature has also been included in this phase (Fig. 2D). The earliest ditch networks are rectilinear, similarly aligned, and contain similar fill types. These early ditch networks date to ~4350 to 3980 cal yr B.P. and pre-date R ash [dated to 3980 to 3630 cal yr B.P. (tables S1 and S2)]. Late ditch networks are older than 3260 to 2800 cal yr B.P. and the deposition of an overlying tephra, Y ash.

Younger ditches form more complex networks that exhibit dendritic, rectilinear, and triangular arrangements. Major drainage channels articulate with both early and late networks; for example, channel 107 pre-dates the deposition of a diagnostic tephra (R ash) and articulates with two ditches of the early subphase and one ditch of the late subphase (Fig. 2D). The innovation of ditching indicates a further refinement

of, and reliance on, wetland cultivation within resource-poor anthropogenic grassland.

Archaeobotanical evidence. There is a variety of evidence for numerous edible plants being present in the Kuk vicinity from the late Pleistocene (table S3). The lack of an intimate association of most plant remains with archaeological features indicates that the plants grew in the forested landscape. Modifications to the catchment and wetland margin at the end of Pleistocene and early Holocene may have been intended to increase the availability of edible and other useful plants. Many of these plants are still gathered, transplanted, and cultivated from wild forms in the Highlands today (16). Microfossils from two plants with abundant starch—taro (*Colocasia esculenta*) and banana (*Musa* spp.)—both record their earliest presence in early Holocene contexts. These two crops were potentially the most important food staples in the Highlands before the introduction

of the sweet potato (*Ipomoea batatas*) after European exploration of the Pacific.

Starch grains from *Colocasia* taro are present on the worked edges of three stone tools from phase 1, phase 2, and the intervening gray clay. The size, shape, surface morphology, clustering, and co-occurrence of raphides (calcium oxalate crystals) removed from the used edge of a phase 1 flake (K76/S29B) all signify *C. esculenta*. *C. esculenta* has also been documented from a Pleistocene site in Island Melanesia (17) and an early Holocene site in lowland New Guinea (18). *C. esculenta* is considered to be a lowland crop, and its current range in New Guinea, exceeding 2000 m AMSL, is considered to be a product of anthropogenic selection (19). Its presence and use at Kuk in the early Holocene are suggestive of deliberate movement of the plant into the Highlands.

Musaceae, including *Musa* spp. (banana), phytoliths are present throughout the Holocene stratigraphy at Kuk (Fig. 3). High percentages are evident in disturbed habitats before 6950 to 6440 cal yr B.P., but these are only suggestive of deliberate planting, because bananas are known to exist in wooded and edge habitats from which they colonize disturbed areas. The high percentages of banana phytoliths in grassland contexts during phase 2 and in the earliest phase 3 feature (dated to 4840 to 4440 cal yr B.P.) are, however, anomalous. First, grasses produce abundant phytoliths, whereas bananas produce relatively few phytoliths in their leaves, bracts, seeds, and pseudostems. Thus,

Table 1. Chronology for archaeological phases 1, 2, and 3 at Kuk Swamp (see tables S1 and S2 for dates and calibrations).

Phase	Golson 1977 (4) (uncal yr B.P.)	Subphase	Wetland remains	New dates (cal yr B.P.)
1	~9000	None	Amorphous palaeosurface	10,220 to 9910
2	6000 to 5500	None	Subcircular paleosurfaces	6950 to 6440
3	4000 to 2500	Earliest	Sinuuous runnel	4840 to 4440
		Early	Rectilinear ditch networks	4350 to 3980
		Mid-late	Rectilinear ditch networks	None
		Late	Rectilinear ditch networks	Pre-3260 to 2800

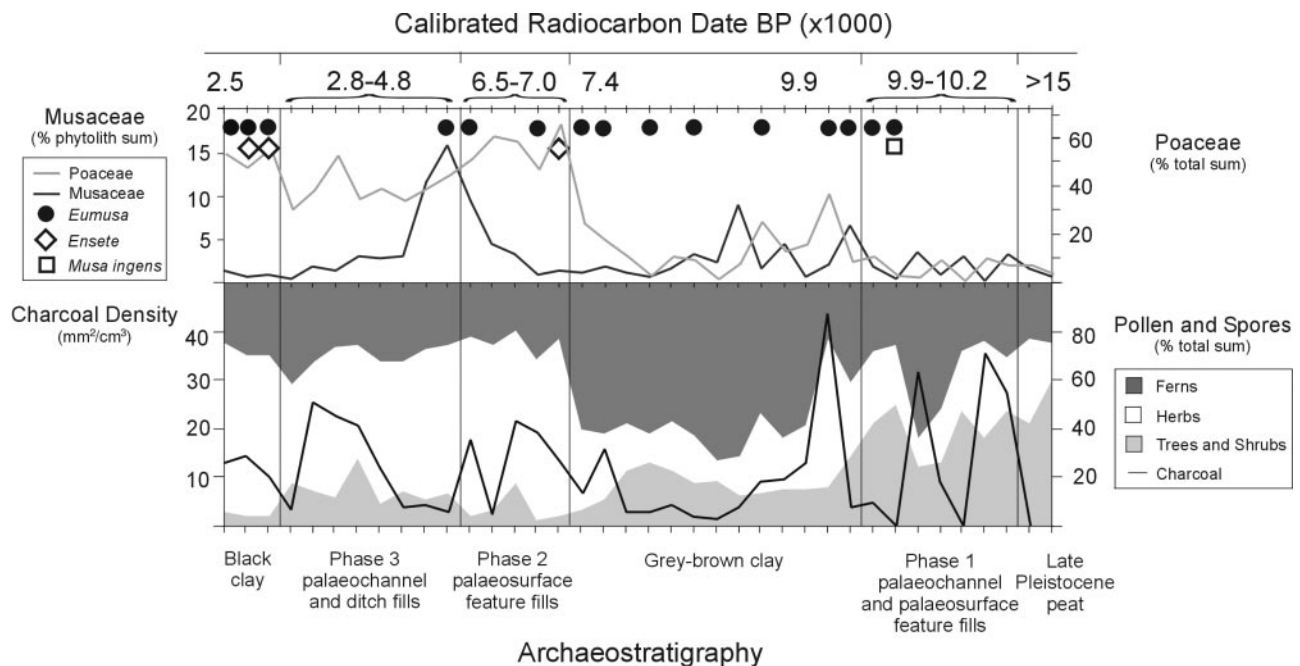


Fig. 3. Selected pollen and phytolith data from the Kuk Swamp samples ($n = 38$). Ages are based on radiocarbon dating of stratigraphic features associated with phases 1, 2, and 3 and intervening stratigraphy (that is, gray clay). Samples are arranged in order of oldest (sample 1, right-hand side of the diagram) to youngest (sample 38, left-hand side). The lower half of the diagram depicts pollen and

spore summary curves (for ferns, herbs, and trees and shrubs) and charcoal density (as area of pollen slide). The upper half of the diagram shows Poaceae (as percentage of total sum of pollen and spores) and Musaceae phytoliths (as percentage of total phytolith sum), with the presence of diagnostic seed phytoliths assigned to *Eumusa*, *Ensete* sp., and *Musa ingens* depicted as symbols.

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high banana phytolith percentages reflect large plant populations rather than high phytolith production relative to other species. Second, large quantities of *Musa* bananas would not be expected in a grassed landscape subject to periodic burning. Other banana species, such as *Ensete glaucum*, are more fire-tolerant and might be expected to thrive in repeatedly burned landscapes; however, they account for only a minor component of Musaceae phytoliths during the Holocene at Kuk. The large percentages of bananas within a managed grassed landscape beginning at 6950 to 6440 cal yr B.P. are interpreted to be diagnostic of deliberate planting.

Eumusa bananas were identified from diagnostic seed phytolith morphotypes throughout the Holocene sequence. Although no diagnostic seed phytoliths of Australimusa bananas were found, other species, including *Musa ingens* and *Ensete glaucum*, were present (Fig. 4). The presence of Eumusa bananas has implications for understanding mainstream banana domestication involving hundreds of diploid and polyploid varieties. Eumusa cultivars were formerly considered to be Southeast Asian domesticates (20). More recent genetic research suggests that the wild Eumusa seeded banana,

Musa acuminata ssp. *banksii*, was domesticated in New Guinea and subsequently dispersed to Southeast Asia, where hybridization with local varieties occurred (21). The Eumusa morphotypes in early Holocene contexts at Kuk, including both seed and leaf morphotypes identical to those found in *Musa acuminata* ssp. *banksii*, corroborate these interpretations.

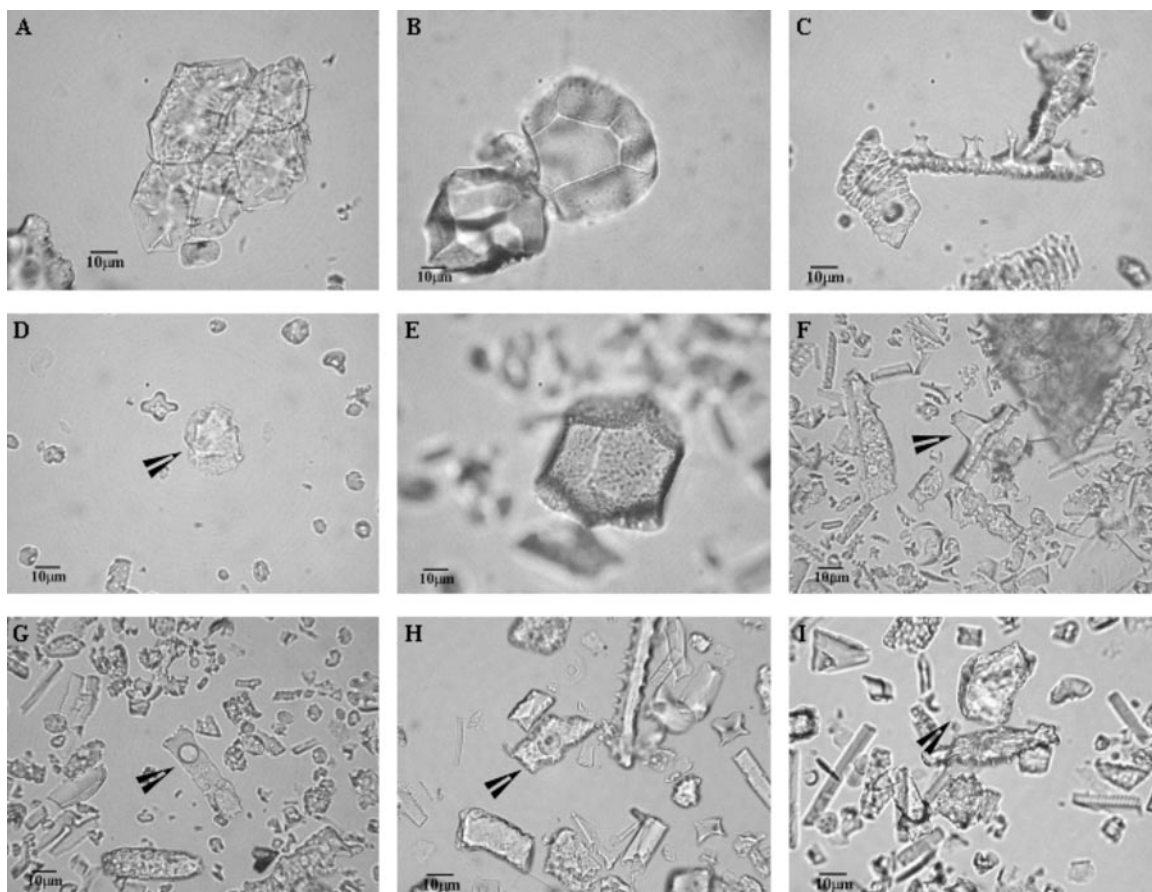
Conclusion. The gradual emergence of agriculture in the Highlands of New Guinea during the early Holocene is suggested by cumulative anthropogenic forest disturbance, the archaeological remains of cultivation on the wetland margin at Kuk, the use of *Colocasia* taro, and the presence of Eumusa bananas. Although this evidence is consistent with shifting cultivation practices, more substantial evidence for deliberate planting and incipient domestication is not unequivocally demonstrable until the mid-Holocene. By 6950 to 6440 cal yr B.P., land use patterns changed dramatically with intensive wetland cultivation (mounding); the creation and maintenance of an anthropogenic grassland landscape; and the deliberate planting of bananas, including Eumusa bananas from which the most important and largest group of banana domesticates arose. These multi-

disciplinary lines of evidence signify that agriculture was being practiced within an anthropogenic landscape.

The idea of early and independent agricultural origins in New Guinea challenges entrenched and pervasive assumptions about the genesis and diffusion of agriculture and about the development of human societies. First, New Guinea has generally been considered to be a secondary center, where agricultural development was derived from or triggered by the arrival of domesticates from Southeast Asia (22, 23). The evidence from Kuk confirms that New Guinea was a primary center of agricultural development and plant domestication before any known Southeast Asian influence. The archaeobotanical finds corroborate genetic interpretations that Eumusa bananas and *C. esculenta* were independently domesticated in Melanesia (21). Only after 3500 cal yr B.P. was New Guinea a recipient of domesticated plants from Southeast Asia, after Austronesian expansion into the region (15).

Second, early and independent agriculture is often linked to large-scale demic expansions, social stratification, and the rise of "civilization" (23, 24), none of which are typical of New Guinean societies today or in

Fig. 4. Photographs illustrating discrimination of contemporary and prehistoric *Musa* spp. phytoliths. (A) Articulated phytoliths from seed of *Musa acuminata* ssp. *banksii* showing distinct dorsal ridging of Eumusa seed phytoliths (modern reference: sample QH067962). (B) Seed phytolith from seed of *Musa ingens* (modern reference sample). (C) Dorsal and lateral views of *Ensete glaucum* seed phytoliths (modern reference: sample QH356652). (D) Fossil Eumusa seed phytolith with distinct dorsal ridging found in the phytolith assemblage from the base of a phase 2 feature fill (sample 5). (E) Faceted phytolith morphotype found in the phytolith assemblage from the upper fill of the phase 1 paleochannel (sample 19). It is similar to the seed morphotype of *Musa ingens*, although its surface is more heavily textured. (F) Lateral view of *Ensete* seed morphotype found in a phase 2 feature fill and the clayey black sediment above (samples 3 and 4). (G) Articulated chain of *Musa* leaf phytoliths from within the gray clay sequence between phase 1 and phase 2 (sample 10). (H) Fossil leaf



phytolith of *Musa acuminata* from the upper fill of the phase 1 paleochannel (sample 19). (I) Fossil Eumusa seed phytolith from the upper fill of the phase 1 paleochannel (sample 19).

the past. Although agriculture may have arisen there over 6500 years ago, highland New Guinea societies are still relatively egalitarian and characterized by “big men,” whose influence is largely persuasive and consensual. The evidence for early agriculture from highland New Guinea signifies the potential diversity of prehistoric trajectories after the inception of agriculture and challenges unilinear, often teleological, interpretations of human prehistory.

References and Notes

- J. Golson, in *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia and Australia*, J. Allen, J. Golson, R. Jones, Eds. (Academic Press, London, 1977), pp. 601–638.
- J. Golson, P. J. Hughes, *J. Soc. Océan.* **36**, 294 (1980).
- G. S. Hope, J. Golson, *Antiquity* **69**, 818 (1995).
- S. M. Wilson, *Arch. Ocean.* **20**, 90 (1985).
- J. M. Powell, *Arch. Ocean.* **17**, 28 (1982).
- P. J. Hughes, M. E. Sullivan, D. Yok, *Zeit. Geomorphol. Suppl.* **83**, 227 (1991).
- J. M. Powell, in *Biogeography and Ecology of New Guinea. Volume 1*, J. L. Gressitt, Ed. (Junk, The Hague, Netherlands, 1982), pp. 207–227.
- S. G. Haberle, G. S. Hope, Y. De Fretes, *J. Biogeogr.* **18**, 25 (1991).
- M. Spriggs, in *The Origins and Spread of Agriculture and Pastoralism in Eurasia*, D. R. Harris, Ed. (University College London Press, London, 1996), pp. 524–537.
- B. Smith, *The Emergence of Agriculture* (Scientific American Library, New York, 1998).
- S. G. Haberle, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **137**, 1 (1998).
- S. G. Haberle, M.-P. Ledru, *Quat. Res.* **55**, 97 (2001).
- D. Walker, G. Singh, in *Climate Change and Human Impact on the Landscape*, F. M. Chambers, Ed. (Chapman & Hall, London, 1994), pp. 101–108.
- S. G. Haberle, in *Tropical Archaeobotany: Applications and New Developments*, J. G. Hather, Ed. (Routledge, London, 1994), pp. 172–201.
- P. Bellwood, *Prehistory of the Indo-Malaysian Archipelago* (University of Hawaii Press, Honolulu, HI, 1997).
- J. M. Powell, in *New Guinea Vegetation*, K. Pajmams, Ed. (Australian National University Press, Canberra, Australia, 1976), pp. 23–105.
- T. Loy, M. Spriggs, S. Wickler, *Antiquity* **66**, 898 (1992).
- S. G. Haberle, *Veg. Hist. Archaeobot.* **4**, 195 (1995).
- D. Yen, *Antiquity* **69**, 831 (1995).
- N. W. Simmonds, *The Evolution of the Bananas* (Longmans, London, 1962).
- V. Lebot, *Gen. Res. Crop Evol.* **46**, 619 (1999).
- C. O. Sauer, *Agricultural Origins and Their Dispersals* (American Geographical Society, New York, 1952).
- J. Diamond, *Nature* **418**, 700 7 (2002).
- N. I. Vavilov, in *Origin and Geography of Cultivated Plants*, N. I. Vavilov, Ed. (Cambridge Univ. Press, Cambridge, 1992), pp. 22–135.
- T.P.D. directed the multidisciplinary research and conducted the archaeological, pedological, and sedimentological investigations. S.G.H. undertook pollen and charcoal particle identifications and counts. C.L. undertook phytolith identifications and counts, with an emphasis on *Musa* spp. R.F., J.F. and M.T. undertook starch grain analysis of stone tool residues. N.P. undertook insect identifications. B.W. undertook diatom identifications and counts.

Supporting Online Material
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Tables S1 to S3
References

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REPORTS

A Young White Dwarf Companion to Pulsar B1620-26: Evidence for Early Planet Formation

Steinn Sigurdsson,^{1*} Harvey B. Richer,² Brad M. Hansen,³
Ingrid H. Stairs,² Stephen E. Thorsett⁴

The pulsar B1620-26 has two companions, one of stellar mass and one of planetary mass. We detected the stellar companion with the use of Hubble Space Telescope observations. The color and magnitude of the stellar companion indicate that it is an undermassive white dwarf (0.34 ± 0.04 solar mass) of age $480 \times 10^6 \pm 140 \times 10^6$ years. This places a constraint on the recent history of this triple system and supports a scenario in which the current configuration arose through a dynamical exchange interaction in the cluster core. This implies that planets may be relatively common in low-metallicity globular clusters and that planet formation is more widespread and has happened earlier than previously believed.

Messier 4 (M4 equals NGC 6121 and GC 1620–264) is a medium mass [$\sim 10^5$ solar mass (M_{\odot})] globular cluster and the one closest to the Sun. It has a moderately dense ($\rho_0 \approx 3 \times 10^4 M_{\odot} \text{ pc}^{-3}$) core. The metal content of the cluster is 5% that of the Sun, with little variation in composition or age

between different member stars. The cluster has a substantial population of white dwarfs (stellar remnants which have exhausted their nuclear fuel), recently detected in deep Hubble Space Telescope (HST) observations (1, 2), that have been used to determine an age for the cluster of $12.7 \times 10^9 \pm 0.35 \times$

10^9 years. Furthermore, M4 contains the binary radio pulsar PSR B1620–26 (3, 4), a recycled millisecond pulsar with a $P = 11$ ms rotation period and a companion in a low eccentricity ($e = 0.025$) orbit with an orbital period of 191 days. For an assumed pulsar mass of $1.35 M_{\odot}$, radio timing observations constrain the companion mass to be $M_c = 0.28 M_{\odot} / (\sin i)$, where i is the unknown inclination of the binary orbital plane to the line of sight (5, 6). The pulsar also possesses an anomalously large second time derivative of the rotational period (\ddot{P}) (7, 8), seven orders of magnitude larger than that expected from the intrinsic pulsar spin-down and of the wrong sign. When discovered, the pulsar had a characteristic spin-down time

¹525 Davey Laboratory, Department of Astronomy, Pennsylvania State University, University Park, PA 16802, USA. ²Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, British Columbia V6T 1Z1, Canada.

³Department of Physics and Astronomy and Institute of Geology and Planetary Physics, University of California at Los Angeles, Math-Sciences 8971, Los Angeles, CA 90095–1562, USA. ⁴Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA.

*To whom correspondence should be addressed. E-mail: steinn@astro.psu.edu