Middle Stone Age Bedding Construction and Settlement Patterns at Sibudu, South Africa

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A third reason may be the neglect of dust radiative forcing in some previous LGM studies (*21*) despite ample evidence from the paleoenvironmental record that dust levels were much higher (*25, 26*). Sensitivity tests (Fig. 3) (SOM section 7) show that dust forcing decreases the median ECS_{2xC} by about 0.3 K.

Our estimated ECS_{2xC} uncertainty interval is rather narrow, <1.5 K for the 90% probability range, with most (~75%) of the probability mass between 2 and 3 K, which arises mostly from the SST constraint. This sharpness may imply that LGM SSTs are a strong physical constraint on ECS_{2xC}. However, it could also be attributable to overconfidence arising from physical uncertainties not considered here, or from misspecification of the statistical model.

To explore this, we conduct sensitivity experiments that perturb various physical and statistical assumptions (Fig. 3 and figs. S14 and S15). The experiments collectively favor sensitivities between 1 and 3 K. However, we cannot exclude the possibility that the analysis is sensitive to uncertainties or statistical assumptions not considered here, and the underestimated land/sea contrast in the model, which leads to the difference between land- and ocean-based estimates of ECS_{2xC}, remains an important caveat.

Our uncertainty analysis is not complete and does not explicitly consider uncertainties in radiative forcing due to ice-sheet extent or different vegetation distributions. Our limited model ensemble does not scan the full parameter range, neglecting, for example, possible variations in shortwave radiation due to clouds. Nonlinear cloud feedback in different complex models make the relation between LGM and CO_2 doubling–derived climate sensitivity more ambiguous than apparent in our simplified model ensemble (*27*). More work, in which these and other uncertainties are considered, will be required for a more complete assessment.

In summary, using a spatially extensive network of paleoclimate observations in combination with a climate model, we find that climate sensitivities larger than 6 K are implausible, and that both the most likely value and the uncertainty range are smaller than previously thought. This demonstrates that paleoclimate data provide efficient constraints to reduce the uncertainty of future climate projections.

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Middle Stone Age Bedding Construction and Settlement Patterns at Sibudu, South Africa

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The Middle Stone Age (MSA) is associated with early behavioral innovations, expansions of modern humans within and out of Africa, and occasional population bottlenecks. Several innovations in the MSA are seen in an archaeological sequence in the rock shelter Sibudu (South Africa). At ~77,000 years ago, people constructed plant bedding from sedges and other monocotyledons topped with aromatic leaves containing insecticidal and larvicidal chemicals. Beginning at ~73,000 years ago, bedding was burned, presumably for site maintenance. By ~58,000 years ago, bedding construction, burning, and other forms of site use and maintenance intensified, suggesting that settlement strategies changed. Behavioral differences between ~77,000 and 58,000 years ago may coincide with population fluctuations in Africa.

Genetic and phenotypic (skull) data indicate that after 80 thousand years ago (ka), human populations went through bottlenecks, isolations, and subsequent expansions (*1–3*). Concurrently, the Middle Stone Age (MSA) of South Africa witnessed a variety of emerging behavioral practices by anatomically modern humans, including use of shell beads and engraving (*4–6*), innovative stone technology (*7*), the creation and use of compound adhesives (*8*), heat-treatment of rock (*9*), and circumstantial evidence for snares (*10*) and bows and arrows (*11*). Less emphasis has been placed on innovations in domestic organization and settlement strategies, which might also have been influenced by major demographic changes that were occurring in Africa. Here, we present geoarchaeological and archaeobotanical evidence (*12*) from the South African rock shelter Sibudu (fig. S1) for changing domestic practices in the form of construction of plant bedding starting at ~77 ka, approximately 50,000 years earlier than records elsewhere. Most evidence for bedding in the Pleistocene has been inferential, except for that from Esquilleu Cave, Spain (*13*); Strathalan B Cave, South Africa, dated 29 to 26 ka (*14*); and Ohalo II, Israel, dated to 23 ka (*15*).

Sibudu is situated on a cliff 20 m above the uThongathi River (figs. S2 and S3), 40 km north of Durban and 15 km inland from the Indian Ocean. Excavations have been conducted here

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since 1998 and have revealed a sequence of several discontinuous MSA occupation layers preserved within 3-m-deep sediments (figs. S4 to S6) (12). Single-grain, optically stimulated luminescence (OSL) ages indicate that the occupations range from ~77 to 38 ka (16) (table S1). The periods of occupation and abandonment during this time are similar to patterns at other southern African sites (16), although Sibudu has one of the most complete later MSA sequences. Between 71 and 62 ka, artifacts at the site include perforated seashells and a suite of bone tools (17, 18). Such artifacts are better known from sites on the coast located >1000 km south of Sibudu.

At least 15 occupation horizons (table S1) (12) incorporate centimeter-thick, compacted layers of finely laminated, herbaceous material, including stems and leaves, that are capped by laminated, articulated phytoliths (Figs. 1 and 2, A to C, and figs. S7 to S9). Here, we describe in detail five plant-rich horizons [Table 1 and supporting online material (SOM) text]. Most of the layers extend for at least 1 m and up to 3 m across the excavated area (fig. S10). Taxon identification of the tangled, broken stems and leaves is not often possible, although a *Cladium* sp. culm has been recognized (Fig. 2A). Other culm fragments with smooth or longitudinally striated surfaces and narrow leaves with longitudinal parallel venation (Fig. 2C) identify the plants as monocotyledons, such as sedges, rushes, or grasses. The arrangement of vascular bundles in plant stems seen in thin section (fig. S11) is an additional attribute of monocotyledons. Grass (Poaceae) phytoliths have been detected in some but not all layers (Fig. 2B and table S2) (12). Sedge and rush identifications are well-supported by the presence of >600 fruits of Cyperaceae (sedges) (19) and Juncaceae (rushes), which are normally plants of wet habitats and could not occur naturally within the dry rock shelter (table S3). Scanning electron microscope (SEM) images demonstrate that most fruits are *Cladium mariscus* subsp. *jamaicense* (L.) Pohl (Crantz) Kük (Fig. 2D), but *Scleria natalensis* C.B. Clarke (Fig. 2E), *Scleria melanomphala* Kunth, and *Juncus* sp. (Fig. 2F) are also represented (Table 1). Occupation debris is intimately associated with all the monocotyledon-rich layers. In thin section, we identified narrow layers of chipped stone and crushed, burnt bone within plant layers (fig. S12); these delimit multiple subsurfaces, implying that the plant layers were regularly refurbished with fresh culms and leaves. Riverine clay occurs as sand-sized aggregates (Fig. 3, A and B) within the layers, suggesting that the plants, with clay still adhering to them, were collected by people from the uThongathi River valley. Several clay fragments exhibit monocotyledonous leaf or stem impressions (Fig. 3, A and C).

In thin section, the finely laminated plant-rich strata appear compressed, probably the result of repeated trampling. The atypical occurrence of wet habitat plants within the shelter, and their laminated, compacted microstructure with artifactual inclusions, implies that the features are of anthropogenic origin. The evidence strongly suggests that the plant layers were used as a type of floor preparation, usually called "bedding" by archaeologists, but probably used—such as in KwaZulu-Natal today (fig. S13) (12)—as a surface for working and sleeping. Similar micromorphological characteristics were produced in experiments designed to burn compacted sedges (fig. S14) (12) and in bedding described from younger archaeological sites (15). Most, but not all, of Sibudu's bedding appears burned, resulting in carbonization of fibrous plant material at its base where oxygen was scarce, and ashing of plant material at the top where oxygen was available. The laminated, articulated phytolith layers formed on the ashed surface of the bedding, where temperatures were higher than in the base (Fig. 1, A and C).

The oldest bedding, dating to 77 ka, is approximately 1 by 2 m in area but may extend beyond the excavation grid. It includes an unburned layer of white, fossil dicotyledonous (broadleaved) leaves (Fig. 4), 0.2 mm thick, overlying an 8-mm layer of monocotyledonous leaves and stems. Well-preserved, articulated monocotyledonous phytoliths are seen in thin section (Fig. 1B and table S2). Fourier transform infrared spectroscopy (12) shows that the leaf tissues are impregnated with opal (fig. S15 and table S4). The leaves preserve distinct venation and stomata (Fig. 4, A to D, and fig. S16), and are all from *Cryptocarya woodii*
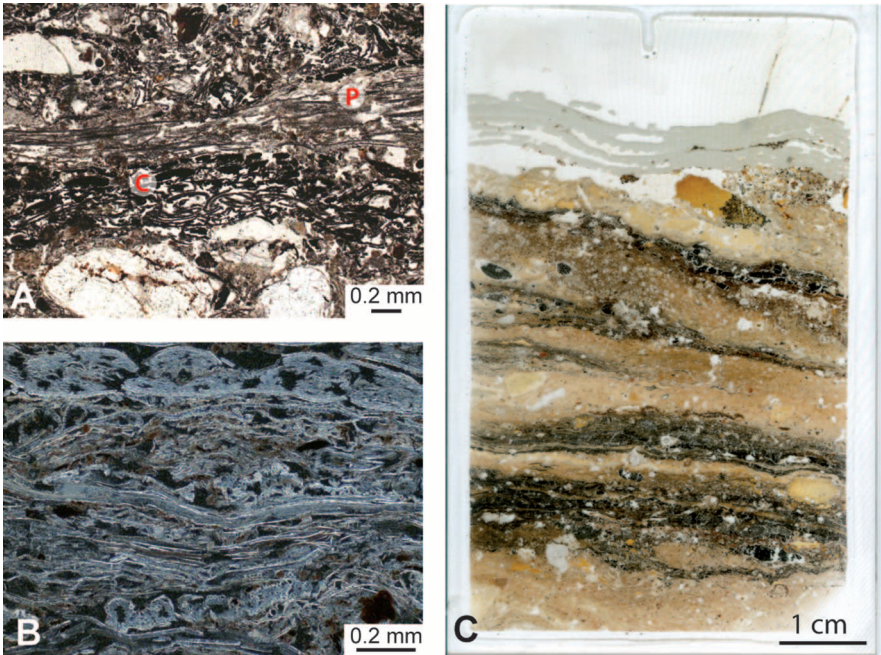

Fig. 1. Micromorphology (photomicrographs and flatbed scan) of selected bedding layers from Sibudu. (**A**) Laminated, articulated phytoliths ("P") overlying laminated, carbonized monocotyledonous stems ("C"), layer Ore (~48 ka). The image was produced with plane-polarized light (PPL). (**B**) Siliceous plant bedding, layer BS6 (~77 ka), PPL, with dark field illumination. (**C**) Flatbed scan of a thin section showing repeated construction and burning of bedding, layer H1 in Br. under YA2(i) (~58 ka). Multiple couplets of laminated phytoliths (light-colored material) and laminated, carbonized monocotyledonous stems (dark-colored material) rest directly on each other.

Table 1. Selected bedding samples from Sibudu: provenances, ages, and identified monocotyledons. "X" denotes presence.

Square	Layer	OSL age (ka) (16)	Monocotyledons	
			Fruits	Stems
B4/C4	BS6	77.2 ± 2.1	*Cladium mariscus*, *Scleria natalensis*, *Scleria melanomphala*	x
B4	LBG	72.5 ± 2.0	*Cladium mariscus*, *Juncus* sp.	x
C4	PGS	64.7 ± 1.9	*Cladium mariscus*	x
B4 and C4	Br. under YA2(i)	between 61.7 ± 1.5 and 58.2 ± 2.4	*Cladium mariscus*, *Cyperus* sp.	*Cladium* sp.
E2	Ore	~48	Not sampled	x

Engl. (*12*). Today, this tree occurs in forest, woodland, ravines, and along streams (*12*). Many woody plants grew near Sibudu during the MSA (*19, 20*); thus, single-taxon windborne leaf litter seems improbable. *Cryptocarya* species are used extensively as traditional medicines. Although *C. woodii* is not as toxic as other South African *Cryptocarya* species, its crushed leaves are aromatic and contain traces of α-pyrones, cryptofolione, and goniothalamin (*21*), chemicals that have insecticidal and larvicidal properties against, for example, mosquitoes (*22–25*). Mosquito-borne diseases are endemic to many parts of Africa, and rural communities still use indigenous plants to dispel mosquitoes (*26*). Early use of herbal medicines may have awarded selective advantages to humans, and the use of such plants implies a new dimension to the behavior of early humans at this time.

After ~73 ka, all bedding at Sibudu is burned. If use of *C. woodii* continued, the evidence was destroyed because the leaves produce few phytoliths (fig. S17), and these cannot presently be identified (*12*). Accidental ignition of bedding may sometimes have occurred, yet repeated carbonization throughout the sequence suggests intentional burning perhaps to eliminate pests and garbage, enabling further site occupation. Such site maintenance is reported in the ethnographic literature (*27*).

Human use of Sibudu appears to have intensified during post-Howiesons Poort occupations. Dating and sediment micromorphology (SOM text and table S1) demonstrate that the rate of anthropogenic sedimentation increased. In a 90-cm stratigraphic column of post–Howiesons Poort occupations dated to a relatively short period with a weighted mean of 58.5 ± 1.4 ka (*12*), 37 clearly distinguishable layers are present. Individual bedding layers are more numerous there than lower in the sequence. Additionally, complex associations—commonly several centimeters thick—seem to represent swept ashes from hearths (*28*), a practice absent before 58 ka. Sweeping and banking of ashes has been recorded historically in the Kalahari (*29*). The density of stone tools also suggests intensified activity ~58 ka. We sampled a sediment column intensively over an area of 2 m^2. We obtained a total of 8033 unbroken stone flakes (*30*) in sediments aged ~58,000 years—that is, 4462 flakes m^3 versus only 2244 flakes m^3 in the 70,000-year-old layers. Intensification at ~58 ka may have resulted from longer visits, more visits, or larger groups than previously and is consistent with the evidence for more regular site maintenance. Other data also support an interpretation of greater populations at ~58 ka. First, ages of MSA occupations from several well-dated southern African sites (*16*) confirm that more sites have occupations at ~58 than ~70 ka. Second, genetic and

Fig. 2. SEM images of Sibudu sedge (Cyperaceae) and rush (Juncaceae) fruits, sedge culm and grass (Poaceae) phytoliths, and a photograph of a monocotyledonous leaf. (**A**) Carbonized stem of *Cladium* sp., square C4b, layer H1 Br. under YA2(i) (~58 ka). (**B**) Grass phytoliths, square B4b, layer BS6 (~77 ka). (**C**) Siliceous monocotyledonous leaf, square C4b, layer BS6 (~77 ka). (**D**) Internal morphology of carbonized half nutlet, *Cladium mariscus* subsp. *jamaicense*, square B4c, layer YA2(i) (~58 ka). (**E**) Siliceous sedge nutlet, *Scleria natalensis*, square C4b, layer BS6 (~77 ka). (**F**) Carbonized rush fruit, *Juncus* sp., square C4d, layer LBG2 (~73 ka). Scale bars, (A) and (C) to (F) 0.5 mm; (B) 50 μm.
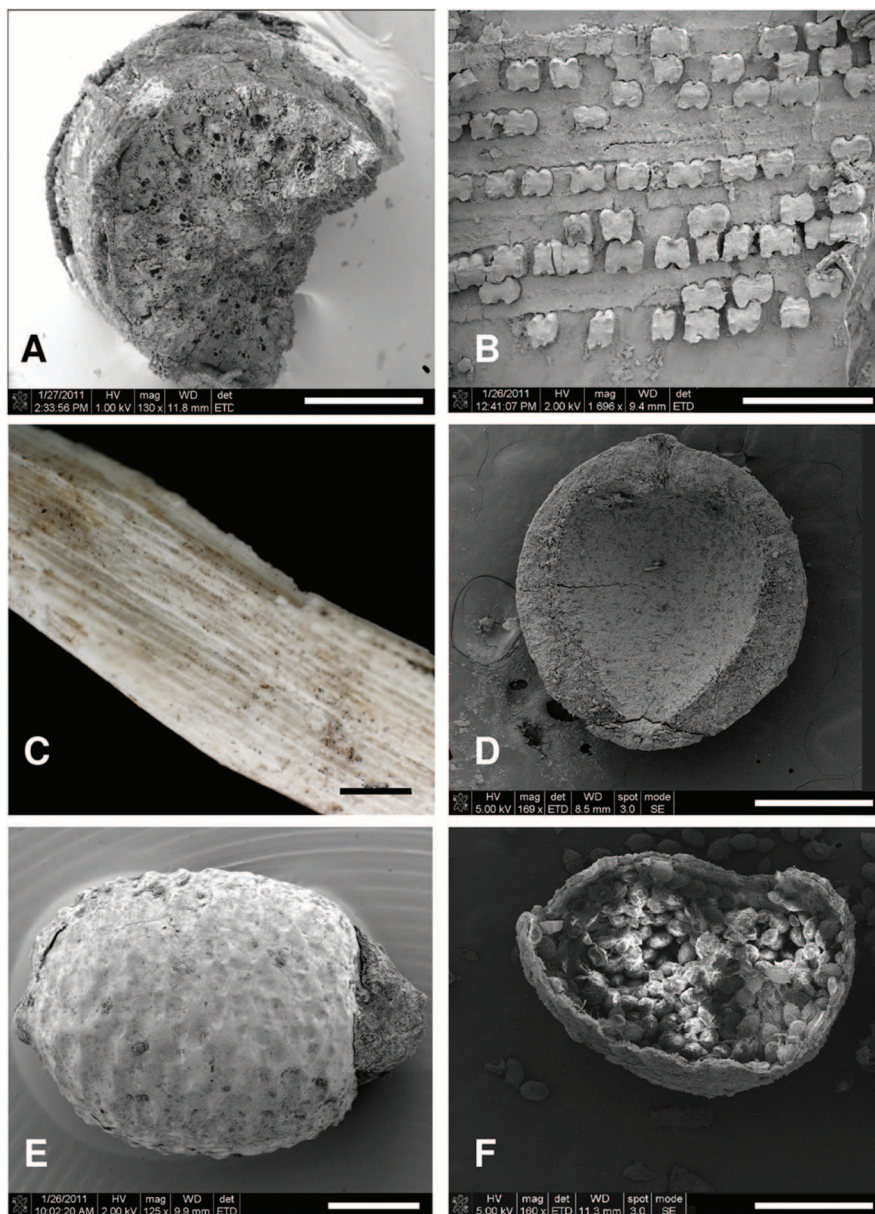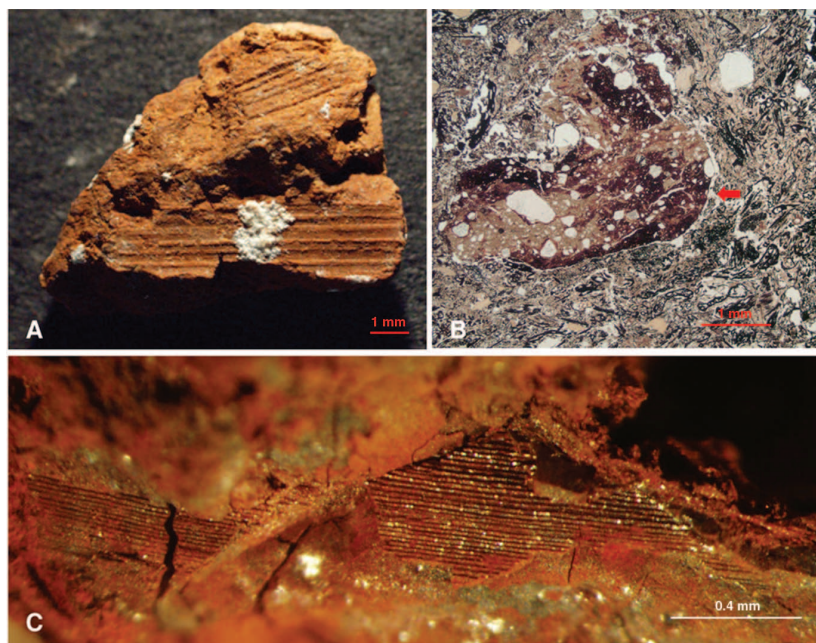
Fig. 3. Selection of riverine clay fragments from Sibudu sediments. (**A**) Clay fragment with monocotyledonous plant impressions, square B5d, layer YA2 (~58 ka). (**B**) Photomicrograph of clay fragment, square B4, layer OMOD (~48 ka). (**C**) Clay fragment with monocotyledonous leaf impressions, square C6c, layer YA (~58 ka).
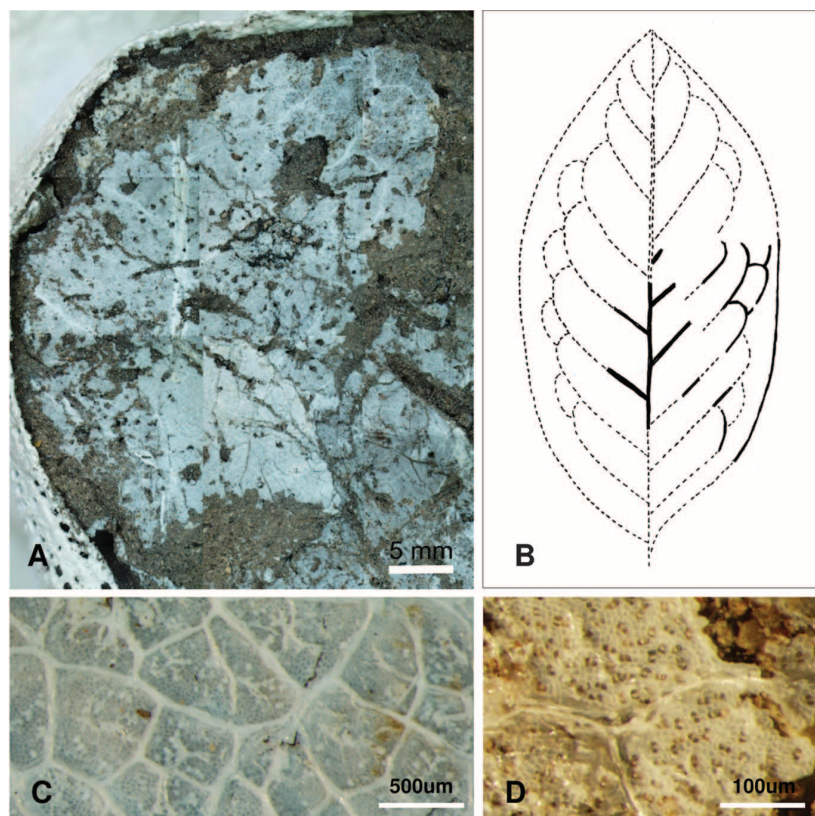

Fig. 4. *Cryptocarya woodii* leaf from Sibudu's ~77 ka bedding. (**A**) Almost complete leaf with wide and irregularly spaced secondary veins arising from the thick primary vein. Loops of the brochidodromous secondary veins can be seen on the top left. (**B**) Sketch of leaf with solid lines representing preserved venation. Dashed lines represent missing part of leaf, based on this and other specimens. The thick margin is visible. (**C**) Detail of fine venation with square to polygonal areoles containing bifid quaternary veinlets. This is the inner view of the upper epidermis, and there are no stomata. (**D**) Inner view of lower epidermis, showing butterfly-like stomata (thin paired cells).

phenotypic variation suggest that bottlenecks at ~80 to 60 ka were followed by rapid population growth, as well as by expansions within and out of Africa at ~56 ka (*2*).

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