500 cd/m² at 5 V. Their spectral response (Fig. 3) reveals that emission arises from the [Ru(bpy)₃]²⁺(PF₆⁻)₂ side of the junction. This is consistent with the energy-level offsets at the heterojunction (Fig. 1C). The barrier for hole injection from DPAS Na⁺ into [Ru(bpy)₃]²⁺(PF₆⁻)₂ is 0.7 eV smaller than that for electron injection from [Ru(bpy)₃]²⁺(PF₆⁻)₂ into DPAS Na⁺. No light emission was detected at reverse bias (the radiant flux was lower than 10⁻¹² W). In the absence of mobile ions, a device with energy levels as in Fig. 1C (dotted lines) and with ITO and Au electrodes would show hole-only current without substantial rectification or light emission. Rectification and light emission in traditional organic light-emitting diodes are associated with the use of an anode and a cathode with a high and a low work function, respectively.

Illumination of the junctions resulted in a photovoltaic response. Under 100 mW/cm² excitation from a halogen lamp, an open circuit voltage of 0.45 V and a short-circuit current density of 0.15 μA/cm² were measured (Fig. 4). Upon sudden illumination the photocurrent took a few seconds to reach steady state, presumably due to redistribution of the ionic carriers under the influence of the photogenerated electrons and holes. The data of Fig. 4 were acquired at steady state. The intensity dependence of the photocurrent was measured up to 500 mW/cm² and was found to be sublinear, with an exponent of 0.85. The internal quantum efficiency (electrons collected per photon absorbed) was estimated to be on the order of 5 × 10⁻⁶. This is low compared to state-of-the-art organic photovoltaics but expected given the low excitation dissociation yield in these materials. Indeed, devices based on the constituent layers did not show any photovoltaic response, confirming negligible ionic dissociation in the bulk and at the electrode interfaces.

The photovoltaic response of the junctions is consistent with the built-in potential assisting the dissociation of excitons and the separation of electrons and holes in the [Ru(bpy)₃]²⁺(PF₆⁻)₂ and the DPAS Na⁺ layers, respectively (Fig. 1C). Estimating the magnitude of the built-in potential is difficult, because the ion density near the junction interface is hard to predict due to ionic effects associated with ion packing. The value of the open circuit voltage represents a lower limit for the built-in potential, considering that there is some resistive loss across the two layers and at the contacts. It should be mentioned that the use of mobile ions in photovoltaics is well established in Grätzel cells (19). In these devices, ions in an electrolyte extract and transport holes from charge-transfer dye attached to titanium dioxide. In the ion-junctions reported here, the ions establish a built-in potential across a heterojunction.

The observations of rectification in current and light emission, and of a photovoltaic response in the PN junction and not in the constituent layers, demonstrate that mobile ionic charge can be used to control the flow of electronic current in solid-state devices. In principle, any organic semiconductor may be modified with ionomers to endow unipolar ionic conductivity, and the technique of lamination described here can be easily applied to fabricate PN junctions from these materials. Such junctions might help decrease recombination and increase the efficiency of organic heterojunction solar cells (20).

Moreover, given that ionic and electronic mobilities often differ by several orders of magnitude, the possibility of realizing ionic junctions that can be reconfigured by the prolonged application of a bias and be used at faster scales to rectify electronic current is exciting.

References and Notes
2. L. Stryer, Biochemistry (Freeman, New York, 1995).

Tectonic Uplift and Eastern Africa Aridification

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The history of Eastern African hominids has been linked to a progressive increase of open grassland during the past 8 million years. This trend was explained by global climatic processes, which do not account for the massive uplift of eastern African topography that occurred during this period. Atmospheric and biosphere simulations quantify the role played by these tectonic events. The reduced topographic barrier before 8 million years ago permitted a zonal circulation with associated moisture transport and strong precipitation. Our results suggest that the uplift itself led to a drastic reorganization of atmospheric circulation, engendering the strong aridification and paleoenvironmental changes suggested by the data.

Several biosphere shifts linked to phases of aridification punctuated East African environmental evolution during the late Neogene (1, 2) 8 million to 2 million years ago (Ma), which corresponds to a key period in hominid evolution (3–5). Isotopic studies (7) have attributed a first Upper Miocene (8 to 6 Ma) transition from woodlands to grasslands to atmospheric CO₂ decrease. A later (5 to 3 Ma) spreading of grasslands (6, 7) was attributed to both Indian Ocean sea surface temperature cooling (8) and the onset of glacial-interglacial cycles (9), whereas topographic changes induced by rifting processes were considered as a second-order forcing factor on climate.

Actually, substantial uplifts affected African topography during the late Neogene. The most important topographic structure is the East African Rift System. It began to uplift by its eastern branch (in southern Ethiopia and the Turkana depression in northern Kenya) during Eocene-Oligocene times, with uplifting reaching a maximum at the Plio-Pleistocene interval (10–12) (Fig. 1D). Ethiopian uplift shoulders were superimposed on an older topography linked to Oligocene volcanic activity (Ethiopian traps) (13). Traps sequence thickness is not very well constrained—a maximum of 2000 m having been observed on the northwestern edge
of the Ethiopian plateau (13). The western branch of the East African Rift System started to develop during the middle-late Miocene, with initiation of the central Tanganyika Basin at about 12 to 10 Ma (14, 15), and with more recent phases of major uplift between 5 and 2 Ma in the Tanganyika and Malawi rifts (16). Major Tanzanian escarpments were present by 3 Ma (17). These features led to a 6000-km-long elevated area (11), mostly oriented north-south and bordered by crests culminating between 1500 and 5100 m. The Karoo plateau in South Africa (20° to 32°S) has been raised during the past 5 million years (10), reaching a mean elevation of ~1400 m at present. Modeling studies of the impact of Cenozoic uplift on climate have been essentially carried out at the global scale, and Mio-Pliocene orographic changes have been implicated as a link between Tibetan plateau uplift and monsoons (18). Nevertheless, the impact of African topography on climate and vegetation has not yet been tested.

Using numerical modeling, we assess both climate and biosphere responses to topographic changes linked to eastern and southern African uplifts. Sensitivity experiments have been carried out with the LMDz4 (Laboratoire de Météorologie Dynamique, Paris) (19) atmospheric general circulation model (AGCM). To improve the AGCM’s ability to simulate climate change induced by the narrow topographic structures of the East Africa Rift System and the Southern African topography, we used a zoom giving a resolution of up to 1° over our region of interest. In addition to a present-day control (CTL) simulation, we made two runs with a reduced topography over eastern and southern Africa (Fig. 1, A to C). As reconstructions for Eastern Africa paleoaltitudes are not available because of a lack of accurate data, we constrained our model according to two extreme scenarios from geological literature (20). The NORIFT simulation considers the Ethiopian traps as being very low. Topography is reduced to 400 m over both eastern and southern Africa. In the TRAPS simulation, we account for a maximum elevation of Ethiopian traps at 2000 m (13), and we set this value as minimal topography over the traps area. Both simulations were prescribed with present-day boundary conditions, namely modern sea surface temperatures, ice-sheet and sea-ice extent, insolation, and greenhouse gas concentrations. Climatic outputs have been used to force the dynamic global vegetation model Organizing Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) (21). Climatic variables (20) have been derived from our three simulations to force the biosphere model. Here, we consider the potential vegetation cover with ORCHIDEE plant functional types (PFTs).

CTL rainfall patterns are in good agreement with reanalysis data (22), except at the land-sea interface of the East African coast where the precipitation amount is overestimated. Present-

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Fig. 1. Experimental design of the three LMDz4 simulations related to topography history of Africa. (A to C) Relief interpolated at the AGCM resolution for CTL, TRAPS, and NORIFT runs, respectively. (D) Simplified history of major African tectonic events during the late Neogene. We note that several phases of uplift occurred during the last 10 million years, a period during which numerous environmental shifts are recorded in East Africa. Tectonic and paleotopographic data as follows: Ethiopia (11–13), Kenya (11, 12), Tanzania (18), Tanganyika (15, 16), Malawi (17), and southern Africa (12). Ovals indicate onset of the most important tectonic movements.
day simulated annual rainfall averages 1310 mm over the horn of Africa [0° to 15°N/35° to 50°E, the Ethiopia-Kenya-Somalia (EKS) region], ranging from 200 to 800 mm for southwestern Ethiopia and Somalia up to 2400 mm in northern Kenya. In these regions, rainfall is strongly influenced by low tropospheric winds (23), which convey a large amount of atmospheric moisture. These winds blow northeasterly during boreal winter and southerly during boreal summer. Continental topography strongly influences the direction of these winds and therefore the location of rainfall. Meridional moisture transport shows that Ethiopian highlands deflect the northeast monsoon flow southward along the Somali coast during winter and that Kenyan highlands deflect the southeast flow northward during summer (Fig. 2, A and B). When the Ethiopian highlands are reduced in height (TRAPS), the Indian monsoon flow enters more deeply westward over the continent during winter, whereas in summer a zonal eastward moisture flow is created from Southern Sudan to Ethiopia (5° to 10°N) (Fig. 2, C and D). This phenomenon, which leads to large-scale rainfall, is enhanced in NORIFT, as no topographic barrier blocks lower atmosphere circulation over Ethiopia (Fig. 2, E and F). Moreover, higher surface temperatures due to lower altitude in our experiments induce more intense convection and associated precipitation. As a consequence, TRAPS rainfall averaged over EKS is increased by 15% (1520 mm/year) with respect to the CTL experiment (Fig. 3, A and B), whereas it is increased by 40% (1830 mm/year) in NORIFT (Fig. 3C). The seasonal pattern is conserved in TRAPS, with rainfall equally increased in winter and summer. However, the total removal of topography favors winter convective rainfall and leads to a peak of more than 4 mm/day in February in NORIFT (Fig. 3E). South to the equator, a winter eastward moisture transport is set between Atlantic and Indian oceans when topography is reduced. Summer westward Indian flow is no longer diverted by Tanzanian relief and penetrates inland between the equator and 25°S. Once again, rainfall is enhanced: Averaging 1150 mm/year over 0° to 20°S/25° to 40°E, the Congo-Tanzania-Zambia-Mozambique (CTZM) region for CTL, it increases by 38% (1590 mm/year) in TRAPS to 62% (1870 mm/year) in NORIFT (Fig. 3D).

Apart from the overestimated vegetation cover over the Tanzanian and Kenyan coasts due to the LMDz4 positive bias in rainfall already mentioned, the CTL “arboreal” and “herbaceous” fractions are in good agreement with preindustrial values, which can be inferred from present-day data and modeling studies (24). Total vegetation cover (Fig. 4A) is globally increased over both eastern EKS and CTZM regions in the TRAPS and NORIFT simulations (Fig. 4, B and C). When the maximal Ethiopian traps elevation is conserved (Fig. 4, B to E), arboreal vegetation is slightly increased over eastern Ethiopia. It becomes dominant over almost all the northeastern rift when topography is totally eliminated (Fig. 4F). Between 15°S and 5°N, the positive shift in arboreal group is the highest, with a transition from 10% to 60% coverage over Ethiopia, Kenya, and Mozambique (NORIFT). These parts of eastern Africa become tree-dominated, whereas they are dominated by herbaceous groups in the present-day experiment (Fig. 4D). In both lowered-topography experiments, we also simulated an arboreal increase connecting western and eastern Africa along the equator. These results suggest a strong impact of Miocene uplift on biosphere, and available data depict strong paleoenvironmental changes during this time interval.

Between 8 and 6 Ma, new families of ungulate mammals with a C₄ (grass-dominated) diet replaced more archaic middle Miocene communities (25) with C₃ (wood-dominated) diets, indicating a decrease in rain forests and an increase of more open “savannah-mosaic” habitats. Isotopic studies on fossil tooth enamel (1) have suggested a global-scale replacement of C₄-photosynthesizing plants by C₃ plants. This change has been linked to atmospheric CO₂ decrease, although the question is still debated (26, 27). Paleoenvironmental data compiled by Cane and Molnar (8) for the past 15 million years suggest a later transition, with wooded habitats existing until 5 and 3.7 Ma in northern and southern Kenya, respectively, and until 3.4 Ma in Ethiopia. Until this time interval, moist environments would have been present in northeastern Africa (28), notably in southern and central Ethiopia (29). The Turkana Basin experienced a strong increase in the number of mammal species adapted to open grasslands, indicating increased aridity after 2.5 Ma (7). This trend to aridification at around 3 Ma was first explained by Indian Ocean cooling associated with a change in Indonesian throughflow conformation, which allowed colder water to come in from the Pacific ocean (8). Moreover, paleoclimatic records (30) suggest an orbital-scale variability in northeast Africa paleoenvironments that increased with the intensification of high-latitude glacial cycles (9). The topographic impact has been considered as a second-order forcing so far, only modulating the variability of regional climate through rain-shadow effects (2).

Despite the high resolution we used, our experiments cannot capture isolated topographic
features like volcanoes or small mountains. Nevertheless, our results provide strong arguments for an impact of topographic changes at the continental scale. Topography clearly affects moisture transport and, therefore, rainfall spatial patterns and amounts. Associated hydrological modifications induce strong shifts in vegetation. Consequently, it appears that uplifts had a first-order impact on Miocene eastern African climate evolution. We cannot pretend to have captured an exhaustive picture of vegetation evolution in the several rift basins of eastern Africa, but these results are a step forward in understanding the mechanisms that led to more open landscapes in eastern Africa. We can assume that the climatic consequences depicted here, along with landscape fragmentation linked to asynchronous uplift events, have largely contributed to the setting of present-day vegetation patchwork of eastern and southern Africa. Consequently, African uplift must be considered as a dominant forcing of the late Neogene climate of eastern Africa, and not as a background factor. Future studies, which will aim to accurately assess the impact of climate change at this period, and notably its potential influence on paleoenvironments that force hominin evolution, will have to constrain accurately the topographic history of eastern Africa.

Fig. 3. Simulated rainfall for the three experiments. (A) Annual amount of rainfall simulated by CTL run. (B and C) Rainfall anomaly of TRAPS and NORIFT runs versus CTL, respectively. Isolines represent topography for each run, in meters. (D and E) Seasonal pattern of rainfall averaged over EKS and CTZM (black boxes), respectively. Rainfall variability is calculated excluding the unbalanced first year of simulation.

Fig. 4. Simulated vegetation for the three experiments. (A) Summed vegetation fraction over every PFT for the CTL run. Zero value indicates the absence of vegetation. 1 represents a gridpoint totally covered by PFTs. (B and C) Anomalies of TRAPS and NORIFT minus CTL, respectively. (D to F) Arboreal-dominant, herbaceous-dominant, and desert-like fractions for CTL, TRAPS, and NORIFT, respectively. We note the massive spreading of arboreal fraction at the expense of herbaceous fraction over eastern Africa.
Measurement of the Entanglement of Two Superconducting Qubits via State Tomography


Demonstration of quantum entanglement, a key resource in quantum computation arising from a nonclassical correlation of states, requires complete measurement of all states in varying bases. By using simultaneous measurement and state tomography, we demonstrated entanglement between two solid-state qubits. Single qubit operations and capacitive coupling between two superconducting phase qubits were used to generate a Bell-type state. Full two-qubit tomography yielded a density matrix showing an entangled state with fidelity up to 87%. Our results demonstrate a high degree of unitary control of the system, indicating that larger implementations are within reach.

The laws of quantum physics provide intriguing possibilities for a tremendous increase in computational power compared with classical computation (1). Because this power is achieved through the controlled evolution of entangled quantum states, a clear demonstration of entanglement represents a necessary step toward the construction of a scalable quantum computer (2, 3). However, direct demonstration of entanglement is challenging because all of the DiVincenzo criteria (4) for quantum computation must be met simultaneously. To date, only subsets of these key requirements have been demonstrated for superconducting qubits (5–9). We demonstrated all of the DiVincenzo criteria simultaneously, thus placing superconducting qubits on the road map for scalable quantum computing.

Circuits made of superconductors and Josephson junctions are promising candidates for scalable quantum computation because of their compatibility with integrated-circuit fabrication technology (5–9). The Josephson phase qubit stands apart from other superconducting qubits because it does not use an optimal operating point. Coupling of phase qubits is thus straightforward, allowing for multiple control methods (10). With recent improvements in coherence times and amplitudes (11), and in particular the ability to measure both qubit states simultaneously (5), it is possible to use phase qubits to produce entangled states and measure them with high fidelity.

In the phase qubit circuit (Fig. 1A), the Josephson junction (with critical current $I_J$) has a superconducting phase difference $\delta$, that serves as the quantum variable. When biased close to the critical current, the junction and its loop inductance, $L$, give a cubic potential that has qubit states $|0\rangle$ and $|1\rangle$, with an energy spacing that corresponds to a transition frequency $\omega / 2\pi \approx 5$ GHz (Fig. 1B). This frequency can be adjusted by $\sim 30\%$ via the bias current.

Single qubit logic operations, corresponding to rotations about the $x$, $y$, and $z$ axes of the Bloch sphere, were generated as follows. Rotations about the $x$ axis were produced from current pulses on the qubit bias line that adiabatically change the qubit frequency, leading to phase accumulation between the $|0\rangle$ and $|1\rangle$ states of the qubit (11). Rotations about any axis in the $xy$ plane were produced by microwave pulses resonant with the qubit transition frequency. They selectively affect only the qubit energy levels, because transitions to higher-lying energy levels are off-resonance due to the anharmonicity of the potential and the shaping of the pulses (12). The phase of the microwave pulses defines the rotation axis in the $xy$ plane. The pulse duration and amplitude control the rotation angle.

The qubit state was measured by applying a strong pulse, $I_p$, so that only the $|1\rangle$ state tunnels out of the cubic well (Fig. 1C). Once tunneled, the state quickly decays into an external ground state that can be easily distinguished from the untunnelled $|0\rangle$ state by an on-chip superconducting quantum interference device (SQUID) amplifier.

Two separate phase qubits were coupled with a fixed capacitor ($5$) (Fig. 1D). With the qubits labeled A and B, the coupling Hamiltonian is $H_C = (S_Z/2)(|0\rangle \langle 0| + |1\rangle \langle 1|)$, where $|0\rangle = |0\rangle_A \otimes |0\rangle_B$. The coupling strength, $S = (C/C)/\hbar$ is proportional to the coupling capacitance $C \approx 3$ FF, where $C \approx 1.3$ FF is the junction shunting capacitance (13) and $\hbar$ is Planck’s constant ($\hbar$) divided by $2\pi$. The two qubits may easily be brought into resonance, even though they are not identical, because each can be tuned over a large frequency range. On resonance, the interaction produces an oscillation with frequency $\sqrt{S} h$ between the states $|0\rangle$ and $|1\rangle$; for an interaction time of $\hbar/4S$, the coupling produces the gate $\sqrt{\text{SWAP}}$. This gate, together with single qubit gates, is universal (14). The coupling also manifests itself as an avoided level crossing of strength $S/\hbar$ in the spectroscopy of the individual qubits (15).

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References and Notes
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