

FIG. 2 Model results for the next 1.6 Gyr. The terrestrial biosphere, whose productivity (Π/Π_0) depends on an adequate supply of atmospheric CO_2 , maintains a gradient between soil and atmospheric CO_2 concentrations. For ~ 1 Gyr, the partial pressure of soil CO_2 (P_{soil}) and Earth's mean temperature (T) covary such that silicate-rock weathering consumes CO_2 at the modern rate. T is a function of both solar luminosity (S/S_0) and the atmospheric CO_2 concentration (P_{atm}). As S/S_0 increases, P_{atm} decreases, diminishing Π/Π_0 and with it the difference between P_{soil} and P_{atm} . When P_{atm} is too low for C4 plants to survive (~ 0.9 Gyr), then $P_{\text{soil}} = P_{\text{atm}}$. (In a C3-only world with $P_{\text{min}} = 150$ p.p.m., C3 plants survive ~ 0.5 Gyr.) After ~ 1 Gyr, silicate-rock dissolution exceeds volcanic CO_2 degassing; P_{atm} is then held at 1 p.p.m. The timescale for the loss of the oceans through hydrogen escape becomes limited by solar extreme ultraviolet when T climbs above 80°C (~ 1.5 Gyr). The loss of surface water by this process would take ~ 1 Gyr, and could ultimately limit the life span of the biosphere to ~ 2.5 Gyr.

temperature would be reached. Only prokaryotes and protozoa can live much above this temperature¹⁷. Beyond this time, planetary warming will probably accelerate. Atmospheric water vapour content increases exponentially with surface temperature if the relative humidity remains constant. This water vapour should trap outgoing longwave radiation and decrease the planetary albedo by absorbing solar near-infrared radiation. Both processes should contribute to planetary warming. In our model, the Earth's surface temperature increases from 50°C to 100°C in <0.2 Gyr. Some archaeobacteria might survive even higher temperatures^{18,19}, but all higher forms of life would certainly be eliminated by this stage.

The final sterilization of the Earth will occur when the planet loses its water. Today, the timescale for the loss of the oceans through photodissociation and hydrogen escape is much longer than the age of the Earth; as the atmosphere warms beyond 60 to 70°C , however, the H_2O mixing ratio in the stratosphere increases markedly²⁰. As surface temperatures approach $\sim 80^\circ\text{C}$, the stratospheric H_2O mixing ratio reaches $\sim 2.5\%$. Above this mixing ratio, the loss of hydrogen to space is limited by the solar extreme ultraviolet heating rate to $\sim 6 \times 10^{11}$ atoms $\text{H cm}^{-2} \text{ s}^{-1}$ (ref. 21), giving a timescale for ocean loss of ~ 1 Gyr. Hence, the complete elimination of water ~ 2.5 Gyr from now could bring terrestrial life to its final close. After Earth's water is lost, silicate-rock weathering will cease; hence, volcanic CO_2 should accumulate in the atmosphere, creating a climate much like that of Venus.

Events such as a collision with the giant comet Chiron²² or a radical reorganization of the carbonate-silicate cycle¹¹ could possibly bring the life of the biosphere to an earlier close. But given the otherwise conservative assumptions that we have made

in constructing our model, our results indicate that the biosphere will probably survive at least another 1 Gyr, and possibly much longer. This prediction ought to be encouraging to humans, as well, because it implies that we could survive for geologically long time periods if we can manage to cope with our other societal problems. □

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Electrical conductivity of carbon-bearing granulite at raised temperatures and pressures

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IT has long been recognized that the electrical conductivity of the lower continental crust is anomalously high. Both pore-saturating brines^{1–5} and conducting films of carbon at grain boundaries^{6–10} have been proposed to explain this, but the evidence remains inconclusive. Here we report measurements of electrical conductivity at high temperatures and pressures^{11–13} on samples of carbon-bearing and carbon-free granulites with a range of electrolyte saturations. The application of pressure to nominally dry carbon-free samples reduces the electrical conductivity as a result of a progressive reduction in pore connectivity, whereas the carbon-bearing samples show an increase in conductivity under the same conditions—an effect that we ascribe to reconnection of carbon conduction pathways during compaction. Moreover, we find a greater increase in conductivity with temperature for the carbon-bearing samples. In the light of work indicating that the abundance of carbon in high-grade rocks has been underestimated in the past^{7,8}, our results provide strong evidence for the role of carbon in lower-crustal conductivity.

Very few laboratory experiments have been done under fully simulated lower-crustal conditions to estimate the contribution of electrolytes to the *in situ* rock conductivity, and only one study, to our knowledge, examined carbon-bearing rock¹⁴. Here we examine carbon-bearing and carbon-free granulites under a

TABLE 1 Description of samples

Sample	Carbon content (wt%)	Orientation*	Saturation state	Maximum temperature (°C)	Maximum confining pressure (GPa)	Porosity (%)
Carbon-bearing granulites from Beni Bousera, northern Africa						
A1	2.70	Parallel	Saturated 0.5 M NaCl	700	0.2	0.88
A2	2.64	Perpendicular	Saturated 0.5 M NaCl	700	0.2	0.93
A3	2.71	Parallel	Unsaturated	25	0.4	0.91
A4	2.75	Perpendicular	Unsaturated	25	0.4	0.94
Mineral assemblage: clinopyroxene, orthopyroxene, plagioclase, garnet, graphite, biotite, spinels						
Carbon-free granulites from Ivrea Zone, northern Italy						
B1	<0.002	No foliation	Saturated 0.5 M NaCl	900	0.2	0.78
B2	<0.002	No foliation	Saturated distilled water	900	0.2	0.72
B3	graphite-free	No foliation	Unsaturated	25	0.4	1.03
B4	graphite-free	No foliation	Unsaturated	25	0.4	0.89
Mineral assemblage: clinopyroxene, orthopyroxene, plagioclase, spinels, hornblende						

Overview of the samples used in this work. Total carbon measurements were made using a Leco induction furnace and infra-red detector which was calibrated against samples of steel with accurately known carbon content. Thin-section studies of the granulites showed the absence of carbonate minerals. The total carbon content has, therefore, been taken as the carbon content and quoted as a percentage weight. The carbon content figures have an associated error of ± 0.1 in the range 1–10%. The carbon-free samples B1 and B2 had less than 20 p.p.m. carbon (the limit of instrumental resolution).

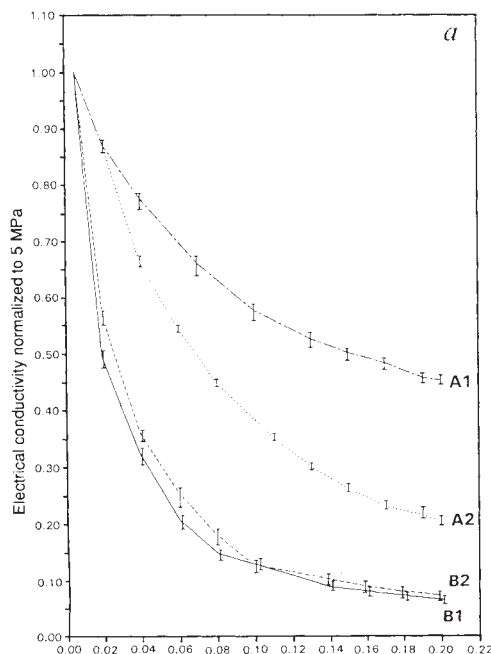
* Orientation of direction of electrical conductivity measurements with respect to the plane of foliation

range of electrolyte saturations, confining pressures, pore pressures and temperatures to assess their contributions to the bulk conductivity of the rock and to help understand the nature of the rocks causing the high-conductivity zones in the lower crust.

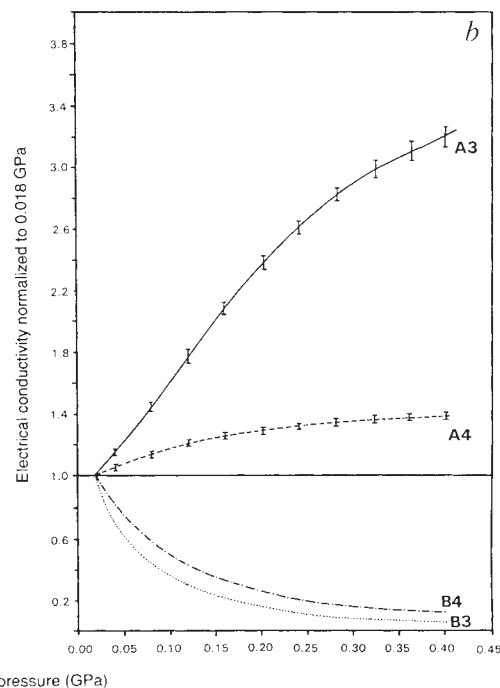
When pressure is applied to an electrolyte-saturated rock, it reduces the rock's electrical conductivity. This is due to the progressive loss of porosity and pore connectivity through which the conduction occurs; the effect is smaller if there is significant conduction through the rock matrix^{2,3}. We found that the electrical conductivity of our electrolyte-saturated carbon-bearing granulite samples (A1, A2) decreased with the application of

confining pressures as expected. The decrease was, however, less than that for the carbon-free granulites, B1 and B2 (Fig. 1a). This is in itself unremarkable and can be explained if, of the two types, the carbon-free granulites have a higher porosity, a weaker matrix or a greater proportion of long thin cracks that tend to close on application of small confining pressures. In our work, however, the carbon-bearing granulite samples have a higher porosity (Table 1) and friable nature, and would be expected to lose much of their porosity, with associated loss of conductivity, when even small pressures are applied. Furthermore, the highly foliated nature of the carbon-bearing granulites suggests that much of their porosity is in the form of long thin

FIG. 1 a, Variation of the electrical conductivity of water- and brine-saturated carbon-free and carbon-bearing granulites as confining pressure is increased. Measurements were made with a Wayne Kerr B642 a.c. transformer bridge operating at 1,592 Hz. The samples were measured with a PTFE sleeve and two-electrode arrangement^{11–13} or with a metal sleeve and three-electrode guard-ring arrangement^{12,13}. All electrical conductivity measurements were taken after any transient changes in the pore structure had occurred. Error bars indicate the range of results from three experimental runs. A1 and A2: carbon-bearing, electrolyte-saturated, measurement direction parallel and perpendicular to planes of foliation respectively. B1



and B2: carbon-free, no foliation, saturated with electrolyte and distilled water respectively. The data are normalized to that at 5 MPa; absolute values for each of the samples at this pressure were as follows: A1, $5.01 \times 10^{-4} \text{ Sm}^{-1}$; A2, $2.51 \times 10^{-4} \text{ Sm}^{-1}$; B1, $1.995 \times 10^{-4} \text{ Sm}^{-1}$; B2, $2.24 \times 10^{-4} \text{ Sm}^{-1}$. b, Variation of the electrical conductivity of unsaturated samples of carbon-free and carbon-bearing granulites as confining pressure is



increased. Measurements and error bars as in a. A3 and A4: carbon-bearing, unsaturated, measurement direction parallel and perpendicular to planes of carbon foliation respectively. B3 and B4: carbon-free, unsaturated, no foliation. The data are normalized to that at 18 MPa; absolute values for each of the samples at this pressure were as follows: A3, $2.24 \times 10^{-5} \text{ Sm}^{-1}$; A4, $3.55 \times 10^{-6} \text{ Sm}^{-1}$; B3, $2.51 \times 10^{-6} \text{ Sm}^{-1}$; B4, $2.3 \times 10^{-6} \text{ Sm}^{-1}$.

cracks rather than less compressible, more rounded pores. If the pressure variation were solely due to electrolytic conduction through the pore fluid, one would expect that the flat thin cracks in the carbon-bearing granulites, confirmed by optical and electron microscopy, and deduced from mercury injection porosimetry, would make the electrical conductivity more sensitive to pressure than was observed. It seems, therefore, that sample pore-space or matrix properties cannot account for the different trends in electrical conductivity.

We expected the conductivity of nominally dry samples to mirror the behaviour of the fully saturated samples but to be lower overall. The reason for this was that the nominally dry samples were not oven-dried and would contain small amounts of remaining pore fluids. The carbon-free samples (B3, B4) showed lower conductivities than the saturated case, as expected. The conductivity of the unsaturated carbon-bearing samples (A3, A4) at near surface conditions was lower than that when saturated with electrolyte, as expected, but increased with the application of confining pressure (Fig. 1*b*). This behaviour is consistent with that of the saturated samples and indicates that

the lower rate of reduction of conductivity with pressure is not associated with electrolytic conduction but with some mechanism that becomes more efficient during compaction.

We found that the electrical conductivity of the electrolyte-saturated carbon-bearing samples increased more steeply with temperature than that for the electrolyte-saturated carbon-free samples (Fig. 2). This increased temperature dependence cannot be explained merely by additional carbon conduction, as graphite conduction is nearly independent of temperature. Further work on the carbon-electrolyte system is needed to ascertain whether the effect is connected with a carbon-water interaction or possibly the formation of carbon-sodium intercalation compounds at high temperature and pressure. These compounds have higher conductivity than graphite, but also have a negative coefficient of conductivity with temperature. The observed effect may be due to increased formation of such compounds as temperature increases.

Most measurements made in this work were at a fixed frequency of 1,592 Hz. The electrical conductivity of most rocks varies slightly with frequency, and considerable variations may occur in carbon-bearing rocks¹⁵. We measured the impedance spectra of rock samples A1, A2, B1 and B2 to check that the conductivities at the fixed frequency were representative. The

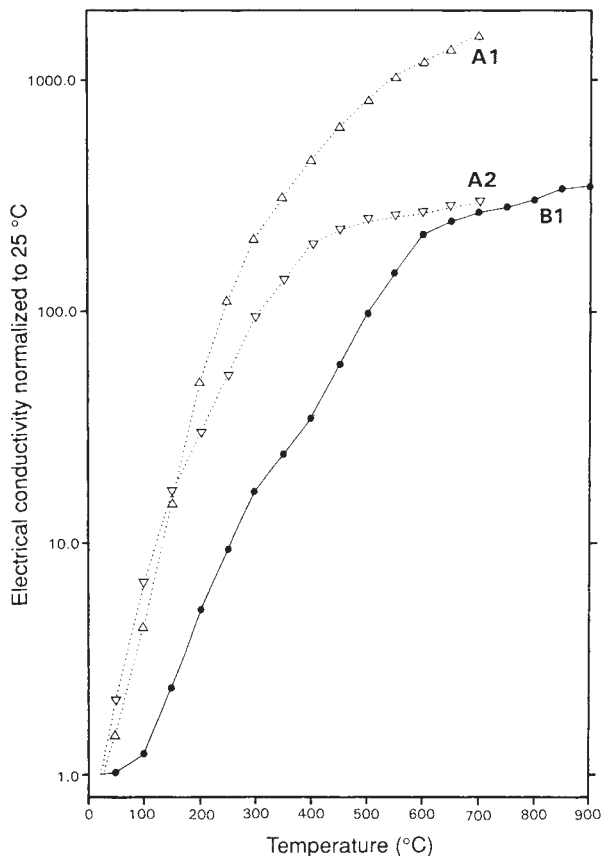


FIG. 2 Variation of the electrical conductivity of 0.5 M NaCl brine-saturated carbon-free and carbon-bearing granulites at constant confining pressure (0.2 GPa) and pore fluid pressure (0.18 GPa) at different temperatures (up to 800 °C). Measurements were made with a Wayne Kerr B642 a.c. transformer bridge operating at 1,592 Hz. The samples were measured with a metal sleeve and three-electrode guard-ring arrangement^{12,13}. The size of symbols indicates the approximate error associated with individual readings. A1 and A2: carbon-bearing, measurement direction parallel and perpendicular respectively to planes of carbon foliation. B1: carbon-free, no foliation. Conductivities during cooling coincided with those during heating. Heating/cooling hysteresis was observed on the first heating cycle. This was removed by holding the temperature high under pressure until all temperature-induced changes had occurred. The values given here are from subsequent heating and cooling cycles applied slowly. The results are normalized to that at 25 °C; absolute values for each of the samples at this temperature were as follows: A1, $1.26 \times 10^{-4} \text{ Sm}^{-1}$; A2, $0.631 \times 10^{-4} \text{ Sm}^{-1}$; B1, $1.26 \times 10^{-5} \text{ Sm}^{-1}$.

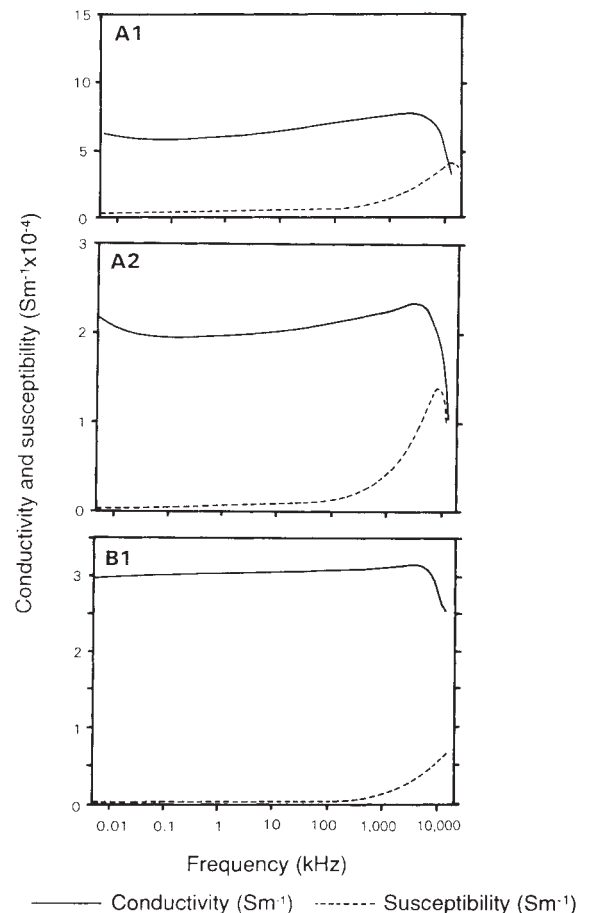


FIG. 3 The complex electrical conductivity of selected samples as a function of frequency of applied electric field. The measurements were made on a HP4192 LCR meter. Measurements of electrical conductivity and susceptibility were made at 20 frequencies per decade from 5 Hz to 20 MHz on samples saturated with 0.5 M aqueous NaCl solution with a two-electrode system. The electrodes were made from platinum-blacked platinum gauze to minimize electrode polarization at low frequencies. A1 and A2: carbon-bearing, electrolyte-saturated, measurement direction parallel and perpendicular to planes of foliation respectively. B1: carbon-free, no foliation, saturated with electrolyte.

mode of conduction in all samples is dominated by the in-phase conduction throughout the complete frequency range (Fig. 3). The electrical phase angles at 1,585 Hz, the nearest measured point to the frequency used in the main measurements, were -2.83° , -1.76° and -0.15° for A1, A2 and B1 respectively. This indicates that more out-of-phase conduction occurs in the carbon-bearing samples, although the effect is still small in comparison with the in-phase component. One possible explanation lies in the way in which charge carriers move between crystal lattice planes: the build up of charge carriers on alternate planes of a graphite lattice gives rise to local electrical fields that oppose the main field and generate the out-of-phase conduction. The presence of the out-of-phase conduction is therefore additional evidence that significant non-electrolyte-mediated conduction is occurring.

We propose that the increase in electrical conductivity in the unsaturated carbon-bearing samples is due to increased connectivity of carbon as the pore volume is lost and pore throats close down, leaving only compacted carbon conduction pathways. If so, the conductivity of the rock at high pressures would be expected to mirror that of carbon. Specifically, the rock's conductivity would depend only upon the amount and conductivity of the carbon fraction present, and have a negligible variation with pressure, as for pure carbon. We were able to create confining pressures of 0.4 GPa; to judge whether our hypothesis is correct, greater pressures are needed to compact the rock completely. Even at the highest pressures used here, the progressive loss of conduction by the small amounts of fluid still remaining in the pores unfortunately prevents quantitative comparisons with a dry rock containing only compact carbon and matrix minerals. It is clear, however, that some conducting mineral is responsible for the anomalous electrical behaviour. Quantitative mineralogical analysis of all the samples shows similar fractional amounts of all minerals but one. The exception is the presence of $\sim 2.7\%$ carbon in those labelled carbon-bearing¹².

Auger spectroscopy of igneous and metamorphic rocks has shown fine films of carbon covering grain boundaries^{7,8}. It has been postulated⁷ that decompression could irreversibly change the electrical conductivity of rocks by rupturing these films, and that laboratory measurements would not be able to duplicate the high conductivity in rocks even if the rocks were subjected to high pressures. Our experiment suggests that, at least to some extent, carbon grain-boundary films will reconnect under high pressures.

From the marked rise in the electrical conductivity of these saturated carbon-bearing samples as temperature and pressure increase, one would expect a high sample conductivity under lower-crustal conditions. The presence of carbon-bearing rocks similar to those studied here would raise the rock conductivity to moderate values if dry and to high values if also saturated with brines, producing values similar to those observed for the crustal high-conductivity zones by magnetotelluric methods¹⁶. It seems increasingly likely that plutonic and granulitic rocks with grain-boundary carbon could have electrical conductivities as high as those deduced in many areas of the lower continental crust. □

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A mantle metasomatic injection event linked to late Cretaceous kimberlite magmatism

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METASOMATISM of the lithospheric upper mantle by magmas and/or other fluids may induce significant changes in its chemical and mineralogical composition. It is not yet clear whether metasomatism takes place earlier than, concurrent with or subsequent to alkaline igneous activity and melt migration. Clues about the timing of metasomatism beneath the Kaapvaal craton in southern Africa are provided by metasomatized peridotites brought to the surface as xenoliths in young (80–95-Myr-old) group I kimberlites^{1,2}; the question that arises is whether the metasomatic alterations of the xenoliths are related to the host kimberlites themselves or to earlier igneous events such as the group II kimberlite eruptions (120–150 Myr)^{1,2}. Here we report a precise U–Pb age of 85 ± 2 Myr for zircons in a veined and metasomatized harzburgite xenolith from Kimberley, which indicates that this particular style of metasomatism (MARID-related³) is concurrent with the migration of the kimberlite magma that hosts the xenolith. This temporal link supports previous isotopic evidence⁴ for a genetic link between the group I kimberlite magmatism and the accompanying metasomatism.

Periodic volcanism has occurred on the Kaapvaal craton in southern Africa since the Archaean era, and each episode will have modified the composition of the subcontinental lithospheric mantle in which the magmas were generated or through which they passed, or in other words caused mantle metasomatism. The most recent volcanic rocks are the Cretaceous kimberlites which erupted in two pulses: group II (120–150 Myr) and

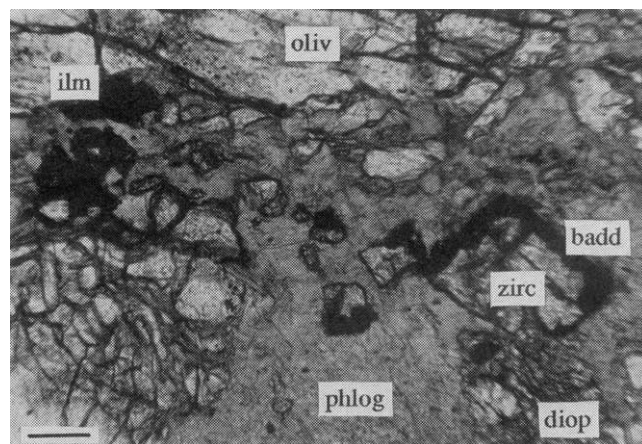


FIG. 1 Photomicrograph of veined harzburgite BD 3024 in plane polarized light, showing euhedral zircon crystals (zirc) with dark baddleyite rims (badd), occupying a phlogopite-rich vein (phlog) cutting olivine (oliv). Additional phases: ilmenite (ilm); diopside (diop). Field of view $750 \mu\text{m} \times 525 \mu\text{m}$, scale bar $70 \mu\text{m}$.