Mission to Earth's core — a modest proposal

Not science fiction, but a technically feasible plan to probe our planet's inner workings.

Planetary missions have enhanced our understanding of the Solar System and how planets work, but no comparable exploratory effort has been directed towards the Earth's interior, where equally fascinating scientific issues are waiting to be investigated. Here I propose a scheme for a mission to the Earth's core, in which a small communication probe would be conveyed in a huge volume of liquid-iron alloy migrating down to the core along a crack that is propagating under the action of gravity. The grapefruit-sized probe would transmit its findings back to the surface using high-frequency seismic waves sensed by a ground-coupled wave detector. The probe should take about a week to reach the core, and the minimum mass of molten iron required would be 10^8–10^{10} kg — or roughly between an hour and a week of Earth's total iron-foundry production.

We live on the Earth's surface, which divides what is above from what is below (Fig. 1). The part above us (the rest of the Universe) is mostly empty, mostly unknown and about 10^{57} times larger by volume. The part below is crammed with interesting stuff and is also mostly unknown, despite its much greater proximity to us. Space probes have so far reached a distance of about 40 astronomical units (6×10^9 km), but subterranean probes (drill holes) have descended only some 10 km into the Earth.

Travel downwards is impeded by the dense intervening matter, and the energy required to penetrate it by melting is about 10^9 times (per unit distance travelled) the energy needed for space travel — a fact that partly explains the large difference in distances attained[1]. Travel downwards has also been impeded by the much more limited allocation of financial and material resources relative to those provided for space travel — there is no underground equivalent of NASA.

One possible means of reaching the core appeals to the 'China syndrome' idea[2] and requires melting of the rock, but the trip times in these scenarios are thousands of years or more — geologically short but too long on a human timescale for any government to contemplate funding. However, a liquid-iron-filled crack initiated in the Earth would propagate downwards (despite very high pressures), closing up behind as it travels, and a neutrally buoyant, insoluble probe could be carried along for the ride.

I use well-established principles of magma fracturing[3,4] (the migration of melt through the Earth's lithosphere). Consider a vertical crack of approximate width d. The other horizontal dimension is $W \gg d$. Let the characteristic vertical extent be L. Provided that

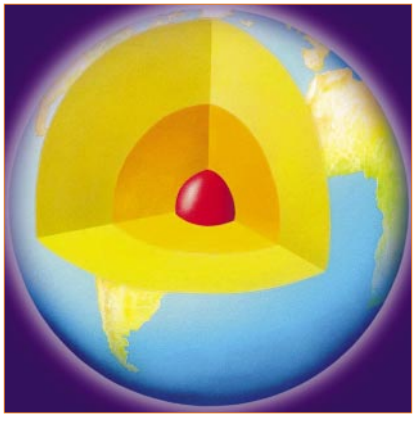

Figure 1 Next to the riches lavished on space exploration, an unmanned journey to the centre of the Earth looks almost frugal.

L is sufficiently large, the propagation speed will be limited by the channel-flow velocity of the fluid. The relevant solution has turbulent flow, with the crack-propagation speed, V_{prop}, being roughly equal to the channel-flow velocity, or $[(\Delta\rho/\rho)gd^{5/4}/\nu^{1/4}]^{4/7}$, where $\Delta\rho\approx\rho$ is the density difference between melt and surrounding rock, g is the gravitational acceleration, and ν is the kinematic viscosity of liquid iron (about 10^{-6} m^2 s^{-1}). Thus, $V_{prop}\approx30d^{5/7}$ m s^{-1}, with d in metres.

A crack of width d and length L would have associated deviatoric stresses of about $\mu d/L$, where $\mu\approx10^{11}$ pascals (Pa) and is the shear modulus of the rock. This stress will be overcome by the pressure head in the crack when it is comparable to $\Delta\rho gL$. This defines a natural crack of length $L\approx(\mu d/\Delta\rho g)^{1/2}\approx(1\text{ km})\times d^{1/2}$ and with a stress level of about $3\times10^7d^{1/2}$ Pa. If stresses of about 10^7 Pa are sufficient (as studies of lithospheric cracking suggest), $d\approx0.1$ m and $L\approx300$ m. Assuming that the other dimension, W, is also around 300 m, the volume of iron contained in the crack will be about 10^4 m^3, or 10^8 kg, which is the amount produced in about an hour by the world's foundries[5].

As the crack propagates downwards at about 5 m s^{-1} (a speed that would give a mission timescale of around a week), the released gravitational energy would cause heating and partial melting of the silicate rock walls[1]. The work required to initiate the crack is plausibly about μLWd, or about 10^{15} joules, which is equivalent to a few megatons of TNT explosive, an earthquake of magnitude 7 on the Richter scale, or a nuclear device with a capability that is within the range of those currently stockpiled. Some aspects of crack migration in the deep Earth may involve modified, less optimistic values[1], however, requiring an iron volume that is greater by one or two orders of magnitude.

It may also be feasible to make use of existing favourable stress environments in the Earth and to avoid the use of nuclear devices. The technological challenge of initiating the crack should be less than that posed by the Manhattan Project.

The embedded, solid-state probe could plausibly have a volume of d^3, or roughly that of a grapefruit. It would be a high-melting-point alloy in saturation equilibrium with the neighbouring liquid-iron alloy and would contain miniaturized instrumentation for measuring temperature and electrical conductivity, detecting abundant and trace elements, and so on — details that would require an instrument-development programme. The Earth's interior is opaque to electromagnetic signals with periods of less than the mission timescale, and neutrinos are difficult to use, so acoustic communication would be best.

I assume a probe power, P, of about 10 watts throughout the mission[1] (similar to that of some current deep-space missions) and treat the probe as a monopole source of compressional acoustic radiation. Let the amplitude of the oscillatory motion of the probe surface be x. For angular frequency ω and wave-propagation speed c, $P=4\pi\rho x^2\omega^4d^4/c$, and the far-field wave-displacement amplitude would be about $\omega d^2x/rc$, where r is the distance from the source[6]. For $f\equiv\omega/2\pi$ and $c\approx10^4$ m s^{-1}, $x\approx300(10^2\text{ Hz}/f)^2$ μm and the amplitude at the Earth's surface would be about $10^{-13}(10^2\text{ Hz}/f)$ m, roughly the radius of an atomic nucleus.

For the high frequencies of interest here, the quality factor of mantle rock[7] is about 10^4, but frequencies in excess of 100 Hz would nonetheless be unacceptably attenuated. However, frequencies much smaller than this would be a problem because of natural seismic energy, part of the reason that the Laser Interferometer Gravitational-wave Observatory (LIGO; a device that seeks to detect gravitational radiation)[8] operates in the kilohertz range. The encoding of the signal would greatly aid its detection, and the amplitude of the signal would be within the detectability limit of LIGO (were it coupled to the ground, rather than being decoupled as at present). For the duration of the mission, about 10^8 cycles of probe oscillation would occur, which would be sufficient to encode the state and composition of the deep Earth.

This proposal is modest compared with the space programme, and may seem unrealistic only because little effort has been devoted to it. The time has come for action.

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Aetiology

Koch's postulates fulfilled for SARS virus

Severe acute respiratory syndrome (SARS) has recently emerged as a new human disease, resulting globally in 435 deaths from 6,234 probable cases (as of 3 May 2003). Here we provide proof from experimental infection of cynomolgus macaques (*Macaca fascicularis*) that the newly discovered SARS-associated coronavirus (SCV) is the aetiological agent of this disease. Our understanding of the aetiology of SARS will expedite the development of diagnostic tests, antiviral therapies and vaccines, and may allow a more concise case definition for this emerging disease.

According to Koch's postulates, as modified by Rivers for viral diseases, six criteria are required to establish a virus as the cause of a disease[1]. The first three criteria — isolation of virus from diseased hosts, cultivation in host cells, and proof of filterability — have been met for SCV by several groups[2–5]. Moreover, of 96 individuals complying with the World Health Organization's definition of SARS[6] in Hong Kong, 86 (90%) yielded laboratory evidence of SCV infection.

We have tested for the three remaining criteria: production of comparable disease in the original host species or a related one, re-isolation of the virus, and detection of a specific immune response to the virus. We inoculated two macaques with Vero-cell-cultured SCV isolated from a fatal SARS case, and monitored their clinical signs, virus excretion and antibody response. The animals were killed six days post-inoculation (d.p.i.), and we then carried out gross and histopathological examinations of them.

Both SCV-inoculated macaques became lethargic from 3 d.p.i. onwards and developed a temporary skin rash, and one suffered respiratory distress from 4 d.p.i. onwards. The macaques excreted virus from the nose and throat at 2–6 d.p.i., as shown by polymerase chain reaction with reverse transcription (RT-PCR) and by virus isolation (see supplementary information). The isolated virus was identical to that inoculated, as shown by negative-contrast electron microscopy (Fig. 1a) and RT-PCR analysis. Seroconversion to SCV, as determined by indirect immunofluorescence assay using infected Vero cells, was demonstrated in two other SCV-infected macaques at 16 d.p.i.. The virus was also isolated from the faeces of one of these animals (see supplementary information).

At gross necropsy, one macaque had severe multifocal pulmonary consolidation, and SCV infection was detected in lung tissue by RT-PCR and virus isolation. Histologically, both macaques had interstitial pneumonia of differing severity. The one with gross lesions had diffuse alveolar damage, marked by necrosis of alveolar and bronchiolar epithelium and flooding of alveolar lumina with proteinaceous fluid, admixed with fibrin, erythrocytes, alveolar macrophages and neutrophils (Fig. 1b). Occasional multinucleated cells (syncytia) were present in the lumen of bronchioles and alveoli (Fig. 1c). These lesions are indistinguishable from those in biopsied lung tissue and in autopsy material from SARS patients[5], including the presence of syncytia in alveolar lumina[4].

SCV thus fulfils all of Koch's postulates as the primary aetiological agent of SARS. This does not exclude the possibility that other pathogens, including human metapneumovirus (hMPV) and *Chlamydia pneumoniae*, may have exacerbated the disease in some SARS patients. However, these were not present in SCV-inoculated macaques (results not shown), were not found consistently in SARS patients, and do not usually cause the lesions associated with SARS. Moreover, lesions in macaques infected experimentally with hMPV isolated from a non-SARS individual[7] were limited to mild suppurative rhinitis and minimal erosion in conducting airways, and disease was not exacerbated in two SCV-infected macaques subsequently inoculated with hMPV (results not shown).

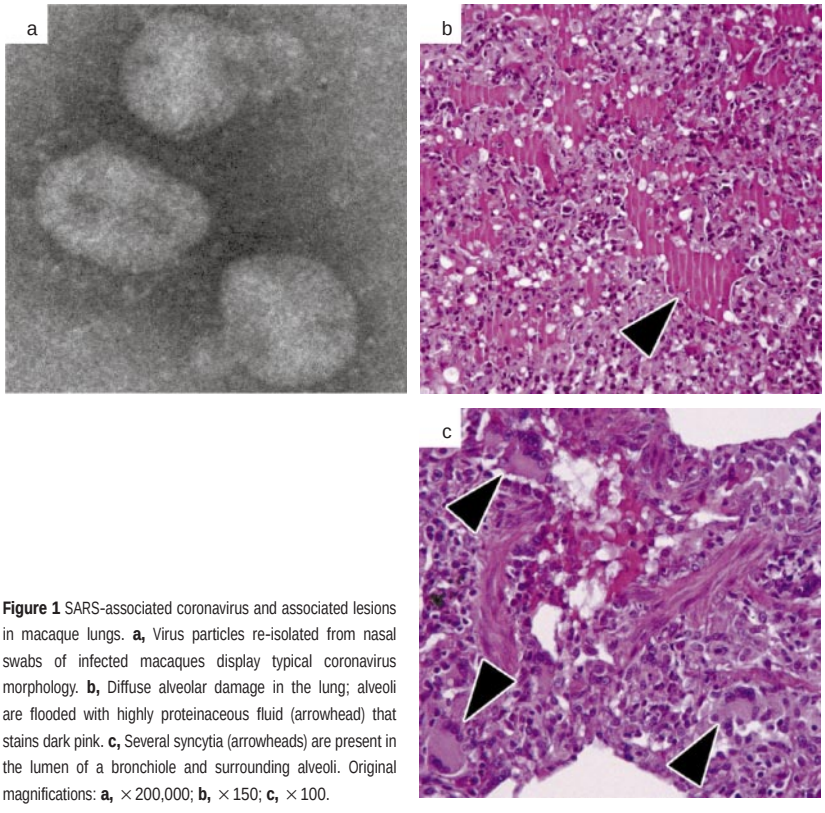

Figure 1 SARS-associated coronavirus and associated lesions in macaque lungs. **a,** Virus particles re-isolated from nasal swabs of infected macaques display typical coronavirus morphology. **b,** Diffuse alveolar damage in the lung; alveoli are flooded with highly proteinaceous fluid (arrowhead) that stains dark pink. **c,** Several syncytia (arrowheads) are present in the lumen of a bronchiole and surrounding alveoli. Original magnifications: **a,** ×200,000; **b,** ×150; **c,** ×100.

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