modes involving gravitational sinking of molten metal or metal sulphide through a partially or fully molten mantle that is often referred to as a 'magma ocean'. Alternative models invoke percolation of molten metal along an interconnected network (that is, porous flow) through a solid silicate matrix\(^8\). But experimental studies performed at high pressures\(^1\)–\(^3\) have shown that, under hydrostatic conditions, these melts do not form an interconnected network, leading to the widespread assumption that formation of metallic cores requires a magma ocean. In contrast, here we present experiments which demonstrate that shear deformation to large strains can interconnect a significant fraction of initially isolated pockets of metal and metal sulphide melts in a solid matrix of polycrystalline olivine. Therefore, in a dynamic (non-hydrostatic) environment, percolation remains a viable mechanism for the segregation and migration of core-forming melts in a solid silicate mantle.

Percolation of core-forming melts by porous flow through a silicate matrix has until now been largely been ruled out as a possible melt segregation mechanism: this has been on the basis of microstructural observations of the distribution of metal sulphide melts in silicate samples that were hydrostatically annealed at high pressures and temperatures\(^1\)–\(^3\). Such observations of melt–solid microstructures are commonly interpreted in terms of the dihedral angle \(\theta\), the angle between two neighbouring grains of the solid matrix in contact with melt. This angle is determined by the value of the solid–melt interfacial energy, \(\gamma_{\text{sm}}\), relative to the value of the solid–solid interfacial energy, \(\gamma_{\text{ss}}\), according to the relation:

\[
\gamma_{\text{sm}}/\gamma_{\text{ss}} = 2\cos(\theta/2)
\]

For \(\theta > 60^\circ\) (that is, large relative values of the solid–melt interfacial energy), the melt does not wet triple junctions, so that percolation is impossible unless the melt fraction exceeds a critical value that increases with increasing dihedral angle\(^4\). For \(0 < \theta < 60^\circ\), the melt phase forms an interconnected network along triple junctions, even at small melt fractions, such that complete drainage of melt by percolation through the solid matrix is possible.

The argument against percolation as a core-forming mechanism is based on the observation that the dihedral angle for metal sulphide melt in the silicate matrix is greater than 60° (refs 1–3). In these high-pressure studies, powders similar in composition to the mantle (that is, olivine with the addition of iron and nickel and iron–nickel sulphides) and powders of a chondritic meteorite believed to be similar in composition to the primitive mantle of Earth were subjected to pressures ranging from 2 to 20 GPa and temperatures of 1,210 to 1,710°C; these temperatures are higher than the melting point of the metal alloys and metal sulphides, but below the melting point of olivine. Dihedral angles ranged from 70° to 125°; this shows that the metallic melt is not interconnected, as long as the melt fraction does not exceed a critical value.

For a metallic melt content greater than this critical value in the early Earth, the melt would have been interconnected; melt would have drained to the core until the critical melt fraction was reached in the mantle. At this point, drainage would have ceased, stranding the remaining metallic melt. In theory, the critical melt content is ~6 vol.% (for a dihedral angle of 100°)\(^1\)–\(^6\), whereas electrical conductivity experiments place the critical melt content for the olivine–iron system at 10–25% (ref. 9). These values are much larger than the amount of metal stranded in the present-day Earth's mantle\(^1\). In view of the large values measured for the dihedral angle, several authors have concluded that percolation is not a feasible mechanism for the extraction of core-forming melts from the mantle\(^1\)–\(^3\). Consequently, they argue that a significant degree of silicate melting is required to efficiently segregate metal-rich melt from a silicate matrix.

The limitation of this conclusion is, as pointed out by Stevenson\(^4\), that it is based on experiments carried out under hydrostatic conditions. In contrast, an evolving mantle would not be static,
the proto-mantle of Earth.

Both types of samples were made with fine-grained (<10 μm) San Carlos olivine powders. The powders for the olivine-with-Au samples (olivine + 4 vol.% Au powder, <2 μm) were hot-pressed in a gas-medium pressure apparatus at 1,250 °C and 300 MPa for 3 h and quenched at 1°C s⁻¹ to below the melting point of Au (1,064 °C). Our olivine-with-metal-sulphide samples (olivine + 6 vol.% FeS and 1 vol.% Ni powder, ~1 μm) were hot-pressed in a piston cylinder device at 1 GPa. In a first step, pressure was raised to its final value and then temperature was increased at 20°C min⁻¹ to 1,300°C. At these conditions, the metal sulphide mixture is molten, while olivine forms a solid matrix. After 3 h at temperature and pressure, the temperature was quickly reduced to below the metal sulphide melting temperature, and then slowly decreased (10°C min⁻¹) to room temperature before the pressure was decreased. For both types of samples, the resulting material had less than 1% porosity.

From the resulting aggregates, thin elliptical disks were cut for shear deformation experiments with major and minor axes of 7.5 and 6.1 mm, and thicknesses ranging from 0.6 to 0.9 mm. Shearing was accomplished by placing samples between two thoriated tungsten pistons cut at 45° to the long axis of the pistons. Load was applied parallel to the long axis of the pistons at constant displacement rates of (2–3) × 10⁻⁶ mm s⁻¹, resulting in shear strain rates of between 10⁻³ s⁻¹ and 10⁻² s⁻¹ and shear stresses ranging from 60 to 100 MPa. The experiments were performed at 1,250°C; confining pressures were 400–450 MPa for the metal sulphide melt samples, and 300–360 MPa for the Au melt samples. To preserve deformation-induced melt microstructures, samples were quenched (at ~1°C s⁻¹) under load to below the melting temperature of the metallic phase before the load was reduced.

In undeformed samples, melt pockets are clearly not interconnected (see Figs 1a and 2a). The gold melt has a very high dihedral angle with olivine, and is located in nearly spherical pockets on grain boundaries and in triple junctions. The distribution and morphology of the metal sulphide melt is similar to that reported in previous studies. After shearing our samples to 250% shear strain, we observe very

but would rather be continually deforming. Hence, the microstructures would reflect dynamic conditions. The shearing motion in a convecting mantle may redistribute the melt, possibly into an interconnected network.

To explore this possibility, and to determine the effect of deformation on the distribution of metal and metal sulphide melts in a crystalline silicate matrix, we performed shear deformation experiments in a high-pressure gas-medium apparatus. Much higher strains can be attained in shear experiments than are possible in deformation experiments with the commonly used triaxial compression technique. We created two types of samples for our experiments. The first was polycrystalline olivine with an elemental gold (Au) melt; this serves as an end-member case for melt connectivity because the dihedral angle is extremely high (>135°). The second was polycrystalline olivine with an Fe–Ni–S melt, which approximates the composition of the upper portion of the proto-mantle of Earth.

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After shearing our samples to 250% shear strain, we observe very
different microstructures characterized by a distinct alignment of melt pockets. In the samples containing Au, this melt-preferred orientation forms an angle of 15° from the shear plane, and an angle of ∼30° with the maximum principal stress, and consists of (1) aligned, elongated (10–20 µm, several grains) melt pockets and (2) rows of isolated pockets oriented 15° from the shear plane (Fig. 1b). Trails of melt containing both of these types of features can be traced for hundreds of micrometres, suggesting that melt pockets have communicated with each other on the scale of the sample during deformation. These trails are part of well-connected sheets of melt extending into the third dimension of the sample, as can be seen in transmitted light with an optical microscope by focusing through extending into the third dimension of the sample, and taking an image of the same area after each polishing step. The series of recent geophysical (as well as geochemical) models of core formation consider the percolation of metal melt through a solid silicate matrix to be impossible (see, for example, refs 4 and 5). These models therefore require a significant degree of melting of the mantle to make it possible for metal to segregate out of the mantle in order to form the core. Even though there is no unequivocal geochemical evidence for complete mantle melting on Earth16–18, a number of recent experiments are in good agreement with the existence of a magma ocean19,20. Lunar science observations, and recent numerical models of the thermal evolution of the Earth, also suggest that our planet was molten during most of its accretionary history, and consequently that core formation was accomplished by metal segregation from a magma ocean21–23.

There are several potential mechanisms that could have caused large-scale or complete melting of the Earth. One is accretion of particles to form the planet at high enough temperatures to cause melting (possibly accompanied by radioactive heating); another energy source for melting of a planet is giant impacts24; alternatively, the release of energy due to gravitational sinking of core-forming metals could lead to significant melting of the mantle (see, for example, ref. 25). The last mechanism requires percolation of a metallic melt through a solid silicate matrix: segregation of metallic melts would have been the cause of a magma ocean rather than a consequence.

Even if the Earth’s mantle was completely molten before core formation—due either to hot accretion or to the energy released by giant impacts—deformation-assisted percolation of metallic melts may still have been an important core-forming mechanism on other terrestrial planets. Recent experimental and theoretical studies on the partitioning of moderately siderophile elements among silicates and metal sulphide melt, and the comparison of these results with estimates of abundances in the mantle of Mars, suggest26 that the martian core formed in a mostly solid planet. If there was an energy source to drive deformation in the martian mantle, deformation-assisted segregation of metallic melts could explain the existence of a core in Mars without the requirement of extensive silicate melting. A significant amount of deformation of the martian mantle was inferred from the recently reported magnetic lineations in the ancient crust of Mars, which, if confirmed, would suggest that plate-tectonic processes were active in the early history of the planet27. Mantle convection, which is associated with plate tectonics on Earth, also causes large-scale deformation in the planetary
mantle, and would also provide the large shear strains necessary for interconnection and thus percolation of metallic melts in a solid silicate matrix.

Our experimental results show that, in a dynamic environment, melt can be efficiently interconnected even if dihedral angles are large enough to cause the melt to be isolated under hydrostatic conditions. Hence, the requirement of a magma ocean as a critical step in the formation of planetary cores cannot be solely based on the argument that percolation of metal sulphide melt is impossible in a solid silicate mantle.

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