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EARTH SCIENCE

The enigma of D"

Kanani K. M. Lee

A phase transition of Earth's most abundant mineral occurs at pressures and temperatures corresponding to those thought to exist just above Earth's core. New experiments shed light on this enigmatic D" region.

At the half-way point in a journey to Earth's centre, at a depth of about 2,900 kilometres, an intrepid explorer would encounter the core–mantle boundary. This is where Earth's rocky mantle meets the fluid, iron-rich outer core, and it is marked by a large change in density and chemistry. The boundary is also thermal, because Earth's core is more than 1,000 K hotter than the mantle¹. Thus, conduction is the characteristic form of heat transfer for some 100 kilometres or so immediately above the core, whereas above that, in the bulk of the mantle, convection dominates.

The sharp change in temperature gradient creates a distinct seismological and mineralogical environment for this region, which is dubbed D" (D double prime). There is, of course, no explorer to send back reports about the region, so the study of D" depends on the analysis of seismic waves or on experiments on minerals at relevant temperatures and pressures. The latter is the approach taken by Catalli *et al.* (page 782 of this issue)², who have come up with a new estimate for the thickness of the D" discontinuity and the nature of this region.

The special mineralogy of D" is produced by a transition in crystal structure from that of magnesium silicate perovskite, MgSiO₃, the most abundant mineral on Earth, to a form known as post-perovskite^{3,4}. Seismic-wave speeds change abruptly in this region, often more than once⁵, providing information for seismological investigation of D". The approach taken by Catalli *et al.*² instead involves experimental determination of a feature called the Clapeyron slope, which marks the coexistence curve between two mineral phases, and is defined by the change in temperature over the change in pressure. For the perovskite-to-post-perovskite transition, this

slope is positive — that is, as one goes deeper into the mantle to higher pressures, higher temperatures are required to produce post-perovskite. In addition, for a material that varies in composition (for example, with iron and aluminium replacing some of the magnesium), there is a finite range of pressures and temperatures for which both the high-pressure and low-pressure phases coexist; thus a 'thickness' of this phase transition will yield a boundary that is either sharp or broad.

Catalli and co-authors have made precise measurements, at simultaneous high pressures and temperatures, using a laser-heated diamond-anvil cell, on compositions of magnesium silicate perovskites that include both iron and aluminium. Attaining pressures above 1 Mbar (a million times room pressure) is fairly routine. But heating a sample at these pressures to the temperatures of the phase transition, above about 2,000 K, requires special attention. This is because diamonds are great thermal conductors and can dissipate the heat produced by the infrared lasers used to create the high temperatures, causing large temperature gradients in the sample chamber. Great care is necessary to thermally insulate the samples, which have dimensions of only tens of micrometres.

Besides the technical difficulties of reaching high pressures and high temperatures in these kinds of experiment, there is the issue of calibration. Previous results have shown a range of positive Clapeyron slopes for the transition that can be attributed, in part, to the different pressure-calibration standards used⁶. To overcome this problem, Catalli *et al.*² used the differences in the phase-boundary pressures rather than the absolute pressures: the absolute values are not important when determining the thickness of the perovskite to post-perovskite

boundary, making the results calibration-independent. The upshot is that the authors conclude that the two phases, perovskite and post-perovskite, could coexist over a depth range of 400–600 (±100) km — a much larger range than the seismically estimated D" discontinuity thickness of about 30 km (ref. 7).

How can this discrepancy between a thin D" discontinuity (that is, a seismically sharp boundary) and the results of Catalli *et al.* be explained? The authors contend that compositional differences, perhaps low aluminium content or high abundance of ferropericlase (Mg, Fe)O — Earth's second most abundant mineral — would sharpen the boundary. But this would run counter to the view that portions of the D" layer contain some oceanic crust, subducted from the surface through plate tectonics. Although oceanic crust mineralogy would have a large proportion of magnesium silicate perovskite, it also has increased amounts of silica (SiO₂) and alumina (Al₂O₃), which, given Catalli and colleagues' results, suggests an even thicker D" discontinuity.

All in all, the D" layer presents many puzzles. One, for instance, is that seismic data indicate that there must be directionality to the minerals present, possibly due to the planar crystal structure of post-perovskite. But there is no consensus as to how post-perovskite would provide a consistent mechanism for such directionality^{8,9}. Another puzzle concerns a region at the very bottom of D" that is dubbed the ultra-low-velocity zone, where large decreases in the speeds of seismic waves are recorded. One explanation for this phenomenon could be the presence of a small amount of minerals in melted form; another explanation is the possible existence of iron-rich post-perovskite produced by reaction with the iron-rich core¹⁰. Indeed, the D" region is evidently chemically diverse — whether owing to interactions with the core, old oceanic crust or other factors — and this is likely to be the root cause of much of its unusual seismic behaviour.

There is much left to pin down in understanding the causes of the seismic signatures in D". Catalli and colleagues' results highlight the need for more experiments and computations on the behaviour of not just Earth-relevant compositions of magnesium silicate perovskite, but also of other mineral assemblages, to tease out the effects of chemical composition on the transition to post-perovskite. Quantifying the effects of melt in D" on density and on seismic wave speeds will also be important to understanding the other puzzles presented by D". In addition to new lab results and sophisticated computations, fine tuning on the D" features that can be resolved by seismological observations are also needed. ■

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IMMUNOLOGY

Dendritic-cell genealogy

Sophie Laffont and Fiona Powrie

The differing origins of gut dendritic cells — white blood cells that modulate immune responses — may explain how the intestinal immune system manages to destroy harmful pathogens while tolerating beneficial bacteria.

The immune system must protect the body from invading pathogens without mounting damaging responses to its own tissues. Dendritic cells, a rare population of white blood cells, have a crucial role in determining the nature of immune reactions and in fine-tuning the balance between tolerance (where the

immune system ignores or tolerates an antigen) and the induction of inflammation to destroy pathogenic organisms. A long-standing question has been how dendritic cells drive these distinct immune outcomes. Two groups, Varol *et al.*¹ and Bogunovic *et al.*², report in *Immunity* that dendritic cells with distinct

functions have different developmental origins, providing a cellular framework for the diverse activities of these cells.

Pioneering work by Steinman and colleagues³ in the early 1970s identified a minor population of immune cells that they named dendritic cells on the basis of their stellate shape and membranous processes. These cells were shown to be potent stimulators of another population of white blood cells, T cells. Dendritic cells are strategically placed within mucosal sites in the body, where they can detect infection and take up microbial antigens. On activation, these cells migrate to secondary lymphoid tissue, such as the lymph nodes, where they present the antigen to T cells. This activates the T cells, causing them to differentiate into effector cells that eradicate the pathogen. In the intestine, dendritic cells also promote regulatory T-cell responses that suppress immune reactions against beneficial commensal bacteria and food antigens, thereby preventing immune-related disease. Thus, intestinal dendritic cells are decision makers, ensuring selection of a T-cell response that is appropriate to the nature of the challenge to the immune system.

It is now known that dendritic cells are a diverse population of cells, differing in their anatomical location, expression of surface proteins and function. The diversity of the dendritic-cell response may reflect the differential activities of hard-wired developmentally distinct populations or may be due to different maturation states induced by environmental signals. Gaps in our knowledge of dendritic-cell developmental pathways have hindered finding answers to these questions. However, recently developed genetic techniques⁴ to ablate dendritic-cell populations, together with an improved ability to identify specific dendritic-cell precursors, have advanced this area of research.

Dendritic cells are closely related to macrophages, which originate from white blood cells called monocytes. They are derived from a common precursor termed the macrophage and dendritic-cell precursor (MDP). Dendritic cells can also be generated⁵ from monocytes in cell culture using a growth factor called granulocyte-macrophage colony-stimulating factor (GM-CSF), and much of what we know about the biology of dendritic cells has been based on the study of these laboratory-derived cells. However, recent elegant work^{6,7} has shown that monocytes and dendritic cells diverge in their developmental pathways downstream of the MDP — conventional dendritic cells in lymphoid tissue arise from a precursor cell in the blood (the pre-dendritic cell), and their differentiation depends on the growth factor Flt3. Hence, under normal conditions, blood monocytes do not give rise to dendritic cells in lymphoid tissue, raising questions about the *in vivo* counterpart of monocyte-derived dendritic cells.

Varol *et al.*¹ and Bogunovic *et al.*² studied the development of dendritic cells in the intestine.

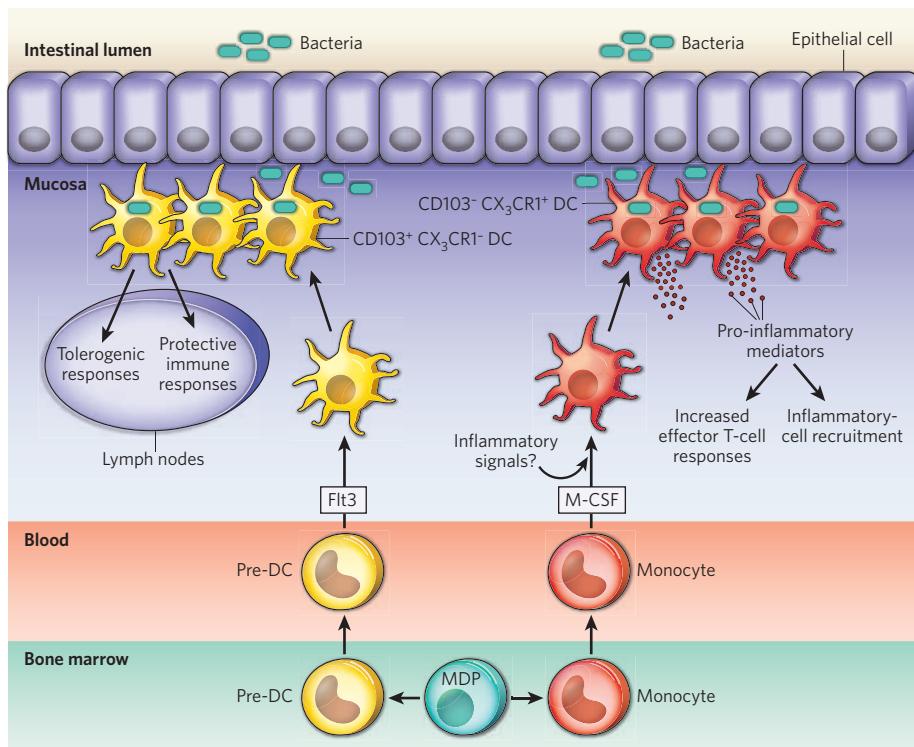


Figure 1 | Intestinal dendritic cells have different origins and different functions^{1,2}. The two main subsets of intestinal dendritic cells (DCs) originate from distinct blood-cell precursors and depend on different growth factors for their development. Before this divergence, a common precursor, the macrophage and dendritic-cell precursor (MDP), gives rise to pre-dendritic cells (pre-DCs) and monocytes in the bone marrow. Pre-dendritic cells give rise to CD103⁺ CX₃CR1⁻ dendritic cells, and depend on the growth factor Flt3 for their development, whereas monocytes develop into CD103⁺ CX₃CR1⁺ dendritic cells, and depend on another growth factor, M-CSF. CD103⁺ dendritic cells transport microbial antigens to the lymph nodes, where they may initiate protective immune responses or promote the generation of regulatory T cells that help to maintain tolerance in the intestine. CX₃CR1⁺ dendritic cells do not seem to migrate to lymph nodes, suggesting a more local role in promoting tissue inflammation by stimulating effector T-cell responses and producing pro-inflammatory mediators.