EARTH SCIENCE

Another energy source for the geodynamo

Magnesium is not usually considered to be a constituent of Earth's core, but its presence there has now been proposed to explain an ongoing enigma — the identity of the energy sources that drive our planet's magnetic field. SEE LETTER P.387

BRUCE BUFFETT

Turbulent flow in Earth's liquid-iron core generates the planet's magnetic field through a process known as the geodynamo. This process is sustained by energy drawn from the core as it slowly cools[1]. Thermal convection is thought to be crucial, but revised estimates[2,3] of thermal conductivity in liquid iron at high pressure have called into question the adequacy of the commonly cited energy sources[1]. On page 387 of this issue, O'Rourke and Stevenson[4] propose a solution to this energy crisis. They argue that if magnesium had dissolved in the liquid iron at high temperature when the core formed, then subsequent precipitation of magnesium-bearing minerals on cooling would be an important source of energy. The authors' theory warrants a serious reassessment of magnetic-field generation in other rocky (terrestrial) planets.

Sustaining a magnetic field is difficult for a terrestrial planet. Creeping flow of the planet's rocky shell (mantle) restricts heat loss from the underlying core. By comparison, the liquid-iron core is an efficient thermal conductor. Thermal convection in the core ceases when heat flow into the mantle falls below the core's capacity to deliver this heat by conduction alone, so high thermal conductivity may push the threshold for thermal convection beyond reach. In this scenario, turbulent flow in the core is driven mainly by buoyancy effects due to variations in the abundance of core constituents — as the core cools, some of the iron solidifies and accumulates on the solid inner core, leaving lighter elements in the liquid outer core and thus causing convection[1].

A problem with this conventional view of the geodynamo's energy sources emerges when we extrapolate back in time. Before the inner core formed (possibly less than 1 billion years ago[1]), the only energy source was thermal convection. But current estimates of iron's thermal conductivity suggest that the heat flow required to sustain such convection at that time was extremely high. Even if this heat flow was feasible, an implausibly high core temperature would be needed to sustain it over geological time. Despite these difficulties, Earth has somehow maintained a magnetic field for at least the past 3.4 billion years[5].

O'Rourke and Stevenson address this quandary by proposing a new energy source. They suggest that magnesium can enter the core to form an iron alloy, even though it is normally considered to be nearly insoluble in liquid iron. Other alloying elements are more commonly proposed[6] to explain why estimates of the core's density, based on seismic data, are less than that of pure iron. But theoretical predictions[7] and some experiments (see ref. 8, for example) suggest that magnesium can dissolve in liquid iron at sufficiently high temperatures. The authors argue that, because of its insolubility in iron, magnesium would probably become supersaturated as the core cools. The subsequent precipitation of magnesium-bearing minerals would leave behind a residual liquid enriched in iron, providing a compositional buoyancy that would drive fluid flow (Fig. 1).

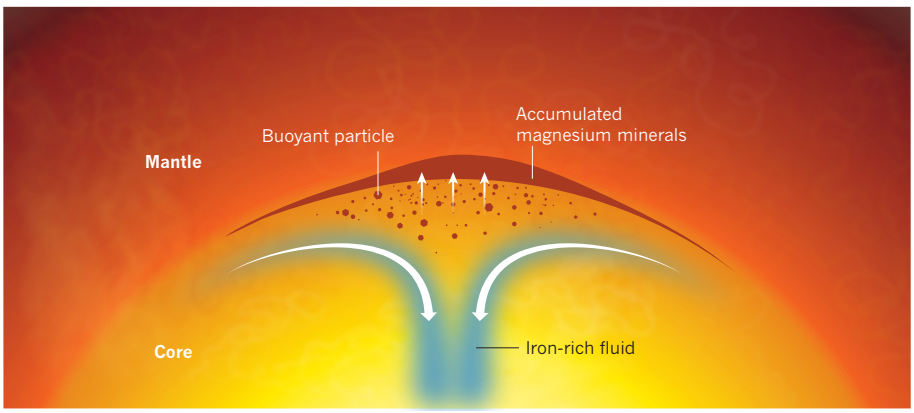

Figure 1 | Possible processes at the boundary between Earth's liquid core and rocky mantle. O'Rourke and Stevenson[4] propose that magnesium dissolved in liquid iron at high temperature when the core formed. Subsequent precipitation of magnesium-containing minerals would produce buoyant solid particles that would rise through the liquid iron and accumulate at the top of the core. The residual liquid would be denser than the surrounding fluid because it is enriched in iron, and would therefore sink. The resulting vigorous convection would stir the core and generate Earth's magnetic field, at modest rates of core cooling.

Two factors determine whether magnesium precipitation is a substantial energy source. First, the amount of magnesium that dissolved in liquid iron during core formation must be sufficient to meet the energy demands of the geodynamo. Second, the temperature dependence of magnesium's solubility must be strong enough to promote supersaturation of magnesium with only a modest temperature decrease of the core (possibly just several hundred kelvin). Otherwise, a delay in the onset of magnesium precipitation could shut off the energy source in the past or present.

O'Rourke and Stevenson tackled the first issue using previously reported experimental data[9] that describe the partitioning of elements between liquid iron and silicate melts, a mixture that represents the composition and state of the mantle during core formation. These data allowed them to estimate the concentration of magnesium, oxygen and silicon in liquid iron, as well as the abundance of siderophile elements (those that have an affinity for iron: nickel, cobalt, chromium, vanadium, niobium and tantalum) in the silicate melt, for two models of core formation. They then used a computational technique (a Monte Carlo method) to assess the average temperature and pressure conditions of core formation in the two models, by sampling many possible outcomes.

Crucially, the researchers could account for the observed abundances of siderophiles in the mantle[9] by using a model that permits a small fraction of the core to equilibrate with silicate melt at high temperatures (greater than 5,000 K). Many of the Monte Carlo outcomes for this model are also compatible with seismological constraints on the abundance of light elements in the core[6]. These results include outcomes in which the liquid core contains 1–2% magnesium by weight. In other words, enough magnesium to power the geodynamo could have been dissolved in the early liquid core without violating known constraints on the composition of the core and mantle[6,9].

However, uncertainties prevent a definitive assessment of magnesium precipitation. Some of the realizations sampled by the Monte Carlo method delay magnesium precipitation into the distant future, whereas others permit precipitation much earlier; early and

abundant precipitation is required to provide an effective solution to the geodynamo energy crisis. Much of the uncertainty derives from the experimental estimates of element partitioning between iron and silicate, particularly at high temperature. For example, the present work used information from a single set of experiments to derive magnesium's solubility[8]. More work is clearly required to address these uncertainties, but the potential contribution of magnesium precipitation to the geodynamo provides plenty of motivation to improve our current knowledge.

Magnesium precipitation would produce a buoyant solid that rises to the top of the core[10]. The dense, iron-rich residual fluid would also contribute to vigorous convection, offering ample energy for the geodynamo at relatively modest cooling rates. Such low cooling rates would allow warm fluid to accumulate at the top of the core, although convection due to magnesium precipitation might mix this warm fluid back to the core's interior. Further complications are suggested by experimental evidence[9] that the core's liquid is not saturated with oxygen and silicon, indicating that these elements might transfer into the core from the mantle. The potential for two-way transfer across the core–mantle boundary in the light of O'Rourke and Stevenson's theory is likely to send Earth scientists back to the drawing board. ■

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CANCER

Bet on drug resistance

Inhibitors of the BET bromodomain proteins are promising cancer therapeutics, but tumour cells are likely to become resistant to these drugs. Anticipated mechanisms of resistance have now been described. SEE LETTER P.413

JEFF SETTLEMAN

Many modern cancer drugs target mutationally activated proteins, but this treatment strategy has limitations. Only a relatively small number of mutations are seen recurrently across human tumours[1], and drug resistance develops rapidly[2]. Targeting the epigenome[3] — the chemically modified form of DNA, and of associated histones and other proteins that facilitate the packaging of DNA as chromatin, all of which influence gene expression — is one of the alternative approaches being explored. Along with two papers[4,5] published in *Nature* last year, a paper[6] on page 413 of this issue provides some insight into the potential of epigenome-targeting drugs called BET inhibitors, and outlines the mechanisms by which tumours might become resistant to these drugs.

It has long been recognized[7] that tumour cells have distinct epigenomic features, which can lead to the overproduction of cancer-promoting transcription factors such as MYC. Transcription factors are challenging therapeutic targets, because they lack structures that can be readily targeted with drugs. But developments in our understanding of the epigenome-regulating factors that influence gene expression, many of which seem to be 'druggable', have provided a potential way to sidestep this hurdle.

Among these factors is the bromodomain protein family, which includes the BET subfamily[8] (BRD2, 3, 4 and T). BET proteins contain two bromodomains, each with small pockets. These pockets bind to histones that have been tagged with acetyl groups, enabling BET proteins to recruit the cell's transcriptional machinery to specific sites in the genome to regulate gene expression. BET subfamily members such as BRD4, which can regulate *MYC* gene transcription, have been implicated in various tumours (particularly in cancers of the blood) and are therefore candidate targets for therapy[8].

A few years ago, the first of several small-molecule BET inhibitors (JQ1) was discovered, and shown[8] to effectively disrupt cancer-cell proliferation. This effect seemed to reflect inhibition of BET-mediated regulation of *MYC* expression. Early clinical trials of BET inhibitors in leukaemia and lymphoma have been encouraging. Investigators are now seeking other disease contexts in which these inhibitors might work, and predicting the acquired resistance mechanisms that will inevitably arise.

The two 2015 studies[4,5] converge on a potential mechanism of resistance to BET inhibition in acute myelogenous leukaemia (AML). In the first, Rathert *et al.*[4] screened mouse AML cells for chromatin-modifying factors that are required for AML-cell survival. They confirmed that AML cells need Brd4, and identified several other factors for which inhibition confers AML-cell resistance to JQ1. In AML cells that were JQ1-resistant, the authors observed changes in specific epigenome features in DNA enhancer regions,

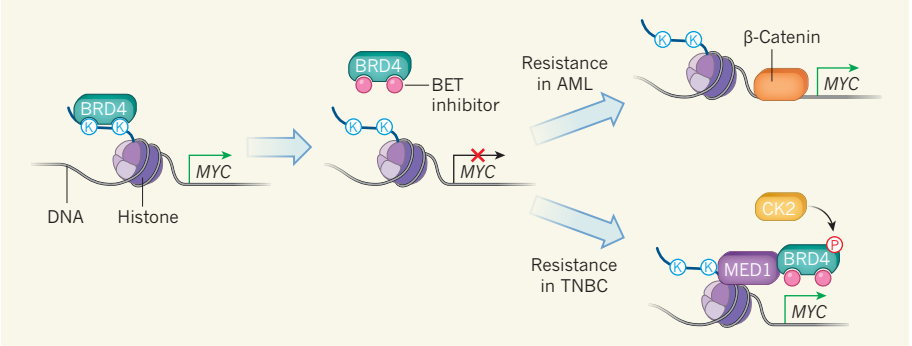

Figure 1 | Circumventing BET inhibition. The BET protein BRD4 can bind to acetyl groups (K) on histone proteins around which DNA is packaged as chromatin. BRD4 recruits the cell's transcriptional machinery, upregulating expression of the cancer-promoting *MYC* gene. Treatment with BET inhibitors can prevent BRD4–chromatin binding, stilting *MYC* transcription, but cancer cells rapidly develop drug resistance. Rathert *et al.*[4] and Fong *et al.*[5] report that, in acute myelogenous leukaemia (AML), drug resistance is conferred by activation of the Wnt-signalling pathway, which leads to DNA binding and *MYC* activation by the protein β-catenin. By contrast, Shu *et al.*[6] find that resistance in triple-negative breast cancer (TNBC) arises owing to activation of the casein kinase 2 (CK2) enzyme. CK2 phosphorylates (P) BRD4, allowing BRD4 to bind to the transcriptional regulator protein MED1 to activate *MYC*.