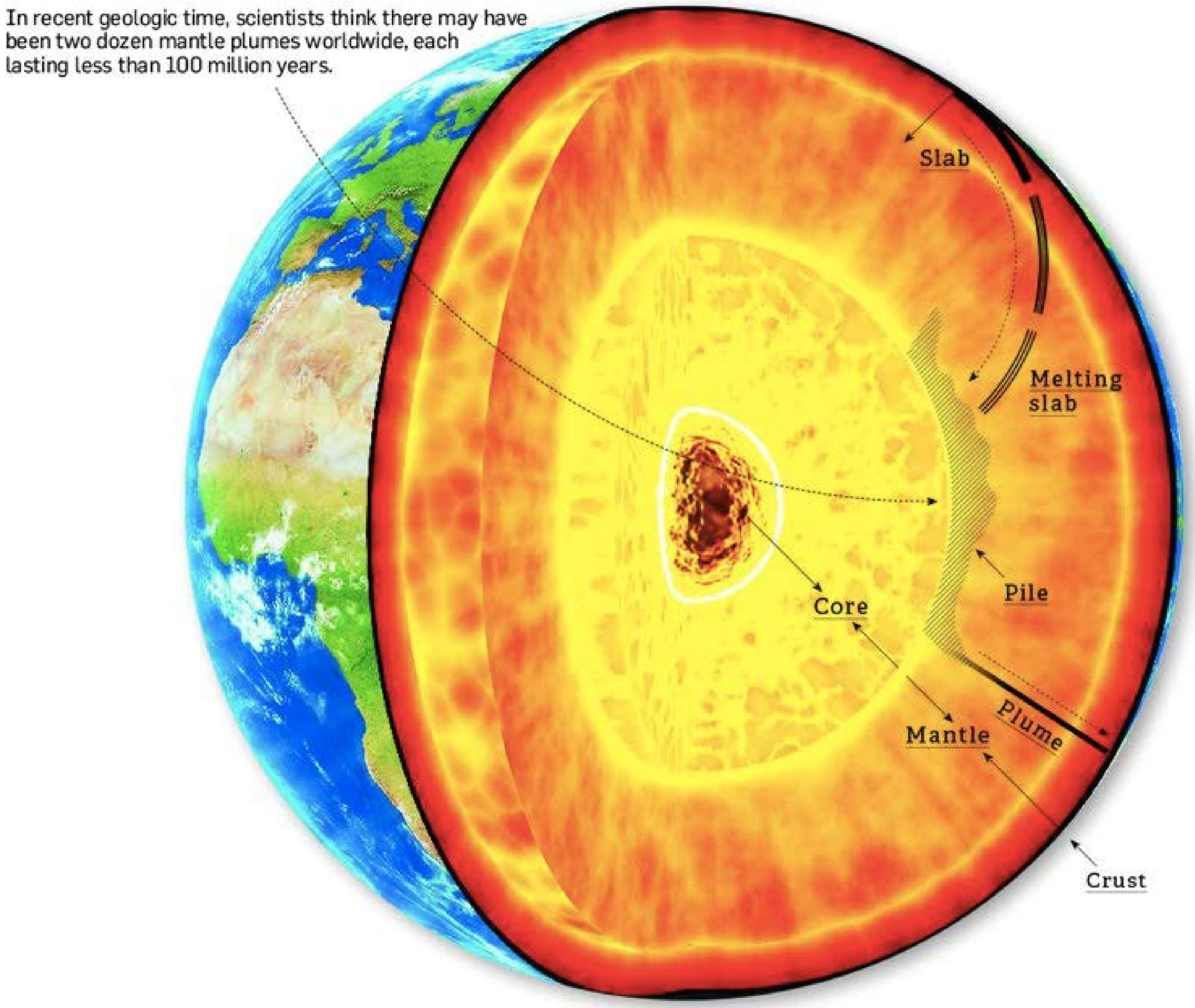
Generace planetárních magnetických polí

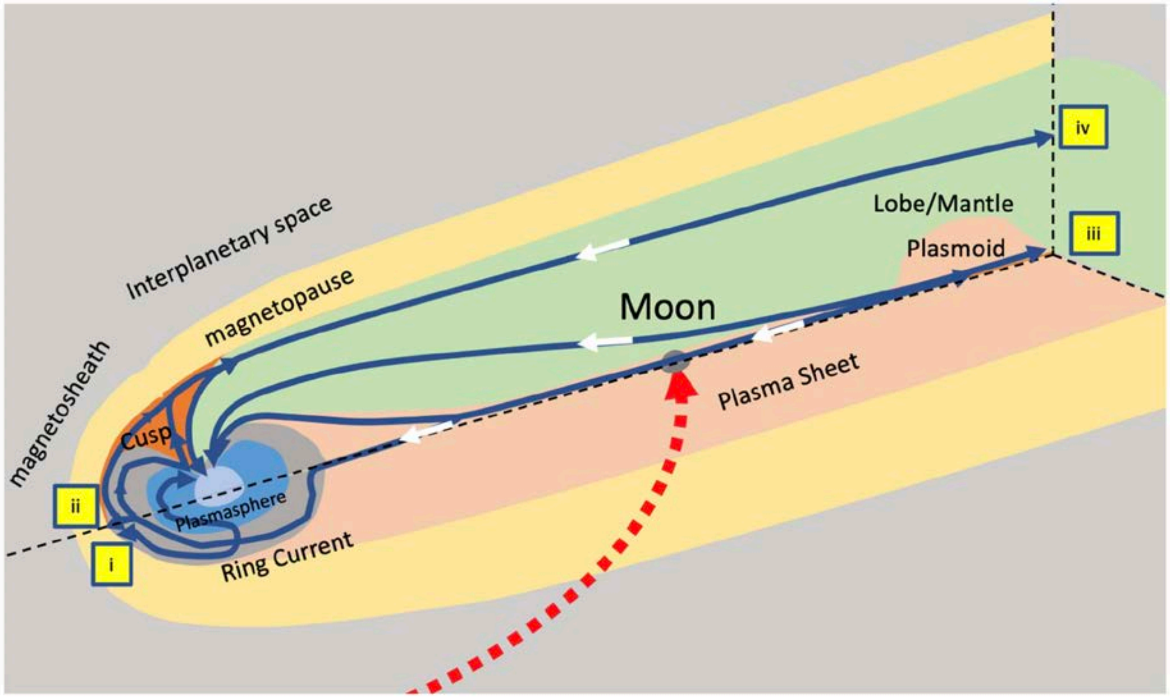


Planetary magnetic field production mechanism

A dominant dipole component of the planetary magnetic field has its source in the planets´s core (outer core in case of Earth), where heavy fluid motion in the core is subjected to the Earth’s spinning, where the field is “somehow” generated and lasted for more than 3.4 billion years (Landeau et al., 2022).

- Precession (too weak for enough flux production),
- Tides (may have played the role early when Earth span faster)
- Convection combined with exsolution of light elements (motion of the highly conducting fluid), attempts towards its understanding and matching the geomagnetic and paleomagnetic observations (Landeau et al., 2022; Stevenson, 2010).

From: Distribution of water phase near the poles of the Moon from gravity aspects



Sketch showing three-dimensional cutaway of Earth's magnetosphere. The blue and white arrows are motion pathways of ions (for details see Seki et al.[5]) illustrating the mechanism for oxygen/hydrogen ions transfer to the Moon. Red dotted line with the arrow shows motion of the Moon into the magnetospheric tail. Escape locations into the interplanetary space is marked by locations i, ii, iii, iv. Image was drown using Microsoft PowerPoint for Mac Version 16.55.

Origin of the planetary magnetic fields from the core's buoyancy

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G. Kletetschka: Evidence for Reversals of the Geomagnetic Field from the Point of View of the Duration of a Particular Polarity. Diploma thesis, MFF UK, Prague1989, (in Czech).

INVESTIGATION OF THE GEOMAGNETIC POLARITY PATTERN (FROM THE CRETACEOUS TO THE QUATERNARY)

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Summary: *The paper deals with the statistical approach to processing the polarity durations of the Earth's magnetic dipole over the past 170 million years. Partial elimination of the random component enables the mutual relation between normal and reversed polarities to be determined. The polarity time sequence has further been divided into several intervals. The frequency distributions for normal and reversed polarities have been established for each of these intervals. It has been found that the random component of the reversal triggering mechanism hides a pattern of behaviour which displays a certain amount of logic.*

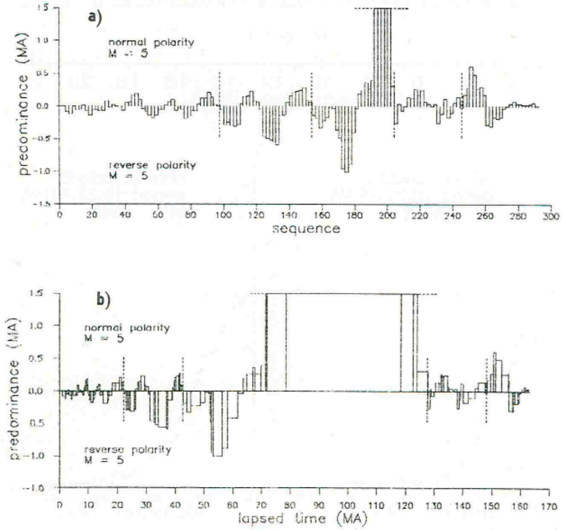


Fig. 3. Residual polarities due to subtracting the reverse set of smoothed data from the normal one. a) Residual set (predominance) on the sequence of polarities. b) Residual set on the age of polarities.

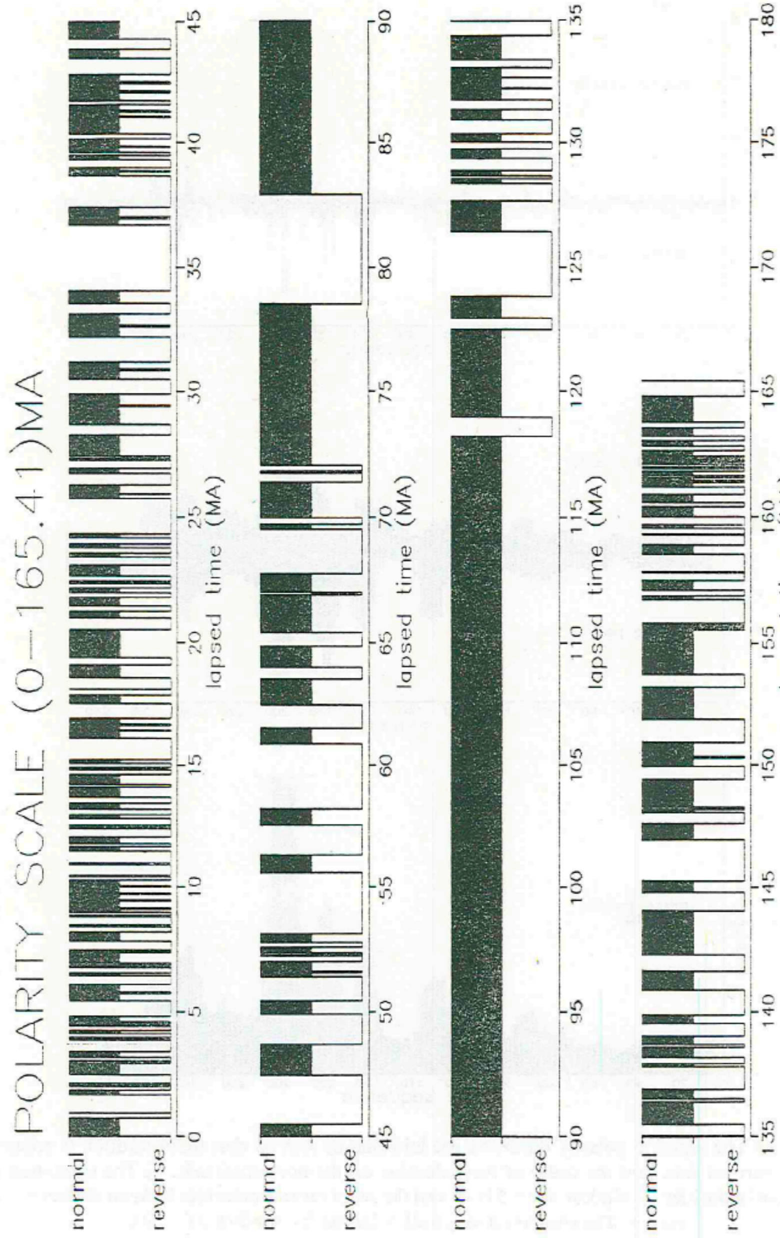
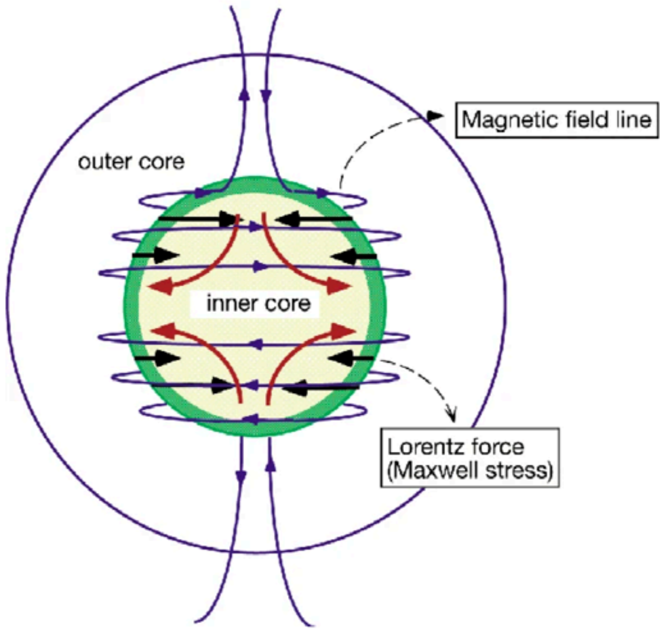


Fig. 1. Scale of reversals of the geomagnetic dipole field for the period (0—165) MA. Data used from [2].

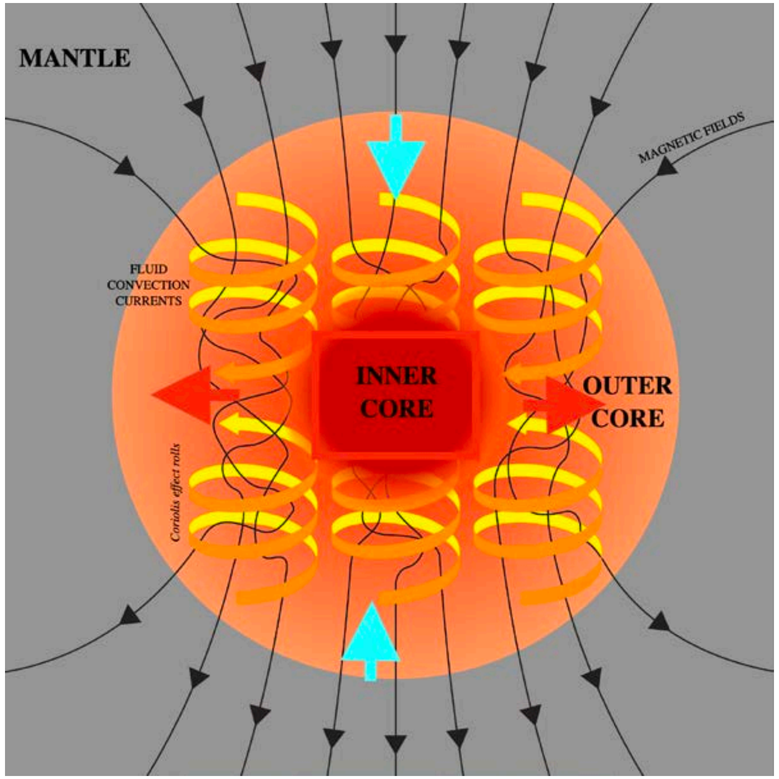
Numerical models are considering a geodynamo mechanism with a turbulent convection in a rotating fluid (Busse, 2000; Glatzmaier and Roberts, 1996; Kono and Roberts, 2002; Kuang and Bloxham, 1997; Landeau et al., 2022).

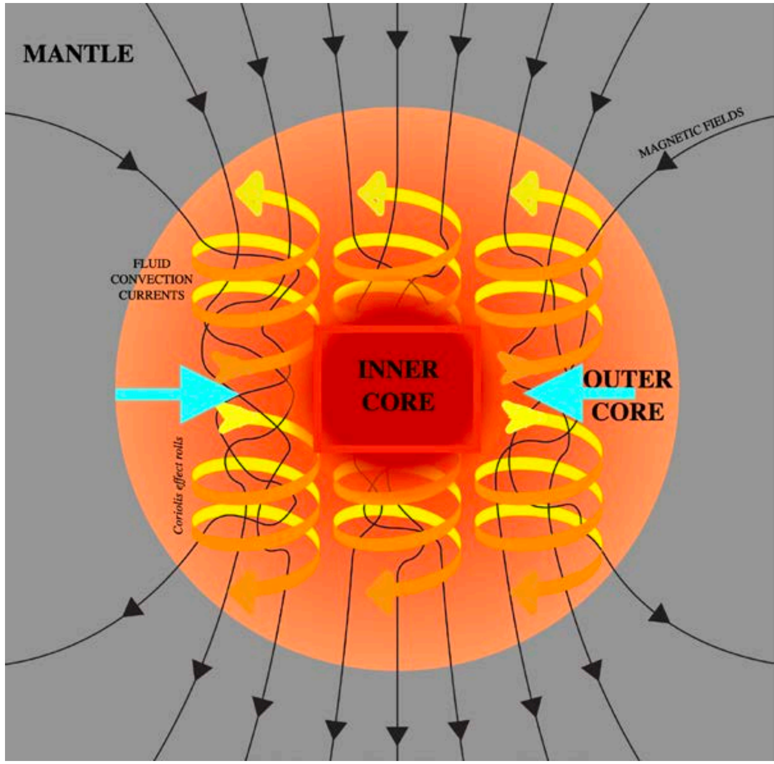
Ability to switch the magnetic field's magnetic polarity, (Berhanu et al., 2007)

Figure 1: A schematic diagram showing the structure and dynamics of the inner core.



The dynamics of the outer portion of the inner core (dark-green, thin layer) is dominated by the direct effects of the Lorentz force (the Maxwell stress). The dynamics in the deep portions are controlled by the force balance between the pressure gradient and the viscous force, with a constraint imposed by the boundary conditions near the surface of the inner core which are dominated by the Maxwell stress. The Lorentz force (the Maxwell stress) caused by the toroidal magnetic field squeezes inner-core materials towards the rotation axis, and causes a flow from strong-field regions to weak-field regions. The flow pattern is sensitive to the geometry of the magnetic field (see Fig. 2). Black arrows, Lorentz force; red arrows, flow directions; blue lines with arrows, magnetic field lines.





Degenerate fermi gas means **that the gas is in a quantum regime**

Perhaps the most important example[25] of the degenerate Fermi gas is **the conduction electrons in metals**

Degenerate gases **are gases composed of fermions such as electrons, protons, and neutrons rather than molecules of ordinary matter**.

Most models consider Boussinesq approximation: neglects density and temperature variations of the reference state (Gray and Giorgini, 1976).

Let's consider a source material inside the core, where its electrons can acquire an approximation of a degenerate Fermi's gas like state (Bologna and Tellini, 2014).

This is because the density of iron inside the core is about 10^4 kg m^{-3} (de Wijs et al., 1998) pointing to the Fermi energy of ~$2x10^{-18}$ J, corresponding to a Fermi temperature of $1.4x10^{5}$ K, higher than the Earth's core temperature, thus supporting the Fermi's electrons presence in the Earth's core.

$$\varepsilon_F = \frac{\hbar^2}{2m}\left(3\pi^2\frac{N}{V}\right)^{2/3} \approx 2 \times 10^{-18}\ \mathrm{J}$$

For a plasma state with a finite conductivity and constant density for the magnetic field we have (Jackson, 1998):

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times [\boldsymbol{v} \times \boldsymbol{B}] + \frac{1}{\mu\sigma}\nabla^2 \boldsymbol{B}$$

In plasma there is a balance between a diffusive magnetic flux and a flux maintaining term v×B balancing the diffusion term.

Many considered this balance as a key factor for magnetic field maintenance in the Earth's core (Stevenson, 2010).

Can a sufficient magnetic flux be produced inside the core of the Earth from thermally induced electrical currents ?

This requires an internal source of heat energy to be utilized from the lateral temperature variation inside the core.

The transfer of this heat energy into electric currents would need to be proportional to the local temperature differences, via thermoelectric current generation.

Such thermoelectric current generation mechanism was already considered for Mercury (Giampieri and Balogh, 2002; Stevenson, 1987) via interaction between the Mercury's core and mantle.

A thermoelectric current was considered both near an inner/outer core boundary (IOB) (Bologna and Tellini, 2014) and core/mantle boundary (Xu et al., 2021).

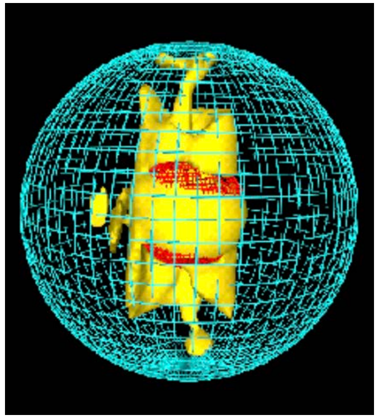
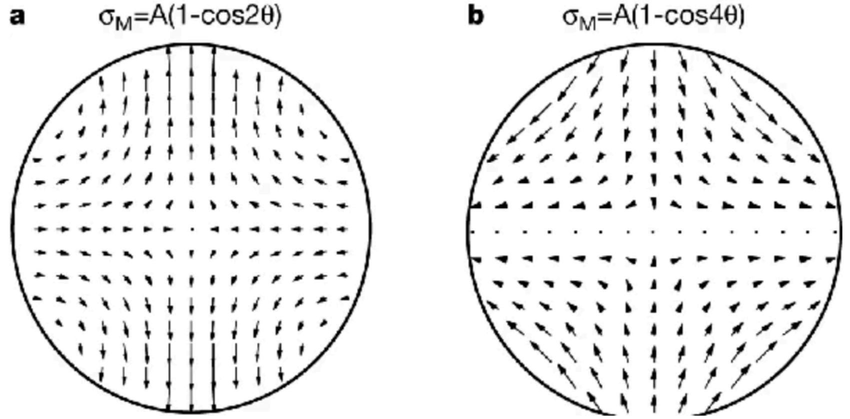


Figure 2: Flow field caused by the magnetic field at the boundary between the inner and the outer core.



Flow velocity vectors in a meridional plane are shown. The geometry of the flow field is determined by the geometry of the magnetic field at the inner–outer core boundary. The flow field corresponding to the Maxwell stress of (panel **a**) $\sigma_M(\theta, \varphi) = A(1 - \cos 2\theta)$ (corresponding to the symmetric toroidal field) and (panel **b**) $\sigma_M(\theta, \varphi) = A(1 - \cos 4\theta)$ (corresponding to the antisymmetric toroidal field) are shown.

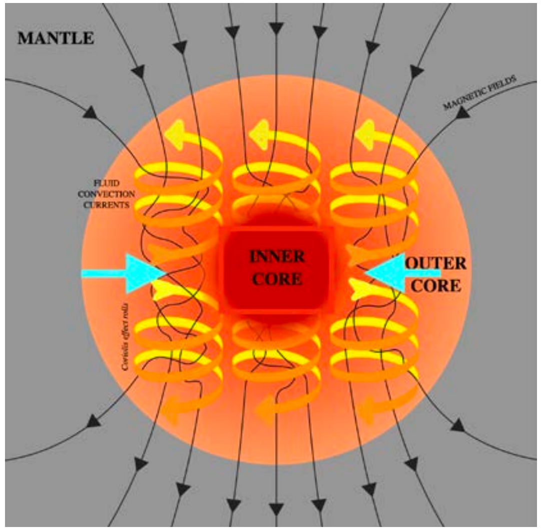
The Fermi electrons' approximation:
A material physics considers a quantum related thermal contribution *α(T)* inside the core (Bologna and Tellini, 2014; Landau and Lifshitz, 1981):

$$|\alpha(T)| \sim k_B \frac{k_B T}{e \varepsilon_F}$$

Where k_B is the Boltzmann constant, e is the electron charge, T is the temperature, and ε_F is the Fermi energy.

We add this thermal contribution to the total current $\boldsymbol{J}$ in the core along with an electric, $\sigma\boldsymbol{E}$, and magnetic, $\sigma\boldsymbol{v} \times \boldsymbol{B}$, terms as:

$$\boldsymbol{J} = \sigma[\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}] + \alpha(T)\nabla T \approx \alpha(T)\nabla T$$



$$\boldsymbol{J} = \sigma[\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}] + \alpha(T)\nabla T \approx \alpha(T)\nabla T$$

Considering solely the thermal contribution to the total current generation (assuming, that neither the electric and magnetic terms do not significantly contribute) and using a Maxwell equation

$$\nabla \times \boldsymbol{B}_T = \mu_0 \sigma \boldsymbol{J}_T$$

(where *μ0* is a vacuum magnetic permeability, subscript T stands for thermal contribution) we have:

$$\nabla \times \boldsymbol{B}_T = \mu_0 \sigma \alpha(T) \nabla T$$

Equation allows a scaling estimate for magnetic flux magnitude:

$$\frac{\boldsymbol{B}_T}{R} = \mu_0 \sigma \alpha(T) \frac{\Delta T}{R}$$

$$\boldsymbol{B}_T = \mu_0 \sigma k_B \Delta T \frac{k_B T_c}{e \varepsilon_F}$$

$$\boldsymbol{B}_T = \mu_0 \sigma k_B \Delta T \frac{k_B T_c}{e \varepsilon_F}$$

Enumerating for

μ_0=1.26e-6 NA^{-1},

k_B=1.4x10^{-23} m^2kg s^{-2} K^{-1},

e=1.6e-19 C,

ε_F=2x10^{-18} J,

core temperature T_c = range of (6+/-2)x10^3 K (Alfe et al., 2002)

core temperature gradient (ΔT ~8x10^2 K (Alfe et al., 2002; Bologna and Tellini, 2014),

$\boldsymbol{\sigma}$ conductivity ~10^6 S m^{-1} (Pozzo et al., 2012)

= thermal heat generated magnetic flux of the Earth core: 0.0002 T to 0.003 T.

Note that we don't use the entire temperature difference of 2000 K for estimate scale of the magnetic field but 800 K. This is because the temperature difference between ICB and CMB is mostly isentropic (or adiabatic), lacking the sufficient degree of horizontal variation

The thermal gradients in the core cause the heat exchange by convection.

In parallel, the thermal gradients in the dense liquid core allow for existence of Fermi electrons to flow in a direction of the convective flow.

Therefore, both the convective flows and Fermi currents need to obey a handedness of the geo-rotation system controlled by Coriolis force (Matsui et al., 2014)).

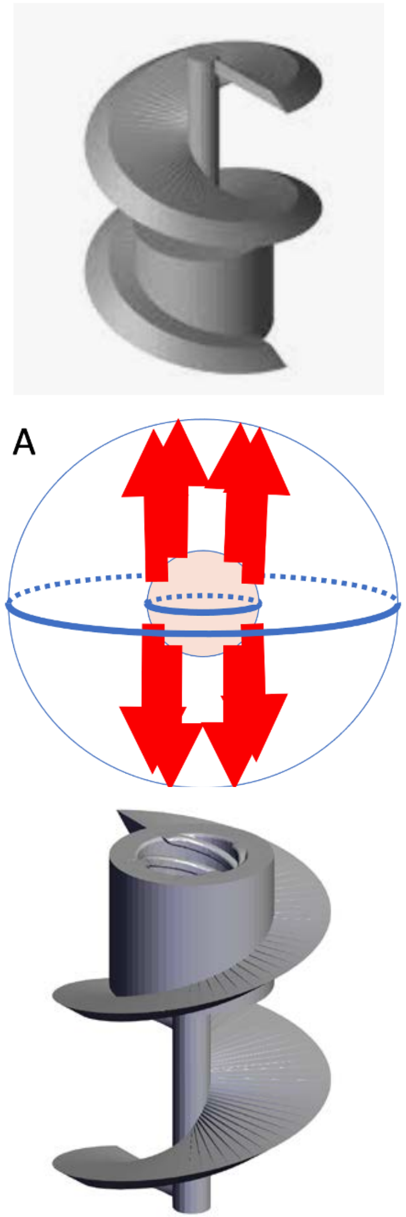
Then for a counterclockwise (CCW) earth's spinning we have a prescribed handedness of the upwelling/downwelling of liquid masses in the Earth's core.

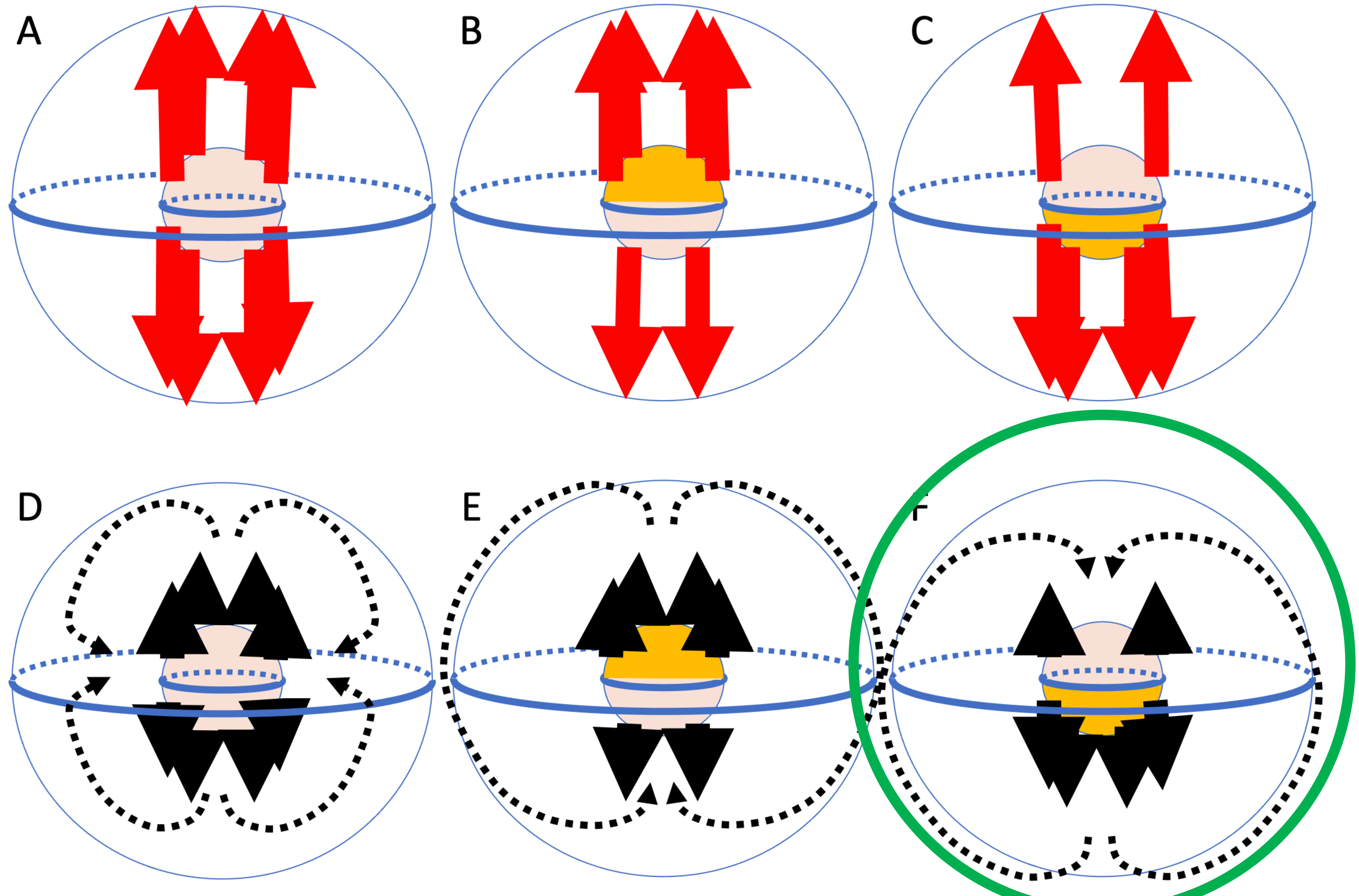
This is supported by observation of the columnar structure from combinations of satellite magnetic data (Gillet et al., 2022).

Upwelling masses in the NH would spin clockwise (CW), while upwelling masses spin CCW in the southern hemisphere (SH) when looking towards the center of the spinning Earth.

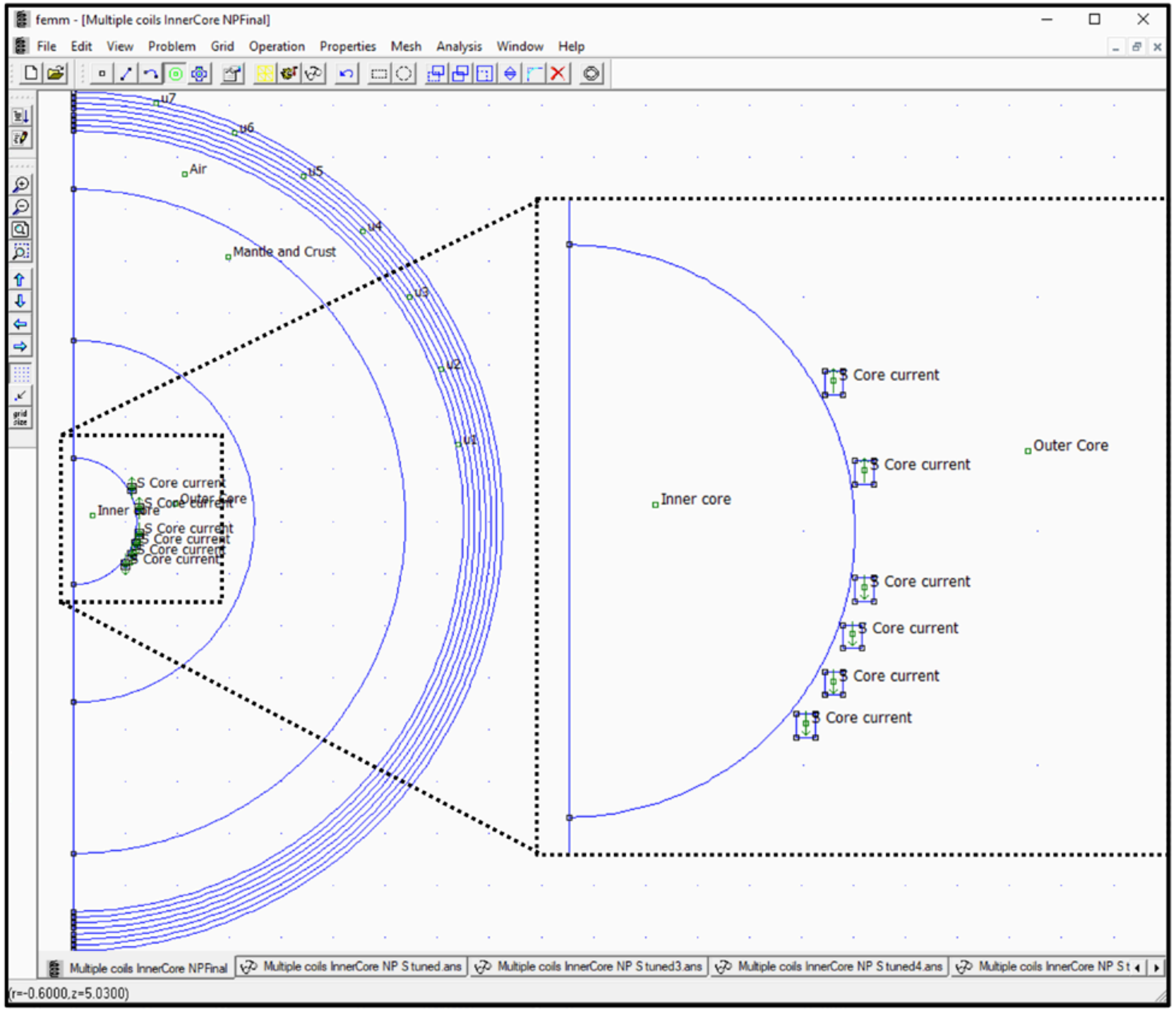
Considering the higher temperature of the core upwelling masses, the resistance of these high temperature compositions is lower than the surrounding colder material (de Koker et al., 2012). This supports the notion that Fermi electrons follow the heat gradients (equations 3 and 4) and are directed via the upwelling plumes of lower density, lower resistance, and different composition (de Koker et al., 2012; Umemoto and Hirose, 2020), towards the maximum temperature gradients, and eventually towards the CMB.

Therefore, in the NH the Coriolis clockwise upwelling spiral would create conduit for clockwise moving Fermi electrons from the inner core to a cooler CMB, generating CCW electric current and thus upward directed magnetic flux forming a reversed magnetic polarity. Same logic goes for the SH where all upwelling conduits generate clockwise electric current generating downward directed flux, normal magnetic polarity, supporting our hypothesis.

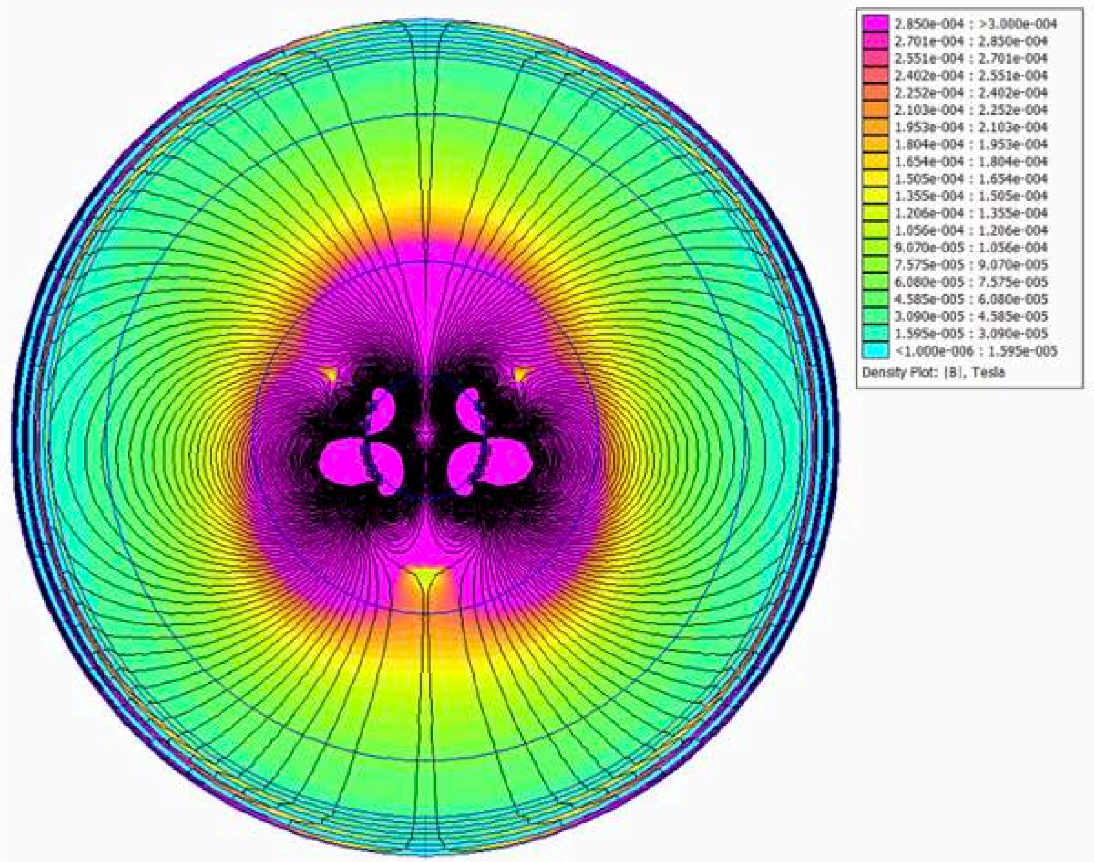




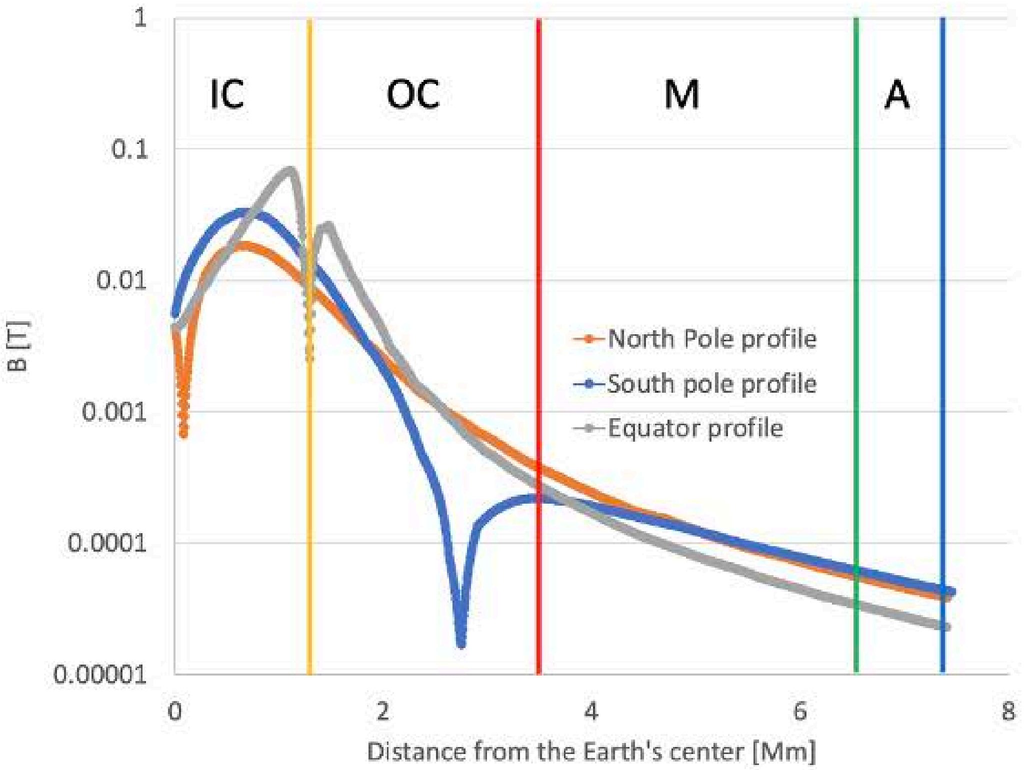
A
B
C
D
E
F



Screen shot from the FEMM software showing the initial setup of the core geomagnetic model with rotational symmetry around the vertical axis along the left edge of the image. Central region of the core is blown out for clarity. The smallest circle is inner/outer core boundary at 1220 km from the center, the next larger circle is outer core/mantle boundary at 3480 km from the center, the third circle is Earth's surface at 6380 km from the center. The set of 7 largest circles at 7500 km, 7600 km, 7700 km, 7800 km, 7900 km, 8000 km, 8100 km, 8200 km is a Dirichlet boundary condition to satisfy the geometry of the infinite dipole field. The green arrows indicate the electric currents that contributes to the dynamo magnetic field, each of them has magnitude of 750 kA/m along the specified direction. The inner core has a prescribed relative magnetic permeability of 14.8. Outer core, mantle and crust, and air have a relative magnetic permeability of 1. Dirichlet condition layers outside have their relative magnetic permeability of 2.4.


2.850e-004 : >3.000e-004
2.701e-004 : 2.850e-004
2.551e-004 : 2.701e-004
2.402e-004 : 2.551e-004
2.252e-004 : 2.402e-004
2.103e-004 : 2.252e-004
1.953e-004 : 2.103e-004
1.804e-004 : 1.953e-004
1.654e-004 : 1.804e-004
1.505e-004 : 1.654e-004
1.355e-004 : 1.505e-004
1.206e-004 : 1.355e-004
1.056e-004 : 1.206e-004
9.070e-005 : 1.056e-004
7.575e-005 : 9.070e-005
6.080e-005 : 7.575e-005
4.585e-005 : 6.080e-005
3.090e-005 : 4.585e-005
1.595e-005 : 3.090e-005
<1.000e-006 : 1.595e-005
Density Plot: |B|, Tesla

A.


IC
OC
M
A
1
0.1
0.01
0.001
0.0001
0.00001
B [T]
North Pole profile
South pole profile
Equator profile
0
2
4
6
8
Distance from the Earth's center [Mm]

B.

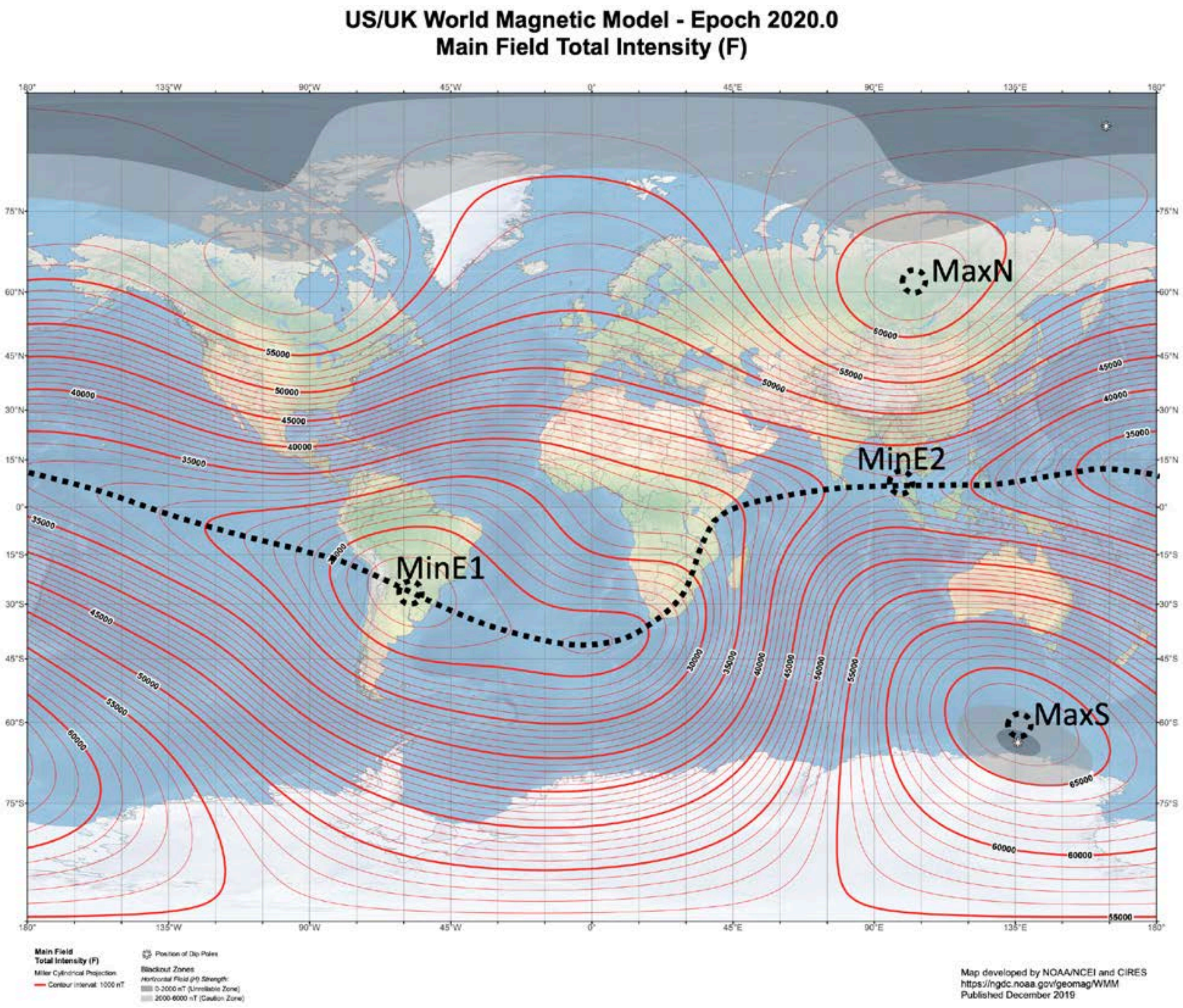
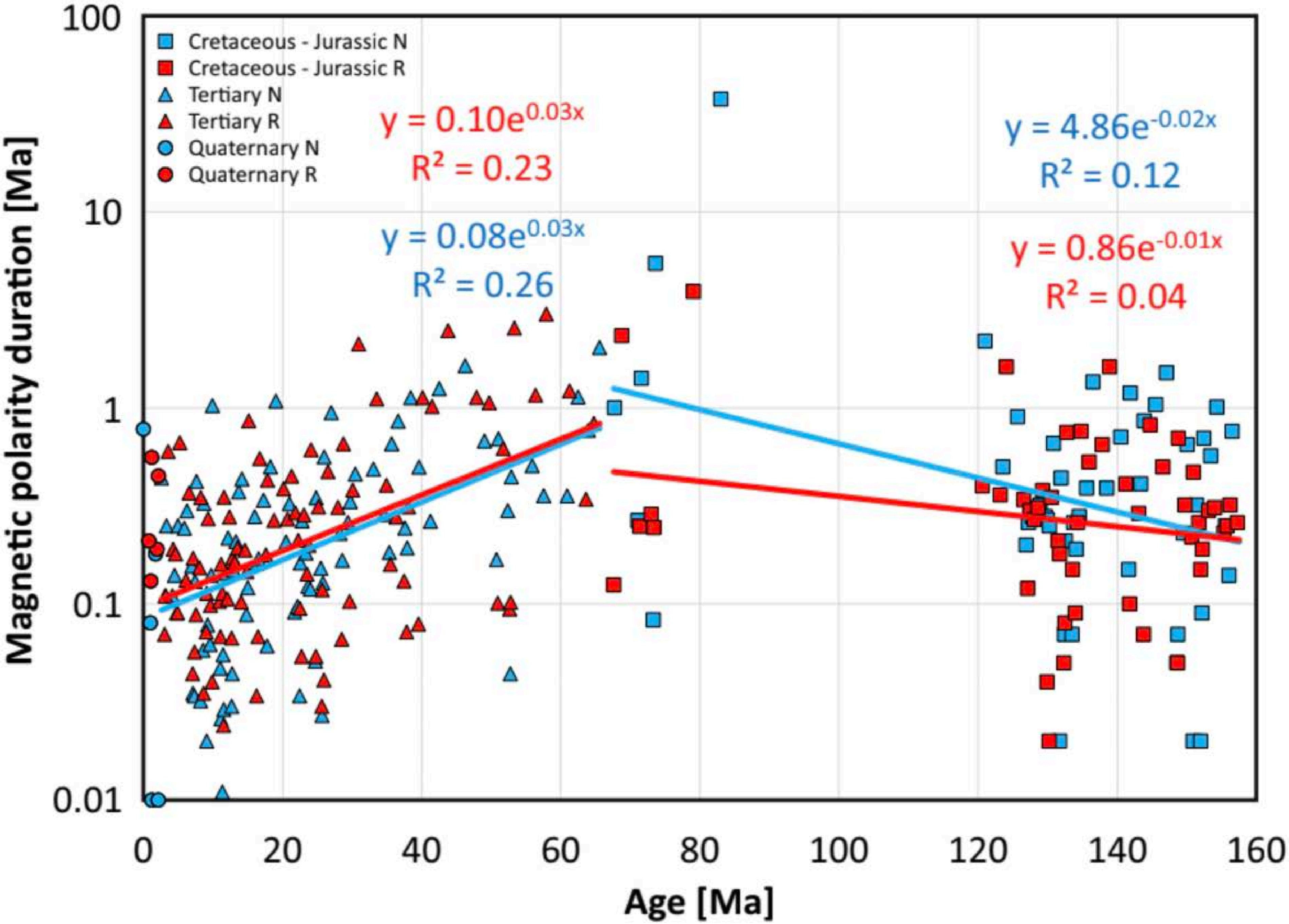
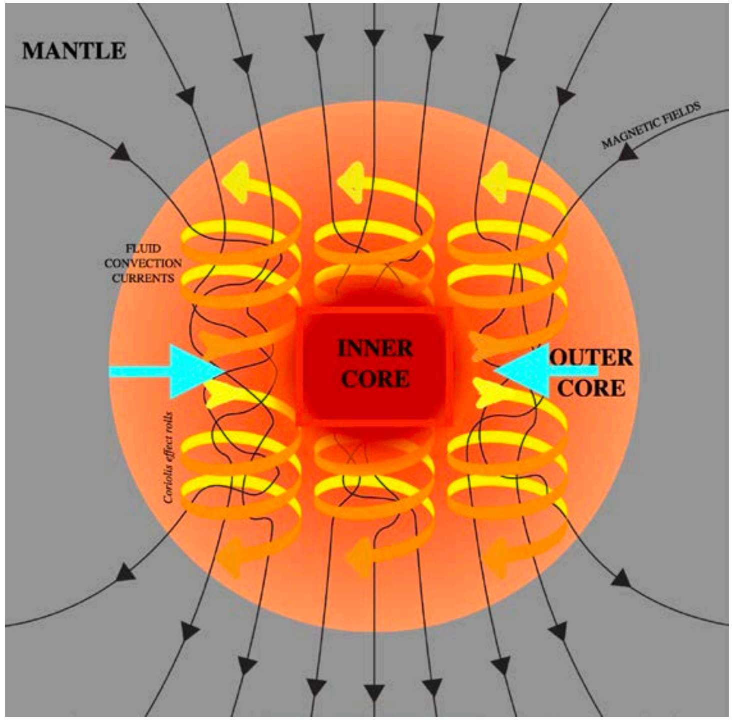


Image of the flux magnetic intensity at the Earth's surface. Maximum magnetic intensity flux over the North pole is just over 61000 nT over the Siberia, Near Tunguska region, Russia, marked as MaxN. Maximum magnetic intensity flux over the South pole is just over 66000 nT, near a French Dumont d'Urville, Antarctica, Victoria Land Station, marked as MaxS. Minimum magnetic Intensity flux distribution over the Earth is marked by a black dotted line and ranges between just below 23000 nT (MinE1) to just below 42000 nT (MinE2).



Cretaceous - Jurassic N
Cretaceous - Jurassic R
Tertiary N
Tertiary R
Quaternary N
Quaternary R
y = 0.10e^0.03x
R² = 0.23
y = 0.08e^0.03x
R² = 0.26
y = 4.86e^-0.02x
R² = 0.12
y = 0.86e^-0.01x
R² = 0.04
Magnetic polarity duration [Ma]
Age [Ma]
100
10
1
0.1
0.01
0
20
40
60
80
100
120
140
160

Thank you….



Can geomagnetic field be generated by Fermi electrons??
Do magnetic polarities present dominance of one hemisphere convection?
Are magnetic reversals controlled by arrival of cold subduction slabs to the CMB?