Earth’s magnetic field: Geodynamo

Topics covered

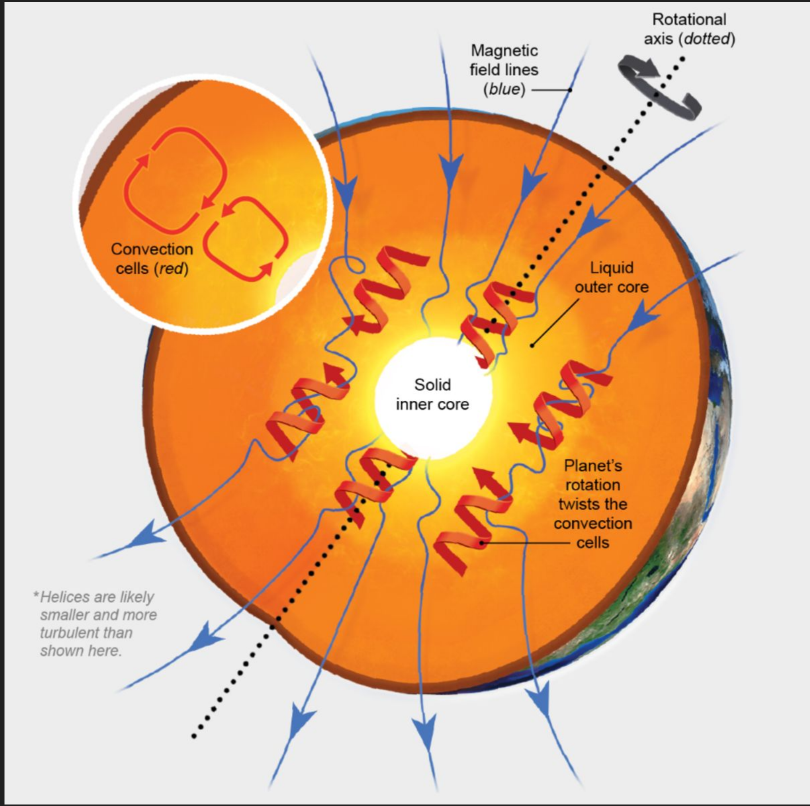
1. Theory of the mechanisms of the geodynamo
2. Scientific discovery of the geodynamo

Introduction: What's the geodynamo?

Mechanism of how the Earth generates and sustains its dipolar magnetic field.

Explained by the dynamo theory

- Proposed by British scientist Joseph Larmor
- Explains how celestial bodies generate and sustains magnetic fields, through a moving conducting fluid.



Dynamo theory

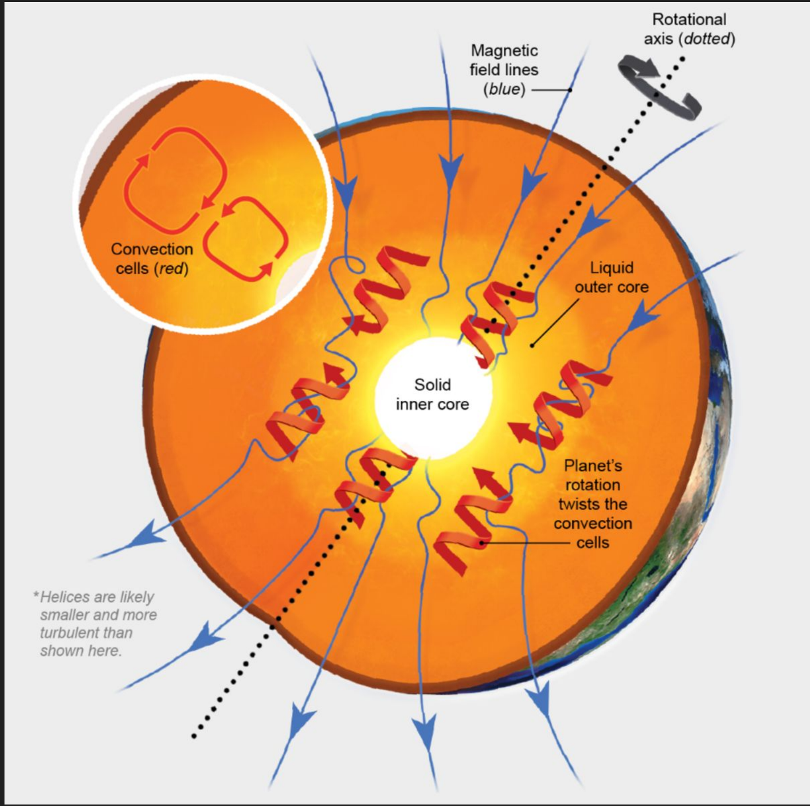
Conditions for a dynamo:

- An electrically conductive fluid medium
- Kinetic energy provided by (planetary) rotation
- An internal energy source to cause convection currents within the fluid

Geodynamo

German-born physicist Walter Elsasser applied this to geodynamo in the 1940s.

- explained that Earth’s magnetic field was formed through **electrical currents induced** by the **convection currents of molten iron-nickel**
- Also pioneered the study of magnetic orientation of minerals in rocks, showing history of the Earth's magnetic field



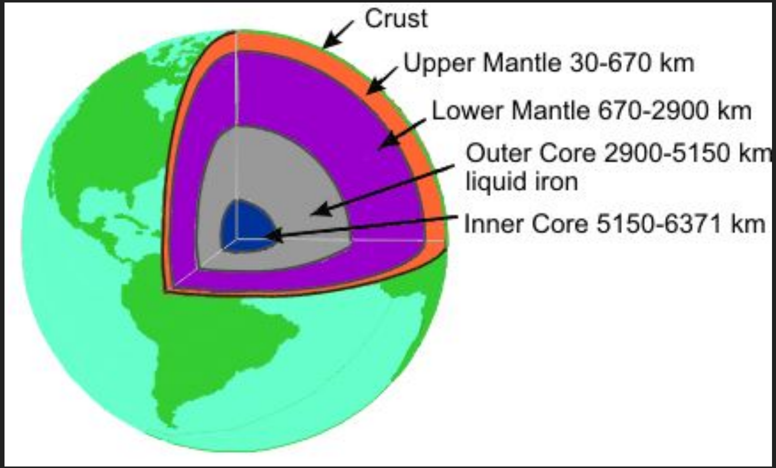
Dynamo theory: Convection

Structure of Earth:

Outer core: Liquid iron-nickel

- Iron and nickel are conductive metals

Inner core: Solid iron-nickel



Dynamo theory: Convection from Compositional gradients (Dominant)

Source:

1. Density differences
    - During inner core crystallisation, where liquid outer core is freezing into inner core,
    - Solid inner core will release lighter non-iron impurities (S, O, Si) which flow upwards
    - This motion contributes to the convection currents

Dynamo theory: Convection from Thermal gradients

Sources of thermal energy:

1. Radioactive decay of isotopes in mantle and core
2. Primordial heat
3. Latent heat released during inner core crystallisation

Supply the Earth’s outer core with thermal energy

- Convection currents where the hot fluid near the inner core boundary rises, and cooler fluid near the mantle sinks

Dynamo theory: Generation of magnetic field

Ampère–Maxwell Law

- An electric current flowing through a conductor generates a magnetic field around it.
- A changing electric field also produces a magnetic field.

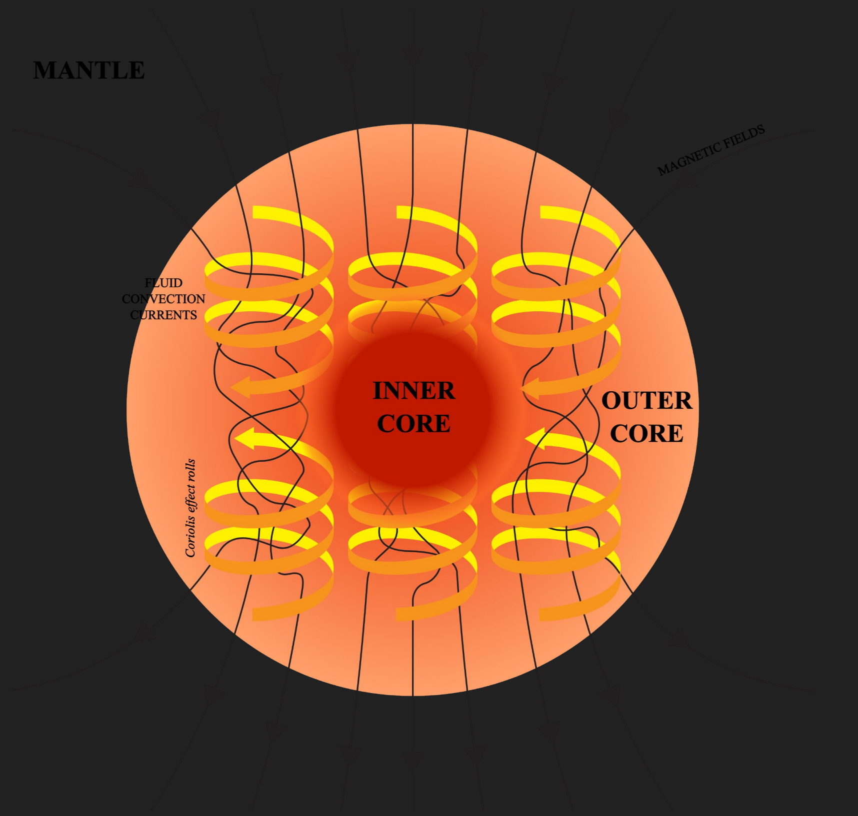
-> The flow of molten iron generates currents, and those currents generate the magnetic field.

Dynamo theory: Faraday's Law of Induction

Faraday's law: Changing magnetic fields induce electric fields

Causes positive feedback loop:

1. Convection of molten iron-nickel generates electric currents.
2. Those currents generate a magnetic field
3. Magnetic field exerts Lorentz forces on the moving charges (in molten iron-nickel) to drive its movement
4. Cycle repeats



Dynamo theory: Alignment of convective currents

However:

If convection currents are random, so will the electrical currents, and Lorentz's right-hand rule shows that the direction of magnetic field lines will also be random.

- Small magnetic fields
- May cancel each other out
- Unable to sustain the geodynamo effect.

But Earth has a coherent, largely dipolar magnetic field

- There is something aligning the convective currents

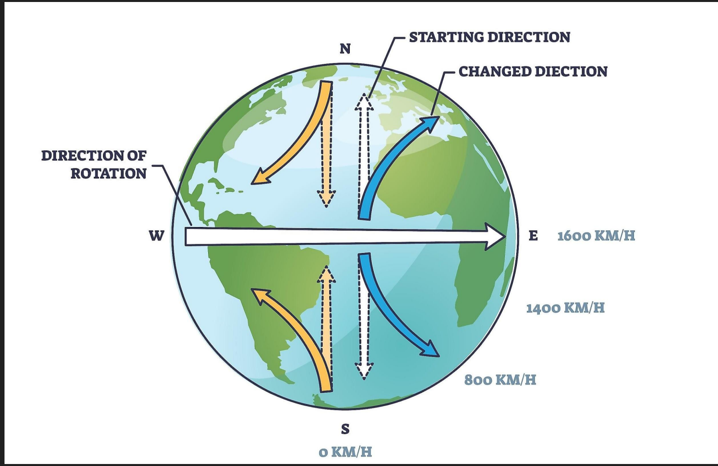
Dynamo theory: Coriolis effect from rotation

Elsasser also highlighted:

Apparent lateral deflection of magnetic field: Coriolis effect

- An effect mathematically derived by French scientist Gaspard-Gustave de Coriolis
- Linear velocity of the Earth is greater near equator, and 0 at geographical poles. This is due to Earth's rotation about the rotations axis along poles
- As such, relative to Earth's rotating surface, there is lateral deflection.

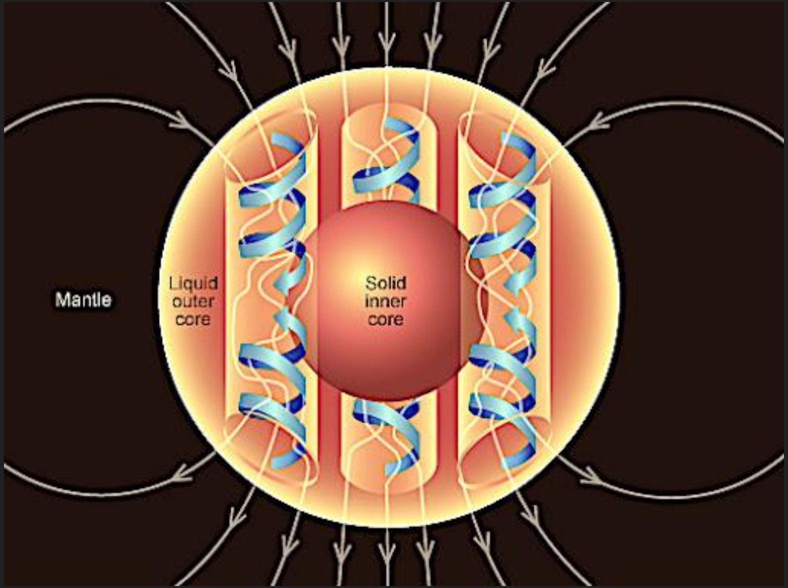
Lateral deflection of molten iron-nickel causes convection currents to also follow.



Dynamo theory: Rotation

Convection currents itself have vertical and horizontal convection patterns

The result is a spiral, helical path, called Taylor's columns. This net pattern causes enough alignment of the convection currents to form a **largely** dipolar and coherent magnetic field.



Dynamo theory: Significance of Coriolis effect

Shown through Rossby number

- Ro = Inertial forces / Coriolis force

Hence, the smaller the Ro, the more significant the Coriolis force is.

Ro $\ll$ 1, Coriolis force dominates

- More Taylor's columns
- Allows for a stronger magnetic field

Ro less than 1, intertidal forces dominate

- Generally weaker magnetic field

$$Ro = \frac{U}{fL}$$

Dynamo theory

Conditions for a dynamo:

- An electrically conductive fluid medium
- Kinetic energy provided by (planetary) rotation
- An internal energy source to cause convection currents within the fluid

Earth meets these requirements to be a dynamo to have a magnetic field

Dynamo theory: magnetic induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

Shows how the geodynamo is generated and sustained, over time and depending on the location of the magnetic field at a point.

Dynamo theory: magnetic induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

Rate of change of magnetic field over time

Partial differential. Value depends on both the location of magnetic field (at a point), and the time.

where $\mathbf{u}$ is velocity, $\mathbf{B}$ is magnetic field, t is time, and $\eta = 1/\sigma\mu$ is the magnetic diffusivity with σ electrical conductivity and μ permeability. The ratio of the second term on the right hand side to the first term gives the Magnetic Reynolds number, a dimensionless ratio of advection of magnetic field to diffusion.

Dynamo theory: magnetic induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

η = 1/μσ
magnetic diffusivity,
μ: conductivity
σ: permeability of the field

∇ ^2B = Laplacian of the field
how the field spreads out or evens out in space.

→ Decay

where **u** is velocity, **B** is magnetic field, *t* is time, and $\eta = 1/\sigma\mu$ is the magnetic diffusivity with σ electrical conductivity and μ permeability. The ratio of the second term on the right hand side to the first term gives the Magnetic Reynolds number, a dimensionless ratio of advection of magnetic field to diffusion.

Dynamo theory: magnetic induction equation

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u×B: Electric field induced by motion of conducting fluid through a magnetic field

∇×(...): change in magnetic field due to currents generated by fluid motion.

Induction

where **u** is velocity, **B** is magnetic field, *t* is time, and $\eta = 1/\sigma\mu$ is the magnetic diffusivity with σ electrical conductivity and μ permeability. The ratio of the second term on the right hand side to the first term gives the Magnetic Reynolds number, a dimensionless ratio of advection of magnetic field to diffusion.

Dynamo theory: magnetic induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

Rm: Relative ratio of induction to decay (can find if dynamo is possible)

Rm≫1: induction dominates → field grows or sustains → dynamo action possible.

Rm ~ 1 -> Weak and unstable dynamo

Rm≪1: diffusion dominates → field decays → No dynamo possible

where $\mathbf{u}$ is velocity, $\mathbf{B}$ is magnetic field, t is time, and $\eta = 1/\sigma\mu$ is the magnetic diffusivity with σ electrical conductivity and μ permeability. The ratio of the second term on the right hand side to the first term gives the Magnetic Reynolds number, a dimensionless ratio of advection of magnetic field to diffusion.

Dynamo theory: magnetic induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

Application:

Faster rotation (higher u) → more efficient field generation.

Higher electrical conductivity of outer core (higher σ) → lower η → slower decay

where **u** is velocity, **B** is magnetic field, *t* is time, and $\eta = 1/\sigma\mu$ is the magnetic diffusivity with σ electrical conductivity and μ permeability. The ratio of the second term on the right hand side to the first term gives the Magnetic Reynolds number, a dimensionless ratio of advection of magnetic field to diffusion.

Secular variations

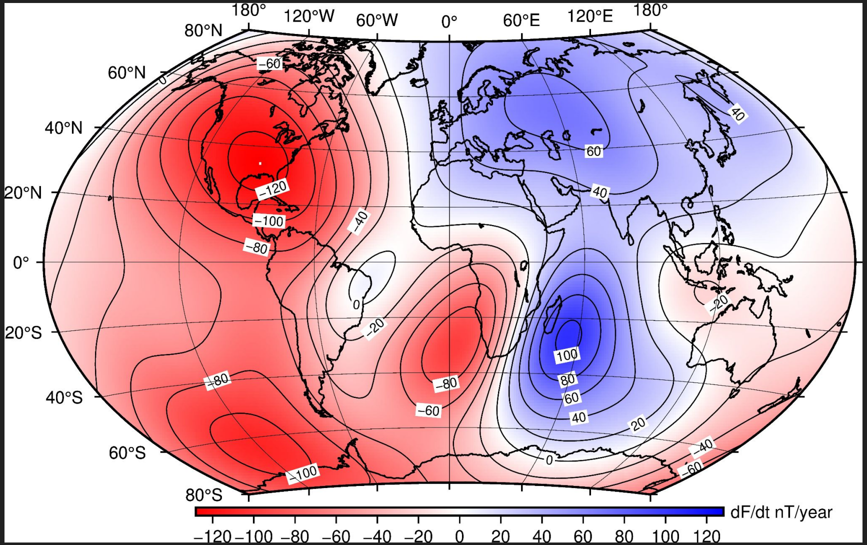


Figure: Map of predicted annual rate of change of total intensity for 2020.0-2025.0

Map shows that the magnetic field changes in intensity over the years.

The magnetic field is dynamic due to constant changes to the fluid motion of the molten iron-nickel.

- Slow, continuous changes in magnetic field over years due to changes in the Earth

Hence sometimes called internal variation

Secular variations

Example 1: Variation in magnetic declination: The angle between magnetic north and true geographic north.

- Why does magnetic declination occur?
  - Non-dipole components (eg magnetised rocks) in the magnetic field cause small and irregular changes to the magnetic field as the vector sum of dipole and non-dipole components changes.
  - Hence field lines are NOT uniform.

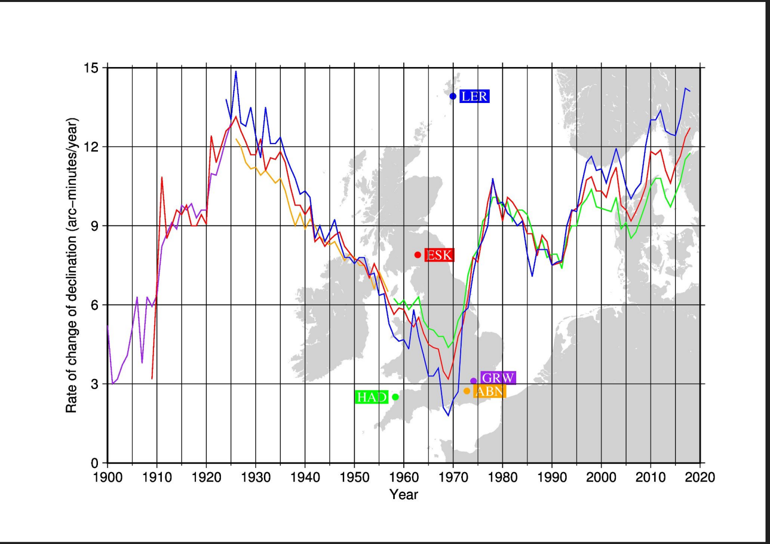


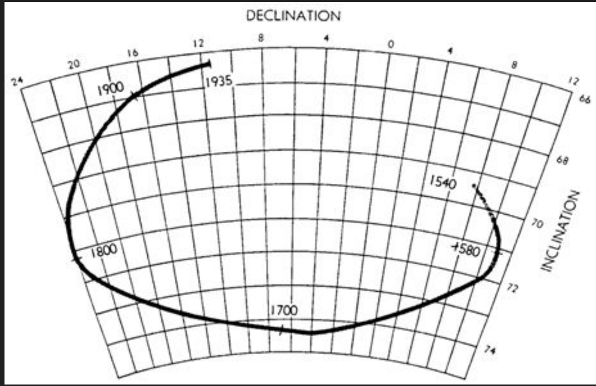
Figure 12: Rate of change of declination at Greenwich (GRW), Abinger (ABN), Hartland (HAD), Eskdalemuir (ESK) and Lerwick (LER) observatories

Secular variations

Example 2: Westward drift

Direct observations of the magnetic field over the past 400 years show the pattern of declination seen at the Earth's surface moving slowly westwards.

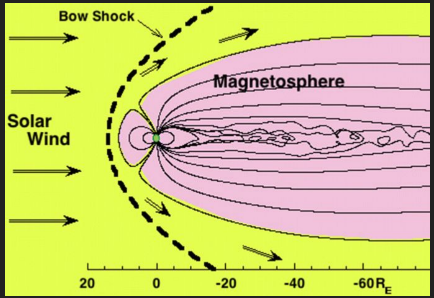
- linked to motion of fluid at the core surface slowly westwards due to the rotation of the earth, and the magnetic field moves with it.



Variations

Other examples: (not limited to this list)

1. Variation in magnetic Inclination: The angle between the magnetic field and the horizontal plane
2. Variation in magnetic field intensity
3. Reversals and Excursions: Reversals and incomplete reversals of polarity
4. External variation: Variation to magnetosphere and ionosphere due to external forces and environments such as space weather



History of the discovery: Understanding of magnetism

300 B.C. ~ pre-1000s

Ancient awareness of magnetism

Lack of awareness of Earth's magnetism

Ancient awareness of magnetism

Observation and application. Examples:

1. The Chinese created the first ***usable compass*** (rough 400-200 BC)
   - 司南 (sīnán), spoon-shaped, made with lodestone, a naturally magnetised ore.

2. Mesoamericans (500 B.C. - 100 B.C.)
   - Evidence shows they used magnetised rocks to build sculptures for cultural purposes

History of the discovery: Theories

300 B.C. ~ pre-1600s

Ancient awareness
of magnetism

Lack of awareness of
Earth's magnetism

Natural philosophy

Empirical observations,
applications of magnets
increase across the world

Natural philosophy: Examples

<u>Attribution of magnetism to something supernatural</u>

- Greek philosopher Thales of Miletus (c. 624 – 546 BCE) was the earliest known Greek to examine magnetism.
    - theorised magnetic forces was due to the ***magnet having a soul***, implying magnetism was a living property.

<u>Inaccurate theories</u>

- Democritus (c. 460 – 370 BCE) theorised that
    - the atoms of the lodestone were smaller and rarer the atoms of the iron
    - Atoms of the lodestone “permeate” through the pores of the iron, disturbing its atoms, causing them to move outside towards the stone -> cause the physical movement between the lodestone and iron.

History of the discovery

300 B.C. ~ pre-1600s

Ancient awareness of magnetism

Proto-science

Natural philosophy

Empirical observations, applications of magnets increase across the world

Proto-science

<u>Epistola De Magnete (1269)</u>

- A letter by French mathematician and scientist Petrus Peregrinus de Maricourt
- During the High Middle Ages, when Europe was in intellectual revival
- Suitable intellectual environment with more available information
- Qualitative experiments involving *terella*, a spherical lobestone

Role of the discovery of the geodynamo

- Did not explicitly argue that that Earth has a magnetic field, but:
    - proved that magnets have poles, and that like poles repel, unlike poles attract.
    - etc.

History of the discovery

300 B.C. ~ pre-1600s

Ancient awareness of magnetism

Proto-science

Natural philosophy

1600:
Earth is a magnet

Empirical observations, applications of magnets increase across the world

De Magnete (1600)

- Written by English scientist William Gilbert

- Systematic experiment with the terella, a spherical lodestone.
    - Moved compass needles around it and realised it behaves similar to how compass needles moves around Earth based on reports by mariners and explorers

Role of the discovery of the geodynamo

- Proposed that the Earth itself is a giant magnet
- First to propose and experientially demonstrate it

Limitations
- Assumed it was a permanent magnetic field
- etc

History of the discovery

300 B.C. ~ pre-1600s

Ancient awareness of magnetism

Proto-science

Natural philosophy

1600: Earth is a magnet

1600s-1700s:

Magnetic field is dynamic

Evidence of dynamic magnetic field

Henry Gellibrand (1630s)

- Measured magnetic declination in London and compared with older records.
- angle between magnetic north and true north had changed over decades.

Evidence of secular variation and that the magnetic field is dynamic

Edmond Halley (1690s)

- Conducted global surveys of magnetic declination
- Found that the magnetic field varies by location

Evidence of the magnetic field not being uniform

History of the discovery

300 B.C. ~ pre-1600s

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1600s-1700s: Magnetic field is dynamic

Early 1800s:

Discoveries in electromagnetism by Oersted, Ampère, and Faraday

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Developed methods for absolute field measurement by Carl Friedrich Gauss

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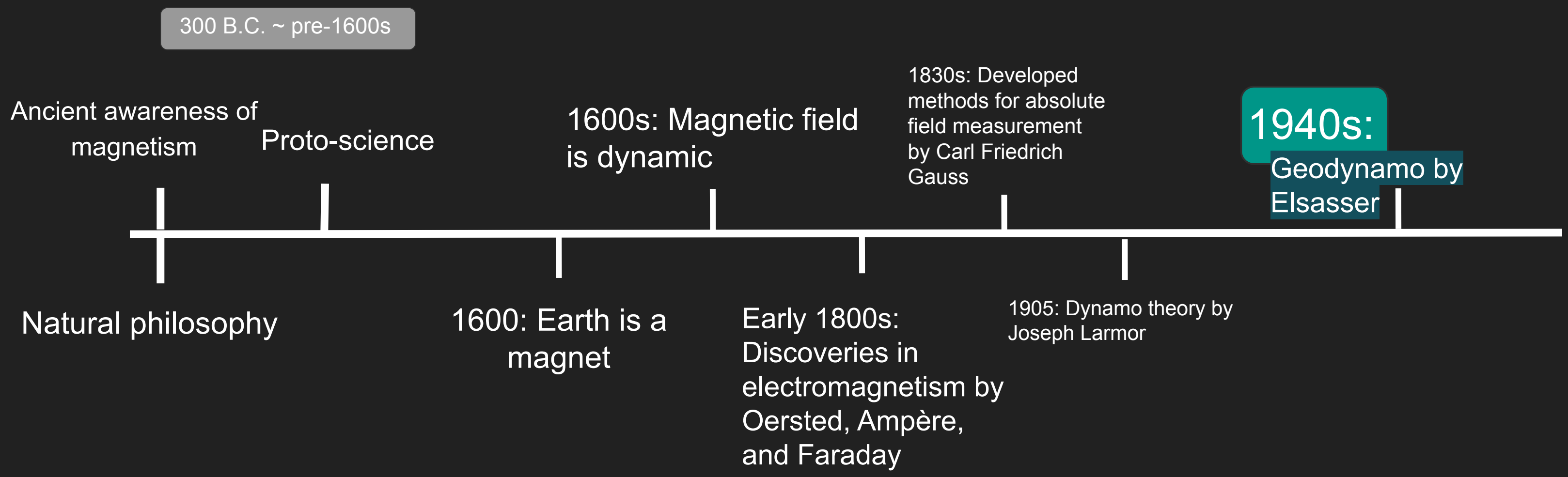
1905:

Dynamo theory by Larmor

History of the discovery



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1905: Dynamo theory by Joseph Larmor

1940s: Geodynamo by Elsasser

1950s:

First computer simulation as proof

Bullard dynamo

1950s – Edward Bullard (UK)

Developed mathematical models and simulations
Bullard and his colleagues made the first computer simulation of the geodynamo
Explained westward drift, secular variation

1950s

History of the discovery

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1950s: First computer simulation as proof

~present:

Continued advancement and technological development

THANK YOU

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