SIOG 231
GEOMAGNETISM AND ELECTROMAGNETISM

Lecture 1

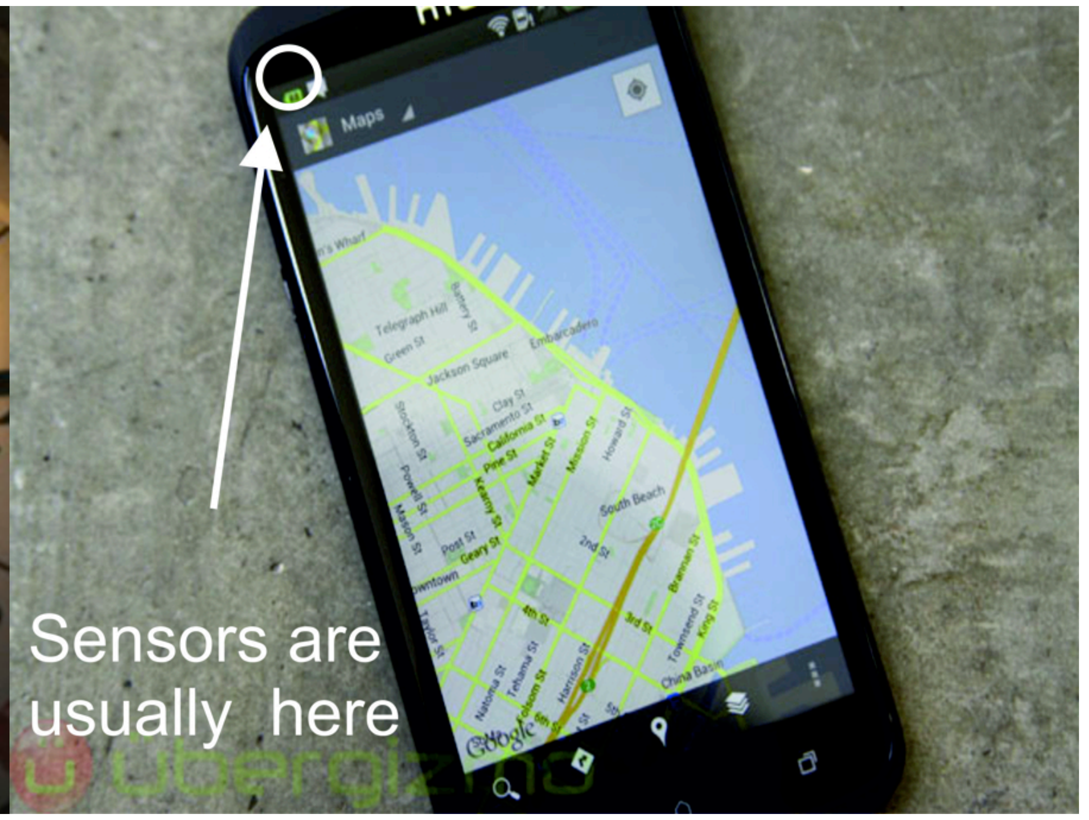
Introduction and Historical Material

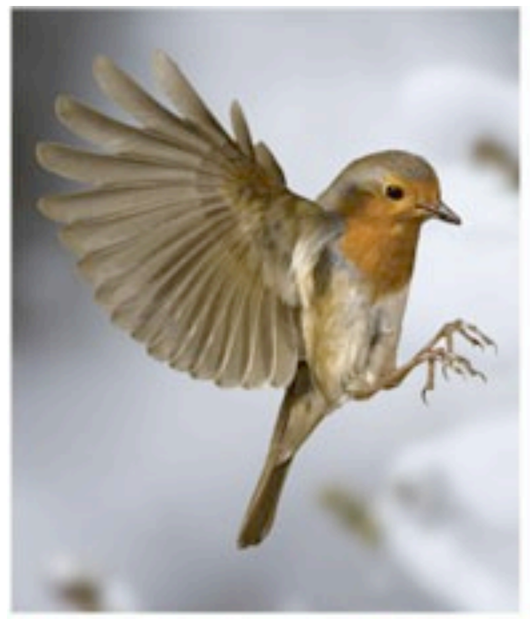
1/9/2024

WHY STUDY EARTH’S MAGNETIC FIELD?

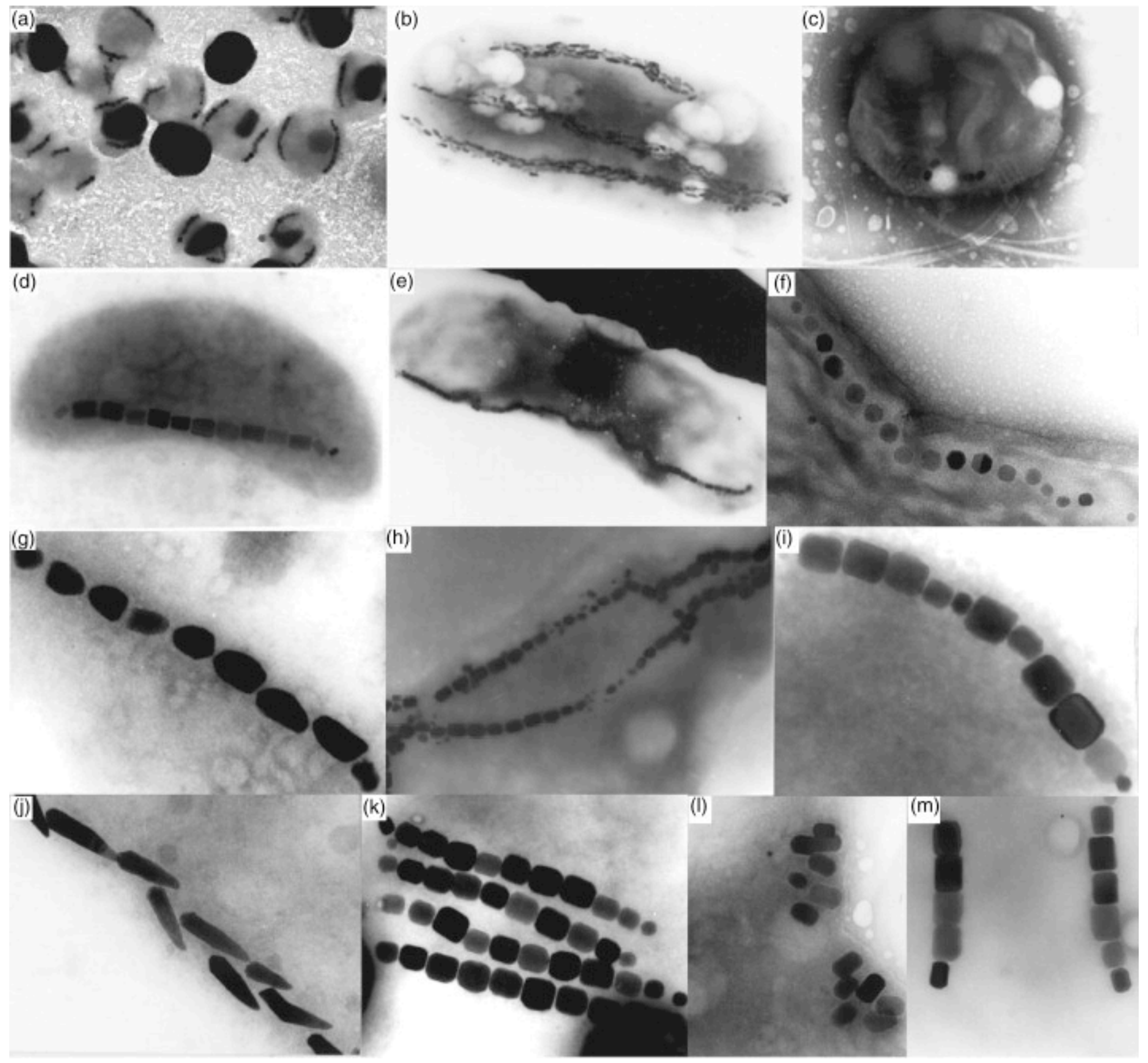
Navigation for people, animals, birds, bacteria







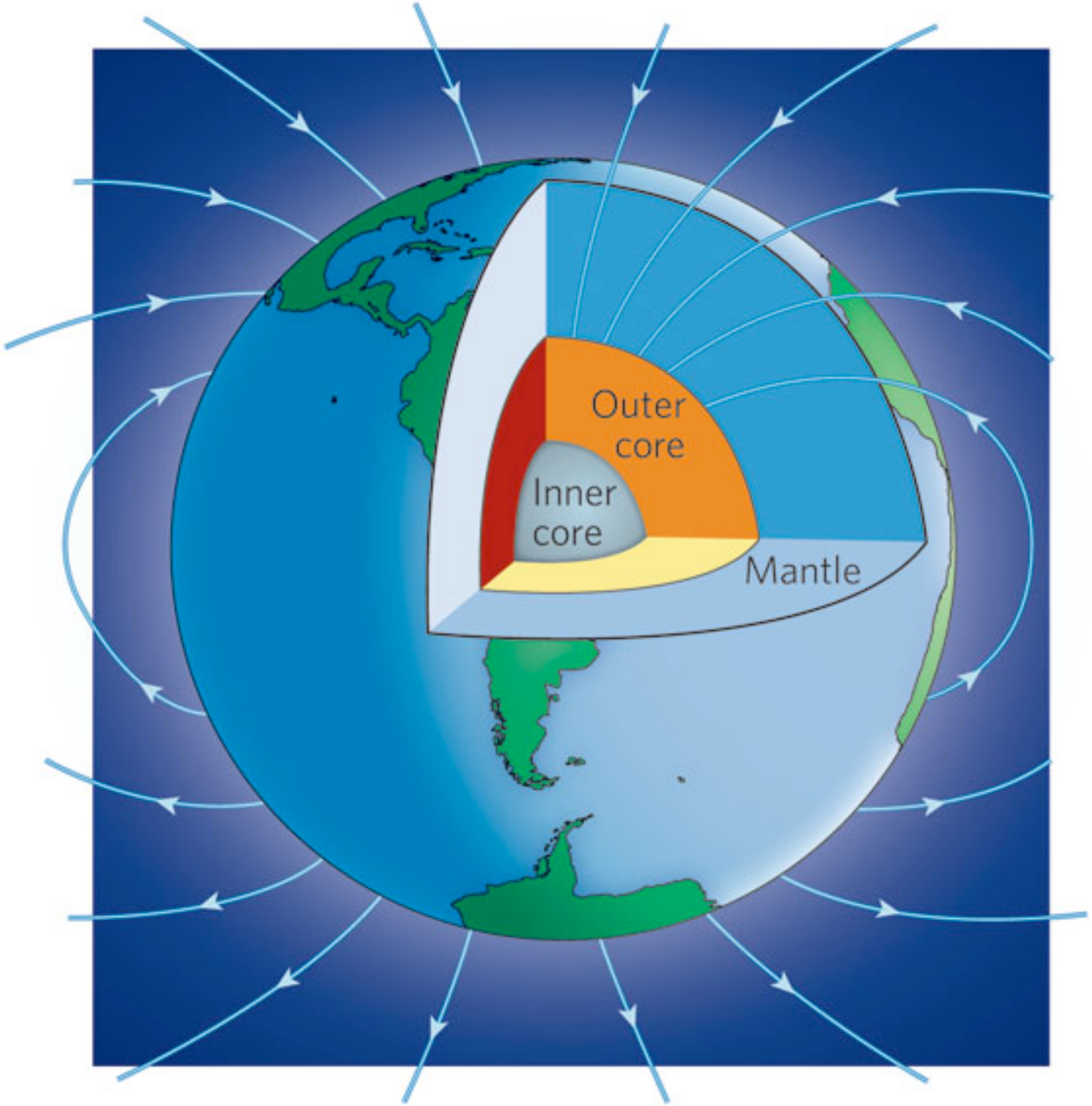


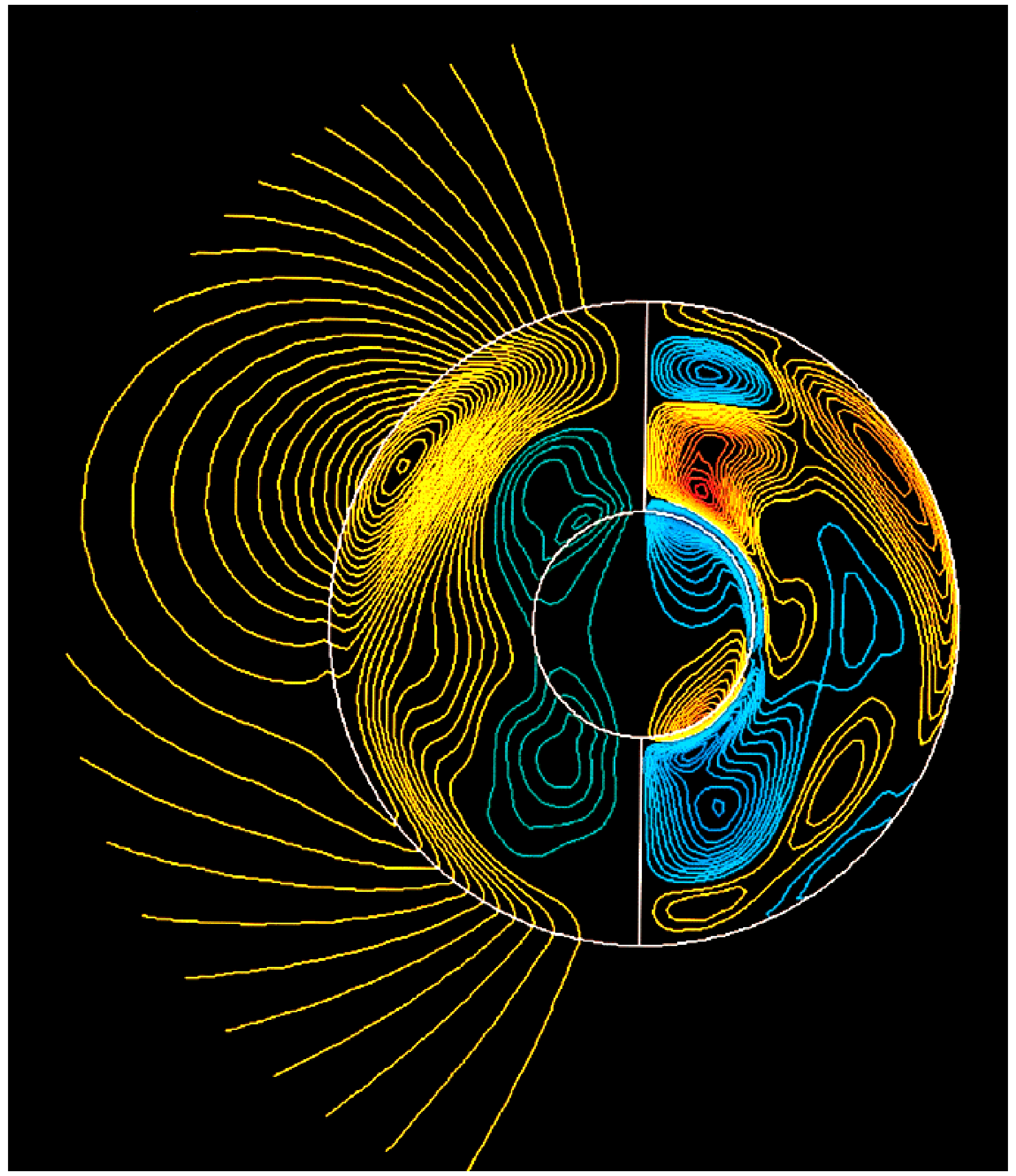



https://www.nature.com/articles/4641140a/figures/1

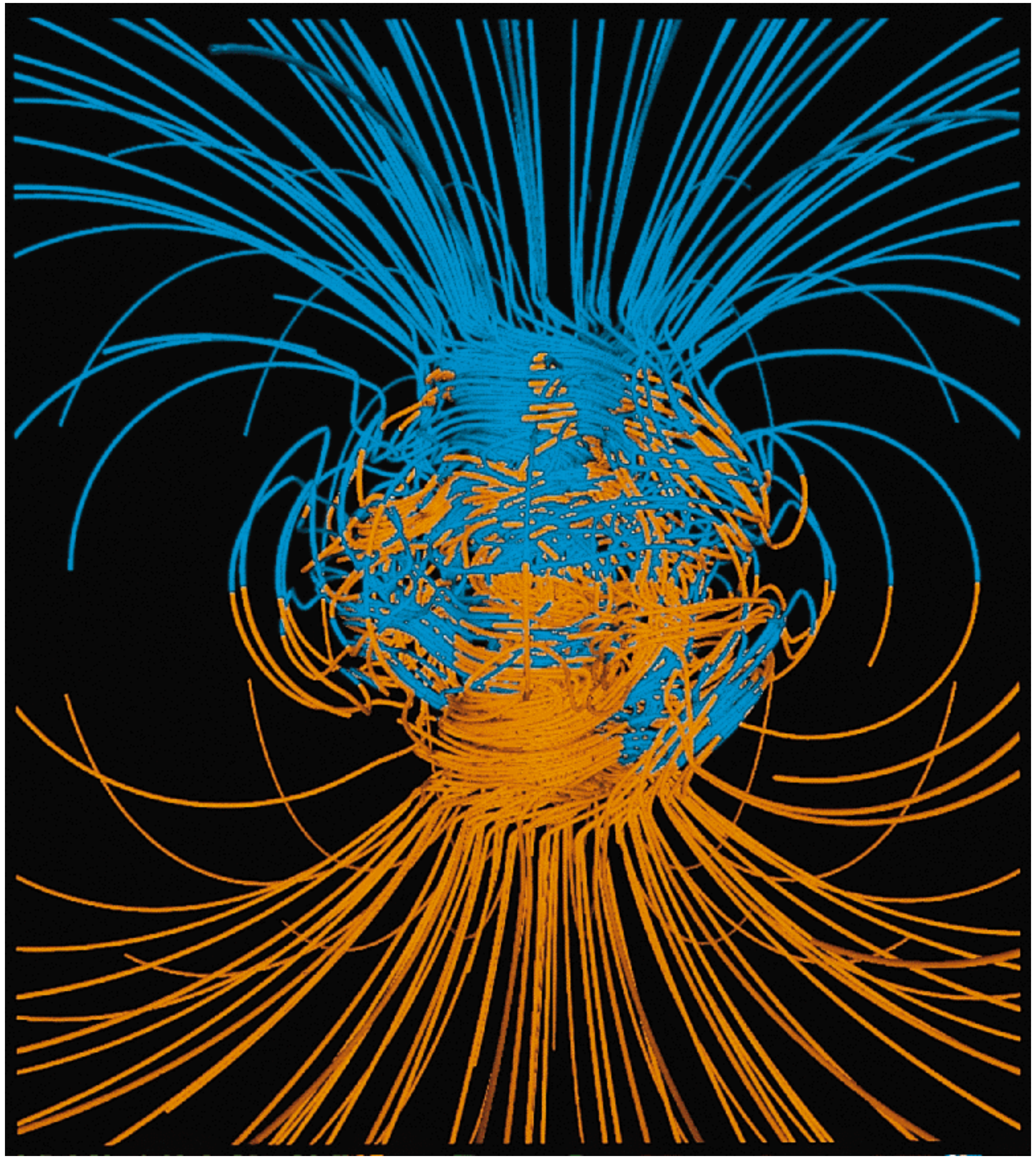
WHY STUDY EARTH'S MAGNETIC FIELD?

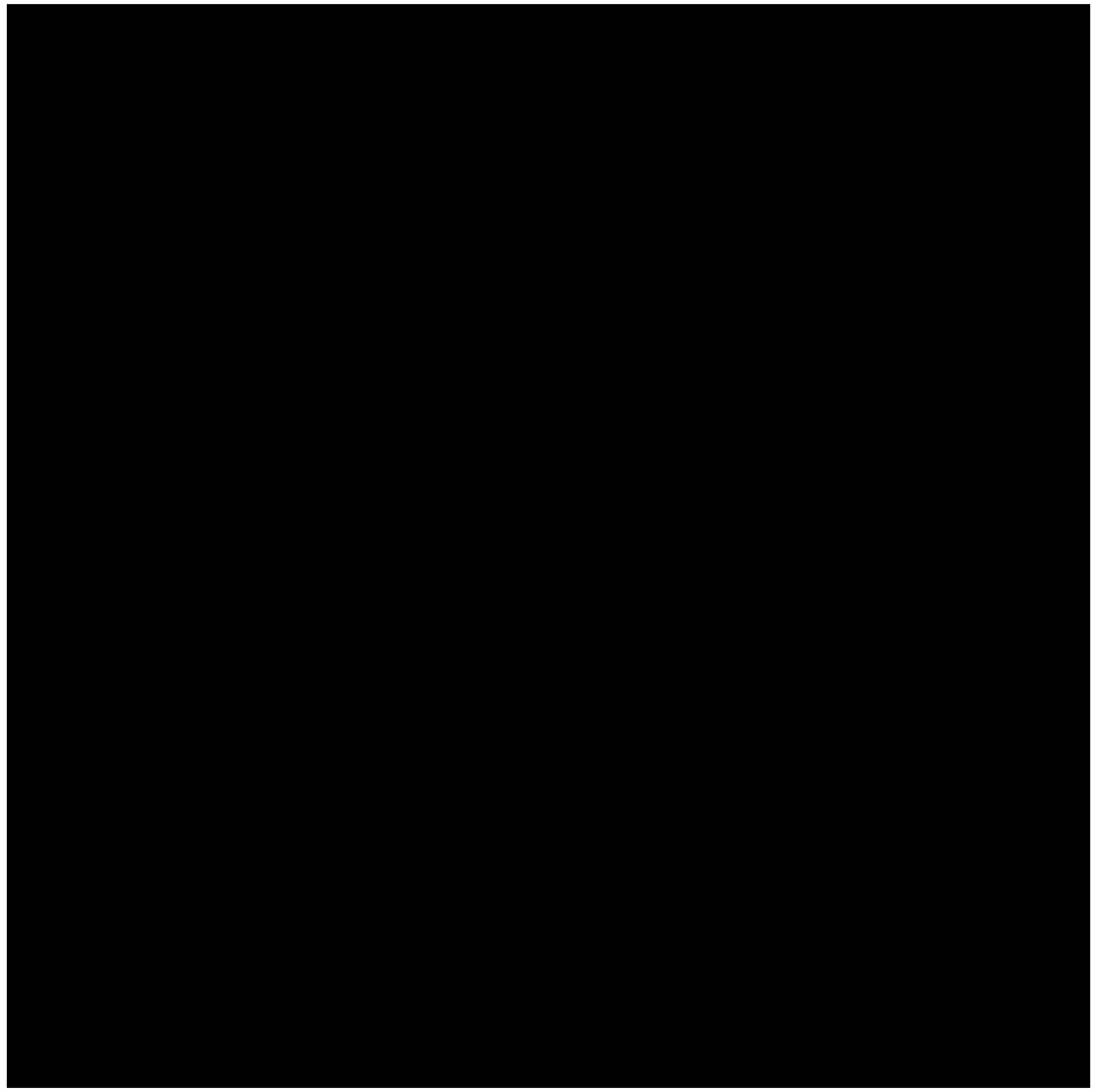
Understand Earth history through origins and evolution of the field





SIMULATING THE GEODYNAMO

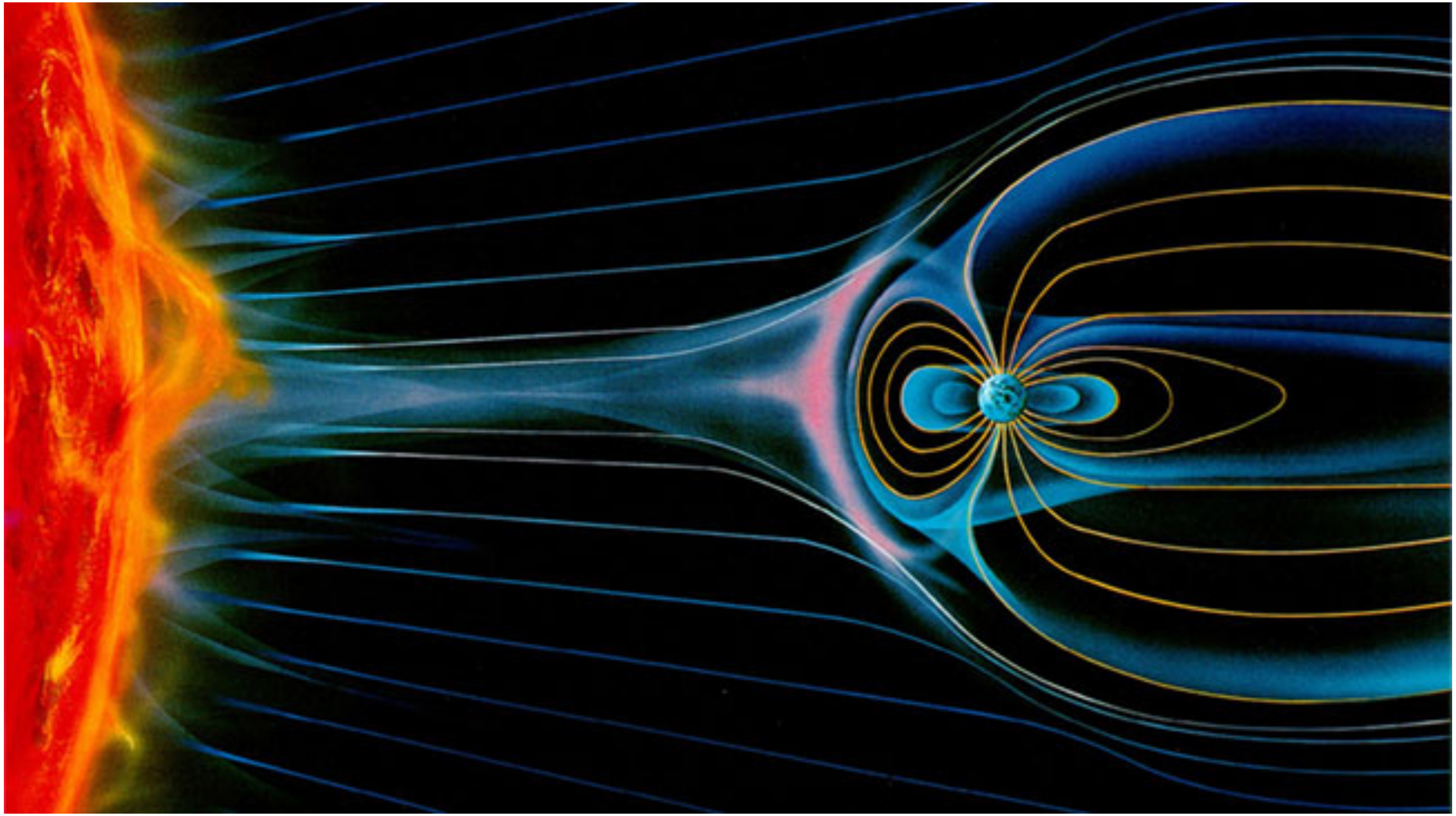




Glatzmaier & Roberts, 1995

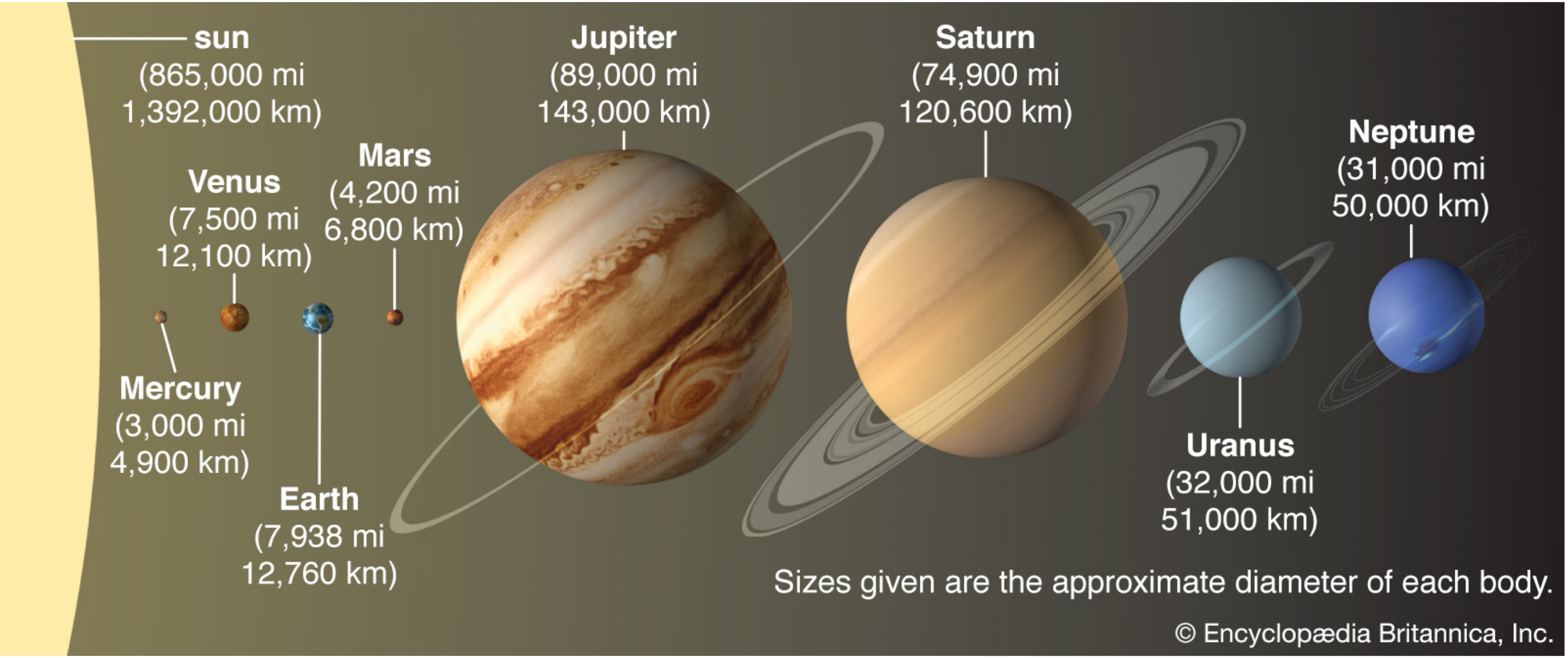
WHY STUDY EARTH'S MAGNETIC FIELD?

Understand the role of magnetic fields throughout the solar system

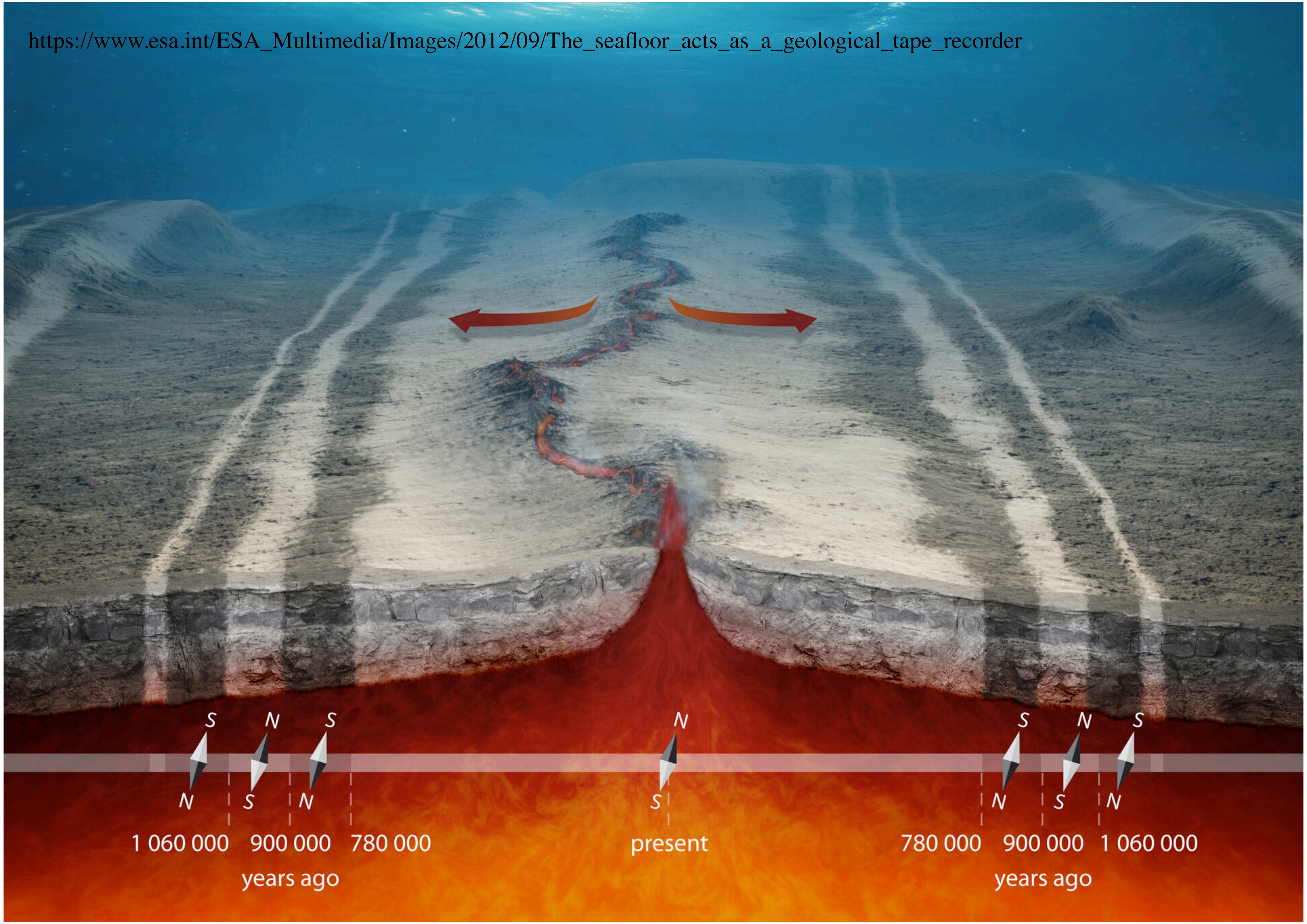


NOT TO MENTION OTHER SOLAR SYSTEM BODIES

Which of them have magnetic fields? dynamos?

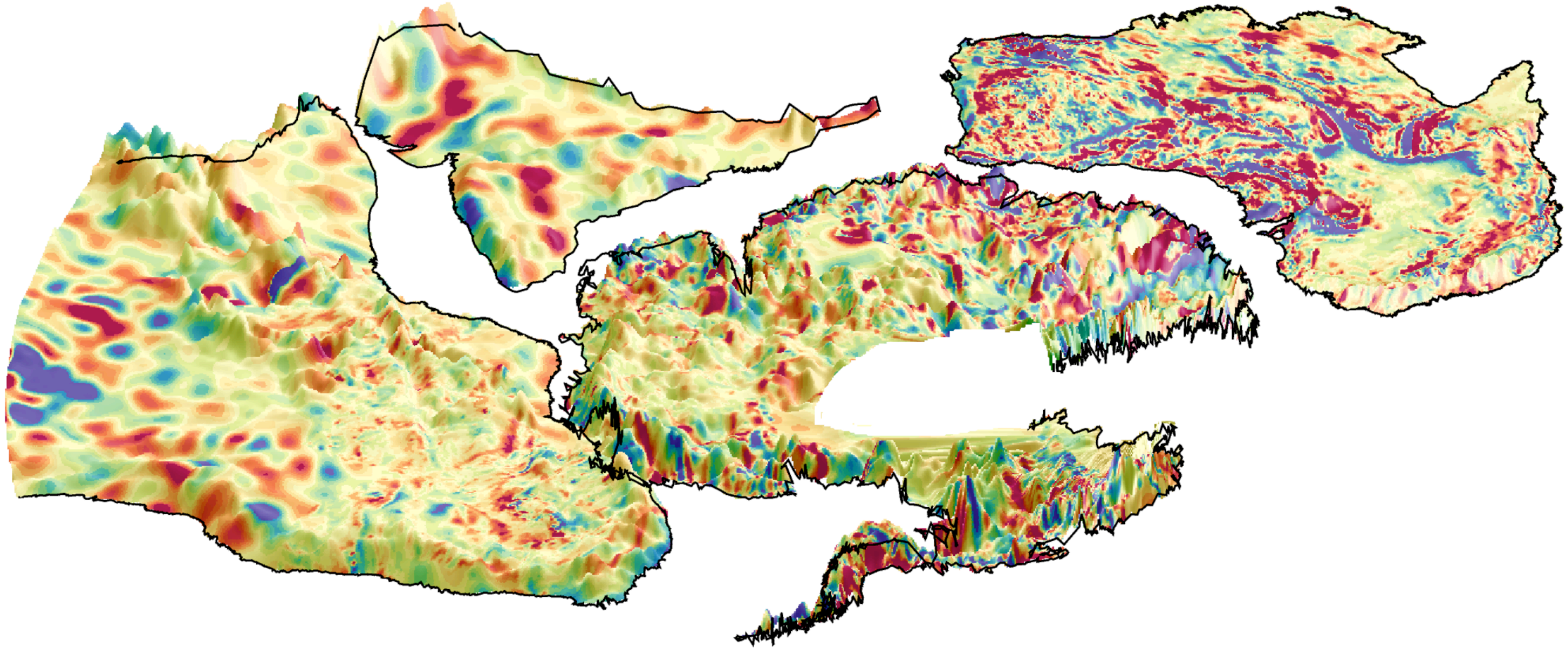


Understand Formation and Evolution of Oceanic Crust and Mantle



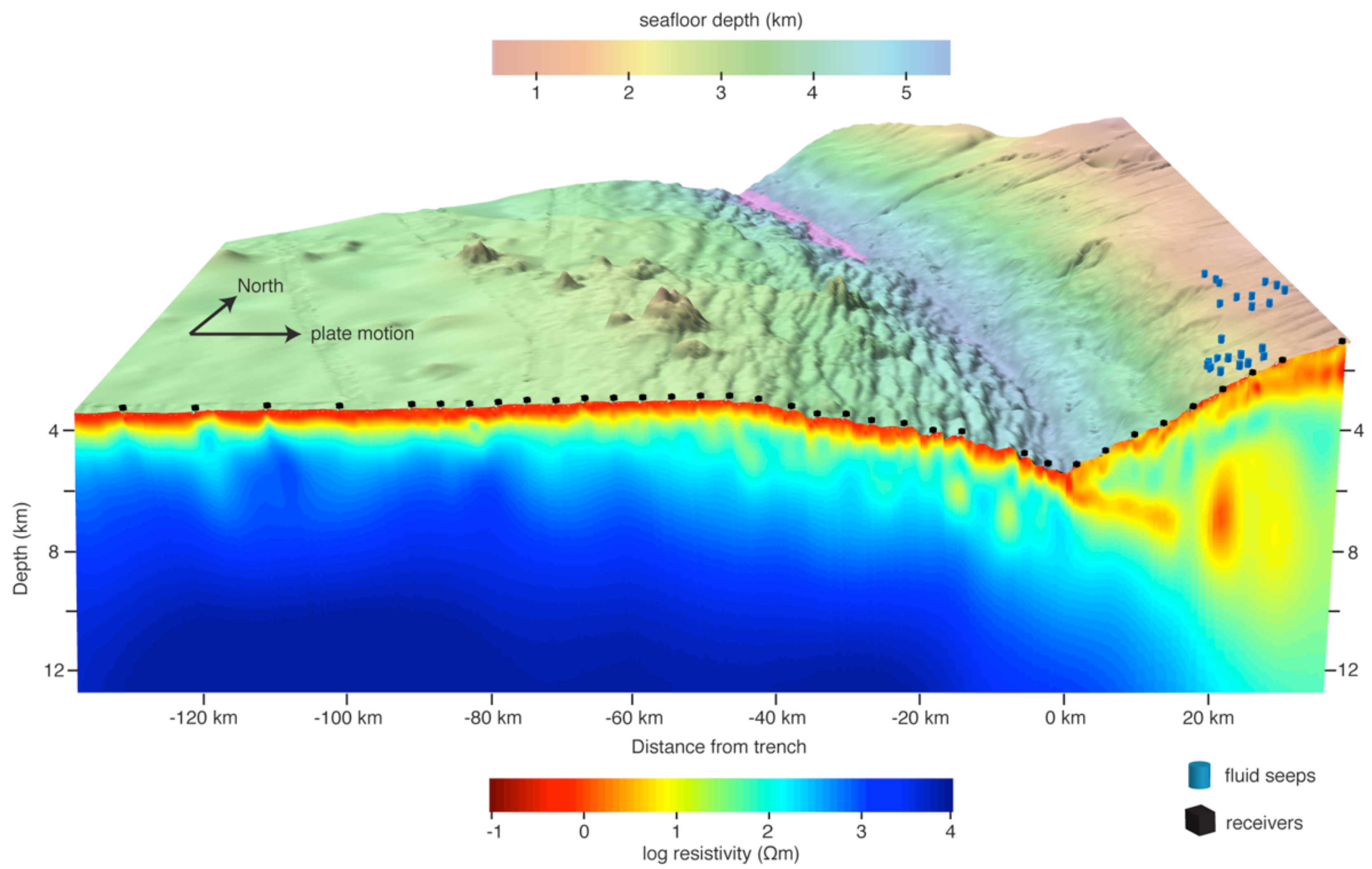
WHY STUDY EARTH'S MAGNETIC FIELD?

Crustal Magnetic anomalies reveal tectonic information, e.g., linking Antarctica to neighboring continents

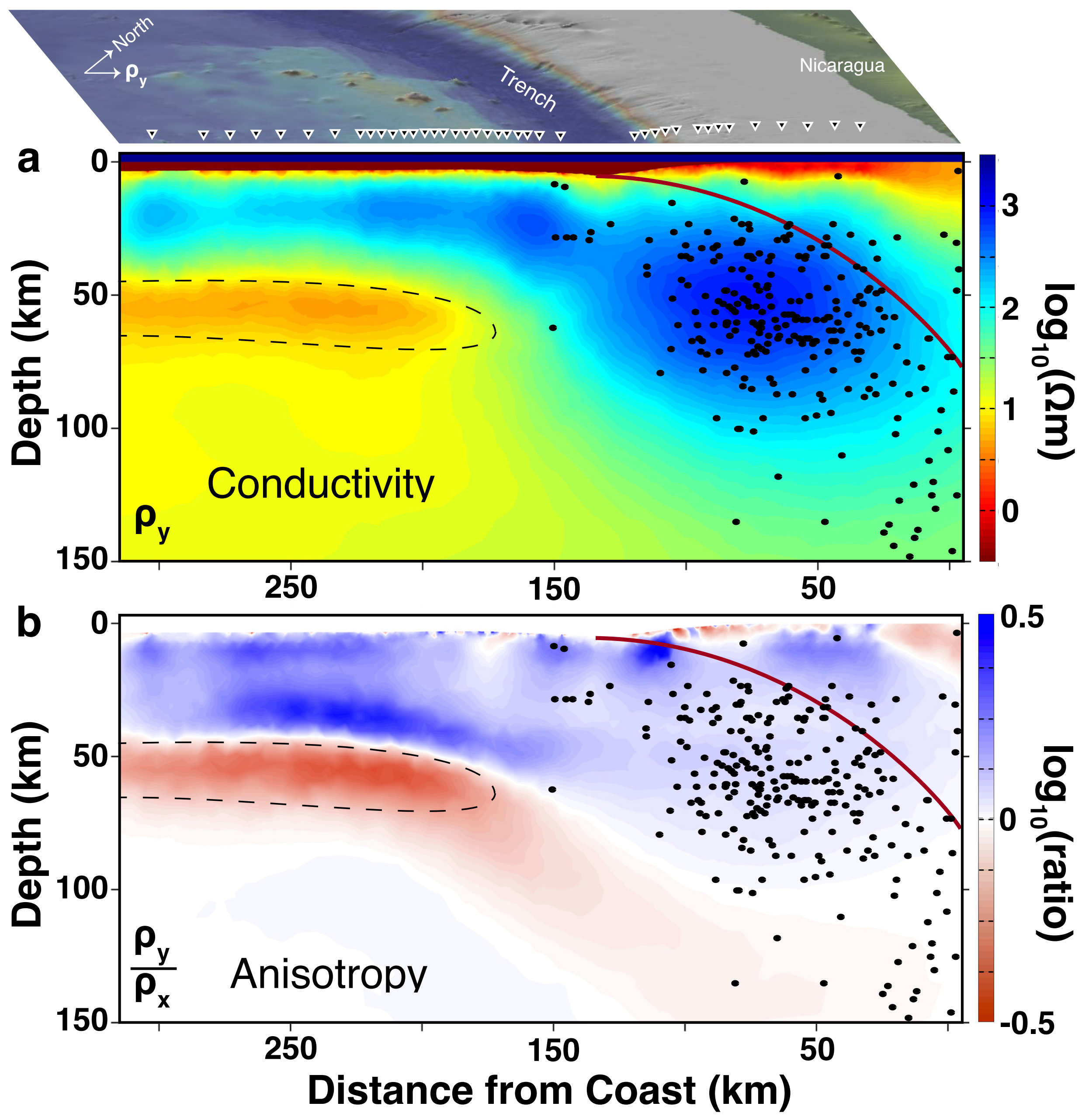


https://www.esa.int/Applications/Observing_the_Earth/Swarm/Antarctica_s_magnetic_link_to_ancient_neighbours

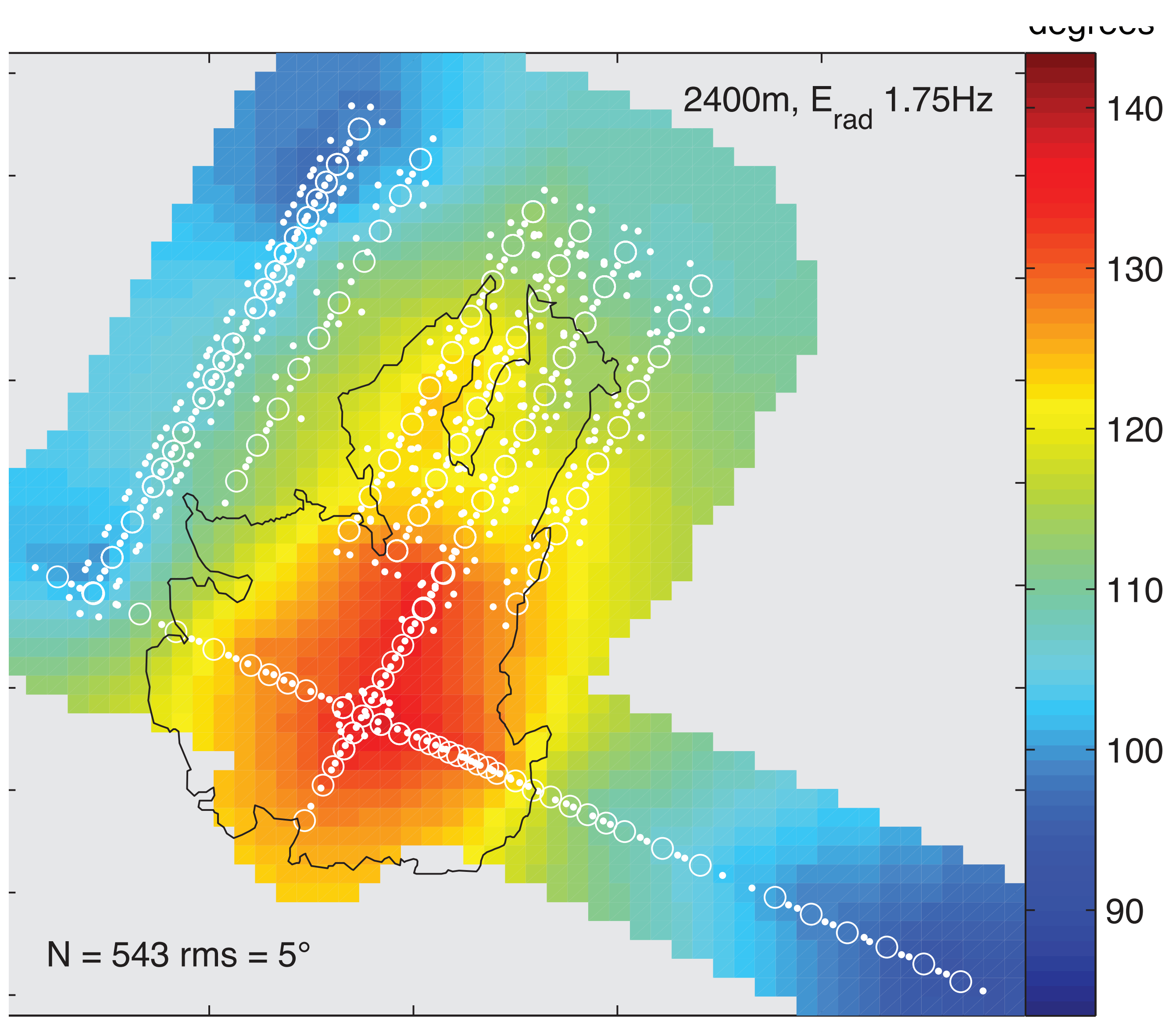
WHY STUDY ELECTROMAGNETIC METHODS?

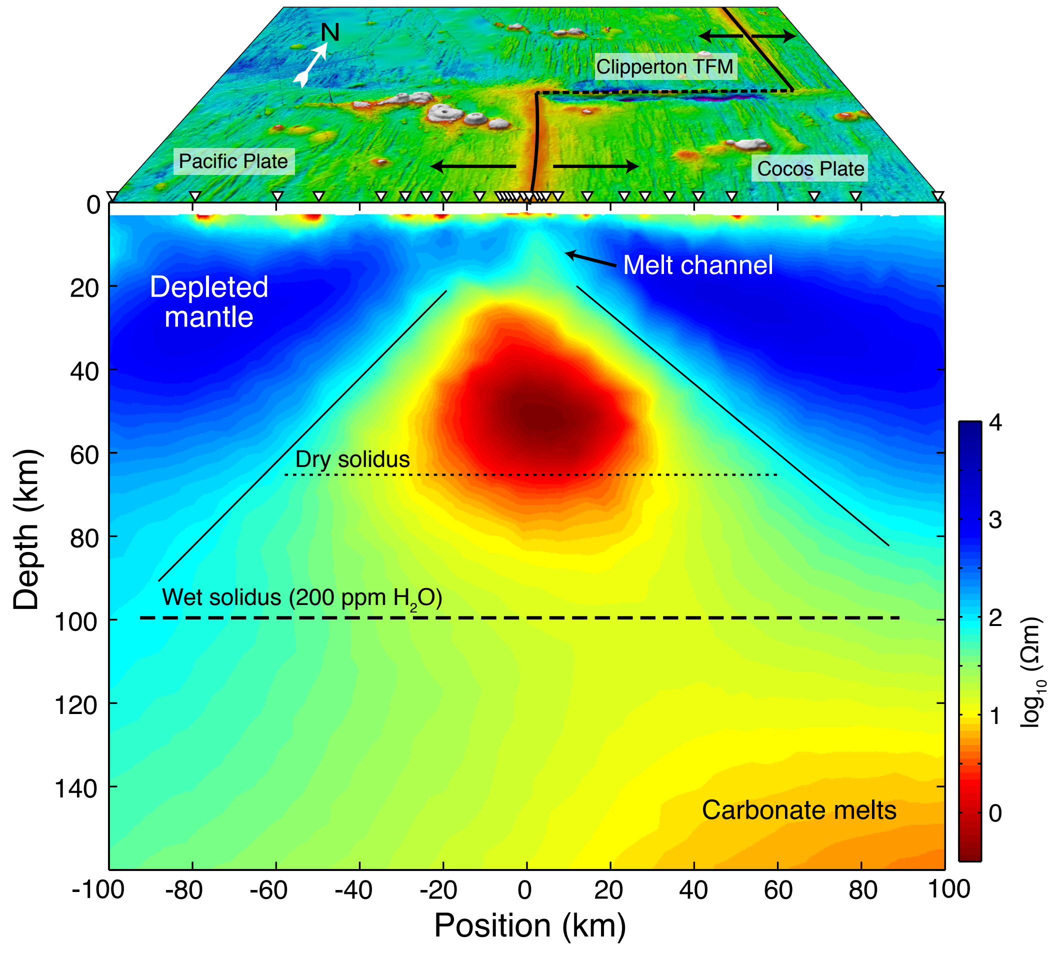


Subduction off Nicaragua



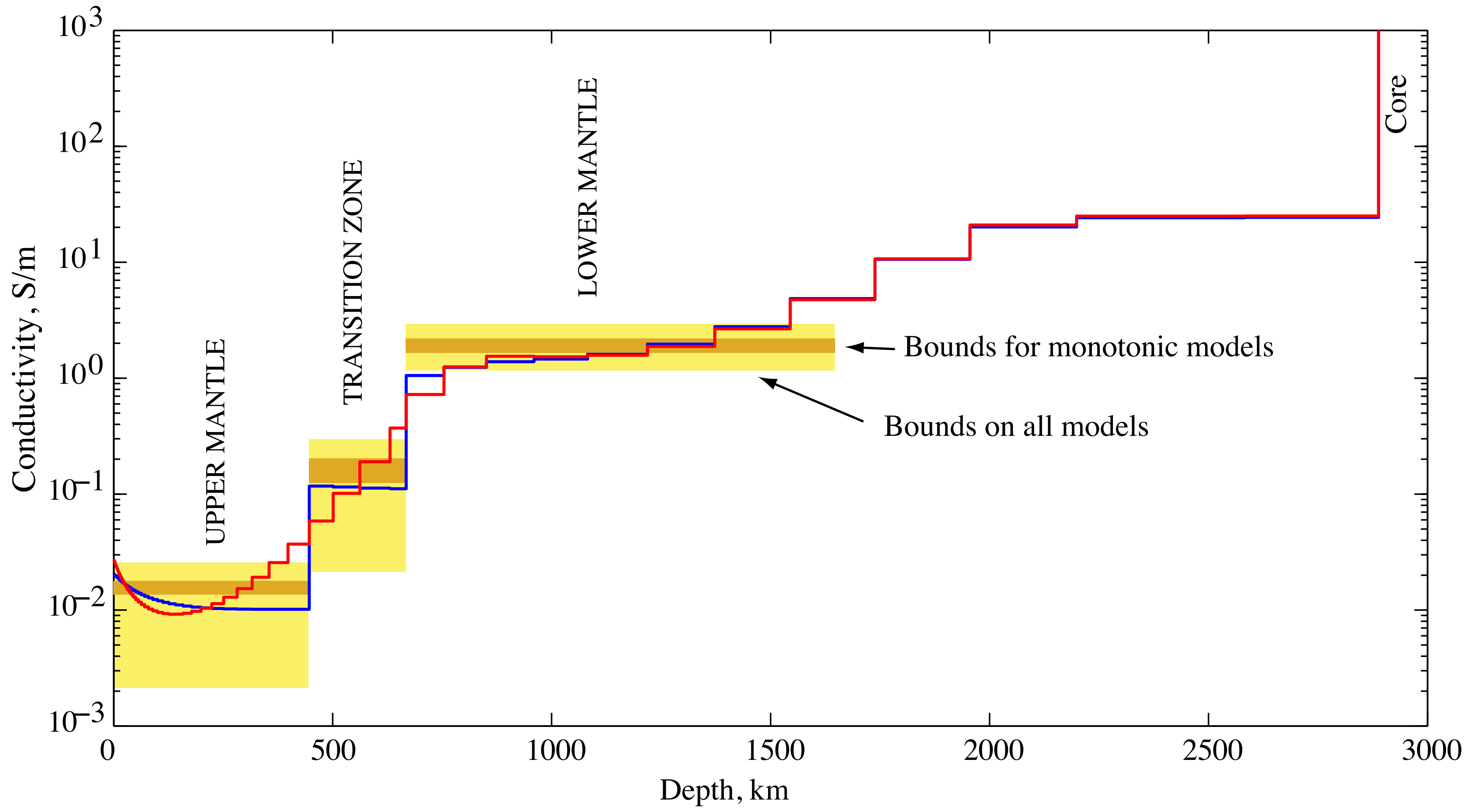
Gas reservoir

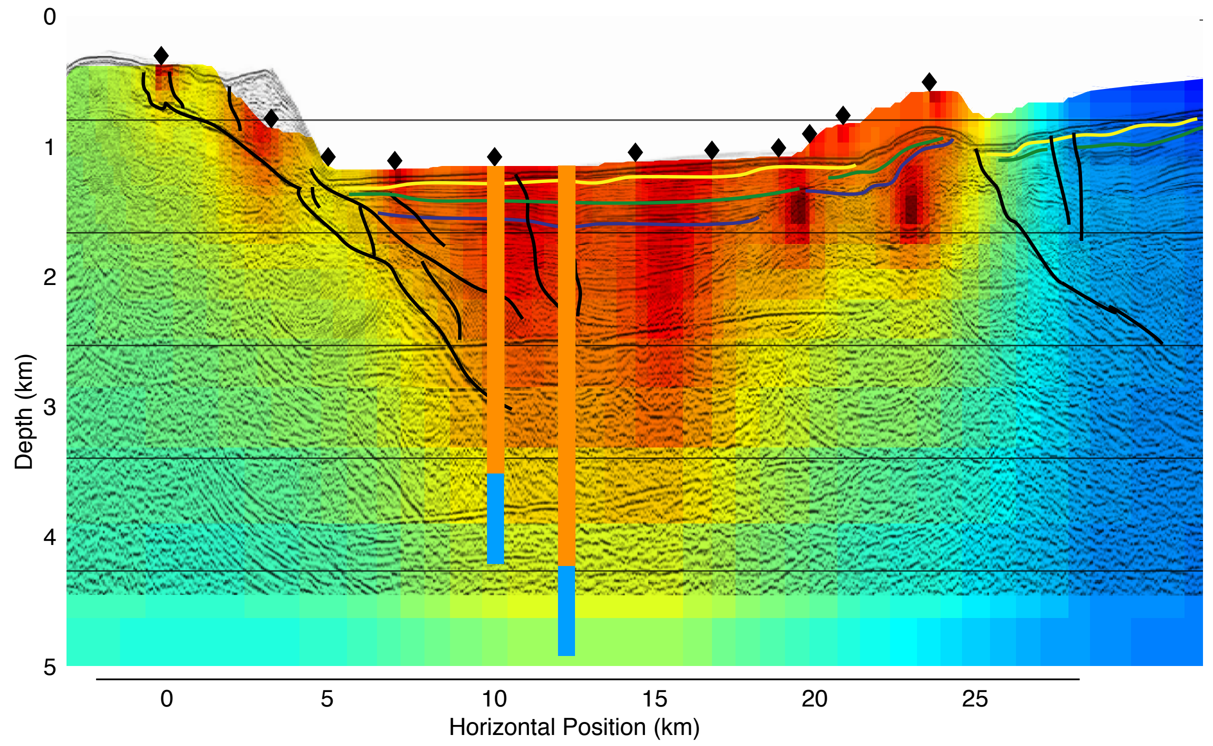




Mid-ocean ridge

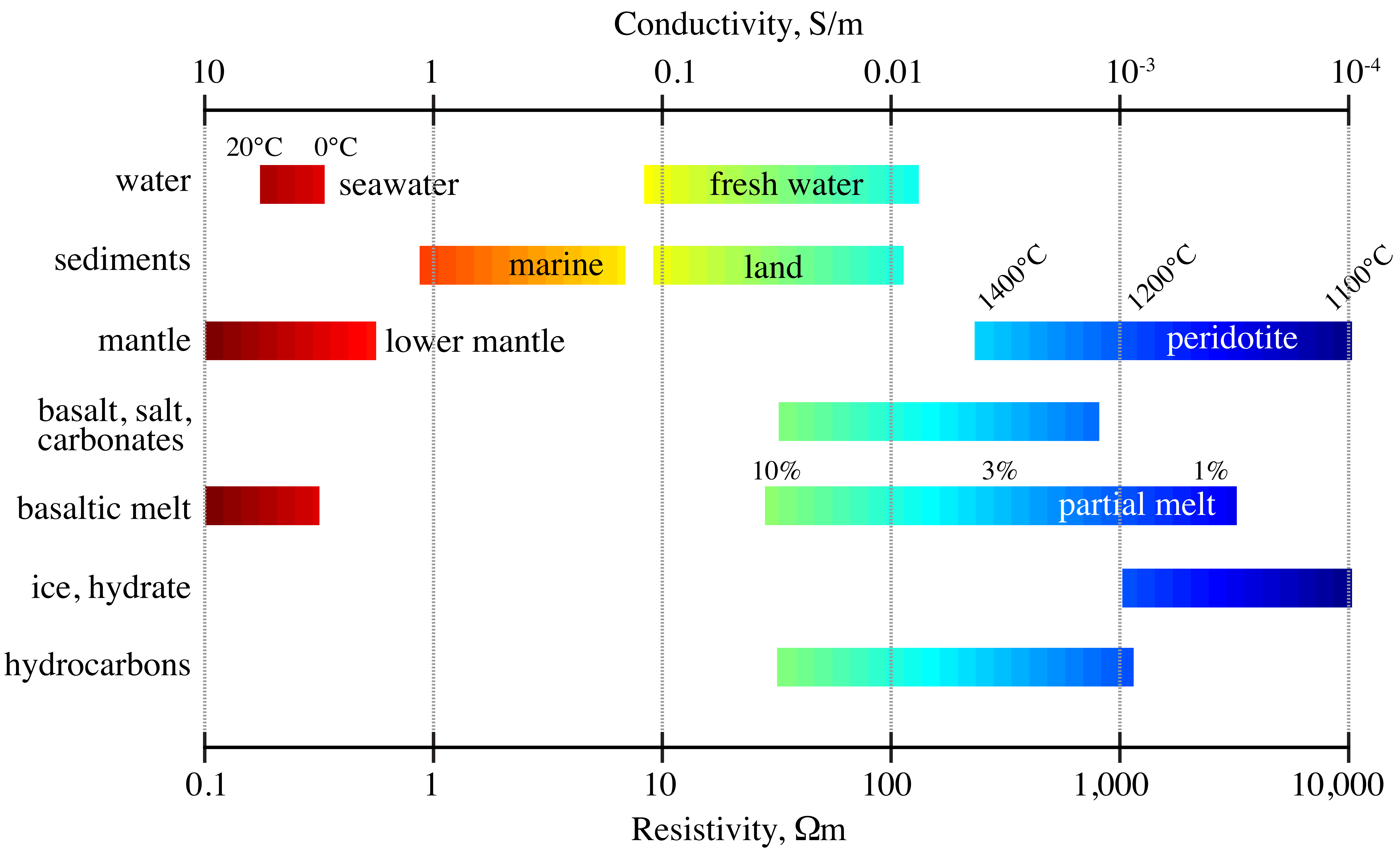
Global conductivity





Basin structure off California

Electrical conductivity varies over 5 orders of magnitude in common Earth materials, and provides the ideal mechanism for studying fluids, water, and melt in the crust and mantle



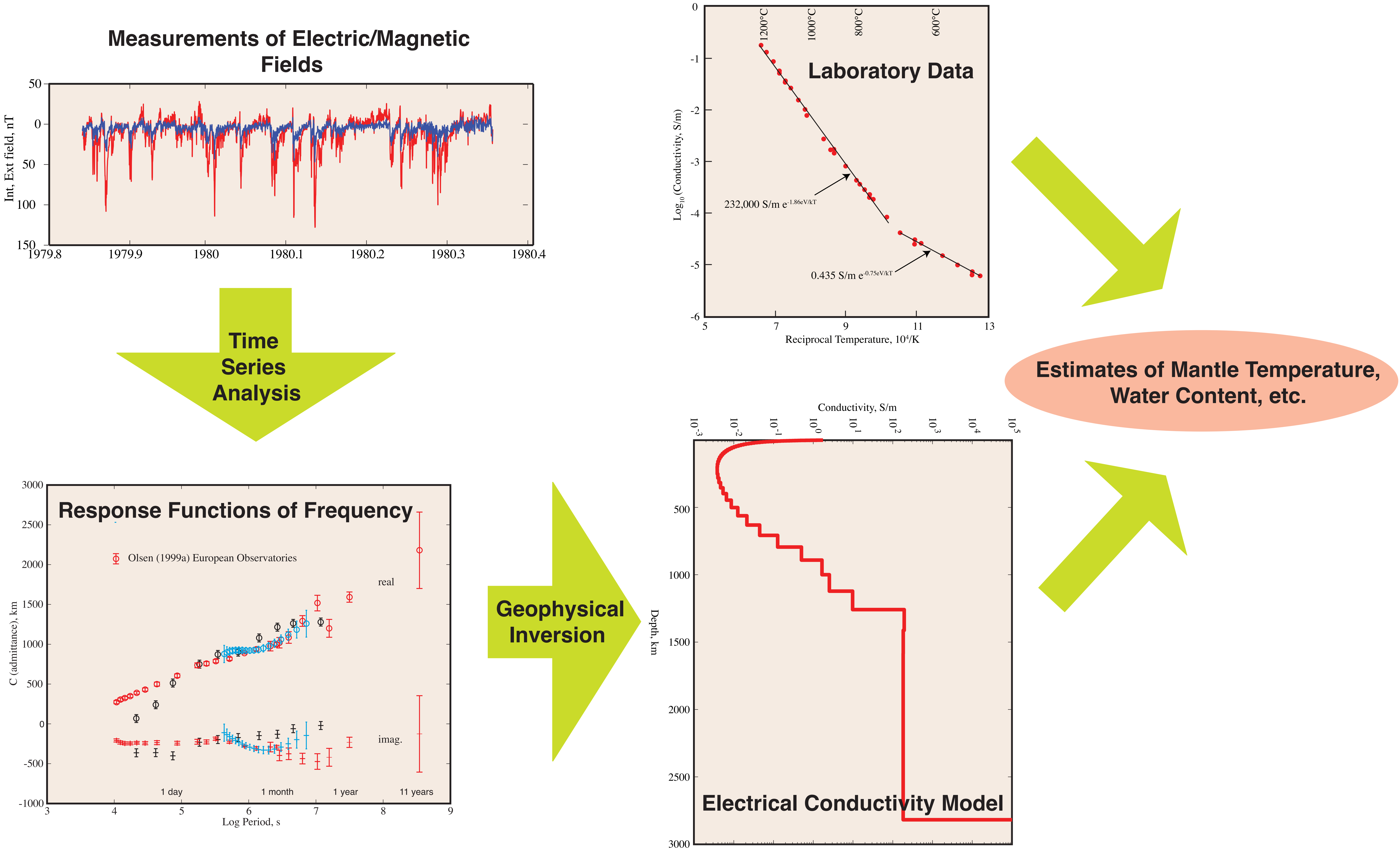
If you want to get useful mantle properties using EM, you need several skills:

Measurement

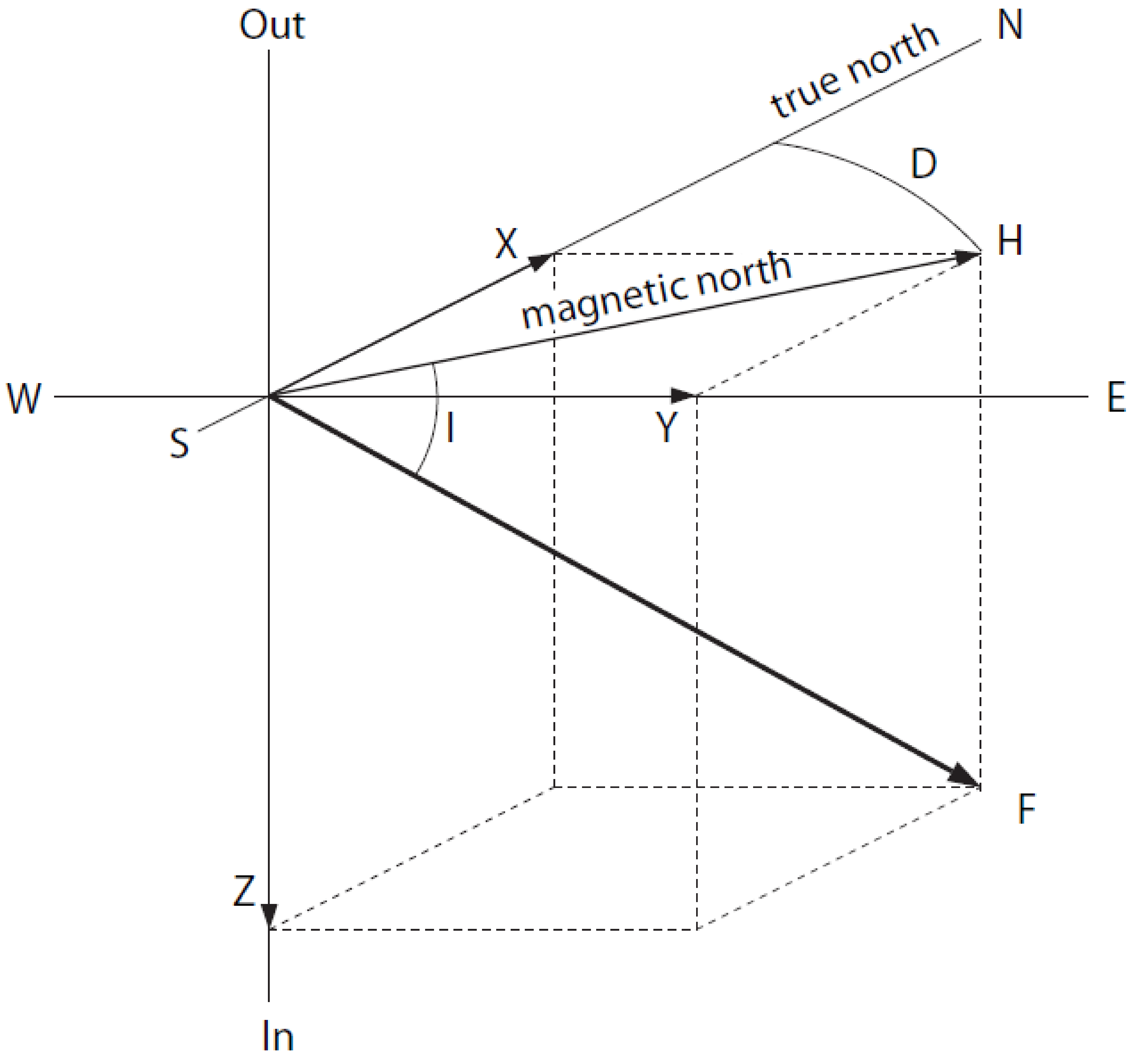
Data processing

Inverse theory

Laboratory studies



Components of the geomagnetic field

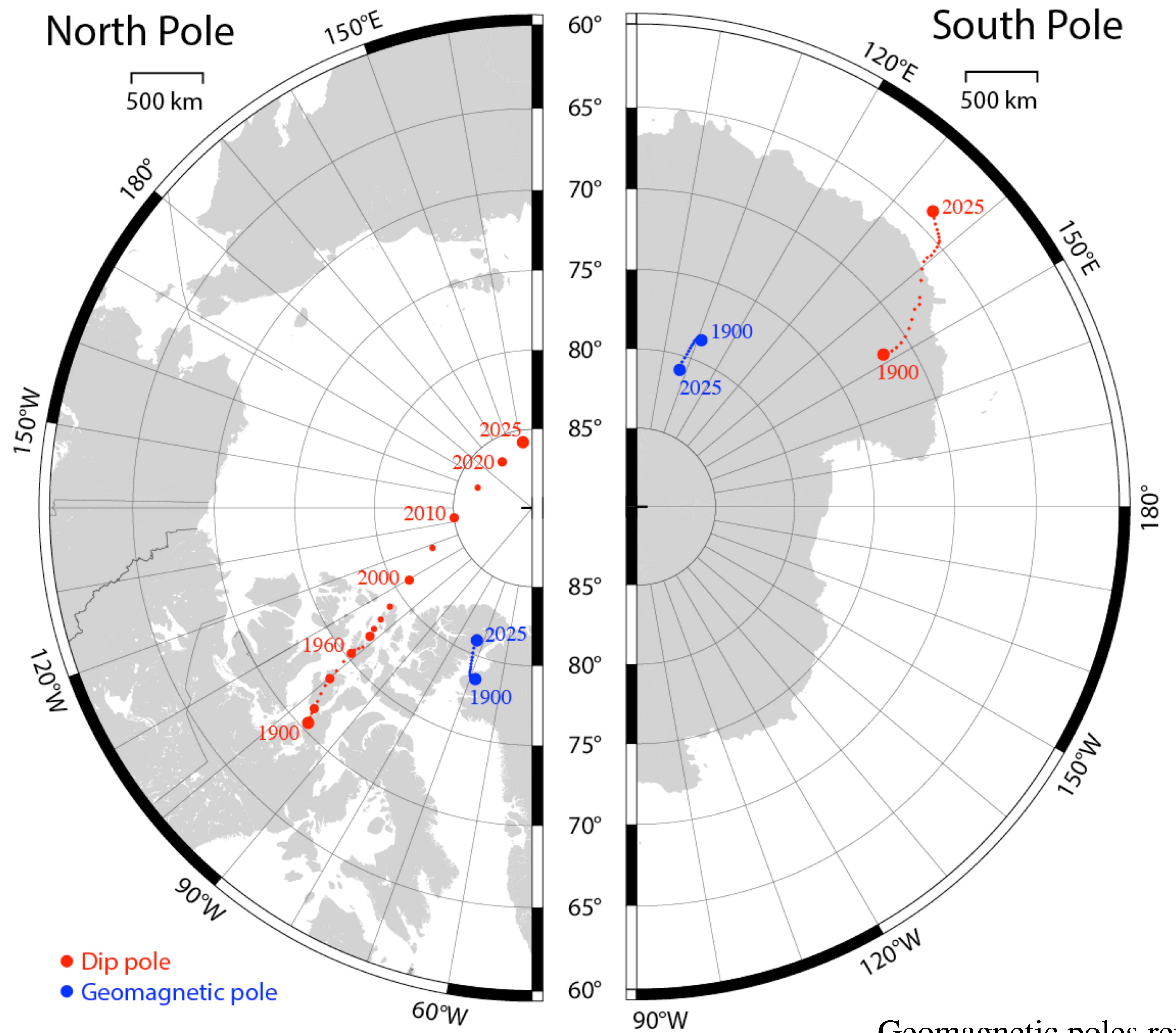


F (or B) - magnitude of total field **B**

X - north component
Y - east component
Z - vertical component, +ve down

D - declination, +ve east
H - horizontal component
I - inclination, +ve down

Where are the poles?



Geomagnetic poles represent the best-fitting dipole axis
Magnetic or dip poles are where the field directions are vertical

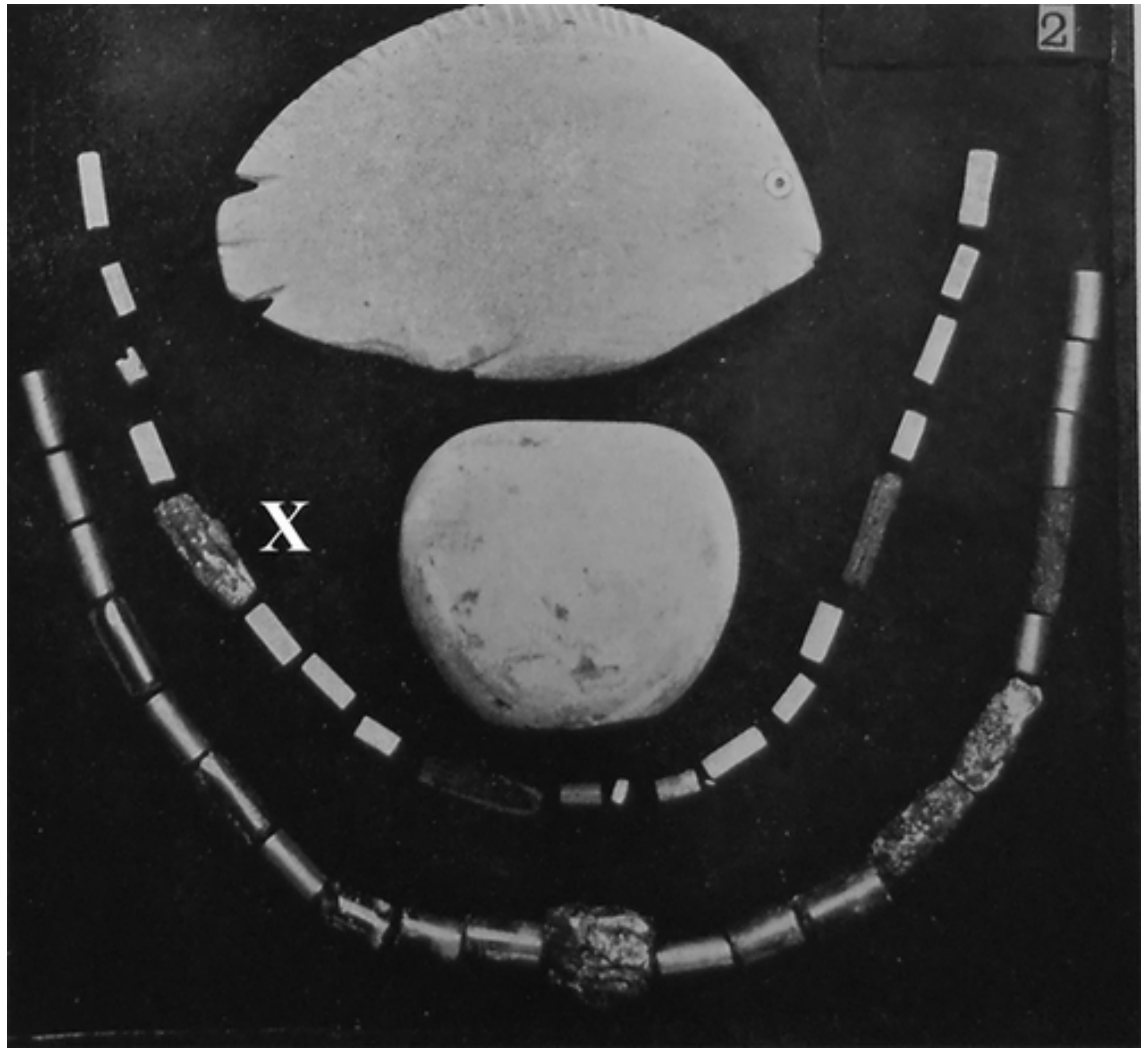
http://www.geomag.bgs.ac.uk/education/poles.html

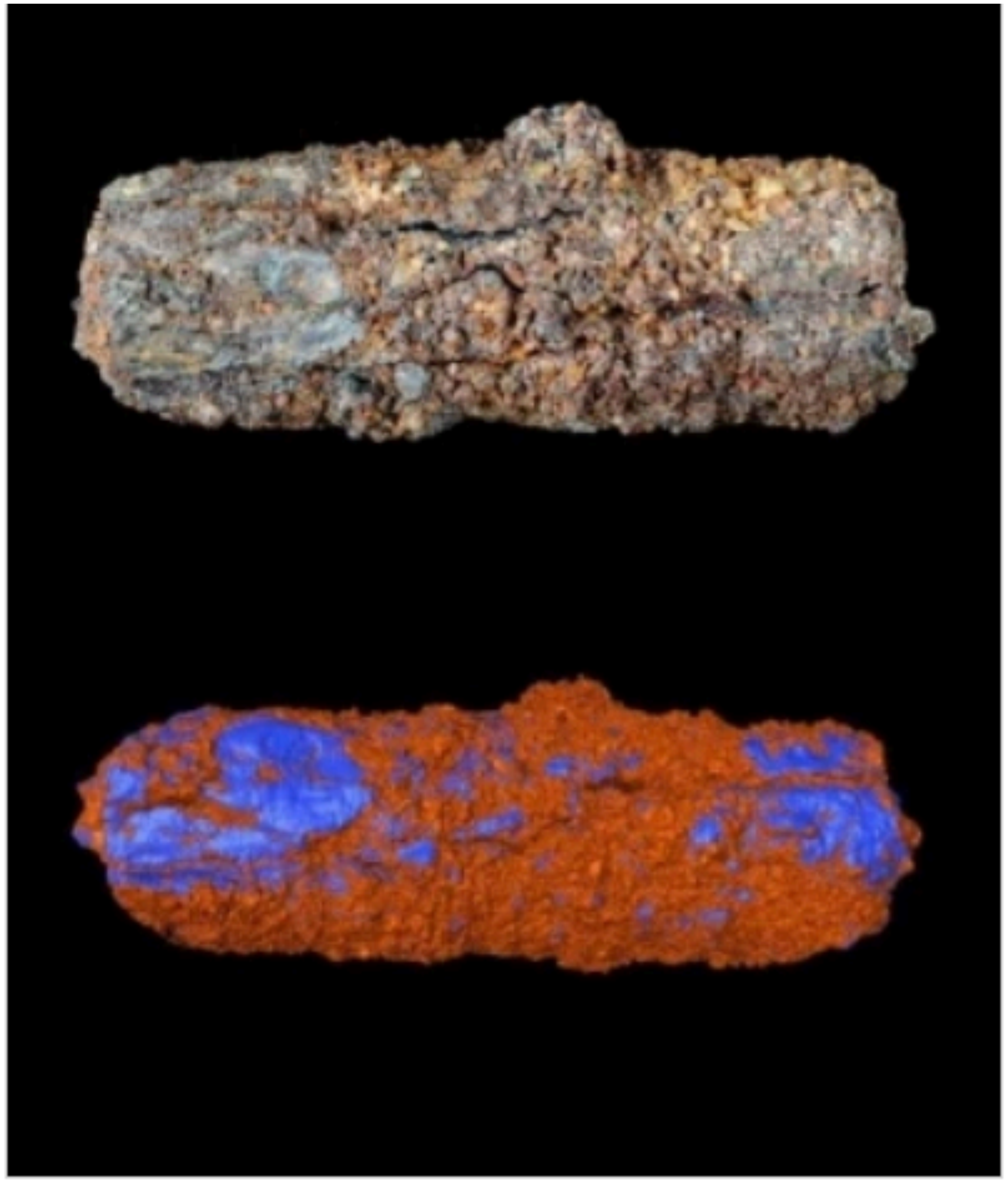
A little history…

DISCOVERY OF IRON: EGYPTIANS USING METEORITE IRON IN 3,000 BCE.

Analysis of a prehistoric Egyptian iron bead with implications for the use and perception of meteorite iron in ancient Egypt

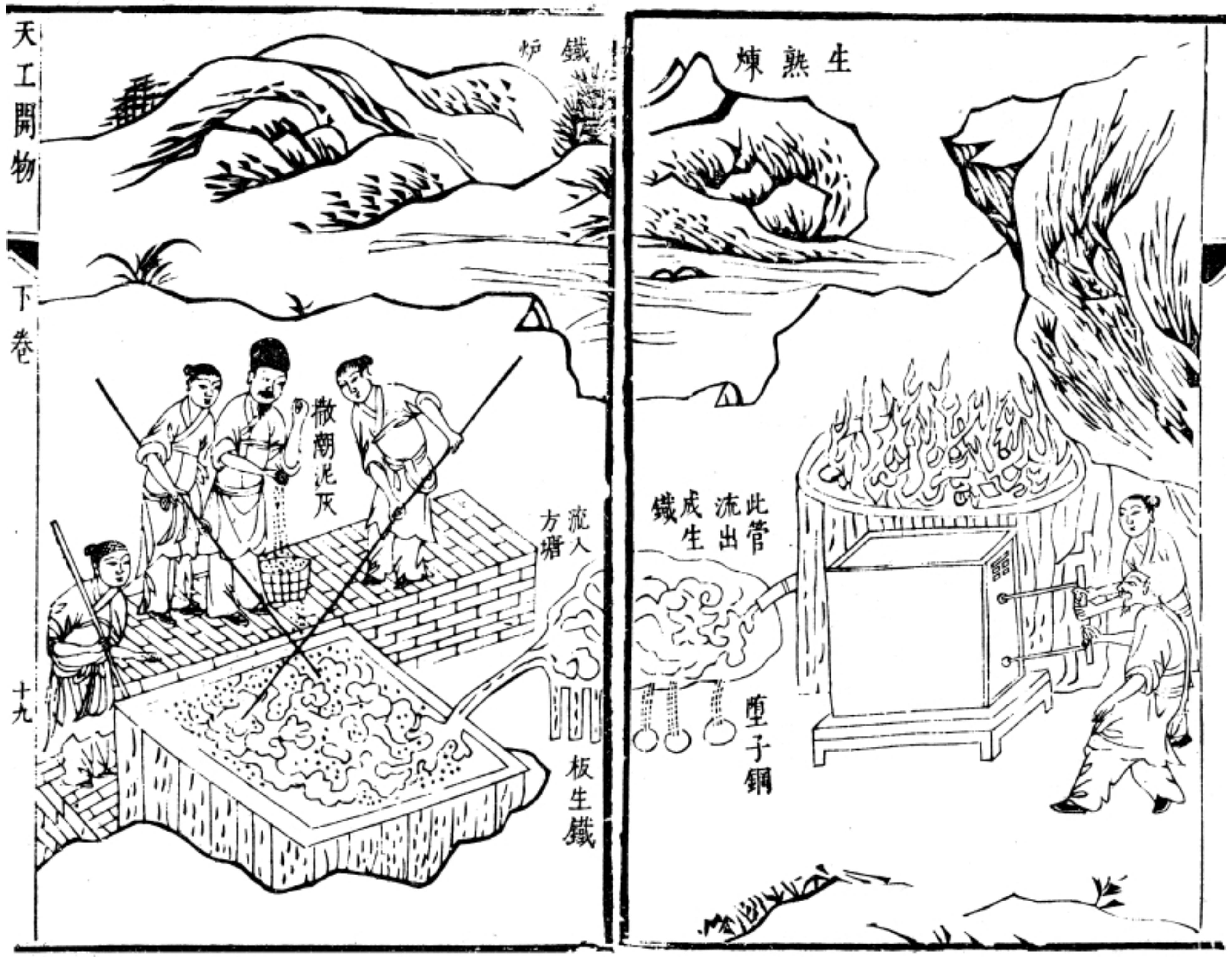
Diane Johnson, Joyce Tyldesley, Tristan Lowe, Philip J. Withers, Monica M. Grady

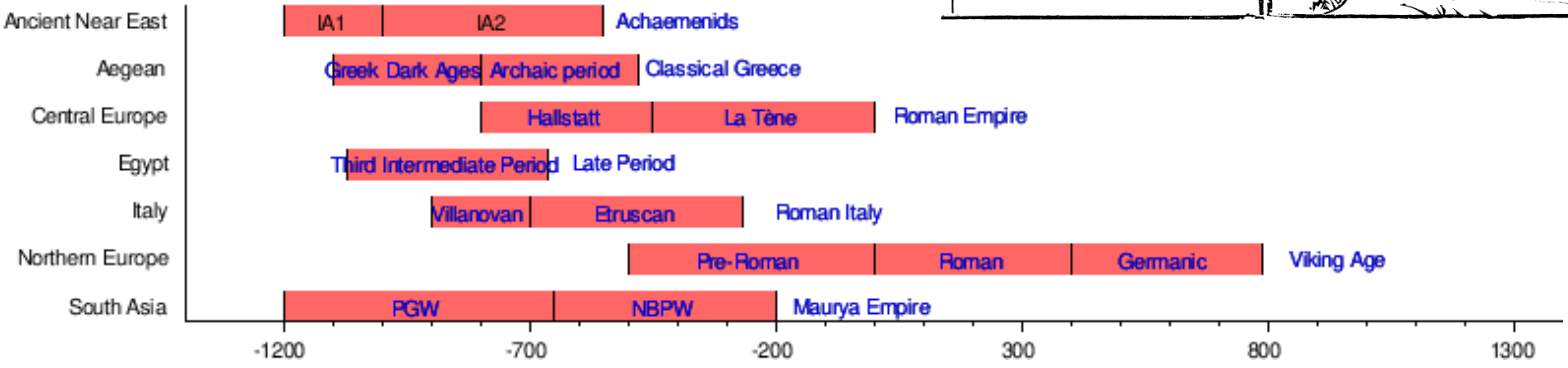




The Gerzeh bead (top) has nickel-rich areas, coloured blue on a virtual model (bottom), that indicate a meteoritic origin. Credit: Open Univ./Univ. Manchester

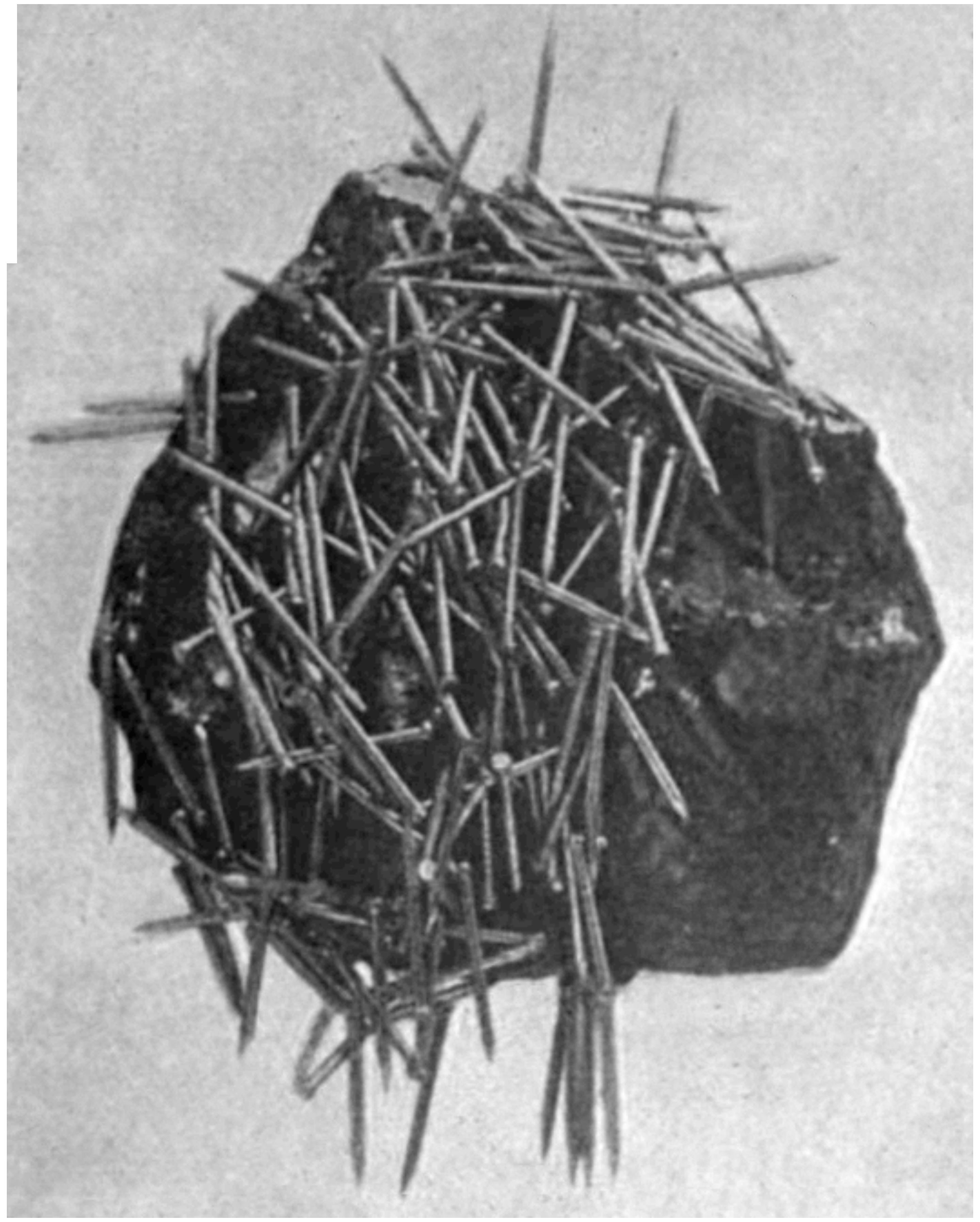
Discovery of iron: Smelting starts about the same time, but the Iron age only starts with the routine smelting of iron (before then iron was many times the value of gold).





Lodestone: Natures Only Permanent Magnet-What it is and how it gets charged

Peter Wasilewski, and Günther Kletetschka



Lodestone is naturally magnetized magnetite. Magnetite is mixed valence iron oxide $FeO.Fe_2O_3$. Lodestone has a high coercivity because of maghemite (Fe_2O_3). It is probably magnetized by lightning.

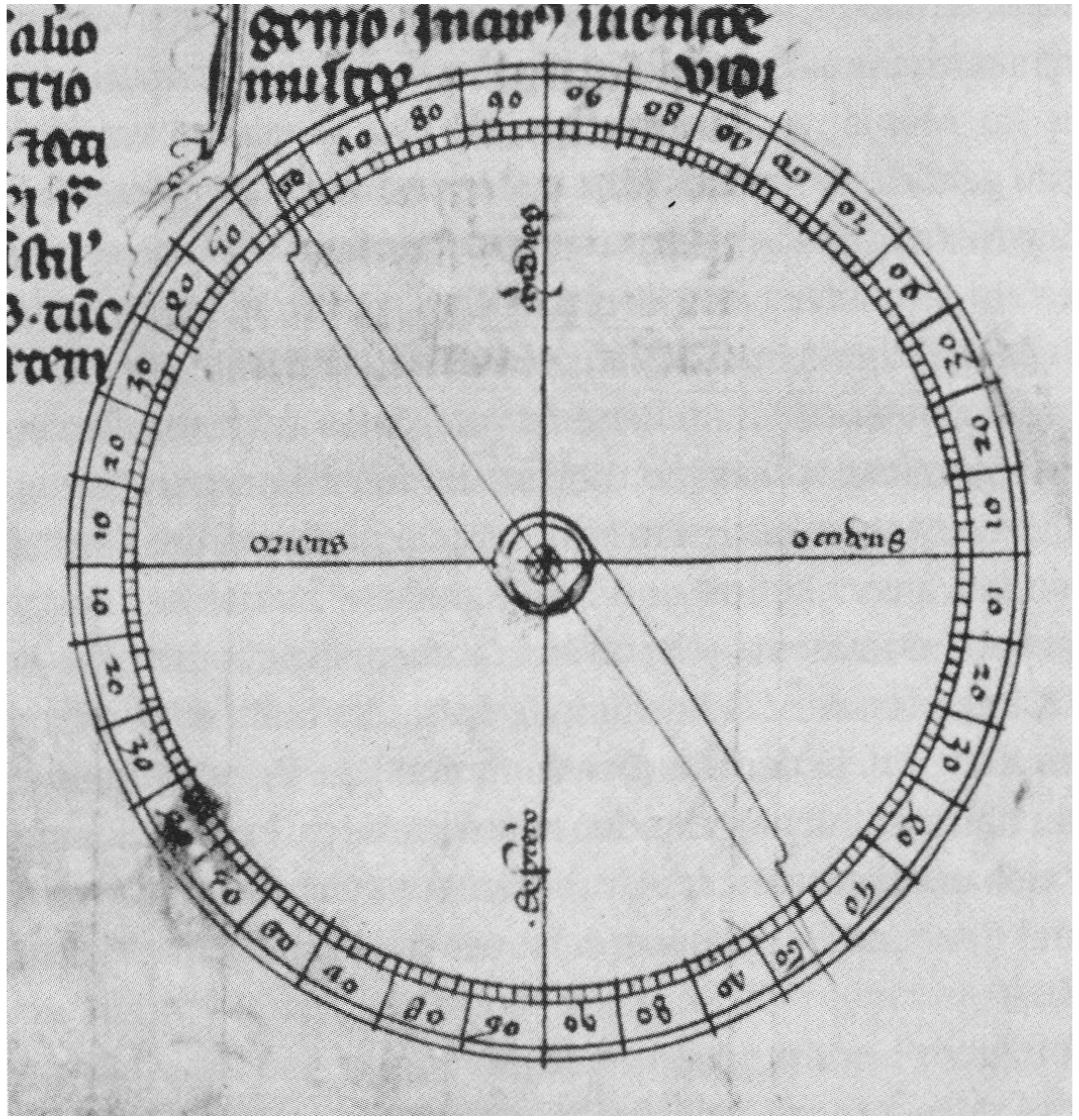
LODESTONE AND NAILS

Thales of Miletus (624—546 BCE) describes lodestone magnetism, and Pliny the Elder recounts the ancient Greek myth of Magnes the shepherd. Chinese texts from around this time mention lodestone, and by 200 BCE Chinese geomancers used lodestone for divination.

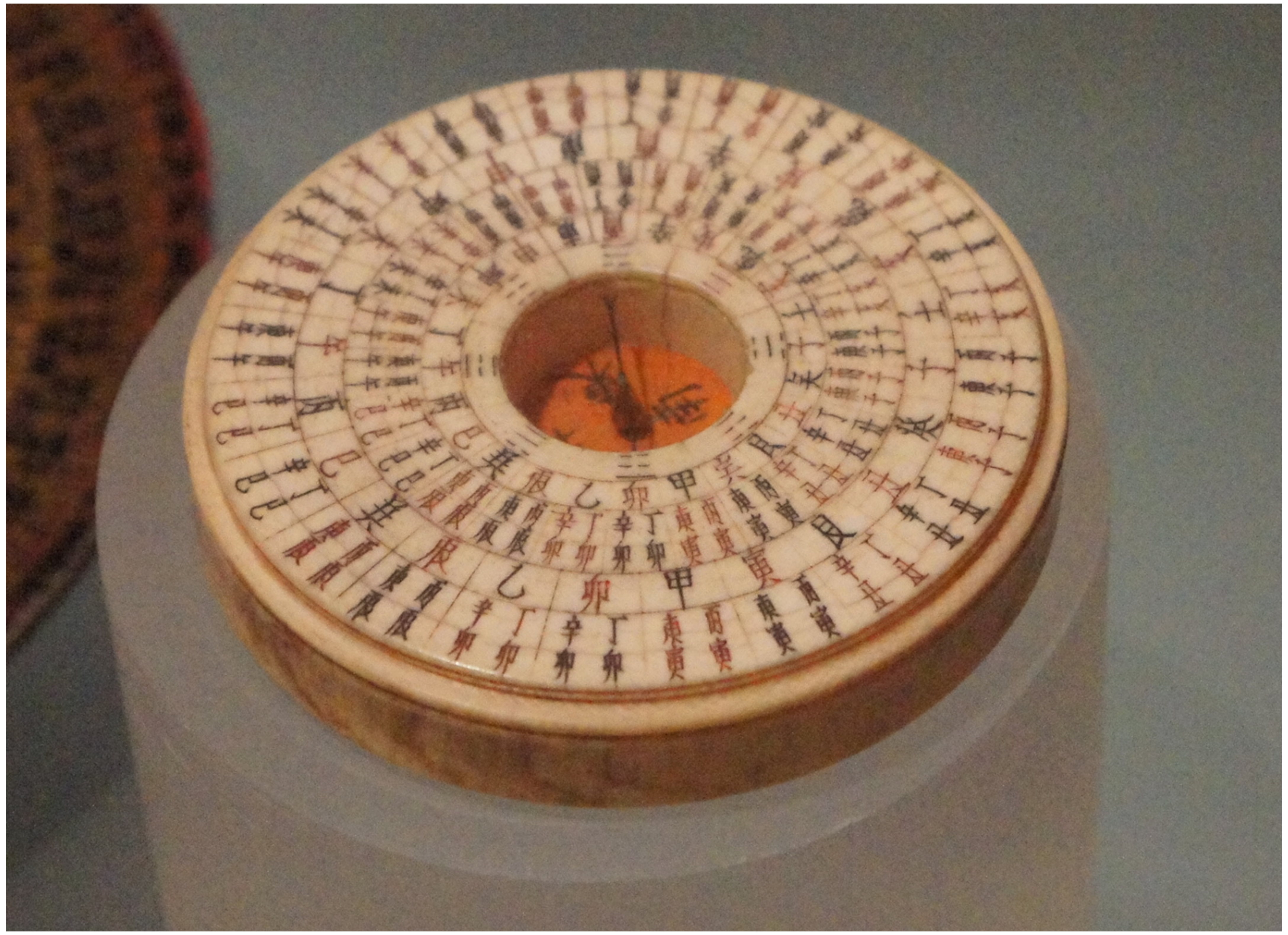
South pointing spoon

Magnes the shepherd

The compass for navigation: Started around 1100 CE, probably independently developed in Europe and China (points north in Europe, south in China).

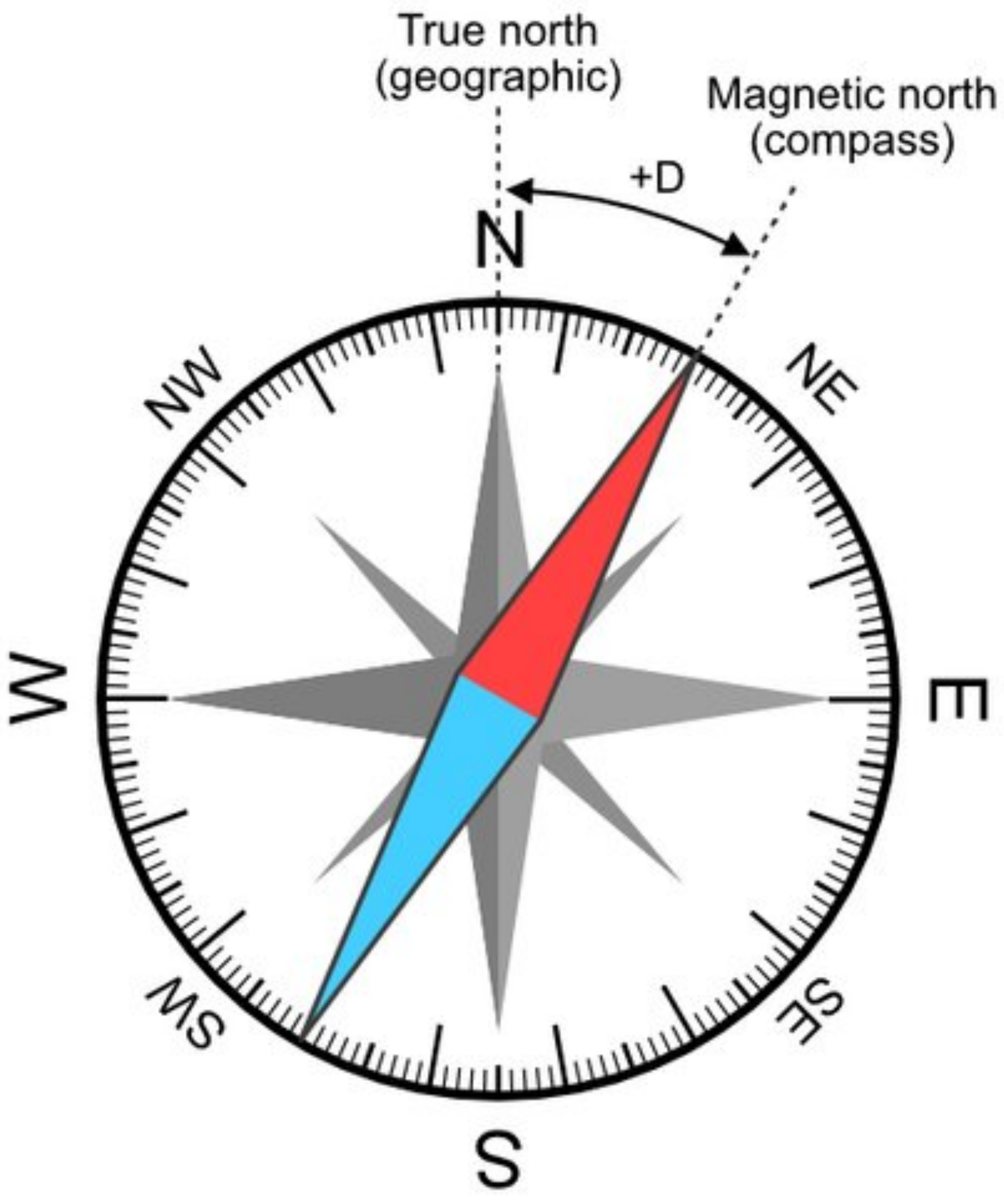


From 14th-C Perigrinus copy

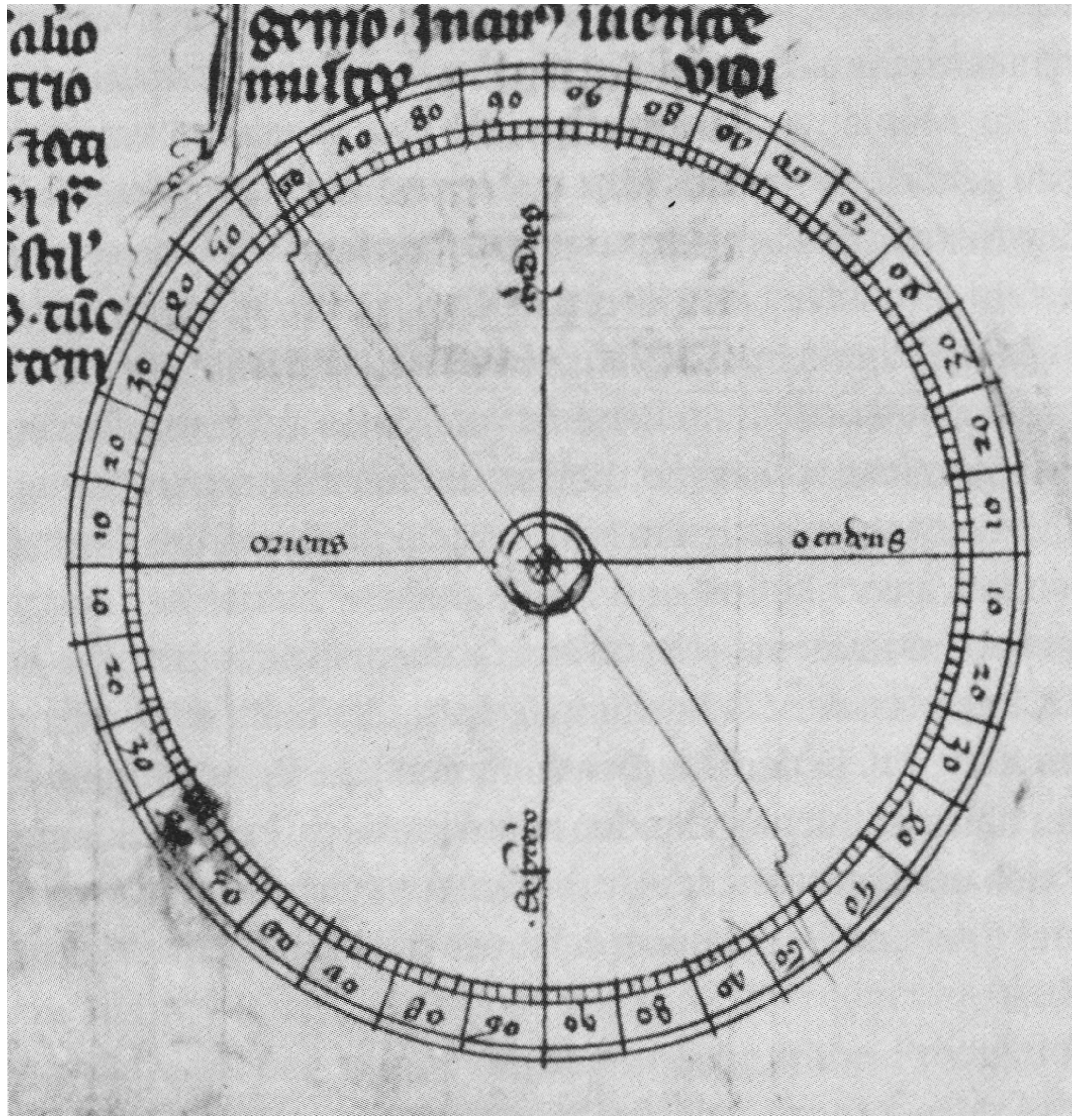


Chinese compass c. 1760

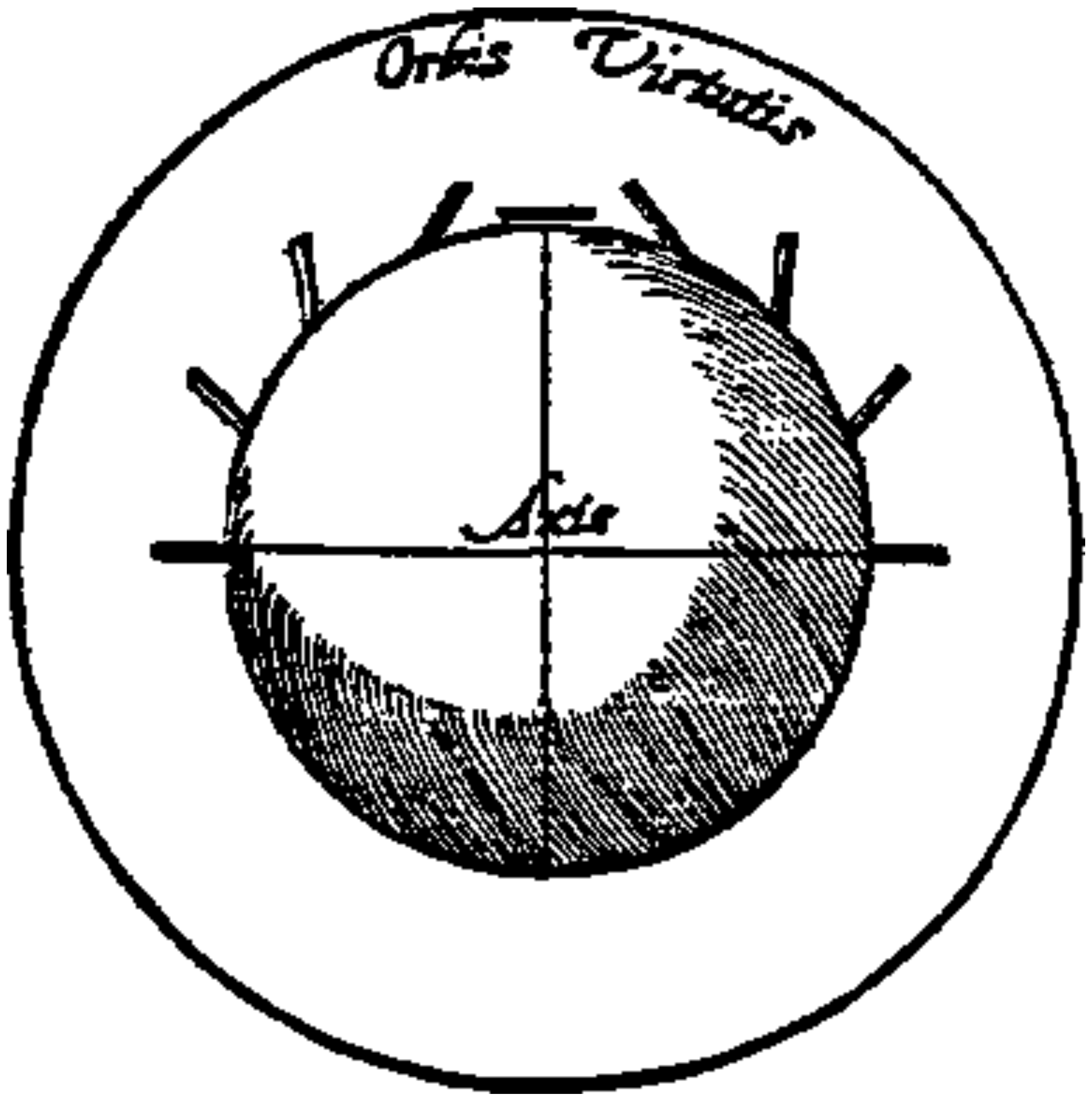
Declination: May have been known as early as 1088 (China) and 1266 (Europe), but first reliable evidence is Nuremberg sundials from Germany in 1450. **Georg Hartmann** measured a declination of 6°E in Rome and 10°E in Nuremberg in 1510.

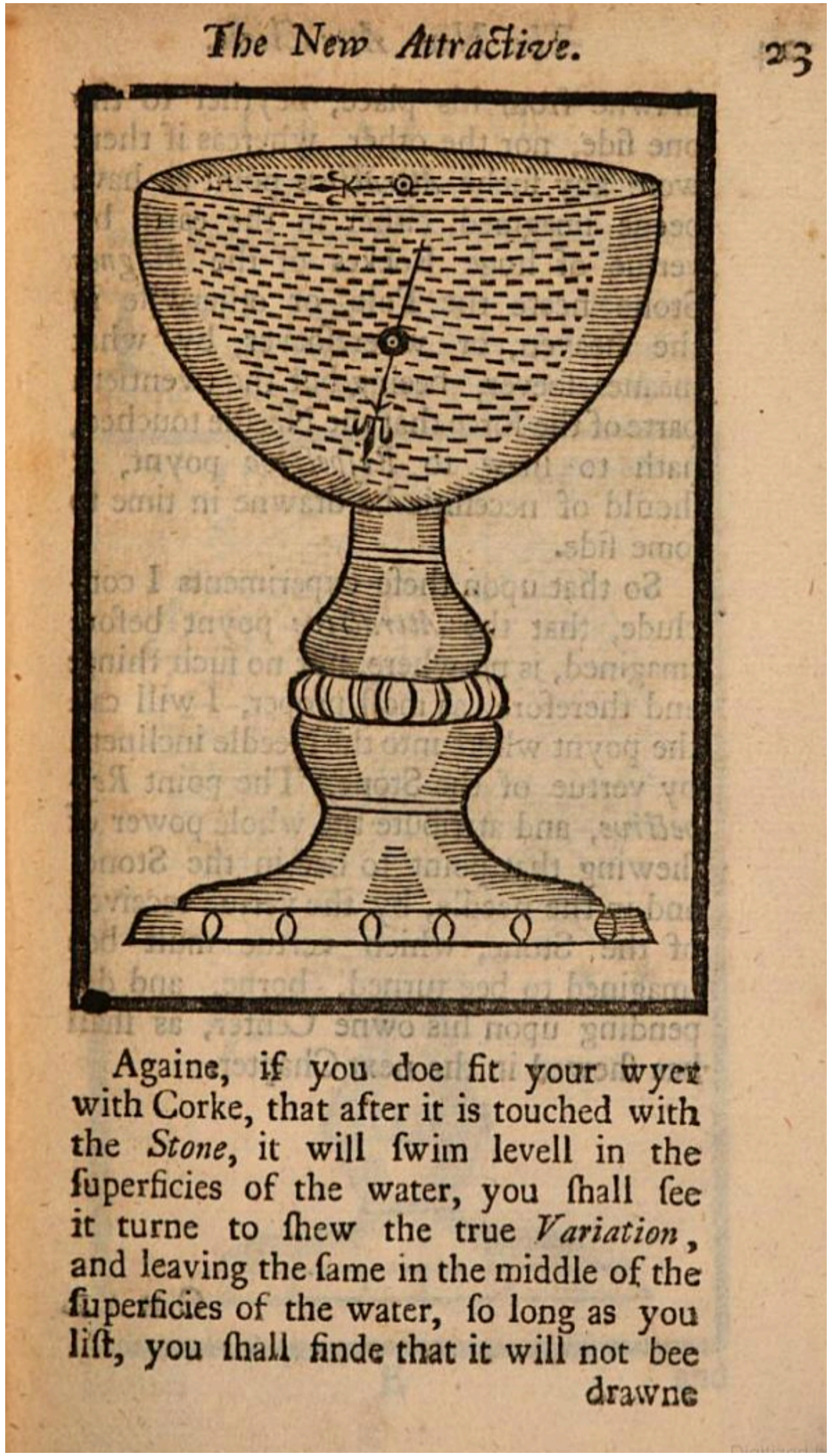


Petrus Peregrinus' *Epistola de magnete*: Describes poles, attraction and repulsion, terrellas, how to make compasses, and more.



Inclination: Hartmann noticed that his compass needle dipped, but **Robert Norman** made the first measurements, published in 1581. William Gilbert, in *De Magnete*, noted the similarity of inclination patterns on Earth and a terrella of loadstone, concluding Earth's magnetic field was internal in origin.





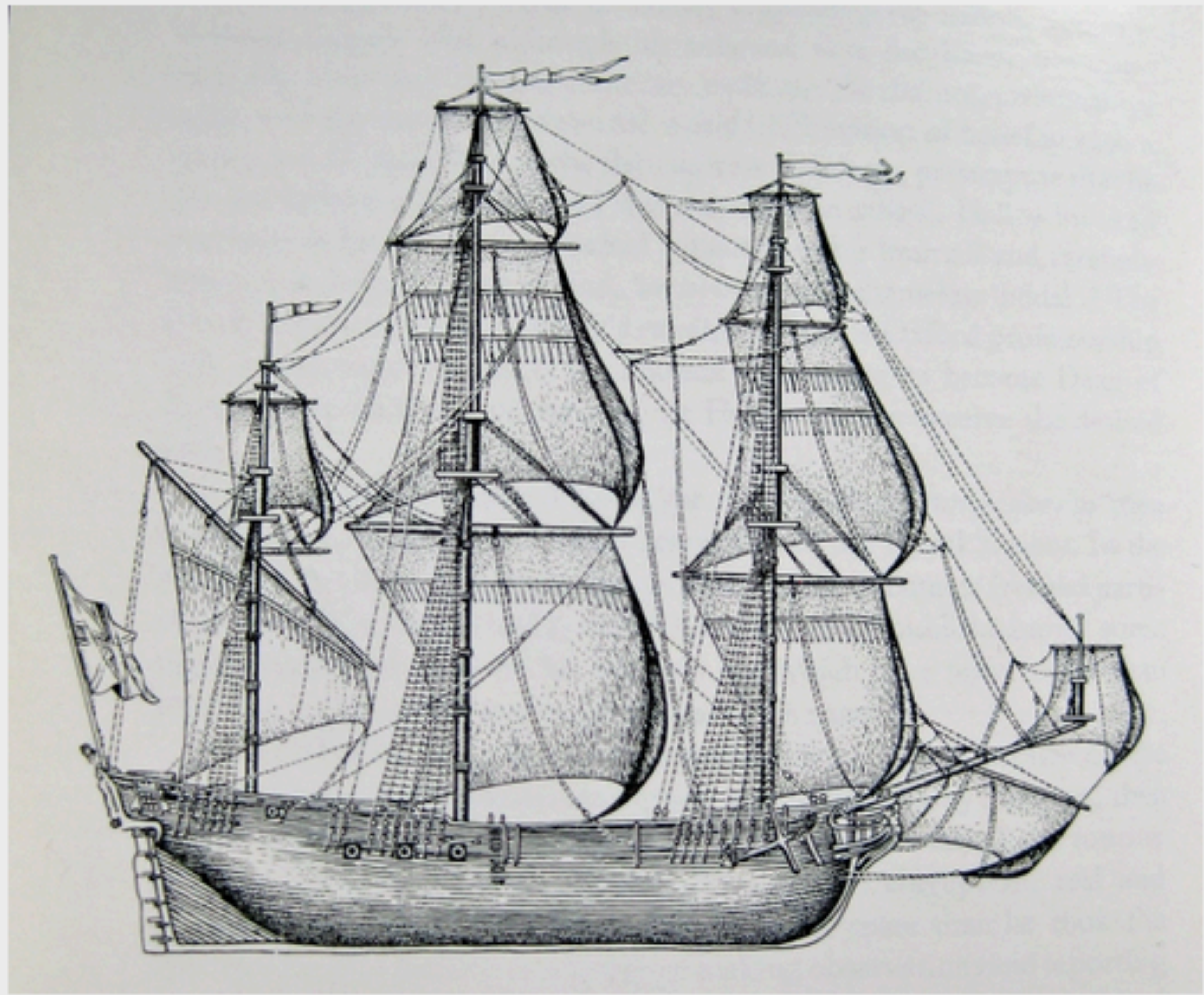
The New Attractive. 23

Againe, if you doe fit your wyer with Corke, that after it is touched with the *Stone*, it will ſwim levell in the ſuperficies of the water, you ſhall ſee it turne to ſhew the true *Variation*, and leaving the ſame in the middle of the ſuperficies of the water, ſo long as you liſt, you ſhall finde that it will not bee drawne

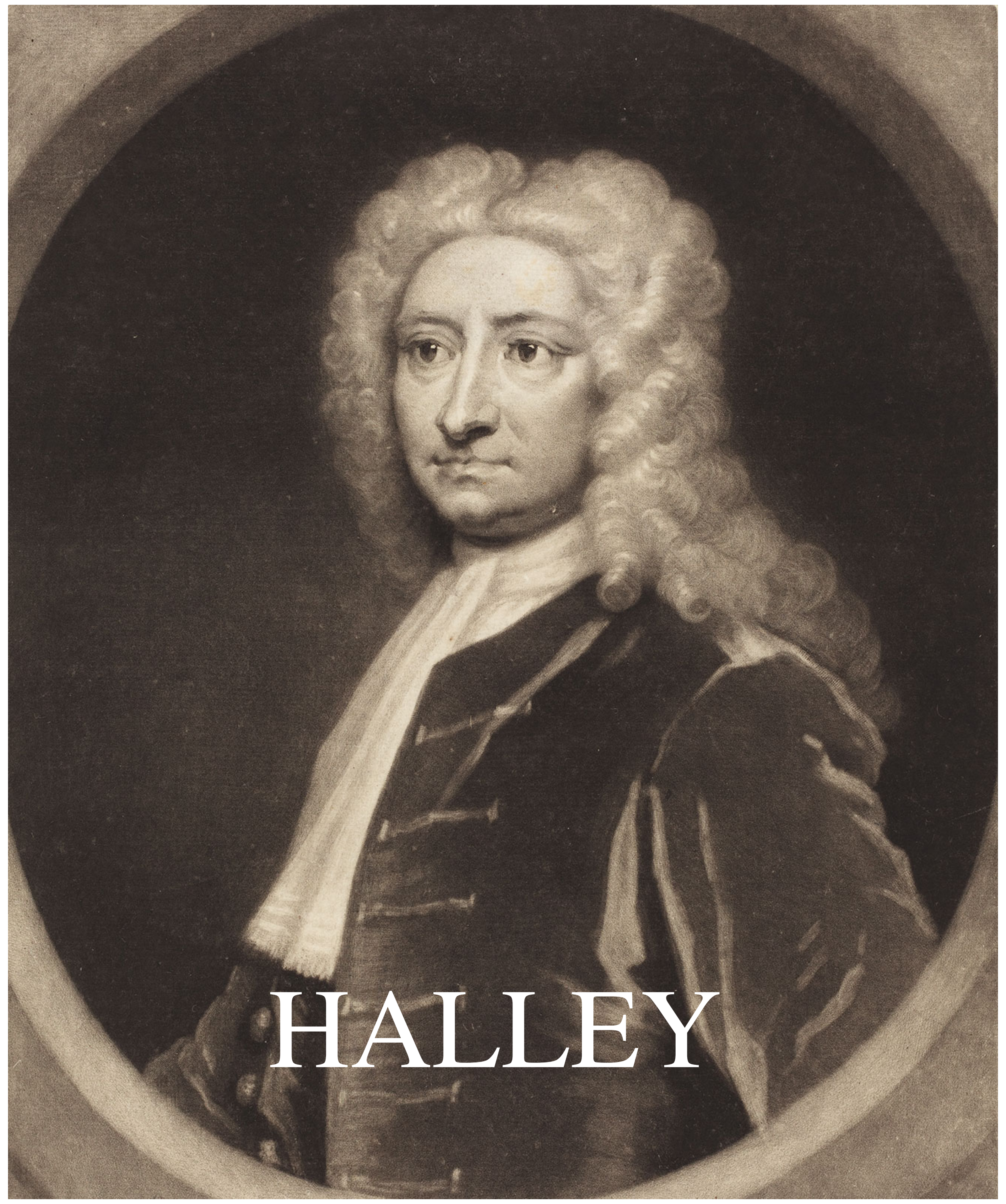
William Gilbert's *De Magnete* (1600) is considered one of the great works on magnetism. However, in Chapter II of Book II, Gilbert considers electric materials such as amber, and describes an electroscope for the first time, and is reported to be the first to use the term electric force. In fact, he was the first to use the term *electric*.

Henry Gellibrand observed in 1633 that declination changed with time in London.

Edmund Halley mapped declination across the Atlantic and produced this 1702 map, the first to use contour lines. He also knew that declination changed with time and tried to explain this.

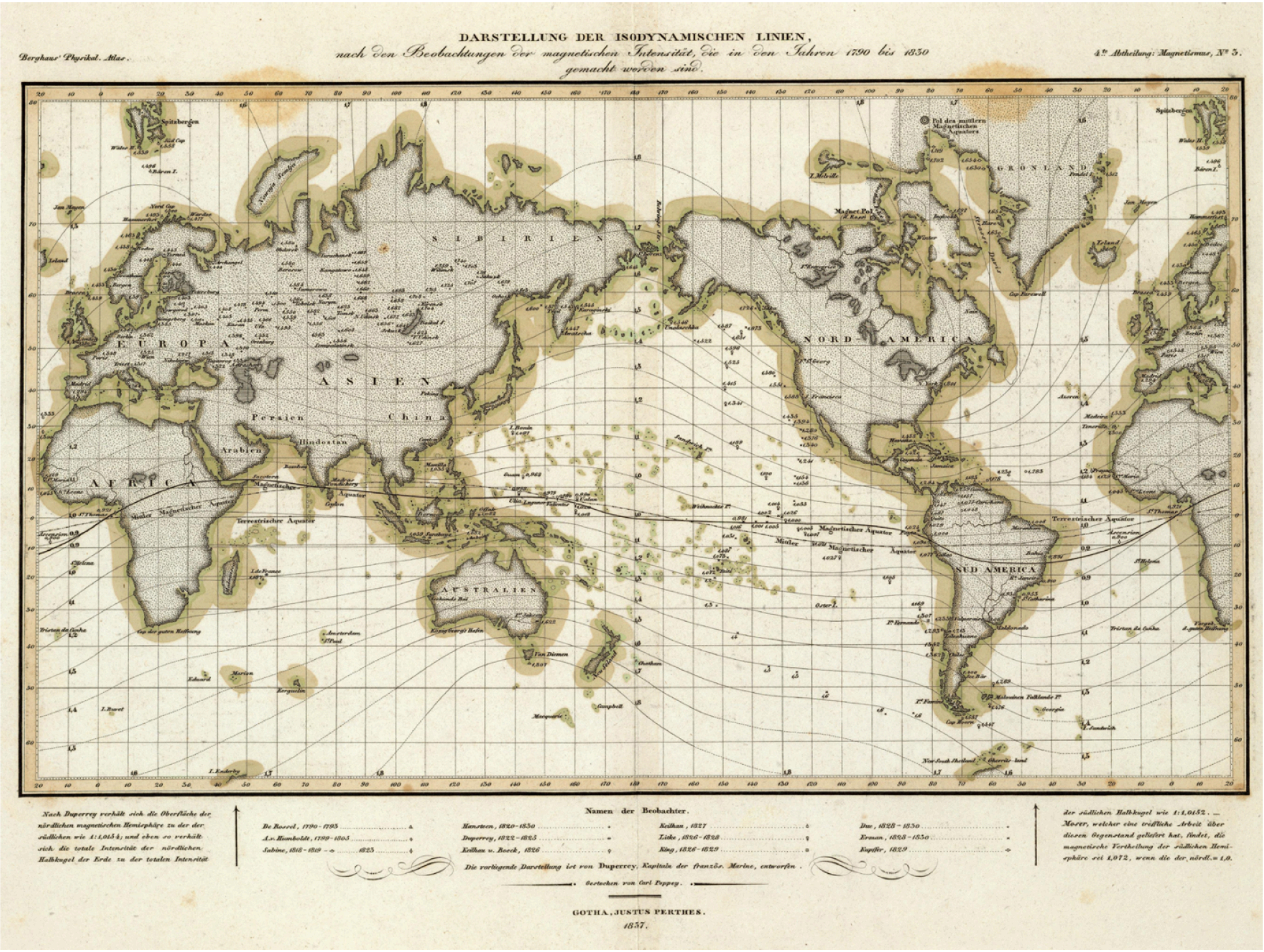


Drawing reconstructing HMS *Paramore* from sources (© Hakluyt Society (£), from Thrower, *The Three Voyages of Edmond Halley*)



Alexander von Humboldt

made measurements of relative field intensity using an oscillating dip needle. He noted the decrease as one moved away from the magnetic equator. He made what he called an “isodynamic” map.



Carl Frederich Gauss (1777—1855) made important contributions to geomagnetism. He extended the oscillating dip needle method to measure absolute fields. He introduced his flux theorem. Importantly he showed how internal and external magnetic fields could be separated using spherical harmonics, and noted that Earth's main field was internal. He helped found the global observatory network.

THE PHYSICS TIMELINE:

1785: **Charles-Augustin de Coulomb** developed a torsion electrometer and used this to develop the inverse-square law that bears his name.

1799: **Alessandro Volta** invents the battery (“Voltaic pile”).

1813: **Gauss** generalizes Coulomb’s Law using his flux theorem

1820: **Hans Oersted** observed that electric currents deflect magnets.

1820’s: **Andre-Marie Ampere** quantified Oersted’s observations and noted that a wire carrying a current exerted a force on a second current-carrying wire. He noted that a coil behaved like a magnetic dipole with a dipole moment of the area times the current.

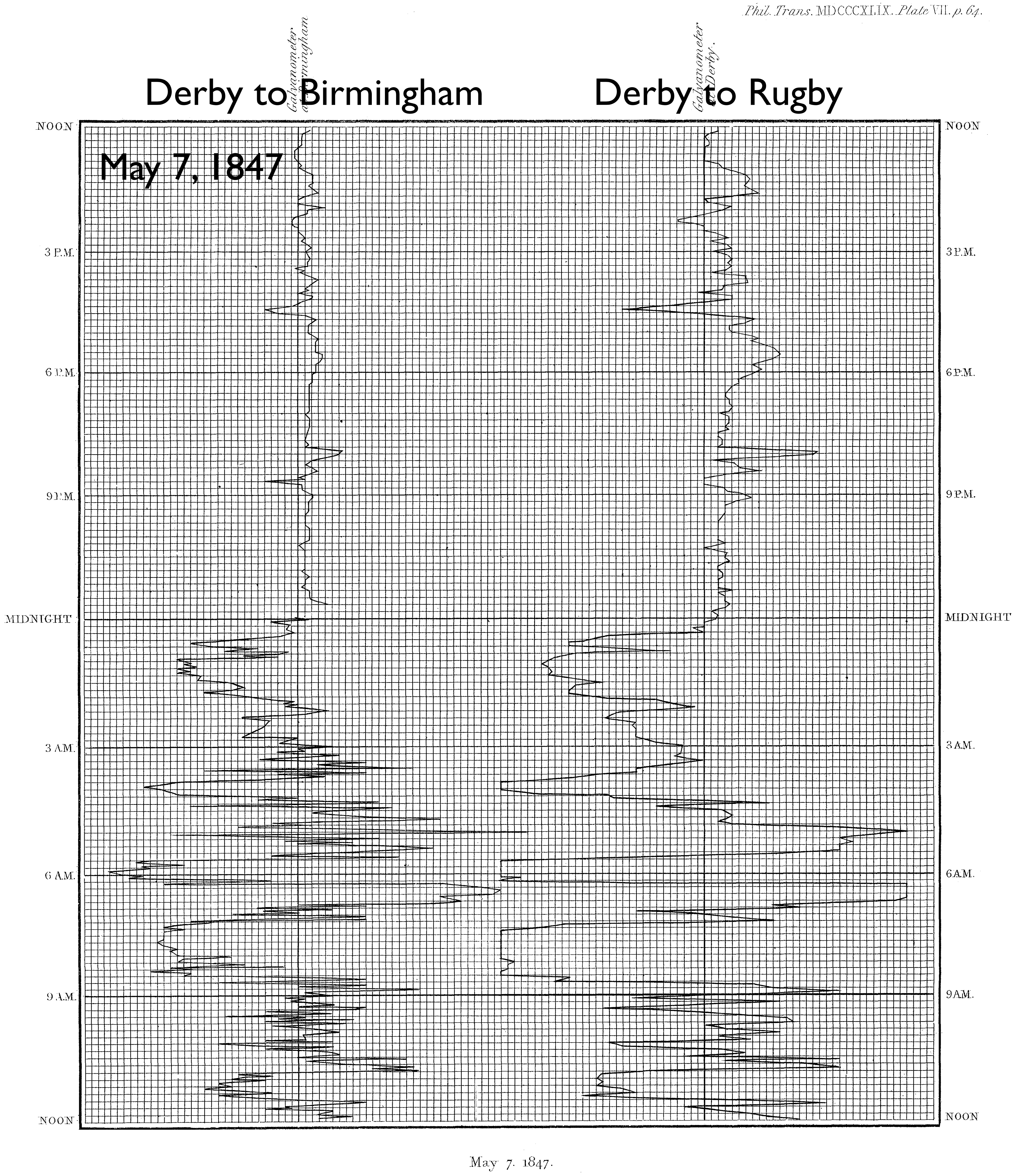
1831: **Michael Faraday** makes current from moving a magnet. In 1832 he predicted that water moving through Earth’s magnetic field would produce an electric field, more than 80 years before this effect was first observed by the British Admiralty in 1918.

1864: **James Clerk Maxwell** recognized Ampere’s and Faraday’s Laws are both aspects of electromagnetic radiation.

1884: **Oliver Heaviside** formulates Maxwell’ equations in the differential form as we now know them.

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_o}$$

$$\nabla \times \mathbf{B} = \mu_o\left(\mathbf{J} + \epsilon_o \frac{\partial \mathbf{E}}{\partial t}\right) \qquad \nabla \cdot \mathbf{B} = 0$$



Barlow, 1849, currents in UK telegraph cables.

The Geophysics timeline:

1838: A large magnetic storm was observed as potentials on Norwegian telegraph cables.

1859: K.T. Clement noted that the aurora of 29 August disrupted telegraphy - preceding the Carrington event, most intense storm ever recorded

1865: Greenwich Observatory starts observing Earth potentials on 15 km grounded lines.

1889: Arthur Schuster noted the relationship between magnetic field variations and earth potentials.

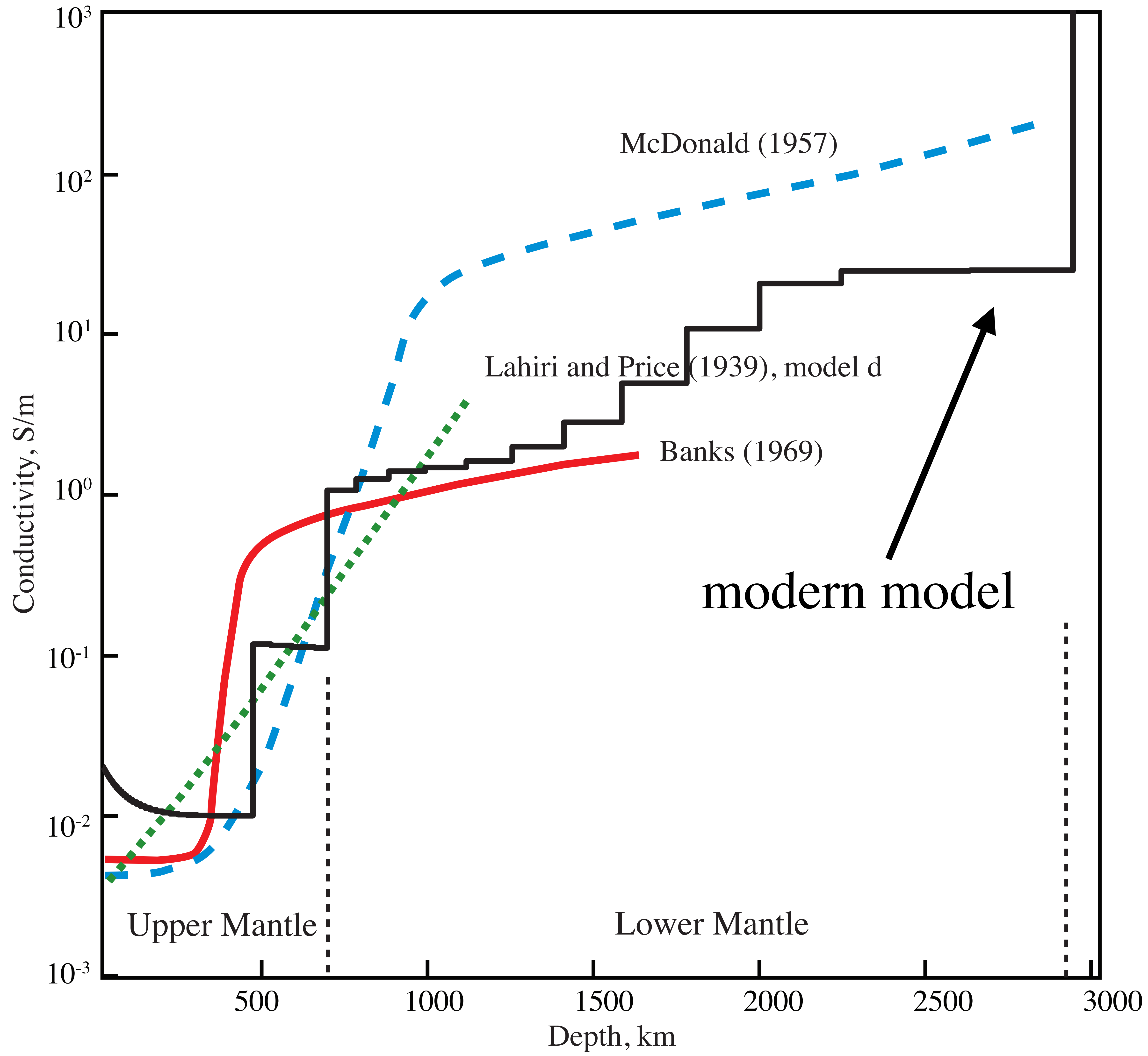
1919: Sydney Chapman models the daily variation a conductive sphere inside Earth.

1939: Lahiri and Price model conductivity to 1,000 km using Gauss internal/external separation.

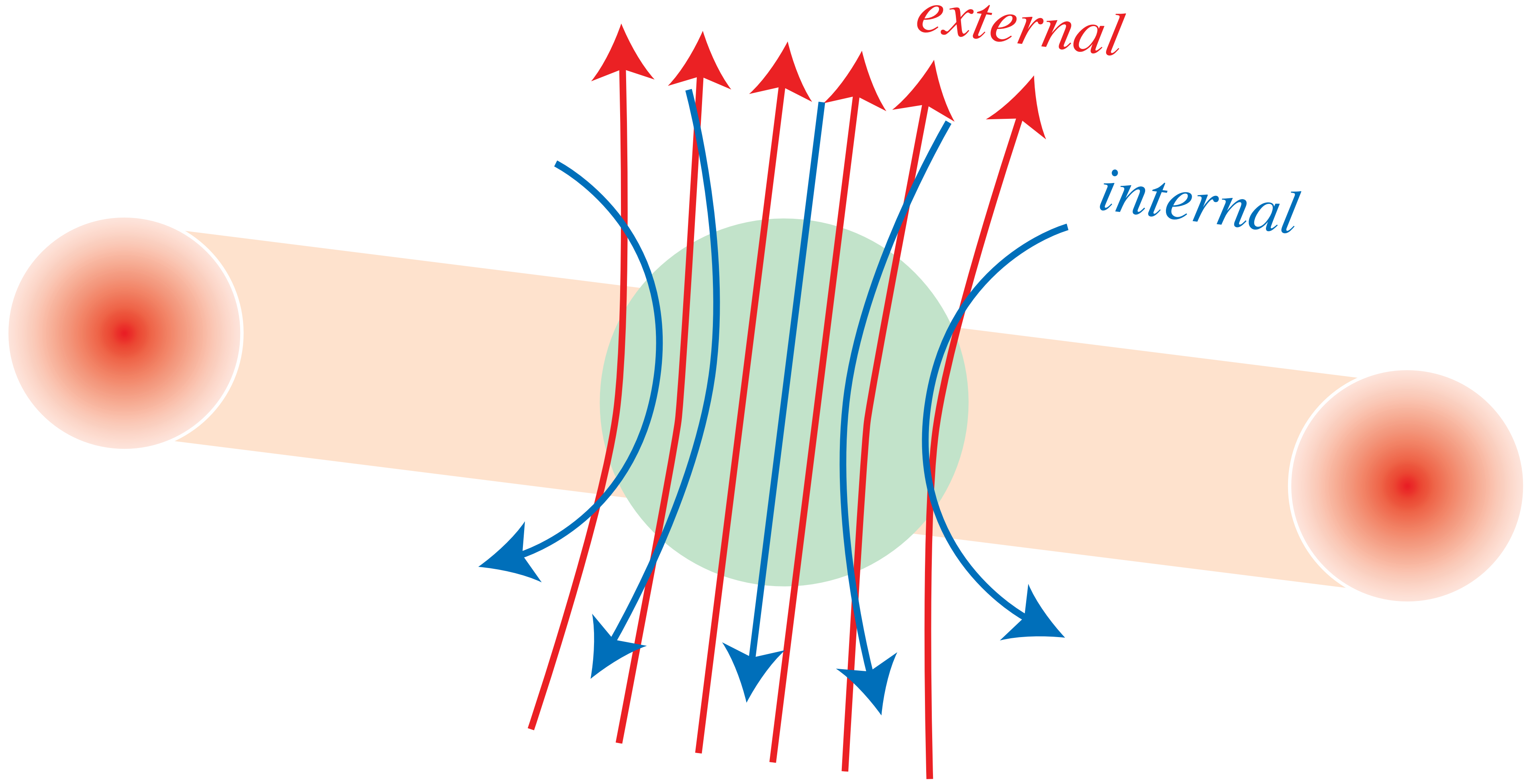
1957: K.L. McDonald modeled lower mantle conductivity based on outward propagation of secular variation.

1969: Roger Banks shows that harmonics of the 27 day variation were P^0_1 geometry and modeled conductivity to 2,000 km.

Geomagnetic Depth Sounding (GDS):



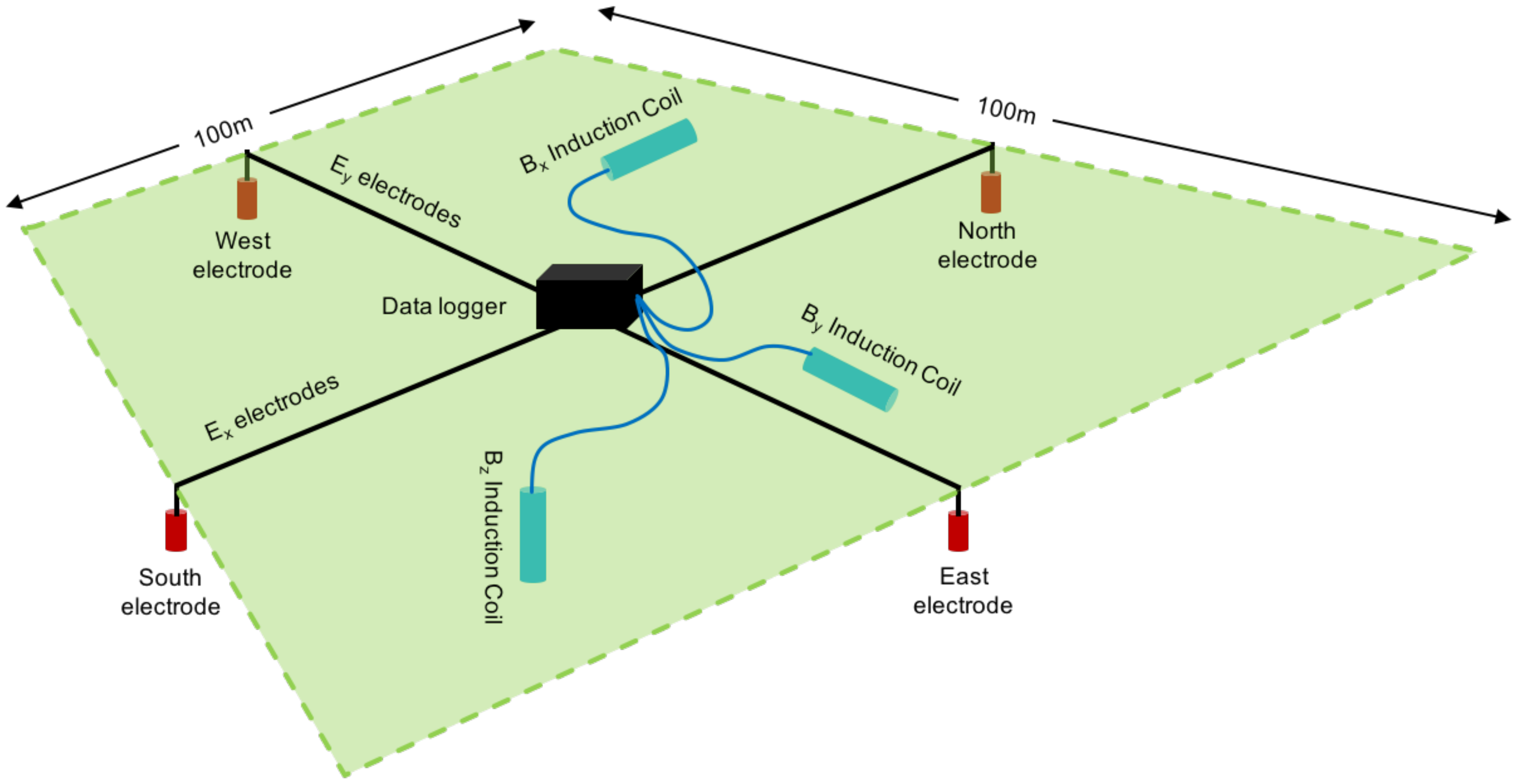
These early models (and current ones, using satellites as well as observatories) using the internal/external separation only require magnetic field measurements, but are of limited use in the shallow parts of the crust and mantle.



The magnetotelluric (MT) Method

1950: A.N. Tikhonov, T. Rikitake, Y. Kato, and T. Kikuchi developed mathematical descriptions for the relationship between induced electric and magnetic fields.

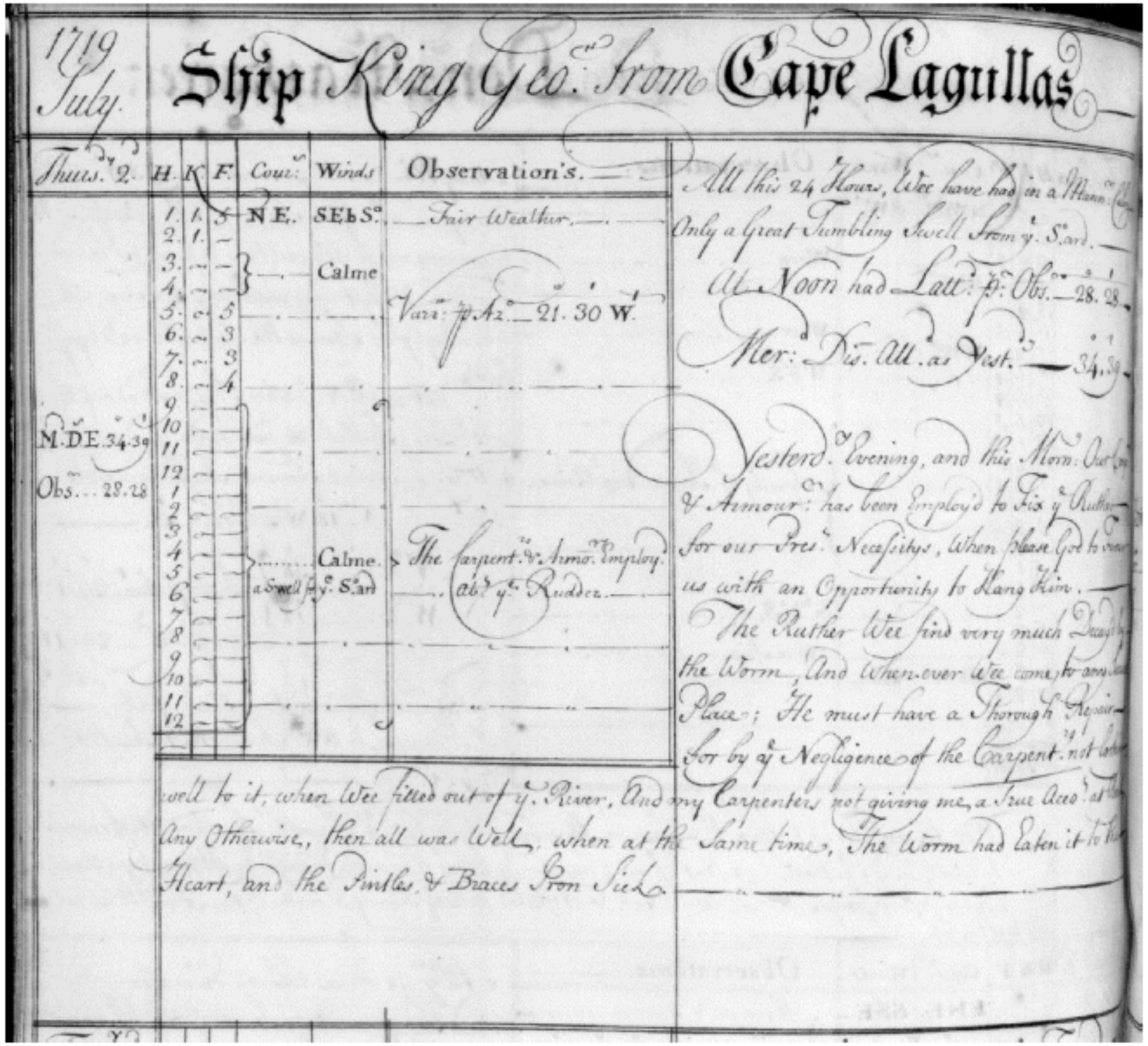
1953: Louis Cagniard described a practical method to use measurements of magnetic and electric fields to estimate Earth conductivity, and called it the magnetotelluric method.



Geomagnetic Data Types

Historical Field Data - Numerous Direct Observations were made on long voyages and recorded in the ships' logs.

Reconstruction of Cook's ship Endeavour



1719 July. Ship King Geo: from Cape Lagullas

Thurs. 2.	H	K	F	Cour:	Winds	Observation's.
	1	1	5	N E.	SEbS°.	Fair Weather.
	2	1	–			
	3	–	–		Calme	
	4	–	–			
	5	–	5			Vari: p Az. 21. 30 W.
	6	–	3			
	7	–	3			
	8	–	4			
	9					
M.DE. 34.39	10					
Obs... 28.28	11					
	12					
	1 – 12			a Swell from y S°ard	Calme.	The Carpent. & Armo. Imploy. ab y Rudder.

All this 24 Hours, Wee have had in a Mann. [illegible] Only a Great Tumbling Swell from y S°ard. At Noon had Latt: p: Obs. 28. 28. Mer: Dis. All. as Yest. 34.39

Yesterd. Evening, and this Morn: Our [illegible] & Armour: has been Imploy'd to Fix y Rudder for our Pres. Necessitys, When please God to send us with an Opportunity to Hang Him. The Rutter Wee find very much Decay'd by the Worm, And When ever Wee come to any [illegible] Place; He must have a Thorough Repair. For by y Negligence of the Carpent. not looking well to it, when Wee fitted out of y River, And my Carpenters not giving me a True Acco. at Any Otherwise, then all was Well, when at the Same time, The Worm had Eaten it to the Heart, and the Pintles & Braces Iron Sick.

Figure 6. Excerpt from the log of the *King George* on 2 July 1719. Note the azimuth observation of magnetic declination around five o'clock in the afternoon and the recording of meridian distance rather than longitude. By permission of The British Library (source: IOBL L/MAR/B 402 B).

Jonkers et al., 2003

Spatial Coverage - early historical data, before 1590, and 1590-1699

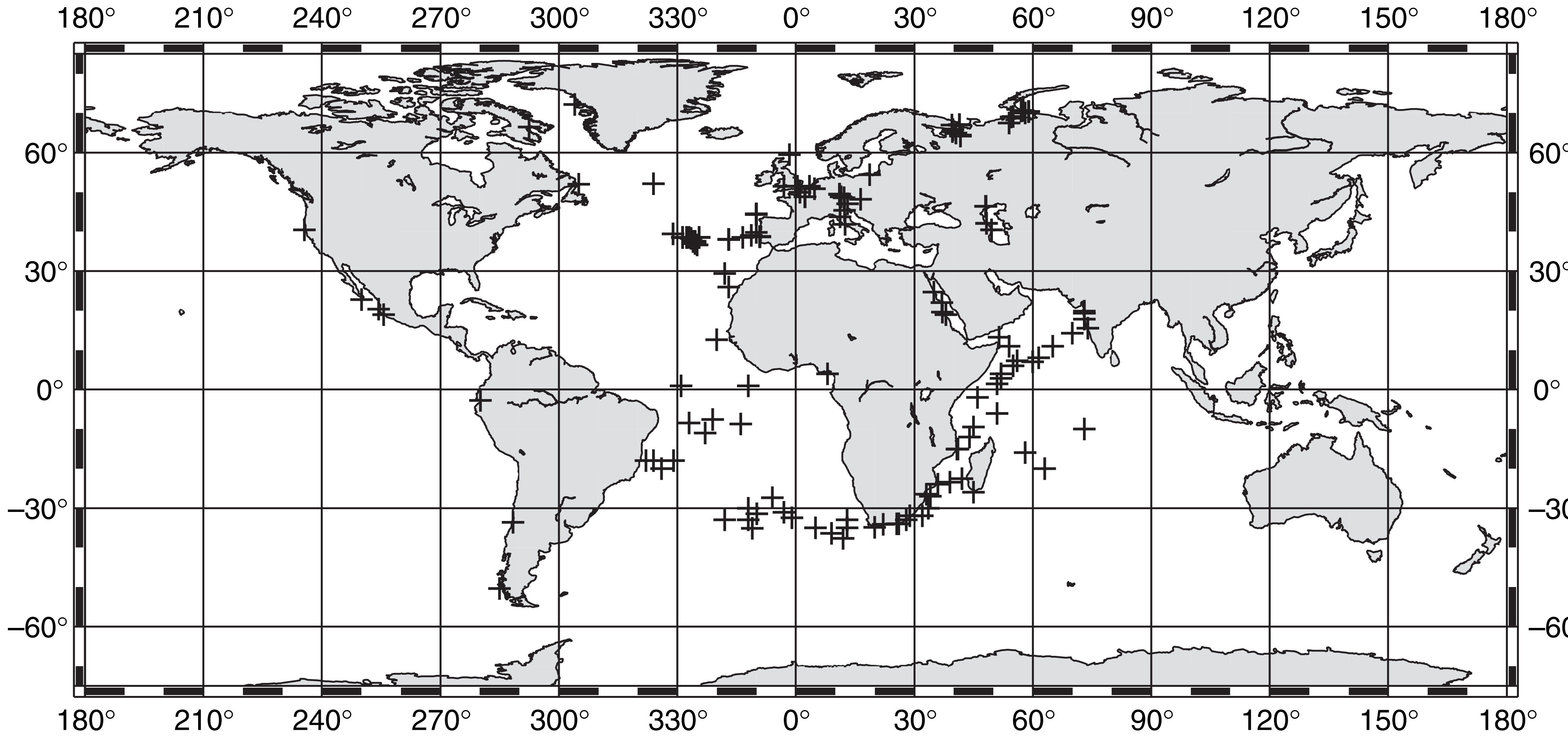


Figure 2 Geographical data distribution of declination observations made before 1590; $n = 160$; some points may overlap; cylindrical equidistant projection.

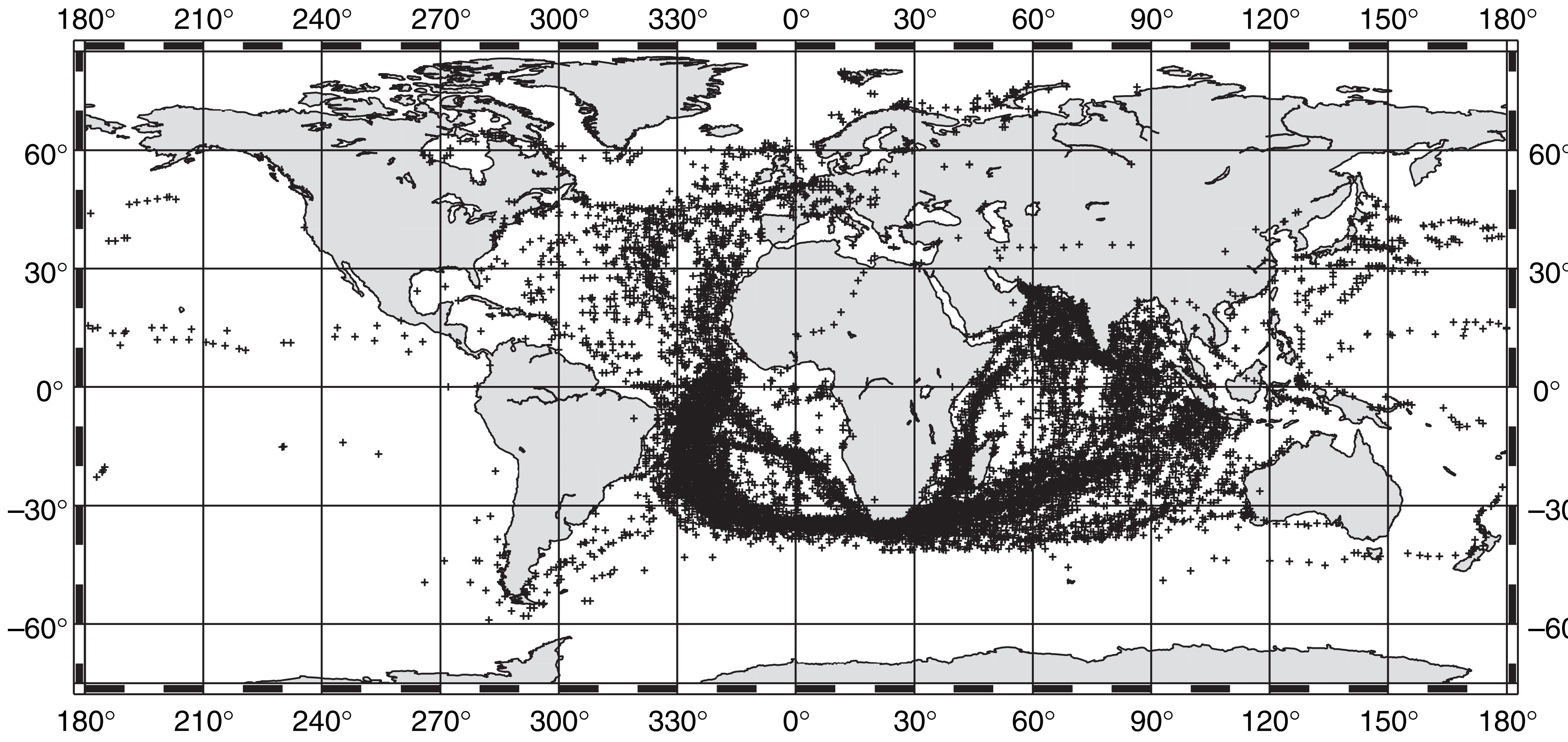
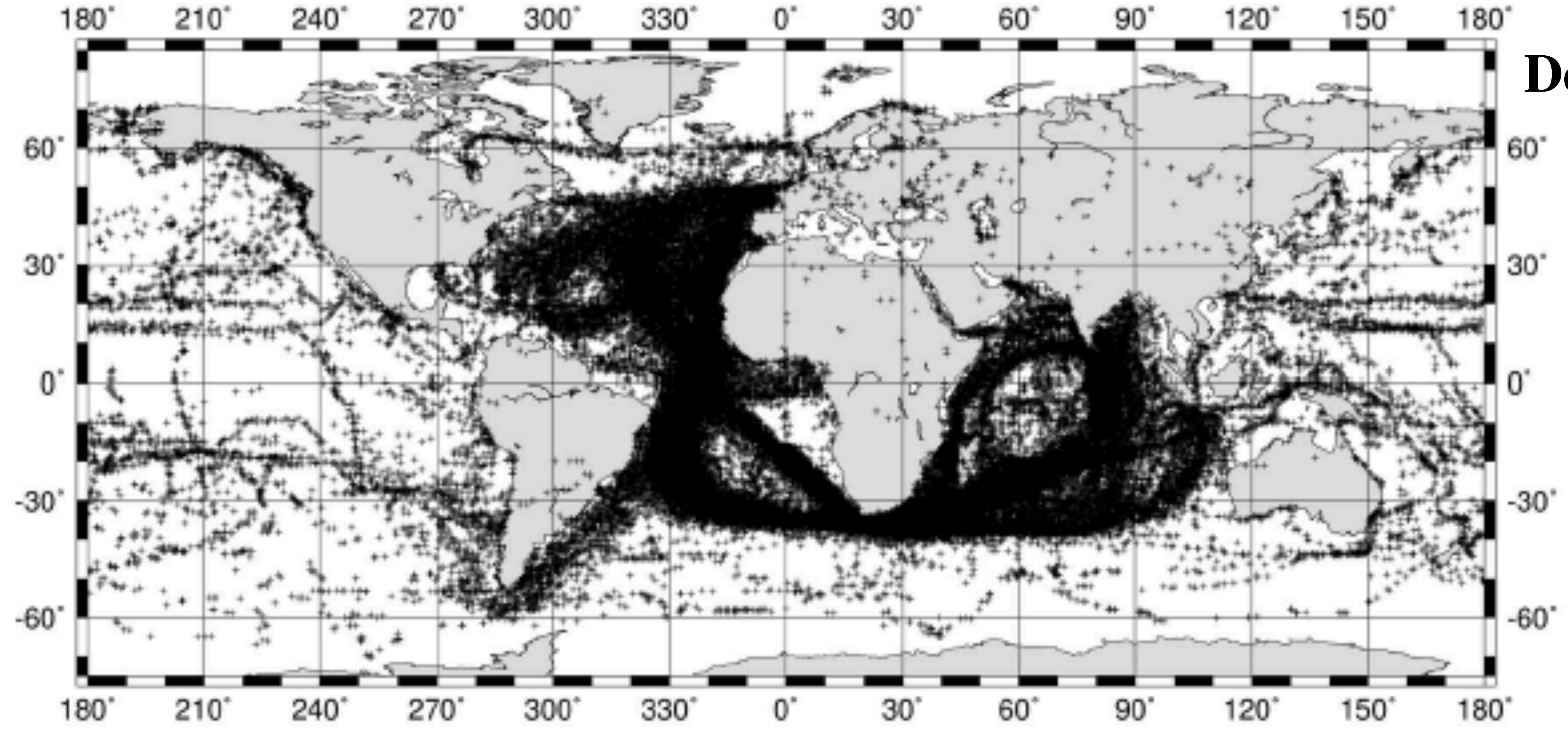


Figure 3 Geographical data distribution of declination observations made in 1590–1699; $n = 12\,001$; some points may overlap; cylindrical equidistant projection.

- Many observations from marine expeditions
- Generally poorer continental coverage and in polar regions
- Poor coverage of Pacific prior to 1700
- Dominated by declination data

Jonkers et al., 2003

Direct Observations - 1700-1799



Declination, n=68,076

Figure 10. Geographical data distribution of declination observations made in 1700–1799. Here $n = 68{,}076$;

Intensity, n=36

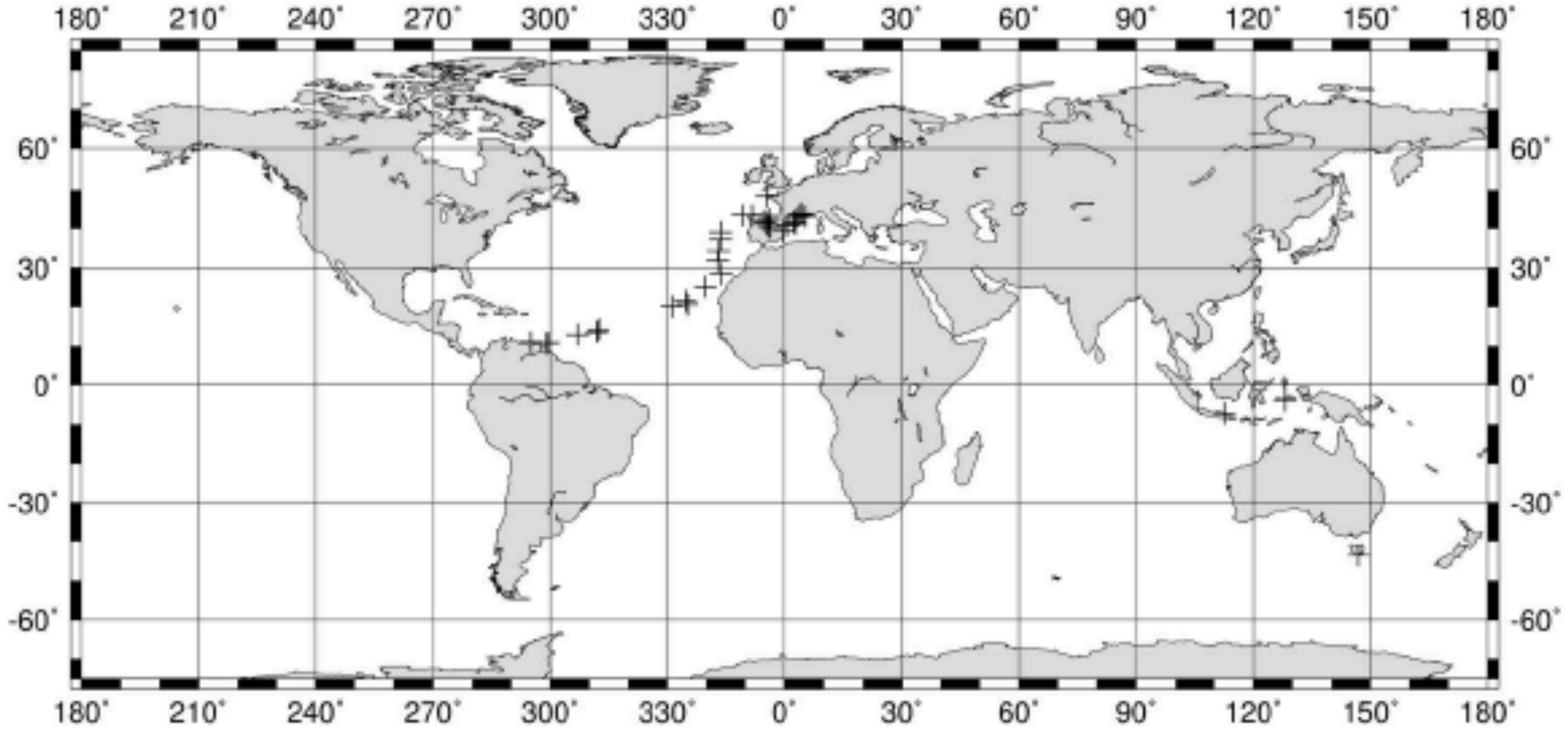
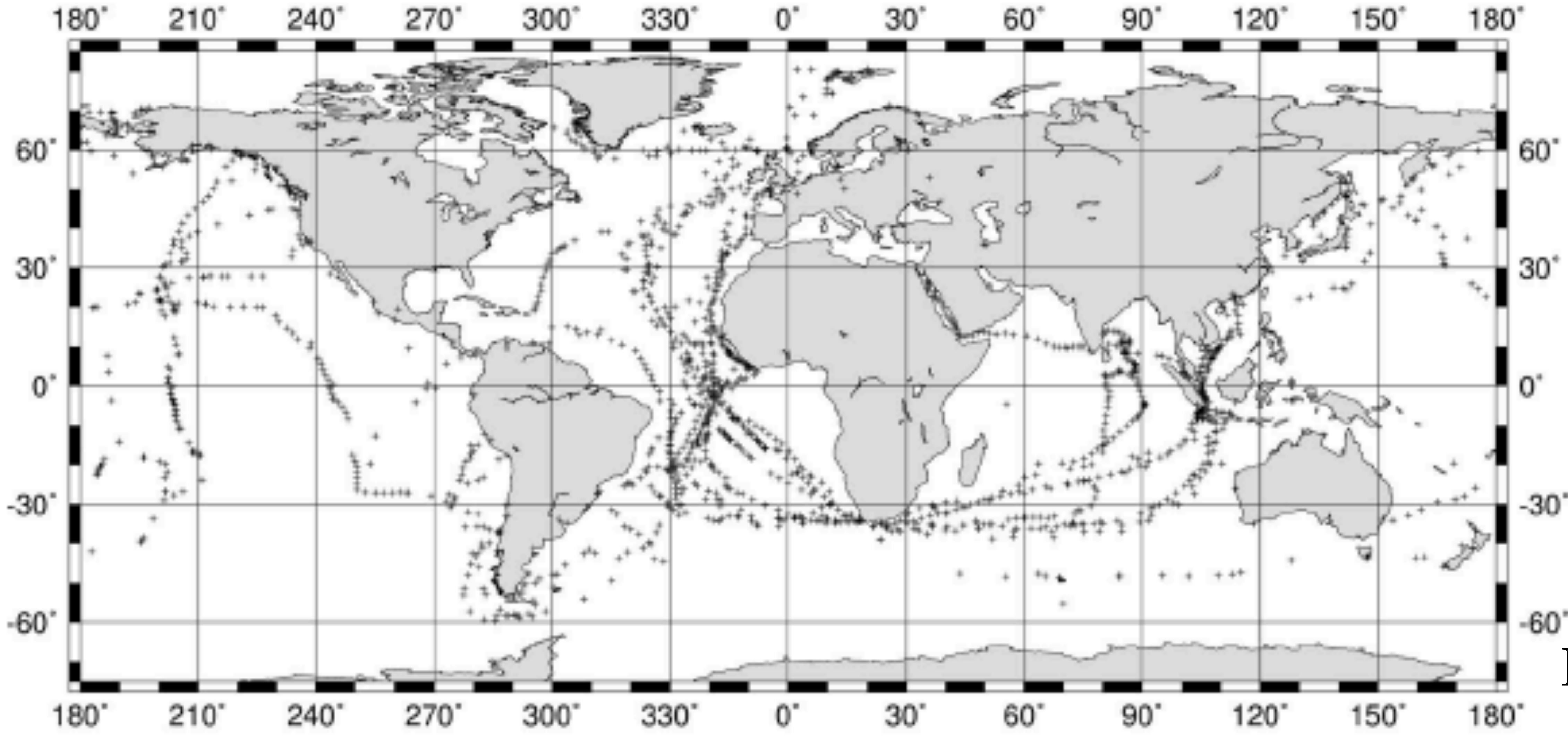


Figure 15. Geographical data distribution of intensity observations made in 1700–1799. Here $n = 36$; some points may overlap; projection is cylindrical equidistant.

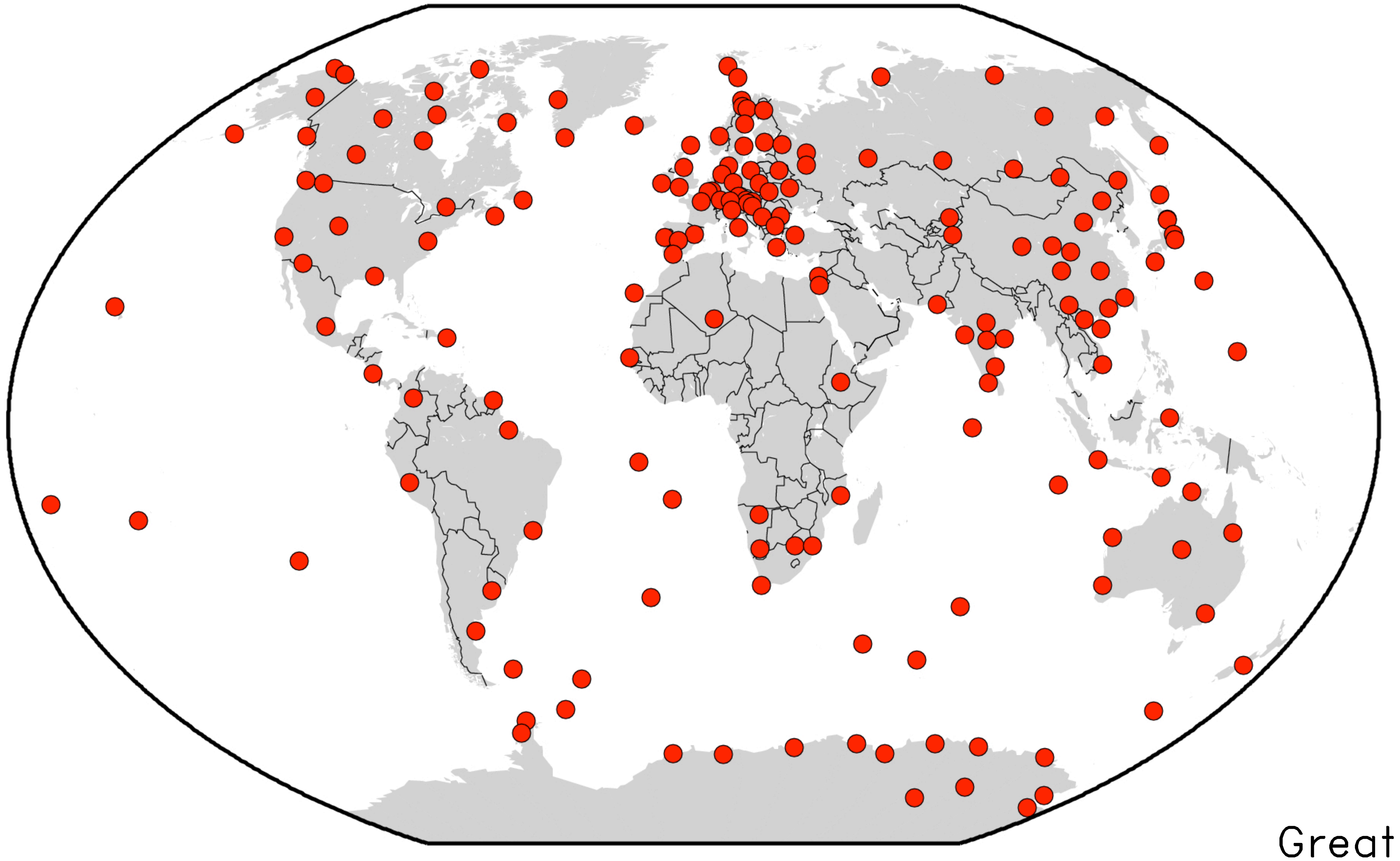


Inclination, n=1747

Figure 13. Geographical data distribution of inclination observations made in 1700–1799. Here $n = 1747$; some points may overlap; projection is cylindrical equidistant.

Jonkers et al., 2003

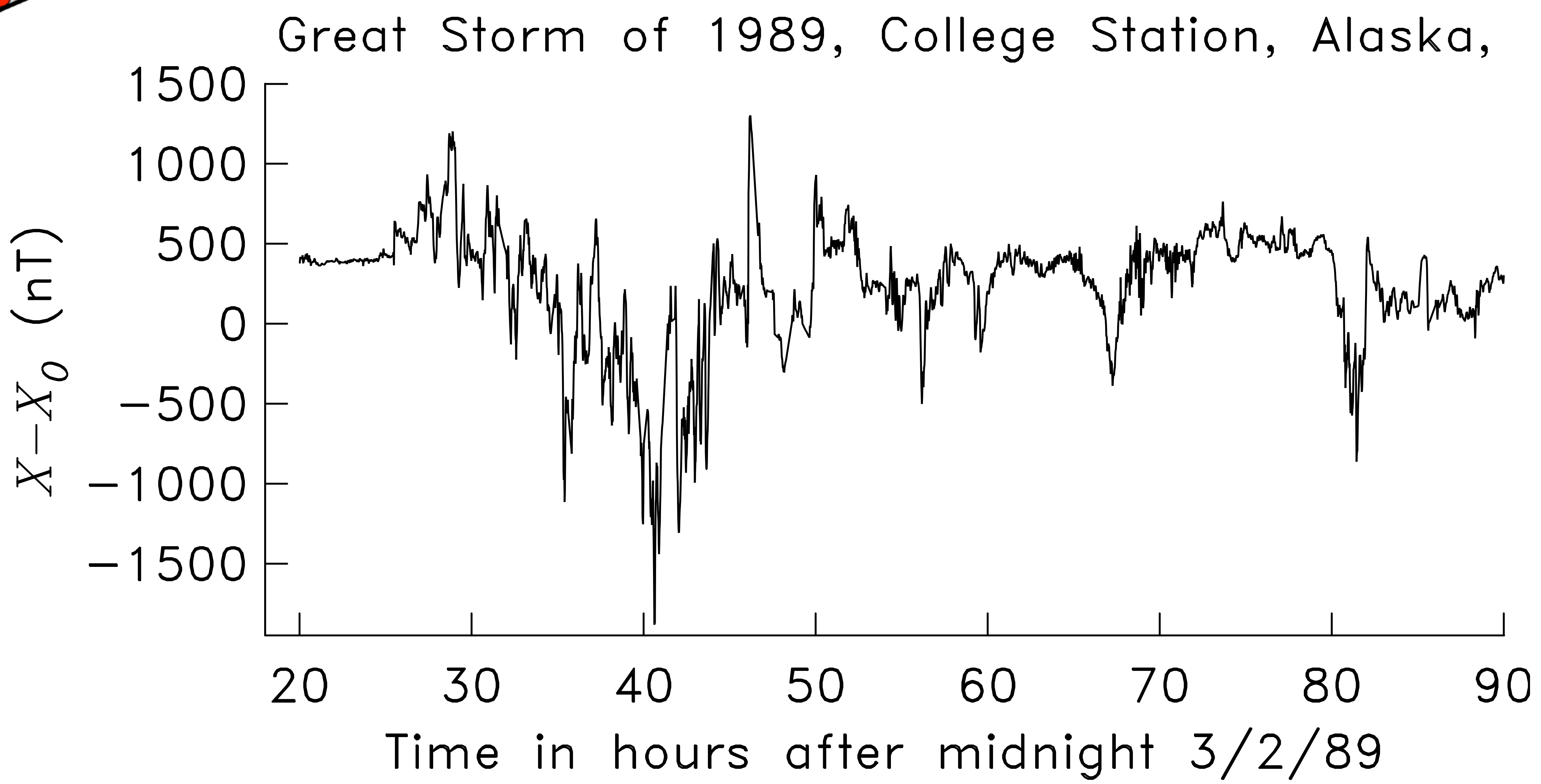
Measuring the Field Today - observatories



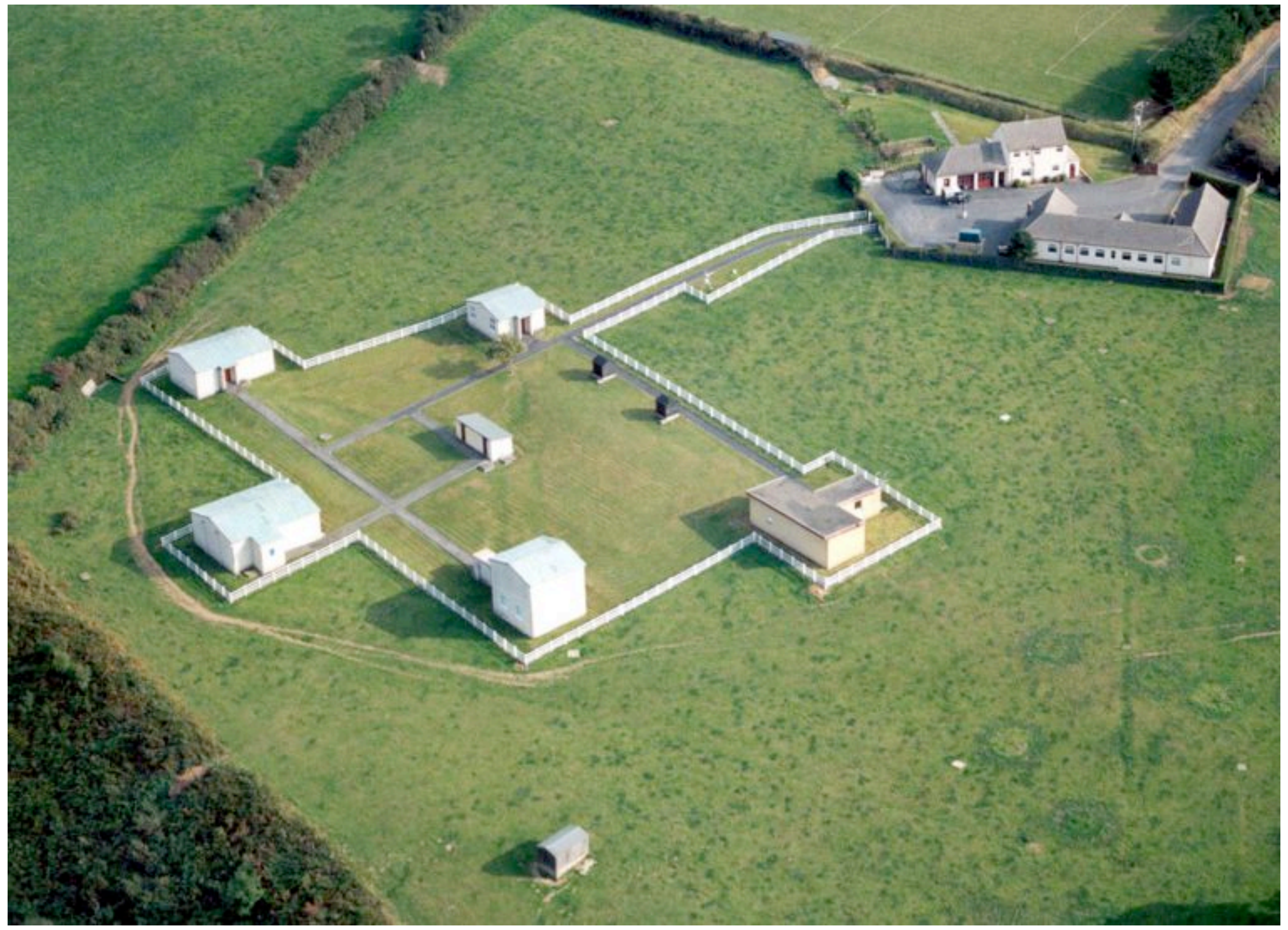
Locations of currently operating geomagnetic observatories

http://www.geomag.bgs.ac.uk/education/earthmag.html

Magnetic storms can disrupt power grids, and make aurorae visible at low latitudes

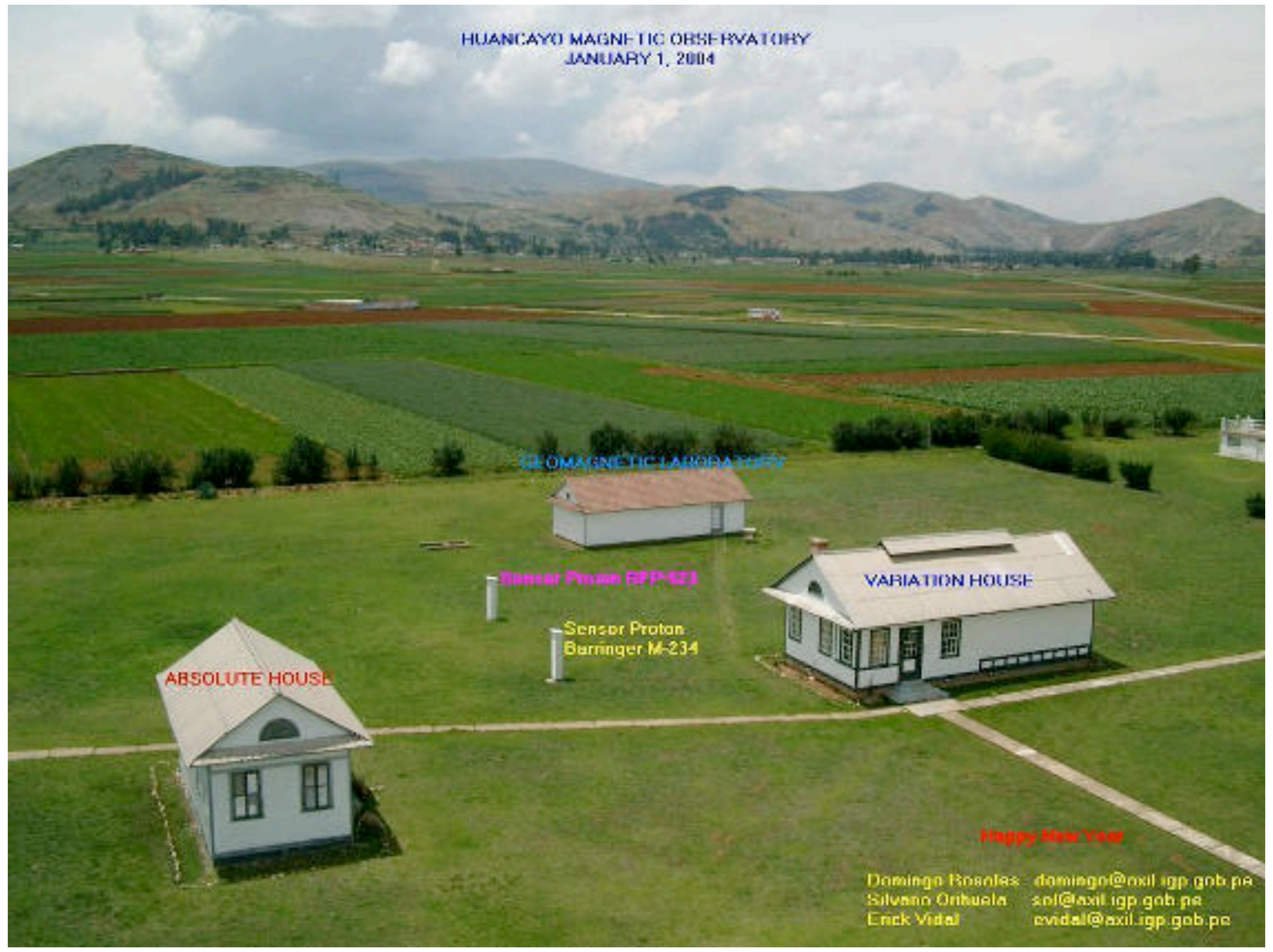


Magnetic Observatories



Hartland, UK

http://www.geomag.bgs.ac.uk/operations/hartland.html



Huancayo, Peru

https://www.intermagnet.org/images/photos/hua.jpg

Boulder, USA

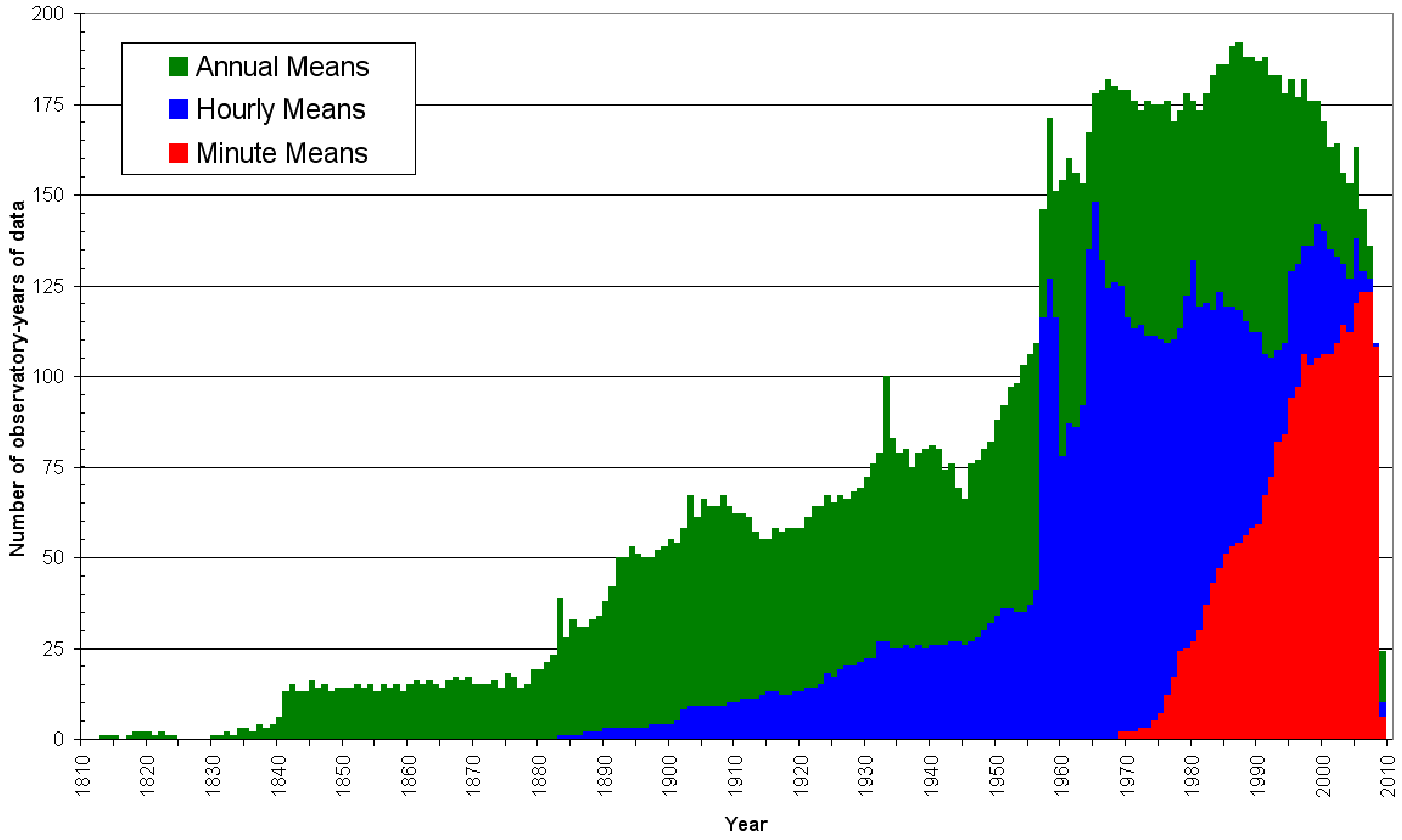
Azimuth mark, Absolutes building and Coil building at Boulder magnetic observatory.

Theodolite, Boulder, USA

Zeiss Jena 010B Theodolite for making absolute measurements at Boulder magnetic observatory.(Public domain.)

Direct Observations

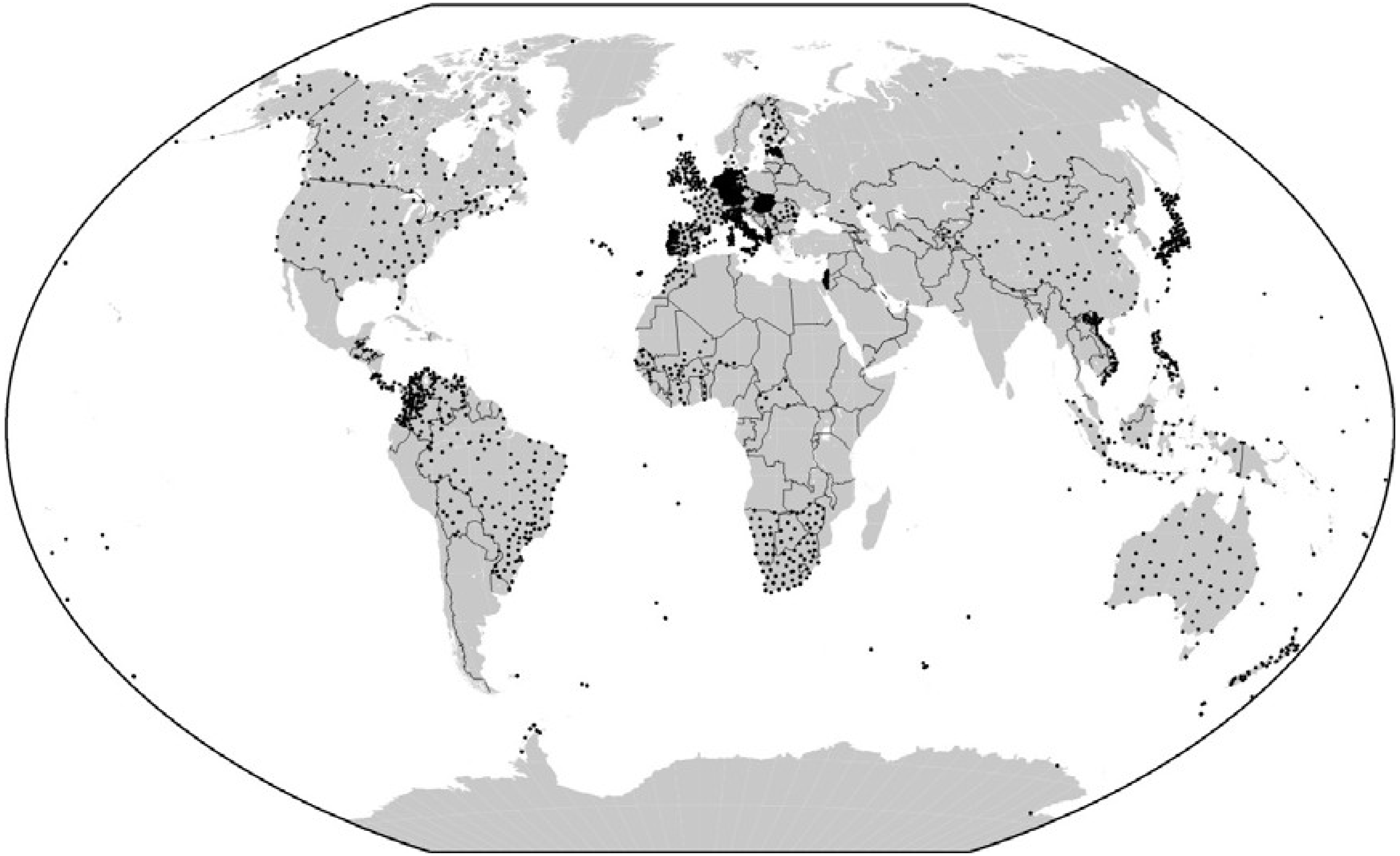
- Magnetic Observatory



The number of data holdings at the World Data Center (Edinburgh) for various time resolutions. (Credit: BGS/NERC)

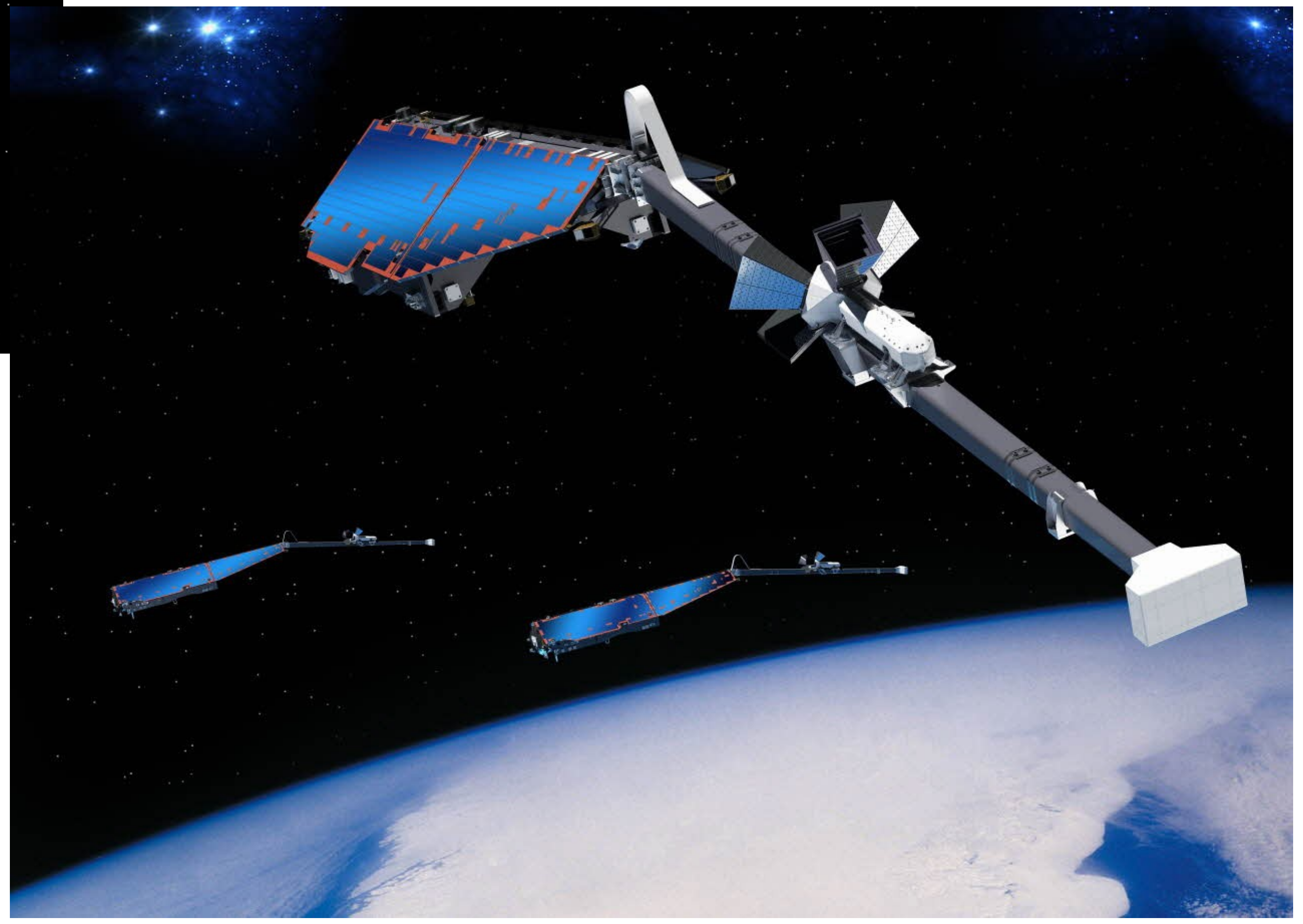
Direct Observations

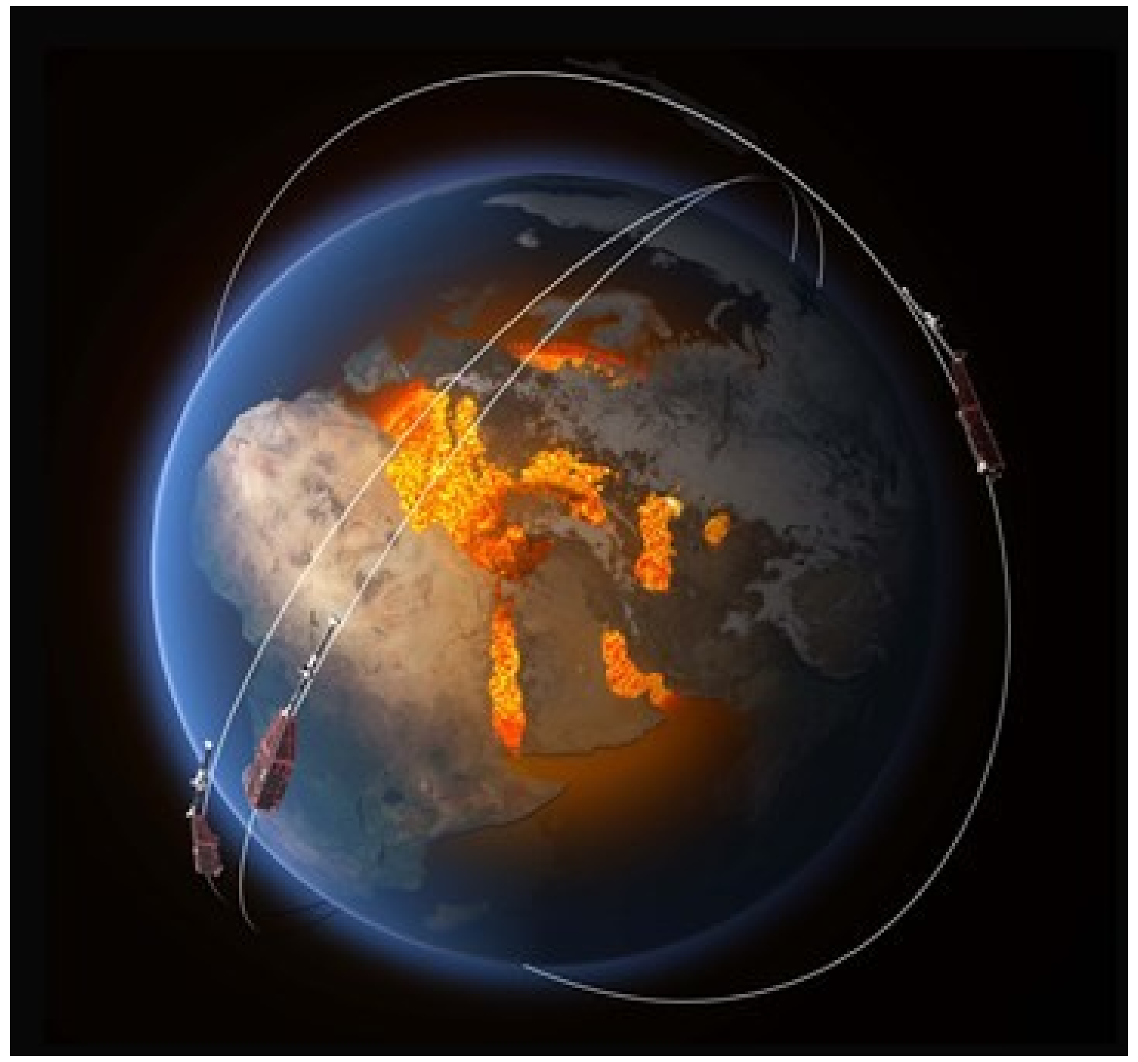
- Geomagnetic repeat stations



Repeat stations positions 1975-2010 (Positions of all repeat stations that have been occupied at least twice since 1975 and have submitted their data to the World Data Centers)
(credit: Geomagnetic Observations and Models, eds. M. Mandea and M. Korte, 2011)

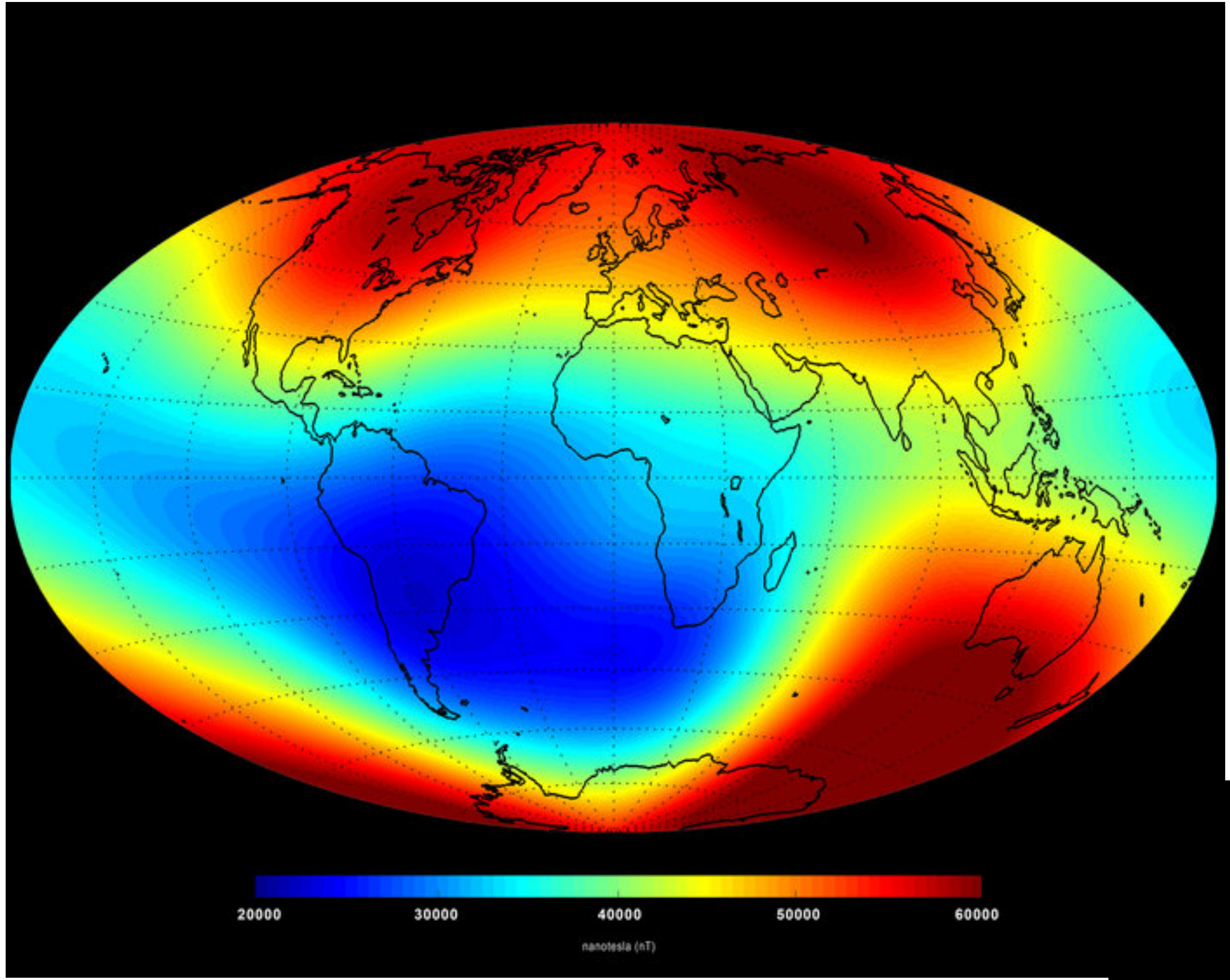
November 2013: SWARM



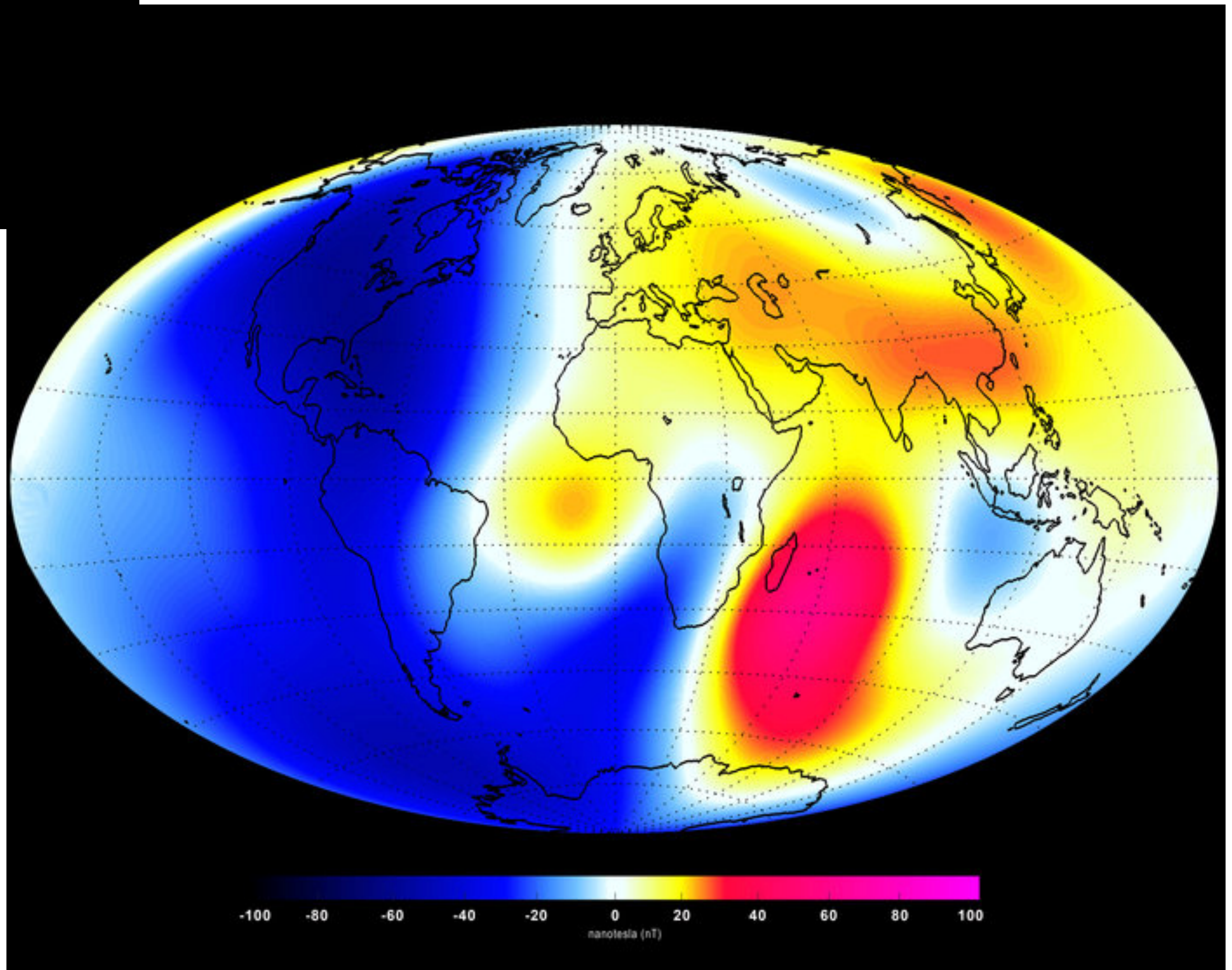


(credit: ESA)

https://www.esa.int/Applications/Observing_the_Earth/Swarm



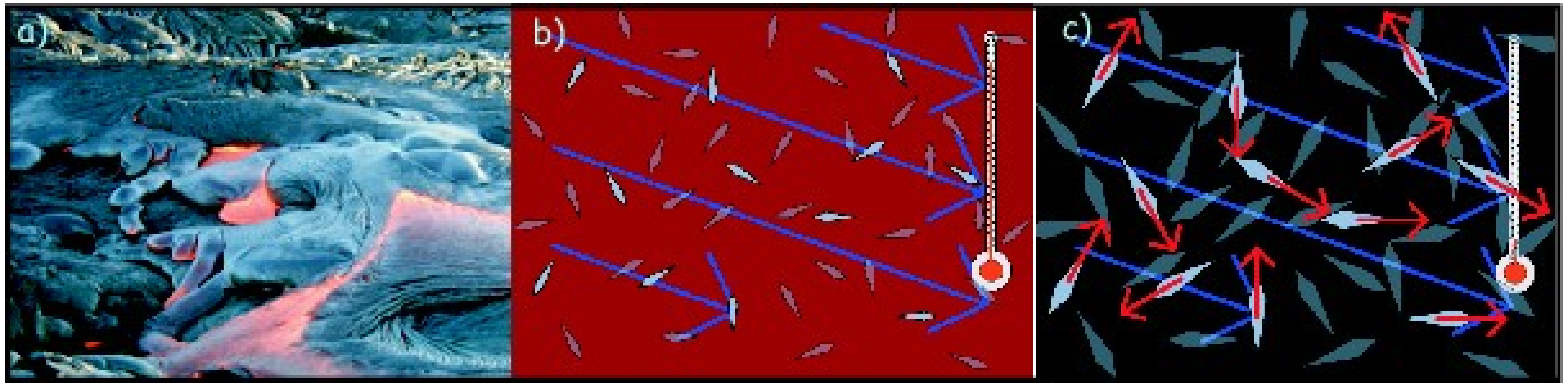
‘Snapshot’ of the main magnetic field at Earth’s surface as of June 2014 based on Swarm data.



Changes in Earth’s magnetic field from January to June 2014 as measured by the Swarm constellation of satellites.

Paleomagnetic Observations

- Lava flows and archaeological artifacts: Thermal Remanent Magnetisation (TRM)

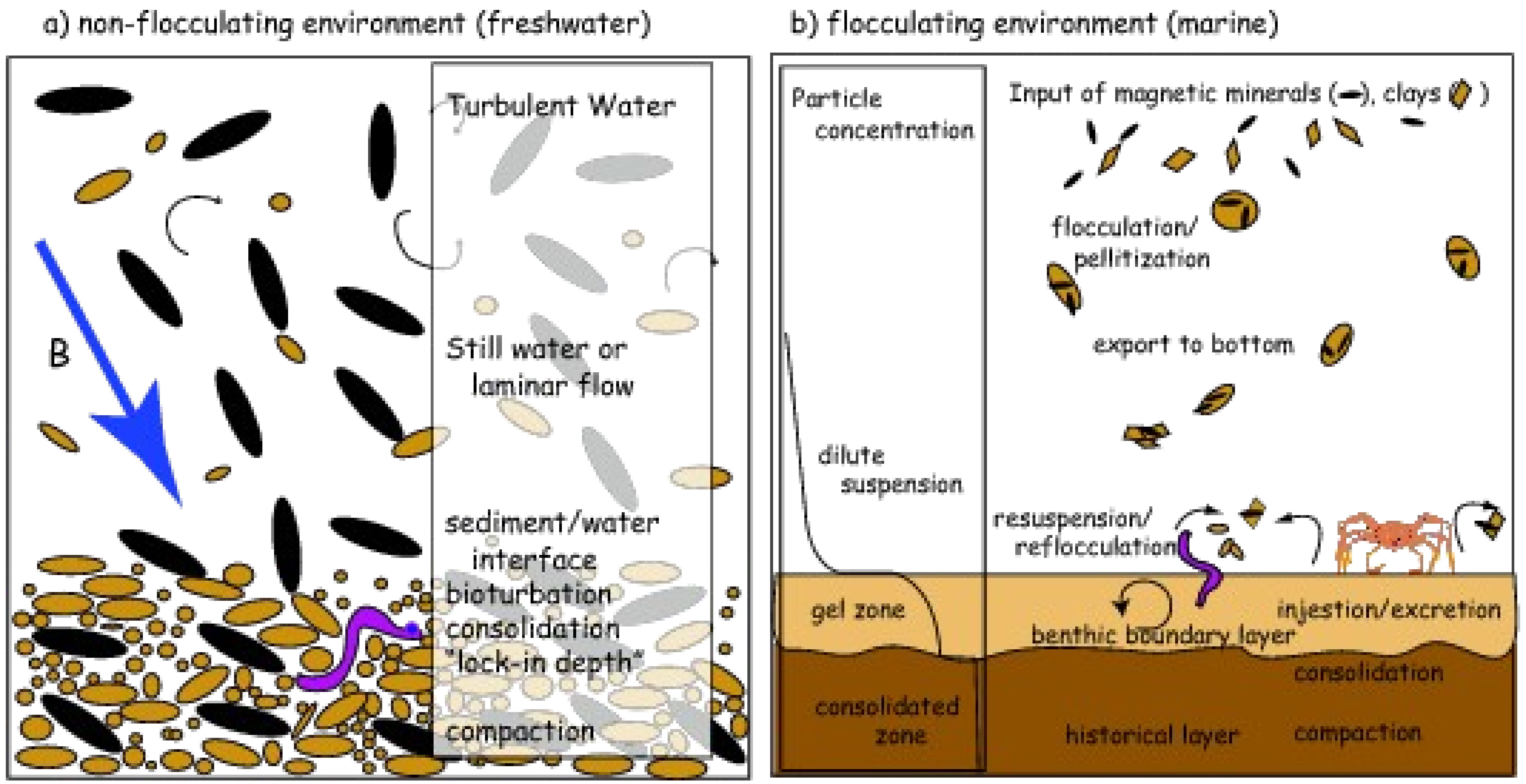


a) Picture of lava flow. b) While the lava is still well above the Curie temperature, crystals start to form, but are non-magnetic. c) Below the Curie temperature but above the blocking temperature, certain minerals become magnetic, but their moments continually flip among the easy axes with a statistical preference for the applied magnetic field. As the lava cools down, the moments become fixed, preserving a thermal remanence.

(Figure from Tauxe and Yamazaki, 2007
http://magician.ucsd.edu/Lab_tour/movs/TRM.mov)

Paleomagnetic Observations

- Lake/Marine/Ocean Sediments : Depositional Remanent Magnetisation (DRM)



a) Schematic drawing of traditional view of the journey of magnetic particles from the water column to burial in a non-flocculating (freshwater) environment. Magnetic particles are black. b) View of depositional remanence in a flocculating (marine) environment.

(Figure from Tauxe and Yamazaki, 2007)