SIOG 231: GEOMAGNETISM AND ELECTROMAGNETISM

Chapter 1: Introduction, motivation, history, overview of the applications

1. Why Geoelectromagnetism?

Earth's magnetic field is a fundamental property of our planet, and has probably existed for most of geological time. It protects life from the damaging radiation of the solar wind and cosmic rays, and protects our atmosphere as well. For the past thousand years it has been used by people for navigation, and even in today's world of GPS location it is still the quickest, cheapest, and most reliable way to tell direction – every modern cell phone is a magnetometer. Directional drilling, shielded from GPS, relies on the magnetic field for orientation. Even before people navigated by the magnetic field, living things from bacteria to birds have used it for navigation and to tell direction. The past magnetic field, recovered by paleomagnetic methods, provides insight into the history of Earth tectonics, and rock magnetic properties inform us about the processes of rock formation. The timescale of polarity reversals of Earth's magnetic field is sometimes the only way available to date geologic sections.

Electromagnetism is one of the four fundamental forces (along with gravity and the strong/weak interactions), and electrical methods and magnetism are important tools in studying Earth structure (along with seismology and gravity). Airborne and marine measurements of the crustal magnetic field provide a wealth of information on near-surface structure, and global long-term measurements of the magnetic field are our main source of information on the dynamics of Earth's core. Electric currents induced by external magnetic field variations allow us to probe the electrical conductivity of Earth from meter scale to the lower mantle. Electrical conductivity, a fundamental property of matter, varies over a vast range in Earth materials, more than 20 orders of magnitude for minerals, about 8 orders of magnitude for crustal materials, and 11 orders of magnitude between the most resistive parts of the mantle and the core. This, of course, is a far larger range than seismic velocity and density; only viscosity provides a physical Earth property that has a comparable range of values. Conductivity can be used to infer temperature, melt content, porosity, and mineralogy of deep structure, and is also used for energy, mineral, and groundwater exploration.

For most of history, the study of magnetism *was* a study rooted in Earth science, since before Ampère's time the only magnets were made from naturally magnetized minerals and Earth's magnetic field was a deep mystery. Today, magnetism is an important part of planetary science.

2. Geomagnetism

Geomagnetism, the study of Earth's magnetic field, has a long history and has revealed much about the way Earth works. As we shall see, the existence and characteristics of the field essentially demand that the fluid outer core be made of electrically conducting material that is convecting in such a way as to maintain a self-sustaining dynamo. The study of the field as it is recorded in rocks is known as paleomagnetism. It allows us to track the past motions of continents and leads directly to the idea of sea-floor spreading. Mapping the signature of the magnetic field in Earth's lithosphere provides information used in large scale tectonic studies. Paleomagnetism also allows the study of longevity of the field (current estimates range from 3.5–4.2 Ga or longer), searches for magnetic signatures of inner core formation, and how the geomagnetic field has evolved over geological time, through tracking of geomagnetic polarity reversals, and variations in the field's strength and direction. Direct observations over the past few hundred years provide more detailed views of the secular variation (change in time). Shorter term variations in the external part of the geomagnetic field induce secondary variations in Earth's crust and mantle which are used to study the electrical properties of the Earth, giving insight into porosity, temperature, and composition in these regions. Changes in the external field are controlled by the interactions between the solar wind and Earth's internal field and are of enormous interest in understanding solar terrestrial interactions.

The magnetic field was the first property attributed to the Earth as a whole, aside from its roundness. This was the finding of William Gilbert, physician to Queen Elizabeth I, who published his inference in 1600, predating Newton's gravitational *Principia* by about 87 years. The magnetic compass had been in use, beginning with the Chinese, since about the second century B.C., but it was not used in Europe until much later, where it became an indispensable tool for maritime navigation. Petrus Peregrinus can be credited with producing the first scientific work devoted to magnetism, discovering magnetic meridians, the dipolar nature of the magnet, and describing two versions of the magnetic compass. His *Epistola de Magnete* was written in 1269, and subsequently widely circulated in Europe, but not actually published until the 16th century. Gilbert placed the source of magnetism within the Earth in 1600, but the temporal variations in the magnetic field (known as secular variation) were not well documented until the middle of the seventeenth century when Henry Gellibrand appreciated that the differences among repeated measurements were not just inaccuracy in the observations. In 1680 Edmund Halley (of Halley's comet fame) published the first contour map of the geomagnetic variation as the declination was then known: he envisioned the secular variation of the field as being caused by a collection of magnetic dipoles deep within the earth drifting westward with time with about a 700 year period, a model not dissimilar to many put forward during the twentieth century, although he did not know of the existence of the fluid outer core. A formal separation of the geomagnetic field into parts of internal and external origin was first achieved by the German mathematician Carl Friedrich Gauss in the nineteenth century. Gauss invented spherical harmonics and deduced that by far the largest contributions to the magnetic field measured at Earth's surface are generated by internal rather than external magnetic sources, thus confirming Gilbert's earlier speculation. He was also responsible for beginning the measurement of the geomagnetic field at globally distributed observatories, some of which are still running today.

The magnetic field is a vector quantity, possessing both magnitude and direction; at any point on Earth a free compass needle will point along the local direction of the field. Although we conventionally think of compass needles as pointing north, it is the horizontal component of the magnetic field that is directed approximately in the direction of the North Geographic Pole. The difference in azimuth between magnetic north and true or geographic north is known as declination (positive eastward). The field also has a vertical contribution; the angle between the horizontal and the magnetic field direction is known as the inclination and is by convention positive downward (see Figure 1.1). Three parameters are required to describe the magnetic field at any point on the surface of the Earth, and the conventional choices vary according to subfields of geomagnetism and paleomagnetism . Traditionally, the vector **B** at Earth's surface is referred to a right-handed coordinate system: north-east-down for x-y-z. But often instead of using the components in this system, three numbers used are: intensity, $B = |\mathbf{B}|$, declination, D, and inclination, I as shown in the sketch or D, H and Z; H, or equivalently B_h, is the projection of the field vector onto the horizontal plane

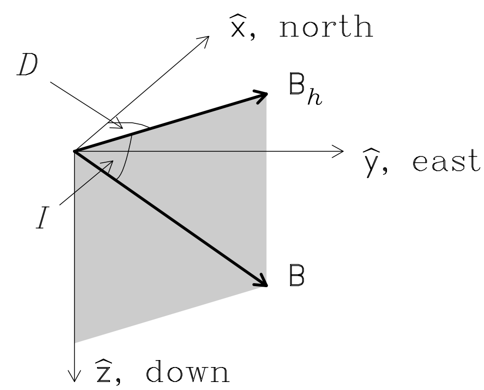


Figure 1.1

and Z, or equivalently B_z, is the projection onto the vertical axis. D is measured clockwise from North and ranges from 0 $\rightarrow$ 360° (sometimes -180° to 180°). I is measured positive down from the horizontal and ranges from -90 $\rightarrow$ +90° (because field lines can also point out of the Earth, indeed it is only in the northern hemisphere that they are predominantly downward). From the diagram we have

$$H = B\cos I; \quad Z = B\sin I. \tag{1}$$

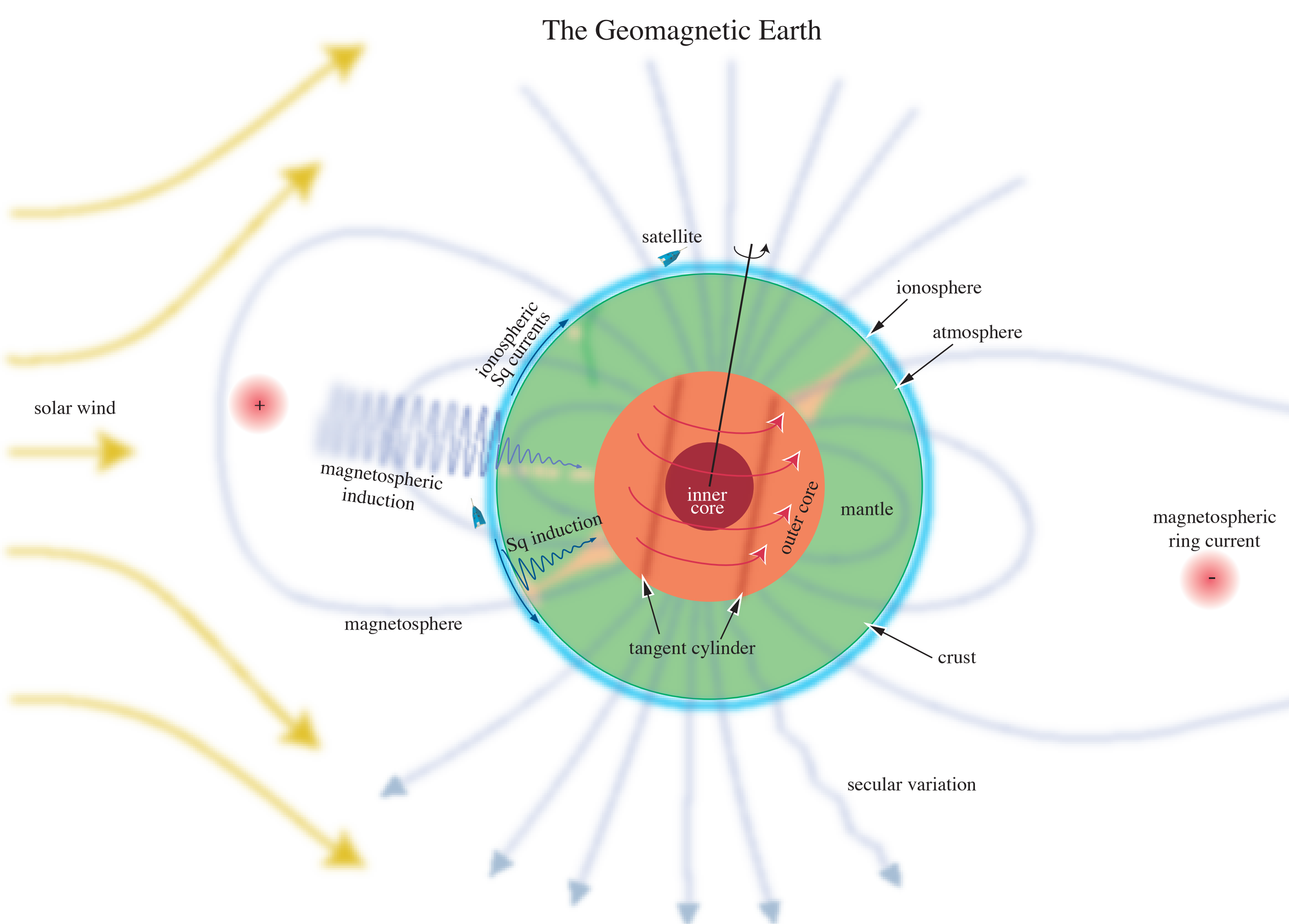
When components of **B** are used they are called X, Y, Z, and:

$$X = B_x = B\cos I\ \cos D; \;\; Y = B_y = B\cos I\ \sin D; \;\; Z = B_z = B\sin I. \tag{2}$$

The CGS unit of B is the gauss; smaller fields were once measured in gammas where $1\gamma = 10^{-5}G$. Today SI units should be universally used: B is measured then in tesla (T); 1 T is a very large field. More commonly in geophysics the unit of choice is the submultiple nanotelsa (nT); 1nT = 10^{-9} T = l gamma, by pure coincidence; often the μT is also used, with 1μT= 10^{-6} T.

When the standard geocentric spherical coordinate system is used the magnetic field elements are usually designated B_r, B_θ, and B_ϕ, corresponding to locally radial, southward, and eastward unit vectors referred to a position vector **r** on a spherical surface $S(a)$. It is generally important to account for the distinction between geocentric and geographic latitude, especially when combining surface and satellite observations. Detailed maps of the present day field show that it is a complicated function of position on the surface of the Earth although it is dominantly dipolar, and can be approximated to first order by a dipole located at the center of the Earth, with its axis tilted by a few degrees relative to the geographic axis. The current magnitude of the field, the magnetic flux density passing through Earth's surface, is about twice as great at the poles (about 60 μT) as at the equator (about 30 μT).

The magnetic equator corresponds to the zero contour B_r = 0 and differs significantly from the geographic equator. At the *magnetic poles* the field is vertical (inclination is ±90 °, and declination is undefined). Note that the magnetic poles are distinguished from the *geomagnetic poles* which correspond to the axis of the best fitting geomagnetic dipole.



Earth's magnetic field is generated in the liquid **outer core**, where fluid flow is influenced by Earth rotation and the **inner core** geometry (which defines the **tangent cylinder**). Core fluid fl
produces a **secular variation** in the magnetic field, which propagates upward through the relatively electrically insulating **mantle** and **crust.** Above the insulating **atmosphere** is the electr
conductive **ionosphere**, which supports **Sq currents** as a result of dayside solar heating. Outside the solid Earth the **magnetosphere**, the manifestation of the core dynamo, is deformed and
modulated by the **solar wind**, compressed on the sunside and elongated on the nightside. At a distance of about 3 Earth radii, the **magnetospheric ring current** acts to oppose the main fiel
also modulated by solar activity. Magnetic fields generated in the magnetosphere and ionosphere propagate by **induction** into the conductive Earth, providing information on electrical conc
variations in the crust and mantle. **Magnetic satellites** fly above the ionosphere, but below the magnetospheric induction sources. The ring current and solar wind are not drawn to scale.

Figure 1.2:

The present and historical magnetic field is measured at observatories, by surveys on land and at sea, and from aircraft. Since the late 1950s a number of satellites, each carrying a magnetometer in orbit around Earth for months at a time, have provided more uniform coverage than previously possible. Early satellites only measured the magnitude of the field: however, it was shown in the late 1960s that measurements of the field's direction are also required to specify the field accurately. Prehistoric magnetic field records can also be obtained through paleomagnetic studies of remanent magnetism recorded in rocks and archeological materials. These are useful for geomagnetic studies if there is an independent means of determining the timing when the magnetization was acquired.

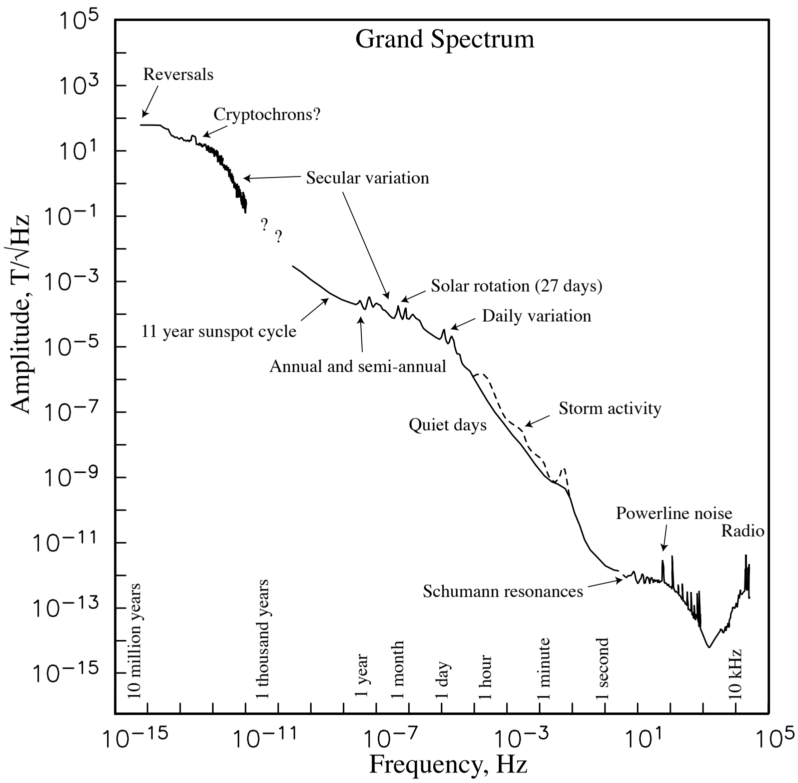


Figure 1.3 Amplitude spectrum of geomagnetic intensity variations as a function of frequency.

A number of different physical sources contribute to the measured field, and Figure 1.2 gives a simplified view of the parts of the magnetic field that are most important for our purposes: these can be roughly divided according to spatial scale and the frequency range in which they operate. The corresponding amplitude spectrum of variations as a function of frequency is given in Figure 1.3 with an indication of the different sources. Figure 1.4 expands and supplements the long period part of Figure 1.3, showing an updated power spectrum of dipole moment variations inferred from various kinds of paleomagnetic data, and including the marine magnetic anomaly record for the very longest periods.

The bulk of Earth's magnetic field is generated in the liquid outer core, where fluid flow is influenced by Earth rotation and the geometry of the inner core. Core fluid flow produces a secular variation in the magnetic field

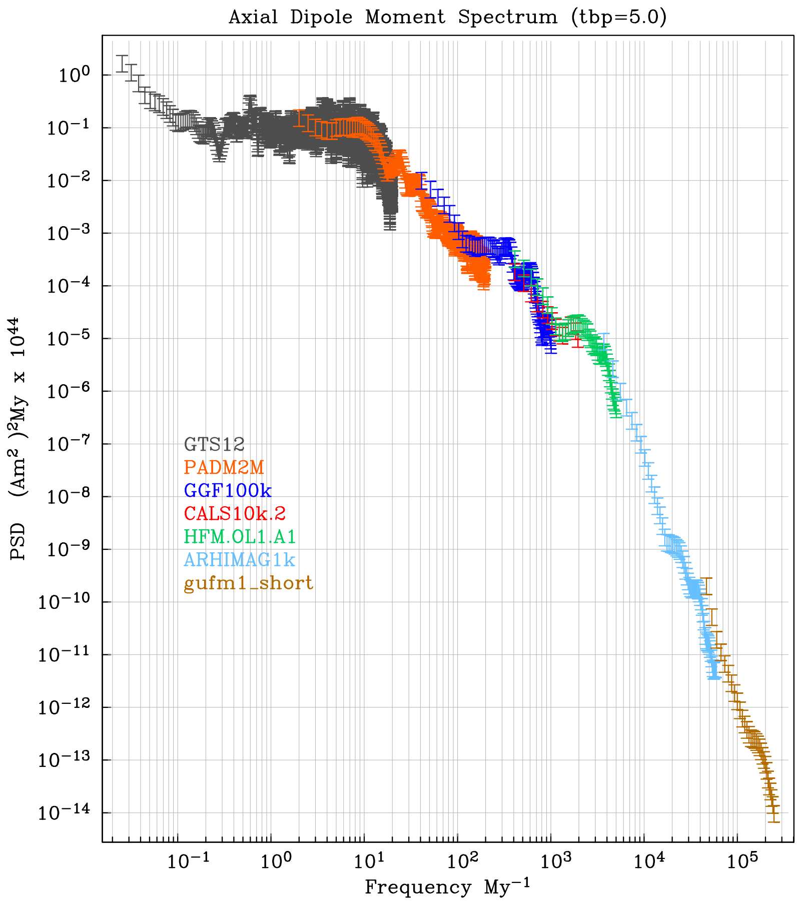


Figure 1.4: Composite power spectrum of paleomagnetic dipole moment variations as a function of frequency. At longest periods the spectrum is derived from the magnetostratigraphic time scale (black symbols, 0-158 Ma), intermediate (orange for 0-2 Ma, blue for 0-100 ka) are from marine sediment paleomagnetic reconstructions, red and green are Holocene combined paleo and archeomagnetic reconstructions (0-10 ka), light blue combine direct and archeomagnetic (1000 CE to 1900 CE) and at the shortest periods (brown) are from direct observations1832-1990 CE.

which propagates upward through the relatively electrically insulating mantle and crust. Short term changes in core field are attenuated by their passage through the mantle so that at periods less than a few months most of the changes are of external origin. At Earth's surface the crustal part is orders of magnitude weaker than that from the core, but remanent magnetization carried by crustal rocks has proved very important in establishing seafloor spreading and plate tectonics, as well as a global magnetostratigraphic timescale. The crust makes a small static contribution to the overall field, which only changes detectably on geological time-scales making an insignificant contribution to the long period spectrum. On very long timescales (about 10^6 years) the field in the core reverses direction, so that a compass needle points south instead of north, and inclination reverses sign relative to today's field. The present orientation of the field is known as normal, the opposite polarity is reversed. The occurrence of reversals is unpredictable and the average rate varies with time but, as is clear from the red spectra with diminishing variability at higher frequency in Figures 1.3 and 1.4, these are by far the largest and most unusual geomagnetic events.

Electromagnetism

Returning to Figure 1.2 we note that above the insulating atmosphere the electrically conductive ionosphere supports *Sq currents* with a diurnal variation as a result of dayside solar heating. Lightning generates high frequency *Schumann resonances* in the Earth/ionsophere cavity. Outside the solid Earth the *magnetosphere*, the manifestation of the core dynamo, is deformed and modulated by the solar wind, compressed on the sunside and elongated on the nightside. At a distance of about 3 earth radii, the *magnetospheric ring current* acts to oppose the main field and is also modulated by solar activity. Although changes in solar activity probably occur on all time scales, at long periods the associated magnetic variations are much smaller than the changes in the core field and only make a very minor contribution to the power spectrum. However, external variations on time scales of decades and less are very important for electromagnetic induction studies.

The Earth's magnetosphere also plays an important role in protecting us from cosmic ray particle radiation, because the incoming ionized particles can get trapped along magnetic field lines, preventing them from reaching Earth. One consequence of this is that rates of production of radiogenic nuclides such as ^{14}C and ^{10}Be are inversely correlated with fluctuations in geomagnetic field intensity. This means that knowledge of Earth's dipole moment in the past plays an important role in paleoclimate studies that use cosmogenic nuclide production to infer solar insolation during prehistoric times.

The advent of modern electromagnetism in physics starts at the beginning of the 19th century, when Volta developed the battery, allowing experiments to be made with electric currents instead of static charges. Soon after Oersted observed that an electric current deflected a magnet, a phenomenon that Ampere quantified with Ampere's Law. Faraday then discovered the complementary phenomena in which a moving magnet produces a current, leading to Faraday's Law. In 1864 Maxwell added an extra term to Ampere's Law (the displacement current) that allowed fields to exist without charges. This allowed for electromagnetic radiation propagating in a vacuum at the speed of light. However, Maxwell's equations were written in a very convoluted way, and few people understood them. What we now know as Maxwell's equations were created by the telegraph engineer Oliver Heaviside, who developed a form of vector calculus in order to recast Maxwell's twenty original equations in twenty unknowns into four differential equations in two unknowns.

Towards the end of this development of electromagnetic theory, observations of natural electrical potentials in Earth were being made. Similar to the way that telegraph engineering drove Heaviside's development of EM theory, the telegraph played a crucial role in the development of geophysical methods to study the deep Earth. It was observed that large and rapid variations in the external magnetic field (magnetic storms), which we now know are caused by energetic particles emitted from the sun (coronal mass ejections), disrupted telegraphy and induced currents in telegraph lines. It was also noted that these phenomena coincided with energetic auroral displays, a result of electric charges flowing down the magnetic field lines near the magnetic poles.

By the early 20th century the relationship between magnetic activity and Earth currents was becoming well-known, and the quantitative separation of internal and external parts of the magnetic field was being investigated in order to infer the electrical conductivity of the deep Earth. In 1922 Sydney Chapman and T.T.

Whitehead concluded that the induced currents were related to Earth conductivity. Chapman inferred that the interior must be more conductive than crustal rocks and modeled the signal induced by the daily variation with a conductive sphere of smaller radius than Earth. Although Chapman and Bartels lamented in their 1940 book that a more quantitative relationship between electrical conductivity and magnetic field variation was not yet available, progress in this direction was being made. Lahiri and Price (1939) modeled the internal and external parts of the magnetic field using a radial conductivity profile to a depth of nearly 1000 km. Later in 1969, Roger Banks proposed that the harmonics of the 27-day solar rotation were dominated by a simple P_1^0 spherical harmonic geometry, associated with the ring of current in the magnetosphere above the geomagnetic equator, and produced a conductivity profile down to nearly 2000 km. These models all feature an increase in conductivity at about the upper/lower mantle transition, a feature of most modern models (see Figure 1.5). These observations represent the beginnings of the geomagnetic depth sounding (GDS) method, in which magnetic fields alone are used to probe Earth conductivity.

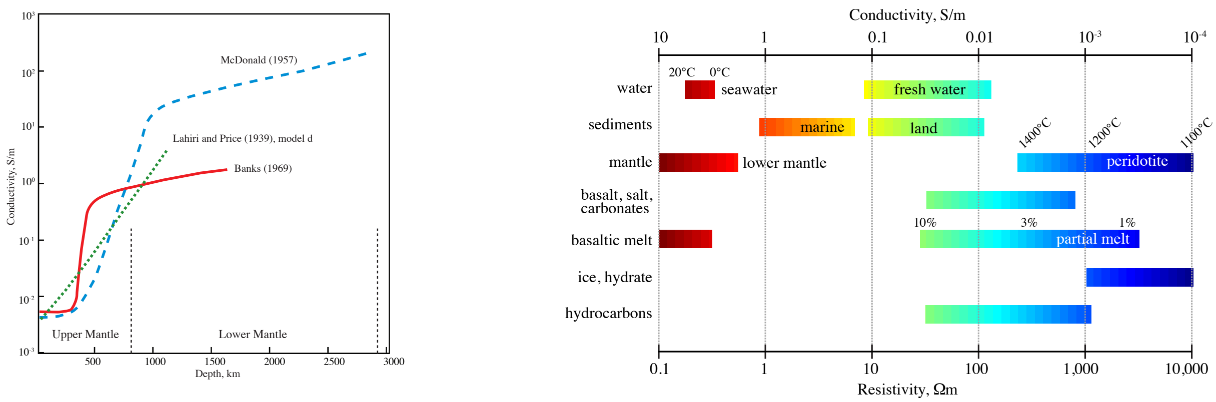


Figure 1.5: Left: Early electrical conductivity profiles of Earth. Right: Typical electrical conductivities (and resistivities) of Earth materials.

Today, data from the global network of magnetic observatories, started nearly 200 years ago by Gauss and colleagues, are supplemented by magnetic satellite measurements, first collected in 1979–1980 by the Magsat mission and continuously to the present day since the launch of the Oersted mission in 1999, allowing three dimensional models of deep Earth conductivity to be attempted.

While the GDS method is useful for probing deep Earth conductivity, it is largely useless for investigating shallow structure. This problem was overcome in the 1950's when Andrey Tikhonov and Louis Cagniard independently developed the theory for the magnetotelluric (MT) method, in which magnetic and electric fields are recorded at the same location and Fourier analysis is used to convert the measurements into an impedance as a function of frequency that is proportional to electrical conductivity. Initially the MT method saw limited application because it was hampered by poor processing algorithms, cumbersome equipment, and interpretation of single sites or small arrays using one dimensional parameterized inversion with, at best, blocky 2D forward modeling. This started to change towards the end of the 20th century with the development of robust, multi-station processing algorithms, regularized inversion codes, and the availability of commercial acquisition equipment.

The most impressive manifestation of these improvements in MT methodology is the advent of initiatives to cover entire countries and even continents with MT stations on a 50 to 100 km station grid. These include campaigns to cover China (SINOPROBE), Australia (AUSLAMP), and the USA (US Array). Although there was some justifiable early concern that the site spacing was too large to allow meaningful interpretations, the 3D coverage and large numbers of stations seems to compensate for this. All three of these initiatives are on-going and are several years away from completion, but some very interesting 3D inversion results are being published from the data that are currently available. The model resolution can be comparable to seismic tomography inversions, and the sensitivity of the geomagnetic methods to melt fraction, temperature, and water content is superior.

A significant and recent expansion of the geomagnetic induction toolkit involves the extension to offshore data collection. The improvements to the MT method described above, along with a steep increase in industry activity and support, has resulted in a capability to collect offshore MT data with data quality and site spacing comparable to land stations. As with land MT, early development of the current generation of instruments was motivated by commercial targets, but academic applications followed, with some high profile results being obtained from mid-ocean ridges and subduction zones.

A Timeline:

5000 – 1000 BCE, discovery of iron:

Iron objects date from 5000–3500 BCE in Egypt, and based on the nickel content we know they were derived from meteorites. Smelting iron from ore may date from about this time, but the earliest objects found that are made from smelted iron date to 3000 BCE. Originally iron objects were ceremonial, and iron was more valuable than gold. The quality of the iron varied, now known to be a consequence of the amount of carbon it contains, and it wasn't until smelting introduced enough carbon and became routine enough that iron replaced bronze and the iron age began around 1200 BCE. It is the low carbon iron that is most easily magnetized, but also demagnetizes quickly. The coercivity of high carbon steel is higher and allows magnets to be made that last.

600 – 400 BCE, magnetic properties of lodestone:

Lodestone is naturally magnetized magnetite. Magnetite is a mixed valence iron oxide, $FeO.Fe_2O_3$, and normally does not stay magnetized for long (it has a relatively low coercivity), but lodestones have inclusions of maghemite (Fe_2O_3) that increases coercivity and allows it to keep its magnetization. Earth's magnetic field is not strong enough to magnetize lodestone, and likely magnetization is a result of being struck by lightning.

The Greek philosopher Thales of Miletus (624–546 BCE) describes lodestone's magnetic properties (attraction to iron and other lodestone). The Chinese text *Guiguzi*, written in the 4th century BCE, as well as later Chinese texts, mention the magnetism of lodestone, and around 200 BCE Chinese geomancers started using lodestones and magnetized iron for divination. The "south pointing spoon" made from magnetite is a famous early example, and later "south pointing fish" were pieces of iron that had been magnetized with loadstone and floated on water. Although these first written records came from Greece and China, based on magnetized artifacts it has been proposed that the Olmecs (from the current-day Veracruz area of Mexico) may have been using lodestones for geomancy as early as 1000 BCE.

The term “magnetism” is probably derived from the Greek city of Magnesia, now in modern-day Turkey, where magnetite is common.

1100 – 1200 CE, use of the compass for navigation:

While it is clear that the Chinese knew how to create a floating compass needle as early as 200 BCE, it was used for geomancy and Feng Shui, not navigation (the Chinese not being a seafaring nation at that time), and it is not until much later that we have records of the compass being used for marine navigation. This is such an important development that much effort has been expended trying to establish when and where the compass was first used in this way, but the first use is not clear – it is possible that European maritime trading groups kept initial knowledge of the compass secret for advantage. The Chinese polymath Shen Kuo is the first to describe a magnetic needle compass in his book “The Dream Pool Essays”, published in 1088 CE, but the first written Chinese record of compass use for maritime navigation dates it from 1086 CE (the maritime historian Zhu Yu writing in 1117 CE), so the compass must have been used in China before that time, possibly much earlier.

The first European written record of the compass for maritime navigation is from the English monk Alexander Neckam in 1187, but again the writing implies that the compass had been in routine use for some time. Although it seems likely the Chinese were using compasses before Europeans, it is not clear that the compass was introduced to Europe from China. There is evidence that it was discovered independently, one thing being that the Chinese reference the south-seeking pole, and the Europeans the north-seeking pole. In contrast, the earliest reference to the compass in Muslim writings describes a fish-shaped needle, a Chinese design.

1088 – 1510, Declination:

Earth’s magnetic field is complex, and the compass does not point to true north, but deviates by some angle. This “variation of the compass”, now called declination, depends on where you are on Earth, and varies slowly with time. It is plausible that the Chinese noticed that their south pointing fish did not point to true south (known from celestial navigation). Shen Kuo is attributed to first documenting this in his writing, although it is unclear if he was describing uncertainty in how to balance a magnetic needle or a systematic deviation in direction. The medieval English philosopher Roger Bacon, one of the first experimentalists, seems to have been aware that compass needles did not point to true north in 1266, but first European documentation for knowledge of declination comes from sundials manufactured in Nuremberg, Germany, around 1450. The sundials had magnetic compasses built into them in order to orient them properly, and had the declination marked so that they could be pointed to true north rather than magnetic north. That declination varies with location was first documented by Georg Hartmann, a German instrument maker, who measured declination in Nuremberg and Rome in 1510, which differed by 4 degrees. Mariners at that time were quickly discovering that declination varied with position, and even suggested that maps of declination could be used to estimate one’s longitude, a challenge before Harrison’s clock was developed in 1773. Writing on navigation in 1535, the Portuguese writer Falero provides instructions for measuring declination, and the Spanish navigator de Castro made measurements on voyages in 1538–1541.

1269, Peregrinus' letter:

Petrus Peregrinus was a French scholar, and possibly military man, who documented experiments in magnetism in a letter to a friend. That this letter was important in the history of magnetism is evidenced by it being copied at least 28 times, although it should be recognized that some of the material was already known at the time. Peregrinus presents the first description of polarity and is the first to use the term "pole", describing how to determine the poles of a magnet. He documents that if you break a lodestone in two, the pieces remain dipolar, and describes the repulsion and attraction of like and unlike poles. He described improved methods for constructing a compass. An English translation of the letter was published by Harradon (1943). Some choice selections are included below:

And just as there are two points in the heavens more noteworthy than all the others because the celestial sphere turns about them as upon axes, one of which is called the arctic or north pole and the other the antarctic or south pole, so also in this stone, you should clearly understand that there are two points, one north and the other south.

In order, therefore, that you may determine one point on the stone exactly, break from the needle or iron a little piece which shall be oblong and about as long as two finger-nails and place it on the spot at which, as already stated, the point has been found, and if it stands perpendicular to the stone, there is no doubt that the place sought is there; if not move it about until it does stand perpendicular. When this has been done mark the point there; and in a like manner you will find the opposite point on the opposite side of the stone. If you do this rightly and the stone is homogeneous and select, the points will be diametrically opposite each other just as are the poles of a sphere.

Having discovered which is the north and which the south pole of the stone, indicate the poles with incisions so that you may recognize them as often as necessary. And if afterwards you wish to see how one stone attracts another, you will arrange two stones, prepared as has been described, in the following manner. Place one in its vessel so that it may float just like a sailor in a ship. ... But hold the other stone in your hand. Present the northern part of the stone which you are holding, to the southern part of the stone floating in the vessel; for the floating stone will follow the stone which you hold, as if wishing to adhere to it. And if, on the contrary, you bring the southern part of the stone in your hand, near the northern part of the floating stone, the same thing will happen, namely, the floating stone will follow the one which you will be holding. Know then, as a rule, that the northern part in a stone attracts the southern part in another stone, and the southern part the northern. But if you do the opposite, that is, present the northern part to the northern part, the stone which you hold in your hand will appear to flee the floating stone, and if you present the southern part to the southern, the same thing will happen.

Take one stone which you may call by AD, in which A is the north and D the south point. Divide it into two parts so that two stones are made from it. After this, place the stone which contains A on water so that it may float; you will see that A turns towards the north as before. For breaking does not take away the properties of the parts of the stone, if it is homogeneous. Hence the part of this stone at the point of fracture which is B, must be the south. Let, then, this stone regarding which we have just been speaking be represented by AB; as to the other stone, which contains D, if it is placed on water, you will see that D is south as at first, because it turns towards the south, if placed on water. But the other part near the fracture, which may be *designated by C, will be the northern; this stone will therefore be CD; let the first stone AB be the agent, CD the patient, and thus you see that the two parts of the two stones which, before the separation, were continuous in one stone, after the separation, were found to be, one the northern and one the southern part. But if the same parts are again brought together, one will attract the other until they are joined together at the point BC, where the break took place. Thus by the natural appetite, they will form one body as at first*

1544 – 1581, Inclination:

Hartmann also observed that a compass needle dips from the horizontal (inclination), but the dip he observed was far too small to be a measure of inclination (also, he documented this in a 1544 letter to Duke Albert of Prussia, which wasn't made public until 1831). An English hydrographer and instrument maker, Robert Norman, made the first accurate inclination measurements. He first floated a neutrally buoyant compass needle in water, and then manufactured pivoting "dip needles", documented in his book "The Newe Attractive" in 1581. He went on to measure inclination at various locations and observed that it too, like declination, changes with position, and could be used for navigation. Parkinson (1983) considers this to be the beginning of geomagnetism as a discipline.

1600, William Gilbert's *De Magnete:*

William Gilbert, 1544–1603, was an English natural philosopher appointed principle physician to Queen Elizabeth I. His book, *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure* (On the Magnet and Magnetic Bodies, and on That Great Magnet the Earth) stands as one of the greatest works of science. Gilbert reviews all that is known about magnetism (drawing substantially from Peregrinus), but uses deduction and logic to sort fact from fiction, then follows with his own experiments. He is famous in geomagnetism for equating the magnetic field of Earth with that of a *terrella,* a sphere of magnetite, noting the pattern of inclination with latitude and that Earth's magnetism must come from iron in its center. He is also the first to use the term *electric,* (from the Greek word for amber) and distinguishes electric action at a distance from magnetic forces:

A loadstone attracts only magnetic bodies; electrics attract everything. A loadstone lifts great weights; a strong one weighing two ounces lifts half an ounce or one ounce. Electrics attract only light weights; e.g., a piece of amber three ounces in weight lifts only one-fourth of a barleycorns's weight.

In order to study electric fields, he invents the electroscope. Although his book focusses mainly on magnetism, he infers the diurnal rotation of Earth and considers the celestial spheres an absurd idea, makes observations on the surface tension of water, and comments on the precession of the equinoxes and how the inclination of the pole produces seasons.

1635, Secular variation:

Henry Gellibrand, using earlier measurements made in 1580 by William Borough and in 1622 by Edmund Gunter, observed that by 1633 declination in London had decreased by nearly seven degrees over 54 years. As Parkinson notes, the implications for navigation were considerable, since some nautical charts were almost a century old.

Edmund Halley (1656–1742), astronomer of comet fame, was interested in geomagnetism and made extensive measurements of declination. He tried to explain the pattern of declination known at the time in terms of 4 magnetic poles, but later realized that no magnet had more than two poles, and in 1692 extended a theory to explain both declination and secular variation by an Earth made of two uniform magnetic shells separated by a fluid medium. Differential rotation of the inner shell explains secular variation. We know now that this doesn't work to explain the observations – the outer shell would still only have two poles – but the idea of internal fluid motion of magnetized material is on the right track. Halley also noted the westward drift of the magnetic field variations.

In 1698 Halley was given a ship (the *Paramour*) and a captain's commission by King William III in order to improve knowledge of declination. He made several voyages between 1698 and 1700, and combined his measurements with other mariners' to produce a chart of the magnetic declination centered on the Atlantic. This famous map is the first use of contour lines. As noted by Chapman (1943), it is a shame that Halley did not make inclination measurements as well.

1778–1829, Intensity:

Jean-Charles de Borda developed a method for making relative field intensity measurements by measuring the period of oscillation of a magnetic dip needle, in 1778 (this is analogous to using a pendulum to measure gravity). During his travels through the Americas, Alexander von Humboldt made relative measurements of magnetic field intensity with this method, using Micuipampa (Peru) on the magnetic equator as the reference. He observed that the period decreased (intensity increased) as he moved both north and south of the equator. He continued to make magnetic field measurements on his other (extensive) travels, and used them to make "isodynamic" maps.

1785: Charles-Augustin de Coulomb:

Coulomb, a French military engineer/physicist, developed the inverse-square law for charges using a torsion balance.

1799: The battery:

Alessandro Volta invents the battery ("Voltaic pile").

1820: Hans Oersted:

Oersted, a Danish scientist, observed that an electric current deflected a magnet.

1820's: André-Marie Ampère:

Ampere (France) quantified Oersted's phenomenon and also noted that an electric current exerts a force on a second electric current. He noted that a coil behaved like a magnetic dipole, and that the moment was the product of the current and coil area.

1831: Michael Faraday:

Faraday (England) observed that moving a magnet through a coil produces an electric current. In 1832 he predicted that water moving through a magnetic field should produce an electric field- this was observed by the British Admiralty in 1918.

1838: Carl Friedrich Gauss:

Gauss (1777–1855), professor of astronomy in Goettingen (Germany) made many contributions to science and mathematics, but fortunately became interested in geomagnetism. He developed the oscillation-deflection method, extending Borda's relative intensity measurements to absolute intensity, including an observatory instrument that could make continuous measurements of horizontal intensity. He related the unit of magnetism to mass, charge, and time. He generalized Coulomb's Law using his flux theorem. In 1838 he published the method of representing a potential field using spherical harmonics, allowing Earth's internal and external fields to be separated. He noted that the observations of the geomagnetic field made to date were consistent with an internal origin. He helped found the global magnetic observatory network.

1838–1859, Induction effects in telegraphy:

The magnetic storm of 1938 is seen as signals on Norwegian telegraph cables. W.H. Barlow reports spontaneous currents in telegraph lines in England. K.T. Clement noted that the aurora of 29 August disrupted telegraphy.

1864: James Clerk Maxwell :

Maxwell (a Scot) recognized that Ampere's and Faraday's laws are both aspects of electromagnetic radiation. Maxwell's equations are (almost) born.

1884: Oliver Heaviside:

Heaviside, a telegraph engineer, developed vector calculus and recast Maxwell's original twenty equations in twenty unknowns down to four differential equations in two unknowns now known as Maxwell's equations.

1889–1908: Arthur Schuster observed the relationship between the diurnal magnetic variation and Earth potentials.

1939: The GDS method:

Lahiri and Price publish the first deep conductivity profile.

1950 – 1953: The magnetotelluric method:

The theory of the magnetotelluric method is published by Tikhonov and Cagniard. Applications soon follow, with nearly 100 papers published in the 1960's.

Supplemental Reading

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