CHAPMAN, SYDNEY (1888–1970)

Sydney Chapman received 17 degrees (mostly honorary doctorates), published seven books and over 400 scientific papers, received nine major medals (including the Royal and Copley medals of the Royal Society), held ten visiting chairs, was president of eight professional societies, and fellow of many more. Rather than try to encompass a career of such breadth and depth, it is mainly his contribution to geomagnetism that is considered here, though he also contributed massively to, *inter alia*, solar-terrestrial physics, ionospheric physics, meteorology, aurorae, and the kinetic theory of gasses.

Chapman was born in Eccles, Lancashire, on January 29, 1888. He was set to enter an engineering firm, but, before doing so, he won the last of 15 university scholarships offered by Lancashire and went on to take an engineering degree at Manchester University. He stayed on for a further year and added a mathematics B.Sc. On the advice of Horace Lamb, he then tried for and obtained a Cambridge mathematics scholarship. He completed the examinations after two years at Trinity College, but was required to stay on for a further year before graduating. During this time he received a visit from Frank Dyson, the Astronomer Royal, offering him the prestigious and well-paid post of Chief Assistant at the Royal Observatory, Greenwich. (The other Chief Assistant at the time was the cosmologist Arthur Eddington, with whom Chapman devised the cycling performance measure n, which is the number of occasions on which n or more miles have been cycled in a day. Eddington achieved $n = 77$, and Chapman rather more.)

Chapman was at Greenwich from 1911 to 1914, and again from 1916 to 1918 to help out when many of the staff were at the war. He was a conscientious objector during the World War I—a far from easy option—but had revised his views by the time of World War II. While at Greenwich, Chapman was introduced to geomagnetism. He organized the re-instrumentation of the magnetic observatory, took part in the routine magnetic observations (on his own admission he was not a good observer), and set about the interpretation of geomagnetic variations.

In 1919 he moved from Trinity College, Cambridge, to succeed Lamb in the chair of mathematics and natural philosophy at Manchester. In the same year he was elected to Fellowship of the Royal Society at the early age of 31. This was largely for his work on the theory of solar and lunar daily geomagnetic variations.

In 1924, Chapman became chief professor of mathematics at Imperial College, London, where he remained until 1946. While there, he won the John Couch Adams essay prize, the subject of which (chosen at the suggestion of Dyson, with Chapman in mind) was the theoretical interpretation of geomagnetic phenomena. One of the conditions of the award was that the work should be published, which Chapman satisfied with a number of papers. But he also felt obliged to turn the essay into a book. In this he collaborated with the young German scientist *Julius Bartels* (*q.v.*) to eventually produce the two-volume *Geomagnetism* in 1940. This became the "bible" for geomagneticians for half a century. Though the instrumental part and the bibliography are now outdated, the mathematical sections are still of sufficient value to make this book an important part of any geomagnetic library.

It was also during his time in London that Chapman started his collaboration with V.C.A. Ferraro on the theory of magnetic storms, which was to be superseded only when satellite observations became available. With another of his students, *A.T. Price* (*q.v.*), he examined the currents induced in the Earth by Sq and their implication for mantle conductivity.

In 1946, Chapman moved to Oxford University to become Sedleian Professor of Natural Philosophy, a post he held until approaching compulsory retirement at 65. Rather than retire, he moved to the United States, where he already held visiting appointments. This was during the lead-up to the 1957/8 International Geophysical Year (IGY) and Chapman, as president of the IGY Special Committee, took the opportunity to travel widely, soliciting support for the project. As well as his theoretical work, he had undertaken many analyses of vast quantities of observational data and was well aware of the need for such data on a world-wide basis.

In the final, though far from inactive, part of his career (more than 150 papers were published after his "retirement"), Chapman divided his time between the Universities of Colorado and Alaska. In Alaska he worked with S.-I. Akasofu on geomagnetic disturbance phenomena and in Colorado with several colleagues, largely updating and extending earlier work in the light of recently acquired data, including IGY data. He was still actively working until a few days before his death on June 16, 1970.

Chapman's personal qualities were as remarkable as his scientific ability. He was slightly built, but very athletic, though his feats were of endurance rather than speed. Some mention has already been made of his cycling prowess. He gave up cycling at about 70, mainly because American highways were not cyclist-friendly, as he and his wife discovered experimentally. He swam half a mile a day throughout his life, going to considerable lengths to avoid missing a day. The nearest he came to owning a car was a half-share in one with Bartels, but only briefly. He much preferred to walk. He was a gentleman with strong moral principles and was always greatly considerate of the feelings of others. His many colleagues and students valued him as much as a friend as for his teaching.

Stuart R.C. Malin

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COAST EFFECT OF INDUCED CURRENTS

Introduction

When changes in Earth's magnetic field are measured on timescales of about 1 hour, the vertical component near most coastlines is abnormally large and correlates with the onshore horizontal component. This phenomenon is known as the geomagnetic coast effect. It is caused by electromagnetic induction occurring naturally in the Earth's surface layer.

The "primary" currents in the induction process are electric currents, which flow external to the Earth and change with time. As the solid Earth and its oceans conduct electricity, "secondary" currents are induced to flow in them. At Earth's surface, observations of magnetic and electric variations record the effects of the primary and secondary fields combined. Because in many instances the primary fields are uniform and spatially uncorrelated from one induction event to the next, spatial patterns occurring systematically reflect spatial patterns in the secondary fields due to structure in the electrical conductivity of the Earth.

The main electrical conductivity contrast at Earth's surface is between land and seawater. Seawater is a relatively homogeneous material, with its electrical conductivity, σ, depending mainly on salt content and temperature. A typical value for σ throughout the world's oceans is 3.3 S/m, in a range of 3 S/m for cold, less saline water to 6 S/m for warm, salty water (Bullard and Parker, 1970).

Land generally consists of inhomogeneous rock material and its conductivity, in contrast to that of seawater, varies by orders of magnitude (Sheriff, 1999). However the electrical conductivity of rock material generally is less than that of seawater. Further, the electrical conductivity of rock material is generally less than 1 S/m, leading to the common use of electrical resistivity ρ (the reciprocal of conductivity σ) when describing rock material. Thus a resistivity of 1 Ωm is equivalent to a conductivity of 1 S/m and a resistivity of 10 Ωm is equivalent to a conductivity of 0.1 S/m.

Then rock material typically has a resistivity of some hundreds of Ω m in the crust and possibly thousands of Ω m in ancient cratonic rocks. In sedimentary basins the resistivity may be less, say tens of Ω m. In ore bodies, and in crustal concentrations of the good conductor graphite, the resistivity may be only small fractions of an Ωm; however such good conductors form only a minor part of the total volume of crustal rocks.

The land-ocean conductivity contrast exerts a strong effect on electromagnetic induction at Earth's surface. Induction at places of such conductivity contrast is characterized by the generation of a vertical magnetic field component. Near a land-ocean contrast, this vertical component is seen as the geomagnetic coast effect.

Discovery of the coast effect

The coast effect was first observed by Parkinson (1959, 1962) and the discovery demonstrated that conductivity contrasts at and near Earth's surface could be detected by using natural electromagnetic induction at periods of about 1 hour. Parkinson's early results for Australia are shown in Figure C7 (see *Parkinson, Wilfred Dudley*).

At about the same time detailed observations of magnetic fluctuation patterns were also made in other continents, for example by Schmucker (1963); Rikitake (1964); Price (1967). The advent of digital recording and time-series analysis using electronic computers led to numerical analysis methods replacing Parkinson's graphical methods and the phenomenon was investigated as a function of frequency (Everett and Hyndman, 1967; Schmucker, 1970). One consequence of this development was then to demonstrate in-phase and out-of-phase components of the coast effect. Generally the in-phase component is stronger than the out-of-phase component (a result of the high conductivity of seawater) and often the effect is described and interpreted simply in terms of the in-phase component. If the out-of-phase component is being studied, care must be taken with the definition of phase (see Lilley and Arora, 1982). See also *induction arrows* (*q.v.*).

Observation of the coast effect

The review by Parkinson and Jones (1979) gives a global survey of the observation of the coast effect, which is still geographically representative. The authors note that the few coastal locations where the coast effect is absent are tectonically anomalous. In a regular coast effect, the strength of the phenomenon, as reckoned by the response in the vertical component of the fluctuating field, reduces to about half its coastal strength at a distance of some hundreds of kilometers inland.

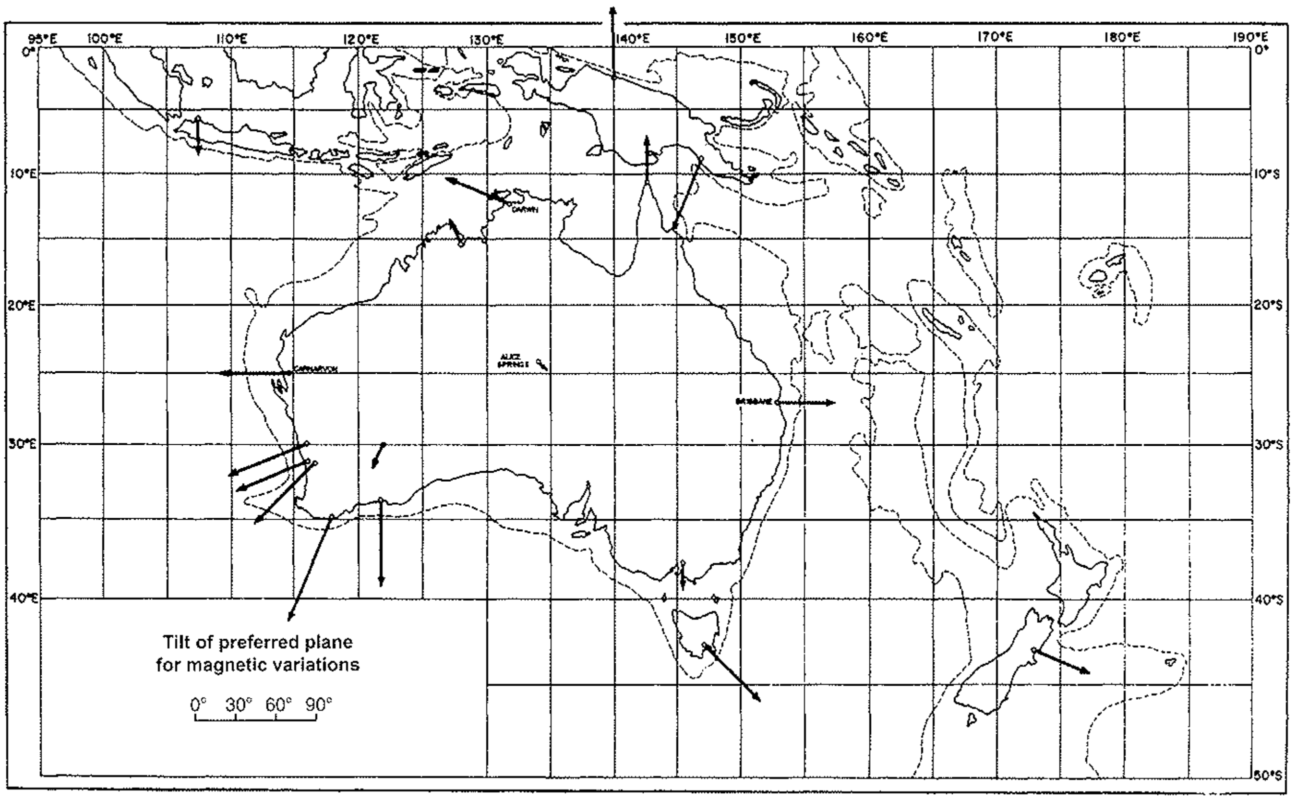

Figure C7 Early Parkinson arrows for Australia, after Parkinson (1964). Small magnetic vector changes at an observatory tend to lie in a "preferred plane." The horizontal projection of the downwards normal to this plane gives arrows as shown which, generally pointing to the high conductivity side of a nearby conductivity contrast, point to the deep ocean.

The authors also note that the coast effect varies only slightly with period, reaching a broad maximum in the period range 30–90 min. An important quantity is the electromagnetic "skin depth," δ,

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \qquad \text{(Eq. 1)}$$

where ω denotes angular frequency and μ denotes the permeability of the material (usually taken as that of free space). For the period range 30–90 min, the skin depth of seawater is some 20 km, which is greater than the ocean depth. Thus an external magnetic fluctuation signal reaches the ocean floor and penetrates the seafloor rock material and the ocean may be regarded as an electromagnetic "thin sheet."

An example of induction arrows for the coast effect of southeast Australia, observed on both land and seafloor, is shown in Figure C8 (White *et al.*, 1990). The site is favorable for a clear demonstration of the effect, as the coastline runs relatively straight for hundreds of kilometers, the continental shelf is narrow, and at the foot of the continental slope the seafloor is deep (almost 5000 m) and flat, comprising the Tasman Abyssal Plain. Included in the compilation are sites spaced down the continental slope. As can be seen from the induction arrows, the coast effect is at a maximum about halfway down the slope into the deep ocean.

An example of the data recorded in this particular case is shown in Figure C9. Displayed are the horizontal and vertical components of magnetic variation at five stations. It is in the vertical components that the coast effect is evident and the signal can be seen to be a maximum at station 4 (the trace marked CS4Z).

Fluctuations in the geomagnetic field occur over a wide frequency band, and the coast effect has also been investigated at shorter and longer periods. At shorter periods, the effect has been demonstrated to occur in "pulsations" of period order 1 min and less. At these short periods the skin depth of seawater no longer is greater than the depth of the deep ocean, and the effect takes place in the upper layer of the ocean. The relatively shallow seawater of the continental shelf becomes important.

At longer periods, a natural frequency band at which to examine the coast effect is that of the magnetic daily variations (termed "Solar quiet," and denoted Sq). However, for these signals different observation and analysis techniques are required due to the presence of a significant vertical component in the Sq source field.

Generally there is agreement that major "electric current gyres" are induced to flow in the oceans by the Sq source fields (Beamish *et al.*, 1983) and these also have a measurable effect at observatories near coast lines. Bennett and Lilley (1973) showed how a coast-effect vertical component could be separated from an observed record by subtracting an inland record observed simultaneously, which was taken to be a "normal" (i.e., background) component.

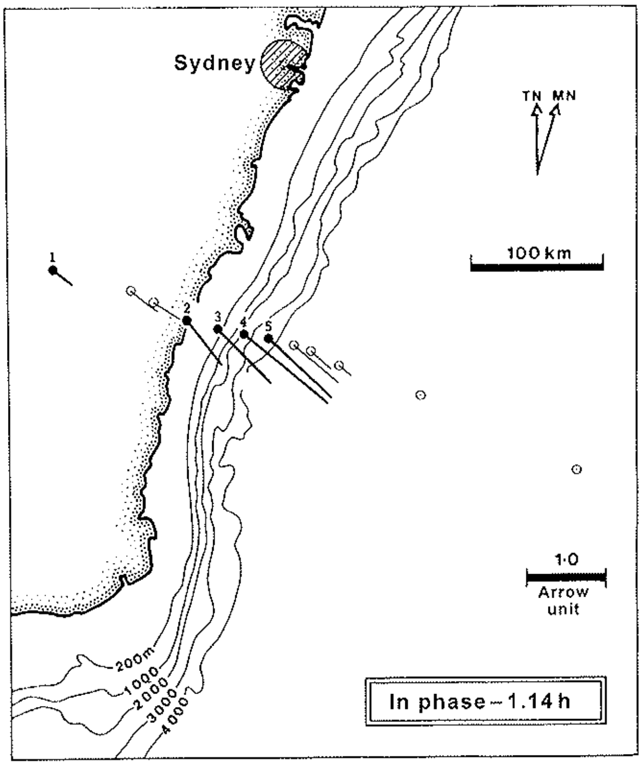

Figure C8 Induction arrows (in-phase, for period 1.14 h) for the coast of southeast Australia, for a line of stations from inland to deep seafloor (Ferguson, 1988; Lilley *et al.*, 1989; White *et al.*, 1990).

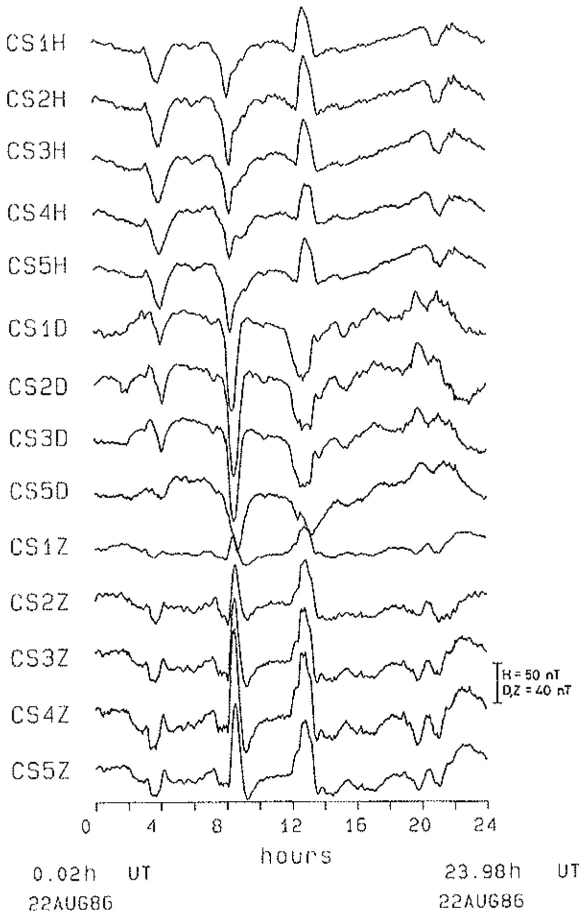

Figure C9 Examples of magnetic fluctuation records for one day, showing the coast effect (White *et al.*, 1990). The top five traces, with suffix H, are the horizontal north components for stations 1 to 5, as marked on Figure C8. The middle set of traces, with suffix D, are the horizontal east components. The lower five traces, with suffix Z, are the vertical components. The strength of the signal in the vertical component characterizes the coast effect, as it is the result of the electrical conductivity structure at the land-sea interface. Note this signal is strongest at station 4, half way down the continental slope.

Analogue modeling of the coast effect

The relative electrical conductivities of rock material and seawater lend themselves to analogue model studies. Following the initial global "terrella" model of Parkinson (1964), model studies have been carried out on geometries seen in coastlines worldwide (Dosso, 1973). These analogue models have the ability to model 3D situations, such as the islands of Tasmania (Dosso *et al.*, 1985) and New Zealand (Dosso *et al.*, 1996).

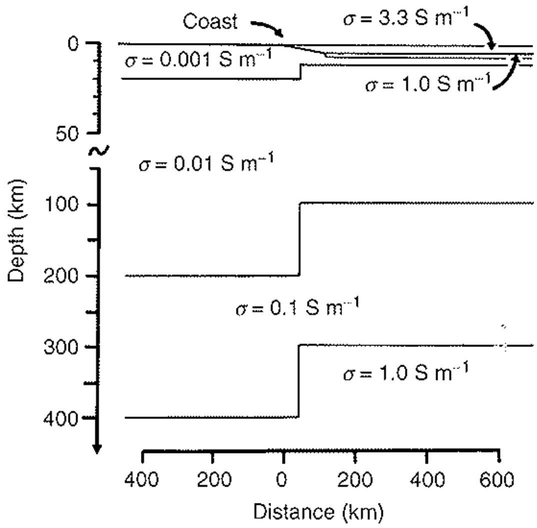

Figure C10 A two-dimensional model for the coast effect shown in Figures C8 and C9, with seawater layer and contrasting electrical conductivity structure beneath continent and ocean (Kellett *et al.*, 1991).

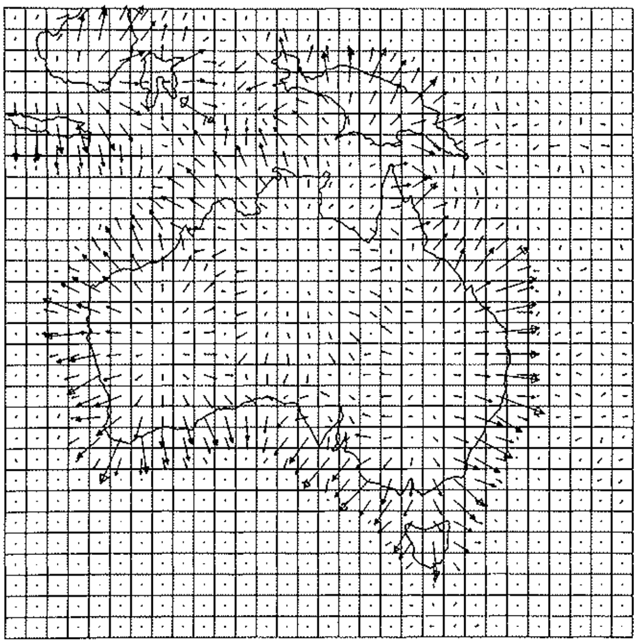

Figure C11 The electromagnetic response of a thin-sheet model of Australia presented as induction arrows, for period 1 h (in-phase) from Corkery and Lilley (1994). (Scale: an arrow which exactly spans a grid unit has a magnitude of 0.3).

Calculation of the coast effect

The basic calculation of the coast effect is a two-dimensional problem and the forward problem was solved in one of the early achievements of numerical modeling of electromagnetic induction in the Earth (Jones and Price, 1970; Weaver, 1994). Given that the ocean bathymetry is generally known well, the calculation becomes an exercise in modeling the rock material beneath the seawater. Figure C10 shows such a 2D model for the observed data shown in Figures C8 and C9.

As abilities in 2D and 3D numerical modelling and inversion have progressed, the coast effect has been a basic case for testing new methods and techniques. As an example, which may be compared with Figures C7 and C8, the induction arrow response for a numerical model of the Australian continent set in its surrounding seas (Corkery and Lilley, 1994) is shown in Figure C11.

Geophysical ocean-coast transects

Geophysical studies now frequently address the tectonic boundaries, which may be present at coastlines. By making observations along a transect, which crosses the coast line from deep ocean to inland, information may be obtained, which characterizes the structure and history of the region. Electromagnetic studies to obtain electrical conductivity information have been foremost amongst such transects, which have included subduction zones (Yukutake *et al.*, 1983; EMSLAB-Group, 1988) and passive margins (Wannamaker *et al.*, 1996). These transects

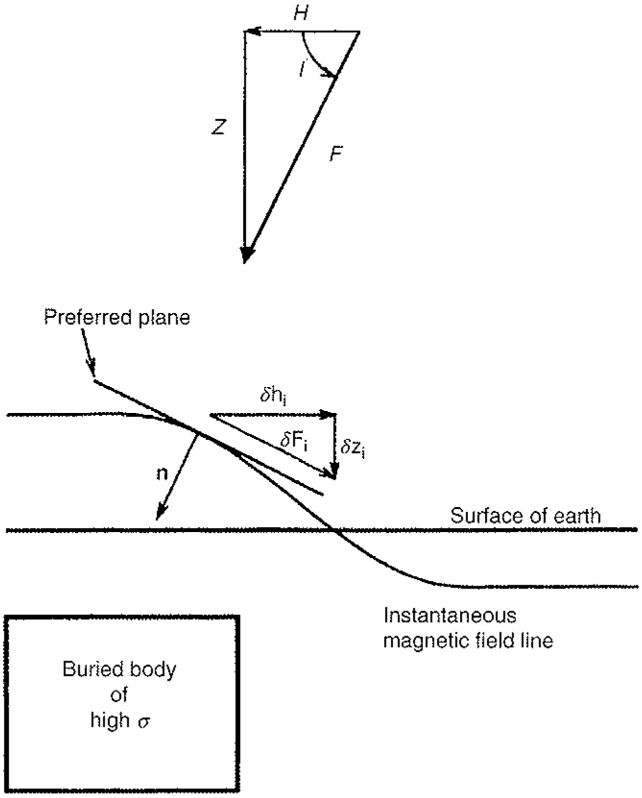

Figure C12 Diagram showing, near a buried body of high electrical conductivity, the "preferred plane" in which small vector magnetic changes tend to lie, and the normal **n** to the preferred plane. When the normal **n** is parallel or antiparallel to the main field **F**, a total-field magnetometer such as a proton-precession instrument will be insensitive to the small vector changes (Lilley *et al.*, 1999).

have given some of the most comprehensive observations of the coast effect, with electric and magnetic field measurements on both land and seafloor. Note also that Hitchman *et al.* (2000) made observations of the coast effect offshore at the sea surface, using a floating total-field magnetometer.

An application of the coast effect

Coast effects cover large regions and their influence may be widespread. An example is the "amphidrome" effect, which, as a result of the coast effect, exists across a wide swath of southern Australia (Lilley *et al.*, 1999). Here the coast effect causes the Parkinson preferred plane to be approximately orthogonal to the main magnetic field vector. Thus fluctuation events, which generally lie in the preferred plane, tend to be orthogonal to the main field and the component of them measured by a "total field" magnetometer (as in an aeromagnetic survey) is much reduced.

Figure C12 illustrates the "amphidrome effect" in which magnetic fluctuation signals, measured by a "total field" magnetometer, are suppressed when the normal to the Parkinson preferred plane is parallel to Earth's main magnetic field vector.

Conclusion

The geomagnetic coast effect is regarded as being well understood, and is primarily due to the electrical conductivity contrast between land and seawater, controlling natural electromagnetic induction in the environs of a coastline.

Ted Lilley

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Cross-references

Electromagnetic Induction (EM)
Geomagnetic Deep Sounding
Induction Arrows
Magnetotellurics
Mantle, Electrical Conductivity, Mineralogy
Parkinson, Wilfred Dudley