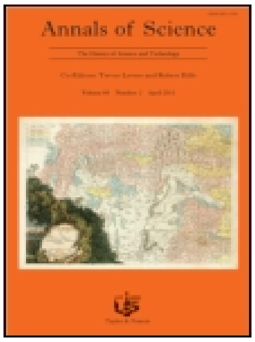

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The Lodestone: History, Physics, and Formation

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Summary

The lodestone is an extremely rare form of the mineral magnetite (Fe_3O_4) that occurs naturally as a permanent magnet. It therefore attracts metallic iron as well as fragments of ordinary 'inert' magnetite. This 'magic' property was known to many ancient cultures, and a powerful lodestone has always commanded a high price. By the eleventh century AD the Chinese had discovered that a freely suspended elongated lodestone would tend to set with its long axis approximately north–south, and utilized this property in the magnetic compass. They also appear to have discovered that this invaluable characteristic could be handed-on to a steel needle if the latter were contacted with, or stroked by, a lodestone.

The magnetism of the lodestone was scientifically investigated by William Gilbert in the sixteenth century, when he defined its 'poles' and the well-known rule that 'like poles repel, unlike attract'. He also studied 'inclination' and 'variation', and means to aid the preservation of magnetic power. How to concentrate it by 'arming' the lodestone with caps or pole-pieces of soft iron was discovered in the same century. These methods have been repeated, confirmed, and improved. The lodestone occupies a vital place in the history of magnetism, but little beyond Gilbert's work can be reached by historical studies because vastly improved steel or alloy permanent magnets, and electromagnets, replaced it before quantitative measurements were developed. These techniques have therefore been applied retrospectively to both museum specimens and contemporary natural lodestones. A good source of the latter was found to be the igneous complex known as Magnet Cove, Arkansas, and this material has been used as the 'type example'. All specimens were discrete, well-rounded, rusty brown pebbles found near the surface. Their unweathered interiors were black titano-magnetite. No significant trace element or crystallographic differences could be found between the lodestones and the magnetically inert material that always accompanied them. The magnetic moment per unit volume (J_v) of the 'as-found' Magnet Cove lodestones varied between 6.5 and $11.6\,\mathrm{emu\,cm^{-3}}$, which compares poorly with the hundreds of units characteritzing modern permanent magnets. Hysteresis loops gave a saturation intensity (J_s) of $27–51\,\mathrm{emu\,cm^{-3}}$, suggesting that intensity has diminished since formation. This agrees with general experience of magnets, especially in the absence of a 'keeper'. The initial volume susceptibility of Magnet Cove magnetite was about 0.18 for low fields, and always remained <1. This means that a normal terrestrial magnetic field with a maximum vector $<1\,\mathrm{Oe}$ is unable to induce even the low magnetic moments we see today, while a field approaching 1000 Oe is required for saturation. These parameters, and the rare occurrence of lodestones as near-surface fragments, support suggestions that they are the product of a lightning strike upon an exposure of a suitable (titanium-rich?) magnetite.

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Transient currents averaging 30 000 A have been measured. This would give rise to a zone of potential magnetic saturation at least 12 cm in diameter, to which some of the ejected fragments would be exposed. An attempt to determine the period elapsed since formation of the Magnet Cove lodestone was made by annealing magnetically saturated specimens at temperatures up to 500°C, and measuring J_v at weekly intervals for 100 days. The decay curves visually resembled exponential functions, but mathematical tests proved that they were not strictly so. Interpretation was therefore difficult, but a pragmatic procedure involving excessive extrapolation suggested an 'age' of about 3500 years.

Contents

1. History

Lodestone is a natural mineral body, rich in iron oxide, that behaves as a permanent magnet. The strange attractive force it consequently exerts upon metallic iron was known to ancient Greek philosophers such as Thales (*c.* 600 BC), with their attempts at explanation tending to involve analogy, magic, and occult forces, or even religion.[1] Mineralogically, the mineral involved is magnetite, Fe_3O_4. This name, and that of the phenomenon of magnetism, may be derived from *Magnesia*, a district in Thessaly where lodestone could be found.

1.1. *Medieval and later studies*

Not until medieval times were serious attempts made at what we would recognize as scientific experiments and explanation, with a letter of Petrus Peregrinus[2] written in AD 1269 marking the beginning of this phase. However, knowledge of magnetism remained fragmentary and disjointed[3]—and sometimes contradictory or ridiculous—until William Gilbert (1540–1603) undertook the task of unification based on a logical sequence of experimental observations. His book *De Magnete*,[4] published in Latin in 1600, remains a classic in the history of science. The title page of the second edition (1628) is reproduced in Figure 1.

Unfortunately, Gilbert's text was not translated in full until 1893, and this hindered widespread knowledge of its contents. Thus Ridley,[5] writing in 1613, appears unaware of the work. It took Barlowe[6] sixteen years to produce an English-language book that appears to be mostly derived from Gilbert, and not until the second half of the seventeenth century was magnetism given further study and featured in works by Kircher,[7] Dalencé,[8] and Boyle.[9] Even by 1730 Savery[10] does little more than freely translate and reorganize Gilbert—without the courtesy of acknowledgement. These and other works are conveniently listed, and sometimes partially reproduced, in a bibliography by Mottelay.[11]

Gilbert noted that iron and steel bars could be 'magnetized' by contact

[1]Joseph Ennemoser, *Der Magnetismus im Verhältnisse zur Natur und Religion* (Stuttgart, 1842). Albert Radl, *Der Magnetstein in der Antike: Quellen und Zusammenhänge* (Stuttgart, 1988). Gudrun Stecher, *Magnetismus im Mittelalter: von den Fahigkeiten und der Verwendung des Magneten in Dichtung, Alltag und Wissenschaft* (Kummerle, 1995).

[22]Petrus Peregrinus, *Epistola de Magnete* (1269), MS reproduced by Quaritch (London, 1900), trans. by Silvanus Thompson (London: Chiswick Press, 1902). A more accessible source is Mottelay (note 11).

[3]Agricola, *De Natura Fossilium* (Basle, 1546), trans. by M. C. and J. A. Bandy, *Geological Society of America, Special Paper 63*, (1953). Agricola, *De Re Metallica* (Basle, 1556), trans. by Hoover (London, 1912). J. B. Porta, *Magia Naturalis* (Naples 1558), trans. as *Natural Magic* (London, 1658), Book VII: *The Magnet*. Robert Norman, *The Newe Attractive: Containing a Short Discourse of the Magnes or Lodestone* … (London, 1581).

[4]William Gilbert, *De Magnete* (London, 1600), trans. by P. Fleury Mottelay (1893; New York: Dover, 1958). Silvanus P. Thompson, *Gilbert of Colchester* (London, 1891). E. B. Gilberd and Lord Penny *William Gilberd* (Colchester: Castle Museum, 1970). The last of these works claims that 'Gilberd' is the correct spelling, based on an extant signature.

[5]Marke Ridley, *A Short Treatise of Magnetical Bodies and Motions* (London, 1613).

[6]William Barlowe, *Magnetical advertisements, or, Divers pertinent observations, and approved experiments concerning the nature and properties of the load–stone* … (London,1616); microfiche edition, 'Landmarks of Science' collection (New York: Readex, 1992).

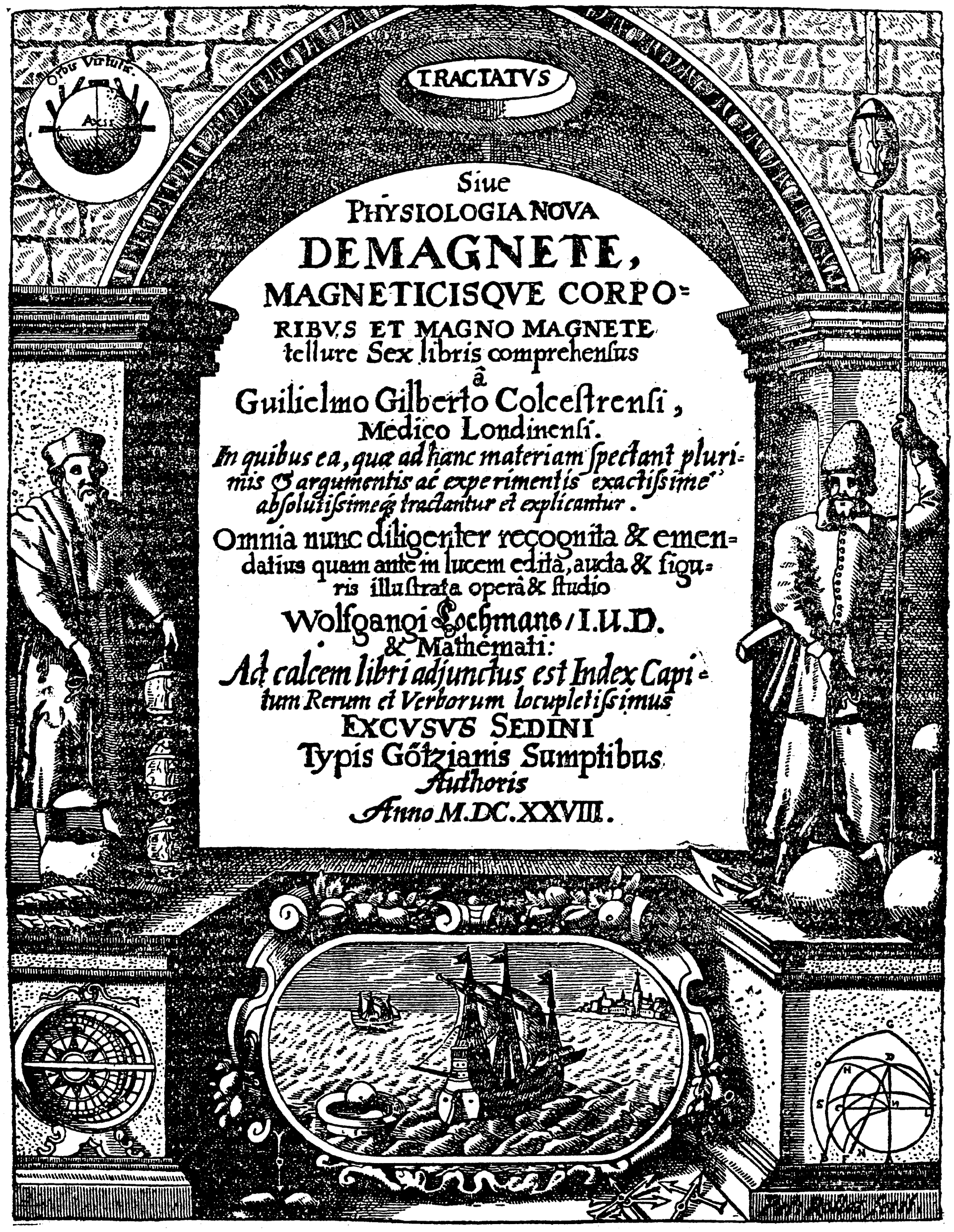
[7]Athanasius Kircher, *Magnes* (Cologne, 1643), and *Magneticum Naturae Regnum* (Rome, 1667).

[8]Dalancé, *Traitte de l'Aiman* (1687).

[9]Robert Boyle, *Experimenta & Observationes Physicae* (London, 1691).

[10]Servington Savery, 'Magnetical Observations and Experiments', *Philosophical Transactions*, 36 (1730), 295–340.

[11]P. F. Mottelay, *Bibliographical History of Electricity and Magnetism* (London, 1922).


TRACTATVS
Siue
PHYSIOLOGIA NOVA
DE MAGNETE,
MAGNETICISQVE CORPO-
RIBVS ET MAGNO MAGNETE
tellure Sex libris comprehensus
à
Guilielmo Gilberto Colcestrensi,
Medico Londinensi.
In quibus ea, quæ ad hanc materiam spectant pluri-
mis & argumentis ac experimentis exactissime
absolutissimeq; tractantur et explicantur.
Omnia nunc diligenter recognita & emen-
datius quam ante in lucem edita, aucta & figu-
ris illustrata operâ & studio
Wolfgangi Lochmans I.U.D.
& Mathemati:
Ad calcem libri adjunctus est Index Capi-
tum Rerum et Verborum locupletissimus
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Authoris
Anno M.DC.XXVIII.

Figure 1. Title page of the second edition (1628) of William Gilbert's book *De Magnete*.

with a lodestone or, better, by unidirectional stroking with one end of a powerful stone. This produced cheaper and more conveniently shaped magnets, which exhibited reasonable stability if produced from high quality hardened steel. In turn, these could be assembled into stacks to magnify the intensity, and then used to manufacture more steel magnets.[12] These had rendered the lodestone obsolescent by the end of the eighteenth century, and its eclipse was completed by the invention of the electromagnet early in the next century. The lodestone is therefore relegated to an introductory section in most works on magnetism from the mid-nineteenth century onwards. Reviews that incorporate more than usual are listed in note 13.

2. Basic properties of the lodestone

Gilbert's monograph was accumulated over many years, so is rather verbose and repetitive by current standards. It is therefore proposed first to summarize what Gilbert had to say, and then to amplify his statements with more recent observations and research.

2.1. *Lodestone is a rare form of magnetite*

All lodestones surviving in museums of the history of science are rich in the mineral magnetite, Fe_3O_4, so it is clear that this high grade iron ore is the one that Gilbert had in mind. The most obvious special characteristic of the lodestone is that it attracts metallic iron, thereby displaying *magnetism*. This is not a property of iron ores in general, or of magnetite in particular. Gilbert makes it perfectly clear that only a very few specimens of magnetite exhibit an obvious external magnetic field, and as such are entitled to be called lodestones. (He spells the word '*loadstone*'—this terminology will be discussed later.) Unfortunately, the distinction became blurred in the nineteenth century, when geologists became accustomed to testing minerals in the field with a pocket permanent magnet. All magnetite and magnetite-rich samples are attracted, and were (and still are) referred to as 'magnetic'. It must therefore be emphasized that attraction to a permanent magnet is not a sufficient test for a lodestone: it must itself be capable of attracting pieces of iron, just like the familiar man-made permanent magnet. In other words, all lodestones are magnetite, but only a very small percentage of specimens of magnetite are lodestones.

2.2. *Value*

Presumably, old-time prospectors and iron miners would set aside any lumps of ore that they observed to possess the mysterious property of attracting iron tools, and subsequently sell these lodestones to travelling dealers. Making their way up the chain to the final user could result in an enormous increase in price, particularly if imported into Europe from romantic faraway countries like the East Indies, China or Bengal. An equal weight in silver might be sought. McKeehan[14] states

[12]Savery (note 10). Gowan Knight, 'An Account of Some Magnetical Experiments …' *Philosophical Transactions*, 43 (1744), 161–66, and 44 (1744), 656–72. J. Michell, *A Treatise of Artificial Magnets* (Cambridge, 1750). J. Canton, 'A Method of Making Artificial Magnets Without the Use of Natural Ones', *Philosophical Transactions*, 47 (1753), 31–38. J. Fothergill, 'An Account of the Magnetical Machine Contrived by the Late Dr Gowin Knight', *Philosophical Transactions*, 66 (1776), 591–99. Tiberius Cavallo, *A Treatise on Magnetism* (London, 1800).

[13]David Brewster, 'A Treatise on Magnetism', in *Encyclopaedia Britannica*, 7th ed (1837). J. B. Kramer, 'The Early History of Magnetism', *Transactions of the Newcomen Society*, 14 (1933–34), 183–200. Alfred Still, *Soul of Lodestone: The Background of Magnetical Science* (New York, 1946). E. N. da C. Andrade, 'The Early History of the Permanent Magnet', *Endeavour*, 17 (1958), 22–30. L. W. McKeehan, *Magnets* (New York, 1967).

[14]McKeehan (note 13).

(without quoting any source) that at one time in England the price of a lodestone was based on the formula

Value in pounds sterling = Weight of stone in pounds avoirdupois
Multiplied by the weight of the heaviest piece of iron it could lift.

Presumably, these were 'cased' lodestones with a matching keeper—see below. Lodestones rated at 100 lb^2 would very effectively advertise their owner's wealth, so so one might speculate that the importance attached to this characteristic is why they were sometimes called '*loadstones*'. Present-day vendors of 'bare' natural lodestones do not demand an exorbitant price for their wares—but on the other hand their examples will lift only a small fraction of their weight in soft iron.

2.3. *The lodestone has an 'affinity' only for magnetite or, better, metallic iron*

Iron was the only metal known to Gilbert that was attracted by the lodestone: he correctly concluded that the phenomenon was quite distinct from electrostatic attraction. Nickel, cobalt, and certain alloys and non-metallic compounds are now recognized to possess this property of 'ferromagnetism'.

2.4. *'Action at a distance'*

Gilbert pointed out that the lodestone is able to exert its attraction on iron before the metal has actually touched its surface, and that this force penetrates paper, wood, and thin sheets of metals other than iron. In a later century these observations were included in Faraday's idea of a 'field of force' surrounding any magnet.

2.5. *The lodestone always has two 'poles'*

Exploring the way in which a lodestone held short lengths of iron wire, or iron filings, Gilbert found that these stood out with respect to the surface of the stone to point towards two buried centres or foci that he named 'poles'. This was most clearly seen if a lodestone shaped into a sphere was employed (Figure 1, top left). These poles tended to lay towards two extremities of the stone, but were never right at the surface. Gilbert surmised that the poles represented the two ends of a magnetic axis passing through the stone.

In later years Gilbert improved the accuracy of his technique by using a small magnetic needle suspended on a silk thread, or resting upon a vertical pointed pivot. He named the latter a '*versorium*'. This instrument, and the spherical lodestone, were the tools that enabled Gilbert to unravel the complexities of magnetism. A miniature version of the versorium is now called a 'plotting compass', and is still used in schools to plot the 'lines of force' around a bar magnet and to locate its poles.

However, it must be remembered that a plotting compass contains a small permanent magnet, so *either* pole held very near a piece of soft iron or ordinary magnetite will induce the opposite pole and be weakly attracted. Attraction is therefore not a sufficient criterion to indicate a lodestone. Much more reliable is the observation of *repulsion* of one pole of the magnetic needle when the plotting compass is brought near a putative lodestone.

2.6. *Dividing a lodestone*

Significantly, Gilbert found that abrading a lodestone would not expose its poles, and that breaking it in two generated two new complete magnets—never two separated poles. It is now realized that 'poles' are no more than a very convenient fiction to help describe the field of a magnet.

2.7. *Making an 'artificial' magnet by 'induction' (stroking)*

Gilbert knew from the work of his predecessors (notably Petrus Peregrinus) that unidirectional stroking of a length of iron rod or wire with one end (near a pole) of a lodestone caused that rod to become a temporary magnet, picking up small pieces of iron or a cluster of iron filings. It was soon discovered that hardened carbon steel wire—most readily available as needles—retained this 'induced magnetism' better than soft iron, although it could weaken over a long period dependent on the temper of the steel.

There was never any detectable change in weight of lodestone or needle, and the magnetizing lodestone did not lose any of its 'virtue' after making large numbers of magnetic needles. It is now recognized that the necessary work is done by the operator when moving stone and needle relative to one another, and separating them at the end of each stroke.

3. Properties of poles

3.1. *A suspended lodestone always points in the same direction*

This observation, potentially invaluable to travellers and navigators, is of a very different order to accidentally observing the attraction of metallic iron. The lodestone must first be supported in a near-frictionless manner: hanging in a loop of paper from silk thread or resting upon a cork float in a basin of water are commonly proposed. Then, if the stone bears some readily identifiable surface feature, this mark will always tend to set towards a particular cardinal point. The prefix '*lode*-' honours this ability to lead, just as it does with Polaris—the '*lodestar*'.

Textbooks are at best unclear to state that a suspended lodestone points approximately north–south: one would not know with an unmarked, near-symmetrical stone. Prior calibration at a location where north and south are known (from observations of the noon Sun and/or stars) is essential—and then, of course, any deviation from true north is automatically compensated. The difference between magnetic and geographic north would only become apparent if the marked lodestone were taken to a distant location.

Needham[15] believes that the first direction-finding instrument was Chinese in origin, being derived from a sort of balanced spoon carved (initially by chance?) from the lodestone variety of magnetite and spun on the smooth surface of a diviner's board.

Gilbert also pointed out that the floating lodestone *rotates*: it is not attracted as a whole towards the north, south, or any other direction. It is now recognized that,

[15] Joseph Needham, *Science and Civilisation in China* (Cambridge, 1962), IV. C. A. Ronan and J. Needham, *The Shorter Science and Civilisation in China* (Cambridge, 1986), III, ch.1. In view of the disputed period of discovery it is perhaps ironic to learn that magnetotactic bacteria were using tiny intracellular grains of magnetite to determine direction in the remote geological past. See R. F. Blakemore and R. B. Frankel, 'Magnetic Navigation in Bacteria', *Scientific American*, 245 (December) (1981), 42–49.

over distances measured in metres, the Earth's field is parallel and isotropic. The suspended lodestone is therefore turned by a couple acting at its poles; there is no net resultant directed in a particular direction.

3.2. *Naming the poles*

Gilbert named the pole of the lodestone that oriented itself in the general direction of geographic north the north pole of the stone, and conversely with the south pole. This led to some confusion when, later, the Earth itself was considered as a giant magnet.

3.3. *Like poles repel, unlike poles attract each other*

This was established with suspended or floating lodestones on which the poles had been identified and marked, but the law was much more obvious with suspended needles of known polarity. It will be appreciated that a lodestone could occasionally and apparently anomalously repel a piece of iron or magnetite either if the latter happened to be another lodestone, or the iron was a permanent magnet, and either was presented in the appropriate orientation.

4. Navigation

4.1. *The mariner's compass*

A magnetized needle is a much more accurate and practical directional instrument than a floating lodestone. Firstly it has a built-in magnetic axis from its shape (it is hard to magnetize a needle obliquely to its length) and secondly it may be supported by a fine thread of unspun silk within a glass jar to shield it from draughts. On long voyages it might well lose some of its magnetic power, but this could be restored by stroking with the lodestone every wise navigator would also take along. Later, a pair of hardened steel bar magnets, with keepers, might also be carried to 'refresh' the compass needle.

Needham has established that the first text clearly describing the magnetic compass needle is a Chinese work of about AD 1080, a century earlier than the first European mention of the instrument in AD 1190. It probably became known to Mediterranean sailors via the Arabs although, interestingly, Gilbert credits it to the transmission of Chinese knowledge by Marco Polo.

In medieval times the compass card was invented by securing, with sealing wax, several parallel magnetized needles on the back of a cardboard disc.[16] The compass rose (and still later a scale of degrees) would be painted or printed upon its surface. The needles were grouped symmetrically either side of the pivot cap, but two would be displaced longitudinally to counteract the dip (see below) and to allow the card to balance and rotate horizontally. The need for protection against wind and weather would soon make evident the requirements of a waterproof box, gimbals, and binnacle. At some stage liquid damping was introduced, using water protected against freezing with alcohol.

4.2. *The 'dip' or inclination*

In 1576 Robert Norman[17] discovered that a sewing needle carefully balanced to be horizontal when suspended on a thread always dipped its north pole downwards

[16]See Agricola, *De Re Metallica* (1556) (note 3).
[17]See Norman (note 3).

when (in Europe) it was magnetized with a lodestone. The angle with the horizontal is now known as the '*inclination*'. In the UK it is currently close to 67°.[18] Gilbert's 'dip circle' substituted a magnetic needle pivoted in a vertical plane—see Figure 1, lower left. This mechanical refinement may indicate that he had access to horological craftsmanship.

5. The Earth as a magnet

5.1. *The 'terrella'*

The second instrument that enabled Gilbert to make such progress in the understanding of magnetism was the '*terrella*'—a lodestone shaped into a sphere (Figure 1, top left). Again he had a predecessor in Petrus Peregrinus but, unlike him, Gilbert published the investigations that led him to think that the Earth behaved as a giant magnet. Employing a spherical lodestone obviated problems associated with an irregular mass, and provided a reproducible reference point at the geometric centre of the sphere.

Gilbert's diagram of the changing dip over his terrella (reproduced here as Figure 2) and his identification of this with the behaviour of the Earth's magnetic field are very well known. It is as if the planet contained a huge buried bar magnet—but we know that the temperature of the mantle and core renders this completely impossible. Modern theories of the geomagnetic field tend to ascribe it to motions in the core and deep mantle producing a self-exciting dynamo.

Magnetite is a very hard and brittle mineral, not amenable to normal turning techniques. It must be ground with abrasives. Gilbert mentions a 'lathe, such as is used in turning crystals and some precious stones', but an uncharacteristic lack of

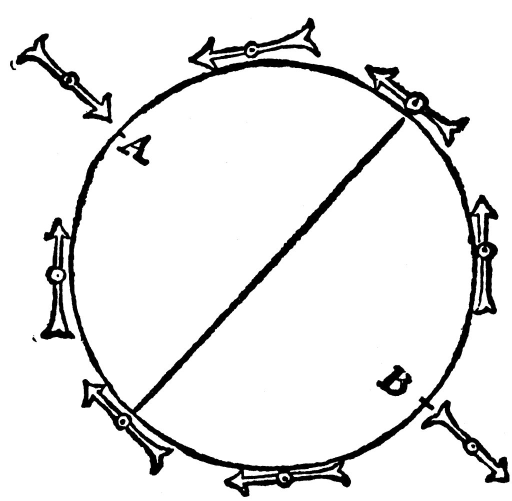

Figure 2. Gilbert's diagram of the changing angle of dip over his magnetic terrella.

[18]Calculated values for the seven elements of the geomagnetic field at any site on any given date are obtainable from the National Geophysical Data Center, Colorado, USA at www.ngdc.noaa.gov. It must be borne in mind that these model values are subject to small and unpredictable variations due to solar activity and local influences.

details suggests that he bought (or commissioned) his terrella. Further, he does not make it clear that the original chunk of lodestone should first be marked up and arranged in the chuck so that its magnetic axis eventually coincides with the geometric axis through the centre of the finished sphere.

5.2. *The declination (variation)*

It became known in medieval China[19] that the magnetic needle did not come to rest exactly along the true or geographic north–south meridian, but would point some degrees west of north towards a '*magnetic north pole*'. (East of south was the convention preferred in the Orient.) This 'error' has been termed 'declination' and 'variation'—both extremely poor and confusing choices, since declination is a standard coordinate in astronomy, and the 'variation' itself varies both in space and time. The magnetic declination in middle England is currently about 3.5°W. (See note 18.)

5.3. *The 'north-seeking' pole of a magnet*

Gilbert defined the north pole of a magnet as that contained within the end of the magnet which, when freely suspended, points in the general direction of geographic north. This led to confusion when compared with the general law 'unlike poles attract while like poles repel'. Is the Earth to be considered as having a south magnetic pole in the Arctic?

There has been a tacit compromise: it is now agreed that the 'north' pole of any lodestone or other permanent magnet should really be called the 'north-seeking pole', but the convention is rarely acknowledged in current publications. An interesting historical hangover into toy and school magnets is the old Admiralty ruling that, to avoid confusion, the north-seeking end of any bar magnet carried on board ship to 'refresh the compass' must be painted red.

6. Effect of increasing temperature

Gilbert found that iron and iron filings are not attracted by a lodestone when the metal is red hot, but are attracted once again when their temperature has fallen somewhat. Similarly, both lodestone and a piece of magnetized iron lose this property on heating to a red heat. Nowadays, this loss of magnetism with heating is more precisely identified with the '*Curie temperature*'.[20]

Pure iron: 770 °C
Magnetite: 578–590 °C (according to exact composition, grain size, etc.)

7. Magnetic strength of lodestones

A strong lodestone, says Gilbert, lifts in air a mass of iron weighing as much as itself, whereas a weak stone hardly attracts a piece of fine iron wire. It appears to have been recognized well before he was writing that the power of a lodestone diminished with time, so perhaps he was fortunate enough to encounter some specimens formed comparatively recently—see Section 17 on origin and formation—whereas ours are of considerable age. If the decay of magnetic intensity follows an

[19]Needham (note 15).
[20]G. W. C. Kaye and T. H. Laby, *Tables of Physical and Chemical Constants* (London, 1966).

exponential law, then our specimens might be expected to be on an asymptotic approach towards magnetic neutrality.

7.1. *Preservation of strength*

To minimize loss of power in storage, Gilbert recommends that any magnet be placed in a box and surrounded with iron filings, crushed natural magnetite, or scales from a blacksmith's forge. (The last are mainly magnetite.) This advice agrees with the modern concept of magnetic circuits, and with the usual placing of a 'keeper' across the ends of a horseshoe magnet.

7.2. *Correlation between power and 'weight raised'*

In connection with this common correlation between 'power' and 'weight raised' it should be noted that, while in general a heavier lodestone will lift more iron, the ratio of weight of stone to weight of iron lifted is prejudiced against heavy stones. This is because attraction is a surface property and therefore related to the square of dimensions, whereas weight is a function of the cube of dimensions.[21] Writing in 1856, von Lamont[22] noted that big (steel) magnets could lift their own weight, whereas smaller examples might well raise $50\times$ their own weight.

8. 'Armed' lodestones

8.1. *The 'capped' lodestone*

Gilbert noticed that a nail or iron bar clinging to a lodestone transmitted its power of attraction. In addition, a piece of iron 'nicely adjusted' to the end of a lodestone supported a greater weight than did the bare stone. These observations led to the only method he describes for increasing the attractive power of a given stone: to fit it with caps beaten from soft iron sheet. These, he writes, should fit closely over the pole ends of a stone smoothed to ovoid shape, and be secured with brass hooks and eyes (Figure 1, top right). He claims such iron caps might increase the lifting power of a given stone by a factor of 3, and illustrates

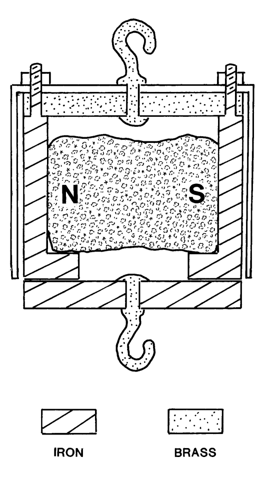

Figure 3. The usual internal construction of a cased lodestone.

[21]McKeehan (note 13).
[22]Johann von Lamont, *Handbuch des Magnetismus* (1856, 1867).

capped lodestones forming a chain one below another (Figure 1, centre left). Stroking with one cap of an ovoid stone was recommended to magnetize compass needles.

Ridley (1613) and Barlowe (1616) mention the improvement of filling any cavities below the cap with a hot mixture of powdered lodestone, iron filings, and resin, which would also act as a cement. A capped stone of this nature came to be recognized as one form of 'armed' lodestone—a term that persists in the 'armatures' of modern electromagnets and electric motors.

8.2. *The 'cased' lodestone*

It is now visualized that magnetic lines of force propagate most easily in ferrous bodies, and that a maximum field (and associated force proportional to the square of the flux density) occurs across a small gap between the north and south arms of such a magnetic circuit. A good practical expression of this principle is the 'cased lodestone', described by Ridley in 1613, but apparently unknown to Gilbert. So significant is the improvement in power and longevity that the cased lodestone became commonly known as '*the lodestone*'.[23] Ridley shows the construction diagrammed in Figure 3, and later authors[24] repeat it. A selected block of lodestone has its poles located, and the ends are abraded down to give two flat surfaces perpendicular to the magnetic axis. Two wrought-iron L-shaped blocks are held in contact with these faces in any convenient manner. The assembly may then be secured within a decorative non-ferrous case equipped with a lifting handle. Ridley refers to the projecting pole pieces as 'teeth', and explains that they are to be kept bridged by a matching iron 'keeper' (complete with its own lifting ring) when the lodestone is not in use. Photographs of 'capped' and 'cased' lodestones are included in Section 12.

According to modern ideas an even better magnetic circuit would be produced by the design suggested in Figure 4, but no historical example of a cased lodestone

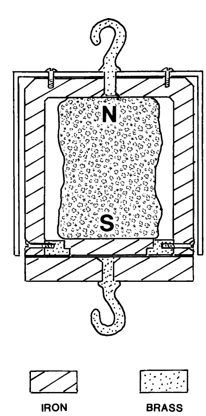

Figure 4. An improved internal construction for a cased lodestone.

[23]Kircher, 1667 (note 7), Dalencé, 1687 (note 8), Cavallo, 1800 (note 12).

[24]P. D. Marianini, 'Armed Magnets and Some Methods of Magnetization', *Nuovo Cimento*, 4 (1856) 231–62.

with this internal construction has been located. One has been made, and shown to work well.

9. Variation of attractive power with distance

9.1. *Experiments at the Royal Society*

A large lodestone from Devonshire, weighing about 60 lb, was recorded along with thirty lesser stones in a catalogue of the possessions of the Royal Society compiled by Nehemiah Grew[25] in 1681. De la Hire[26] mentioned it in 1687 in connection with his new design for a magnetic compass. Both authors claimed that this stone, although not armed, visibly affected a compass needle at distances of up to 9 feet.

In 1687, in a corollary to the *Principia*,[27] Isaac Newton mused on whether magnetic attraction decreased according to the inverse square or inverse cube of distance. Not until 1712 was he in a position to find out: as President of the Royal Society he proposed an experimental test using the Society's 'Great Lodestone' be conducted by Dr Halley assisted by Mr Hawksbee.[28] A subsequent report appeared under the name of Hawksbee alone.[29] Surprisingly, he worked with a smaller 6 lb stone set in the magnetic meridian, and merely quotes the deflection of a magnetic needle away from its normal north-pointing direction with distances up to 5 feet away from the stone. He does include an engraving of this lodestone showing its magnetic axis. Two years later Brook Taylor[30] produced a paper implying that he was the chief investigator of Newton's proposal, Hawksbee being no more than his assistant, and appended a table of deflections obtained with the 'Great Lodestone' in a broadside-on position. Neither author came to any definite conclusions, and Musschenbroek and Desaguliers[31] were no more successful with a direct weighing method in 1724. These investigations formed the subject of a review by Palter[32] in 1972. A mathematical analysis provides the key to the situation, and to all subsequent quantitative work.

9.2. *Theoretical analysis*

9.2.1. *Law of force between poles*

The force F between two isolated poles is related to the product of their pole strengths m_1 and m_2. It also varies inversely as the square of the distance d between

[25]Nehemiah Grew, *Catalogue and Description of the Natural and Artificial Rarities Belonging to the Royal Society* … (London, 1681).

[26]A. de la Hire, 'A New Sort of Magnetical Compass', *Philosophical Transactions*, 16 (1687), 344–51.

[27]Isaac Newton, *Principia* (London, 1687), Book 3, Prop.6, Theorem 6, Cor.5.

[28]*Journal Book of the Royal Society, 1702–1714*, 10, 373 (for 20 March 1712).

[29]Francis Hawksbee, 'An Account of the Experiments Concerning the Proportion of the Power of the Load-stone at Different Distances', *Philosophical Transactions*, 27 (1712), 506–11 and Figure 4 on separate plate.

[30]Brook Taylor, 'An Account of an Experiment Made by Dr Brook Taylor Assisted by Mr Hawksbee, in Order to Discover the Law of the Magnetical Attraction', *Philosophical Transactions*, 29 (1712), 294–95.

[31]P. Musschenbroek and J. T. Desaguliers, 'De Viribus Magneticis', *Philosophical Transactions*, 33 (1724–5), 370–78.

[32]Robert Palter, 'Early Measurement of Magnetic Force', *Isis*, 63 (1972), 544–58.

them. So,

$$F = \frac{m_1 m_2}{d^2}. \quad (1)$$

9.2.2. *Intensity of the magnetic field around an isolated pole*

Consider an isolated pole of strength m (emu). By definition, the magnetic intensity H (oersted) at a distance r from it is measured by the force felt by a unit north pole placed at that spot. Hence

$$H = \frac{m \times 1}{r^2} = \frac{m}{r^2}. \quad (2)$$

The force is repulsive (positive) if the pole under consideration is a north pole, and attractive (negative) if that pole is a south pole.

9.2.3. *Intensity along the axis of a real magnet—'end-on' position (Gauss[33])*

Consider a lodestone with poles N and S of equal strengths m separated by a distance 2ℓ (the 'magnetic length') along the magnetic axis joining them (Figure 5).

For simplicity, the magnetic intensity at a point D along an external prolongation of the axis (the 'end-on' position) will be considered. Also, the Earth's field will be temporarily neglected. Imagine a unit N pole placed at D:

$$\text{repulsive force due to N pole of strength } m \text{ in the lodestone} = \frac{m}{(\mathrm{ND})^2}$$

$$\text{attractive force due to S pole of strength } m \text{ in the lodestone} = -\frac{m}{(\mathrm{SD})^2}.$$

The total intensity H at point D is therefore given by

$$H = \frac{m}{(\mathrm{ND})^2} - \frac{m}{(\mathrm{SD})^2}$$

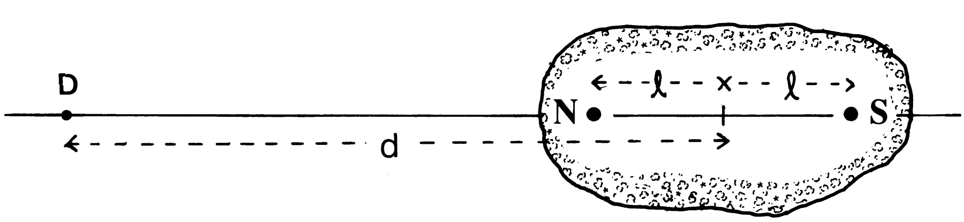

Figure 5. Axial magnetic intensity produced by a lodestone with poles at N and S separated by a distance 2ℓ.

[33]J. K. F. Gauss, *Intensitas Vis Magneticae Terrestris* (1832), Not easily accessible—see C. C. Gillispie (ed.), *Dictionary of Scientific Biography* (New York, 1972), v, 298–315. A portion is reproduced in F. Magie, *Source Book in Physics* (New York, 1935), pp. 519–24.

However, $ND = d - \ell$ and $SD = d + \ell$, and therefore

$$\begin{aligned} H &= \frac{m}{(d-\ell)^2} - \frac{m}{(d+\ell)^2} \\ &= \frac{m(d+\ell)^2 - m(d-\ell)^2}{(d-\ell)^2(d+\ell)^2} \\ &= \frac{m \times 4d\ell}{[(d-\ell)(d+\ell)]^2} \\ &= \frac{4m\ell d}{(d^2-\ell^2)^2}\,. \end{aligned} \tag{3}$$

9.2.4. *The magnetic moment*

The magnetic moment M of a magnet is defined as the moment of the couple acting on that magnet when it is held at right angles to a field of 1 Oe, i.e.,

$$M = \text{pole strength} \times \text{magnetic length}.$$

In the diagram of Figure 5,

$$\begin{aligned} M &= m \times 2\ell \\ &= 2m\ell\,. \end{aligned} \tag{4}$$

M can be accurately measured, and is a real physical property of a magnet that can be identified with its ‘strength’. Pole strength and magnetic length are no more than convenient concepts that, pedantically speaking, should not be separated and have no real physical existence.

9.2.5. *Intensity along the axis of any magnet in terms of its moment*

Substituting $M = 2m\ell$ in equation (3) we have

$$H = \frac{2Md}{(d^2-\ell^2)^2}\,. \tag{5}$$

9.2.6. *Intensity along the axis of a short magnet*

When the half-length ℓ of a magnet is short compared with the distance d from its centre (say 10% of it) then ℓ may be neglected. Hence

$$\begin{aligned} H &\approx \frac{2Md}{(d^2)^2} \\ &\approx \frac{2M}{d^3}\,. \end{aligned} \tag{6}$$

9.2.7. *‘Broadside-on’ position*

It may be shown that, if the magnetic axis of the magnet is placed at right angles to the distance being measured, then

$$H \approx \frac{M}{d^3}, \tag{7}$$

where d is large compared with the length of the magnet. The magnetic intensity at any distance perpendicular to the axis of the magnet is only one-half of that experienced in the 'on-axis' direction.

9.2.8. *Variation of force with distance from a magnet*

The intensity H along or perpendicular to the axis of a real bipolar magnet is therefore nearly inversely proportional to the *cube* of the distance from its centre when that distance is large compared with the length of the magnet. At shorter distances more complex formulae apply.

The force experienced by an isolated pole of strength m (oersted) held at a distance d is given by mH, so follows the expressions given above for H. This situation may be experimentally approximated by using one end of a long magnetized steel rod terminated by steel spheres ('Robison magnet'). However, with another lodestone or bar the two intensities must be further compounded together. It can be seen why Hawksbee, Taylor, and Musschenbroek were frustrated in their endeavours to find a simple correlation of force with distance.

10. Contemporary natural lodestones and qualitative tests

10.1. *Museum specimens*

The Royal Society's examples disappeared long ago, as have some Edinburgh specimens,[34] but at least thirty-five are catalogued as still existing in the UK.[35] Most are of the 'cased' form. Major collections are at the Oxford Museum of the History of Science[36] and the Science Museum, London,[37] with examples once used on board ship to 'refresh the compass' concentrated in the National Maritime Museum, Greenwich. Certain Italian lodestones have recently been catalogued and illustrated by Brenni.[38]

10.2. *Recent sources*

Ordinary magnetite is a common mineral of worldwide occurrence. It is found as an accessory mineral in basic and ultrabasic rocks (igneous rocks rich in iron and magnesium) and gravity settling can produce rich ore bodies. It can also occur in veins. Weathering may lead to concentration in beach sands and metamorphosed rocks.

To obtain some idea of the prevalence of the lodestone variety, many samples of magnetite from around the world, housed in the teaching collections of the Department of Geology of the University of Leicester, were tested for their ability to pick up small steel paperclips each weighing 0.27 g. One specimen (Catalogue number 69287) was found that could lift a chain of three clips or cause a number of small nails to adhere to its surface (Figure 6). One other specimen (Catalogue number 69289) could just about lift a single clip. Both of these were from Magnet Cove, Arkansas, USA. Although many other specimens from this site were inert, the name of this inland locality does suggest that some pioneer's hand compass had

[34]J. Deuchar, 'Large Loadstones', *Memoirs of the Wernerian Natural History Society, Edinburgh*, 4 (1821), 386–95 and Plate XII.

[35]Mary Holbrook, *Science Preserved* (London, 1992).

[36]See their website www.mhs.ox.ac.uk

[37]A. Q. Morton and J. A. Wess, *Public and Private Science*, (Oxford, 1993). Also NMSI website.

[38]Paolo Brenni, *Gli strumenti di fisica dell'Istituto Tecnico Toscano. Elettricita e Magnetismo* (Florence, 2000).

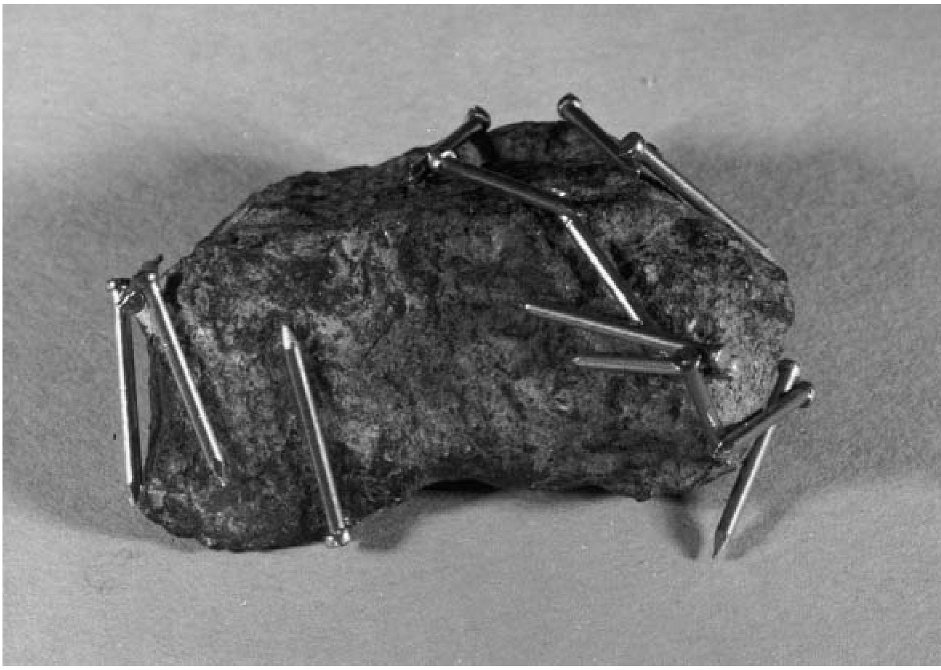

Figure 6. Lodestone (specimen A) from Magnet Cove, Arkansas, attracting small nails to its surface.

behaved in an anomalous manner there. This igneous complex[39] is now well known to American collectors as a source of many rare and beautiful minerals. The two lodestones were for brevity named Magnet Cove A and B respectively. Additional small specimens of both 'lodestone' and 'inert' varieties of magnetite from this site were obtained through the courtesy of M. Howard of the Arkansas Geological Survey. He explained that all had been collected years ago[40] from near-surface outcroppings either as loose residual material or from disaggregated vein systems found as 'pods' near the surface.[41] The four small lodestones were labelled C–F in order of size, and the magnetically inert specimens as numbers 1–6. This availability of a number of specimens resulted in the Magnet Cove material being used below as the 'type example'. A larger lodestone was also obtained by purchase,[42] and was stated to have been collected near Cedar City, Utah. A greenish magnetite-rich skarn deposit recently collected from the Kilchrist quarry on Skye (grid references NG621201) was presented by Dr R. England. It weakly affected a nearby compass, so was technically a lodestone.

All the above specimens were irregular in shape, their surfaces a dull rusty

[39]J. F. Williams, 'The Igneous Rocks of Arkansas', in *Arkansas Geological Survey, Annual report for 1890*. R. L. Erikson and L. V. Blade, 'Geochemistry and Petrology of the Alkalic Igneous Complex at Magnet Cove, Arkansas', *USGS Professional Paper 425* (1963).

[40]This site is now closed to public collecting. It is rumoured that both raw and tumble-polished pieces of ordinary magnetite from various localities have occasionally been artificially magnetized by exposure to a strong magnetic field and then sold as charms.

[41]This agrees with Still (note 13), who writes 'The lodestone found at Magnet Cove in Arkansas is frequently in the form of brown pebbles turned up by the plow.'

[42]Ward's Natural Science, PO Box 92912, Rochester, NY.

brown in colour. Where fractured, the interior was exposed as a hard black mass exhibiting specular reflections. For comparison, a hand specimen of high grade magnetite from Ishpeming, Michigan, was also obtained from the above supplier. It was a handsome glistening polycrystalline block, near black in colour, that did not exhibit any detectable external magnetic field. Weights, volumes, and densities of these samples were determined by weighing in air and in water: results are shown in Table 1. Densities ranged from 4.4 to 4.7, indicating that the specimens were neither pure nor homogeneous, paler minerals being present in addition to magnetite.

Table 1. Physical properties.

Name		Mass (g)	Volume (cm^3)	Density ($g\,cm^{-3}$)
Lodestones				
Magnet Cove	A	58.9	13.2	4.46
	B	178.7	38.8	4.61
	C	36.5	8.0	4.56
	D	36.5	8.0	4.56
	E	25.2	5.5	4.58
	F	13.8	3.1	4.45
Cedar City		605	129	4.69
Kilchrist, Skye		437	112	3.89
Ordinary magnetites				
Magnet Cove	1	69.1	14.9	4.64
	2	61.1	13.1	4.66
	3	32.8	7.1	4.62
	4	31.9	7.0	4.56
	5	37.3	8.2	4.55
	6	21.1	4.6	4.59
Ishpeming		675	131	5.15

10.3. *Magnetic structure and poles*

Exploring the surface of Magnet Cove A with a modern liquid-filled plotting compass and marking points of repulsion produced the result illustrated in Figure 7. Magnet Cove B gave the anomalous result shown in Figure 8. There appear to be at least two magnetic portions opposing one another. A similar multipolar structure was exhibited by Kilchrist. This is presumably why these specimens are, overall, such weak lodestones. It also indicates that Gilbert was incorrect in supposing every lodestone to have only two poles. Perhaps he only saw examples that had been selected to be strongly attractive towards pieces of iron. Poynting and Thompson[43] state that any irregularity in the stroking of a bar in the process of magnetization—for example, magnetizing it first in one direction and then in the other—is liable to result in poles of the same kind being formed together within the bar. They say that it is easy to produce a steel knitting needle with north poles at the ends and two south poles somewhere between them. The authors refer to this phenomenon as the formation of '*consequent poles*'.

Gilbert surmised that the poles represented the two ends of a magnetic axis

[43]J. H. Poynting and J. J. Thomson, *A Textbook of Physics* (London, 1920), IV: *Electricity and Magnetism*.

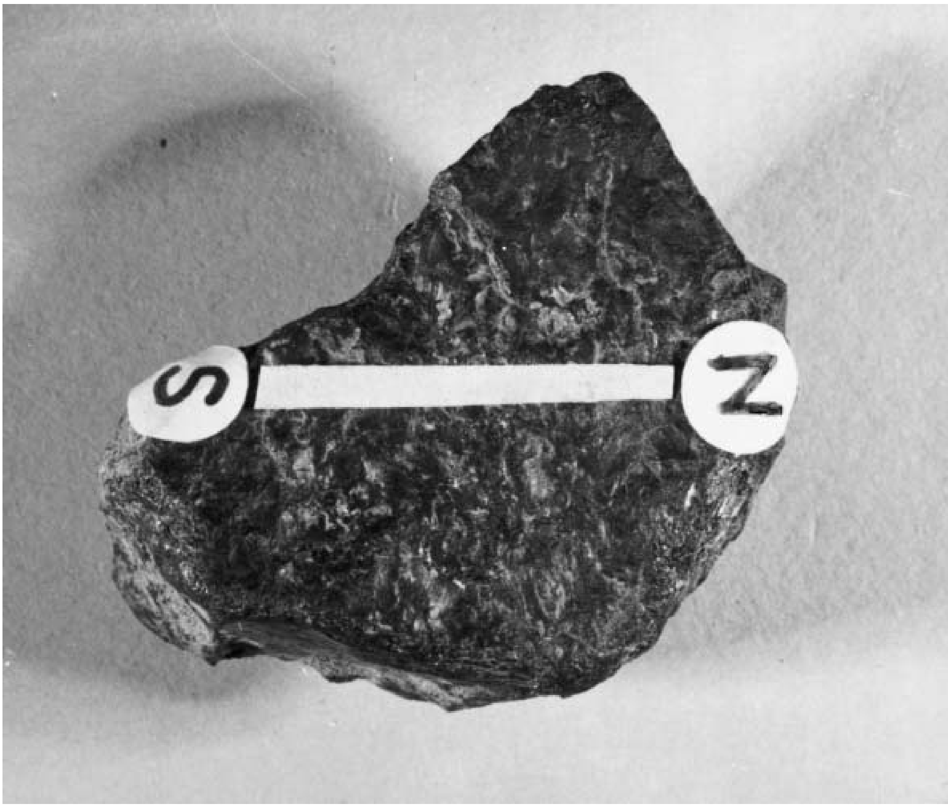

Figure 7. Magnetic poles associated with Magnet Cove A. A simple dipole.

passing through the stone. Figure 7 shows that it is not necessarily an axis of symmetry, and may not connect the two points most distant from the centre of gravity. The magnetic axis of this lodestone has been indicated in the illustration as a projection upon its surface.

10.4. *Comparison with historical stones*

None of the above contemporary lodestones could lift its own weight in iron. It may be that all are quite old, with substantial decay of the magnetic intensity, but in addition it is thought likely that 'cased' lodestones were meant when making this claim.

10.5. *Utility as a magnetic compass*

A practical test was made with the lodestone Magnet Cove A by placing it in a small plastic basin floating in water, with a large inverted glass basin keeping out draughts. Eventually its marked axis came to rest approximately north–south. However, the arrangement was so susceptible to vibration and disturbance that it is not thought this particular floating lodestone would be practical: a more powerful specimen differently mounted proved far better—see Section 13.8.

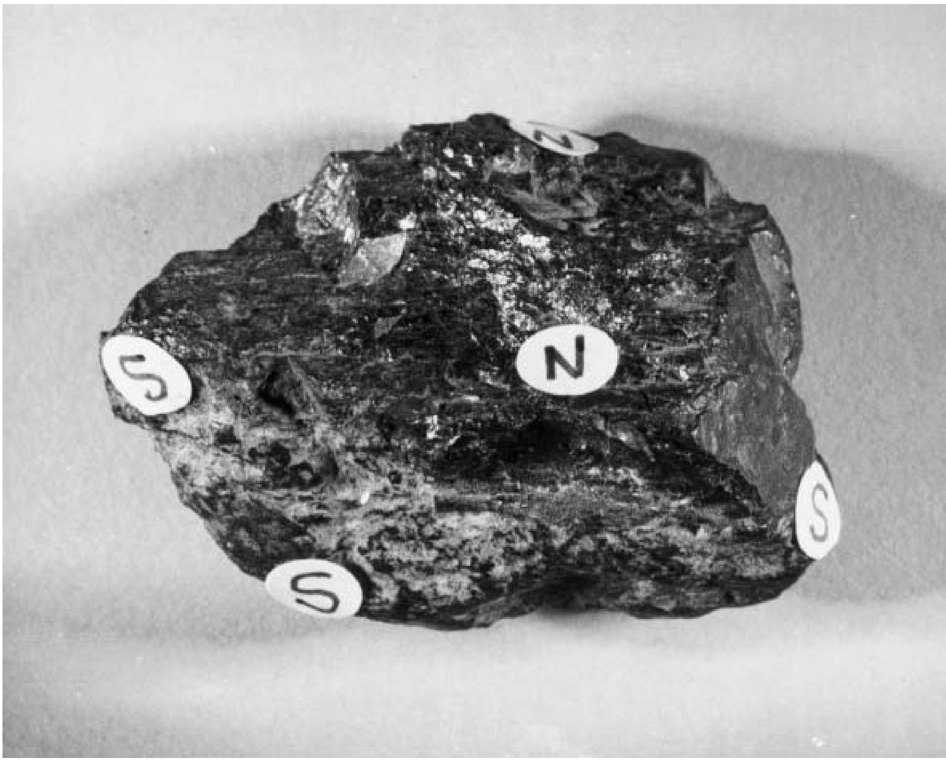

Figure 8. Magnetic poles associated with Magnet Cove B. A complex multipolar structure.

11. Quantitative studies on natural lodestones

11.1. *Comparatively recent literature*

In 1929 the economic geologists Newhouse[44] and Gruner[45] published short papers on the identity and genesis of lodestone magnetite, and Davis[46] took matters a little further in 1935. A 1948 paper on ships' lodestones, although appearing in the *Mineralogical Magazine*,[47] mostly reiterates well-known historical material. Perhaps its most valuable feature is a list of places in Britain where lodestones are said to have been found.

It was the emergence of rock magnetism as a distinct area of geophysical research that stimulated a few applications of techniques evolved in that field to the lodestone. Quite early on, Weiss[48] checked that the magnetic properties of crystalline magnetite varied as expected with direction in its cubic crystal lattice. The first specific measurements on the magnetic characteristics of a lodestone were

[44]W. H. Newhouse, 'The Identity and Genesis of Lodestone Magnetite', *Economic Geology*, 24 (1929), 62–67.

[45]J. Gruner, 'The Identity and Genesis of Lodestone Magnetite', *Economic Geology*, 24 (1929), 771–75.

[46]C. Davis, 'Geological Significance of Magnetic Properties of Minerals', *Economic Geology*, 30 (1935), 655–62. Repeated in *US Bureau of Mines Bulletin*, 425 (1941), 362–66.

[47]C. E. N. Bromehead, 'Ship's Loadstones', *Mineralogical Magazine*, 28 (1948), 429–37.

[48]P. Weiss, 'Magnetization of Crystallised Magnetite', *Comptes Rendus Academie des Sciences, Paris*, 122 (1896), 1405–09.

in a 1919 paper by Wilson and Herroun.[49] These workers were interested in the induced magnetic characteristics of samples of ordinary magnetite from various locations, and therefore not displaying external permanent magnetism, but incidentally included a lodestone from Arkansas (Magnet Cove?). However, as a general rule, geophysicists looking at the magnetism of lavas, basalts, etc. as a guide to the direction and intensity of the Earth's field in the past would avoid areas where a hand compass was visibly affected.[50] Perhaps this is why the first detailed investigation of the magnetic and microstructural properties of lodestones emanated from NASA's Laboratory for Extraterrestial Physics.[51] These two highly specialized papers were followed by more accessible general reviews by Blackman,[52] the last being published in 1983. Nothing has been traced in the literature since that date.

11.2. *The laboratory*

In order to carry out the quantitative investigations described below on weakly magnetized lodestones, a laboratory free of magnetic influences other than the normal Earth's field was required. A non-magnetic bench was therefore prefabricated from timber and brass screws, and erected in the loft of a brick-built house beneath a timber and tile roof. Search with a sensitive magnetic compass disclosed no anomalies such as could have been caused by hidden iron fittings. The bench top was checked to be horizontal with a spirit level, A3 drawing paper fixed upon it with adhesive tape, and a straight line ruled through its centre. The bench was then oriented so that this line lay in the magnetic N–S meridian indicated by a high quality prismatic compass.

11.3. *Practical units*

11.3.1. *The emu system*

In my opinion, the electromagnetic units (emu) originally defined on the centimetre–gram–second system are more suitable for quantitative studies of lodestones than the definitions and units applied in modern magnetism and electromagnetism. Emu will therefore be employed henceforth, in the knowledge that interconversion is always possible (see below).

11.3.2. *Pole strength (oersted, Oe)*

Unit pole strength is defined as the strength of that pole which repels a similar pole 1 cm away in vacuum with a force of 1 dyne. For the present purposes air may be considered equivalent to vacuum, and such an atmosphere will be assumed. The intensity of the horizontal component of the Earth's magnetic field in the above Leicester laboratory was assumed to be 0.18 Oe. This value applies to an accuracy adequate for the present work over most of Britain.

[49] E. Wilson and E. F. Herroun, 'The Magnetic Properties of Varieties of Magnetite', *Proceedings of the Physical Society*, 31 (1919), 299–318.

[50] D. Strangway, *History of the Earth's Magnetic Field* (New York, 1970).

[51] P. J. Wasilewski, 'Lodestone—Nature's Own Permanent Magnet', NASA-GSFC, X691-76-110 (1976). P. J. Wasilewski, 'Magnetic and Microstructural Properties of Some Lodestones', *Physics of the Earth and Planetary Interiors*, 15 (1977), 349–62.

[52] M. Blackman and N. D. Lisgarten, 'On the Intensity of Magnetisation of Lodestones', *Journal of Magnetism and Magnetic Materials*, 30 (1982), 269–72. M. Blackman, 'The Lodestone: A Survey of the History and the Physics', *Contemporary Physics*, 24 (1983), 319–31.

11.3.3. *Interconversion into other units*

$$1\,\text{emu} = 10^{-4}\,\text{T} = 0.1\,\text{mT}$$
$$= 10^{5}\,\text{nT (gammas)}\,,$$

where T denotes the tesla. Still more units are used in the modern SI system. Magnetism has not been well served in its units.

11.4. *Field of force surrounding a 'bare' lodestone*

Lodestones C–F were explored with a plotting compass and their poles marked. All were found to be simple dipoles, but only with specimen D was the magnetic axis reasonably symmetrical with respect to the outline of the stone.

This particular lodestone was placed at the centre of a piece of A4 graph paper taped with its long rulings in the magnetic meridian of the laboratory bench described above The stone was oriented so that its magnetic axis also lay in the magnetic meridian, but with its north pole facing south, so as to oppose the Earth's field. The orientation was refined until the needle of a plotting compass moved along the meridian line from south towards north always pointed along that line, although in one region it turned through exactly 180°. The field lines surrounding lodestone D were then marked out in the usual way, the compass being considered to set itself tangential to the field lines. Marking its head and tail on the graph paper gave the pattern shown by broken curves in Figure 9. It was approximately symmetrical, and inward extrapolation suggested the positions of the poles within the lodestone.

11.5. *Locating the neutral points*

It will be observed that two areas along the N–S axis appear to be avoided in Figure 9. These are in the vicinities of the '*neutral points*' (NPs), where the horizontal magnetic field due to the lodestone is exactly equal and opposite to the horizontal component of the terrestrial field. The resultant is therefore zero, so the needle of a plotting compass is unaffected: it points randomly, as brought to rest by friction at the pivots. Even a few centimetres away from a neutral point the combined field is still so low that the needle reacts sluggishly, making it difficult to plot the lines of force and to locate the NP, accurately. The standard textbook procedure[53] is therefore unsatisfactory.

A technique to overcome this problem was published by Owen.[54] The plotting compass was placed on one side of the meridian to the south of the lodestone, and moved around until its needle pointed E–W, *i.e.*, along the lines of the graph paper perpendicular to the meridian. A pencil was then held above the centre of the needle, the compass drawn away, and the pencil moved down vertically to mark the paper. The compass was then moved nearer the meridian in such a way as to keep its needle E–W, and the procedure repeated. When motion became too sluggish the compass was transferred to the other side of the meridian, and the technique repeated. The pencil marks then outlined a curve that, when drawn in, crossed the N–S meridian (Figure 9). With care, this crossing would define the neutral point to

[53] F. Tyler, *A Laboratory Manual of Physics* (London, 1959).

[54] D. Owen, 'To Find the Magnetic Neutral Points of a Bar Magnet in the Earth's Magnetic Field', in *The Science Master's Book*, ed. by G. H. J. Adlam, S. R. Humby and G. N. Pingriff (London, 1950), Ser. III, Part I (Physics), pp. 167–69.

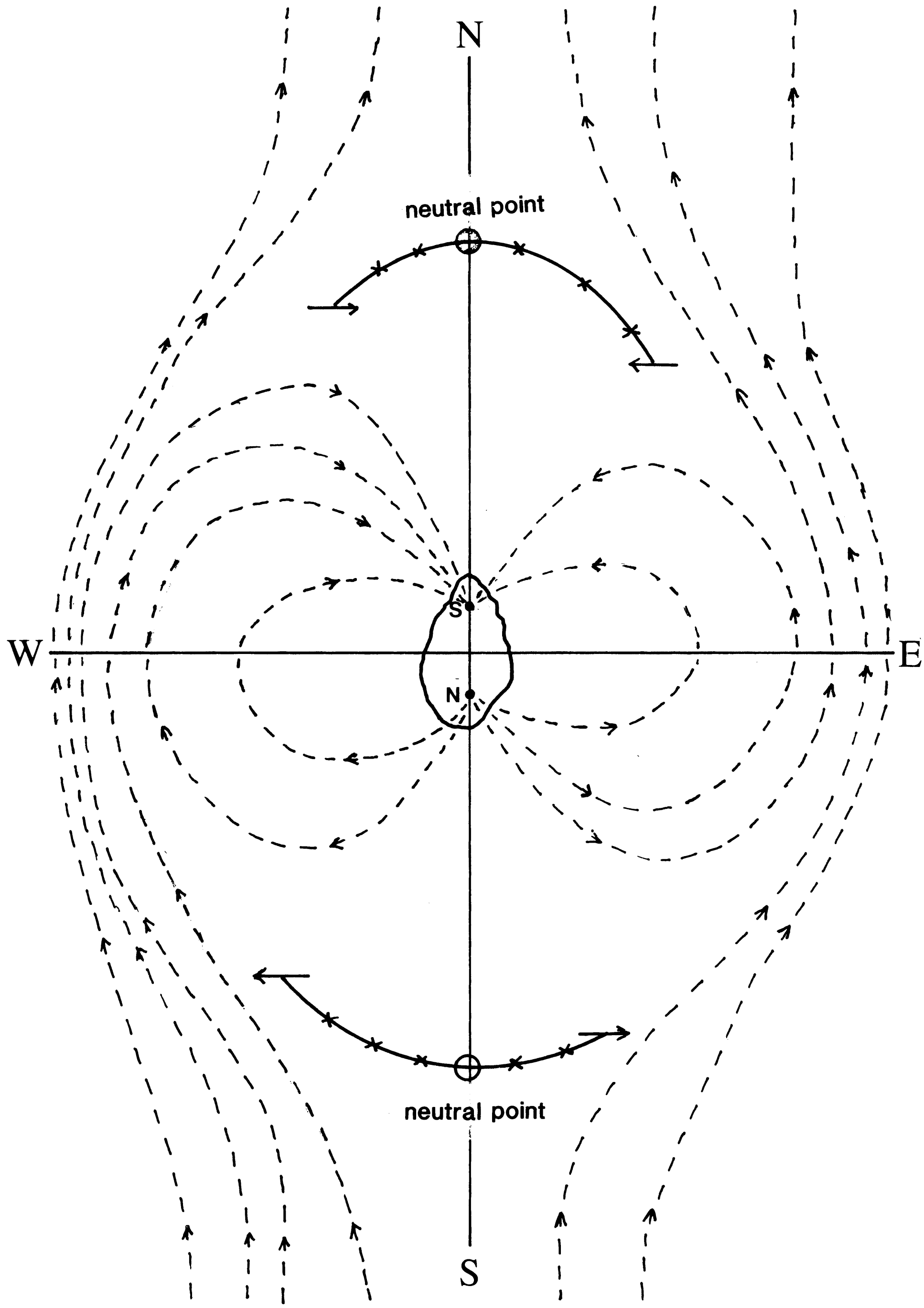

Figure 9. Field surrounding lodestone D when placed in the Earth's field with its north pole to the south. Two 'neutral points' are produced.

± 1 mm. A corresponding NP was located to the north of the lodestone in the same manner. The point midway between them gave the magnetic centre of the stone. This is equivalent to saying that the distance D between the NPs is $2d$ (Figure 5).

11.6. *Deriving the magnetic moment from the neutral point*

From equation (5) the intensity H along the axis of any magnet is given by

$$H = \frac{2Md}{(d^2 - \ell^2)^2}.$$

However, at a neutral point this intensity is equal to that of the horizontal component H_o of the Earth's field, so

$$H_o = \frac{2Md}{(d^2 - \ell^2)^2} \quad (8)$$

or, approximately,

$$H_o \approx \frac{2M}{d^3}$$

and therefore

$$M \approx \frac{H_o}{2} d^3. \quad (9)$$

If we take H_o as 0.18 Oe (Section 11.3) then

$$M \approx 0.09 d^3 \text{ emu}. \quad (10)$$

The term 'oersted cm' is not used.

For lodestone D, Figure 9 gives $2d = 18.0$ cm, so $d = 9.0$ cm. Substituting in equation (10) gives $M \approx 0.09 \times 9^3 = 66$ emu. In this particular case inward extrapolation of the fully plotted field lines gives the distance (2ℓ) between the poles as 1.8 cm. Substitution in the more accurate formula (8) then gives $M = 64$ emu. It is tempting to continue by applying the defining expression (4) and saying that the pole strength of lodestone D is 37 Oe, but this is frowned on theoretically.

11.7. *Magnetic moments per cm^3 and per gram*

M may be accurately measured, and could be quoted in terms of Oe cm. To compare magnets of different sizes and composition, it is necessary to calculate magnetic moment per unit volume from

$$J_v = \frac{M}{\text{volume in cm}^3}, \quad (11)$$

which of course comes out as Oe cm per cm^3. This cancels down to oersted per square centimetre, equivalent to pole strength per unit area. However, in the cgs system it appears that it was usual to quote J as emu cm^{-3}. This unit was used up to the 1950s to rate and compare permanent magnets.[55] Even then, however, researchers in the field of geomagnetism were preferring magnetic moment per gram, J_m, when recording the characteristics of basalts and other rocks.

[55] G. R. Noakes, *A Textbook of Electricity and Magnetism* (London, 1947). M. Nelkon, *Advanced Level Magnetism and Electricity* (London, 1954).

From Table 1, the mass of lodestone D is 36.5 g, and its volume 8.0 cm^3. Therefore

$$\text{Magnetic moment per gram is } 66/36.5 = 1.8 \text{ emu g}^{-1}$$
$$\text{Magnetic moment per cm}^3 \text{ is } 66/8.0 = 8.2 \text{ emu cm}^{-3}.$$

Application of this procedure to all the lodestones mentioned above gave the results listed in Table 2. (A modern magnetometer was not available.)

The values of magnetic moment per gram obtained for the specimens from Magnet Cove, Arkansas, may be directly compared with the figures obtained by others for lodestones apparently from this site:

	emu g^{-1}
Wilson and Herroun[56]	6.4
Nagata[57]	2.53
Wasilewski[58]	0.83–7.98
Blackman and Lisgarten[59]	0.84–6.8
The present work (Table 2)	1.4–2.6 (mean 2.1)

Table 2. Magnetic characteristics.

Specimen		D (cm)	Total magnetic moment M (emu)	Moment per gram J_m (emu g^{-1})		Moment per cm^3 J_v (emu cm^{-3})	
Lodestones							
Magnet Cove	A	11.7	144	2.4	Mean 2.1 (A–F, Cedar City)	10.9	Mean 9.5 (A–F, Cedar City)
	B	Not applicable	Not applicable	Not applicable		Not applicable	
	C	9.7	83	2.3		10.4	
	D	9.0	66	1.8		8.2	
	E	7.4	36	1.4		6.5	
	F	7.4	36	2.6		11.6	
Cedar City		23.0	1095	1.8		8.5	
Kilchrist, Skye		11.7	146	0.33		1.3	
Steel permanent magnet							
Tungsten steel (?) bar magnet, no keeper		35.4	3993	10		79	
Modern alloy magnets							
'Alnico' horseshoe magnet (old, but stored with keeper; latter removed for measurement)		36.2	4269	36		265	
'Alcomax III' bar magnet (recently purchased, as pair stored with keepers; latter removed for measurement)		20.7	798	46		338	

[56]Wilson and Herroun (note 49).
[57]T. Nagata, *Rock Magnetism* (Tokyo, 1953, 1961)
[58]Wasilewski (note 51).
[59]Blackman and Lisgarten (note 52).

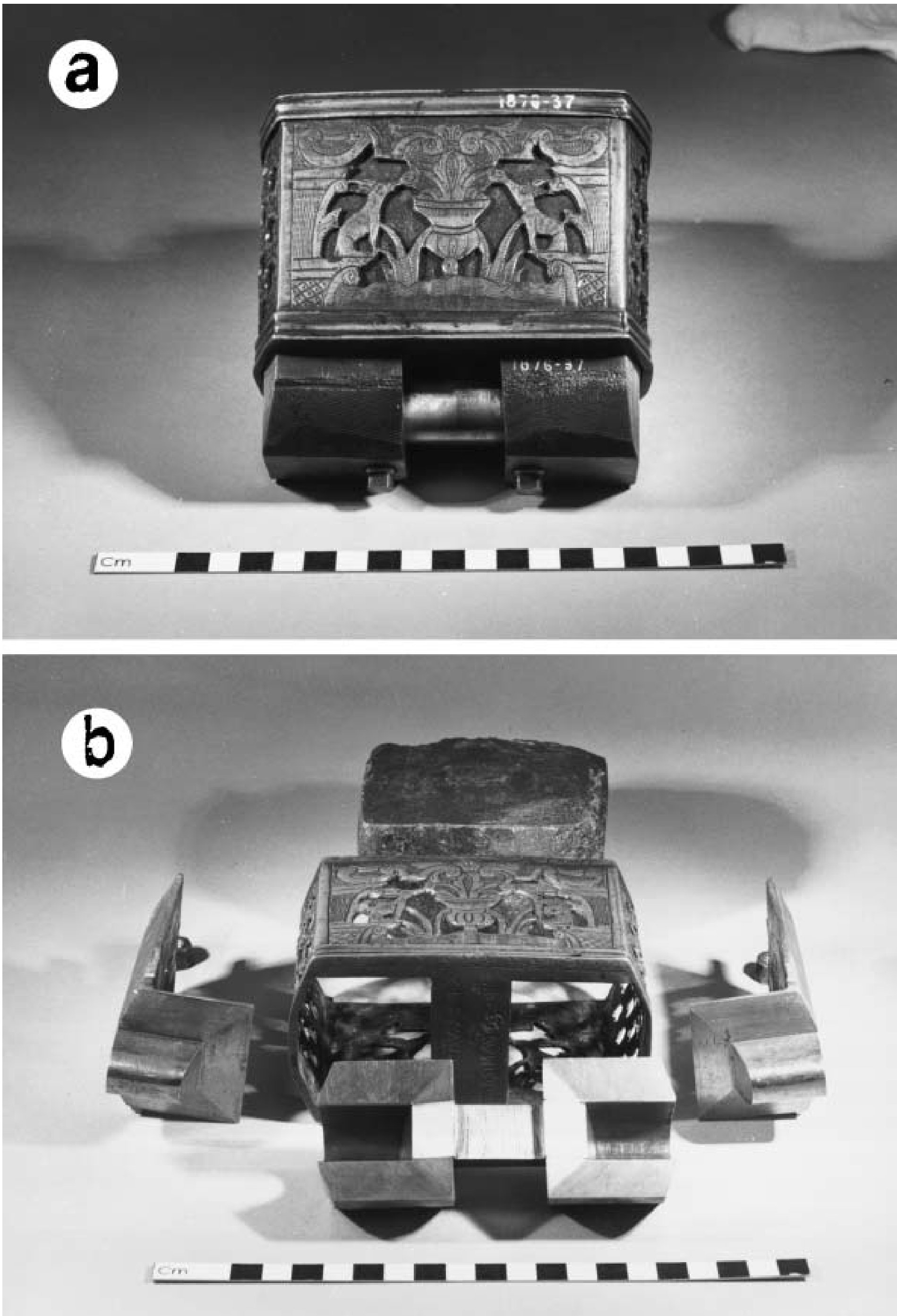

Figure 10. Science Museum, London, lodestone 1876–37: (a) external appearance; (b) dismantled to show internal construction.

Figure 11. Lodestone 1878–37.

Figure 12. Lodestone 1954–404.

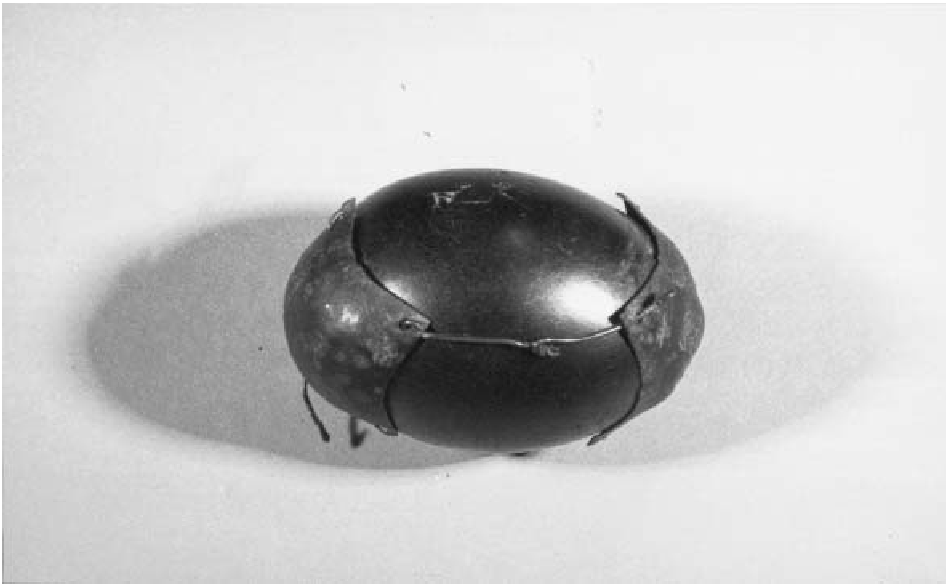

Figure 13. Lodestone 1959–189.

Figure 14. Lodestone 1981–2160.

Corresponding values obtained with steel and alloy magnets are included in Table 2 for comparison: they confirm the earlier qualitative impression that all the natural lodestones examined so far are very weak magnets.

12. Measurements on some museum lodestones

Thanks to the helpful cooperation of the Curator, Mr C. N. Brown, it was possible to examine five lodestones held in the Electricity and Magnetism Collections of the Science Museums, London:

Figure	*Science museum catalogue number*	*Description*
10	1876–37	Large armed stone in a pierced and engraved brass case. With keeper. Russian. Eighteenth century? Woodcroft Bequest.
11	1878–37	Medium size stone in a leather-covered case with floral decoration. With keeper. Woodcroft Bequest.
12	1954–404	Small cased lodestone on a frame support. With keepers.
13	1959–189	Ovoid stone with thin steel end-caps. A dipole, with its magnetic axis at 50° to long axis of egg.
14	1981–2160	Bare lodestone of unknown origin. A simple dipole.

Although the cased stones were temporarily dismantled for photography of their interiors, all were re-assembled for measurement of their magnetic moments. This was accomplished by the technique outlined in Section 11.6, the lodestone being arranged with its N pole to the south along a magnetic meridian ruled on a sheet of graph paper supported by a wooden table. The outline of the artefact was marked in pencil, and the neutral points were found by Owen's procedure. If d represents one-half of the distance in cm between the neutral points, then equation (10) shows that $M \approx 0.09d^3$ emu.

Results are gathered together in Table 3. It will be observed that the magnetic moments per gram of these highly selected lodestones are about twice the values found for the geological specimens listed in Table 2.

Table 3. Magnetic properties of Science Museum lodestones.

Science museum catalogue number	Mass (g)	Volume (cm^3)	D (cm)	Magnetic moment (emu): Total (M)	J_v	Per gram: This work	Per gram: Blackman
1876–37	2198	510	56.4	16,147	31.7	7.3	5.0
1878–37	500	116	33.6	3414	29.4	6.8	4.2
1954–404	137	30	15.6	342	11.4	2.5	1.8
1959–189	168	40	17.9	516	12.9	3.1	2.5
1981–2160	1133	240	46.1	8817	36.7	7.8	5.3

The present results are consistently about 30% greater than Blackman's figures for magnetic moments per gram, even though the weights and volumes he quotes for the bare stones were used in calculations. This was initially thought to be because the cased stones were measured in the 'armed' condition here (with keepers removed), whereas Blackman and Lisgarten assessed the stones separated from their pole pieces. The latter are, of course, designed to concentrate the magnetic flux. However, this idea does not account for the differing results obtained for the bare stone 1981–2160. The discrepancy remains unresolved. Either way, this specimen appears to be the best of the lodestones examined so far, exhibiting about 78% of the magnetic moment per gram possessed by an elderly tungsten steel bar magnet stored for perhaps 30 years without a keeper. This underlines the fact that all extant lodestones are poor magnets by present-day standards.

This naturally leads to questions of the maximum possible magnetic intensity of a 'newly made' lodestone, and how well it can retain this strength with the passage of time.

13. Magnetic characteristics of the Magnet Cove lodestone

13.1. *The hysteresis loop*

Consider a ferromagnetic specimen placed within a magnetizing field H, so that the material exhibits a certain magnetic moment J per unit volume. Beginning with the sample 'wiped free' of any intrinsic permanent magnetism (see below), a low value of H is applied and the corresponding J measured. H is then increased in small steps, and a plot of J vs H constructed with J as the ordinate against H as the abscissa. It will be found to exhibit the general sigmoid shape indicated in Figure 15. Along that part of the curve from the origin to point a, the point of inflection before the slope steepens, if the magnetizing field is removed the specimen loses its magnetization: this part of the process is reversible.

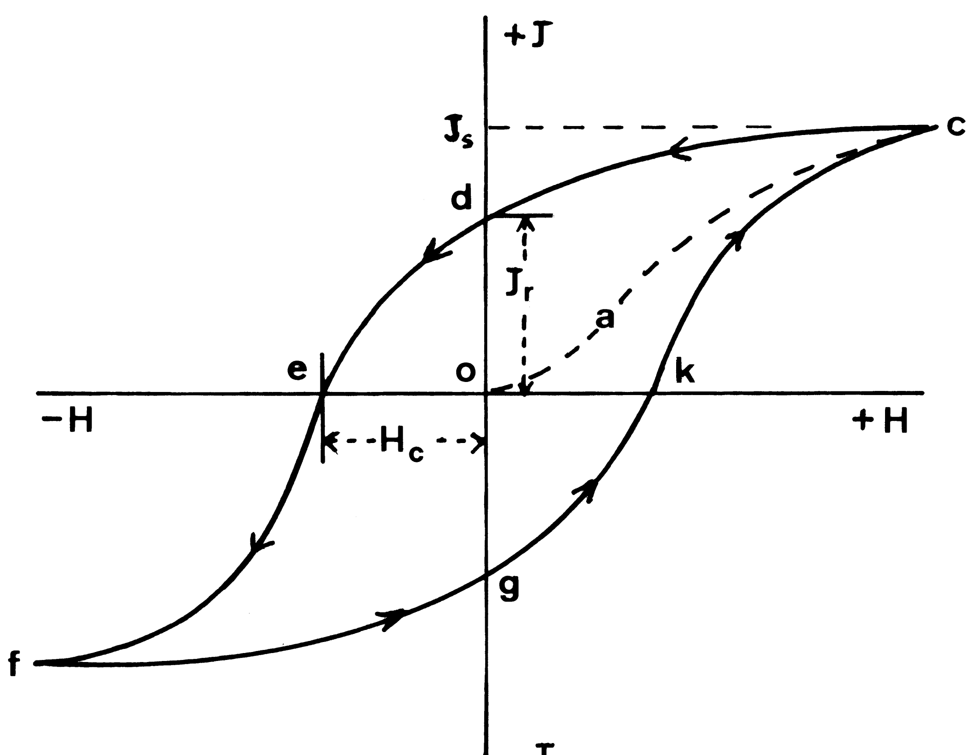

Figure 15. A generalized hysteresis loop.

With increasing H the initial curve flattens as it rises, until it approaches saturation J_s at c. If H is now gradually decreased the sample no longer loses its magnetization entirely when H has been reduced to zero: the residual permanent magnetism corresponds to point d, and J_r is called the residual magnetism (remanence) of the ferromagnetic material. On reversing the magnetizing field the curve def is followed, with saturation in the reverse direction at f. The reverse field e required to remove the induced permanent magnetism entirely is called the coercive force or coercivity H_c of the sample. On decreasing the reverse field the portion fg is followed, and then changing it back to the original direction at g enables gkc to be traversed, with resaturation at c.

It will be noticed that J always lags behind H in the cycle, reaching zero only when H has already been reversed. This lag is called hysteresis, and the closed sigmoid curve is referred to as a hysteresis loop. The area within the loop represents the energy in ergs used in taking unit volume of the material under test through the cycle: it will be dissipated as heat. It will be self-evident that ferromagnetic materials for the construction of good permanent magnets should display high values of saturation, remanence, and coercivity.

At no stage beyond that denoted by point a in Figure 15 can the specimen be removed unmagnetized. To accomplish this, it is necessary to take the sample through a number of cycles of gradually diminishing maximum H. One method is to reduce the magnetizing current slowly to zero while continually reversing it; another scheme is to withdraw the specimen slowly from a coil carrying an alternating current. The latter method is employed by horologists to demagnetize watches and steel tools and, in a more sophisticated form, for studies of rock magnetism.

13.2. *Experimental apparatus*

A fairly strong magnetic field of known intensity may be generated by a multi-turn helical coil, wound on a non-ferrous former, that is long compared with its diameter. It may be shown[60] that the field H at any point within such a solenoid (well removed from its ends) is given by

$$H = \frac{4\pi n I}{10}\ \text{Oe}, \tag{12}$$

where n is the number of turns of wire per cm, and I the current in amperes.

However, accurately measuring the extra intensity exhibited when a ferrous object is within a coil is difficult when currents sufficient to generate high fields are flowing. It is better to annul automatically the ‘empty’ or ‘air-core’ magnetizing field by using a balanced pair of coils, so that any subsequent field is due to a sample inserted into one coil.[61] An early method of accomplishing this was by connecting two opposing coils in the circuit diagrammed in Figure 16. Two identical formers were constructed from 38 mm outer diameter aluminium tubing held between plywood supports so as to expose 15.4 cm between the cheeks. 680 turns of 24 SWG (0.91 mm diameter) enamelled copper wire were wound as four full layers within the space, giving 44.16 turns per cm length. The field within each coil is given by equation (12) to be $55.5I$ Oe when I is the current flowing in amperes. The resistance of each coil proved to be 3.3 Ω at room temperature.

[60] Noakes (note 55).
[61] Tyler (note 53).

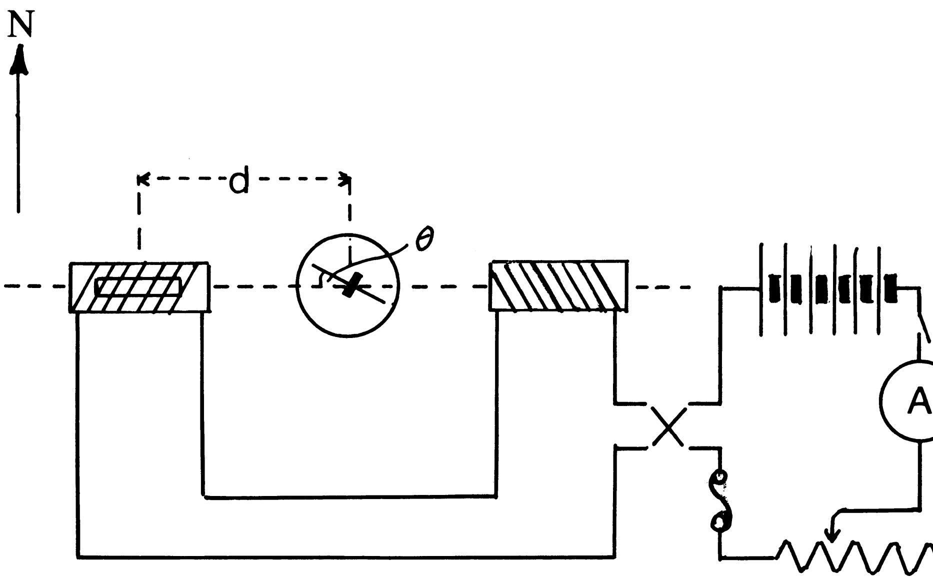

Figure 16. Circuit for quantitative plotting of hysteresis loops.

The coils were mounted 12 cm apart along wooden rails oriented east–west, and a mirror-base tangent galvanometer was mounted between them at a height that placed its magnet on the common axis of the coils. They were connected in opposite directions to give the desired region of zero field between them. The power supply consisted of two 12 V car batteries connected in series, regulated by a chain of 250, 180, 16, and 0.4 Ω heavy duty resistances. The current was measured with an LCD ammeter reading up to 10 A in 0.01 A steps. A maximum current of 3.4 A could be achieved, and was initially employed to refine the position of the compensating coil until the needle of the tangent galvanometer remained at zero even when the direction of the current was reversed. Greater fields than the 190 Oe generated by this current would have been desirable—and could have been achieved by using more batteries—but the >40 W dissipated in each coil already produced sufficient heating to cause concern.

13.3. *Specimens*

Samples of soft iron and hard steel were included for comparison with lodestone and 'ordinary' magnetites.

Soft iron	A rod 3.75 mm diameter × 65 mm long cut from a mild steel nail. Annealed by heating to a red heat and allowing to cool slowly. Volume 0.718 cm^3.
Hard steel	A carbon steel rod ('silver steel') 4.00 mm diameter × 65 mm long. Hardened by heating to a red heat and quenching in cold water. Volume 0.817 cm^3.
Lodestone	Magnet Cove C, cut into a rectangular block of size 18.0 mm × 12.5 mm × 8.2 mm. Volume 1.84 cm^3. It was checked that the specimen's inherent magnetism survived the cutting procedure.
Magnetite	Magnet Cove 4, cut into a rectangular block of size 14.5 mm × 10.5 mm × 7.0 mm. Volume 1.07 cm^3.
Magnetite	Ishpeming. Produced as a core sample 8.70 mm diameter × 25.0 mm long. Volume 1.486 cm^3.

All specimens were routinely demagnetized just before each run with a Bergeon 230 V, 50 Hz, horological demagnetizing apparatus. Each sample was held within the coil, the pushbutton on/off control depressed, and the sample withdrawn. None affected a small magnetic compass after treatment. The samples were wedged axially at the centres of plywood discs that were a sliding fit in the aluminium core of one coil of the hysteresis apparatus.

13.4. *Calculation and method*

It may be shown[62] that

$$J_v = \frac{(d^2 - \ell^2)^2}{2d} \frac{H_o}{V} \tan\theta. \qquad (13)$$

The iron and steel rods were positioned within the magnetizing coil with their centres at a distance of 12.0 cm from the needle support of the magnetometer, i.e. $d = 12$ cm. The magnetite specimens gave more reasonable deflections when placed so that $d = 10$ cm. Starting at 0.05 A, the current was increased unidirectionally in steps of about 0.2 A, and the corresponding deflection θ tabulated. Once the maximum value had been achieved the current was decreased in similar stages to zero, at which point the reversing switch was operated to begin applying the field in the opposite direction. The cycle was continued until a maximum field in the original direction was once again achieved. The (warm) sample was removed, demagnetized, and stored.

At each point H was calculated from equation (12) and J_v from equation (13) by using the known or measured values of d, ℓ, V, and $\tan\theta$ and assuming $H_o = 0.18$ Oe. Plots of H vs J_v were then drawn for all the specimens, that for lodestone C being reproduced in Figure 17. Values for J_s, J_r, and H_c were read off, and the hysteresis energy in ergs per cm^3 was obtained by counting squares within the closed loops.

13.5. *Results*

13.5.1. *Soft iron*

Soft iron readily follows the applied field, so a narrow hysteresis loop was exhibited and little permanent magnetism remained when the magnetizing field was removed. This behaviour is reflected in $J_s = 900$ emu cm^{-3}, $J_r = 37$ emu cm^{-3}, and $H_c = 3$ Oe. The work done per cycle was 18 200 erg cm^{-3}, equivalent to 2320 erg g^{-1}.

13.5.2. *Hard steel*

The classic broad hysteresis loop was exhibited, the metal being harder to magnetize than soft iron but retaining this magnetism better when removed from the magnetizing field. The curve did not achieve a horizontal portion at the apex, indicating an insufficient magnetizing field to achieve saturation. The indicated values of $J_r = 193$ emu cm^{-3} and $H_c = 33$ Oe would be expected to be somewhat larger if exposure to a saturating field had been possible: the literature value of H_c for hard steel is about 40 Oe. The work done per cycle was 72 400 erg cm^{-3}, equivalent to 9260 erg g^{-1}.

[62] Tyler (note 53).

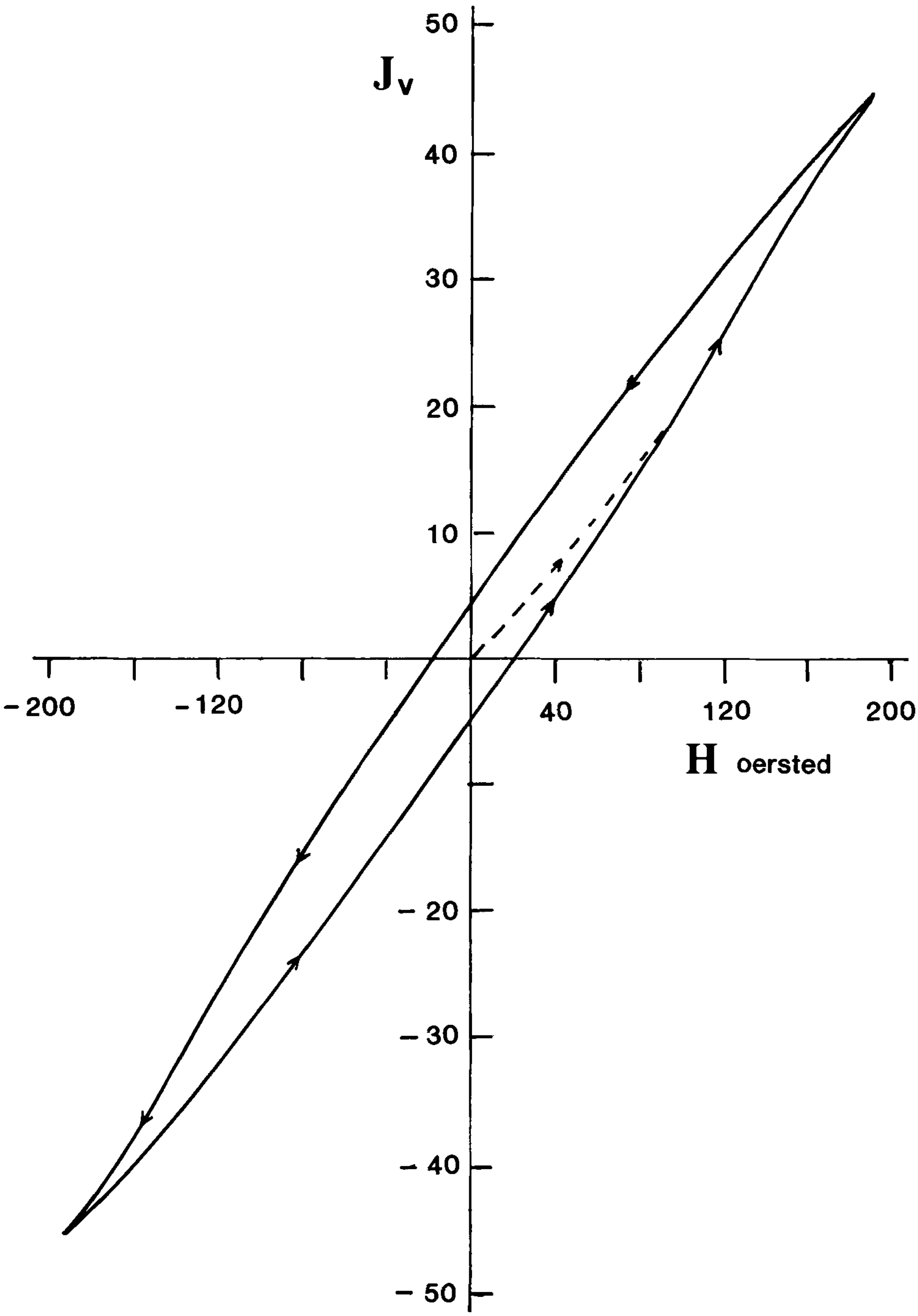

Figure 17. Hysteresis loop for lodestone C, Magnet Cove.

13.5.3. *Lodestone, Magnet Cove C* (Figure 17)

The hysteresis curve was intermediate in shape between those of soft iron and hard steel, but the parameters were different. Thus $J_s = 45\,\mathrm{emu\,cm^{-3}}$, $J_r = 4\,\mathrm{emu\,cm^{-3}}$, and $H_c = 20\,\mathrm{Oe}$, with work done per cycle $2310\,\mathrm{erg\,cm^{-3}}$, equivalent to $506\,\mathrm{erg\,g^{-1}}$. The remanence is poor, but this low permanent magnetism was retained better than by soft iron.

13.5.4. *Magnetite, Magnet Cove 4*

The hysteresis curve was virtually identical with that of the lodestone from the same area shown in Figure 17. $J_s = 38\,\mathrm{emu\,cm^{-3}}$, $J_r = 4\,\mathrm{emu\,cm^{-3}}$, and $H_c = 22\,\mathrm{Oe}$. Work done per cycle was $2180\,\mathrm{erg\,cm^{-3}}$, equivalent to $480\,\mathrm{erg\,g^{-1}}$. These figures support the hypothesis that lodestones differ from associated magnetites not exhibiting permanent magnetism only in that the former have at some time been exposed to a strong magnetizing field.

13.5.5. *Magnetite, Ishpeming*

The narrow hysteresis loop was similar in shape to that of soft iron, but at a very different scale. $J_s = 110\,\mathrm{emu\,cm^{-3}}$, $J_r = 4\,\mathrm{emu\,cm^{-3}}$, and $H_c = 6\,\mathrm{Oe}$. Work done per cycle was $2240\,\mathrm{erg\,cm^{-3}}$, equivalent to $440\,\mathrm{erg\,g^{-1}}$.

13.6. *Susceptibility (K)*

The ratio of the intensity of magnetization of a material to the field intensity is commonly referred to as the susceptibility K of that material, i.e.,

$$K = \frac{J}{H}. \tag{14}$$

This is more precisely termed the volume susceptibility. If ρ is the density of the material, then its mass susceptibility χ is defined by

$$\chi = \frac{K}{\rho}, \tag{15}$$

All materials show some effect in a magnetic field. Substances that are magnetized in the direction of the field, thereby having positive values of K, are known as paramagnetics. Materials which are (very feebly) magnetized in the opposite direction constitute diamagnetics, and K is very small and negative. Iron, nickel, cobalt, and certain alloys are very strongly magnetized in the direction of the magnetizing field, so K is both positive and large—although it varies with the field, temperature, etc. This special group constitutes the ferromagnetics. Important properties are the initial susceptibility in small fields and the maximum susceptibility. The former should be obtained from the initial curves from an unmagnetized state, as shown by the broken curves from the origin in Figures 15 and 17.

13.6.1. *Soft iron*

The volume susceptibility was about 6 for a 10 Oe field, i.e., the induced magnetic moment per unit volume was $6\times$ the magnetizing field.

13.6.2. *Hard steel*

The initial volume susceptibility was about 2 for a 10 Oe field, so that the induced magnetic moment per unit volume was about twice the magnetizing field.

13.6.3. *Magnetite*

The initial volume susceptibility was about 0.18 for low fields, and remained <1 although positive. This is another characteristic of the special class of paramagnetic substances known as ferrites. So, a terrestrial magnetic field unlikely to exceed 1 Oe would induce a magnetic moment per unit volume of only 0.18 emu—far less than the values of 6.5–36.7 observed even with the weak lodestones listed in Tables 2 and 3. This is obviously very relevant to theories of their origin—see Section 17.

13.7. *Field to saturate lodestone*

Plotting an entire hysteresis loop in the apparatus described in Section 13.2 led to overheating when a current exceeding 3.4 A was employed. This generated a magnetizing field of 189 Oe, which the resulting curves showed to be insufficient to reach saturation in both hard steel and magnetite. A field going up to 1000 Oe is generally recommended for studies of the former, and it was of interest to ascertain whether a similar limit applied to lodestone.

Much higher values of magnetizing field are available between the poles of an iron-cored electromagnet, but before trying this method it was desired to exploit the air-cored coil technique to the limit. This was possible because a very brief (milliseconds) exposure to a field is sufficient to induce the associated permanent magnetism, and even a very high transient current should produce no more than acceptable heating within the coil—particularly when beginning from cold.

One coil of the hysteresis apparatus was detached for these experiments, connected to a digital d.c. ammeter, and arrangements were made to make brief manual connection to up to six 12 V car batteries connected in series. Magnet Cove sample 1 had a thin, flattish shape, and could just be slid horizontally into the aluminium tube core of the coil. It weighed 58.9 g, had a volume of 13.2 cm^3, and a density of 4.46 $g\,cm^{-3}$. Although not exhibiting any natural permanent magnetism, it was nevertheless passed through the a.c. coil to make sure it was in the same magnetic condition as other samples. It was then inserted at the centre of the magnetizing coil. Brief connection to one battery was made manually via a heavy copper knife switch, with note taken of the maximum current that flowed, and then the sample removed and its magnetic moment measured by the 'neutral points' method described in Section 11.6. Finding the points north and south of the specimen gave 2d, and from equation (10) we know that $M=0.09d^3$. More batteries were successively connected in series, and measurements made up to 20 A (1110 Oe).

Access to a Newport Instruments type E electromagnet enabled the effect of higher magnetizing fields to be checked. The 7 in diameter flat pole pieces had been set 3 in apart, and the manufacturer's literature suggested that a maximum field intensity of about 4000 Oe might be achieved before water cooling became necessary. In practice, the field in the central region between the poles was measured with an Electronica digital fluxmeter and the current through the magnet adjusted to produce fields of 1000 or 2000 Oe. Magnet Cove sample 3 was held in a wooden clamp, and exposed longitudinally to each known field. The induced magnetic moment was found by the usual neutral points technique, and the magnetic moment per unit volume (J_v) calculated from the predetermined volume.

A plot of magnetizing field H vs the induced magnetic moment per unit volume J_v is shown in Figure 18. The points found for sample 3 at high fields fitted well with those determined for sample 1 at lower fields by the solenoid method. The curve shows that little increase in induced permanent magnetism occurred in fields above 1000 Oe, which produced a magnetic moment of 53 emu cm^{-3} when measured within an hour. The resulting lodestone could lift about 23 g of paper clips, equal to some 40% of its own weight. No doubt it would have done even better (lift its own weight?) if 'armed' or 'cased'. It would also pick up small pieces of ordinary magnetite.

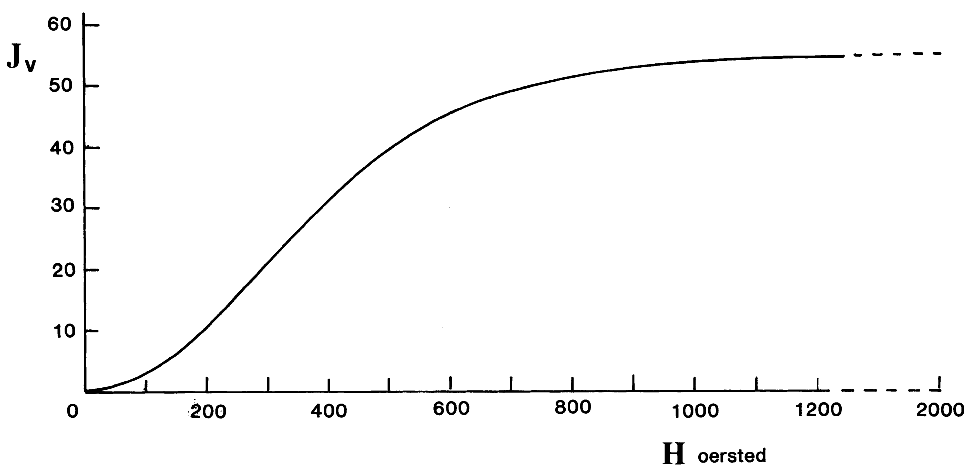

Figure 18. Plot of J_v vs H at fields up to 2000 Oe for Magnet Cove magnetite specimen 3.

13.8. *Reassessment of the direction-finding ability of the lodestone*

An early test to find the N–S magnetic meridian with the natural lodestone Magnet Cove A was disappointing (Section 10.5), but it has now been confirmed quantitatively that with a magnetic moment of only 10.9 emu cm^{-3} this was a weak lodestone. A much better specimen was now available as the artificially augmented Magnet Cove 1 prepared above, with a strength of 53 emu cm^{-3}. It had an elongated shape, and had been deliberately oriented in the electromagnet to give a magnetic axis along the longest dimension.

Placing this lodestone in a small plastic dish floating on water contained in a glass basin (with a transparent cover to reduce draughts) gave strong hints of taking up a N–S orientation, but always the small dish (or a cork float) would soon drift to the side of the container and 'stick' owing to capillary attraction. Suspension of the 'enhanced' lodestone within the basin on a multifilament thread of unspun silk proved better, but even when a perforated cover was placed over the basin the stone tended to oscillate continually about a mean N–S orientation. Pouring sufficient water into the basin to cover the stone was the vital breakthrough: the long, narrow lodestone maintained an impressive stability along the magnetic meridian even when the table was deliberately disturbed. This 'damped suspension' was so simple and effective that it is hard to imagine it was not employed by early Chinese navigators and their European followers. It has already been pointed out that initial marking-up of the stone with respect to the geographic N–S meridian determined from Sun or stars would automatically allow for the deviation until well removed from the site of calibration, or with the passage of many years.

13.9. *Magnetism with strong permanent magnets*

Stroking a ferrous specimen in one direction with one pole of a bar magnet, and placing it across the poles of a horseshoe magnet, are additional classic methods of making magnets. An Alcomax III bar magnet and the Alnico horseshoe magnet listed in Table 2 were used to test these techniques on the magnetite Magnet Cove 3. This weighed 32.8 g and had a volume of 7.1 cm^3. It was always demagnetized with the a.c. coil before each test.

Stroking 10 times in the longest direction with one pole of the bar magnet induced a magnetic moment of 8.4 emu cm^{-3}. This compares with the rather poor 'natural' lodestones from the source area. Placing the specimen across the poles of the powerful Alnico horseshoe magnet led to strong attraction and, when removed, a residual moment of 38 emu cm^{-3}. This simple procedure therefore gives a degree of magnetization comparable with that induced by a 475 Oe field in an air-cored solenoid—but is, of course, limited to vaguely defined single values of the magnetizing field.

14. Magnetic induction, *B*

Nowadays, and particularly when considering the design of electromagnetic equipment such as motors and transformers, it is usual to work in terms of magnetic induction. 4π lines of induction are imagined to leave a unit N pole, and the magnetic induction B (flux density) at any point in a magnetic circuit is equal to the number of lines of induction passing normally through unit area at that point. The unit of induction, one line per square centimetre, is called the gauss (G).

The induction inside a ferromagnetic specimen is generally assessed by the relationship

$$B = H + 4\pi J \tag{16}$$

So, for the samples examined above,

	B_r gauss (G)
Hard steel	2425
Soft iron	465
Lodestone	50

However, it was considered that, in general, values of magnetic moment per unit volume quoted as emu cm^{-3} were more suited to the quantitative study of the lodestone.

15. Structure and composition of magnetites

15.1. *General*

In older works magnetite is simply assigned the formula Fe_3O_4, but more recent texts[63] explain that it is a *ferrite* possessing an inverse spinel structure more precisely written $Fe^{3+}[Fe^{2+},Fe^{3+}]O_4$. It is a ferric ferrite. A number of oxide materials share the spinel structure, so cation substitution results in extensive solid solutions between them. Important examples are those between magnetite and ulvöspinel $Fe^{2+}[Fe^{2+},Ti^{4+}]O_4$, producing ferromagnetic titanomagnetites that act as the main carriers of magnetism in rocks.

In the absence of an applied magnetic field a ferro- or ferrimagnetic material is divided into macroscopic magnetic domains. There is a specific direction of magnetization within each domain, but this changes from one domain to the next. When an external magnetic field is applied to a multi-domain crystal the domain walls move in response to this applied field, increasing the net magnetization of the crystal. As the applied field is increased the magnetization increases until saturation is reached. This saturation magnetization is a property of the mineral that can be related to the cation ordering. In a magnetically hard material the domain walls are difficult to move, and a high coercive force is required to remove the magnetization. Besides composition, particle size and shape are very important in controlling this property, small (but not too small) needle-shaped grains being particularly effective for promoting high coercivity. Certain ferrites, as finely divided particles, form the basis of modern audio and video tapes and computer discs.[64]

15.2. *Chemical analyses of Magnet Cove magnetites*

Two specimens of Magnet Cove magnetite were analysed by the Analytical Services Group of the Department of Geology, University of Leicester. One sample (4) was magnetically inert; the other (C) was a natural lodestone. The technique employed was automated X-ray fluorescence of the powdered material fused with a lithium metaborate flux and then pressed into a glassy disc. Analyses are quoted in Table 4 in weight percent.

Table 4. Chemical analysis of Magnet Cove specimens.

	Magnetite 4	Lodestone C
SiO_2	1.23	0.49
TiO_2	9.09	8.51
Al_2O_3	3.59	2.56
Fe_2O_3	81.70	82.77
MnO	0.75	1.42
MgO	3.70	4.37
V_2O_3	0.25	0.17
CaO	0.24	0.09
Na_2O	0.01	0.13
K_2O	0.07	0.04
P_2O_5	0.09	0.05
Loss on ignition	−0.97	−1.95
Total	**99.95**	**99.65**

[63] Andrew Putnis, *Introduction to Mineral Sciences* (Cambridge, 1992).

[64] E. Köster, 'Particulate Media', in *Magnetic Recording Technology*, ed. by C. D. Mee and E. D. Daniel (New York, 1995), ch. 3.

The Magnet Cove magnetite is a titanium-rich structure with minor vanadium. No significant chemical differences could be distinguished between the magnetically inert and lodestone varieties.

15.3. *Reflected light microscopy*

Two samples from Magnet Cove were prepared as polished sections. One (F) was a natural magnet—a lodestone—and the other (6) a magnetically inert sample of magnetite from the same location. The preparations were examined by reflected light (Figures 19 and 20 respectively). The lodestone F was a relatively homogeneous magnetite, whereas that constituting sample 6 exhibited extensive alteration products and inclusions along with separation into Ti-rich and Ti-poor zones. It would be expected that F would both accept a higher magnetic intensity and retain it more efficiently, but a considerable research programme would be required to prove this.

16. Magnetic characteristics of magnetites from other localities

The lodestone/magnetite from Magnet Cove, Arkansas, has been used as the type example in these studies. However, it is expected that minor and trace element composition, particle size and shape, etc. will modify quantitative aspects of intensity and longevity, with the concentration of magnetite in a heterogeneous mineral obviously also affecting the overall magnetic moment per unit mass or volume

To provide some check on the validity of extending Magnet Cove data to other magnetites, a number of magnetites from other locations around the world were gathered from collections. Some displayed permanent magnetism (i.e., were

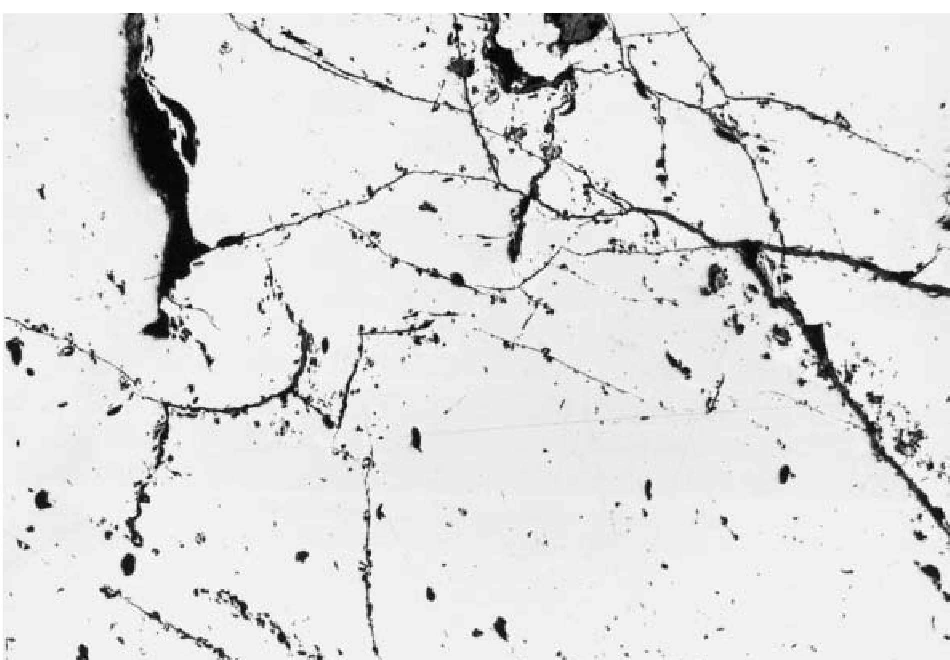

Figure 19. Reflected light micrograph of lodestone F.

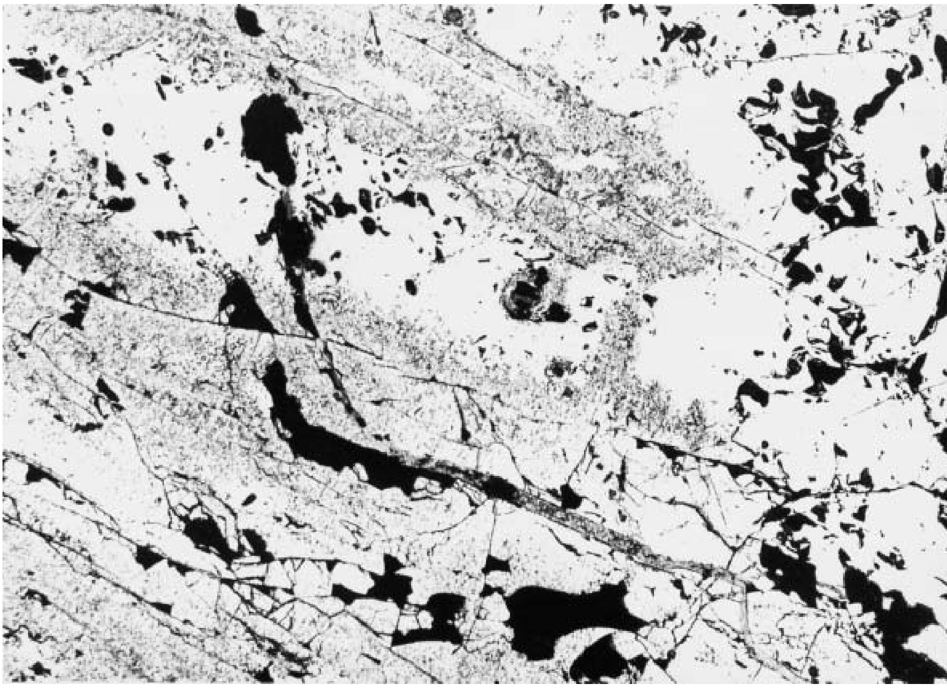

Figure 20. Reflected light micrograph of magnetite 6.

lodestones), but, as they were in teaching collections and may have been tested with pocket magnets, this property must be treated with caution.

Together with some Magnet Cove specimens for comparison, all were first passed through the a.c. demagnetizer and then subjected to the 1000 Oe unidirectional field of the d.c. electromagnet. The resulting saturation magnetic moments were immediately assessed by the 'neutral points' method of Section 11.6. Values were re-determined after 5 weeks storage at room temperature, but in no case was any change detected. Masses and densities were measured to enable calculation of magnetic moments per cm^3 and per gram. Results are shown in Table 5.

16.1. *Magnetizability*

It was found that all the magnetites tested were permanently magnetizable (i.e., could be made into artificial lodestones), and that their intensities did not measurably decay after some weeks at ambient temperature.

16.2. *Magnetic moments*

It will be seen that the magnetic moments per cm^3 and per gram were generally low compared with the values found for Magnet Cove specimens: only Cedar City was comparable. In particular, the magnetite-rich specimens Ishpeming, 95298, and 95299 exhibited low saturation intensities. It is apparent that a number of variables determine whether a given magnetite is potentially capable of being made into a 'good' lodestone, and not just the concentration of magnetite in an impure specimen. It is suspected that titanium content (as titanomagnetites) could be an

Table 5. Saturation magnetism induced in various magnetites.

Locality	Catalogue number	Description	Pre-existing magnetism	Mass	Density ($g\,cm^{-3}$)	J_v ($emu\,cm^{-3}$)	J_m ($emu\,g^{-1}$)
Magnet Cove	1	Rust brown, rounded	—	68.6	4.76	28.8	6.1
Magnet Cove	3	Rust brown, rounded	—	32.9	4.70	50.7	10.8
Magnet Cove	D	Rust brown, rounded	+	36.4	4.79	26.6	5.6
Magnet Cove	E	Rust brown, rounded	+	25.3	4.69	33.0	7.0
Cedar City	—	Brown–black	+	71.7	4.78	30.3	6.3
Skye	—	Greenish black	+	25.2	3.82	6.6	1.7
Ishpeming	—	9 mm core, massive	—	7.5	5.36	7.3	1.4
Unknown	95298	Massive, black, crystalline	—	58.0	4.79	6.2	1.3
Unknown	95299	Massive, black, crystalline	—	123.6	4.59	2.6	0.6
Unknown	95300	Cluster of three large black crystals	+	22.6	4.91	11.8	2.4
Tasmania	71731	Magnetite schist	+	16.3	4.53	7.2	1.6

important factor, but a considerable analytical research programme would be required to establish this. Meanwhile, it does seem that Magnet Cove provides a good type example.

17. Genesis of the lodestone

17.1. *General requirements*

The following requirements must be satisfied:

(a) All known lodestones contain magnetite, Fe_3O_4, in varying degrees of purity.
(b) Only a very small proportion of specimens of magnetite display the phenomenon of natural permanent magnetism that qualifies them to be called lodestones.
(c) All lodestones appear to come from surficial deposits as discrete irregular weathered fragments, masses in the range 10–100 g being the most usual size. Historical lodestones exceeding 1 kg are extremely rare.
(d) When found *in situ* (e.g. at Magnet Cove, Arkansas) individual lodestones are accompanied by many magnetically inert specimens. All are identical in appearance and general chemical composition.
(e) Natural lodestones tested at the present time exhibited magnetic moments in the range 6–37 $emu\,cm^{-3}$. They are weak by comparison with modern permanent magnets.
(f) Inert specimens of magnetite may be artificially magnetized by exposure to a strong unidirectional magnetic field. A brief exposure measured in

milliseconds is enough. Saturation (about 53 emu cm^{-3} with Magnet Cove material) is achieved in a field of 1000 Oe (0.1 T).

(g) The geomagnetic field does not appear to have exceeded 1 Oe over the past million years, so as the initial susceptibility of magnetite is <1 it does not seem possible for magnetization by simple induction to reach anywhere near the levels observed in natural lodestones.

(h) Historical accounts of lodestones speak of them as displaying considerably greater magnetic prowess than the specimens known today. However, re-magnetization to saturation by exposure to a 1000 Oe unidirectional field does produce 'artificial' lodestones comparable in strength with those in the old accounts. It therefore appears that the magnetism of natural lodestones is induced by some sudden and rare natural event occurring near the surface, and then slowly decays with time.

17.2. *Lightning*

The only worldwide natural phenomenon known to be capable of generating a transient electromagnetic field of the required intensity is lightning. In 1630 Gassendi[65] observed that an iron cross struck by lightning had become magnetic, but Pockels[66] was the first to study carefully the effect in rocks when he discovered that basalts around the roots of a tree struck by lightning affected a hand compass. Bricks, too, could become magnetized.[67] Modern authors in the field of rock magnetism[68] are well aware of the phenomenon, but simply advise researchers to avoid anomalous zones that obviously deflect a pocket compass. They make no connection with the generation of lodestones by a lightning strike to an outcrop rich in magnetite.

Much work on lightning has been conducted by Schonland[69] and Uman.[70] They found the most frequent value of the peak current in ground-to-cloud return discharges to be 30 000 A, although it could reach as much as 110 000 A. One source of these figures was 'surge-crest ammeters'[71] – pieces of hard steel installed at locations likely to be struck by lightning. These reacted similarly to Pockels' rocks, but in a more controllable and reproducible manner that aided calculation of peak currents from the intensity of the induced magnetism.

The field due to a current moving in a straight wire is given[72] by:

$$H = \frac{I}{5R}, \tag{17}$$

where H is the intensity in oersteds, I the current in amperes, and R represents the

[65]See Brewster (note 13).

[66]F. Pockels, 'Über das magnetische Verhalten einiger basaltischer Gesteine', *Annalen der Physikalische Chemie*, 63 (1837), 195–201. 'Bestimmung maximaler Entladungs-strom-stärken aus ihrer magnetisirenden Wirkung', *Annalen der Physikalischer Chemie*, 65 (1898), 458–75, 'Uber die Blitzentladungen erreichte Stromstarke', *Physikalische Zeitung*, 2 (1900), 306–07.

[67]P. Gamba, 'Magnetization of Bricks by Lightning', *Atti della Royale Accademia dei Lincei (Roma)*, 8 (1899), 316.

[68]A. Cox, 'Anomalous Remanent Magnetization of Basalt', *US Geological Survey Bulletin*, 1083-E (1961), 131–60. R. Thompson and F. Oldfield, *Environmental Magnetism* (London, 1986). R. F. Butler, *Paleomagnetism: Magnetic Domains to Geologic Terranes* (Oxford, 1992).

[69]Basil Schonland, *The Flight of Thunderbolts* (Oxford, 1964).

[70]Martin A.Uman, *Lightning* (New York, 1969).

[71]C. M. Foust and H. P. Kuehni, 'The Surge-Crest Ammeter', *General Electric Review*, 35 (1932) 644–48.

[72]See Noakes (note 55).

radial distance from the wire in cm. On substituting $I = 30\,000$ A and $H = 1000$ Oe, this formula suggests any magnetite within a zone 12 cm in diameter around a strike will be magnetized to saturation. A 100 000 A discharge will produce a zone of magnetic saturation some 40 cm in diameter. It will be noted that the heavy current does not have to traverse a piece of magnetite in order to magnetize it, and that material outside the above limits could still be strongly magnetized. The evidence of lightning strikes to unprotected buildings suggests that a fractured mass of lodestones of various strengths up to the maximum, accompanied by magnetically weaker and multipolar specimens, plus inert material, will be flung out following a strike to a magnetite outcrop. It is essentially a near-surface phenomenon, the hollow branching structures known as fulgurites produced by a stroke to dry sand going down perhaps 2 m, with a diameter of 50 mm near the top.[73]

The confirmed and undisputed discovery of a strong lodestone *in situ* at depth in an iron mine would, of course, vitiate this proposed origin.

18. Age of the Magnet Cove lodestones

Historical evidence suggests that the intensity of magnetization in natural lodestones diminishes slowly with time, just as it does with 'man-made' permanent magnets. To try to obtain some quantitative idea of the rate of decay, specimens of Magnet Cove magnetite were subjected to the following procedure:

(a) The specimens were demagnetized in a diminishing a.c. field.
(b) They were remagnetized to saturation in a 1000 Oe unidirectional field generated by an electromagnet (Section 13.7).
(c) The resulting saturation magnetic moments per unit volume (J_v) were measured by the 'neutral point' method of Section 11.6.
(d) Specimens were placed in thermostatted furnaces, or an oven, as follows:

Sample	**Temperature (°C)**
E	500
3	450
1	300
2	110

(e) At known intervals—initially daily, but later every 5–10 days—the samples were removed, allowed to cool to room temperature, and J_v was re-measured. The specimens were then returned to the relevant furnace. This annealing process was maintained for 100 days. Unfortunately, data at 300 °C were lost and the specimen was destroyed when the furnace severely overheated as a result of thermostat failure.

Results are shown in Figure 21. Rapid initial falls in J_v were followed by progressively slower diminution, giving an impression of exponential decay. However, testing by plotting $\log J_v$ or the reciprocal of J_v vs time gave smooth concave or convex curves rather than the linear graphs associated with first- or second-order kinetics.[74] This is hardly unexpected, for solid state mechanisms would surely be more complicated than simple gas phase reactions.

[73]See Schonland (note 69).
[74]S. R. Logan, *Fundamentals of Chemical Kinetics* (London: Longman, 1996).

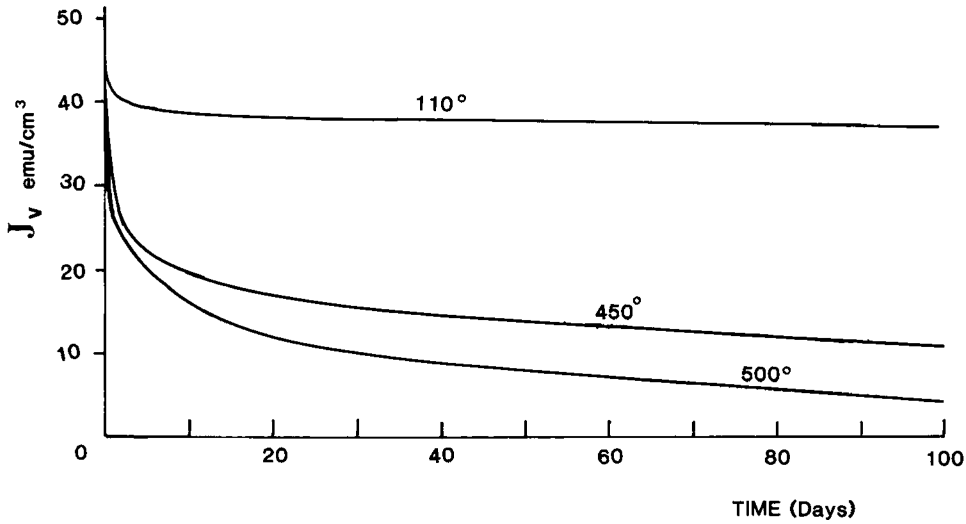

Figure 21. Decay of J_v with time at various temperatures. Magnet Cove lodestone.

An attempt to obtain a semiquantitative interpretation was made by plotting the logarithm of the time in days to fall to $J_v = 9$, the mean value for 'as found' Magnet Cove lodestones, vs the logarithm of the annealing temperature in °C. A gross linear extrapolation of this doubtful procedure to an ambient temperature of 10°C (Figure 22) suggested a period of $(1.0–1.6) \times 10^6$ days, equivalent to 2700–4400 years (with a mean of 3500 years), since generation by the proposed stroke of lightning. This period appears geologically reasonable.

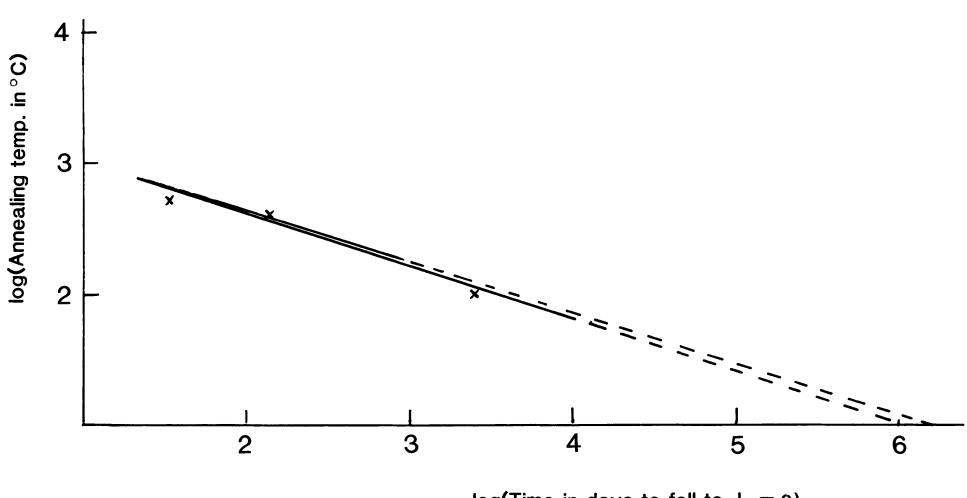

Figure 22. log(annealing temperature) vs log(period to fall to $J_v = 9$) for Magnet Cove magnetites. Extrapolated linearly to intercept the abscissa for 10°C.

19. Conclusions

Lodestone is an extremely rare form of the otherwise common mineral magnetite where pieces behave as natural permanent magnets. In past centuries, these were of vital importance in establishing the basic laws of magnetism and in the invention of the magnetic compass. However, when improved man-made steel and alloy magnets, and the electromagnet, were developed in the eighteenth and nineteenth centuries the lodestone became obsolete and forgotten. This was before the growing technological importance of magnets stimulated the development of quantitative methods for their appraisal. Previous studies of the lodestone therefore tend to be historical and descriptive, although explanation of their remarkable magnetic properties clearly demands quantitative data.

Standard measurements of magnetic moment per unit volume and mass, hysteresis, saturation intensity, and susceptibility have therefore been made, using contemporary lodestones from Magnet Cove, Arkansas, as the type example. Museum examples of 'capped' and 'cased' lodestones have also been measured and replicated.[75] Chemical and mineralogical analyses have been conducted. The results support the hypothesis that lodestones have their origin in rare strokes of lightning upon suitable (Ti-rich?) magnetite-bearing exposures, which both disrupt the rock and expose some of the fragments to transient—but intense—induced magnetic fields. Annealing experiments suggest the Magnet Cove lodestones were produced about 3500 years ago.

Acknowledgements

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[75] A. A. Mills, 'Armed Lodestones', accepted by the *Bulletin of the Scientific Instrument Society* (publication expected 2004).