Experimental Research on the South-Pointing Loadstone Spoon (*Sinan*)¹

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Abstract: In the 1940s, Wang Zhenduo 王振铎 re-created the *sinan* 司南 (south-pointing loadstone spoon) mentioned in ancient texts. However, subsequent researchers were unsuccessful in their attempts to replicate this design, resulting in longstanding questions over its feasibility. Loadstones with high natural remanent magnetization acquired today resemble the magnetism of those recorded in premodern Chinese documents. By simulating ancient stoneware processing techniques, a loadstone was cut and polished into a spoon shape. It was found that during the course of processing the loadstone spoon, demagnetization was negligible, while after completion, the internal magnetic field was rebalanced due to the change in shape, and the magnetic moment decreased slightly then stabilized for the long term. Experiments of this sort carried out by the author have testified to the enduring and reliable directivity of the resulting loadstone spoon. Paleo-magnetic research indicates that over the past two millennia the horizontal component of the geomagnetic field intensity in northern China underwent a clear M-shaped development. The level in the Qin and Han dynasties is approximately double that of the current day. Using a simulated ancient geomagnetic field, experiments have revealed that multiple methods, such as the “water floating method” and “hanging method,” could manifest a degree of geo-directivity. The comprehensive studies carried out demonstrate that the loadstone spoon is the most optimal among these diverse means for attaining magnetic directivity from the Pre-Qin period (before 221 BCE) to the Tang dynasty (618–907 CE) in view of the availability of loadstone, the state of the

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2 Research interests: History of physics, history of iron smelting technology, history of machinery, and the computer simulation research for ancient technology. Email: huangxing@ihns.ac.cn

geomagnetic field, and existing knowledge and techniques.

Keywords: compass, south-pointing loadstone spoon (*sinan*), loadstone, geomagnetic field, magnetic moment

摘要: 20 世纪 40 年代, 王振铎复原了古文献中提到的天然磁石勺“司南”, 但后人始终未能重复实现此方案, 其可行性长期受到质疑。本文作者采集到了具有较高天然剩余磁化强度的磁石, 与中国古文献记载的磁石磁性相近。仿照古代石器加工技术, 将这种磁石切割、打磨成勺状。在加工过程中, 磁石勺的退磁可以忽略; 加工完成后, 外形变化引发内部磁场重新平衡, 磁矩略有下降, 后又长期保持稳定。实测证明, 磁石勺始终具有很好的指向性。古地磁研究显示, 中国北方地磁场水平分量在两千多年来呈显著的 M 形变化, 秦汉时期约为现今的 2 倍。模拟古代地磁场进行实测, 磁石勺指向性显著提升。此外, 实测显示, 磁石水浮、悬吊等多种方式都具有一定的指向性。综合研究表明, 在先秦至唐代的磁石资源、地磁场、知识和工艺等条件下, 古人有多种方式实现磁性指向, 磁石勺是其中的最佳方案。

关键词: 指南针, 司南, 天然磁石, 地磁场, 磁矩

1 Introduction

The date when the Chinese invented an effective south-pointing compass is a long-discussed and much debated issue in the academic world. Clear references to the compass in Chinese literature can be traced back to the middle of the ninth century. However, earlier records document various instruments developed by alchemists, who made use of the magnetic properties of mutual attraction and repulsion, the magnetism of attracting iron, and the evocation ritual of hanging loadstones.

Before the early twentieth century, some scholars thought that devices such as the south-pointing chariot and the *sinan* mentioned as existing in the Pre-Qin period were magnetic compasses (Anonymous 1876; Anonymous 1891; Friedrich 1906; Jin [1781] 1986, 7; Zhang 1924), while others believed the magnetic compass should date back to the Northern Song dynasty (960–1127 CE) (Yamamoto 1924). In 1928, Zhang Yinlin 張蔭麟 delved into the saying “When the south-directing spoon is thrown upon the ground, it comes to rest pointing to the south” (司南之杓, 投之於地, 其柢指南) (Wang [1535] 1991, 274) from the *Shiying pian* 是應篇 (Chapter of the justifiable) in Wang Chong’s 王充 *Lunheng* 論衡 (Discourses weighed in the balance) of the first century. Zhang considered that what was described here was a magnetic pointer, and that the term *sinan* 司南 found in other ancient documents could indicate the same kind of utensil (Zhang 1928). In the 1940s, Wang Zhenduo proposed a program to re-create the *sinan* known as the “loadstone spoon bronze Earth-plate,” and produced several loadstone spoons with effective directivity (Wang 1948). In 1952, Joseph Needham observed a demonstration of such a *sinan* when he came to China (Needham 1962, 268), and in 1954, Li Shu-hua 李書華 published an article in *Isis* to promote Wang

Zhenduo's work (Li 1954, 180–181). Loadstone spoons made by Wang were presented to the nations of Cuba and Sweden as gifts, and were exhibited at the National Museum of Chinese History (the current National Museum of China) in the 1980s (Li 2016; Lin 1987). To date, most researchers have been of the opinion that the loadstone spoon is the best solution for such a re-creation (Dai 2001, 408–409; Dai 2014; Lin 1986; Li 1993; Pan 2002, 329–330), and it has even come to be seen as the symbol of ancient Chinese inventions.

These ancient texts, however, do not clearly explicate the relationship between *sinan* and magnetism, and no ancient loadstone spoons are known to exist or have been discovered by archaeologists, while other researchers have not been able to produce loadstone spoons with effective directivity. Therefore, Wang's re-creation and its technical feasibility have met with incredulity in some scholarly quarters. Other scholars have variously interpreted *sinan* as the Big Dipper or the Plough asterism (*beidou* 北斗), as an official position, power, destiny (Liu 1956; Liu 1986; Liu 1995; Liu 2006; Liu B. and Liu F. 1995; Liu B. and Liu Y. 1997; Liu et al. 2010), or a south-pointing chariot (Sun 2005). In recent years, new attempts to re-recreate the *sinan* have been attempted, such as the *piaozhen sinan zhuo* 飘针司南酌 (a water-floating compass using a south-pointing magnetic needle installed on a tiny gourd scoop) (Wenren 2015), and "magnetizing iron spoons by friction" (摩擦磁化铁勺) (Cen 2017). However, these all adopt the techniques of magnetizing iron by friction on modern artificial magnets, thus not solving the issue of whether loadstone spoons can point south.

The unravelling of this question warranted further experimental research. So, the author of this paper borrowed the remaining three loadstone spoons made by Wang and preserved by his offspring together with other surviving remnants (Figure 1), and carried out tests on their directivity. These tests confirmed outstanding performance by the smaller ones, numbered 3 and 4, and the failure of the larger one (unnumbered).

This experimental research on loadstones was designed by the author to solve the following riddles: Under ancient conditions, can loadstones be utilized to make an effective south-pointing spoon-shaped device? What changes in magnetism occur before and after the production of the loadstone spoon? Is there any evidence of a technical nature that would firmly rule out the production of objects with magnetic directivity before the Tang dynasty?

2 Loadstone spoon production and directivity experiments

2.1 Collection and examination of loadstone

This research was premised on finding appropriate loadstones. Many ancient

documents record that Cishan 磁山, Wu'an, Hebei abounds with loadstones. The author made frequent visits to explore Cishan, where the mine is already exhausted and now closed. The natural remanent magnetization of loadstones still to be found there is so weak that a suspended sewing needle can only be attracted to a slight angle. The *Bencao gangmu* 本草綱目 (Compendium of materia medica) of 1578 cites Su Song 蘇頌 of the Northern Song dynasty that “the northern tribes offered loadstones as presents” (今北番以慈石作禮物) (Li [1596] 2014, 264–265), indicating the relative scarcity of loadstones in the Central Plains at that time.

Figure 1: Loadstone spoons made by craftsmen commissioned by Wang Zhenduo (upper left: no. 3; upper right: no. 4; lower left: unnumbered) and the remaining fragments of loadstone (lower middle: a lump of ore from Cishan; lower right: a remaining ore slice).

At the Longyan diggings at Zhangjiakou, Hebei, the author discovered iron ores with high magnetic remanence at several spots (Figure 2). Their texture is fine and dense, and hairy ore fragments are attached to the surface, the Mohs hardness being 6 to 7. According to X-ray diffraction analysis, maghemite is the main constituent of the loadstones collected here, with a small amount of goethite and silica (Figure 3,

Table 1).³ Andradite is the chief component of ores gathered at Cishan (Figure 4, Table 2).⁴ Wang Zhenduo used ores from Cishan to make his loadstone spoons, and the author has examined the remaining loadstone, the composition of which basically matches the ones procured there by me.

Figure 2: Iron ore field and loadstones at the Longyan diggings.

Figure 3: The X-ray diffraction pattern of loadstone samples from the Longyan diggings.

Table 1: Main chemical composition of magnet samples from the Longyan diggings

Composition	Total iron content (TFe)	Maghemite ($\gamma\text{-Fe}_2\text{O}_3$)	Goethite ($\text{Fe}_2\text{O}_3\cdot\text{H}_2\text{O}$)	Quartz (SiO_2)
Content/ %	62	76	11	13

³ Beijing Beida Yanyuan MicroStructure Analytical Lab was commissioned to undertake the analysis using an X-ray diffractometer (D/max-rB). Algorithm standard: "SY/T 5163-2010: Analysis method for clay minerals and ordinary non-clay minerals in sedimentary rocks by the X-ray diffraction."

⁴ Andradite is prolific in contact metamorphosed limestones and marbles, and is produced from the replacement of calcium in the rock by the iron-containing solution; some also come from syenite, serpentinite, and chlorite schist, having intergrown magnetite and slight magnetism.

Figure 4: The X-ray diffraction pattern of ore samples from Cishan.

Table 2: Main chemical composition of ore samples from Cishan

Composition	Total iron content (TFe)	Andradite (Ca ₃ Fe ₂ [SiO ₄] ₃)	Magnetite (Fe ₃ O ₄)	Hematite (Fe ₂ O ₃)	Quartz (SiO ₂)
Content/%	17	87	5	7	1

2.2 Making the loadstone spoons

The author crafted a number of loadstone spoons using loadstones from the Longyan diggings. The essential steps involved were: select a long narrow crack-free loadstone with only two magnetic poles along its length; suspend it with a fine thread, wait until it stays motionless, and draw a line on it along the direction of north-south; draw a spoon-like outline symmetrically along this line, and cut it into shape. In a bid to enhance its geo-directional sensitivity, the spherical radius of the bowl bottom should be made as small as possible. The small size may result in the spoon having a tendency to tip over, necessitating the carving of the bowl to lower the center of gravity. To prevent the handle from dropping, part of the bowl near the handle should be deepened, thereby retaining the center of gravity at the spoon center. Finally, the bowl bottom is polished into a smooth spherical shape (Figure 5).

Wire saws for linear cutting and rotary cutters were used for water-cooled and low-speed cutting and grinding. The spoon bowl was polished using rotating machines and grinding heads, and its spherical bottom smoothed with files and sandpaper (P1200). The loadstones were easy to cut, rarely breaking or cracking, so long as they had no obvious fissures.

Figure 5: Production process of a loadstone spoon.

There have been some doubts raised over the technical difficulties of shaping loadstones into spoons in ancient times. However, recent micro-wear analysis and experiments have shown that a wide variety of suitable techniques were already in use during Hongshan culture (6000–5000 BCE) in north-east China and Liangzhu culture (5300–4500 BCE) in eastern central China, such as grinding, engraving, linear cutting, and drilling, as well as finer and more detailed cutting, grooving, piercing, and polishing that could be finished by processes of chopping, chiseling, punching, pressing, and pointing (Deng and Cao 2015, 6–12; Sun 2007). The adoption of metal tools from the second millennium BCE greatly increased the efficiency of stone processing, embodied in the stone-carving techniques in the Han dynasty (206 BCE–220 CE) (Liu 2002). According to records by French missionaries, in the Qing dynasty (1616–1911 CE), *tuo* 坨 (rotary incising wheels) and *jieyusha* 解玉砂 (abrasives) for cutting jades could effortlessly cut loadstones (Lecomte [1687–1692] 2004, 204–206). Therefore, from the Pre-Qin period, there has been no technical hinderance to the processing of loadstones into spoon shapes and burnishing the bowl bottom, leading to progressive advancements in production efficiency.

2.3 Changes of loadstone spoons' magnetic moments

Among the existing devices for measuring magnetic moment, the “Helmholtz coil-fluxmeter” method requires that the magnets to be measured should be square,

cylindrical or circular; some equipment can theoretically examine samples of any shape, but the testing chamber can only accommodate those shorter than 1 cm. Thus, these available devices cannot be used to identify the magnetic moments of the loadstones in this research, which are irregular and measure around 10 cm in length. Preceding researchers substituted magnetic moment with surface magnetic induction intensity, which means the magnetic induction intensity at certain points on a magnet's surface, though this differs from the dimension of magnetic moment, and strictly speaking is not directly proportional to it.

The author of this paper developed a magnetic moment measuring device (Figures 6–7)⁵ to meet the demands of this experiment. It is applicable to loadstones of any shape, and scales from 1 to 10 cm. The principle can be elucidated as follows: Place the magnet on a freely rotatable hanging plate, make sure that the north and south poles follow the east-west direction of the external magnetic field, and let the torque from the magnetic field equally transmit to two electric resistance strain gauges. Next, put this device in the uniform magnetic field generated by a Helmholtz coil (Firester 1966),⁶ steadily increase the horizontal component of the magnetic field intensity, conduct the linear fitting of the “torque-magnetic field,” and the slope of the fitted straight line will be directly proportional to the magnetic moment. After calibration, the loadstone's magnetic moment can be measured, and the magnetization becomes calculable. With regard to the linearity of this magnetic moment measuring device, the maximum deviation of the measurement is 2.50%; as for the repeatability, the standard deviation is 1.416% of the average value (when the magnetic field is 0.637 Gs); the effective precision is 0.01 emu.

This device in essence measures the loadstone's torque, and then converts it into magnetic moment, obtaining the overall average value of magnetization, thus effectively evading the complexity of the magnetic induction lines which needs to be taken into account for measuring the loadstone's magnetic moments by the principle of electromagnetic induction. In doing so, direct and accurate measurement of the loadstone's directivity is achieved.

Table 3 indicates the magnetic variation parameters during and after the making of loadstone spoon no. 2, and the data indicates that the loadstones' magnetic variation is anything but simple. A comparison can be drawn between parameters in Table 3 and those of the magnetic moments and magnetization of Wang Zhenduo's loadstone

5 This device has been granted a national invention patent (patent number: ZL201710144060.4.).

6 The coil's winding diameter is 0.60 mm, its physical side length is 800 mm, the number of turns of a single coil is 174, and the total coil resistance (20°C) is 69.4 Ω. Measurement was undertaken using the fluxgate meter produced by Beijing Cuihaijiacheng Magnetic Technology Co., Ltd.: the uniformity of the cubic space of 10 cm³ is 99.4%; that of the cubic space of 20 cm³ is 98.2%; the formula for the “magnetic field-current” (including geomagnetic field) is $B = 3.49I + 271.21$ mGs (B: magnetic induction intensity at the coil's center, unit: mGs; I: coil current intensity, unit: mA).

spoons (Table 4).

There are slight fluctuations in the magnetization data during processing. This could be attributed to the impreciseness and inadequate repetition of this measurement. Or it could be due to the unevenness of magnetization or inconsistency of direction in some constituent parts, namely that the magnetization or direction of the loadstone that remains after processing is different to that of the original source material. It is clear that low temperature cutting or grinding should not substantially impact on the remanent magnetization. Furthermore, despite the fact that loadstones, whether utilized in ancient times or in this paper, underwent blasting and hammering during mining, and friction and collision during transporting, significant magnetism remains after collection of the loadstones, and low temperature cutting has little bearing on this magnetism.

Figure 6: Magnetic moment measuring device.

Figure 7: One-dimensional square Helmholtz coil.

Shortly after being shaped, loadstone spoon no. 2's open circuit magnetization seemed to increase slightly. For a period of time after its production, there was a decline in magnetization, which stabilized at 80.3% of the original intensity after a while and persisted at this level until the 289th day. This drop should be ascribed to the changed shape of the loadstone, which fractured the previous magnetic potential balance into a low energy state. It stayed unchanged after a new balance came into being. On the 500th day, processing recommenced, so that the spoon bottom could be better shaped to withstand rough shaking. The process here was minor and led to a small decrease in the magnetic moment, but the magnetization endured unaffected until the 530th day. Furthermore, in ancient times, cutting, carving, and polishing were techniques requiring low-speed friction with water cooling, which would result in only slight demagnetization.

2.4 Producing the “Earth-plate”

A loadstone spoon's directivity is also dependent on the resistance of the “Earth-plate” on which it is placed, which is in turn influenced by the plate's surface hardness and roughness. To compare the roles played by various materials and processing methods in effecting the loadstone spoon's directivity, the author prepared four kinds of Earth-plates roughened with sandpaper (P1200) and polished with white felt and charcoal powder (Table 5).

Table 3: Changes in magnetism during and after the processing of loadstone spoon no. 2

Measurement time	Mass (g)	Shape (cm)	Both ends' surface magnetic induction (Gs)		Magnetic moment (emu)	Magnetization (emu g ⁻¹)
Original state	628.08	15.8 × 10.3 × 3.9	894.8	639.8	12,203.02 ± 172.79	19.43 ± 0.28
Rough blank	315.07		804.3	655.8	5959.25 ± 84.38	18.91 ± 0.27
Shaped	237.96	Length: 12.3 (body: 7.6; handle: 4.7); width: 5.0; height: 3.5	790.9	690.4	4597.48 ± 65.10	19.32 ± 0.27
Day 88			698.2	593.1	3714.43 ± 52.60	15.61 ± 0.22
Day 209			699.2	592.6	3706.52 ± 52.48	15.58 ± 0.22
Day 289			695.0	597.2	3719.26 ± 52.66	15.59 ± 0.22
Day 500	230.42	Length: 12.3 (body: 7.6; handle: 4.7); width: 5.0; height: 3.2	683.3	584.3	3578.42 ± 50.10	15.53 ± 0.22
Day 530			685.0	592.1	3594.55 ± 50.32	15.60 ± 0.22

Table 4: Parameters of Wang Zhenduo's loadstone spoon

Spoon	Mass (g)	Shape (cm)	Both ends' surface magnetic induction (Gs)		Magnetic moment (emu)	Magnetization (emu g ⁻¹)
3	24.85	Length: 5.2 (body: 2.8; handle: 2.4); width: 2.1	83.5	27.2	76.71 ± 1.08	3.09 ± 0.04
4	61.15	Bowl diameter: 4.4; height: 2.0; handle length: 4.3	110.5	36.2	138.70 ± 1.96	2.27 ± 0.03
Unlabeled	63.76	Length: 10.4 (body: 5.7; handle: 4.7); width: 4.0; height: 3.34	58.0	16.1	52.14 ± 0.74	0.82 ± 0.01

Table 5: Parameters of Earth-plates

No.	Material	Hardness	Surface processing	Roughness **
I	Tin bronze	350 (Leeb)*	Polished	Ra: 0.172–0.345 μm; Rz: 0.487–0.975 μm
II	Tin bronze	350 (Leeb)*	Roughened by sandpaper	Ra: 0.350–3.655 μm; Rz: 1.783–8.825 μm
III	Marble	3 (Mohs)	Roughened by sandpaper	Ra: 1.120–13.234 μm; Rz: 5.547–39.056 μm
IV	Elm	—	Roughened by sandpaper	Ra: 1.520–15.160 μm; Rz: 4.299–42.880 μm

* Yace (Shanghai) Instrument Technology Co., Ltd.'s portable hardness tester TH170 was employed to measure multiple points for the average value.

** Guangzhou Landtek Instrument Co., Ltd.'s SRT-6200 (pin: 10 μm) was used for Ra (a single measurement of the area's average roughness) and Rz (a single measurement of the area's maximum roughness), as well as the average value through multi-point measurement.

2.5 Performance tests of the loadstone spoons' directivity

Multiple testing proved the exceptional directivity of these loadstone spoons. The method was as follows: position a loadstone spoon in the center of an Earth-plate

(Figure 8), the handle pointing due east; exert appropriate downward force on the handle, and the spoon will swing vertically and turn horizontally (what Wang Zhenduo referred to as “jolt and sway” [播动]), then finally point south; then, place the handle due west and due north, respectively, and repeat the same steps. To raise measurement accuracy, a thin copper wire was attached to the handle, and a full-circle protractor placed beneath the Earth-plate.

Figure 8: Directivity test of a loadstone spoon on a bronze Earth-plate.

In the case of loadstone spoon no. 2, the directivity test results after the magnetic moment had stabilized (magnetization: around 15 emu/g) are given in Table 6. On a polished bronze surface, the spoon can start to move automatically, achieving precise directivity. On roughened bronze, marble and elm-wood surfaces, the automatic movement appears to be slightly cumbersome, but if the handle is touched, the spoon can still exhibit high directivity on the former two plates, while slightly underperforming on the one made of elm. Additionally, effective directionality can also be achieved on surfaces such as common tables and flat cement floors.

Table 6: Test data of loadstone spoons' directivity

Earth plate	Start from due west					Start from due north					Start from due east					Range	Standard deviation
I	-3	1	4	2	1	3	2	-3	-1	4	1	4	-3	4	2	7	3.43
II	4	2	2	2	5	7	3	1	3	4	-3	-3	-2	-2	4	10	4.25
III	-1	4	-5	4	2	5	-4	4	8	-1	-3	-5	6	5	1	13	5.46
IV	6	4	6	1	4	2	-5	-4	-3	-1	-6	4	7	9	6	15	6.32

* Deviation: Positive for southwest; negative for southeast.

3 Identification of loadstone

As shown in the above experiments, the key factor that contributes to loadstone directivity is its level of natural remanent magnetization (NRM). In fact, loadstone spoons can be made, as long as the producers have the appropriate loadstone. Previous researchers, however, did not select appropriate loadstone, which explains why their experimental attempts were unsuccessful and further experimental study was delayed for decades. Based on a literature review (Huang 2017) and face-to-face discussions, it emerged that some previous researchers lacked sufficient understanding of some relevant issues, such as the definition of loadstone, sources of remanent magnetization, and characteristics of demagnetization. For example, some “loadstone spoon” supporters considered that common magnetite is commensurate to loadstone, while in some of the experiments by “loadstone spoon” sceptics, common iron ore was used in place of loadstone. As a result, all their loadstone spoons did not point to the south, thus contributing in large measure to the lack of convincing conclusions resulting from compass research over past decades. In order to clarify what actually constitutes loadstone, the following explanation is essential.

Theories on rock magnetism and mineralogy (Takeshi 1959, 35, 38, 47–48; Carmichael [1981] 1990, 73–74; Zhao et al. 2011, 292–293, 312) hold that certain types of minerals possess natural magnetism because their internal electron spin magnetic moments to some extent follow a sequential order, which demands certain conditions on the micro, sub-micro, and macro levels simultaneously.

On the microscopic level, spontaneous magnetization is rooted in the fact that atoms (positive ions) possess magnetic moments, which primarily derive from electron-spin magnetic moments. For an atom to have a magnetic moment, its electron shell must be in an incompletely filled state. In the $3d$ state, there are four vacancies in iron, three in cobalt, and two in nickel. Minerals with natural magnetism contain at least one of these three elements.

With regard to crystal structure, if the neighboring magnetic moments of atoms

within the crystal are aligned in parallel fashion, strong ferromagnetism will be formed. If the magnetic moments of atoms are unequal, and are in an antiparallel alignment, some degree of spontaneous magnetic moment can still be generated, thus leading to slightly weaker ferrimagnetism. In nature, the minerals with spontaneous magnetization are all ferrimagnetic iron ores.⁷ Among them, three categories of minerals with the highest saturation magnetization are: first, magnetite (Fe_3O_4): 92–93 emu/g⁸ (theoretical value, room temperature); and second, maghemite ($\gamma\text{-Fe}_2\text{O}_3$): 83.5 emu/g, both of which have the inverse spinel structure of an isometric crystal system; the third is pyrrhotite (FeS_{1+x}): 18 emu/g ($x = 0.125$), which belongs to the dihexagonal-dipyramidal class of a hexagonal crystal system. Ferrimagnetism for iron ores of other structures are weaker, and those of the common ones are exceedingly weak, such as hematite ($\alpha\text{-Fe}_2\text{O}_3$, the corundum structure in the trigonal crystal system) and goethite ($\text{Fe}_2\text{O}_3\cdot\text{H}_2\text{O}$, in the orthorhombic crystal system, and crystallizes into the α phase). Due to the interactions between adjacent crystal magnetic moments, the magnetic dipoles of adjacent crystals will be aligned in a small area with saturation magnetization, resulting in a large net magnetic moment – magnetic domain. When not subjected to a magnetic field, magnetic moments in magnetic domains are arranged in random directions, and the overall net magnetization is zero. If an external magnetic field is applied, the magnetic domains in the material rotate in the direction of the applied field, thus reinforcing the magnetic field within the material. After the external magnetic field disappears, if the magnetic moments in magnetic domains remain aligned to some extent, this gives rise to remanent magnetization, and magnetism is manifested on a macro level, that is, being magnetized.

Loadstone remanent magnetization mainly comes into existence at mineralization. Iron ores are a solid solution or an admixture of various minerals. Their remanent magnetization is influenced by mineral type, iron content, the size and shape of particles, internal stress, crystal orientation, the formation environment, and one or more magnetization mechanisms at later stages.⁹ Thermoremanent magnetization is the remanence resulting from the heating of rock above the Curie point (600°C–700°C) and then cooling to room temperature in the geomagnetic field. The alignment of magnetic moments in magnetic domains is to a large extent maintained. Its remanence

7 Naturally generated iron on the Earth has been only found in Greenland; meteoric iron is found in different regions, but none is magnetic.

8 There are multiple units for magnetic moment and magnetization. Gaussian emu and emu/g are applied to describing the magnetic properties of iron ore on a macro level.

9 The mechanisms for rocks' remanent magnetization consist of primary remanent magnetization and secondary remanent magnetization. The former includes thermoremanent magnetization (TRM), detrital remanent magnetization (DRM), and chemical remanent magnetization (CRM); the latter, which is a product of external factors after rock formation, chiefly comprises viscous remanent magnetization (VRM) and isothermal remanent magnetization (IRM).

is tens to several hundred times stronger than isothermal remanent magnetization (such as frictional magnetization), and has high stability and an extremely long relaxation time. During geological evolution, ores could gain thermoremanent magnetization several times, causing complex phenomena, such as uneven magnetization intensity and multiple magnetization directions, which lead to a single loadstone having multiple magnetic poles, or having a closed magnetic circuit. The overall weak magnetism will increase after the circuit becomes an open one. In addition, most magnetite, maghemite, and pyrrhotite have a low level of natural remanent magnetization, and only a minority of them can attract iron, or mutually attract or repel other loadstones, with theoretical saturation magnetization being unattainable. In addition, natural iron ores of all kinds have some remanence of greatly varying levels.

The properties of loadstones are markedly distinct from those of magnetic needles magnetized by friction (belonging to isothermal remanent magnetization), and from those of ferrite or NdFeB magnets, which are uniformly magnetized at one time by modern magnetizers. Due to an inadequate understanding of magnet formation mechanisms, some researchers have equated loadstones with ordinary iron ores, and conducted their experiments using such ores with little remanence. Such experiments proved an ineluctable failure. Some attempted to magnetize ordinary iron ores or weak loadstones at room temperature by simulating geomagnetic fields or slightly stronger magnetic fields. This also was certain not to produce transferred results. It is also wrong to deem the processed loadstones vulnerable to demagnetization based on transferring experience of frictional magnetization easily entailing demagnetization to loadstones.

4 Viability of loadstone spoons' directivity in ancient conditions

Let us now turn to considering the potential directivity of loadstone spoons under the conditions prevailing in ancient times. To do this, the author carried out a comparative study based on the magnetism and geomagnetic fields of loadstones available in ancient times.

4.1 A comparison with magnetism recorded in ancient records

Ancient Chinese documents abound with records of loadstones' magnetic attraction. One of the most useful for our purposes can be found in a paragraph on testing loadstones' magnetism from Lei Xiao's 雷教 *Lei Gong pao zhi lun* 雷公炮炙論 (Lei Gong's treatise on the preparation and boiling of materia medica), which was compiled during the Liu Song dynasty (420–479 CE) in the fifth century.

To examine the loadstone quality, select magnetic stones of one *jin* to be verified: those attracting iron of one *jin* on four sides are called *yannian sha* 延年砂, those attracting iron of eight *liang* on four sides are designated as *jiwei shi* 績未石, and those attracting iron of five *liang* on four sides are given the appellation *cishi* 磁石 (loadstone). (Lei [ca. the fifth century CE] 1985, 47–48)¹⁰

The quantities of the attracted iron are connected with the magnets' magnitude of open circuit magnetization, volume and shape, as well as the iron's magnetic permeability and space among particles. In *Lei Gong pao zhi lun*, the iron attracted to four sides of loadstones should be regarded as iron powder (sand). Even though the size of the iron powder particles is not mentioned in ancient texts, the author performed tests based on common sense using iron powder (0.01 mm in particle size) and iron beads (1 mm in diameter). One *jin* in the Liu Song dynasty was the equivalent of present-day 220 g (Qiu et al. 2001, 447). Six randomly shaped loadstones, which weigh close to, slightly higher than, and far greater than one *jin*, were chosen to attract iron. The loadstones were covered in iron powder, then carefully removed so that loosely attached powder fell off naturally (Figure 9). Measurement of the mass of the attracted iron powder was repeated twelve times, as shown in Table 7.

The results demonstrate that the magnetic attraction of loadstones nos. 1, 2, 3, and 6 equaled that of the upper-middle level ones in ancient records. Nos 4 and 5 proved less capable of attracting iron, because their long thin shape and longer magnetic circuits led to a decline in magnetic attraction, though this does not necessarily suggest a weakening of remanent magnetization. If loadstones in ancient texts were also long and thin, their remanent magnetization should be seen as stronger, and thus more conducive to magnetic directivity.

Figure 9: Testing iron-attracting loadstones (iron particle size: left: 0.01 mm; right: 1 mm).

10 “夫欲驗者，一斤磁石，四面只吸鐵一斤者，此名延年砂。四面只吸得鐵八兩者，號績未石。四面只吸得五兩以來者，號曰磁石。”

Table 7: Experimental data for iron-attracting loadstones

Number		1	2	3	4	5	6
Mass (g)		215.55	218.12	233.89	352.98	353.14	628.08
Volume (cm ³)		45.64	45.22	50.21	75.03	75.13	135.75
Density (g/cm ³)		4.72	4.82	4.66	4.7	4.7	4.63
N pole's max surface magnetic induction intensity (Gs)		672.0	520.3	581.1	586.4	752.2	639.8
S pole's max surface magnetic induction intensity (Gs)		403.4	304.3	425.5	386.2	597.3	894.8
Iron powder (0.01 mm)	Average quantity of attracted iron (g)	197.12	206.57	243.08	110.47	42.81	401.61
	Mass ratio of attracted iron to loadstones	0.91	0.88	0.69	0.31	0.2	0.64
Iron beads (1 mm)	Average quantity of attracted iron (g)	141.5	204.36	236.69	77.04	31.5	446.32
	Mass ratio of attracted iron to loadstones	0.66	0.87	0.67	0.22	0.14	0.71

Note: The CH-1600 high-precision digital Gauss meter (from Beijing Cuihaijiacheng Magnetic Technology Co., Ltd.) was used for measuring surface magnetic induction intensity.

4.2 Directivity tests of loadstone spoons in ancient geomagnetic environments

The rotating movement of magnetic pointers is driven by horizontal torque. This makes it necessary to investigate the horizontal component of geomagnetic field intensity in historical periods, in other words, the product of the geomagnetic total force and the cosine of geomagnetic inclination, which is a nonlinear superposition of three functional relationships and susceptible to large fluctuations. In the course of his research, the author noticed that the horizontal component of geomagnetic field intensity in premodern China experienced a unique course of development.

Paleomagnetism draws on the information concerning the Earth's magnetic field found through analysis of the thermos-remanent magnetization of rocks, sediment, and fired archaeological remains (such as ancient pottery, kiln bricks, stoves, tiles, etc.). This method allows researchers to determine variations in the magnetic field through time in multiple places in China. Indeed, variations in the geomagnetic total force and geomagnetic inclination are relatively complete for places such as Beijing, Luoyang, and Tianshui (Cai et al. 2016; Nagata et al. 1963; Teng and Li 1965; Wei et al. 1981). The author's calculations result in a graph that displays a clear M-shaped development of the horizontal component of geomagnetic field intensity in these three regions (Figure 10). From the fourth century BCE to the early eighth century CE, the values remain at a high level, while from around the tenth century to the present, the numbers are consistently low, the peak value being almost twice that of the lowest.

Figure 10: Evolution of the horizontal component of geomagnetic field intensity in Beijing, Luoyang, and Tianshui during the past 2000 years, calculated according to Lecomte [1687–1692] 2004, 204–206; Firester 1966; Lei [ca. the fifth century CE] 1985, 47–48; Qiu et al. 2001, 447.

Situated in the Central Plains, Luoyang was the capital of the Eastern Han dynasty and a focus for Chinese culture at that time. Between Tianshui to the West and Luoyang lies the Guanzhong Plain, and the capital of the Western Han dynasty, Chang'an. Beijing is located at the northern extreme of the North China Plain. The alchemists of the states of Yan and Zhao who knew loadstones best and made most use of them were active in this region between Beijing and Luoyang, and Cishan, by then the principal source of loadstones, is also there. The geomagnetic field data for this large area is thus representative for the heartland of Chinese civilization from the Pre-Qin period to the Tang dynasty.

The author tested the directivity of loadstone spoons by means of a simulated paleo-geomagnetic field using the large Helmholtz coil in Figure 7, and found that the spoons' directivity would significantly improve in the geomagnetic environment of this ancient period. For instance, during Wang Chong's lifetime (27–97 CE) in the capital, Luoyang, where the horizontal component of geomagnetic field intensity was 0.6 Gs, the spoon, with no external intervention, would move strongly by means of magnetic force alone and point due south. With an average horizontal component of geomagnetic field intensity of 0.5 Gs (as was the case from around the Warring States periods to the early Tang dynasty), the loadstone spoon could still swivel automatically on a tin-bronze plate and accurately point south, while a touch of the handle would be sufficient to cause the spoon to swivel on the terrazzo and elm plates and align to the

south. This evidence indicates that the ancient geomagnetic environment in these areas was certainly more favorable for generating loadstone spoons' directivity.

Due to weak magnetism, Wang Zhenduo's spoons required the supporting surface to be extremely smooth, leading to his interpretation of the term *di* 地 in the *Lunheng* as a glossy bronze Earth-plate. However, actual measurements have determined that *di* 地 can be explained in a common-sense fashion as a smooth masonry floor or hard wooden board, which is more consistent with the ancient records.

Huainan Wan Bi Shu 淮南萬畢術 (The ten thousand infallible arts of the prince of Huainan) (the second century BCE) records: "Wrap loadstones in the deceased's clothes, hang it in a well, and the departed will return" (Li et al. [983] 1960, 3266).¹¹ Some opinions have it that suspending loadstones was for ascertaining direction, which could be of importance in certain rituals, and reflected an early understanding of magnetic directivity (Dai 2002, 128, 139). The author's procedures for making loadstone spoons further corroborate that a loadstone, after being hung up, will maintain steady directivity (Figure 5: I). If marked, it can function as a south-pointing device. However, it should be noted that air damping and air flow would all impact on the steadiness of the loadstone. The author also has experimented with the water floating method. However, the surface tension of the water can drive the floating object to container's sides where they stick, making this device less effective than the loadstone spoon design.

4.3 Loadstone pointer and the discovery of magnetic declination

Chinese records on geomagnetic declination known to-date are all from the late Tang dynasty and later, such as the Tang *Guanshi dili zhimeng* 管氏地理指蒙 (Mr. Guan's geomantic indicator) and the Northern Song *Mengxi bitan* 夢溪筆談 (Dream Pool essays), and pertain to "needles." Some researchers have suggested that magnetic declination was discovered in the Tang dynasty, so the loadstone pointer could not have been made and used in the Han dynasty (Yamamoto 1924).

Based on our experiments, such an assertion, that no loadstone pointing devices were invented before the Tang dynasty, would seem to be untenable. To make loadstone pointers, materials with remanent magnetization are cut or assembled into certain shapes, and then directions are calibrated in accordance with the geographical north-south direction that have been determined by other methods in advance, that is to say, first magnetization and then calibration. Naturally, the finished device's pointer is aligned with the pre-determined direction, meaning geomagnetic declination is cannot be obtained solely by using loadstone products based on the producing techniques. Conversely, the discovery of geomagnetic declination serves as an exact

11 “取亡人衣，裹磁石懸井中，亡者自歸矣。”

indication of the emergence of the artificially magnetized compass.

5 Conclusion

The experiments conducted by the author have validated the practicability of re-creating Wang Zhenduo's "loadstone spoon bronze Earth-plate," and corroborated the records in the Eastern Han *Lunheng*. Given the constraint that the open-circuit remanent magnetization of loadstones rarely exceeds 30 emu/g, the spoon shape is an excellent design. The spherical structure of the spoon's base allows it to rotate easily and orientate quickly, without undue random movement. The hemispherical shape lowers the center of gravity, enhancing the stability of the base's spherical curvature. The handle also can enhance the overall moment of inertia and prolong the time of shaking for accurate pointing. These characteristics are of great significance for the ability of loadstone spoons to point exactly south, for those used in periods with a low horizontal component of geomagnetic field intensity or those of weak magnetism.

Considering the magnetic resources available, the geomagnetic environment, and the technical level, knowledge, and experience of craftsmen from the Pre-Qin period through the Han to the Tang dynasties, the Chinese people of that era should be able to produce a variety of loadstone south pointers of high-caliber and steady directivity.

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