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The Pointed Bottom Bottle: An Ancient Instrument for Monitoring Earth-air

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Abstract: The pointed bottom bottle (PBB) is a specific type of pottery with a pointed bottom widely produced in the Yangshao culture (7000–5000 BP) of prehistoric China. Since its discovery, opinions vary regarding its usage and purpose of design. Monitoring the air pressure enclosed in the PBB, this paper potentially reveals its usage and a possible reason for such a unique shape: it is an instrument of monitoring the earth-air by the general public as a practice of hou-qi. Ancient Chinese buried the PBB under the earthen floor in a sheltered room. Due to a moderate size of the room, daily temperature fluctuation of the earthen floor was limited, and the height of PBB was consistent with the depth of the earthen layer with a daily temperature change. However, using PBB to define solar terms on a yearly basis could have been interfered by the daily temperature variation of soil. Ancient people took advantage of the large daily temperature variation in the top layer of the soil and the small fluctuations with a hysteresis of ~12 hours in the lower layer, so that the temperature changes in upper and lower levels of soil exist in different directions. This counterbalances the interference of daily temperature response on pressure through spatial and temporal differences of temperature fluctuations in upper and lower parts inside PBB. The PBB can further eliminate the influence of daily fluctuation peaks of the atmospheric pressure, making changes in air pressure inside the bottle completely following the yearly temperature, functioning as farming seasonal guidance.

Keywords: Pointed Bottom Bottle, Earth-Air, Yangshao Culture, Hou-Qi

1. Introduction

The pointed bottom bottle (PBB) is a kind of pottery once popular in a large part of the northern and central China including Gansu, Shaanxi, Shanxi, Henan, Inner Mongolia, Qinghai, Sichuan, southern Hebei and northern Hubei in the prehistoric cultural period of Neolithic Yangshao (7000–5000 BP) [1] shown in Figure 1. PBB is widely known for its pointed bottom and small mouth. Usually, the ratio of its diameter to height is 1:1.8–1:2.6. The height of small and medium BBPs is 30–40 cm, and large ones 60–100 cm. BBP generally has good sintering features and a hard texture. According to its shape differences, PBB can be divided into three general categories: (a) the olive type, of which the upper and lower parts are basically symmetrical; (b) the round shoulder type which has a short upper part; and (c) the collected waist type, shown in Figure 1. The mouth of PBBs also has various types such as the cup straight type, gourd like type, heavy lip type and bell type. Considering the shape of mouth, the length of the bottle neck and the size, PBBs can be categorized into more than ten specific types [1].

However, since the discovery of PBB, opinions about its usage have always been controversial. The literature review is as follows: A theory of using PBB to draw water was proposed initially [2-6]. The idea was that by putting an empty bottle into the water, it would sink to be automatically filled. With a gradual lowering of its center of gravity, the mouth of the bottle would stay upward while filling up. Then using a string tied to the ears on its side, the bottle could be lifted without spilling, and the small mouth guaranteed no leakage during transportation. Later, Sun et al., [7-10] found that most Banpo-type PBBs could not be used to draw water automatically even if being turned upside down, because its

center of gravity is above the ears. Thus Wu et al. [2, 3, 5, 7-15] put forward that the PBB was a kind of Qi-qi (欹器) which would lean to one side when empty, keep straight up when half-filled with water, and overturn when fully filled. Meanwhile, theories of irrigators [9], ritual vessels [17, 18], wine storage containers [7-9] and thermos [18] were put forward. Owing to the discovery of a large number of PBBs as burial objects in tombs, there are theories of funerary ware [19], the soul jar [20] and coffins [21]. Among these, the earliest and most influential one is the usage of drawing water. Introduced in the middle school textbook, it is still widely considered as the standard interpretation in exhibitions in Shaanxi History Museum, Dadiwan Museum in Gansu province, etc. At the same time, the drawing water theory has the most opposing views [7-10, 18]. In recent years, Liu et al. proposed that PBB was an ancient instrument of brewing wine through the study of remains attached on the PBB [15, 22], and Wei further theorized that the main function of its pointy-bottom structure was beneficial to the sedimentation and filtration of the brewing wine [1].

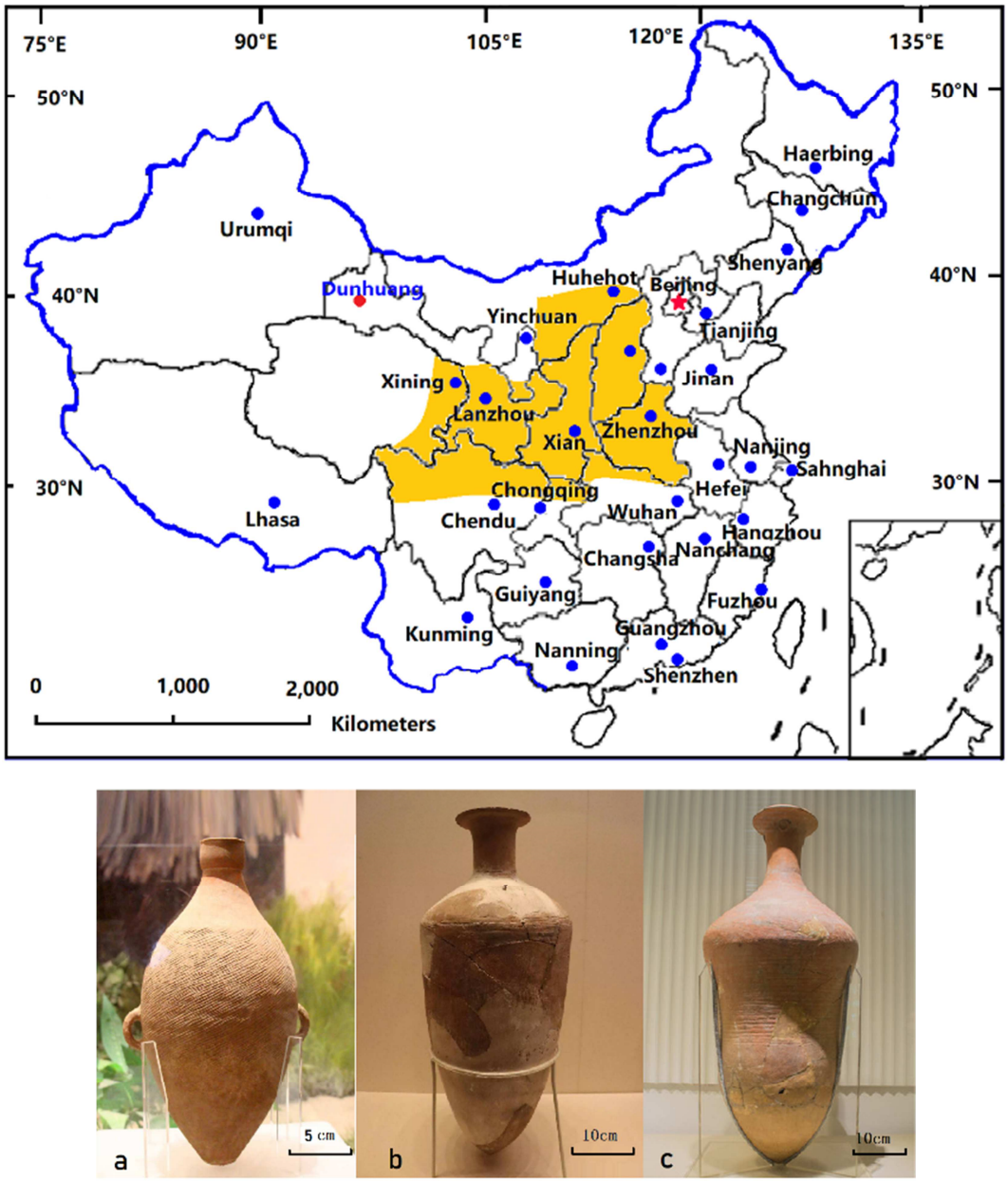


Figure 1. *The distribution range of PBB in China and representative types: (a) olive type (Dadiwan), (b) round shoulder type (Banpo), (c) collected waist type (Banpo).*

In relation to the author's research, the earth-air (地氣) is referred to as air in the soil, and its theory has profoundly influenced the Chinese culture. It plays an important role in the development of astronomy, geophysics, music, art, rhyme, arithmetic, meteorology in China, and is also the source of qi (氣) in Chinese philosophy and traditional Chinese medicine [23]. Therefore, earth-air is regarded as the one that generates everything [24]. The monitoring of earth-air was called

hou-qi (候氣) in ancient China, on which the calendar was drafted. However, as detailed knowledge of hou-qi has been long lost, it was thought to be one of the most astonishing frauds in the history of Chinese science in 2,000 years [25, 26].

The present author conducted a long-term study of deeply buried phreatic water evaporation [27-30] and earth-air in the arid area [24, 31]. It is found that the autonomous breathing of earth-air exists in soil, which is caused by the change of soil temperature, and there is a linear relationship between air pressure and temperature in the closed system [24]. Meanwhile, fingerprint evidence [32] shows that there is passive breathing in the open system [33]. The earth-air fluctuates with atmospheric pressure, which has an important effect on phreatic evaporation [34] and haze [35]. It is the earth-air that results in the formation of dew, fog [35] and desert mirages [36].

To further explain earth-air and hou-qi, its inventor Fuxi applied Yin (the temperature declining process) and Yang (the temperature rising process) to draw the Eight Diagrams in explain of earth-air's response to seasonal temperature changes [37]. Having established the I-ching system, he provided one of the highly recognized origins of Chinese culture. Solar terms were monitored by a group of jade tubes with different lengths buried in different depths underground. This configuration was called Lv (律), which was the basis to establish standard units of the rhythm, length, volume and weight. The process of setting up a group of Lv-tubes for hou-qi was named feng-jian (封建): Feng refers to the action of sealing or closing; and Jian refers to constructing Lv, recorded by Shuowenjiezi in Chinese. The famous historian Sima Qian wrote in the Grand Historian: "The king establishes the rules, legislations, laws, units of measurements, all of which are based on the six Lvs, which are the foundation for all things (王者製事立法, 物度軌則, 壹禀于六律, 六律为萬事根本焉)". The feng-jian, hou-qi [23, 38], Lv-calendar and Eight Diagrams are interconnected definitions, contributing to a complete system [37]. In practice, people used the jade tubes attached with a closed membrane to monitor the earth-air pressure [24, 34]. When the pressure exceeded the critical value of the bamboo/reed membrane covering the tube, the air would burst through the membrane with a sound of "bang" and blow out the ash or charcoal originally filled the tube, creating a response to the upcoming season/solar term [23]. The Chinese term Xiang Ying (響應) was derived from this feature, meaning to respond with a sound. Plus, hou-qi also means waiting for the arrival of earth-air or the pressure reaching the critical point to respond [38]. Ancient Chinese followed earth-air to formulate solar terms and the calendar, which was always vital in agricultural production.

It needs to be addressed that monitoring of earth-air with jade tubes required special spaces in ancient time, that is, to construct a large house, namely a double-roofed palace to provide shelter and avoid diurnal temperature variations in soil caused by the solar radiation [37]. The diurnal air pressure fluctuations caused by temperature create interference rather than contributing to the monitoring because defining solar terms requires the air pressure to fluctuate with the annual/seasonal temperature in a closed system. However, the construction of a palace and the use of precious jade objects required a strong economic foundation. Usually only the king or the tribal chiefs had such power far too difficult for ordinary families to achieve. For ordinary people who wanted to monitor earth-air in a house of dozens of square meters to guide farming and daily life, one needed to overcome the daily temperature fluctuations in the earth inside the house, especially those transmitted from around the house, to guarantee the accuracy of monitoring. After years of research, the present authors found that using BBP can satisfactorily solve this problem, so that in ordinary households one could conduct the monitoring of hou-qi. Based on this finding, we propose a hypothesis on the usage of PBB. This paper uses a simulated PBB to monitor the response of air pressure on temperature in an enclosed system, revealing the structure and function of PBB in hou-qi, and shows the main purpose of this design and the its utilization. This paper is also based on archaeological findings [39-43] and documented literature with discussions of the origin and development of PBB in prehistoric China.

2. Research Methods

In order to monitor earth-air in a closed system and use its response to the 24 solar terms to formulate a calendar [37], the influence of daily soil temperature fluctuations in an ordinary room needs to be eliminated. The diurnal soil temperature variation is shown in Figure 2. Under solar radiation, the temperature of upper soil fluctuates greatly, its range decreasing with the increase of depth, and there is temperature hysteresis varying with depth. When the temperature of 10 cm below earth rises, the temperature at 40 cm-depth decreases, and vice versa. Usually, the depth of daily soil temperature variation layer is ~60 cm, and the temperature in the upper layer fluctuates oppositely to the lower [27]. In the central area of the shaded room farthest from the outside, the range of temperature fluctuation in soil is much reduced, which decreases with the distance from the exposed outdoor area, and the daily fluctuation pattern basically remains unchanged. Namely, temperature of the upper layer has more fluctuation, which is opposite to that of the lower layer.

As a type of pottery, PBB has certain air permeability. However, to conduct *hou-qi*, the vessel needs to be airtight, thus requiring a special treatment usually of smearing with blood, which is called *Xin* (釁) [31]. Generally, it needs to be inconveniently smeared many times to ensure airtightness. In this research, we used glass containers to simulate the olive-shaped and round-shoulder PBBs, and the flat bottom bottles and suction filter bottles to conduct experiments. The size, volume and shape of simulation containers are shown in Table 1.

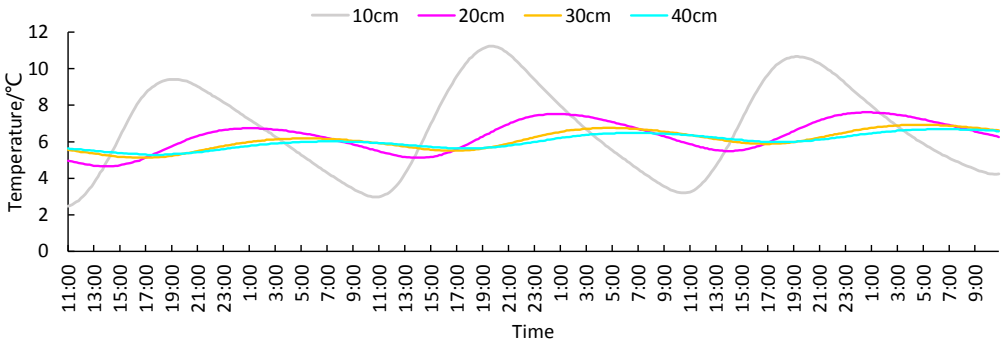


Figure 2. *The diurnal soil temperature variation in the Gobi soil of Dunhuang.*

Table 1. *The volume, size and shape of the containers.*

Bottle type	Maximum diameter	Height (mm)	Volume (ml)	Shape
Olive-shaped glass PBB (O-PBB)	110	190	650	
	142	260	1300	
	155	280	1800	
	160	320	2000	
Round-shouldeglass PBB (R-PBB)	98	124	650	
	134	260	1300	
	145	355	1500	
	150	365	2600	
Flat bottom bottle (F-B)	145	360	760	
	210	420	2450	
	215	400	2600	
Suction filter bottle (S-B)	180	270	2500	

The design of this research is described in detail below:

(1) Using the glass PBB simulation containers and other bottles of different shapes, such as the flat bottom bottles and suction filter bottles, we have conducted the experiment of the response of bottles of different shapes, sizes and internal filling materials to temperature in a climatically controlled chamber (CTHC, model SETH-Z-040, China). This experiment also determined the response of air pressure of different materials such as air, soil, alcohol, plant ash, activated carbon, *etc.* (These are key materials in traditional Chinese sacrificial rituals/*hou-qi* [23]) to temperature under sealed conditions. The experiment endeavored to analyzing the functional relationship between air pressure and temperature, and evaluating material properties and their potential usage in ancient earth-air monitoring. Then, we tried to reveal the *hou-qi* method of PBB and its evolution in ancient time.

The specific method of the experiment was: we filled the bottle with air (empty bottle), clay, loessal soil of the Loess Plateau, 10% loess in water as a paste smeared in the bottle (representing the earthenware which absorbed water), 60 ml of 95% ethanol, 60 ml of 75% ethanol, activated carbon, activated carbon with adsorption ethanol in a closed system for more than 2 weeks, activated carbon stirred in 60 ml of 75% alcohol, plant ash, plant ash with 30% activated carbon added, saline soil (from Gobi soil in 20 cm-depth at the Mogao Grottoes) in the olive type PBBs (O-PBB), round shoulder PBBs (R-PBB), flat bottom bottles and suction filter bottles. Then, bottles were sealed and placed in a CTHC. The grain size of soil is shown in

Table 2, and its salt content shown in Table 3. The temperature was controlled within the range of 5–40°C to simulate the daily/yearly temperature variation in the 60 cm-deep soil in the loess plateau. The temperature was increased by a 5°C increment, and the system was left to reach equilibrium for 4 or 8 hours at each temperature increase to ensure adequate time for the experiments. We used a temperature sensor HOBO-U23-001 (accurate to ±0.2°C over the range of 0–50°C) to monitor temperature inside the bottle. Hard plastic conduits connected the bottles to an atmospheric pressure transmitter (model HD9408T, made in Italy and accurate to ±0.5 hPa at 20°C). A paperless recorder (BT805) was placed outside the chamber of controlled temperature–humidity to record the air pressure every 10 minutes [24]. The effects of temperature on air pressure were subsequently analyzed according to the results of monitoring.

(2) Then, we filled representative materials, including air, clay, loessal soil and activated carbon in the O-PBB (2000 ml), O-PBB (1800 ml), R-PBB (2600 ml) and R-PBB (1500 ml), respectively. We used a hard pipe to place an atmospheric pressure transmitter HD9408T within each sealed bottle, and recorded every 10 minutes. We placed each PBB's maximum diameter at a 10-cm depth in the Gobi soil of Mogao Grottoes and buried HOBO-U23-001 sensors at 10, 20, and 30 cm distances in the soil near the experiment bottles, to monitor the influence of temperature on air pressure. According to the monitoring results of air pressure and those calculated by the temperature monitored with fitting formulas in the experiment (1), we consolidated the influence of PBB on air pressure: if the pressure inside bottle is less than the pressure calculated by the temperature at 10 cm-depth, then there is a pressure offset phenomenon in the bottle.

Table 2. *Salt content, salt composition and water content in the clay, saline soil, and drift sand (mass %).*

Soil name	Cl^-	NO^{3-}	SO_4^{2-}	Na^+	K^+	Mg^{2+}	Ca^{2+}	Salt content	Water content
Clay	0.09	0.00	0.18	0.09	0.01	0.01	0.05	0.42	11.40
Saline soil	0.55	0.04	1.85	0.76	0.03	0.02	0.35	3.60	8.81
Loessal soil	0.01	0.00	0.00	0.18	0.02	0.04	0.18	0.42	3.70
Plant ash	0.41	0.60	0.03	0.01	0.17	0.00	0.01	1.24	—

Table 3. *Particle size distributions of clay, Gobi soil and loessal soil.*

Particle diameter (μm)	1–2	2–5	5–10	10–20	20–50	50–75	75–200	200–500	500–1000
Clay	52.10	28.25	12.29	7.36	0	0	0	0	0
Saline soil	0	0	0	31.22	4.88	22.40	4.37	29.25	7.89
Loessal soil	15.05	18.83	16.47	20.98	20.10	5.79	2.78	0	0

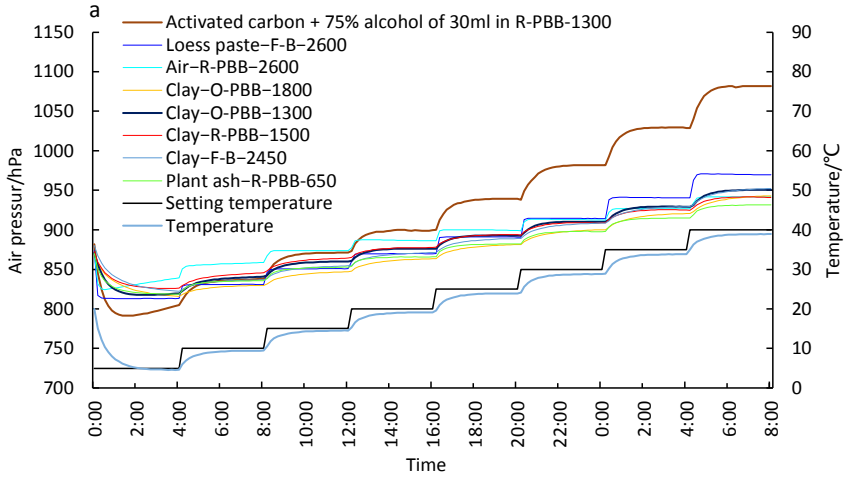
(3) Then, based on archaeological findings and documented literature of PBB, we revealed the method of using PBB to monitor solar terms, and studied the origin and development of PBB types.

3. Results

3.1. Experimental Results in CTHC

When the olive type PBB, round shoulder PBB, flat bottom bottles and suction filter bottles were filled with air, clay, loess soil, alcohol, saline soil, plant ash, activated carbon, etc., the response of air pressure to temperature is shown in Figure 3.

In Figure 3, air pressure of all materials changed with the gradient of temperature. Each bottle reacted differently in pressure, having individual pressure gradient. The pressure in the empty bottle changed with the setting temperature following a right-angled line, while bottles with other materials changed with the measured temperature in a curve. This indicates that in the process of a gradient temperature change, the temperature of soil and other materials takes about 3 hours to balance. The fitting relationship between air pressure and temperature is shown in Table 4.



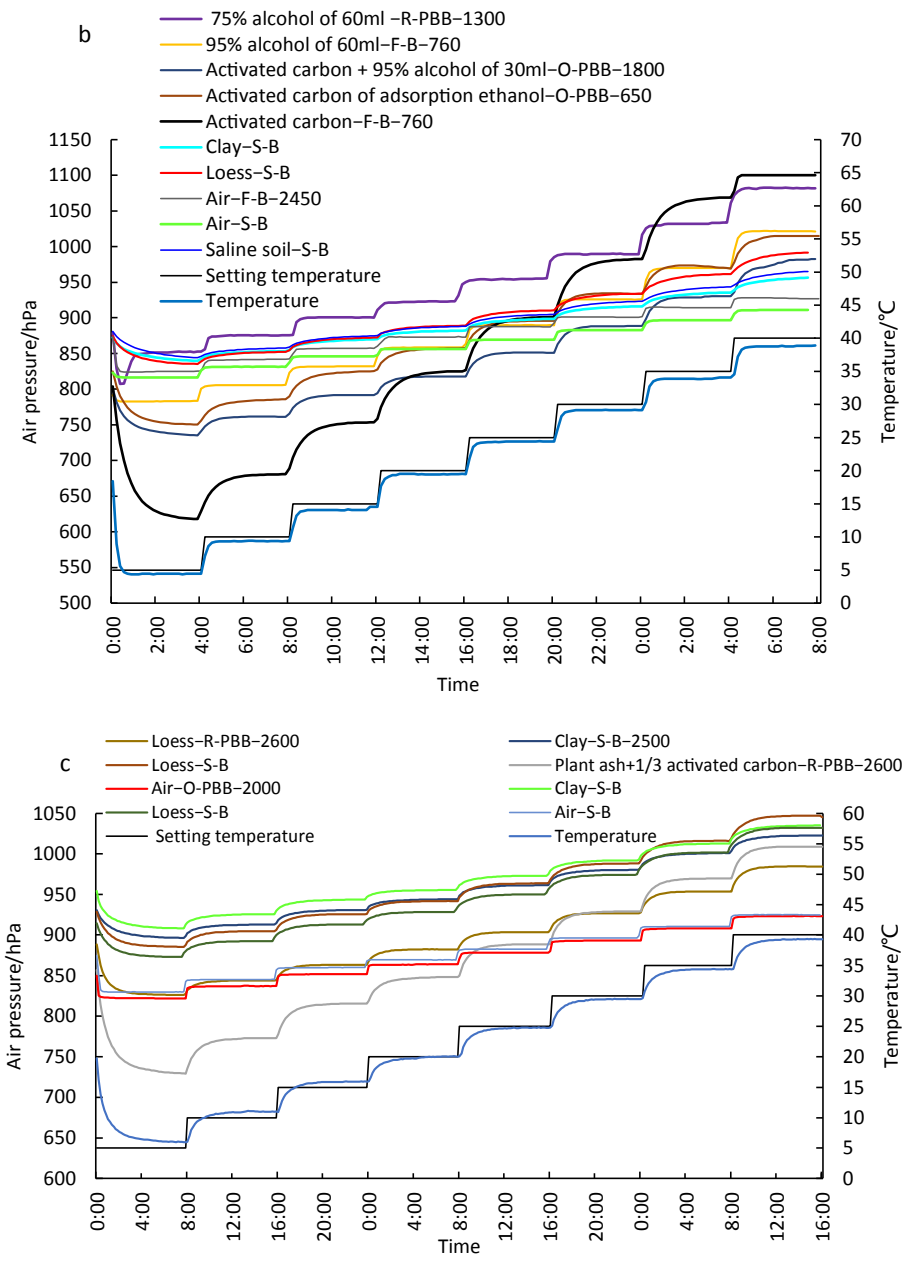


Figure 3. *Response of air pressure to temperature of different materials in different bottles.*

Table 4. *The fitting formula of relation between air pressure and temperature.*

Materials	Bottle type	Volume (ml)	Fitting formula	R^2 (p = 0.01)	In Figure
Air	R-PBB	2600	$P = 2.9311t + 824.96$	0.9780	Figure 3a
	S-B	2500	$P = 2.6252t + 804.72$	0.9975	Figure 3b
	F-B	2450	$P = 2.9002t + 813.34$	0.9871	Figure 3b
	O-PBB	2000	$P = 2.848t + 808.07$	0.9968	Figure 3c
	S-B	2500	$P = 2.6277t + 818.62$	0.9885	Figure 3c
Clay (From Daquan River sediment in front of Mogao Grottoes)	O-PBB	1800	$P = 3.5701t + 796.55$	0.9891	Figure 3a
	R-PBB	1500	$P = 3.7779t + 802.13$	0.9974	Figure 3a
	O-PBB	1300	$P = 3.3276t + 812.49$	0.9982	Figure 3a
	F-B	2450	$P = 3.6507t + 802.84$	0.9898	Figure 3a
	S-B	2500	$P = 3.1626t + 823.81$	0.9776	Figure 3b
	S-B	2500	$P = 3.7127t + 884.52$	0.9951	Figure 3c
	S-B	2500	$P = 3.7318t + 871.84$	0.9956	Figure 3c
Loessal soil (From Dadiwan of the Loess Plateau in 3–4 m depth)	S-B	2500	$P = 4.2407t + 811.59$	0.9733	Figure 3b
	S-B	2500	$P = 4.7638t + 851.27$	0.9915	Figure 3c
	S-B	2500	$P = 4.6918t + 840.04$	0.9906	Figure 3c
	R-PBB	2600	$P = 4.7158t + 791.89$	0.9928	Figure 3c

Materials	Bottle type	Volume (ml)	Fitting formula	R^2 (p = 0.01)	In Figure
Loess paste (10%)	F-B	2600	$P = 4.335t + 787.21$	0.9785	Figure 3a
Plant ash	R-PBB	650	$P = 3.2635t + 804.14$	0.9995	Figure 3a
Activated carbon	F-B	760	$P = 14.279t + 553.51$	0.9860	Figure 3b
60 ml of 95% alcohol	F-B	760	$P = 6.5887t + 737.34$	0.9777	Figure 3b
60 ml of 75% alcohol	R-PBB	650	$P = 6.4842t + 804.68$	0.9742	Figure 3b
Activated carbon of adsorption ethanol	O-PBB	650	$P = 7.4728t + 715.70$	0.9920	Figure 3b
Activated carbon stirred in 30 ml of 75% alcohol	R-PBB	1300	$P = 8.21t + 750.22$	0.9900	Figure 3a
Activated carbon stirred in 30 ml of 95% alcohol	O-PBB	1800	$P = 6.7066t + 697.91$	0.9773	Figure 3b
Plant ash stirred 1/3 activated carbon	R-PBB	1300	$P = 8.3429t + 682.53$	0.9993	Figure 3c
Saline soil	S-B	2500	$P = 3.2401t + 827.91$	0.9699	Figure 3b

Materials in a closed system act differently in terms of its response of air pressure to temperature, and the relationship between air pressure and temperature is linear:

$$P = at + b \quad (1)$$

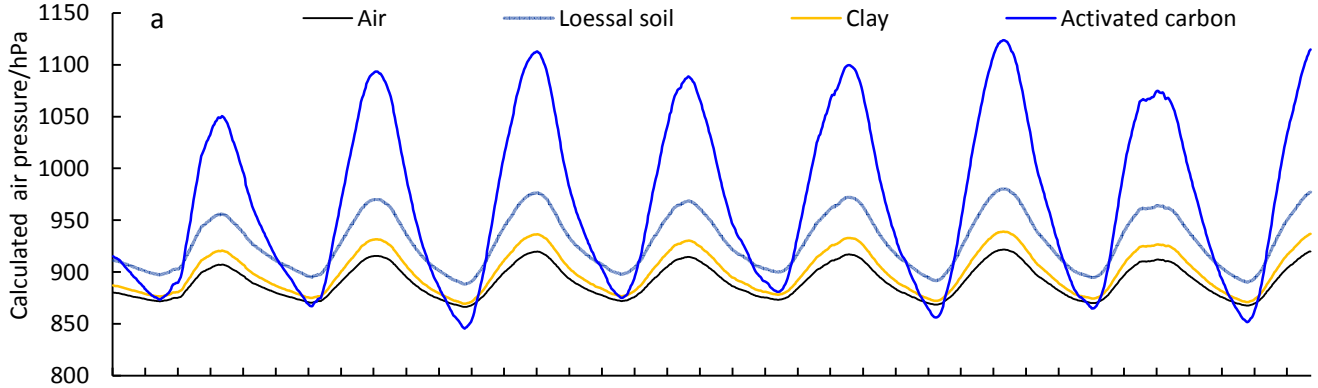
In which a is the specific pressure coefficient of individual materials, and b is a constant related to the atmospheric pressure at the initial closure. The Pearson correlation coefficient between air pressure and temperature is very high (all above 0.97). The a of the air, clay, and loessal soil in different bottles varied from 2.63 to 2.93, 3.33 to 3.78, 4.24 to 4.76, respectively. The same material in one type of bottles had a certain experimental error, of which the degree was consistent with other bottles (Table 4). These results have shown that the shape and volume of the bottle has no impact on air pressure, and that different materials have specific air pressure responding characteristics.

The measurements have shown that air pressure coefficients of different materials follow the trend: activated carbon > plant ash stirred with 1/3 activated carbon > activated carbon stirred in 30 ml of 75% alcohol > activated carbon of adsorption ethanol > activated carbon stirred in 30 ml of 95% alcohol > 95% alcohol > 75% alcohol > loess soil > loess paste > clay > saline soil > plant ash > air.

The a of activated carbon was the highest. Plus, it maintained high responding performance when using 1/3 of activated carbon combined with plant ash. However, plant ash had poor responses. Water was usually used for *hou-qi* and had an a of 4.30 in the experiment [24], whereas the responding performance of ethanol was greater than water. The performance of activated carbon fully adsorbed with ethanol vapor decreased, because ethanol molecules have strong binding force with activated carbon, which was not to desorb. Similarly, the response of activated carbon stirred in 30 ml of 75% ethanol was greater than those stirred in 95% ethanol. The experimental results of loess pastes in PBB showed that the wet earthen bottles had good air pressure response, even higher than air. Therefore, it is an indication that ancient people could have sufficiently used activated carbon, water, wine, and plant ash to regulate and control air pressure. As a matter of fact, it was recorded in ancient literature that water and wine were commonly used in traditional Chinese sacrificial rites, and carbon and ash were used in *hou-qi* [23].

3.2. Experimental Results in the Soil

The variations of air pressure and temperature of PBBs buried in Gobi soil are shown in Figure 4c. The air pressure in the bottles fluctuated with the daily temperature change. The air pressure was calculated by temperature at 10 cm-depth and corresponded to the formula in table 3, results shown in Figure 4a. The mean daily pressure fluctuation range of the air, clay, loessal soil and activated carbon was 45.04, 74.58, 56.46, and 225.83 hPa, comparing to those of the monitored air pressure of 41.30, 35.77, 37.21, and 74.70 hPa. Each calculated values were high than the monitored ones (3.74, 38.81, 19.25, 151.13 hPa, respectively). This shows that the pointed bottom structure reduces pressure inside the bottle, and there is a pressure offset phenomenon.



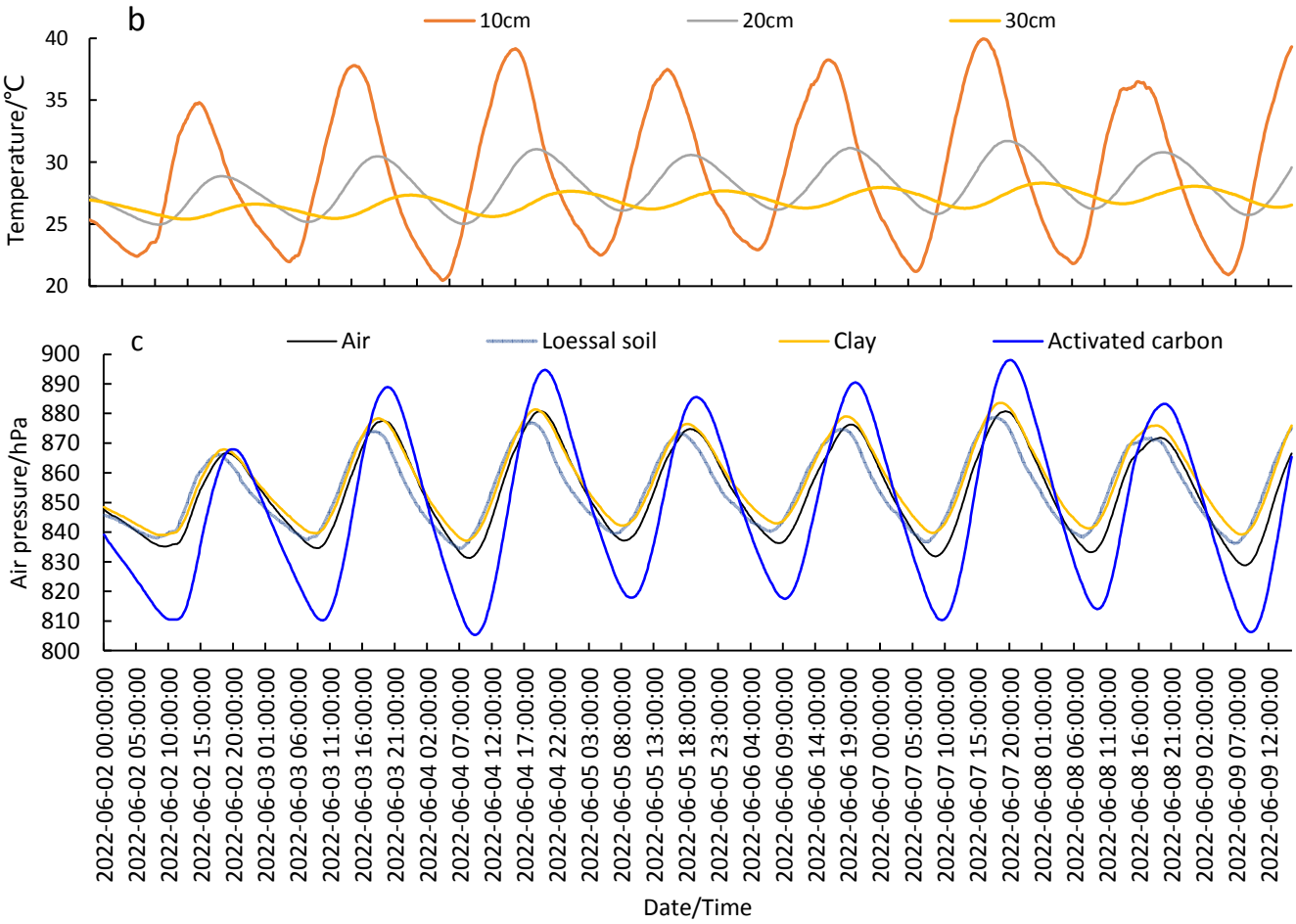


Figure 4. *Calculated pressure (a), and monitored temperature (b) and air pressure (c) in PBBs buried in the Gobi soil.*

The fitting formula between air pressure and temperature is shown in Table 5. The coefficient a in the bottle generally decreased and R^2 was also significantly reduced. This also indicated the existence of internal air pressure offset caused by reverse temperature variations. In addition, it is found that the pressure in the bottle was more synchronous with temperature of the 20 cm-depth soil and its correlation coefficient of fitting formula was high, but because the temperature at 20 cm-depth decreased significantly, the calculated pressure was lower.

Table 5. *Fitting relationships between pressure and temperature variation in the bottles.*

Materials	Bottle type	Volume (ml)	Fitting formula	R^2 (p = 0.01)
Air	O-PBB	2000	$P = 1.8596t + 799.24$	0.5087
Clay	O-PBB	1800	$P = 1.8703t + 802.93$	0.6299
Loessal soil	R-PBB	2600	$P = 2.1163t + 792.69$	0.8815
Activated carbon	R-PBB	1500	$P = 2.4215t + 776.76$	0.2614

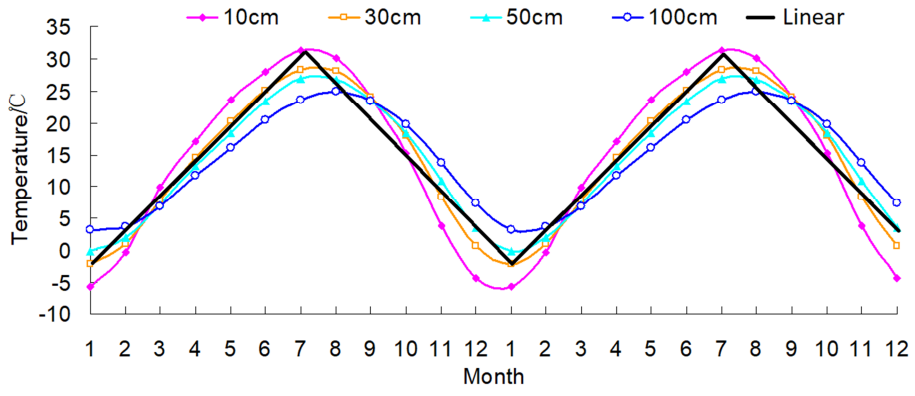


Figure 5. *The map of soil temperature variations in shallow layers.*

3.3. The Monitoring Method of the Solar Terms by PBB

The PBB was buried indoors in ancient China to monitor solar terms and set a calendar. According to the monitoring results of the monthly average temperature of 10, 30, 50, 100 cm in the Gobi soil at the Mogao Grottoes in 2013–2014 [37], the temperature changes are shown in Figure 5. The amplitude of soil temperature variation decreased with depth and temperature hysteresis existed. Each layer showed relatively stable sinusoidal periodic change.

Therefore, ancient Chinese buried the specially designed BPP in soil, then sealed the bottle to make its pressure responding time in correspondence with the solar terms. The specific distribution of a 12-month calendar is shown in Figure 7 with a specific arrangement of different sizes and depth of burial to achieve individual responding time, i e. the monitoring instrument matched the soil temperature in space and time. After many years of adjustment, the calendar could have been accurately obtained with the accurate correspondence. The BPP monitor, in addition to making temperature and date form a linear relation, was mainly affected by official/orthodox monitoring [37], and embodied the *Lv* of the core in *hou-qi*. From archaeological findings, PBBs were used in group and in proportion [*Lv* also means ratio (率), the height of the bottle varied regionally due to different depths of the daily temperature variation layer, but the ratio of height was consistent]. This has reflected the original idea and aesthetics of *lv*.

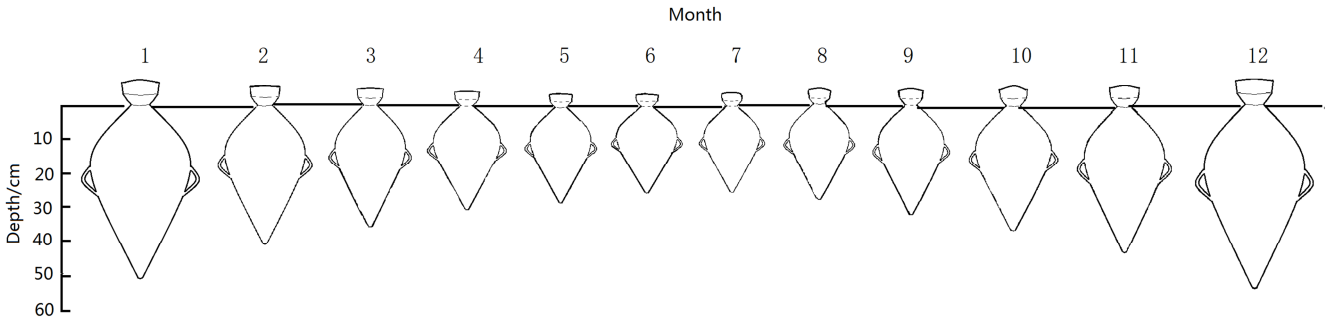


Figure 6. *The schematic diagram of the PBBs' depth of burial and corresponding months in hou-qi.*

The PBB became a completely independent and closed system after smearing blood [31] or by other sealing methods which are already extinct. Along with the rising temperature, there was a corresponding response from larger bottles to smaller ones. The mechanism is: in the lowest temperature in the middle of January, people used reed or bamboo membrane to seal the bottle corresponding to January; when the temperature went higher and reached a certain threshold (about 5°C), the pressure inside the bottle would help break up the sealing membrane, forming a sound response. Then, people would seal the bottle corresponding to February and wait for its response, then sealing the bottle of March..... and so on. In the temperature rising period from January to July, the PBBs would have broken through the closed membrane in sequence. Similarly, in the temperature dropping period from July to December, water adsorption in the bottle makes air pressure lower to a certain threshold, resulting in an inward breaking of the sealing membrane to indicate solar terms. So that the ancient solar terms were based on actual measurements of pressure/temperature rather than sun-earth angles.

4. Discussions

4.1. Jieqi and Solar Terms

Usually, *Jieqi* (節氣) is translated as the terminology of solar terms, which corresponds to the 15° angle between the rotation of the earth and the sun. In fact, in ancient times, it was on the basis of the response of the *Lv*-tubes in the big house (palace) that the actual changing intervals were determined. It is related to temperature, of which the basic principle is the same as that of PBB, but it also has a certain degree of randomness affected by factors such as the atmospheric pressure. The length of each *lv*-tube is different; there are 12 *jie* (節), and between each two *jie*s there is a *qi*. According to historic records, the earliest *lv*-tubes were made with bamboo, and their lengths were similar to bamboo sections between two *joints (also named jie* 節 in Chinese), which are naturally unique in length. Therefore, seasonal changes of the earth-air were called *jieqi* (earth-air of *jie*). This kind of gradual change is probably originated from the tradition of making instrument following images of the hexagram (制器尚象), which shows that direction of temperature conduction is downward, and that it is highest in summer [37].

Groups of PBB of various sizes have been found in archaeological excavations (Figure 7). However, it needs to be emphasized that at an earlier time period, people used a 10-month calendar [44-46] and 10 bottles to match. This earlier configuration matches the Five Movement (五行), i. e. six lines of the hexagrams. Hexagram varies with Yin and Yang [37]. The early six hexagram images are those that divide the annual temperature variation layer into five sections. The last one of the hexagram is *Tai ji* (太極, the maximum depth of temperature variation), and when it changes, the next new cycle begins. It is acknowledged that people commonly used the 10-month calendar in the Yangshao culture, with 36

days per month [45, 47]. At the beginning, there were only 10 solar terms throughout the year and the empty PBB could be completed by *hou-qi*. It could be simplified by reusing only 5 bottles. However, with the increasing demands of agricultural production, there might have been a calendar of 20 solar terms, which was twice the number of responses per month (18 days/solar-term). {This may have created a calendar with 18 months and 20 days every month [46] similar to the Mayan calendar. This may have further resulted in 36 solar terms (10 days each), even 72 solar terms (5 days each)}. During the Yangshao period, the 10-month calendar with 36 days per month and 30 solar terms (12 days, that is three responses per month) were used more commonly throughout the year [47]. This calendar was clearly recorded in *Guanzi* (管子) in the Spring and Autumn Period, and is still used by the *Yi* (彝) ethnic group to this day [46].

Figure 7. *A group of the collected waist type of PBBs (Yangguanzhai) and the bottle cap.*

Around the time of the Yellow Emperor (~4700 BP), people realized that the movement of the moon influenced the earth-air, and changed the 10-month calendar to a 12-month calendar, forming 24 solar terms (15 days each). Later, summarizing previous monitoring of *hou-qi*, it was developed into 72 *hou* (候, 5 days/*hou*), which became the mainstream of earth-air monitoring after the Yellow Emperor in China. *Hou-qi* developed progressively from a *longer response interval with a smaller number of solar terms* to a shorter response interval with a larger number of solar terms, an evolution from simple to complex. However, when the response interval is shortened, it means that the amplitude of temperature variation becomes smaller in a solar term. Therefore, it is necessary to use activated carbon, water, wine, and other materials to increase the amplitude of pressure change or reduce the critical value of the breaking of the sealed membrane. These two problems are not difficult to solve by artificial means. However, the influence of daily bimodal fluctuations of atmospheric pressure must be taken into account, because daily maximum fluctuations of around 5 hPa [33] have a great impact on accurate monitoring of earth-air (~20 hPa/*hou*, even if using activated carbon). Therefore, the strategy to overcome the influence of daily fluctuations of atmospheric pressure becomes the key to *hou-qi*. The annual changes in atmospheric pressure are shown in Figure 8.

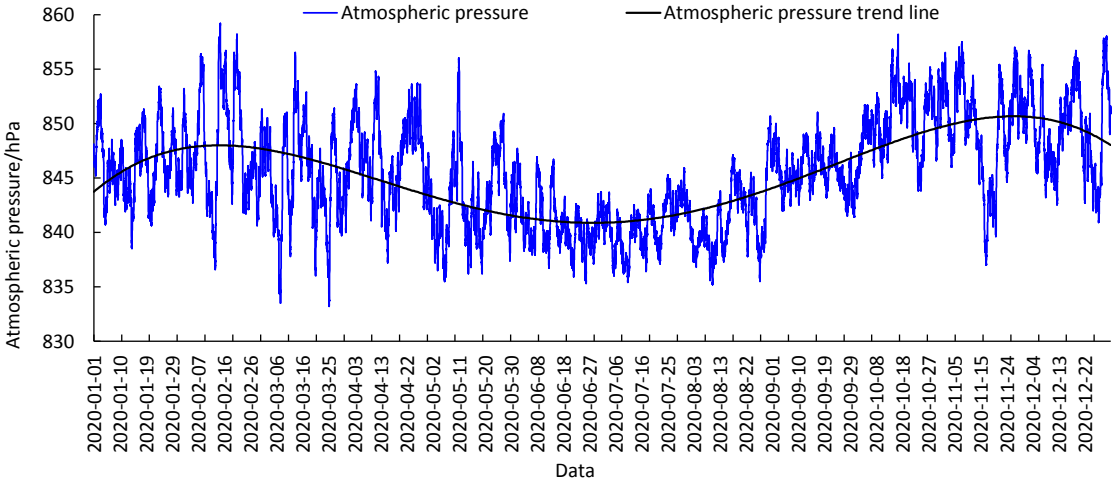


Figure 8. *Yearly variation of atmospheric pressure (Tianshui Dadiwan in Loess Plateau).*

As seen from Figure 8, there was about 36 weather processes in the whole year of 2020, and the atmospheric pressure fluctuation range was 10−22 hPa. However, weather processes in this region are usually a cooling process from the north, with a subsequent falling of temperature and atmospheric pressure. So, during the first half of the year, the sealed membrane would not break abruptly with the decline of atmospheric pressure because a temperature decrease has already made air pressure drop in advance, therefore the response/break would take place while temperature was rising. In the second half of the year, because temperature decreased, the responses would be coupling with weather processes. According to the annual changes of atmospheric pressure in Figure 8, the average daily atmospheric pressure fluctuation recorded every 10 minutes is shown in Figure 9. We made comprehensive analyses of the shape and size of the collected waist type of PBB corresponding to the daily temperature change of 10, 20 and 40 cm in soil as below.

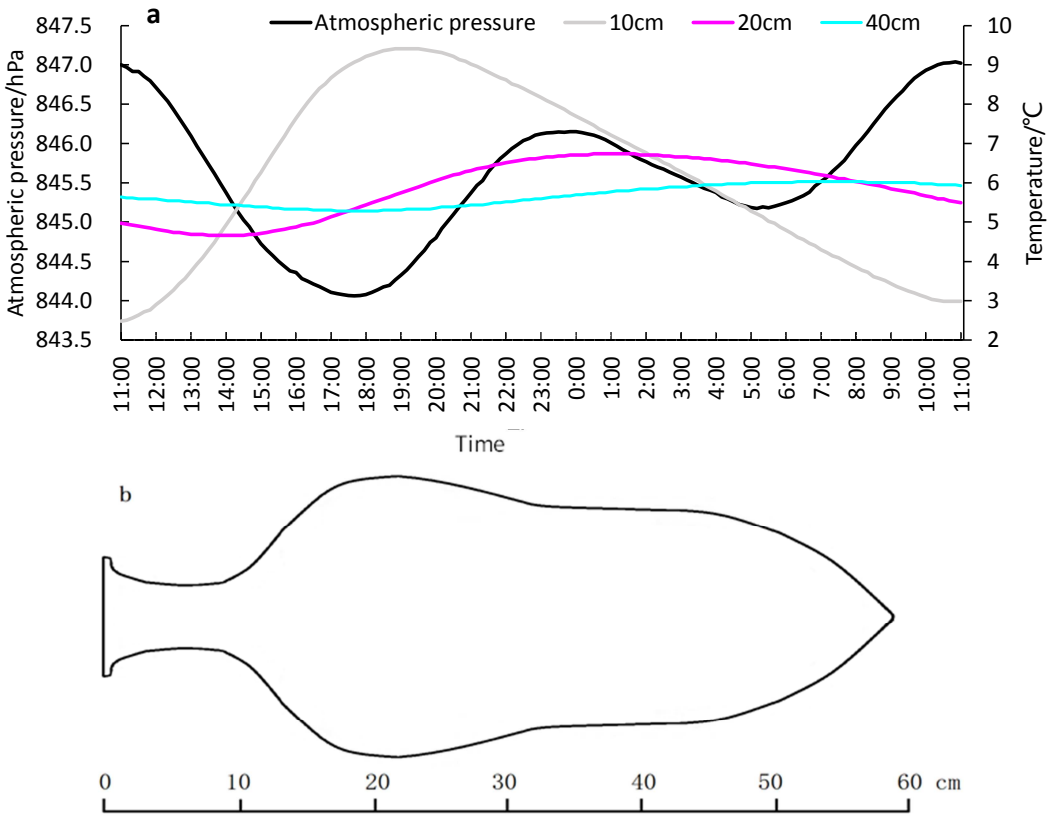


Figure 9. *Daily variation of atmospheric pressure (a) and the collected waist type of PBB (b).*

The daily change of atmospheric pressure presents bimodal characteristics (Figure 9a). From 11:00 to 17:30, atmospheric pressure drops, which requires that the pressure in the bottle also drops to balance the influence of external pressure drop and maintain the accuracy of *hou-qi*. The temperature of the upper layer represented by the 10 cm-depth rises significantly (~6°C), but the volume in the bottle corresponding to this depth is small. On the contrary, the lower layer in the depth of 20−40 cm has a temperature drop (~1°C) but the corresponding space in the bottle is larger (Figure 9b). Therefore, as long as the temperature in the lower part of the bottle drops, the decreasing of pressure (caused by contraction and adsorption) [24] is greater than the increased pressure as a result of the temperature rise in the upper part of the bottle. This is approximately equal to the influence of rising temperature in 0−20 cm depth and the amplitude of external atmospheric pressure drop. Later at night time, from 17:30 to 24:00, when the external atmospheric pressure rises, pressure inside the bottle could also increase: the temperature in the bottle drops slowly at the height of 10 cm, and rises sharply below 20 cm. Therefore, pressure inside the bottle increases to balance the increase of external pressure. From 0:00 to 5:00, with a temperature drop at 20−40 cm, the internal pressure also decreases gradually. From 5:00 to 11:00, the temperature at 40−60 cm depth experiences a small rise, which affects the pressure increase inside the bottle, and may even make it rise slightly to balance with the external pressure. The accurate pressure in PBB should be calculated by the volume and corresponding temperature of bottles at different depths. So, the ancient people eliminated the influence of daily atmospheric pressure fluctuation [33] utilizing the shape of the bottle (at least the daily maximum atmospheric pressure fluctuation from 11:00 to 17:00 can be eliminated), and made air pressure in the bottle change with the season (solar terms). Also, it differentiated PBB from daily utensils. The accurate design of PBB reflects wisdom of the ancient people.

4.2. Sealing and Burying of PBB

PBB is one of the instruments to monitor the earth-air's pressure response to temperature. Earth-air variations in soil in *I-ching* was called *long* (龍) in the Fuxi era; Earth-air was call god (神) in the Shennong era (in Yangshao culture). Because when temperature rises, earth-air stretches out (伸), so it was called *Shen* (神); when temperature decreases, earth-air is absorbed by soil which was considered as returning, or *Gui* (鬼 ghost, 鬼者歸也, a ghost is the returning one) [37]. Therefore, *hou-qi* was promoted to a religious level with high status. It had been deified to facilitate the teaching of people (神而化之, 使民宜之. 圣人因以神道设教). The management of hou-qi was called *Ji si* (祭祀 sacrifices) from a religious perspective. According to the literature of *Li ji·Jiao te sheng* (禮记·郊特牲), the utensil used for sacrifices to heaven and earth was PBB (器用陶匏). Therefore, PBB used in *hou-qi* was called *pottery of divinity* (神器) and worshiped by ancient people. It was also a *ritual vessel* (禮器) as people followed its indications to conduct activities.

Through observation of the degree of concave/convex, or

the breaking of the membrane as an indicator of the variation of earth-air, such worship is called *Mo bai* (膜拜, membrane-worship). Apart from the jade ware system, PBB is another type of instrument for *hou-qi*. In order to conveniently paste the bamboo membrane on PBB, ancient people have developed a special design of its mouth. The evolution was from the straight mouth (Figure 1a) → the gourd mouth → the double lips mouth → the bell mouth [6]. The size of the straight, gourd and heavy lip mouth was the same as the width of the bamboo (*Phyllostachys glauca*) membrane, which could be directly glued onto the mouth. This is another important reason that this type of pottery is also known as *small-mouth* PBB. However, a perforated cap is required for the bell mouth bottles (Figure 7, the cap/plug's vertical plane is in a trapezoid shape, apparently shaped by a special grinding technique. It was often wrongly classified as a kind of spindle whorl. which is not needed for grinding trapezoid shapes), and the cap hole would have been pasted with membrane. This plug or cap was convenient for filling silk-packaged ash, which was a response indicator.

In theory, the sequence of bottle sizes can be completely reversed (the biggest in July) if we consider the temperature variation in Figure 6 and use characteristics of different materials to control the pressure in bottle. In fact, subtle changes in pressure due to temperature in different depths can be addressed by adjustment in the bottle, such as the ratio of different materials, water content (it affects the change of air pressure when the soil is too dry and relative humidity is not saturated; the higher the relative humidity, the greater the response), salt content [24] and so on. For this reason, the general public could have monitored earth-air with only one PBB, observing its continuous response to simplify *hou-qi*.

The monitoring of groups of PBB is not commonly found in archaeological sites, and it is more common to bury a single PBB in the middle of a room (中溜). Zhu pointed out that in almost every residential area of Yangshao culture sites, a complete large PBB has been excavated [21], of which the height is generally about 80–90 cm. For example, in Yuanzitou there is a 90 cm-tall PBB unearthed from house F22 which doesn't have a fire pit (the high temperature of fire affects earth-air monitoring). According to the archaeological report: "This house was possibly for special purposes" [43]. Therefore, the usage of single PBB continuously existed in a large part of the Yangshao culture, because making a group of bottles to match the spatio-temporal temperature of soil was complex and difficult.

The present authors think that the specially designed tool of *ge* (戈), which is commonly found in archaeological sites, was used to dig a pit named *ke jiu* (窠臼) to bury PBB. The outer arc of the *ge* matches the shape of PBB (Figure 10). Because the burial pit is usually an exact match for the bottle, the size and depth of the mold needs to remain constant. Once it is established, the pit and PBB would be used repeatedly, which is named *Tao fu tao xue* (陶复陶穴) in historic records. As a result, the Chinese word *ke jiu* (窠臼) has become synonymous with the idea of being conservative and unchanging. In archaeological sites of Banpo, Dadiwan and Yangshao cultures, many holes with a depth of about 50 cm and a pointed shape had been treated with clay or other materials, which are wrongly classified as pillar holes [3, 39]. After backfilling the soil, it was tamped with a pestle. In *I-Ching*, it was referred to as the pit and pestle bringing benefit to the people (杵臼之利, 以濟萬民).

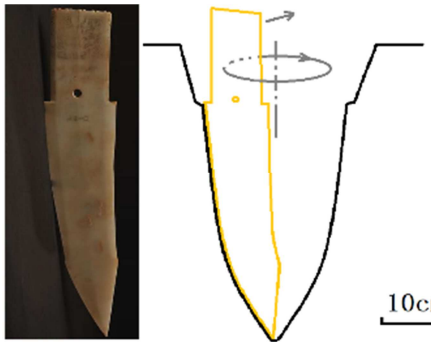


Figure 10. *Jade ge (Qingyang Museum) and the schematic diagram of excavating a pit for the burial of the PBB.*

Therefore, PBB is a special instrument designed to monitor earth-air to offset the influence of daily temperature and atmospheric pressure fluctuations to facilitate its embedment and convenient re-installation in soil (after a certain period, PBB starts to have air tightness issues, or the adsorption force of activated carbon or other materials will decline, so it needs to be taken out and resealed or refilled). Meanwhile, PBB is inconvenient in daily use, which could also distinguish itself from daily appliances.

4.3. History of PBB Evolvement

From archaeological excavations of *Jiahu* (贾湖) site (dated 9000–7500 years ago) [48], the bottle used for *hou-qi* does not have a pointed bottom (Figure 11, a, b). Pottery jars of similar shape were found elsewhere before or in the early period of Yangshao culture [41, 42]. It usually has small volume and its mouth was directly shaped to a smooth curved surface to facilitate the pasting of membrane (Figure 11 c-k). Most bottles have a long thin neck and a shape of an inverted trapezoidal or depressed globose, which conforms the air pressure inside the bottle in response to the soil layer's temperature. It can be seen that it was the imitation of jade tubes in the monitoring of earth-air traces [37]. However, this type of pottery was inconvenient to bury and could be easily damaged in the digging process. Plus, it was especially affected by daily temperature changes and atmospheric pressure, so that it could not accurately monitor the solar terms. Later, it was gradually replaced by the larger olive-shaped PBB. Then the olive type gradually evolved into the round shoulder type and collected waist type [1]. The accuracy of monitoring gradually improved and the number of bottles used evolved from multiple to single. The size of the bottle depends on the depth of the diurnal temperature variation layer (~60 cm). This layer is affected by topography, landform, soil texture and moisture content, therefore the depth of the temperature variation layer varies regionally. In addition,

because the filling material and humidity can regulate the internal pressure offset, it is possible that even if the bottle is not the collected waist type, it may still be able to offset the influence of daily atmospheric pressure fluctuations by water/wine or other materials placed in different positions.

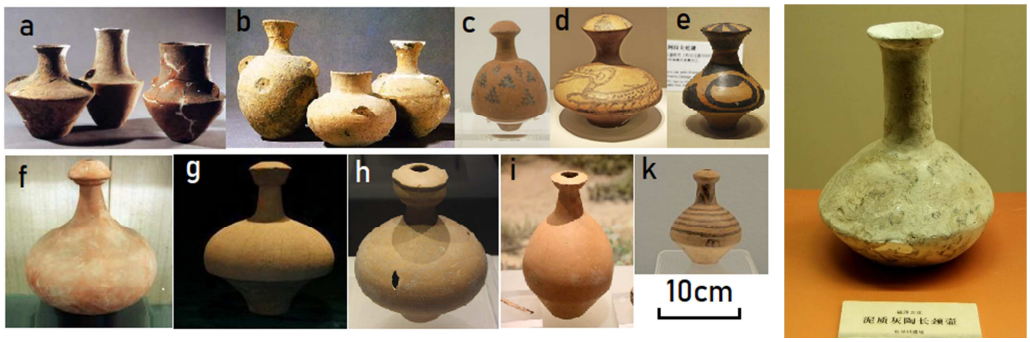


Figure 11. *PBBs before or in the early Yangshao culture excavated from: Jiahu (a, b); Baoji (c); Baishouling (d, g); Banpo (f); Jiangzhai (e); Majiayao (h); Xi'an (i); and Miaodigou (k).*

In the late Yangshao culture (4500−5500 BP), using a single PBB to *hou-qi* was very popular, almost every family had one PBB. Therefore, China was called the *land of gods* (神州大地) in ancient times, well deserving its name. In *Zhuanxu* (颛顼) era (about 4500 BP), due to the excessive abuse of divine pottery in monitoring activities, there was no distinction between the divinity and human settlements, and a lack of rigor in monitoring seriously affected the nation to unify standardized solar terms and decrees. Therefore, non-governmental *hou-qi* among the general public was completely prohibited by *Chongli* (重黎), and only jade ware monitoring in state-wide temples remained, which is the so-called *Jue di tian tong* (绝地天通). Therefore, PBB suddenly disappeared. Since the Xia dynasty (about 4000 BP), earth-air monitoring became a prerogative of rulers, and *hou-qi* was completely banned except in areas remotely uncontrolled such as Sichuan, Tibet, and Taiwan. This tradition lasted for hundreds, even one thousand years in these areas.

Feng-jian (meaning to set up *lv* by sealing — 封土建律 in this research, unlike the common translation as *feudalism*) autocracy had been the main political system in ancient China since the Xia dynasty. In its early stage, it referred specifically to the ruler's exclusive right to conduct *hou-qi*. The main purpose of autocracy at that time was to unify the *Lv* and the measurement units of length, weight and volume (同律度量衡), also the national calendar and management law (i e., system of rites). For more than 4,000 years, the general public was prohibited to practice *hou-qi* and set calendar until the end of the Qing Dynasty. Later, the ruler's monitoring of earth-air in the capital gradually lost its authority due to a lack of competition and management. The underlying reason was that earth-air monitored in one place is affected by the local microclimate and the weather process, and it cannot represent weather conditions in other regions. Instead, it is less accurate than the theoretical value such as the stipulated every 15 days of a solar term, by which earth-air monitoring was unnecessary. So, the solar terms were promulgated in this easier theoretical way, just like modern solar terms, and eventually the practice of earth-air monitoring may have been lost in Xia Dynasty. However, the theoretical model of the eight diagrams and the practice of *hou-qi* behind *feng-jian* autocracy laid the foundation of Chinese culture, which has far-reaching influence on Chinese ideology, political system, religion, and philosophy.

4.4. Other Usage of PBB

PBB has been widely found in tombs in Yangshao culture as a funerary ware [19], namely the soul jar [20]. It has the same function as jade ware buried in tomb, for these burials were profoundly influenced by *hou-qi*, and that people believed the soul was the same as earth-air. When temperature rises, earth-air flows out like the movement of the soul. When temperature decreases, the soil absorbs air, which resembles the return of soul. Because the PBB was easy to obtain and was considered similar as the spiritual destination which holds the sustenance of human soul and belief, it was widely used as funerary ware [21] and gradually formed the customs that are still kept in some areas such as the Hexi Corridor. For the same reason, PBB was directly usable as a coffin, especially for the minors. In addition, since wine was a good material for fine-tuning the air pressure in earth-air monitoring, it is not surprising that wine residues are detected in excavated PBBs. Based on *hou-qi*, it was possible to convert the large PBB into wine-brewing equipment [15, 22, 45]. In the loess plateau area, there is a habit of burying the jar in the shallow soil to brewing wine. The temperature variation in the soil is small, and the liquid convection of wine can make the temperature in the bottle more stable. Therefore, a suitable season helps form a temperature and environment to the successful growth of microorganisms and brewing of high-quality rice wine. We also noticed that the amphorae in ancient Greek and Egypt is strikingly similar to BPP [50], which was widely used in wine-making, transportation, and temple worship.

PBB as a *hou-qi* instrument has many advantages such as being sensitive, economic, and convenient about 7500 to 4500 years ago. There was nearly 3000 years of its usage in history, mainly in the Yangshao culture (5000–7000 BP). PBB has a tenacious vitality. It is one of the earliest human

pre-scientific monitoring systems, which has epoch-making significance. This suggests that the Chinese civilization originated on a scientific basis — by *hou-qi*. People made a calendar and used it to instruct their own labor, which wisely satisfied their survival needs and overcame challenges from the nature. People gained more freedom of living, and made a fundamental difference entering the civilized era. The theoretical basis of *hou-qi* is the hexagram model of *I-ching* [37]. Therefore, the Chinese civilization has only one source of *I-ching* and has multi-cultural forms. *Hou-qi* monitoring fully reveals the reason why the Chinese culture is respectful to the nature, advocating the unity of heaven and mankind.

5. Conclusions

PBB was widely distributed in prehistoric China in the Yangshao culture. This paper reveals the possible usage of PBB and purpose of its pointed-bottom design through an experiment of air pressure in response to temperature. PBB can offset the effect of vertical daily temperature variation and eliminate the interference of daily atmospheric pressure fluctuation. It was an instrument of *hou-qi* carried out indoors by the general public. The pointed bottom made air pressure in the bottle change with seasonal temperature fluctuations, from which solar terms and calendars were formulated to guide farming activities. The *hou-qi* practice of PBB was an important part of *feng-jian* in the Chinese history, and there is evidence of systematic correlation of its design, principle of usage, and building. PBB was also a pottery of worship and ritual vessel. This study shows that human civilization possibly originated as early as 9000 years BP in China with this significant scientific invention.

Acknowledgments

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