ความผิดปกติทางแม่เหล็กของเวคเตอร์ในเตาเผา
เมืองโบราณศรีสัชนาลัย จังหวัดสุโขทัย

นาย วีรพงษ์ คำด้วง

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาโลกศาสตร์ ภาควิชาธรณีวิทยา
คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2552

VECTOR MAGNETIC ANOMALY OF KILNS AT SRI SATCHANALAI ANCIENT CITY, CHANGWAT SUKHOTHAI

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science Program in Earth Sciences

Department of Geology
Faculty of Science
Chulalongkorn University

Academic Year 2009

Thesis Title	VECTOR MAGNETIC ANOMALY OF KILNS AT SRI SATCHANALAI ANCIENT CITY, CHANGWAT SUKHOTHAI
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วีรพงษ์ คำด้วง:ความผิดปกติทางแม่เหล็กของเวคเตอร์ในเตาเผา เมืองโบราณศรีสัชนาลัย จ.สุโขทัย. (VECTOR MAGNETIC ANOMALY OF KILNS AT SRI SATCHANALAI ANCIENT CITY, CHANGWAT SUKHOTHAI) อ.ที่ปรึกษาวิทยานิพนธ์หลัก :ผศ. ดร. สมชาย นาคะผดุงรัตน์, อ. ที่ปรึกษาวิทยานิพนธ์ร่วม ศ. ดร. โตชิฮิโกะ อิเยโมริ, 63หน้า.

เตาเผาเมืองศรีสัชนาลัย เป็นแหล่งผลิตเครื่องถ้วยสังคโลกที่สำคัญในช่วงคริสศตวรรษที่ 13-16 (800ปี) ได้ถูกเลือกมาเพื่อหาทิศทางสนามแม่เหล็กโบราณของเตาเผา โดยประดิษฐ์เครื่องมือการตรวจวัดที่เรียกว่า เวคเตอร์ แมกเนติก เกรดิโอมีเตอร์ เพื่อตรวจหาสนามแม่เหล็กโลกโบราณของเตาเผาศรีสัชนาลัยโดยไม่ทำลายโบราณวัตถุ โบราณสถานเลย

การศึกษาครั้งนี้ได้เลือกเตาศึกษา 2 เตา คือ เตาเผาหมายเลข1 และเตาเผาหมายเลข 2 ของเตาเผาบ้านเกาะน้อยโดยใช้เครื่องมือฟลักซ์เกต แมกนีโตมีเตอร์ ตรวจวัดสภาพสนามแม่เหล็กในแนวดิ่งของเตาเผาทั้งสอง พบว่ามีค่า 50-500 นาโนเทสลา ซึ่งมีความเข้มเพียงพอที่จะจัดเครื่องมือมาตรวจวัดทิสทางสนามแม่เหล็กได้ จากการตรวจวัดโดยใช้เครื่องมือ โปรตอน แมกนีโตมีเตอร์ซึ่งวัดความเข้มสนามแม่เหล็กรวม ค่าความเข้มที่เหมาะสมที่ใช้โปรตอน แมกนีโตมีเตอร์ ในระดับ 2 ซึ่งมีค่า 22,000-24,000 นาโนเทสลา เพื่อนำไปใช้เป็นแนวทางตรวจวัดโดยเครื่องมือที่ประดิษฐ์ขึ้นมา เครื่องมือ เวคเตอร์ แมกเนติก เกรดิโอมีเตอร์ ที่ประดิษฐ์ขึ้นมาประกอบด้วย 3 ตัวแปรที่อยุ่บนแผ่นจานที่สามารถหมุนได้ทั้งแนวนอนและแนวดิ่ง เพื่อจะได้ข้อมูลสนามแม่เหล็กทุกทิศทาง ซึ่งผลการตรวจวัดความเข้มสนามแม่เหล็กมีปริมาณมาก ต้องใช้การรวบรวมและคำนวนโดยใช้โปรแกรมคอมพิวเตอร์เฉพาะทาง ผลการศึกษาพบว่ายังมีค่าความผิดพลาดจากทฤษฎีประมาณ 4 องศาและค่าสนามแม่เหล็กผิดพลาดประมาณ 100-200 นาโนเทสลา เครื่องมือนี้ยังต้องได้รับการพัฒนาทั้งเครื่องมือ ฟลักเกตซ์ แมกนีโตมีเตอร์ที่มีความละเอียดและพัฒนาระบบซอฟท์แวร์ โปรแกรมคอมพิวเตอร์เพื่อแก้ค่าของข้อมูลให้ถูกต้องเพิ่มขึ้น

ภาควิชา ธรณีวิทยา ลายมือชื่อนิสิต วีรพงษ์ คำด้วง
สาขาวิชา โลกศาสตร์ ลายมือชื่ออ.ที่ปรึกษาวิทยานิพนธ์หลัก
ปีการศึกษา 2552

#4972488423 : MAJOR EARTH SCIENCES

KEYWORDS : SANGKALOK/ / KILN/ MAGNETIC DIRECTION/ INTENSITY

WEERAPONG KAMDUANG: VECTOR MAGNETIC ANOMALY OF KILNS AT SRI SATCHANALAI ANCIENT CITY, CHANGWAT SUKHOTHAI . THESIS ADVISOR :ASSIST. PROF. SOMCHAI NAKAPADOONGRAT, Ph.D., THESIS CO-ADVISOR : PROF. TOSHIHIKO IYEMORI, Ph.D, 63pp.

Sri Satchanalai ancient kiln which produced the Sangkalok (ancient ceramic) around 13th to 16th century (all 800-500 years ago) were selected for measuring the ancient magnetic direction of the kiln.

Two kilns i.e. kiln no.1 and kiln no.2 were studied, Fluxgate magnetometer was employed and the results show that the magnetic susceptibility vary from 50-500 nT. This figure indicate that magnetic susceptibility of the kiln were high enough to be investigated. Moreover, Proton magnetometer was also use. The results show that Proton magnetometer step two is most suitable. The total magnetic intensity vary from 42,000-44,000 nT. Vector magnetic gradiometer was invented. It consist of three axis sensors that are x, y and z. This equipment can measured in both horizontal and vertical magnetic direction. The data from this measurement are enormous. It need special computer software to calculate and compile. The result show that there is four degrees of mis-alignment and offset about 100-200 nT from the theoretical calculation. Therefore, the newly invented vector magnetic gradiometer need to be improved both hardware (more sensitive fluxgate magnetometer) and computer software.

Department : Geology .... Student's Signature ....

Field of Study : Earth Sciences .... Advisor's Signature ....

Academic Year : 2009 ....

ACKHOWLEDGEMENT

I would like to express my sincerd gratitude to Assist. Prof Dr. Somchai Nakapadungrat my advisor and Prof Dr. Toshihiko Iyemori my co-advisor who advise and guide me throughout the whole research work. Grateful acknowledgement is also made to Archan Boossarasiri Thana for comment and valuable suggestions. Thanks to Mr. Preecha Laochu for suggestion on geomagnetism to Archan Akkaneewut Chabangborn for suggestion, Mr. Tharapong Srisuchat for suggestion on archaeology and to Prof Dr Michio Hashizume for introducing this project.

I am greatly appreciate my dearest friends: Mr. Surapol Buppakosum, Mr. Putthinan Sukumonchan, Ms. Wichuratree Klubseang, Ms. Chanita Duangyiwa, Mr. Thawatchai Sudjai, Ms. Wirongrong Sukha, Ms. Chinchula Chotipithayanon for various helps. Several persons not mentioned here, who have helped me in many way during my study are also appreciated. Last but not least, I would like to thank my parent who strongly support me on finance and encouragement.

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CHAPTER I

INTRODUCTION

Sri Satchanalai is one of the most important ancient city of Thailand that is prospered in accordance with Sukhothai. Archaeological evidences showed that Sri Satchanalai is in most development of economics, political culture and art. Arachaeological study on various type of art work and architecture with reveal the thought idea or precept of the ancient people. This resulted in the type of religious, building, temple etc. In addition, the ancient product for examples, Sangkalok in Sri Satchanalai can be used as an indicator for economics. This have been supported by historical record which mentioned about the trading of Sangkalok between the Sukhothai kingdom and others countries (Nathaphinthu,2003).

According to archaeological excavation in Sri Satchanalai, it indicated that Wat Chom Chuen was constructed in Pre-Sukhothai period. Fifteen inhumation human burials were firstly occupied during the 3^{rd} to the 4^{th} century A.D. and they were continued up to the11^{th} century (Tvarvadi period). During Sukhothai period, Sri Satchanalai was an important retinue city mostly for economic development. This can be notified by the fact that produced Sangkalok were found. There are two kiln sites group i.e. Ban Kho Noi group and Pa Yang group. Archaeological study on the ceramic kilns at Ban Kho Noi clearly illustrated the development of ancient ceramic technology. The earliest type of this kilns site, appeared around the 11^{th} – 12^{th} century A.D. was the underground bank kilns. Two type of kilns i.e. updraft and crossdraft were observe. In this study, a crossdraft type was chosen. Due to the fact that the data obtained from archaelogical data are relative age. So it is not precise. Isotopic dating has been introduced to date the archaeological materials in order to receive an absolute date. For instance, C-14 and Thermoluminescence (TL) dating for archaeological materials were reported at Ban Chiang pottery. In Thailand, some archaeological materials dated by TL method were reported at Hub Khoa Wong Pra Chan (Nathapinthu,1988). Consequently, Palaeomagnetism and K-Ar dating for basalts that lie over pebble tools at Mae Tha, northern Thailand were reported .It was found that the orientation of some Khmer temples such as Pra Sat Hin Phimai does not lie in the present N-S direction as if should. So Palaeomagnetism might be a suitable method to answer this question.

1.1 Objectives

To develop an instrument to estimate the direction of remanent magnetization (gradient of magnetic field) of old kilns at Sri Satchanalai without any damage on the archaeological remains.

1.2 Scope of research

To investigate ancient magnetic field at Ban Kho Noi kiln group and correlate with archaeological data of Sri Satchanalai.

1.3 The study area

Ban Kho Noi ancient kilns group located about 5 kilometres from the north wall of Sri satchanalai ancient town and near the Yom river (see Fig.1)

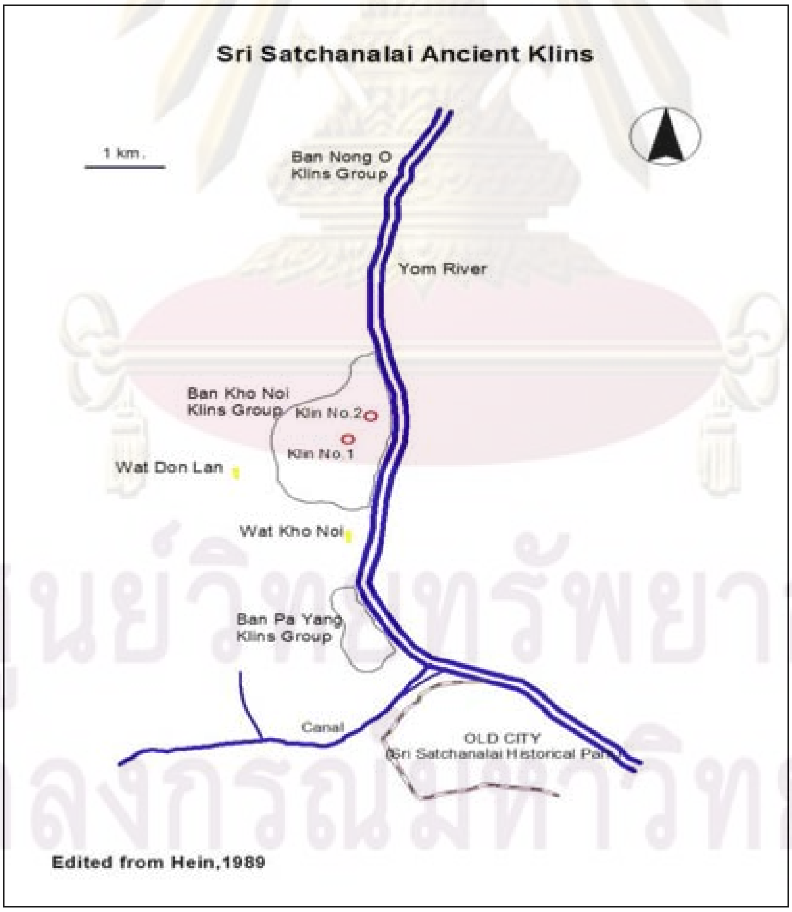

Figure 1 The kiln sites in Sri Satchanalai

1.4 Review literatures

In Buddhism it is believed that the Buddha (statue), accordingly the structure of the temple, should face to the east. The orientation, however, varies in accordance with the period of construction as observed in China and other places.

In Thailand, the northeastern region was dominated by Khmer kingdom and influenced to the construction of temple and religious remains in Buddhism and Hindu. The plan of the Khmer temple is based on Hindu cosmology. The wall represented the earth, moats and ponds symbolize the oceans around the towers which designate the peak of Mount Meru, the home of gods. A Prasat, a tall central on a cruciform plan and crowned by a lotus bud, houses statues of Hindu gods; smaller Prasats frame the central tower. The lintels, pediments and antefixes are ornamented with intricate carving. The temple is built with large blocks of sandstone assembled without mortar. Only priests could access to the interior for ceremonial rituals. When the Khmer kings instituted the tradition of the Devaraja, the god-king, they became the object of worship. After Buddhism was adoped, crowned images of the Buddha were enshrined in the sanctuary (Iyemori, 2007).

And the most important instrument for construction the Buddhism or Hindu of Khmer temples was campass. Magnetic compass had been already invented in 6th century in China. The compass had been developed and improved mostly by diviners or geomancers. Therefore, it was considered to the numerous secret. Record of application of compass to navigation is said to have initiated in AD 1110 but most probably it should had been used some time earlier. Magnetic compass was brought into Europe from China around AD 1190. However, compass was not much popular until 1300. Therefore, influence of Europe in the usage of magnetic compass should not have taken place earlier than Ayuthaya period (Needham, et al. 1962)

In Chinese literature referred and said about the first purpose of magnetic compass in Southeast Asia for navigation. In Yuan time (around 12th century to 13th century), the account of ambassy to Cambodia by Chou Ta – Kuan, which has been translated by Pelliot and others. By this time 1296, not merely mentions of the compass, but actual compass bearing, have got in to the literature, as follows:

"*Embarking at Wenchow (in Chekiang) and bearing the S.S.W., one passes the ports of the coastal prefectures of Fukien and Kwangtung, as also those of the overseas prefectures(of Hainan), then crossing the sea of the Seven Ises (Taya Island) and the sea of Annam, one arrives at Champa (somewhere near Qui-nhon). Then with a good wind one can arrive in 15 days at Chen-Phu (somewhere near cape St James),which is the frontier of Cambodia. Then bearing S. 52 1/2° W. One cross to the Khun - Lun Sea (north of Pulo Condor island) and enters the river mouth.*"

And at the beginning of Ming (around 13th century to 16th century), there must have been quite an abundant literature of sailing directions recording compass-bearing. Huang Sheng – Tseng named as one of his sources a Chen Wei Pien (collection of needle positions). At an the earlier point a few words have already been said about the way in which the compass was used by the pilots of Cheng Ho's time. Some idea of there skill may be gained by the fact that in circumnavigating Malaya they laid their course through the present Singapore Main Strait which was not discovered (or at least not used) by the Portuguese till 1615 when they had been in those water for over the century (Needham,1962)

In order to make an easier understanding, Thai history starting from Dvaravati to Ayutthaya kingdom has been summarized and shown in table 1.

Table1. Summary of Thai History (During the Dvaravati kingdom to Ayuthaya Kingdom)

(Iyemori,2007)

The Dvaravati Kingdom (6^{th} Century-12^{th} Century)	
Mid 6^{th} century - 7^{th} century	Evidence of a Dvaravati kingdom in the central plain
7^{th} century – 8^{th} century	Foundation of Haripunchai
9^{th} century – 10^{th} century	Rise of the Khmer Empire under Jayavaraman II and Yasovaraman I. Practice of Brahmanism and institution of cult of Devaraja (god king).
11^{th} century – 13^{th} century	Decline of Dvaravati civilization as the Khmer empire Gain control of large territories. Jayavaraman VII adopts Mahayan Buddhism as the Official religion of the Khmer empire. Angkor reaches the peak of its glory.
The Sukhothai Kingdom (13^{th} century – 14^{th} century)	
13^{th} century	Tai leaders from an alliance and depose the Khmer Governor of Sulhothai. Sri Intratit became the king. Glorious reign of King Ram Kamheang. The Khmer Are driven out of the country. Revival of the Theravada Buddhism.
The Lanna Kingdom (mid 13^{th} century – 16^{th} century)	
13^{th} century	Mengrai becomes ruler of Chiang Saen and conquers Neighbouring principalities. Foundation of Chiang Mai Promotion of Singhalese Buddhism and forging of Lanna identity.
Mid 16^{th} century	Lanna comes under Burmese supremacy which last 200 years.

The Ayuthaya Kingdom (late 13th century – late 18th century)

1351 – 1369	Ramathibodi I (U-Thong) founds Ayuthaya.
1569 to late 16th century	Ayuthaya falls to Burma.
1590 – 1605	Naresuan the Great frees Ayuthaya from Burmese Rules.
	Ayuthaya is referred to as the Kingdom of Siam.
17th century	Growth of the population. Golden age of the kingdom.

Chapter II

HISTORY OF SRI SATCHANALAI

2.1 Background

Sri Satchanalai is an important historical city since the Sukhothai era. It was earlier known as Muang Chaliang. Today, it is an archaeological monuments, located in Sri Satchanalai district in the upper northern part of Sukhothai. Chaliang, an old city of Sri Satchanalai has a long historical background whose name can be found in legends and stories related to hermit and cultural heroes who found cities, it is also related to Glorious King Pra Ruang of Sukhothai.

In the area of Chaliang there are remains of late prehistoric metal age communities that continued up to the historical Dvaravati period. It is possible that this area was an old trade route since the 11^{th} century A.D. during the time of Suriyavarman I of Khmer kingdom. Chaliang developed and grew from the 12^{th} to 13^{th} century, during the time of King Jayavarman VII of Khmer kingdom and the king promoted and spread Mahayan Buddhism to different areas. During that time, Lavo kingdom became an important centre for economics, trade, political and religious in the Chao Phraya river basin after the glorious period of Tvaravdi and Lavo kingdom was also a centre for art and architecture style which is known as Lopburi art. The Lopburi art had spread cultural influence to important distant inland cities that are located on the communication land route and these cities are Sukhothai and Sri Satchanalai formerly know as Chaliang. During the 12^{th} to 13^{th} century many new cities in the region of Thailand developed comtemporaneously with Sukhothai and Sri Satchanalai and the development of Sri Satchanalai city remains of the old Chaliang city which are visible from the architectural remains of Lopburi art style at Wat Phra Borommathat Muang Chaliang and Wat Chao Chan. Chaliang is situated on a limited space of the meandering bank on both sides of the Yom river that contributes to the narrowing of the land. Due to this phenomenon the city expanded northward to where Sri Satchanalai is located. The city expansion coincides with the political expansion of the royal Pha Muang family and finally, Sri Satchanalai became an important city of the Sukhothai kingdom during the reign of the royal Bang Klang How family which is later know as Phra Ruang family of the Sukhothai kingdom (see Fig.2).

Figure 2 Sri Satchanalai ancient city.

(th.wikipedia.org/wiki/%E0%B9%84%E0%B8%9F%E0%B...)

Pho Khun Bang Klang How and Pho Khun Pha Muang are the persons who combined their forces and drove out the "Khomsabadkhonlamphong" or Khom, the savages. It is hypothesized that this group of people was composed "Kha Phra" or "Silbal" (donated laborers) who took care of the religious sanctuaries and the leader of the group is know as "Khonlamphong". Sri Satchanalai is situated on a strategic lacation. The strong and stable city had encountered several wars since Sukhothai period. The founders of the city had used the natural setting and incorporated it with the city and the mountain surround the city like the outer wall and the Yom river serves as the city moat. The city had strong gates and wall.

2.2 Geomorphology

Existing record are imprecise concerning exactly when and how Sukhothai and Sri Satchanalai established as habitation centers. The Yom river that is one of tributaries of Choa Praya river debauches from the hill north of the old city of Sri Satchanalai and pass in a sweeping big bend around the city. Yom river flows through a strike ridge where it is broken into unnavigable rapid name "Khaeng Luang" and below the city it continues almost due south fifty kilometres to Sukhothai which its course is southeast until it meets the Nan river at Nakon Sawan province.

Figure 3 Geographic of Sri Satchanalai city(Google Earth).

The broad terrace through which the Yom river flows is largely flat with some hills, low undulating rise and outcrops of laterite beds lying just below the surface. The terrace is broadly composed of two sediment layers, the upper several metres deep of weakly mottled to homogeneous brown clay loam, clay, and the overlying a much thicker layer of grey and buff mottled clay (Bishop,et al 1992:160). The environment is subtropical with an annual rainfall of $1040mm^3$ that falls in the rainy season between May and Octobre of the southwest monsoon (see Fig.3).

2.3 Sangkalok Meaning (Ancient ceramics or Celadons)

Sangkalok was the ancient ceramic which manufactured from Sri Satchanalai and Sukhothai. This ceramic was stoneware cover by various colour glazing for example green, pale green, bluish-green, sky bluish-green. From archaeological evidences, found various pots, spitchers, tiles and architectural decorations.

The Sri Satchanalai ancient ceramic or Sangkalok had been range between 200–250 years (around mid 13th century to mid 17th century). From many evidences, sangkalok was most popular in domestic area and international regions because many shipwrecks (Pra Sare, Pattaya, Kram) and many Sangkalok were found in the Gulf of Thailand. In Southeast Asia, the Sangkaloks were discovered at Santa Ana, Calatagon in Philippnes; Indragiri, Djambi in Indonesia. Futhermore, in Japan, the Japanese used the Sangkalok for the important ritual “Pi Thee Chongcha” so had been a Japanese word “ Sunkoroku” or “Sonkoroku” which this one reason of the originated word of Sangkalok. This word Sunkoroku appeared in the first Japanese literature in the early 16th century and had been a commerce and communication between Japan and Ayuthaya kingdom at that time. Sunkoroku was dissimilar from Sawankalok which appeared at middle Ayuthaya period (mid 16th century). At this time, Sangkalok was a important goods for exportation to another countries which produced mostly from Sri Satchanalai kiln group and somepart of Sukhothai kiln group.

Futhermore, historian, archaeological evidences and linguistic study found the word “Sangkalok” likely dissimilar from Sawankalok that is one district in Sukhothai Province but the ancient time, Sawankalok was dominated area that had been many ancient kiln sites in Sri Satchanalai district.

2.4 Archaeological kiln sites

At the beginning of ceramics development, ancient man could not build a high quality kiln so the first type of kiln was domestic fires or Open hearth that take pottery on the ground and make the fire around its or put the pottery near the furnace. This method can be found in some parts area of Africa. From domestic fired method, the development of ceramics technology evolve about construction kiln that was the kiln hole type. Later on, the low kiln wall was constructed for keeping heat. Finally, the high kiln wall made of bricks for strong and permanent was established. It was higher quality to control heat and fired large amount of potteries.

Potteries in Thailand were continuously produced and developed. This can be notified by a large number of ancient kilns that were discovered. From archaeological evidences, there are many ancient kiln sites in Northern of Thailand. Accordingly, six large kilns group were suggested that are:

1. Turiang Group kiln, Sukhothai province
2. Ban Pa Yang Group kiln, Sri Satchanalai
3. Ban Kho Noi Group kiln, Sri Satchanalai
4. San Kampheang Group kiln, Chiang Mai province
5. Wiang Ka Long Group kiln, Chiang Rai province
6. Boe Suank Group kiln, Nan province

From archaeological evidences, ancient ceramics found in many countries around the Sukhothai kingdom came from Turiang kiln site in Sukhothai and Ban Kho Noi kiln site in Sri Satchanalai. In Sri Satchanalai, more than 200 ancient kilns were discovered along Yom river covering about 1.5 kilometres long and 250 metres wide. They were grouped into two areas i.e. Ban Kho Noi and Ban Pa Yang. Ban Kho Noi kiln site were highly developed. In addition, large number of kiln sites were discovered at Ban Kho Noi. Therefore, Ban Kho Noi kiln site was chosen for this study.

Ban Kho Noi was located in the low land which is about 65–70 metres above mean sea level, about 5 kilometres north of Sri Satchanalai. There was a six metres width canal, south of the kiln site run from the west passed Ban Pa Yang to Yom river (Klong Nong Kam). Ancient ceramics produced from Ban Kho Noi kiln site were high quality and the production still exists

for almost 200 years.

There were three kinds of ancient ceramics, produced from Ban Kho Noi kiln site i.e.

1. Earthenware, it was coarse grained, pinkish or pale yellow colour and fired at the temperature which is lower than 1,100 degree celcious. Circle pot with wide rim, pitcher, waterpot and tiles were examples of the earthenware type.

2. Stoneware, they were coarse and fine grained and fired at the emperature about 1,200 degree celcious. This pottery was dense and able to keep water. The examples were jar, pot.

3. Glaze ware, it was most distinguished ancient ceramics in Sri Satchanalai. It was better looking and higher quality than the others. The typical colour was green, dark

green, sky-bluish green. This was called as Sangkalok. However, the quantity of Sangkalok was not as good as that of Chinese ceramics of the Sung and Ming dynasty.

Significant characteristic from this kiln were manufactured by white soil that firing finish was seem texture of rock, higher quality than internal kin site. In addition, the color of glazing was especially green, dark green, sky-bluish green. It was different from the Sung and Ming dynasty of Chinese ceramics.

Glazing techniques and characteristics were differences, some types to glaze one size and thick side type especially the green ceramic(Celadon). Glazing ceramics of Ban Kho Noi were separated

1. Stoneware, glazed for bright and to glazed during 1,200-1,250 degree celcious. The glazing color was dark brown, white, brown, dark green, sky-bluish white. This type includes bowl, dish, jar, tray or stem bowl, figurine, roofing tiles, lantern, architecture ornaments.

2. Kaolinite glaze, fired during about 1,250-1,300 degree celcious. This type was the highest development of celadon which was dish, bowl, cup, tray that exported.

2.5 Kiln types in Sri Satchanalai

1. Crossdraft kiln type, predominantly found in Sri Satchanalai, located on surface and underground. This type was oval roof, dense, opaque located on slope during 10-30 degrees from furnace in front of kiln. The architecture was seem egg or back of tortoise. The materials were constructed mostly by bricks. Sometime, it was found that they used the support (Ki) to renovate some part of damaged kiln. For underground or in-ground construction used clay slab. Some kilns showed mix bricks and clay slab technique which used clay to wip then take bricks cover at the chimney only. The characteristics of materials and the depth of kiln showed the value of technique for manufactured the ancient ceramics of Sri Satchanalai very well. Kiln outside especially located on hill to filled soil around kiln because stronger for construction and protected that the composition area of crossdraft kiln devide three parts. Front part was large part, lower level part of fuel situated in front of kiln almost arc, width and height depend on purpose for firing with type of ceramics. Fire box was using for putting in the fuel and was chance to put in ceramics into the firing chamber. Fire box

have area for put into the fuel backside of fire box and have a upper level located between fire box and fire chamber.

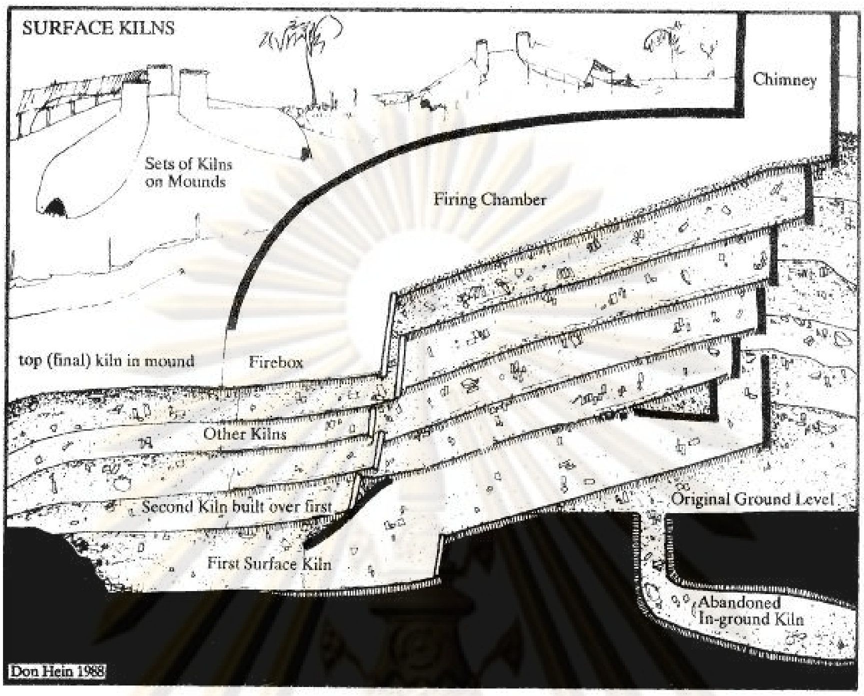

Figure 4 The surface kiln type (Hein,1988)

Central part was firing chamber which is the largest area. The width of firing chamber depend on kiln size (see Fig.4). The ground was faded by sand about 10 centimetres thick for holding on the support that underline ceramics. Beside part was chimney, circle shape, mostly found average diameter about 1 metres. This part was highest about 50-70 centimetres from the roof. Crossdraft kiln, heat move from fire box passed firing chamber and the last to chimney. Temperature averaged about 1,300 degree celcious which produced many high quality ceramics. In this case, heat moved horizontally inside the kiln (Pinsri, et.al.,1992).

2. Updraft kiln type, three kilns can be found in Ban Kho Noi. Kiln shape was circle and the checker work or grate which part of underline the ceramics. Diameter of the checker work was about 160 centimetres and was made from clay and bricks(clay cover the brick). Thicknese was about 15 centimetres and perforated many circle gaps for heat from firing box (lower part) passed to firing chamber and ceramic on the checker work. Upper part of checker part built by clay wall about 20-30 centimetres high. There were no roof covering all three kilns.

All of kilns development at Sri Satchanalai for the production of stoneware were of the crossdraft type with an inclined firing chamber. They can be devided into two broad groups i.e. those contained in the ground and built on the surface, called in-ground and surface kilns. In-ground crossdraft kilns can be sub-divided into a number of type depending on the context or construction method. Those made by tunneling into a bank or sloping ground are generally called bank kilns. The untreated surrounding earth formed the walls and in-ground kilns required a deep pit outside the firebox and these are called firing-pit kilns. A third type of in-ground kiln is defined as transitional because it has characteristics of both in-ground and surface kiln. Some part of the chimney and firehole were built of clay brick while the firing chamber was made of clay slab.

The first surface kiln was partly set into the ground but more than half was above ground level, supported by an earth mound. Although a few have been found with slab clay walls, most are built of clay brick. Some later surface kilns had sections of wall made of re-cycle pieces of tabular support (kiln furniture).

The kiln typology indicates a gradual development in which change were introduced slowly. For example, at Ban Kho Noi, a series of stages are evident which demonstrate the introduction of firewall to offset the firing chamber from the fire. In the early in-ground kilns type they were on the same baseline, but build up of slag on the step firing chamber floor. Later kilns had deliberate firewall to separate the fires from the wares. They had a greater chimney diameter and floor slope, to give more even flow of air and better temperature control. The change to surface kilns brought three main advantages. The first was that new kilns could be built over the ruins of the earlier ones, removing the need to adjust or move the factory infrastructure. The second was that they could be used all year round with fewer problems of dampness or flooding. The third that was the most important advantage, permitted more convenient repair and maintenance and encouraged changes such as increase in size, new stacking methods in which most wares were placed on supports rather than the floor , and design improvements toward greater temperature control (Barbetti and Hien,1989). The pattern of kiln location also changes with time, in the initial phase kilns appear to have been independent units, perhaps operated on the family basis. The need to locate new kilns in fresh ground caused their spread along many kilometres of river bank. In-ground kilns account for the large spatial dimentions of the Ban Kho Noi and Ban Nong O sites, and are more numerous than the surface kilns (Hien and Barbetti,1988). Later on more contralised management seem to have been imposed and the Sri Satchanalai kilns became organized as production to order.

2.6 Ceramic typology

The earliest ceramic typology is a class of wares called MON. These are characterized by the use of a dark, coarse secondary clay, white slip, olive glaze and the use of sgraffito decoration technique. The MON wares are associated with the in-ground kilns commonly found at Ban Kho Noi and Ban Nong O sites. This type of wares were produced for a long period of time. A major change occurred with the introduction of the fine white levigated primary body clay. This new clay use much finer incised and under-glaze pained decoration.As these wares were firstly found together with to MON wares they were called MON Associated Stonware (MASW) (Barbetti and Hein,1989). MASW wares represent a relatively short transitional phase. The third phase consists of higher quality wares with more sophisticated ranges of forms and designs, they were call as Later Stoneware (LASW). LASW wares were exclusively associated with the surface kilns were exported.

2.7 Trade Route and End of Sangkalok

There were two lines of trade route during Sri Satchanalai period i.e. toward south to the Gulf of Thailand and toward west passing Tak to the Mua Ta Ma Bay of Mynmar. Archaeological wares, found from the shipwrecks in southeast Asian sea indicated that the wares came from Sri Satchanalai, Sukhothai, China and Vietnam. In Phillipines, Indonesia and Malaysia, a large amount of ancient ceramics were discovered in the gravesites. The data of shipwrecks were the mid 14th century which were based on Chinese historical record.

There were many reasons for the decline and cessation of Sri Satchanalai. The first one might be the effect of Burmese invasion in the mid 15th century (around 1584-1592 A.D.) during the reigne of King Naresuan the great. The Burmese military

destroyed northern cities of Thailand. Accordingly, potters in Sukhothai, Sri Satchanalai and another cities were destroyed. This causes the artisans migration to Ayutthaya and Northern city. Discovering the ancient kilns sites and wares near Phayao, Sankamphang, Chiang Mai and Phan which reflected the styles and traditions of Sri Satchanalai could be significant evidences. Particularly, ancient wares produced from Phan were similar to those of later phase of Sri Satchanalai. In addition, Burmese wares at Bogo and Twante were also similar to those of Sri Satchanalai wares and kilns style
(in-ground and surface kiln type). In the south, Sri Satchanalai and Sukhothai potters and artisans might moved to Sing Buri and created the Ban Mae Nam Noi kilns group.

Flooding of the Yom river might be the cause of termination of Sri Satchanalai ceramic industry, particularly, those kilns in the lowland and habitation site of inner city such as Wat Prasrirattanamahathat.

Sri Satchanalai was a greatest manufacturer and important centre to export the ceramic to Southeast Asia region because the Chinese ceramic production was droped during that time. The reason was the war and royal prohibition against private foreign trade which is so call "Ming Gab" in the mid 15^{th} century (Brown 1997,Ho and Smith1999). It was clear that from 1371 A.D. in the reign of Hongwu to the mid 15^{th} century, the proportion of Chinese ceramic in Southeast Asian trade area declined. The shortage of Chinese ceramic resulted in the increasing of Sri Satchanalai ceramis productions (Brown 1997). After the mid 15^{th} century, Chinese ceramics returned to dominate the market again because the politic were to stable and China has high quality kaolin clay and higher technology. China process a high production of fine, thin, white stoneware and translucent porcelain. Gu(1985) estimated that each of 200 Song dynasty kilns in Guangdong province can produced 50,000 pieces a month or altogether 10 million pieces. The number of Chinese ceramic produced were enomous. Moreover, the quality of Sri Satchanalai ceramics were lower than those of Chinese ceramics. It could not compare with those produces in Sri Satchanalai where each kiln produced about 2,000 pieces per month only.

Disadvantages of Sri Satchanalai ancient ceramics were the lacked of technical sophistication and labour saving processes. The product depend on handmade which the rate of manufacture was slow and it was also difficult to control quality. In addition, Sri Satchanalai city was located about 500 kilometres north of the Gulf of Thailand. This was undoubtedly increase the cost of the product.

2.8 Palaeomagnetic Study in Sri Satchanalai

At Sri Satchanalai ancient town, Barbetti and Hein (1989) studied the palaeomagnetic in the ancient kilns which they used the taxonomy of kilns by attributes of technical sophistication provides a sequence that can be used in relation to dating. Kiln size and construction details are measured and recorded such as a cross-section of the firing chamber, firehole design, slope of the floor (see Fig.5).

For palaeomagnetism, core are drilled in kiln walls and carefully oriented in situ that it is necessary to collect fifty of more cores from each kiln, to get a good average direction for the structure with the best possible accuracy. Measurement of remanent magnetization were made on a Digico spinner magnetometer at the Australian National University and on a Molspin magnetometer at the University of Sydney. Magnetic direction are expressed as declinations measured east from true north and inclination downwards from the horizontal. Palaeomagnetic sampling has been done two purpose. Firstly, past changes at the earth's magnetic field are of great interest to geophysics and to studies of the earth's interior, since the magnetic field is generated by convection currents in the molten core inside the earth. Palaeomagnetic techniques are the only way that changes of magnetic field can be obtained for times before the earliest direction measurements of magnetic direction, which began in Europe in the 16th century and in Thailand in the 17th century. Past changes in the earth's magnetic field in different regions are not the same, and the results from Thailand are different from those obtained in Europe, Japan, China, Australia and the Americas. Secondly, palaeomagnetism is able to resolve quite small age differences between kilns if the magnetic field happened to be changing rapidly at that particular time in the past.

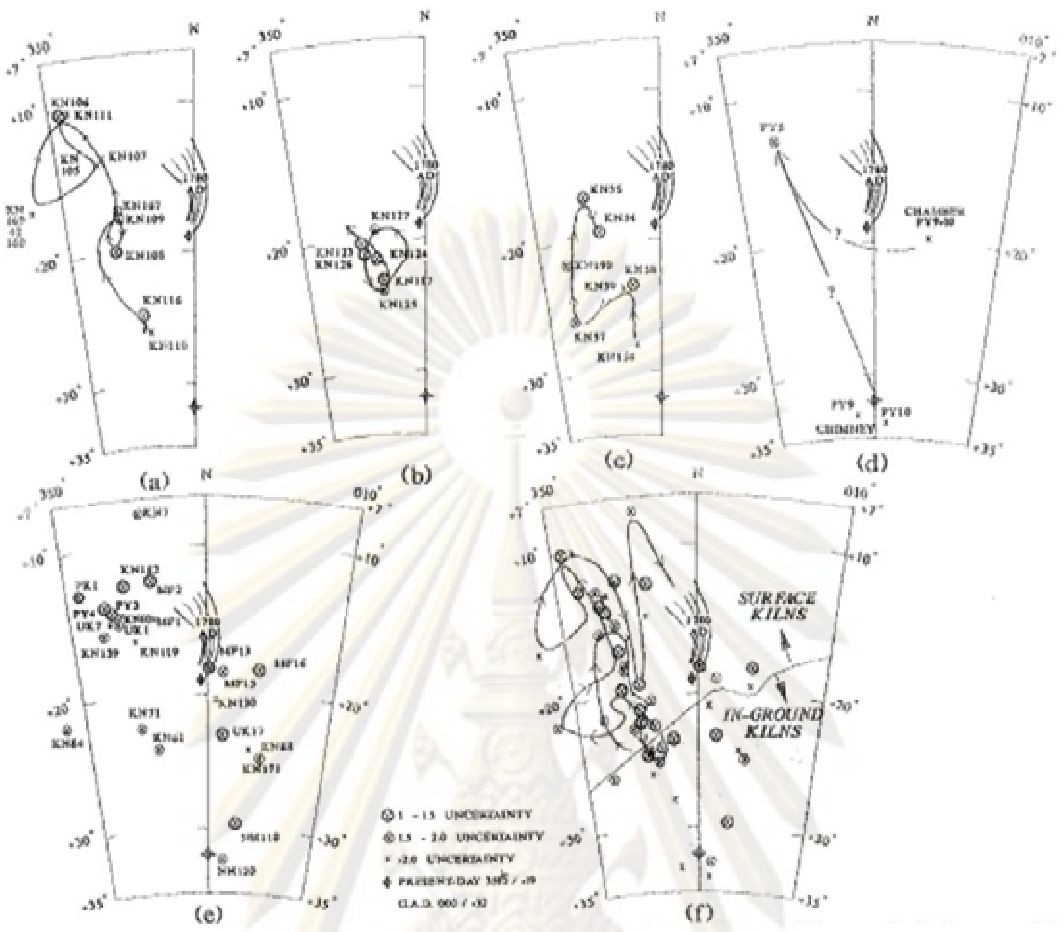

Figure 5 Stereographic projection of directions of magnetization; declinations are measured cast from true north, and inclination downwards from the horizontal. The present day direction and the change since AD 1780 are indicated; earlier seventeen century instrumental record indicate more westerly declination, but inclination are not measured. Fig (a) to (d) show the changes in magnetic direction with time for the four stratigraphic sequences (KN42, KN123, KN54 and PY5 sequences). Fig (c) shows the directions from the other kilns and metal furnaces which are not related to each other stratigraphically. Fig (f) shows all of the kilns and metal furnace directions together, with curves indicating the sequence of changes in magnetic direction. (Hein: Barbetti, 1989)

The only overlap between the in-ground and surface kilns occurs where the KN123(KN=Kho Noi kiln site) loop (surface kiln) is close to the directions of KN110, KN187, KN61, KN58 and KN59 (in-ground kilns). Kiln KN187, however, predates the KN123 loop and this might also be the case for the other in-ground kilns; if so, the overlap is fortuitous and does not indicate that in-ground kilns were operating at the same time as surface kilns. There is sufficient stratigraphic and typological information for the surface kilns to allow a tentative reconstruction of the path of magnetic direction change. The earliest surface kilns on kiln typological grounds are KN190, KN139, KN116, KN109 and KN55, with inclinations ranging from about +25°to +15°. We choose to start with KN116, followed by KN190, KN139, KN55 and KN109.

The KN123 sequence of kiln is younger than KN109 on the typological ground, and is followed by KN108, KN71 and KN84. Thereafter comes the younger part of the KN42 sequence, with a trend to shallower inclination (see Fig.5). The palaeomagnetic direction show a separation between the in-ground and surface kiln. This separation accords well with the evidence from kiln typology, ceramic typology and stragigraphy of kiln Ban Kho Noi and Ban Nong O site, all indicating that in-ground kilns predate the surface kiln.

In 2007, it had been studying about geomagnetic declination measurement in ancient temples in Thailand. By the reason, in buddhism it is believed that the Buddha statue or the main building of Buddhist temple should look toward the east. The results had been the trend of the global pattern of geomagnetic declination did not change in the past but it drifted westward at the rate of 0.2 degree/year (see Fig.6) (Iyemori,2007).

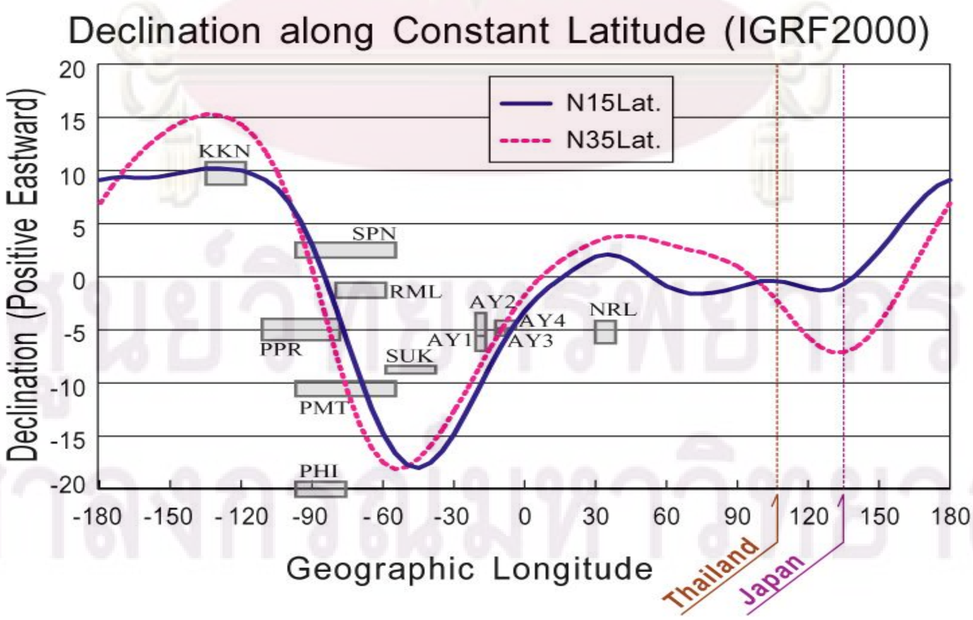

Figure 6 Thai declinations measured at old temples that are modified in the scale of geographic longitude with an assumption that the global pattern of geomagnetic declination did not change in the past and it drifted westward at the rate of 0.2 degrees/year. Longitudinal variation of declination at constant latitudes for western Japan (N15Lat.) and the central Thailand (N35Lat.) calculated with the International Geomagnetic Reference Field (IGRF 2000) are given altogether(Iyemori, 2007).

It should be mentioned that archaeological materials from Sri Satchanalai were dated by radiocarbon and thermoluminescence (TL), shown in table 2 (Barbetti and Hein, 1989). From table 2, the date obtained from radiocarbon dating are concordant with those of thermoluminescence. It indicated that Sri Satchanalai kilns had been operated during 13th -16th century.

In addition, Laochu (1995) reported that geomagnetic survey was carried out at Songkram river, Sakon Nakhon province and Turiang ancient kiln site in Sukhothai province. The results showed that there are 25 ancient kilns in Sukhothai province and 2 crossdraft kilns in Sakon Nakhon province.

Table2 Radiocarbon and Thermoluminescence dates of Sri Satchanalai kilns (Barbetti and Hien, 1989)

In-ground kilns					
Kiln-material	Lab Code	Radiocarbon Conventional Age yr. b.p.	Radiocarbon Calibrated Age yr. b.p.	Thermoluminescence Age yr. A.D.	Comments
K 130 charcoal	SUA-2504	210+/-120	1700+/-260		spurious sample
K61 charcoal	OAEP-691	580+/-60	1360+-80		
K61	OAEP-692	490+/-80	1460+/-170		
K61 firebox	OAEP-693	590+/-100	1360+/-110		
K61 charcoal	OAEP-775	650+/-90	1330+/-110		
K61 bone	OAEP-777	660+/-130	1250+/-210		
K61 bone	OAEP-778	450+/-80	1480+/-160		
K61 weighted mean		570+/-40	1360+/-70	1240+/-70	
K176 bone	OAEP-690	430+/-130	1620+/-340		
K110 firehole	SUA-2747	680 Q 60	1320+/-80	1220+/-80**	
k59 between chimney floors	SUA-2086	720+/-170	1230+/-250		
k59 between chimney floors	SUA-2696	620 Q 80	1350+/-90		
K59 weighted mean		640 70	1350+/-90		
K110 ground surface	SUA-2192	970+/-100	1070+/-190		
K187 upper fill outside	SUA-2693	580 Q 50	1360+/-80		
K187 middle fill outside	SUA-2694	520 Q 60	1350+/-80		
K187 basal fill outside	SUA-2695	640 Q 60	1340+/-80		
K118 firing chamber floor	SUA-2695	640 Q 60		1440+/-60	
K120 firing chamber floor				1400+/-70	
Transitional Kiln					
Kiln-material	Lab Code	Radiocarbon Conventional Age yr. b.p.	Radiocarbon Calibrated Age yr. b.p.	Thermoluminescence	Comments
K171				1320+/-130	SW sherd C7812
Surface Kilns					
Kiln-material	Lab Code	Radiocarbon Conventional Age yr. b.p.	Radiocarbon Calibrated Age yr. b.p.	Thermoluminescence	Comments
K5 base of fill outside	SUA-2664	350 Q 60	1550+/-150		jar kiln
K54 sealed in firebox ash	SUA-2665	390 Q 60	1540+/-120		jar kiln
K111				1650+/-60	
K109 ground surface	SUA-2193				

Chapter III

INSTRUMENTS AND METHODOLOGY

3.1 Introduction

The geomagnetic field is one the most intriguing aspects of the earth and is also one of it earliest geophysical properties to be studied scientifically (Gilbert,1600). Understanding of the origin and behavior of the geomagnetic field is therefore crucial to any understanding of the core itself and also the interaction between the core and mantle. Apart from the instinct value of such palaeomagnetic studies, the hypothetical models for the nature of the past geomagnetic field are fundamental to most of the geological interpretation that have revolutionized the understanding of the tectonic processes that have and continue to operate on the rocks of the earth's surface.

Geomagnetism provides us with various information related to the interior and exterior of the earth of the present and the past. The earth consists of several distinct parts with particular physical parameters as investigated by seismological observations. The chemical component of the core is Fe (ca. 90%), Ni (ca 5%) together with minor element. The physical of the Inner core is solid and the Outer core is molten in accordance with the seismological evidence that S waves do not penetrate the Outer core. The geomagnetic field is generated by a physical forcing in the Outer core called "Dynamo" and it is essential generated by electro-magnetic reaction induced by thermo-hydro dynamic movements within the Outer core. The problem is to solve the non linear different equations in three dimension giving realistic parameters of properties of materials and appropriate boundary conditions between Outer core and inner core as well as Outer core and mantle. So you can applying analogy to meteorology, the electro-magnetic field in the Outer core has been illustrated by a set of cyclonic and anticyclone convections resulting in magnetic dipole as observed on the earth. The dipole directs north and south although it is not exactly symmetrical when we observed geomagnetic field on the earth surface, the geomagnetic field is expressed as a vector (see Fig.7).

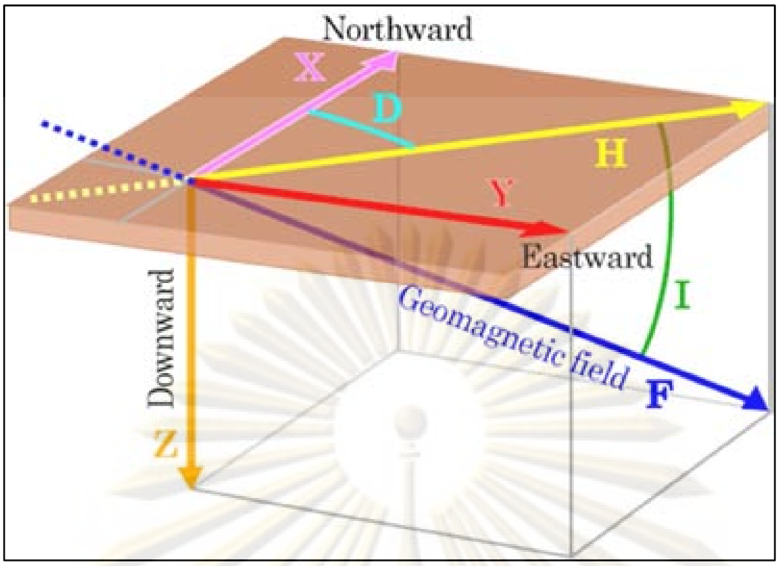

Figure 7 Three dimension component of geomagnetic field (Iyemori, 2006)

When we use the magnetic compass, angle between the astronomical north and geomagnetic north is called "declination" then with observation of contemporary geomagnetic field, investigation of geomagnetic field in the past will give important constraint to the dynamo model to help about the result of geomagnetic reversal that is one of the phenomena anticipated in the dynamo theory but the sequence and the transitions needs further study (see Fig.7) (Iyemori,2006).

In the past of history since twenty-five hundred years ago, the Greek discovered the magnetic properties of lodestone, the mineral called magnetite. It took about another thousand years for the Chinese to invent the first crude magnetic compass which was simply a piece of lodestone suspended on a string. In fourteenth century, travelers brought new of this discovery back to Europe, where it was adopted as the navigational aid and making possible the great feats of such men as Columbus and Magellan during the age of Exploration. In Southeast Asia, the magnetic compass influenced by Chinese migration and navigator or merchants. The plan of Khmer temple is based on Hindu cosmology and the wall represents the earth, moats and ponds symbolize the oceans surrounding the tower which designate the peaks of Mount Meru that is the home of god. A prasat, a tall central tower on a cruciform plan and crowned by lotus bud.

The earth's magnetic field can be well described by postulating a small but powerful permanent bar magnet located near the centre of the earth and inclined about 11 degree from the geographic axis. A magnetic needle that is free to swing under the influence of this magnetic force rotates into a position parallel to the local line of force approximately in the north-south direction. The north end of the needle points to the magnetic north pole and a compass needle that is free to swing in a horizontal plane does not point to true geographic north but deviates slightly east or west, depending on where the observer is. The angle of east or west deviation from true north is call the declination for example in New York, the compass point about 10 degree west of geographic north and in California is about 20 degree east (Press&Siever,1974). A magnetized needle free to pivot in a vertical plane measured the " inclination" of the magnetic field that is, its angle of deviation from the horizontal. At the magnetic poles, the dip needle swings into a vertical position which is early explorers located these two points on the earth's surface and near the equator where the inclination is zero, the dip needle takes a horizontal position. The compass and dip needle give the direction of geomagnetic field. To characterize the field fully, we need to measure the intensity or strength with a device called a magnetometer which some versions of this instruments simply measures the force exerted by the earth's magnetic field.

Because the magnetic compass was a key factor in navigation, as the result, magnetic observations have been made since the 16th century.The historic documentation of the geomagnetic field over the last 400 years show that the declination, inclination and field strength vary gradually around the world over a phenomenon called secular variation for example in London the compass needle has swung from 11 degree east of true north in 1580, to due north in 1660, to 24 degree west of true north in 1820 and back to 7 degree west of true north in 1970
(Press&Siever, 1974). This amounts to a drift of about 0.1 degree per year, a rapid rate of change compared to most geological processes. But recently, the declination sometimes change several degrees to a few ten degree at particular sites over several hundred years and generally recognized that the pattern of the geographical variation of geomagnetic declination drift westward with 0.2 degrees per year (Iyemori, 2006) The solid parts of the earth, even when they creep plastically change much more slowly

because fluid motions can occur this fast , again we resort to the fluid core as the likely source of the secular variation.

In addition, the increase temperature is influences the ferromagnetic material that have a magnetic property to not have magnetizing call “ Curie temperature”. Each specific components of magnetic minerals has a unique curie temperature for example cobalt, iron, nickel, gadolinium and diprosium is about 1151-1131°c, 770°c, 354-358°c, 17-19°c and -185°c. In iron case, it is a high temperature more than 770°c that the atom of magnetic moment disappear. But the temperature lower than 770°c circumstance, the atom of magnetic moment was alignment in the magnetic line at that time (see Fig.8).

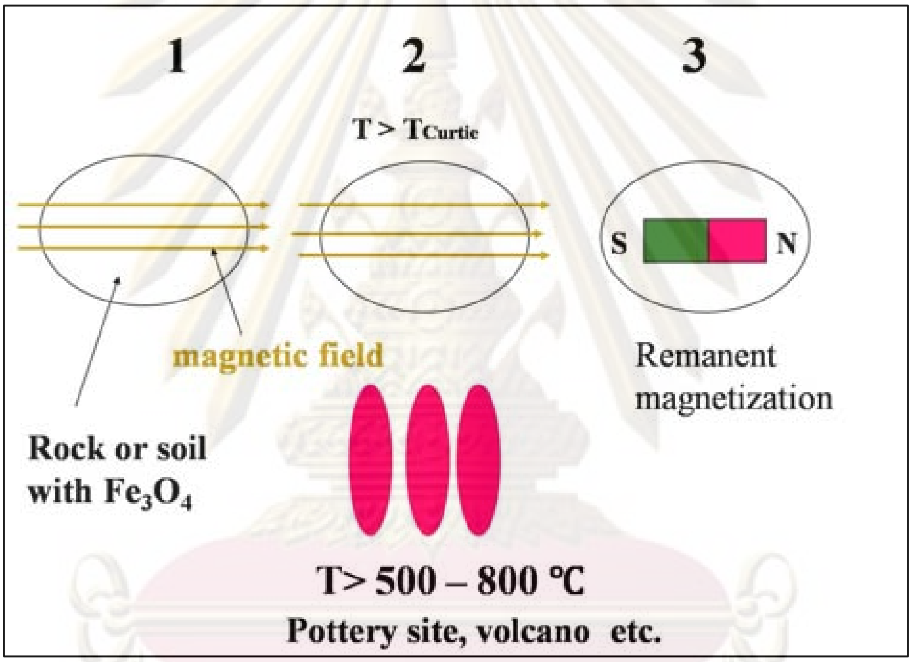

Figure 8 Curie temperature (Iyemori, 2006)

The attractive power of the lodestone was know both in China and the West from the early time about the middle of the 1st millennium. Knowledge of magnetism appear in Europe at the end of the 12th century. Actually, the Chinese that were the first to understand and using the directive property of lodestone has been admitted. From Han dynasty onwards Chinese text speak of the “south-pointing carriage”.

The history of the magnetic compass in China has been revolutionized by the contributions of Wang-Chen-To, who has been able to explain a fundamental text in Lun-Heng (1st century) and to reveal a connection between the magnetic compass and the diviner's board of the Han people and the first text clearly describing the magnetic needle compass is undeniably of about 1080 A.D. It is a century earlier than the first European mentioned of this instrument that mentioned the declination directively the failure of the magnetic needle to point to the astronomical north. The declination was discovered in China sometime between the 7^{th} century and the 10^{th} century and the use of needle which permitted the construction of an accurate pointer reading instrument, was limit factor for discovery and belong to the beginning of this period. The original Chinese compass was a kind of spoon carefully carved from lodestone and revolving on the smooth surface of a diviner's board. In Middle age, it had been established that the lodestone attract pieces of iron, the attract iron adheres to the magnet, the magnet induces a power of attraction. The magnetic influence through substances other than iron and some magnets would repel some pieces of iron as well as attract them. The earliest observation on the magnet are supposed to have been made by Thales in the 6^{th} century who explained animistically.

3.2 Instruments

For this study, three kind of geophysical instruments are use for measuring magnetic susceptibility, strength of magnetic field and gradient of magnetic field i.e. Fluxgate magnetometer, Proton magnetometer and Vector magnetic gradiometer, respectively.

3.2.1 Fluxgate magnetometer

Principle

The sensor of a fluxgate magnetometer consists of two parallel strips of the special alloy. They are wound opposite directions with primary energizing coils. When the current flow in the primary coils, the parallel strips becomes magnetized in opposite directions. A secondary coil wound about the primary pair detects the change of magnetic flux in the cores, which is zero as soon as the cores saturate. While the primary current is rising or falling, the magnetic flux in each strip changes an a voltage is induced in the secondary coil. If there is no external magnetic field, the signal due to the changing flux are equal and opposite and no output signal is recorded. When the axis of the sensor is aligned with the Earth's magnetic field. The latter is added to the primary field in one strip and subtracted from it in the other (see Fig.9).

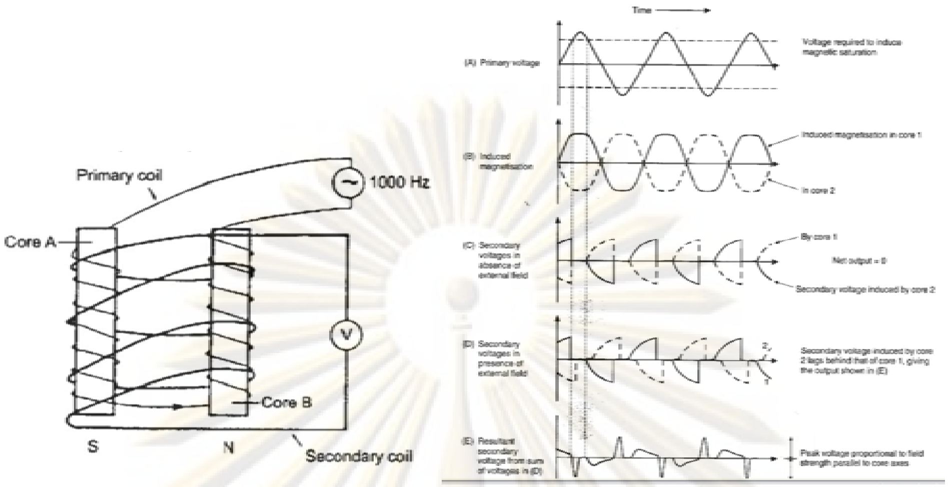

Figure 9 Systematic of fluxgate magnetometer
(http://pkukmweb.ukm.my/~rahim/magnetic%20lecture.htm)

The phase of magnetic flux in the alloy strips are now different; one saturates before the other. The flux-changes in the two alloy strips are no longer equal and opposite. An output voltage is produced in the secondary coil that is proportional to the strength of the component of the Earth's magnetic field along the axis of the sensor.

The fluxgate magnetometer is a vector magnetometer, because it measures the strength of the magnetic field in a particular direction, namely along the axis of the sensor. This requires that the sensor must be accurately oriented along the direction of the field component to be measured. For the total field measurements three sensors are employed. These are fixed at right angles to each other and connected with a feedback system which rotates the entire unit so that two of the sensors detect zero field. The magnetic field to be measured is then aligned with the axis of the third sensor.

Figure 10 Fluxgate magnetometer

The fluxgate magnetometer does not yield absolute field values. This output is a voltage, which must be calibrated in term of magnetic field. However, the instrument provides a continuous record of field strength. Its sensitivity of about 1 nT makes it capable of measuring most magnetic anomalies of geophysical interest. It is robust and adaptable to being mounted in an airplane, or towed behind it. The instrument was developed during Word War II as the submarine detector. After the war it was use extensively in air borne magnetic surveying.

Procedures

1. Check the output from proton magnetometer, minimum distance (height) from ground to get correct output (at the several point). Measurement of shape and direction of the kiln (to confirm where they put fire which the place where the temperature was highest).

2. Use fluxgate magnetometer (see Fig.10) and measure at the point close to the wall then move backward and measure at every five centimeters until leaching 25 centimetres. If the strength of magnetic field (F) measurement can not be measured, it indicate that the place is not suitable to study (see Fig.11-12).

Strength of magnetic field (F) can be calculate from:

Formular

$$F = | Bo + SB |$$

SB = dipole moment on the wall

Bo = geomagnetic field at present

F should be change depending on the location in the kiln

Figure 11 The fluxgate magnetometer measurement

Figure 12 Fluxgate magnetometer measurement (close look)

3.2.2 Proton magnetometer

Principle

A proton magnetometer is an instrument used to measure the strength of magnetic field. Magnetometers are used to measure variations in the earth's magnetic field in -objects such as submarines or shipwrecks. The proton precession magnetometer operates on the principle that the protons in all atoms are spinning on an axis aligned with the magnetic field. Proton tend to line up with the earth's magnetic field. When subjected to an artificial induced magnetic field, the proton will align themselves with the new field. As they change their aligment, the spinning proton precess, or wobble, much as a spinning top does as it slow down. The frequency at which the proton precess is directly proportional to the strength the earth's magnetic field. This is the proton Gyromagnetic Ratio equal to 0.042576 hertz/nano Tesla for example, in an area with a field strength of 57,780 nT, the frequency of precession would be approximately 2460 Hz.

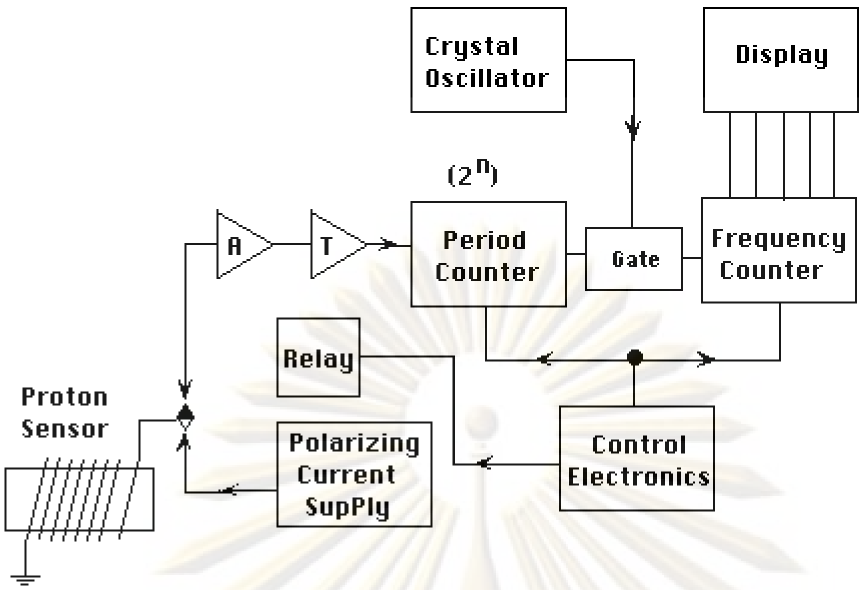

Figure 13 Systematic of proton magnetometer

(www.irf.se/Observatory/protonmagneto.gif)

magnetic moment of proton and have an electric current (j) ⟶ cut the electric current

(j = 0) ⟶ sudden cut ⟶ coherent precession of all proton⟶ precession of proton generate

macroscopic magnetic field ⟶ oscillation current oscillation is induced in the coil

F : frequency (F α f F) (see Fig.13)

Proton magnetometer does not work if there is strong magnetic gradient.

near the ground. Therefore, it may be not useful to measure the anomaly distribution. Proton magnetometer measures the total strength of magnetic field (*F*), it should be carried out reverse points as many as possible at the same high from the ground. If it does not work, let's use it by putting at a point to monitor temporal variation of strength of magnetic field, and the measurement of anomaly distribution should be done by fluxgate magnetometer. Because the height of proton magnetometer is shorter than one metre, the spacing between two points should be less than 1 metre.

Procedures

1. Measuring magnetic intensity at various points in the kiln using all three step of proton magnetometer.

2. Measuring magnetic intensity around the kiln using only step two of proton magnetometer.

3. Measuring along the present magnetic north starting from the kiln toward the north for 50 metres and measure every 5 metres using step two of proton magnetometer.

4. Measuring along the line which is perpendicular to the present magnetic north starting from the kiln toward the west for 50 metres and measure every 5 metres using step two of proton magnetometer (see Fig.14-15).

Formular

dBi = Bi – Bo

Bi = value in each position

Bo= reference value

Figure 14 The proton magnetometer measurement (kiln no.1)

Figure 15 The Proton magnetometer measurement outside kiln no.1

3.2.3 Vector magnetic gradiometer

Principle

Fluxgate gradiometer or Vector magnetic gradiometer has been invented for measuring the magnetic gradient. The equipment consists of X, Y and Z sensors on the disk. X and Y sensors are on the same line where z sensor is vertical (see Picture 9). Picture 10 shows that it also contain fluxgate magnetometer, terminal box and computer. The magnetic gradient can be obtained from the different values between X and Y sensors (see Fig.16).

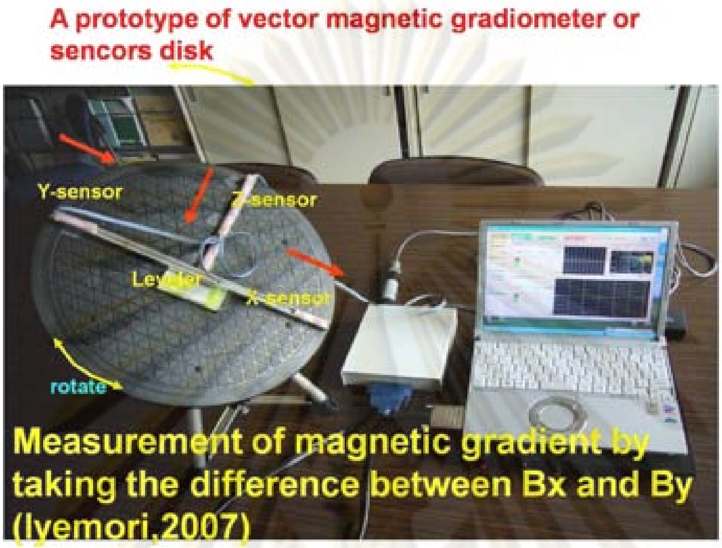

Figure16 Vector magnetic gradiometer (Iyemori, 2006)

In addition, Z sensor will give the direction of sensor. The disk can be rotated, so the z sensor lie in the magnetic north. Generally, observed magnetic field is equal to geomagnetic field plus artificial origin and noise. It should be noticed that small changes in angle of geomagnetic field may be a large influence to reading value.

Magnetic field = Geomagnetic field + artificial origin + noise

Geomagnetic field = (observed 40,000 – 45,000 nT)

Artificial origin = (natural origin 40,000 – 45,000 nT)

Noise = (10 – 1000 nT , we need this)

Magnetic gradient (ΔB) = X - Y

Procedures

1. Use sensor disk (x,y,z) and measured the true fix point magnetic north at outside the kiln(west of kiln). They are 10 positions .

2. Measured each vertical and horizontal at 0 degree and 180 degree that located near the kiln no.1, distance about 50 metres. To turn the x knob (x parameter) that show the value (red line) near the y parameter (green line) in the software.

3. Used the sensor disk measured inside the kiln and measured each in horizontal and vertical at 10 positions inside the kiln (10 positions in the chimney). The positions started on the left to moved the right hand inside the chimney. Measured the distance from the kiln wall to the sensor disk and high from the ground and to turn the disk go and back (that show curve in the software). The kiln no.2 was seem the first kiln that start measuring outside the kiln (at the yield east of kiln), the x and y sensor to turn at the true magnetic north. Inside the kiln, they were 13 positions that measured around the kiln (at the fire box and the chimney). The position started at the left to right hand and have a one centre position (see Fig.17,18,19,20).

From a preliminary analysis of calibration data

$$Bx - By \approx 185 \text{ nT},$$

that is the red line should be about 185 nT abouve green line , i.e., we need to adjust x and y sensor direction to keep 185 nT

$$Bx = \mu H + S1$$

$$By = úH + S2$$

$$S1 = S2 + 185$$

Even if H = 0 (i.e. sensor is orthogonal (90°) to magnetic field

Formular

Sources of error : sensitivity and offset of fluxgate magnetometer

$$B\,(\text{observed}) = B\,(\text{real}) \times \text{sensitivity} + \text{offset}$$

Mis-alignment α of X and Y sensors

$$Bx\,(\text{observed}) - By(\text{observed}) = [Bx(\text{real}) - By(\text{real})] + Bz \times \sin(\alpha)$$

* *continuation by Least square method*

The data showed x, y, z values. X and Y were the gradient of magnetic field in the meantime, Z was the direction of sensor and B was the magnetic field. The values has been plus and minus.

Figure 17 The vector magnetic gradiometer measurement in horizontal

Figure 18 The vector magnetic gradiometer measurement in vertical

Figure 19 Measurement a high level of gradiometer in kiln no.1

Figure 20 The vector magnetic gradiometer measurement in kiln no.2

Chapter IV

RESULTS, CONCLUSIONS AND DISCUSSIONS

4.1 Fluxgate magnetometer investigation

Magnetic susceptibility of the kiln no.1 and no.2 were investigated by fluxgate magnetometer. Eight positions i.e. P1, P2, P3, P4, P5, P6, P7 and P8 and four positions i.e. P1, P2, P3 and P4 were measured (see Figure 21 and 22). The results are shown in Table 3. the data, investigated for kiln no.1 from Table 3 can be illustrated in Figure 23-30 whereas the data of the kiln no.2 are shown in Figure 31-34.

Determination of raw data

Figure 21 The positions in kiln no.1 to measured by fluxgate magnetometer

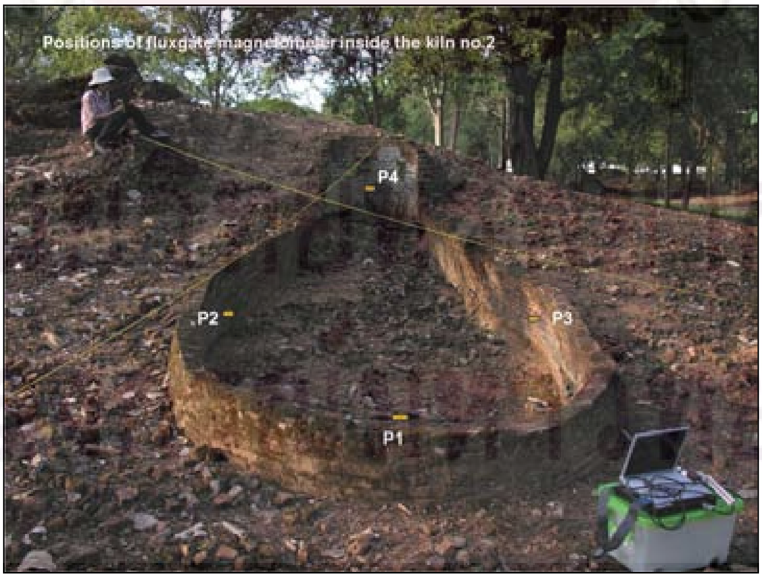

Figure 22 The positions in kiln no.2 to measured by fluxgate magnetometer

Table 3 Fluxgate magnetometer data

Kiln no.1

positions	distance (cm)		nT
p1	0	43352+(-36.5)	43315
	5	43352+(-25)	43327
	10	43352+(-32.5)	43319
	15	43352+(-47.5)	43304
	20	43352+(-60)	43292
	25	43352+(-75)	43277
p2	0	43352+(-242.5)	43109
	5	43352+(-230)	43122
	10	43352+(165)	43187
	15	43352+(132.5)	43219
	20	43352+(-130)	43222
	25	43352+(-155)	43197
p3	0	43352+(-45)	43307
	5	43352+35	43387
	10	43352+97.5	43449
	15	43352+227.5	43579
	20	43352+282.5	43634
	25	43352+320	43672
p4	0	43352+(-37)	43315
	5	43352+(-44)	43308
	10	43352+(-45)	43307
	15	43352+(-60)	43292
	20	43352+(-55)	43297
	25	43352+(-100)	43252

p5	0	43352+(-45)	43307
	5	43352+(-770)	42582
	10	43352+(-815)	42537
	15	43352+(-915)	42437
	20	43352+(-960)	42392
	25	43352+(-975)	42377
p6	0	43352+(-55)	43297
	5	43352+(-645)	42707
	10	43352+(-825)	42527
	15	43352+(-875)	42477
	20	43352+(-887.5)	42464
	25	43352+(-600)	42752
p7	0	43352+(-485)	42867
	5	43352+(-525)	42827
	10	43352+(-587.5)	42764
	15	43352+(-400)	42952
	20	43352+(-402.5)	42949
	25	43352+(-410)	42942
p8	0	43352+(-960)	42392
	5	43352+(-737.5)	42614
	10	43352+(-625)	42727
	15	43352+(-593)	42759
	20	43352+(-577.5)	42774
	25	43352+(-545)	42807

Kiln no.2

positions	Distance (cm)		nT
p1	0	43352+1320	44672
	5	43352+450	43802
	10	43352+205	43557
	15	43352+132.5	43484
	20	43352+105	43357
	25	43352+120	43472
p2	0	43352+(-820)	42532
	5	43352+(-655)	42697
	10	43352+(-530)	42822
	15	43352+(-390)	42962
	20	43352+(-382.5)	42969
	25	43352+(-340)	43012
p3	0	43352+(-1115)	42237
	5	43352+(-785)	42567
	10	43352+(-700)	42652
	15	43352+(-680)	42672
	20	43352+(-677.5)	42675
	25	43352+(-740)	42612
p4	0	43352+(-682.5)	42669
	5	43352+(-620)	42732
	10	43352+(-575)	42777
	15	43352+(-530)	42822
	20	43352+500	43852
	25	43352+540	43892

Results

Magnetic Susceptibility (3-axis fluxgate magnetometer)

Kiln no.1

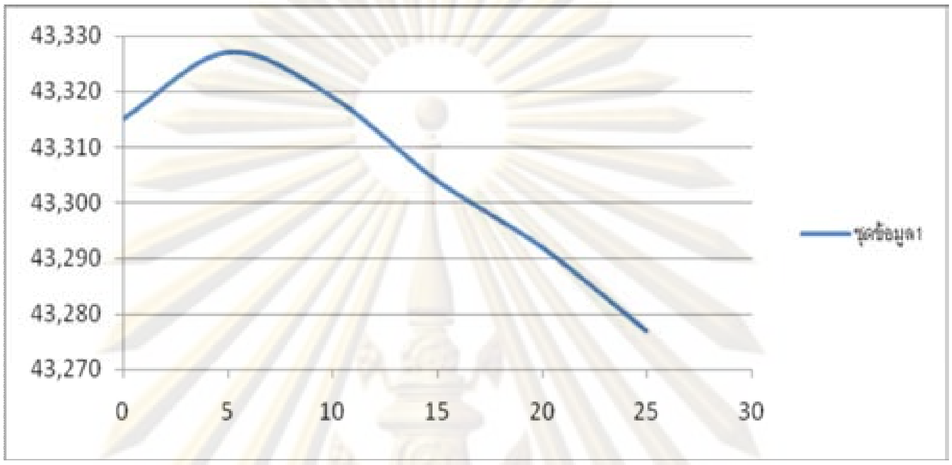

Figure 23 Fluxgate magnetometer investigation at kiln no.1, position 1

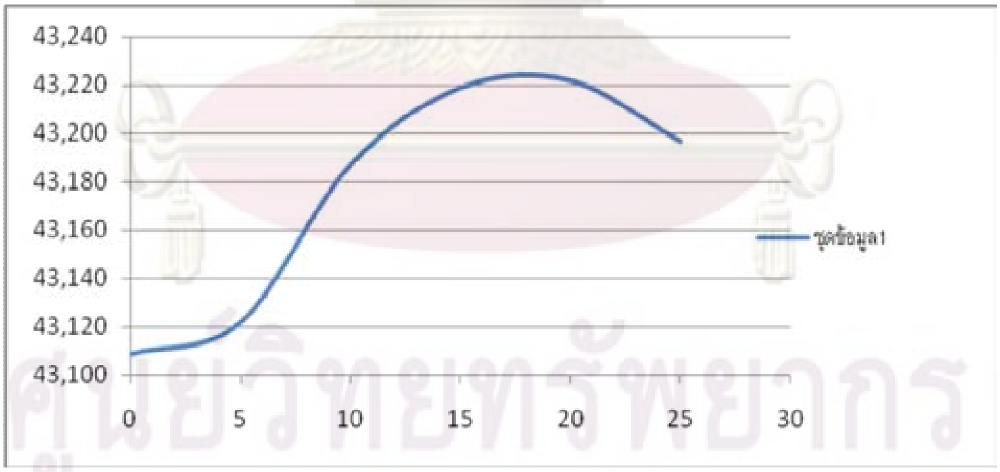

Figure 24 Fluxgate magnetometer investigation at kiln no.1, position 2

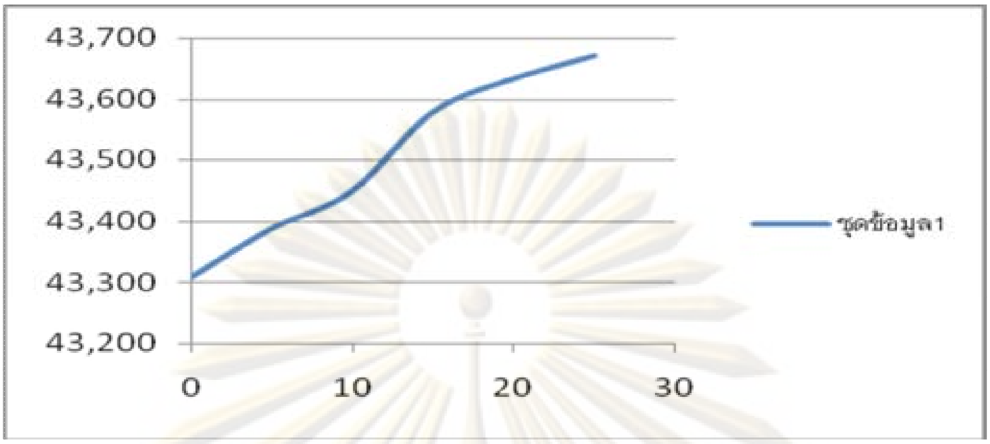

Figure 25 Fluxgate magnetometer investigation at kiln no.1, position 3

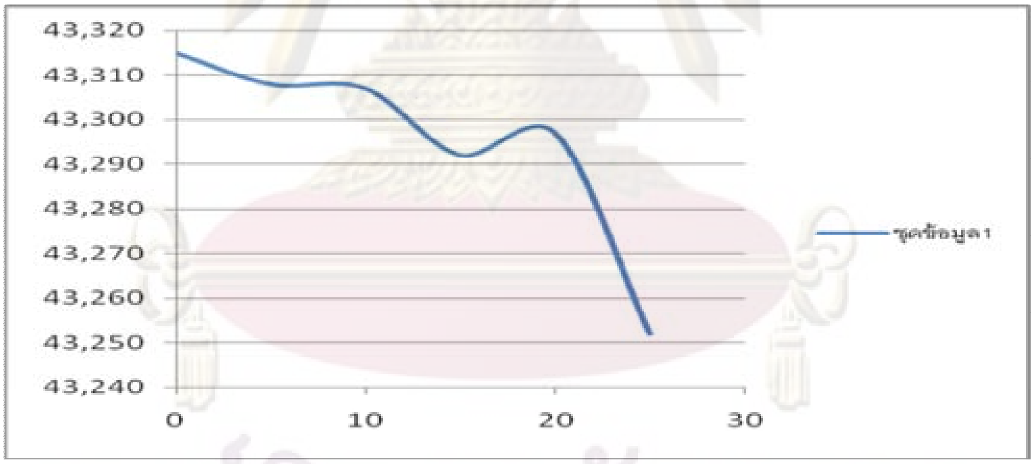

Figure 26 Fluxgate magnetometer investigation at kiln no.1, position 4

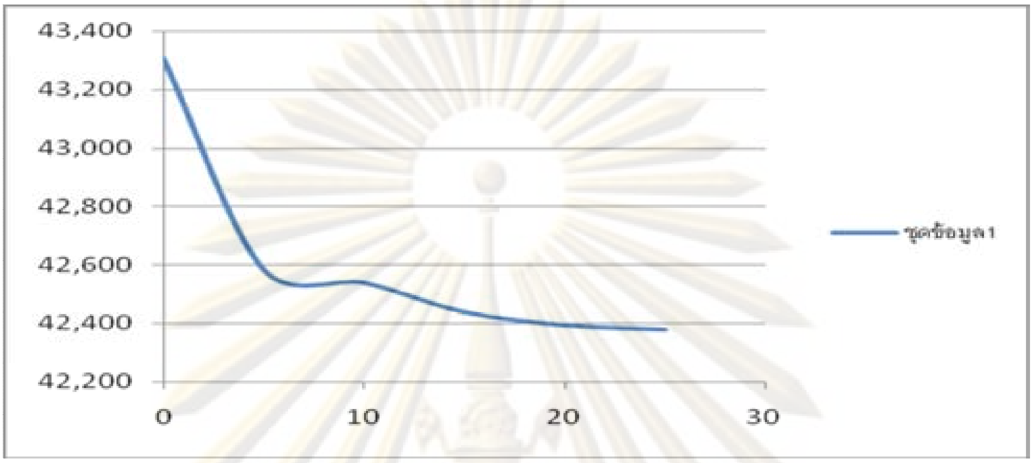

Figure 27 Fluxgate magnetometer investigation at kiln no.1, position 5

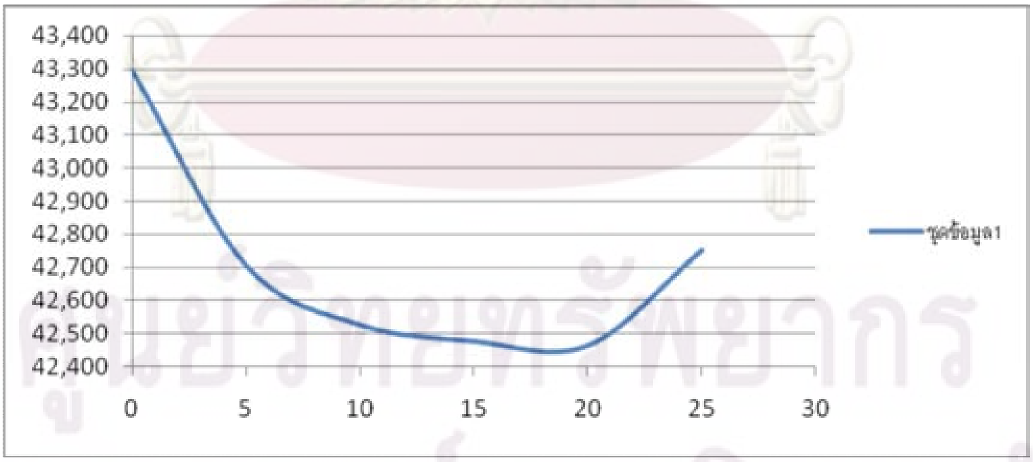

Figure 28 Fluxgate magnetometer investigation at kiln no.1, position 6

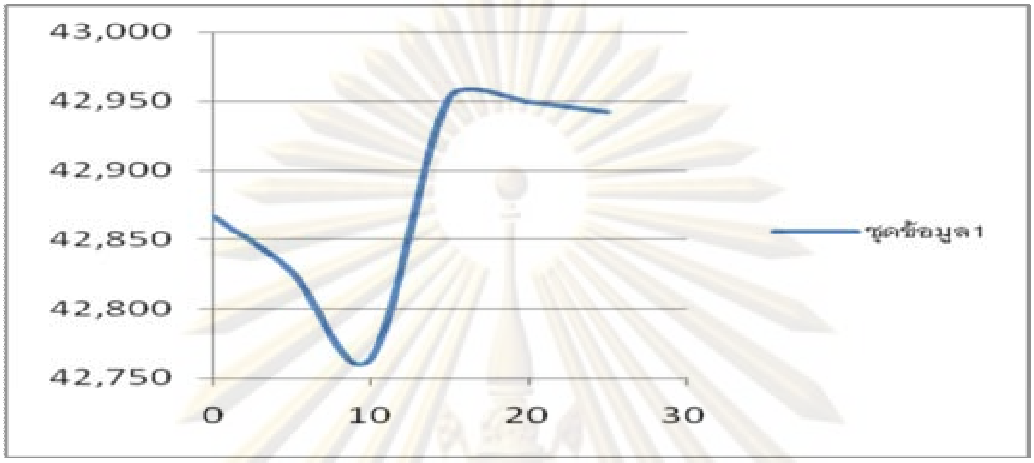

Figure 29 Fluxgate magnetometer investigation at kiln no.1, position 7

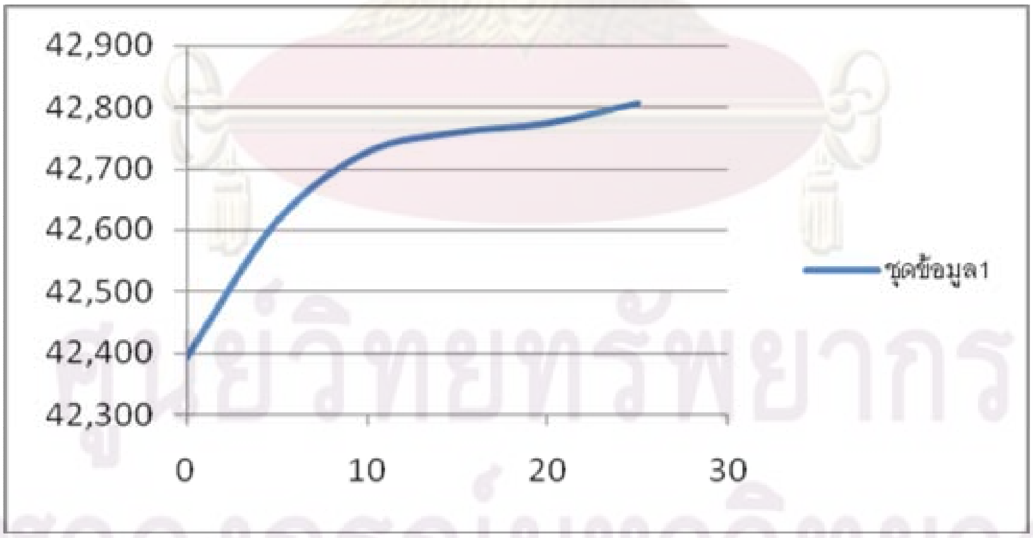

Figure 30 Fluxgate magnetometer investigation at kiln no.1, position 8

It can be seen from Figure 23-30 (see also Fig.21) that, there are two groups of magnetic trend in the kiln no.1. The first group consisting of P1, P4, P5 and P6, the magnetic susceptibility decreases when a fluxgate magnetometer moves away from the kiln wall (see Fig. 23-30). Their magnetic intensity decrease from 43,320 nT to 43,280 nT, 43,310 to 43,250 nT, 43,400 nT to 42,400 nT and 43,300 nT to 42,500 nT, respectively.

On the contrary, the second group consisting of P2, P3, P7 and P8, their magnetic susceptibility increase when a fluxgate magnetometer moves away from the kiln wall. Their magnetic intensity increase from 43,100 nT to 43,220 nT, 43,300 nT to 43,700 nT, 42,750 nT to 42,950 nT and 42,400 nT to 42,800 nT, respectively (see also Fig 31-34)

The result shows that magnetic susceptibility along the chimney wall of the kiln no.1 is regular.

Kiln no. 2

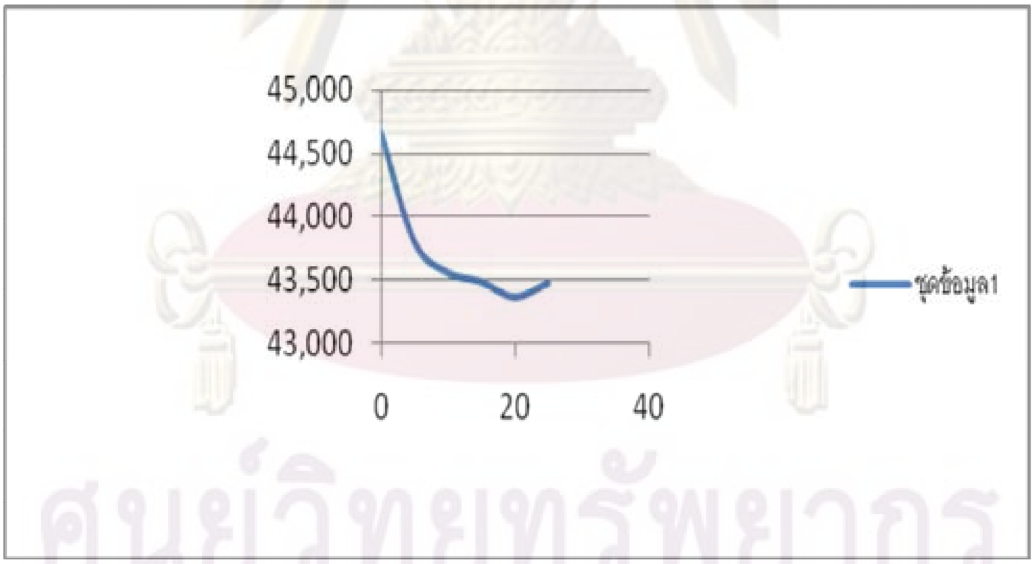

Figure 31 Fluxgate magnetometer investigation at kiln no.2, position 1

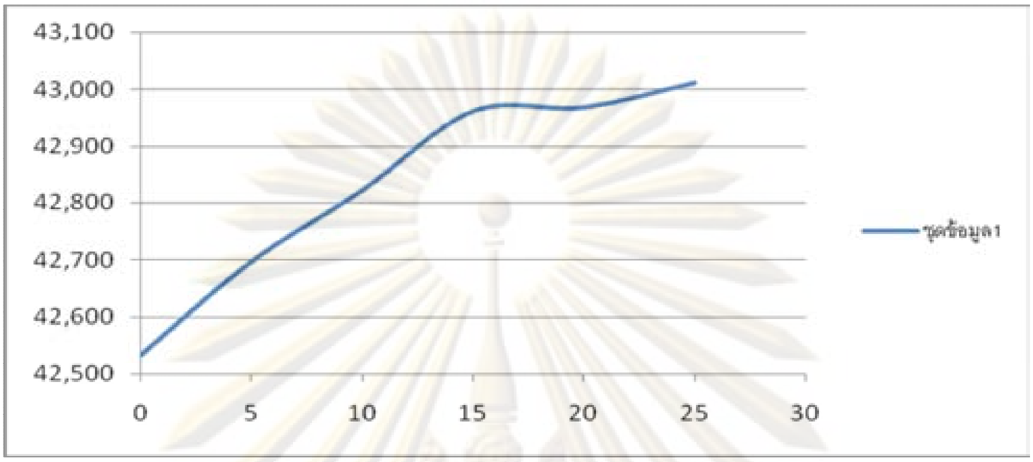

Figure 32 Fluxgate magnetometer investigation at kiln no.2, position 2

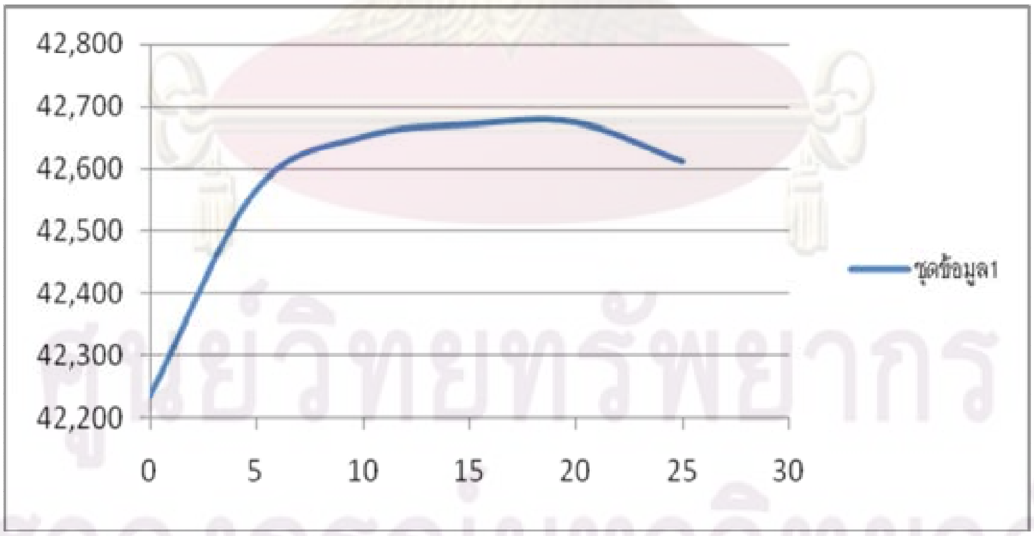

Figure 33 Fluxgate magnetometer investigation at kiln no.2, position 3

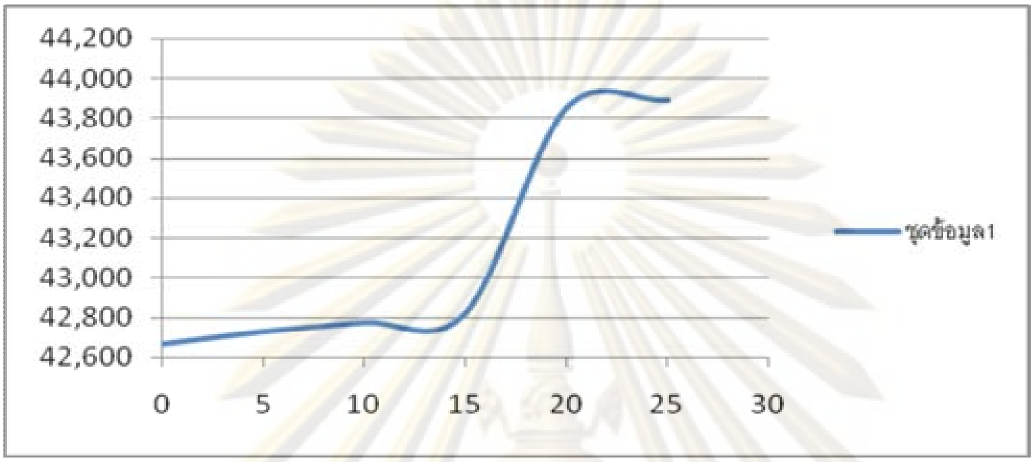

Figure 34 Fluxgate magnetometer investigation at kiln no.2, position 4

In the kiln no.2, four positions i.e. P1, P2, P3, and P4 (see Fig.22) were measured. P4 is located on the chimney where the others are located on the kiln wall. It can be that only location P1 which its magnetic intensity decrease where as the other increase. For P1, magnetic susceptibility decrease from 44,500 nT to 43,500 nT. For those of P2, P3 and P4, their magnetic intensity increase from 42,500 nT to 43,000 nT, 42,200 nT to 42,700 nT and 42,600 nT to 43,800 nT, respectively.

It should be mentioned that the magnetic intensity increase toward the centre of the kiln (firing chamber) (P2, P3 and P4). P1 which its magnetic intensity decreases may indicate the specific location that is the fire box.

Proton magnetometer investigation

Magnetic intensity of both kilns (kiln no.1, and kiln no.2) were also investigated by proton magnetometer. For the kiln no.1, eight locations in the chimney were investigated using all three steps of proton magnetometer. In addition, thirteen locations around the kiln, ten location along the present magnetic north and eleven locations along the west direction were measured using only step two of proton magnetometer. The study locations is shown in Figure 35.

For the kiln no.2, only twenty-one locations inside the kiln were measured using step two of proton magnetometer (see figure 36).

The results of proton magnetometer investigation of kiln no.1 inside the kiln, around the kiln, north-south direction and east-west direction are shown in table 4, 5, 6 and 7, respectively. They can be demonstrated clearly in Figure 37-39, 40, 41 and 42, respectively.

Moreover, the magnetic intensity in kiln no.2 that was shown in table 8 can be illustrated in Figure 43.

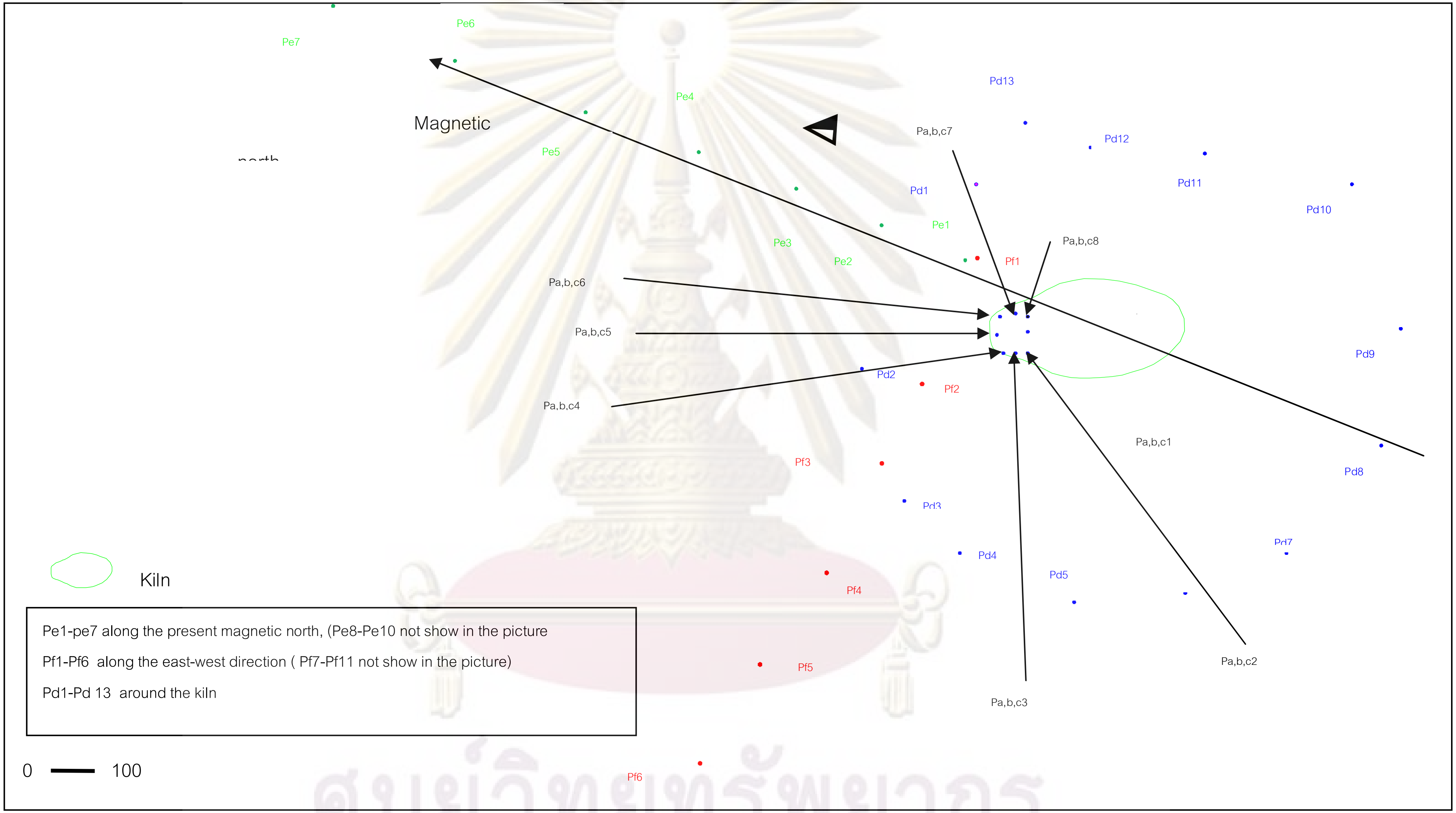

Figure 35 The positions in kiln no.1 measuring by proton magnetometer

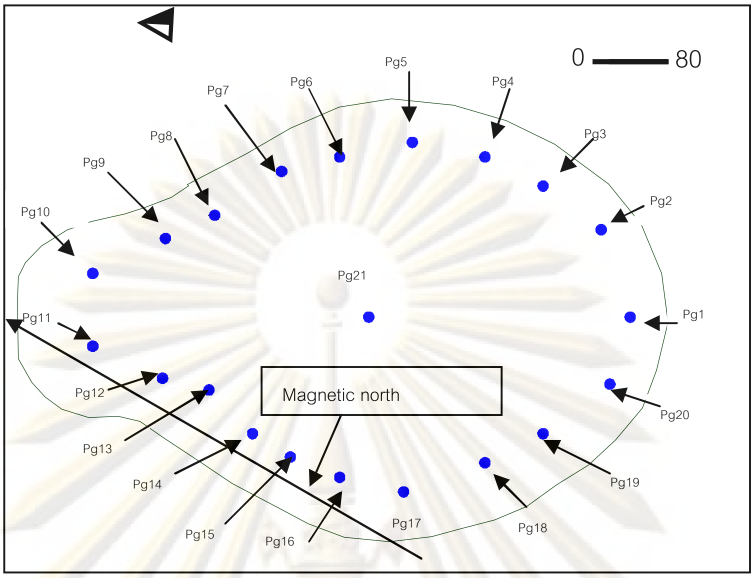

Figure 36 The positions in kiln no.2 measuring by proton magnetometer

Table 4

Proton magnetometer data inside the kiln no.1: a – step two, b – step one and c – step three

Table 4a step two

kiln no.1

positions		x	y	Z(nT)
pa1	325.5-43352	8	6	43026
pa2	359.5-43352	5	6	42992
pa3	321-43352	5.5	4.5	43031
pa4	333-43352	6.5	3.7	43019
pa5	390-43352	8	3.5	42962
pa6	379-43352	9.6	3.8	42973
pa7	370.5-43352	10.5	5	42981
pa8	367-43352	11	6	42985

Table 4b step one

pb1	295.5-43352	8	6	43056
pb2	300-43352	5	6	43052
pb3	256-43352	5.5	4.5	43096
pb4	327.5-43352	6.5	3.7	43024
pb5	352.5-43352	8	3.5	42999
pb6		9.6	3.8	
pb7	303-43352	10.5	5	43049
pb8	308.5-43352	11	6	43043

Table 4c step three

pc1	359.5-43352	8	6	42992
pc2	384-43352	5	6	42968
pc3	377.5-43352	5.5	4.5	42974
pc4	393-43352	6.5	3.7	42959
pc5	394.5-43352	8	3.5	42957
pc6	369-43352	9.6	3.8	42983
pc7	364.5-43352	10.5	5	42987
pc8	377.5-43352	11	6	42974

Table 5 Proton magnetometer data around the kiln no.1

pd1	463.5-43352	14	7.5	42888
Pd2	390-43352	8	4	42962
Pd3	424.5-43352	3.7	5.3	42972
Pd4	581-43352	2	7	42771
Pd5	658.5-43352	0.4	10.5	42693
Pd6	561.5-43352	0.7	13.9	42790
Pd7	513.5-43352	2	17	42838

Pd8	504-43352	5.5	19.9	42848
Pd9	489.5-43352	9.3	20.5	42862
pd10	428-43352	14	19	42924
Pd11	397-43352	15	14.5	42955
Pd12	422-43352	15.2	11	42930
Pd13	420-43352	16	9	42932

Table 6 Proton magnetometer data along north-south direction of kiln no.1

pe1	338.5-43352	4.9	22	43013
pe2	458.5-43352	6.7	19.5	42893
pe3	492-43352	8.3	17	42860
pe4	494-43352	9.8	14.5	42858
pe5	481-43352	11	12	42871
pe6	500.5-43352	12.8	9.5	42851
pe7	495-43352	14.2	7	42857
pe8	509-43352	15.6	4.5	42843
pe9	432.5-43352	16.7	2	42919
pe10	488.5-43352	17.7	0	42853

Table 7 Proton magnetometer data along east-west direction of the kiln no.1

pf1	522-43352	12.5	26	43030
pf2	542.5-43352	10.7	23.5	42809
pf3	516.5-43352	9.7	21	42835
pf4	485-43352	8.8	18.5	42867
pf5	471.5-43352	7.7	16	42880
pf6	470-43352	6.6	13.5	42882
pf7	472.5-43352	5.5	11	42879

pf8	467.5-43352	4.2	8.5	42884
pf9	469-43352	2.9	6	42883
pf10	465-43352	1.7	3.5	42887
pf11	467.5-43352	0.1	0.9	42884

Table 8 Proton magnetometer data of the kiln no.2

kiln no.2

positions		x	y	Z(nT)
pg1	522.5-43352	8	24	42829
pg2	557.5-43352	11	23	42794
pg3	490.5-43352	12.5	21	42861
pg4	410-43352	13.5	19	42942
pg5	365-43352	14	16.5	42987
pg6	433.5-43352	13.5	14	42918
pg7	436-43352	13	12	42916
pg8	525-43352	11.5	9.7	42827
pg9	498.5-43352	10.7	8	42853
pg10	502.5-43352	9.5	5.5	42849
pg11	468.5-43352	7	5.5	42883
pg12	451-43352	5.9	7.9	42901
pg13	466.5-43352	5.5	9.5	42885
pg14	450-43352	4	11	42902
pg15	483.5-43352	3.2	12.3	42868
pg16	477-43352	2.5	14	42875
pg17	370.5-43352	2	16.2	42981
pg18	375.5-43352	3	19	42976
pg19	384.5-43352	4	21	42967
pg20	540-43352	5.7	23.3	42812
pg21	428.5-43352	8	15	42923

Strength or intensity of magnetic field (Proton magnetometer)

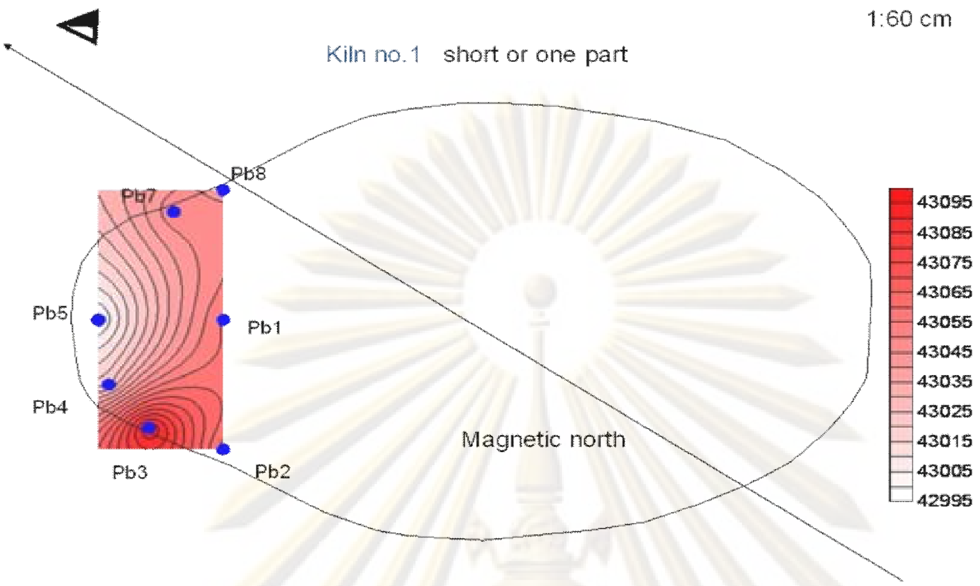

Figure 37 The contour map of magnetic susceptibility or magnetic intensity measuring by proton magnetometer using one part or first level.

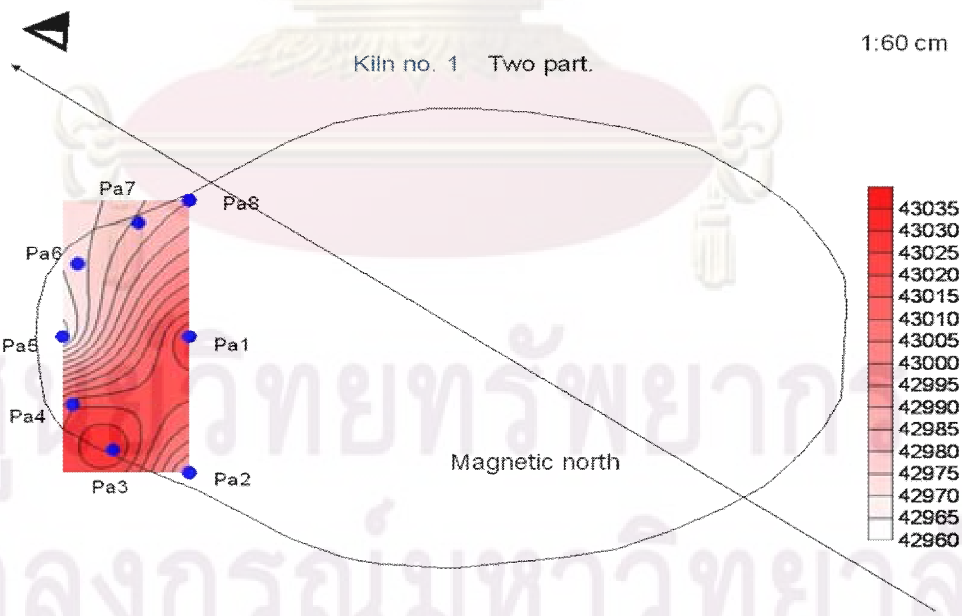

Figure 38 The contour map of magnetic susceptibility or magnetic intensity measuring by proton magnetometer using two part or second level.

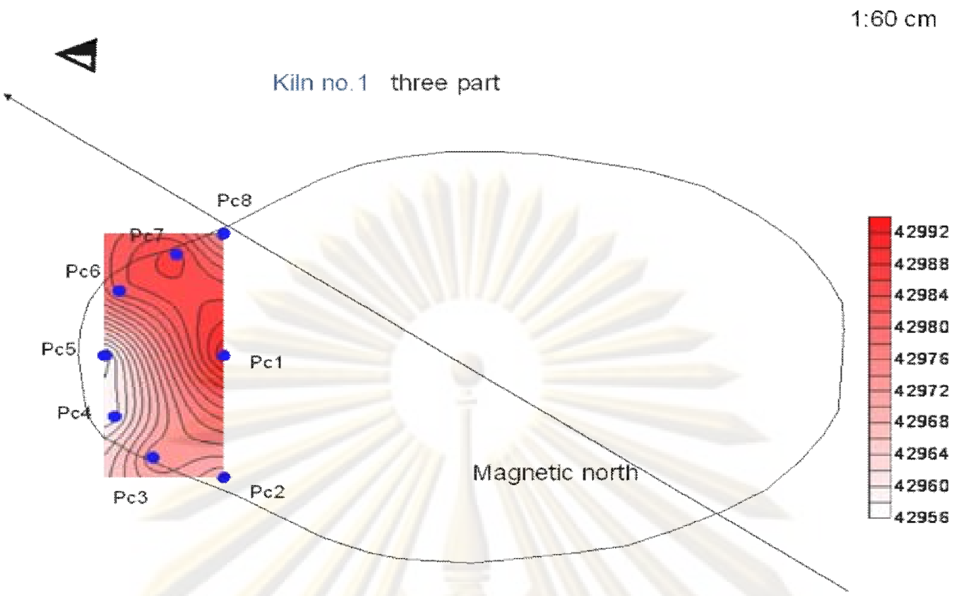

Figure 39 The contour map of magnetic susceptibility or magnetic intensity measuring by proton magnetometer using three part or third level.

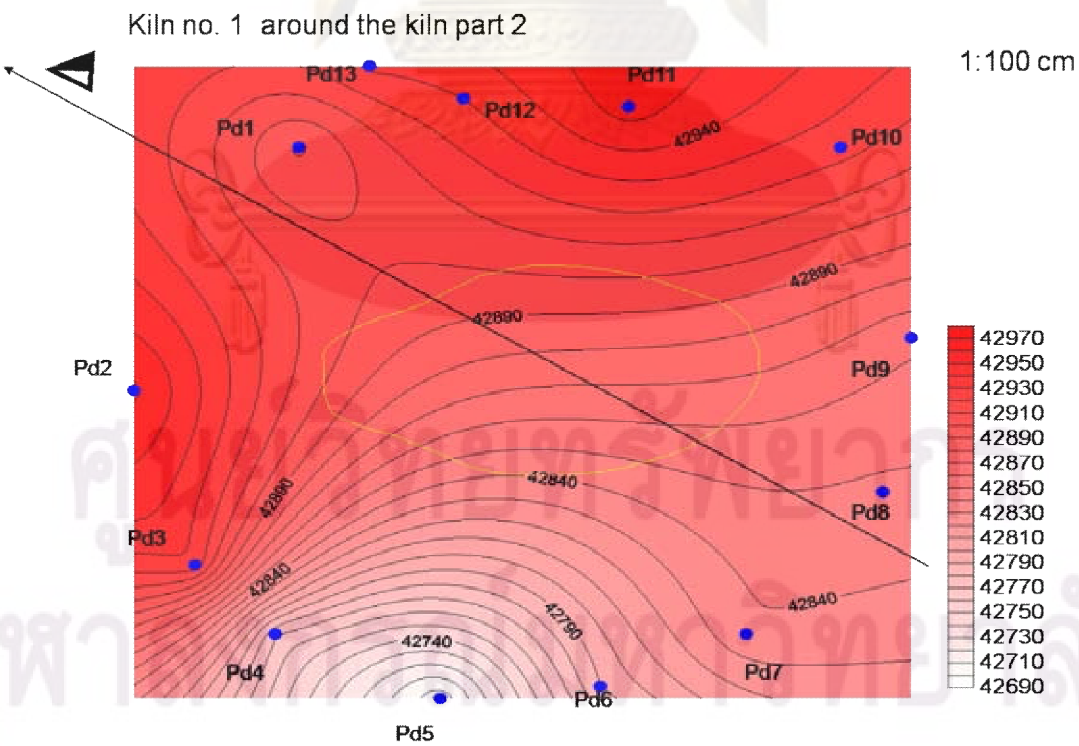

Figure 40 The contour map of magnetic intensity around the kiln no.1

Kiln no. 1 north-south to extend the magnetic north

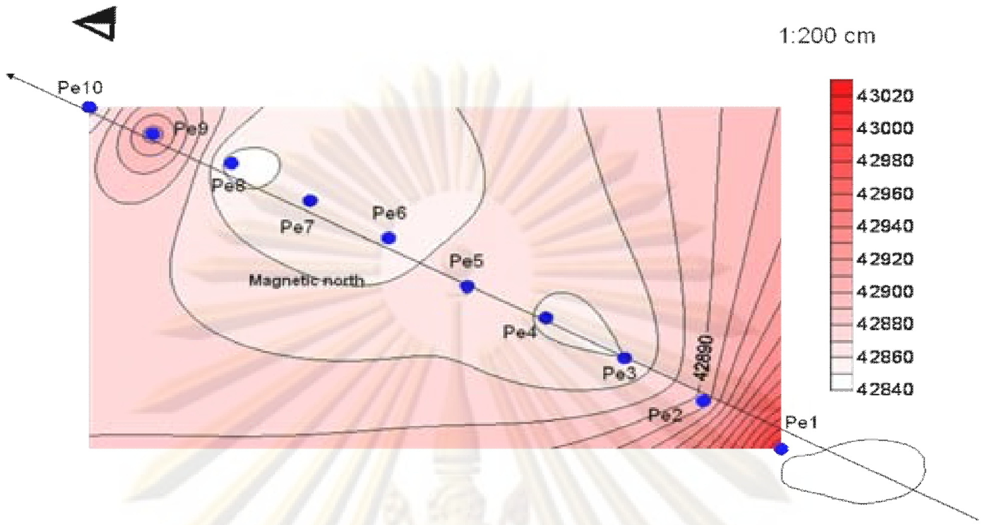

Figure 41 The contour map of magnetic intensity aligned the magnetic north present

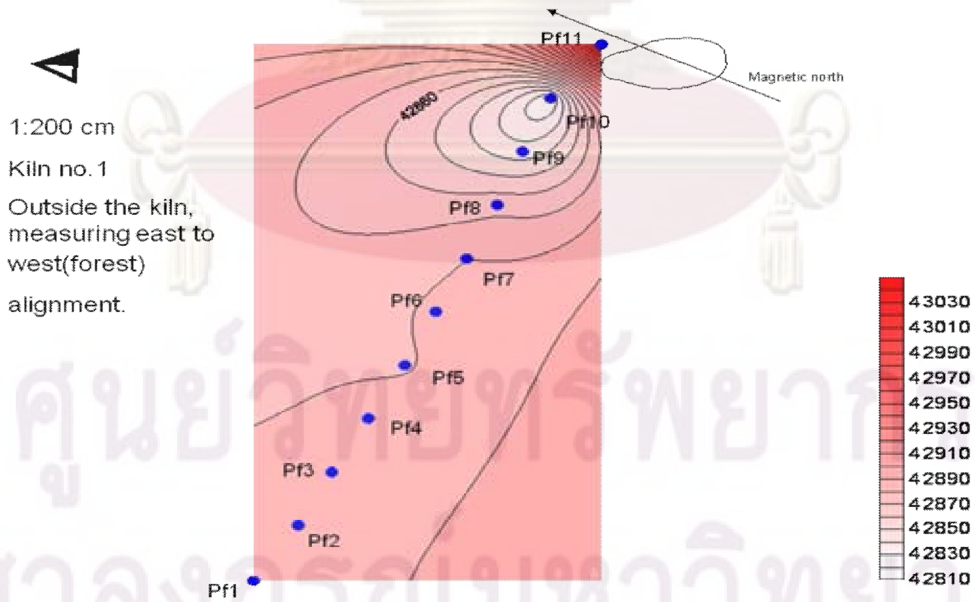

Figure 42 The contour map of magnetic intensity aligned east-west or right the angle of the magnetic north present

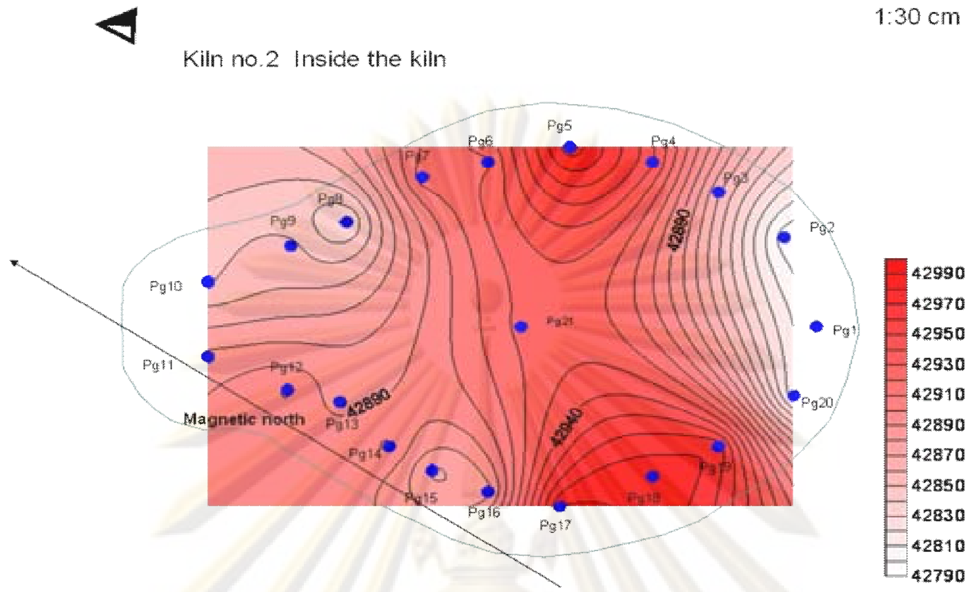

Figure 43 The contour map of magnetic intensity inside the kiln no.2

Proton magnetometer investigation inside the kiln no.1 uses all three steps of the magnetometer in order to study the general phenomena of the total magnetic intensity within the kiln. Accordingly, the other areas were measured using step two of magnetometer. It can be seen from Figure 37 that the highest magnetic intensity i.e. 43,095 nT occurs in the west of the chimney. At step two of the magnetometer (see Fig.38), there are two points of high magnetic intensity. Figure 39 which is step three shows that the highest magnetic intensity moves to the east of the chimney.

It can be seen that (see Fig.40) outside the kiln no.1, Pd3 (on the west) has highest magnetic intensity up to 24,972 nT. Consequently, area east (Pd11) and northeast (Pd1), also show positive anomaly. In addition, Pd5 which is on the west show strong negative anomaly (42,693 nT).

Figure 41 and Figure 42 which show the magnetic intensity along north-south and east-west indicate that the highest magnetic intensity located next to the kiln and the negative magnetic anomaly located just to the north and the west, respectively.

The kiln no.2, proton magnetometer investigation was carried out the whole area inside the kiln. Because, the kiln no.2 is still in perfect body while, the kiln no.1 consist only of the chimney. Figure 43 shows that two positive anomalies occur on the west and east of the kiln where as two negative anomalies occur on the north and south.

Vector magnetic gradiometer investigation

A prototype of vector magnetic gradiometer was used to investigate the magnetic gradient with in the kiln no.1. Altogether, thirteen locations were carried out. Due to a huge numbers of data, the data observed is shown in attached CD. However, some data was selected and shown as an example in table 9.

The data are better demonstrated in Figure 44, 45, 46, 47 and 48. The results show that there is mis-alignment about 4 degrees and offset about 100-200 nT.

Table 9 Conversion file of vector magnetometer

The X and Y values are the axis direction of X and Y parameters and Z is a vertical direction values. B is present magnetic field values.

Hour	minutes	second	order				X	Y	Z	B	
10	43	11	1	38591	15	1062.3	-40026.3	-39224	11064.2	1023.2	-285.7
10	43	11.1	2	38591.1	15	1062.9	-40026.2	-39223.3	11064.3	1023.7	-285.9
10	43	11.2	3	38591.2	15	1062.4	-40025.8	-39223.4	11064.4	1023.3	-285.7
10	43	11.3	4	38591.3	15	1061.8	-40025.6	-39223.8	11064.3	1022.7	-285.6
10	43	11.4	5	38591.4	15	1062.7	-40026.1	-39223.4	11064.2	1023.5	-285.8
10	43	11.5	6	38591.5	15	1062.5	-40025.8	-39223.3	11064.5	1023.4	-285.8
10	43	11.6	7	38591.6	15	1062.3	-40025.9	-39223.6	11064.4	1023.2	-285.7
10	43	11.7	8	38591.7	15	1062.5	-40026.4	-39223.9	11064.2	1023.4	-285.7
10	43	11.8	9	38591.8	15	1062.6	-40026	-39223.4	11064.4	1023.4	-285.8
10	43	11.9	10	38591.9	15	1061.9	-40025.4	-39223.5	11064.4	1022.8	-285.6
10	43	12	11	38592	15	1062.2	-40025.6	-39223.4	11064.3	1023.1	-285.7
10	43	12.1	12	38592.1	15	1062.6	-40026.2	-39223.6	11064.2	1023.5	-285.8
10	43	12.2	13	38592.2	15	1062	-40025.4	-39223.4	11064.6	1022.9	-285.6
10	43	12.3	14	38592.3	15	1062.1	-40025.7	-39223.6	11064.4	1023	-285.6
10	43	12.4	15	38592.4	15	1062.7	-40026.5	-39223.8	11064.4	1023.5	-285.8
10	43	12.5	16	38592.5	15	1062.2	-40025.8	-39223.6	11064.6	1023.1	-285.7
10	43	12.6	17	38592.6	15	1062.3	-40025.5	-39223.2	11064.9	1023.2	-285.7
10	43	12.7	18	38592.7	15	1062.5	-40026.2	-39223.7	11064.5	1023.4	-285.8
10	43	12.8	19	38592.8	15	1062.7	-40026.2	-39223.5	11064.5	1023.5	-285.8
10	43	12.9	20	38592.9	15	1062.4	-40025.5	-39223.1	11064.5	1023.3	-285.7
10	43	13	21	38593	15	1062.1	-40025.8	-39223.7	11064.5	1023	-285.6
10	43	13.1	22	38593.1	15	1062.2	-40026.3	-39224.1	11064.5	1023.1	-285.7

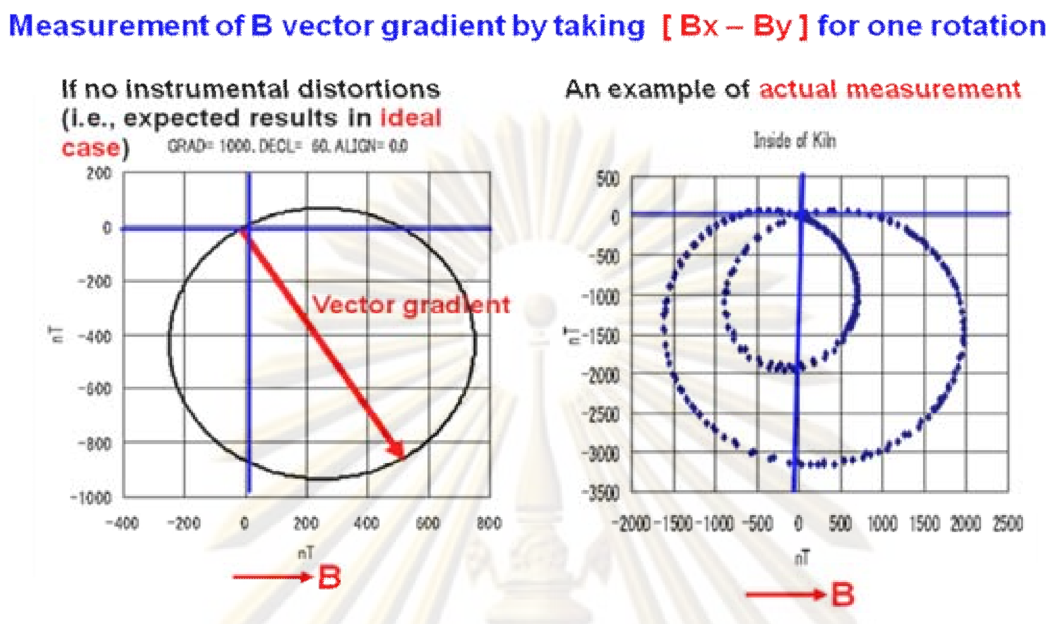

Figure 44 Measurement of B vector gradient of magnetic field (Theory)

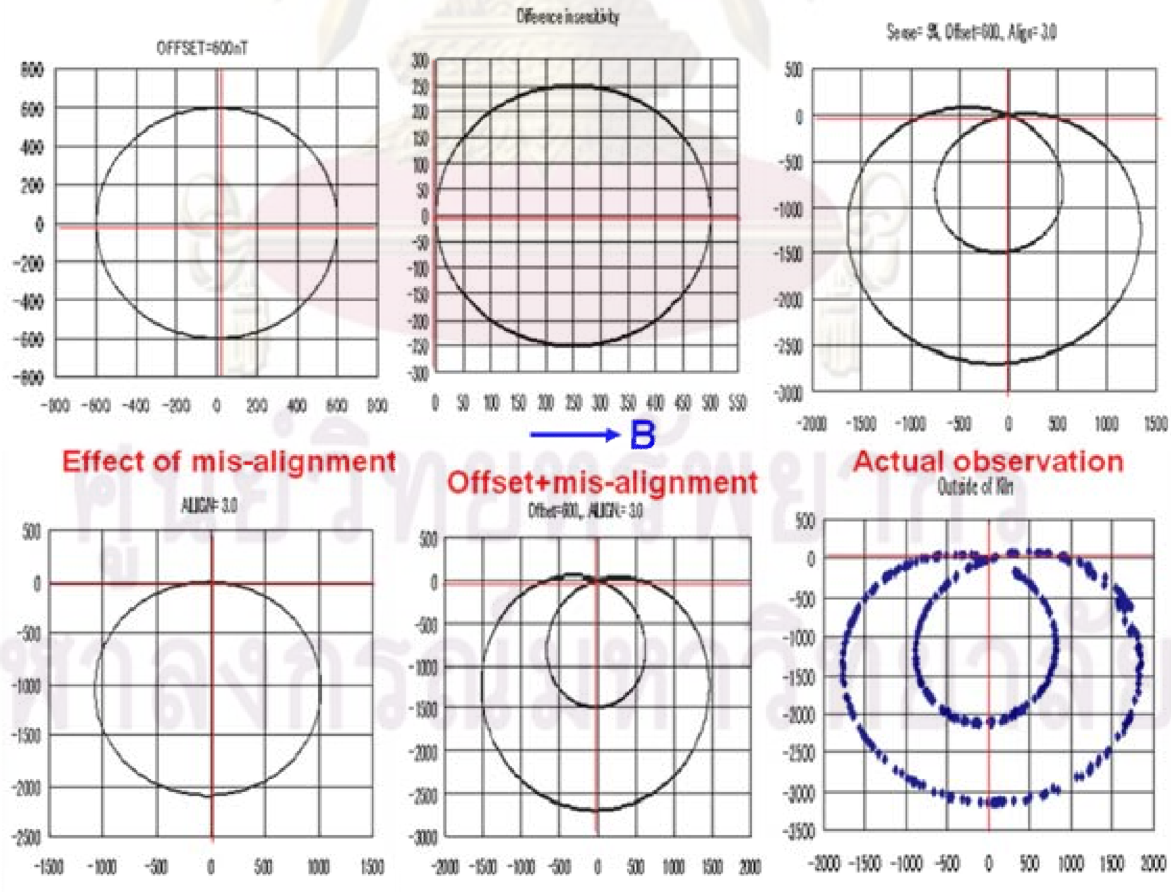

Figure 45 Actual measurement of B vector gradient of magnetic field

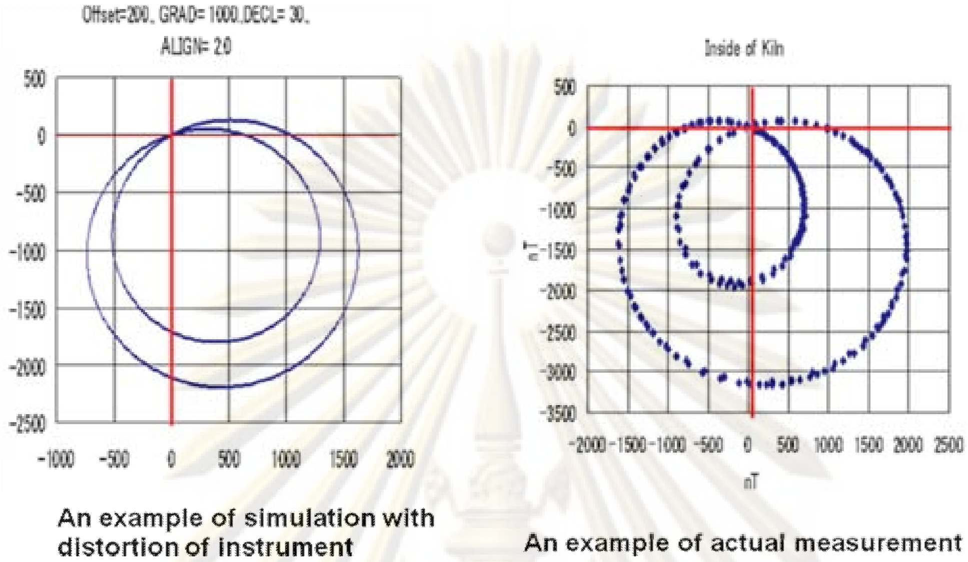

Figure 46 Actual measurement with distortion of instrument

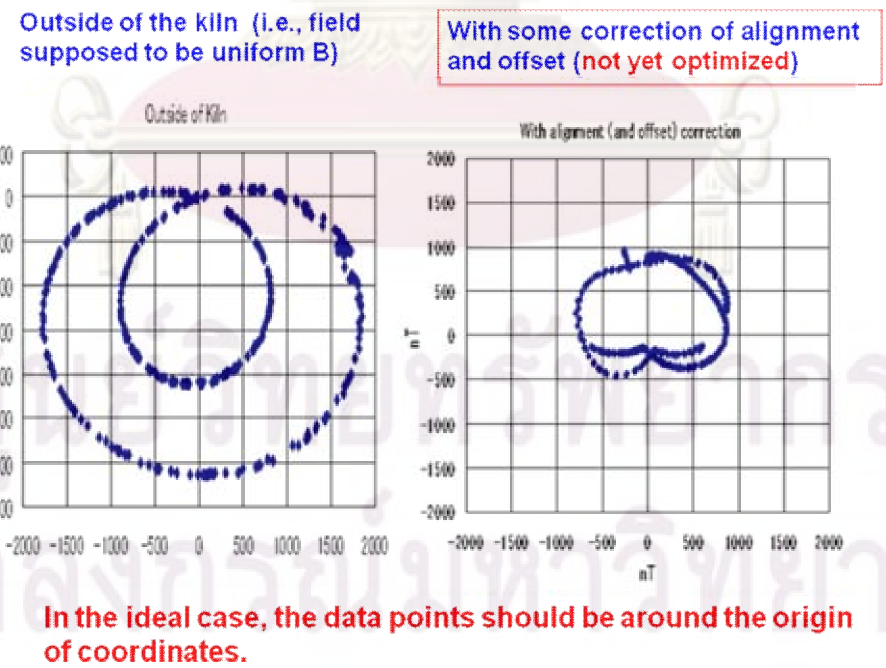

Figure 47 Measurement with some correction is not yet optimized

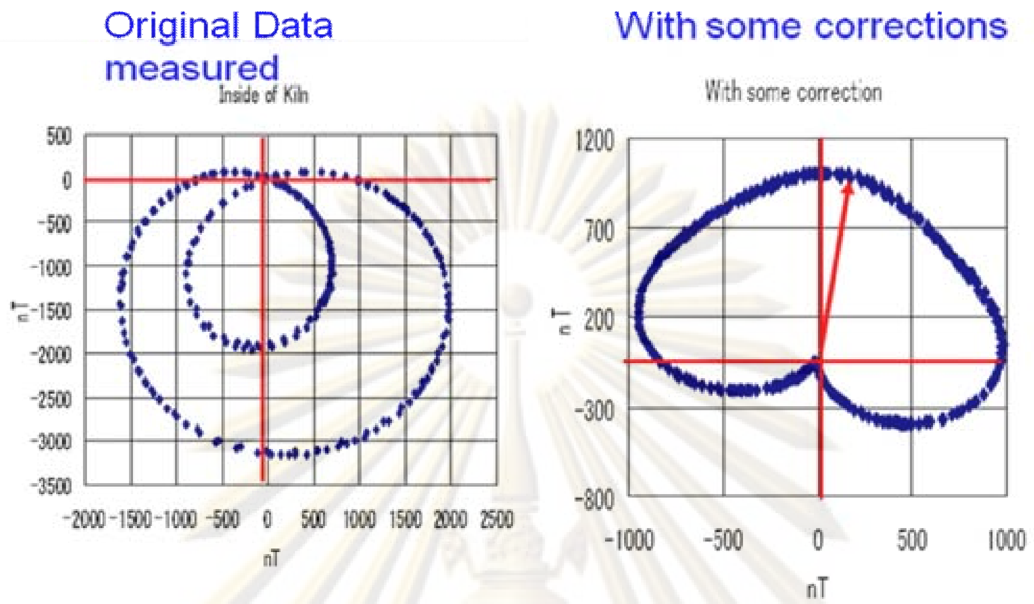

Figure 48 Final, actual measurement with some correction

Conclusion and discussions

1. Sri Satchanalai ancient kilns were selected for this study.

2. The study was carried out according to hypothesis that the Khmer temple was deviated from the present north due to the geomagnetic pole.

3. Fluxgate and Proton magnetometers were employed in order to find out the magnetic intensities and characteristics of the ancient kilns.

4. Vector magnetic gradiometer was invented in order to measure the magnetic vector without damaging the ancient materials.

5. The results show that the data from prototype magnetic gradiometer had mis-alignment about 4 degrees and offset about 100-200 nT.

6. Therefore more precise measurement by adding a mechanism to adjust the alignment and by making a software for optimization of correction to the data are needed

7. The age of Sri Satchanalai kilns obtained from radiocarbon and thermoluminescence is about 13th-16th century.

8. If the Palaeomagnetism for archaeological material has to establish, several archaeological data measuring by the precise magnetic gradiometer are needed in order to set up palaeomagnetic references.

9. On the contrary, the construction of the Khmer temple may rely on astrological north instead of using a compass.

10. The direction of the khmer temples in Thailand may lie on the direction towards the Angkor Wat (Mr. Srisuchat, personal communication).

11. The deviation of temple may be caused by neotectonism (Charusiri, personal communication).

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BIOGRAPHY

I was born at Sukhothai province in 6^{th} Octobre 1982. I graduated from the primary education in Watchohasuwan and high school from Sukhothaiwittayakom school at Sukhothai. Then, I studied and graduated from Department of Archaeology, Faculty of Archaeology, Silpakorn University. I started to learned the Earth Sciences programme, Chulalongkorn University since 2006. I have a many good experiences from this place. I like to study about archaeology, anthropology and geology. In the future, I will to be a good archaeological teacher for give the knowledge for general people and student. I would like to thank my parent, my teacher and my friends again for support which budget, knowledge and give will power for me.