# การหาอายุตะกอนยุคควอเทอร์นารีด้วยวิธีเปล่งแสงความร้อนชนิดโททัลบลีชและรีเจเนอเรชัน

นายสันติ ภัยหลบลี้



วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต

สาขาวิชาโลกศาสตร์ ภาควิชาธรณีวิทยา

คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

ปีการศึกษา 2547

ISBN 974-17-6714-5

# THERMOLUMINESCENCE DATING OF QUATERNARY SEDIMENTS USING TOTAL BLEACH AND REGENERATION METHODS

Mr. Santi Pailoplee



A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Earth Sciences
Department of Geology
Faculty of Science
Chulalongkorn University
Academic Year 2004
ISBN 974-17-6714-5

| | |
|---|---|
| Thesis Title | Thermoluminescence dating of Quaternary sediments using total bleach and regeneration methods |
| By | Mr. Santi Pailoplee |
| Field of Study | Geology |
| Thesis Advisor | Associate Professor Punya Charusiri, Ph.D. |
| Thesis Co-advisor | Professor Isao Takashima, Ph.D. |

---

Accepted by the Faculty of Science, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

..............................................Deputy Dean for Administrative Affairs.
Acting Dean, The Faculty of Science
(Associate Professor Tharapong Vitidsant, Ph.D.)

THESIS COMMITTEE

..............................................Chairman
(Assistant Professor Veerote Daorerk, M. SC.)

..............................................Thesis Advisor
(Associate Professor Punya Charusiri, Ph.D.)

..............................................Thesis Co-advisor
(Professor Isao Takashima, Ph.D.)

..............................................Member
(Assistant Professor Chakkaphan Sutthirat, Ph.D.)

..............................................Member
(Krit Won-in, Ph.D.)

สันติ ภัยหลบลี้ : การหาอายุตะกอนยุคควอเทอร์นารีด้วยวิธีเปล่งแสงความร้อนชนิดโททัลบลีชและรีเจเนอเรชัน. (THERMOLUMINESCENCE DATING OF QUATERNARY SEDIMENTS USING TOTAL BLEACH AND REGENERATION METHODS) อ. ที่ปรึกษา : รศ. ดร. ปัญญา จารุศิริ, อาจารย์ที่ปรึกษาร่วม : ศ. อิซาโอะ ทาคาชิมา 179 หน้า. ISBN 974-17-6714-5.

การหาอายุตะกอนด้วยวิธีเปล่งแสงความร้อนและการหาอายุด้วยวิธีคาร์บอน-14 ได้นำมาประยุกต์ใช้ในการกำหนดอายุตะกอนยุคควอเทอร์นารีในบริเวณพื้นที่ศึกษา 2 แห่ง คือ 1) ร่องสำรวจแผ่นดินไหวบ้านบอมหลวง ภาคเหนือของประเทศไทย และ 2) แหล่งโบราณคดีบ้านทุ่งตึก, ภาคใต้ของประเทศไทย ทั้งสองพื้นที่ศึกษานี้มีศักยภาพที่สามารถกำหนดอายุได้ด้วยวิธีเปล่งแสงความร้อนจากตัวอย่างตะกอนและวิธีคาร์บอน-14 จากตัวอย่างอินทรียวัตถุ เพื่อเปรียบเทียบกัน

ในกรณีของการหาอายุตะกอนด้วยวิธีเปล่งแสงความร้อน ให้ความสำคัญในด้านเทคนิคการประเมินค่าปริมาณรังสีที่ตัวอย่างตะกอนได้รับจากธาตุกัมมันตภาพรังสี (เช่น ยูเรเนียม, ทอเรียม และโปแตสเซียม) ตั้งแต่ตะกอนสะสมตัวครั้งสุดท้าย เทคนิคที่ใช้ในการวิจัยประกอบด้วย 2 เทคนิค คือ ชนิดโททัลบลีชและรีเจเนอเรชัน โดยค่าอายุตะกอนที่กำหนดได้จากทั้งสองเทคนิคนั้น นำมาเปรียบเทียบกับค่าอายุที่ได้จากการหาอายุด้วยวิธีคาร์บอน-14

ผลจากการวิจัยบ่งชี้ว่าปริมาณรังสีที่มีอยู่ในตัวอย่างตะกอนให้ค่าแตกต่างกันในแต่ละเทคนิค โดยที่ค่าอายุที่ได้จากการกำหนดอายุด้วยเทคนิครีเจเนอเรชัน มีความสอดคล้องกับค่าอายุที่กำหนดได้จากวิธีคาร์บอน-14 มากกว่าค่าอายุที่ได้จากการกำหนดอายุด้วยเทคนิคโททัลบลีช ซึ่งเป็นผลมาจากปรากฏการณ์ supralinear, superlinear และ saturation ของสัญญาณในตัวอย่างระหว่างการอาบรังสี

นอกจากการเปรียบเทียบค่าอายุที่ได้จากวิธีเปล่งแสงความร้อน และวิธีคาร์บอน-14 ในพื้นที่ศึกษาแล้ว ผู้วิจัยได้รวบรวมข้อมูลการเปรียบเทียบค่าอายุที่ได้จากวิธีเปล่งแสงความร้อนและค่าอายุอื่นๆ ที่ผู้วิจัยก่อนๆ ได้ทำการวิจัยไว้ในประเทศไทย และประมวลผลเปรียบเทียบกันทั้งหมด จากการประมวลผลพบว่า อายุที่กำหนดได้จากวิธีเปล่งแสงความร้อน และวิธีคาร์บอน-14 ให้ค่าอายุที่ใกล้เคียงกันโดยแสดงผลจากค่าการถดถอยเชิงเส้น เท่ากับ 0.992 แต่อีกนัยหนึ่ง การกำหนดอายุด้วยวิธีเปล่งแสงความร้อนมีข้อดีมากกว่าการกำหนดอายุด้วยวิธีคาร์บอน-14 ในข้อจำกัดของช่วงอายุที่แต่ละวิธีนั้นสามารถกำหนดได้ โดยที่การหาอายุด้วยวิธีคาร์บอน-14 มีประสิทธิภาพเพียงช่วงอายุ 0-45,000 ปีในขณะที่วิธีเปล่งแสงความร้อนนั้นสามารถกำหนดอายุได้ถึง 2 ล้านปีในตัวอย่างตะกอน และ 7 แสนปีในตัวอย่างอุลกมณี

ภาควิชา...............ธรณีวิทยา......ลายมือชื่อนิสิต............................

สาขาวิชา...............โลกศาสตร์.......ลายมือชื่ออาจารย์ที่ปรึกษา..................

ปีการศึกษา.............2547..................

# # 457 25279 23: EARTH SCIENCE
KEY WORD : THERMOLUMINESCENCE DATING/ TL/ TOTAL BLEACH/ REGENERATION/ RADIOCARBON DATING/ CALIBRATION.

SANTI PAILOPLEE: THERMOLUMINESCENCE DATING OF QUATERNARY SEDIMENTS USING TOTAL BLEACH AND REGENERATION METHODS. THESIS ADVISOR: ASSOCIATE PROFESSOR PUNYA CHARUSIRI, Ph.D. THESIS COADVISOR: PROFESSOR ISAO TAKASHIMA, Ph.D. 179 pp. ISBN 974-17-6714-5

Thermoluminescence (TL) dating of sediments inconjunction with accelerator-mass-spectrometry (AMS) radiocarbon dating of organic materials have been carried out on Quaternary samples from Ban Bom Luang trench, northern Thailand and Thung Tuk archaeological site, southern Thailand. These two sites permit detailed comparisons of thermoluminescence and radiocarbon chronologies. Both techniques produce self-consistent chronologies for the colluvial deposits (Ban Bom Luang trench) and beach sand deposits with the ancient remain (Thung Tuk archaeological site).

In case of TL dating focuses are placed on problems connected with equivalent dose (ED) estimation. The dated results obtained by using two techniques: regeneration and total bleach techniques were compared with AMS radiocarbon dating. The obtained results show that the ED values are strongly dependent on the applied technique. Most of TL ages obtained by the regeneration technique were confirmed by AMS radiocarbon ages while total bleach technique seems to be discrepancy. The discrepancy dates evaluated by total bleach technique effect from supralinear (underestimation), superlinear (overestimation) and saturation (overestimation).

In order to make the TL-dating results more reliable and accurate, we compared the TL-age dating results with those of the radiocarbon ages and the widely accepted other ages from selected samples of the same sedimentary layers from various places in Thailand. The calibration curve of TL and other dating results displays a good positive correlation with the linear regression of about 0.992. This strongly advocates that our current TL-age dating results are more consistent with that of the AMS radiocarbon dating than that of the conventional radiocarbon dating. Moreover, the TL dating method is more powerful than the AMS radiocarbon dating in a sense that the TL data are well applicable to the fine-grained quartz-rich sediments of up to 2 Ma and tektite samples of about 0.7 Ma.

Department………..Geology….. Student's signature …………………………….

Field of study.……Geology….. Advisor's signature……………………………...

Academic year….2004………

# ACKNOWLEDGEMENT

Great acknowledgement goes to my thesis Advisor, Associate Professor Dr. Punya Charusiri, Department of Geology, Faculty of Science, Chulalongkorn University for his valuable supervision, encouragement. His inspiration on scientific thinking is greatly appreciated. I acknowledge to Professor Isao Takashima –my co-advisor (the Research Institute of Materials and Resources, Akita University, Japan) with sincere thanks for his advice on laboratory experiments on TL dating. Dr. Krit Won-in (Soil Crete Co. Ltd.) for their valuable advises and experiences on thermoluminescnece dating theories and technical knowledge, particularly his valuable consistent helpful and comment both technically and nontechnically. Special recognition and thanks are to Mr. Suwith Kosuwan, Mr. Preecha Saithong and staff members from the Geological Survey Division, Department of Mineral Resources (DMR) for field assistance investigation and sampling experience.

During the fieldwork, specials acknowledgements and thanks go to an army captain Boonyarit Chaisuwan and the director of 15th Regional Office of Fine Arts, Phuket province, Thailand for their welcome, and facilities during my time in Thung Tuk archaeological site, Phang Nga province. Thanks go to bachelor's degree students of the Department of Geology, Chulalongkorn University for their helping at Ban Bom Luang trehch, Lampang province; without their physical strength, I could not manage collecting all samples.

Also, I wish to acknowledge Mr. Pisarn Tungpitayakul and Mr. Arag Vitittheeranon from Office of Atomic Energy for Peace (OAEP), Thailand for measurement radioactive elements and the section of artificial irradiation.

It is not easy to mention all persons who have contributed to my research study. I, personally, have already expressed my gratitude to everyone that has direct and indirect assistance with this research. Finally, the knowledge that this research is concluded will be sufficient gratification to those I have omitted. I have to thanks my parents for their moral support and encouragement and Miss Teerarat Napradit who invariably help me directly and indirectly.

CONTENTS

Page

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

Page

Page

Page

# CHAPTER I

# INTRODUCTION

## 1.1 Background

Scientific dating method for Quaternary materials includes a variety of relative age dating and absolute age dating for example amino acid racemisation (Miller and Brigham-Grette, 1989; Wehmiller and Miller, 2000), electron spin resonance-ESR (Ikeya, 1993; Grün, 2001), optically stimulated luminescence-OSL (Huntley, Godfrey-Smith, and Thewalt,1985; Aitken,1998), fission track (Wagner and Van den haute,1992; Dumitru, 2000), U-series (Ivanovich and Harmon, 1992; Schwarcz, 1997; Ku, 2000), K/Ar and $^{40}Ar/^{39}Ar$ (McDougall and Harrison, 1999), radiocarbon (Taylor, 1997; Hedges, 2000), dendrochronology (Kuniholm, 2001) and thermoluminescence-TL (Wintle and Huntley, 1982; Aitken, 1985; Takashima and Honda, 1989). When geologists or archaeologists start to work on a given sites. The high quality of information has created an urgent need for chronological data. Normally, the main problem encountered when trying to determine the age of a site or a sample in prehistoric times, there were no written records to document the story of the past. These methods can be used to solve how old a sample is, or how old the sites may be. However, before applying scientific dating methods to a particular site, three more factors have to be considered carefully, they are:

- Material (Table 1.1): which dating method should be used and suitable with the composition of the sample (bone, sediments, shells, organic, etc.).

- Age range (Figure 1.1): given the approximate age of the sample, which method can be used to ascertain a more certain date.

- Errors and uncertainty (Figure 1.2): how about the errors and uncertainty associated with the age estimate.

The dating range and the errors associated with the result are determined by the underlying principles of the method, the detection limits of the measuring equipment and sample pre-treatment techniques (Bird et al., 1999). The combination of material available, dating range and error can determine which method can be applied for our samples and which ones cannot.

Figure 1.1 shows the approximate age range that is covered by common dating methods. Radiocarbon is one of the most versatile dating methods, but it reaches only 45,000 years back in time (Figure 1.1). This is known as the radiocarbon barrier (Roberts, Jones, and

Smith, 1994). Therefore, the samples that are older cannot be dated. Fission track, K/Ar and $^{40}Ar/^{39}Ar$ methods are good for older samples as well and cover most of the Earth's history (Figure 1.1), but are only applicable on igneous minerals (Table 1.1).

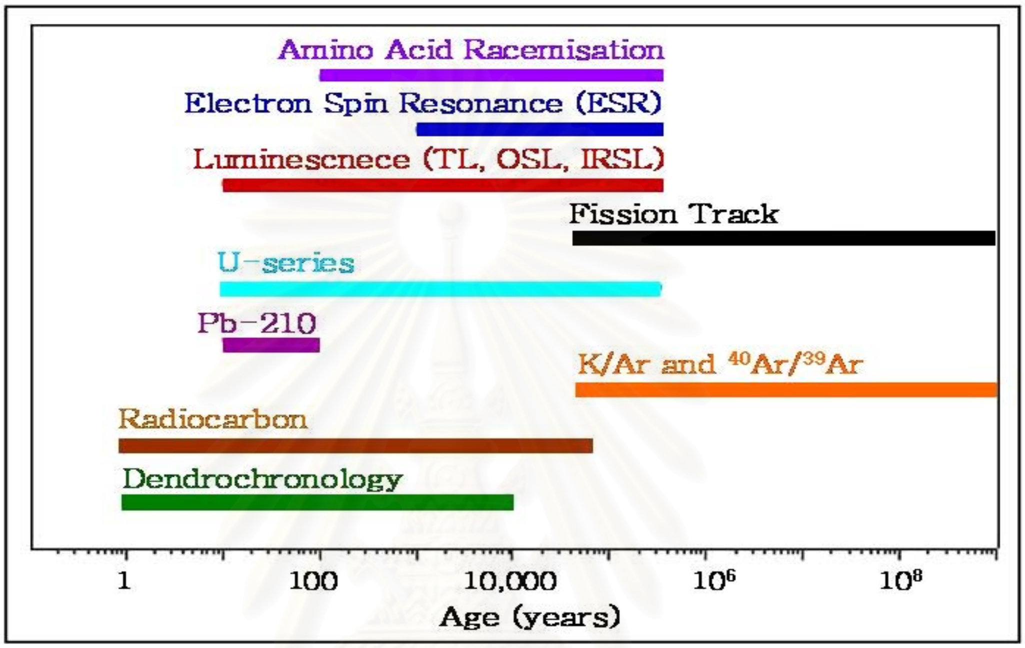



Figure 1.1 Approximate dating ranges for various Quaternary dating methods (modified from Colman, Pierce, and Birkeland, 1987; Colman and Pierce, 2000).

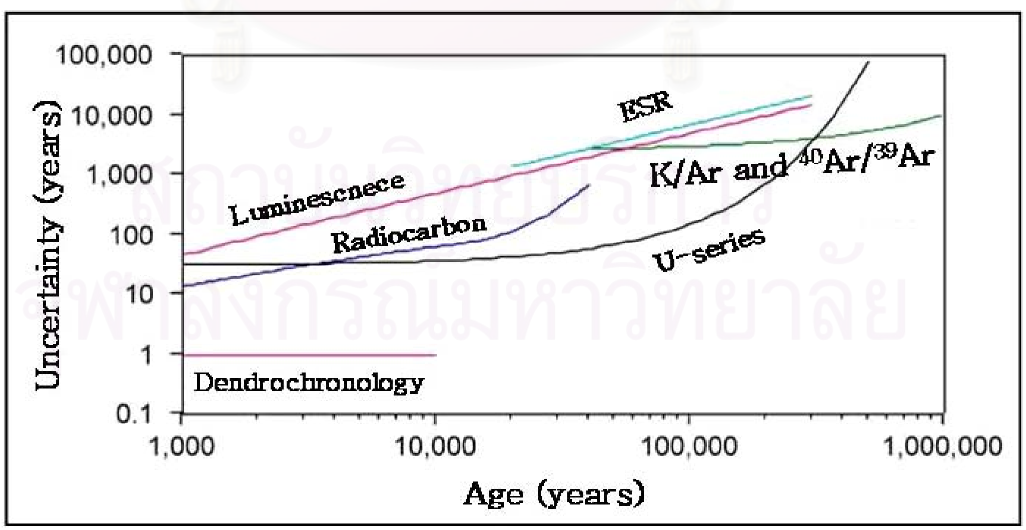



Figure 1.2 Approximate errors of selected dating techniques for optimal materials (http:// www.rses.anu.edu.au/environment /eePages/eeDating/ QuaternaryGeochronology/Quat_info.html).

Table 1.1 Applicability of some Quaternary dating methods (modified from Aitken, 1990). The chart shows how well suited the various dating methods are for different materials. Three degrees of datability are expressed by the symbol (***, ** and *). Symbol *** mean materials that can be well dated by the method, symbol ** mean materials with the methods give sometimes satisfactory results but sometimes not, and symbol * mean materials where dating studies usually lead to unsatisfactory results.

| Material / Dating method | Wood/Plants | Bones | Tooth Enamel | Shells | Corals | Sediments | Obsidian Glass | Volcanic Materials | Burn Flint | Pottery |
|---|---|---|---|---|---|---|---|---|---|---|
| Amino Acid Racemisation | | * | * | ** | | | | | | |
| Electron Spin Resonance | | | ** | ** | *** | | | ** | ** | |
| Luminescence (TL, OSL) | | | | | | *** | | * | *** | *** |
| Fission Tracks | | | | | | | *** | *** | | |
| U-series | | ** | ** | * | *** | * | | *** | | |
| K/Ar, $^{40}Ar/^{39}Ar$ | | | | | | | | *** | | |
| Radiocarbon | *** | *** | * | *** | ** | ** | | | | ** |
| Dendrochronology | *** | | | | | | | | | |

| | |
|---|---|
| *** | Well suited materials |
| ** | Results may sometimes be unreliable |
| * | Results often unreliable |

Formerly, if we would ask the question of which sediments relate to human activities or geological event in the past, we were not able to answer it, because we do not have a dating technique available for dating sediments. Until the mid 1970's, thermoluminescence (Wintle and Huntley, 1982) allows the direct dating of sediment deposition and has already gone a significant distance to revolutionize Quaternary sciences including archaeological studies in the same way as radiocarbon dating (Yokoyama et al., 2000; Beck et al., 2001).Thus, we can start answering questions that previously were not possible to be answered about chronology both of geological and archaeological work by thermoluminescence (TL) dating.

## 1.2 Objectives and Scope

Due to the fact that there are many techniques (or approaches) that can be applied for TL age determination (Singhvi and Wagner, 1986; Yeats, Sieh, and Allen, 1997). In this research, both of total bleach technique (Yeats et al., 1997) and regeneration technique (Takashima and Honda, 1989) are considered carefully for the appropriate technique applied in this study.

Grain size between 74 µm and 250 µm (60-200 mesh) (Takashima and Honda, 1989) were separated into 2 size ranges; i.e., 149-250 µm (60-100 mesh) and 74-149 µm (100-200 mesh) in each TL dating technique for checking an influence from grain size with age results.

The dates of this research aim to construct the chronological information of the study areas and revise/confirm the previous ages from Charusiri et al. (2003) in case of Ban Bom Luang area (see Appendix-H) and from Chaisuwan and Naiyawatt (2002) in case of Thung Tuk area (see Appendix-H). The resulting TL ages obtained from these well-dated samples were used as a reference condition for selection of the suitable measurement procedure and the accuracy of the technique. The improved measurement procedure, including TL dating techniques and the components of the annual dose assessment, are also proposed in this research.

In order to provide the reliability of TL dating, we construct the calibration curve between TL ages versus independent ages from selected samples of the same sedimentary layers from various places in Thailand. All of these procedures are aimed to reveal the reliability of TL dating and a select the suitable technique that can be used potentially and give high accuracy with sediments in Thailand.

## 1.3 Study Area

Two areas were selected for this research, one for geological application and the other for archaeological application. The fist one is at Ban Bom Luang trench (see Appendix-H) representing the area that TL-dating application for geological work and the one is Thung Tuk archaeological site (see Appendix-H) representing archaeological work.

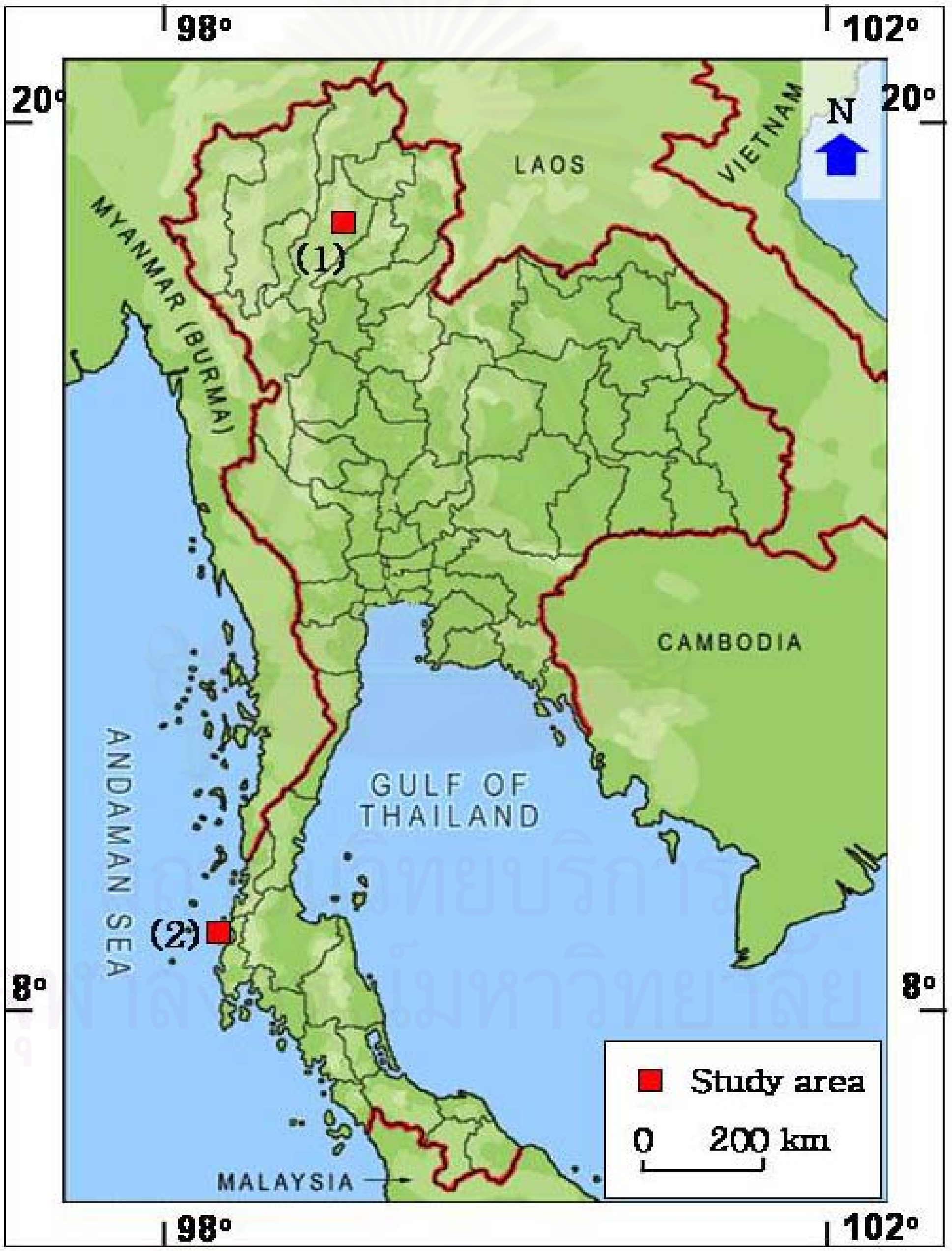



Figure 1.3 Index map of Thailand showing location of the study areas; (1) Ban Bom Luang trench, and (2) Thung Tuk archaeological site.

### 1.3.1 Ban Bom Luang Trench

Ban Bom Luang trench (Figure 1.5a) is the one of the study area in Amphoe Mae Tha (see Appendix-H), Lampang province, northern Thailand (Figure 1.3). It is situated at latitudes 95°50 N and longitudes 50°20'E (Figure 1.4). Charusiri et al. (2003) investigated these active faults in kanchanaburi, Lampang and Prae province and 6 trenches were made for TL dating studies. A trench was made across the Ton Ngoon fault for detailed study characteristic of the fault. Ban Bom Luang trench was excavated on young sediment deposit cross fault trace perpendicularly. The trench was excavated in the direction of north-south (Figure 1.5b). This trenches show colluvial deposit characteristic which is closely related to fault movement (Charusiri et al., 2003).

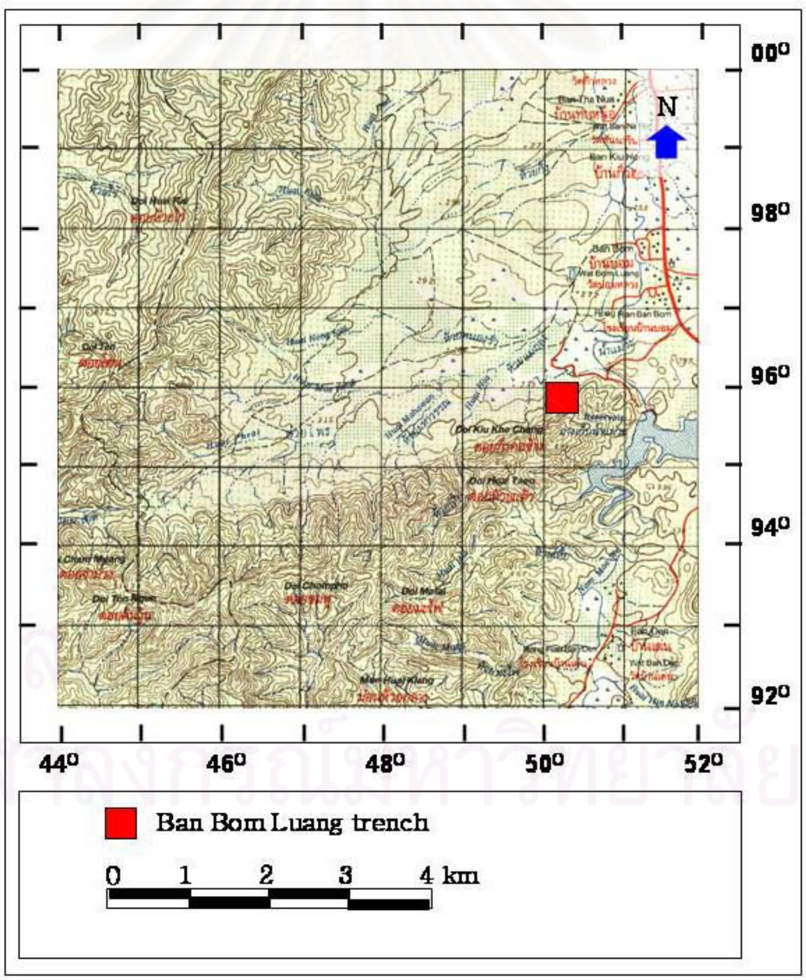
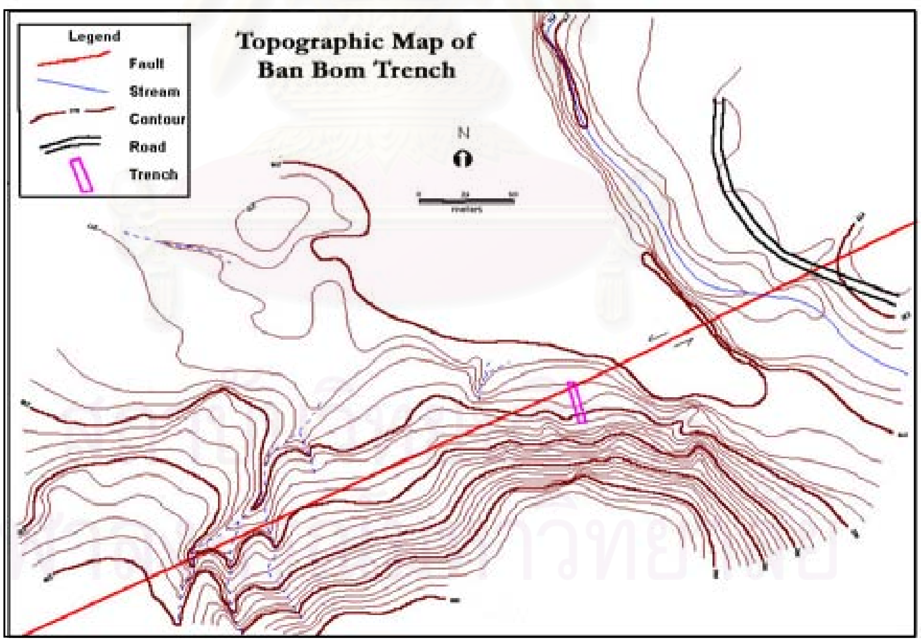



Figure 1.4 Location of Ban Bom Luang trench shown in a topographic map, Amphoe Ko Kha Series L7017 Sheet 4845 II (Royal Thai Survey Department, 1997).

(a)




(b)

Figure 1.5 (a) An appearance of Ban Bom Luang trench, and (b) Detailed topographic map of Ban Bom Luang trench showing locations of fault trace (red-color line) and exploratory trench (Charusiri et al., 2003).

Ban Bom Luang trench can be accessed from the Highway no.1036 from Amphoe Mae Tha, Lam pang province to the south 15 kilometers approximately, then turn right at Hua Fai temple and take a local road about 2 kilometers to Ban Bom Luang. Afterward go to Doi Kiu Kho Chang (see Appendix-H) on foot to Ban Bom Luang trench (Figures 1.4 and 1.6).

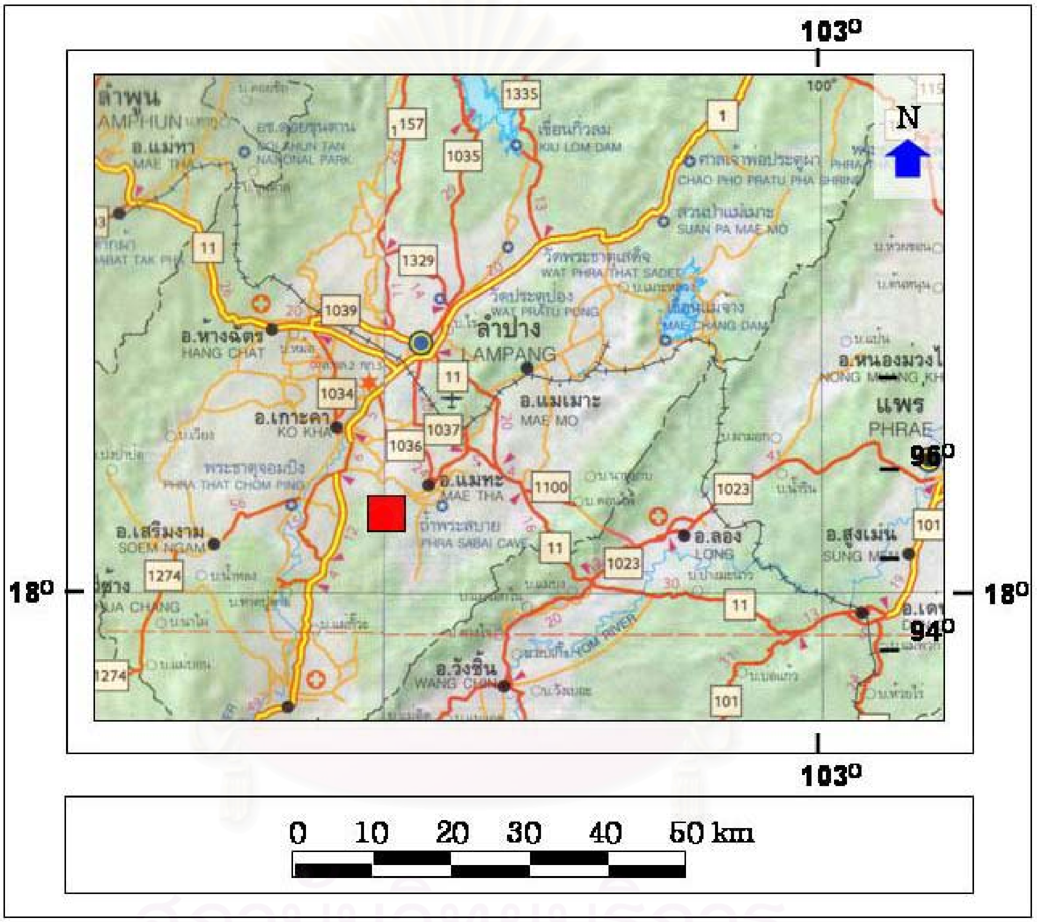
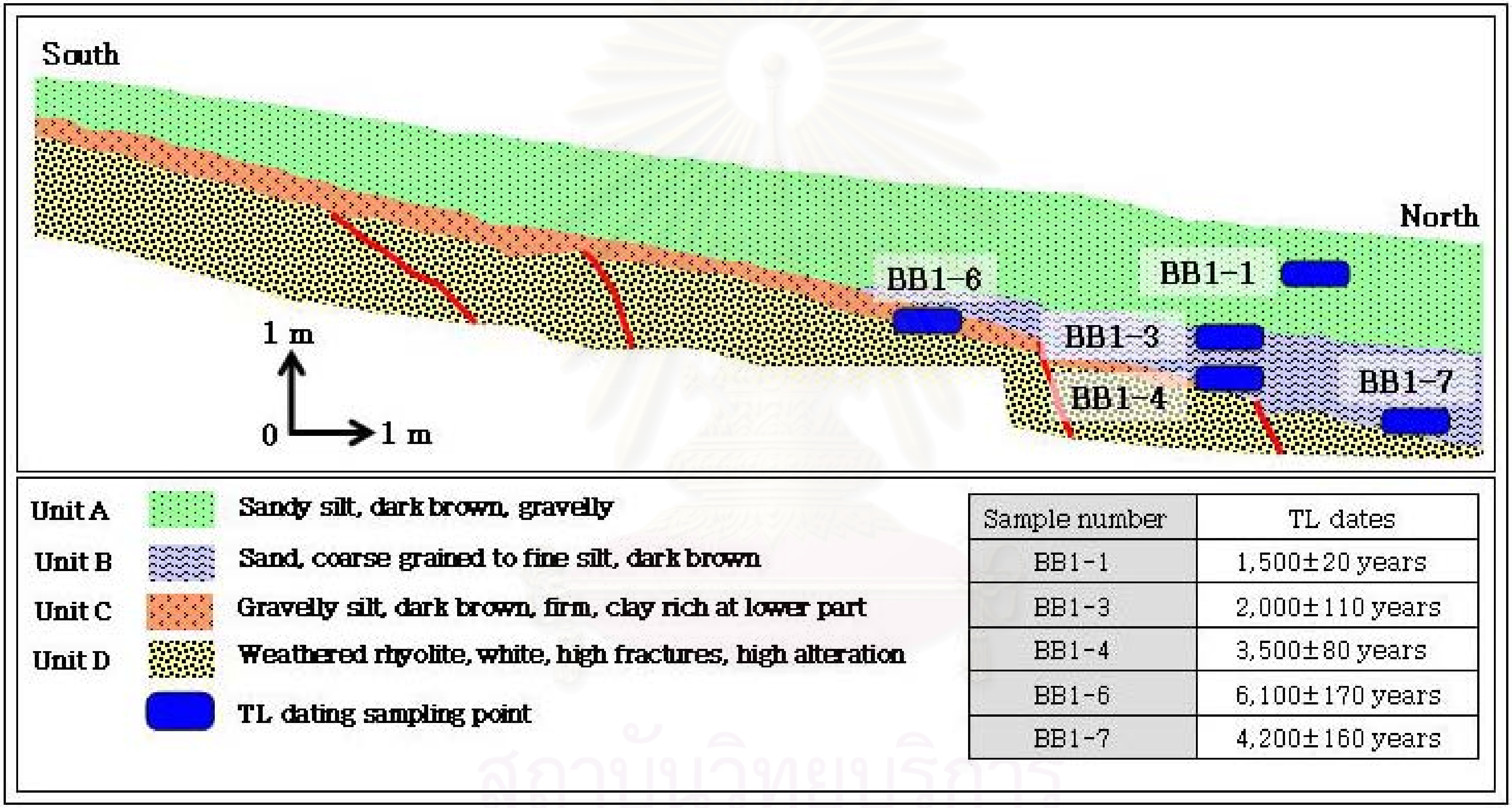



Figure 1.6 Part of northern Thailand route map showing the location and accessibility to Ban Bom Luang trench (red box).

The size of Ban Bom Luang trench is 22-meter long and 2-meter wide. The deepest part is 2.5 meter in the northern part of trench. In the excavation site a large number of white weathered rhyolite was observed.

The detailed trench logging shows a geologic interpretation of the structural and stratigraphic relations exposed in the trench. After logging, representative samples were collected from west wall of trench for age determination of faulting by TL dating method with regeneration technique from Charusiri et al. (2003) (Figure 1.7).




| Sample number | TL dates |
|---|---|
| BB1-1 | 1,500±20 years |
| BB1-3 | 2,000±110 years |
| BB1-4 | 3,500±80 years |
| BB1-6 | 6,100±170 years |
| BB1-7 | 4,200±160 years |

Figure 1.7 West wall of Ban Bom Luang trench showing the detailed of structure and stratigraphy of sediment deposition with TL age data from Charusiri et al. (2003).

1.3.2 Thung Tuk Archaeological Site

Thung Tuk archaeological site is one of the study areas located in Kho Khao island, Amphoe Khura Buri, Phang Nga province, southern Thailand (Figure 1.3).It is situated at latitudes 82°05'N to 82°30'N and longitudes 20°20' E to 20°45'E (Figure 1.8). This site is located on the back part of Tambon Ko Kho Khao (see Appendix-H), Mu 3 area, Amphoe Khura Buri between the ends of Muang Thong Canal (see Appendix-H) and Thung Tuk Canal which is the mouth of Takua Pa River area. Characteristics of the area are low-lying area dominated by sand plain, mainly covered with trees and some spots of bushes.

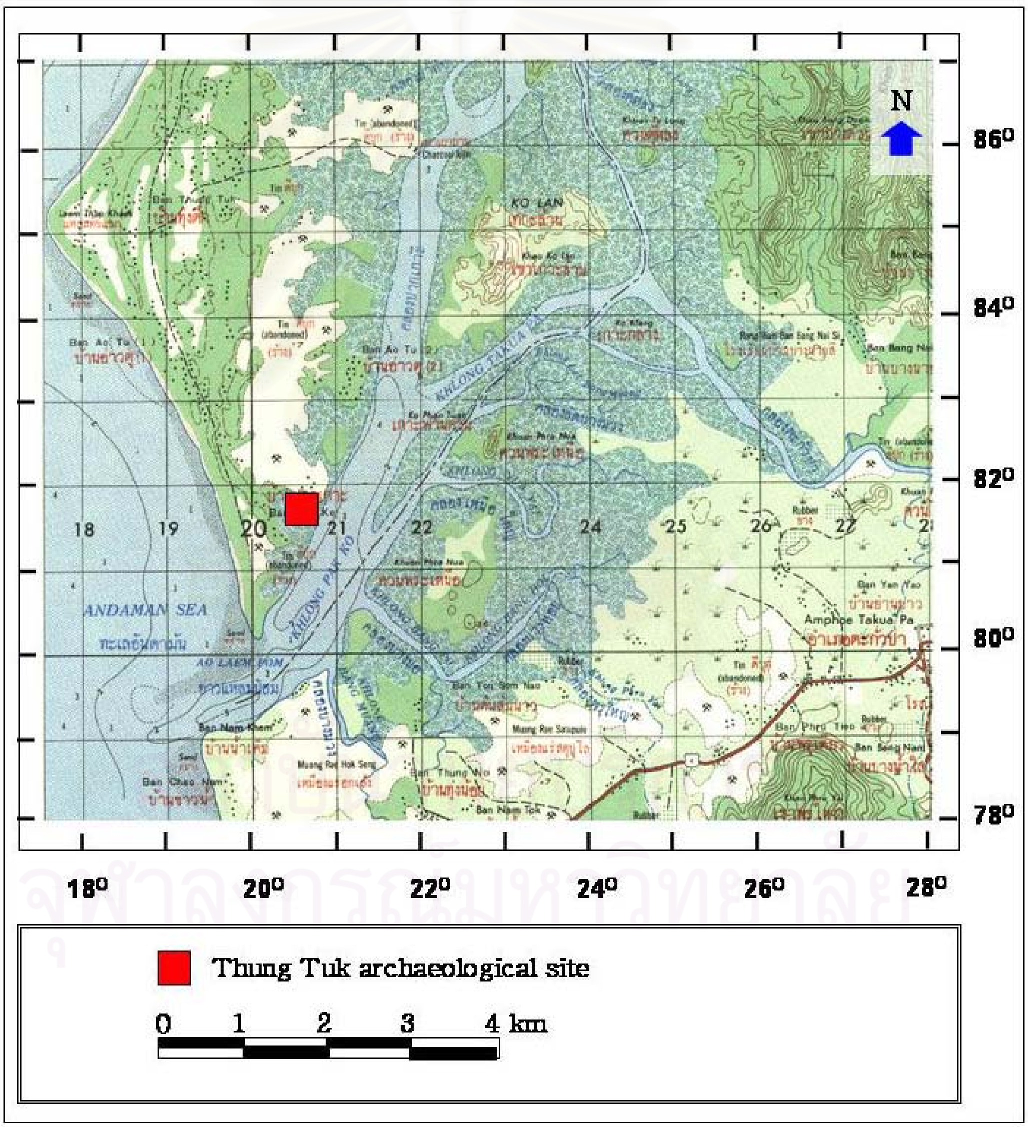



Figure 1.8 Location of Thung Tuk archaeological site from topographic map, Amphoe Khura Buri Series L7017 Sheet 46272 II (Royal Thai Survey Department, 1997).

The reason this area generally called, by the villagers, "Thung Tuk" is that there are at least three archaeological remains. They look similar to a building or sanctuary, rising on this sand plain in the bush area. Parts and components of a Bhraman religious place and religious symbols are stone carved into a pedestrian shape with a pit at the bottom that looks like a base whereupon a Siva Linga or an idol is placed. In addition, pieces of local earthenware (Figure 1.9a), Chinaware (Figure 1.9b), Persia pottery (Figure 1.9d) as well as various types and colors of beads (Figure 1.9c) are scatteredly found on the ground of Thung Tuk archaeological site.

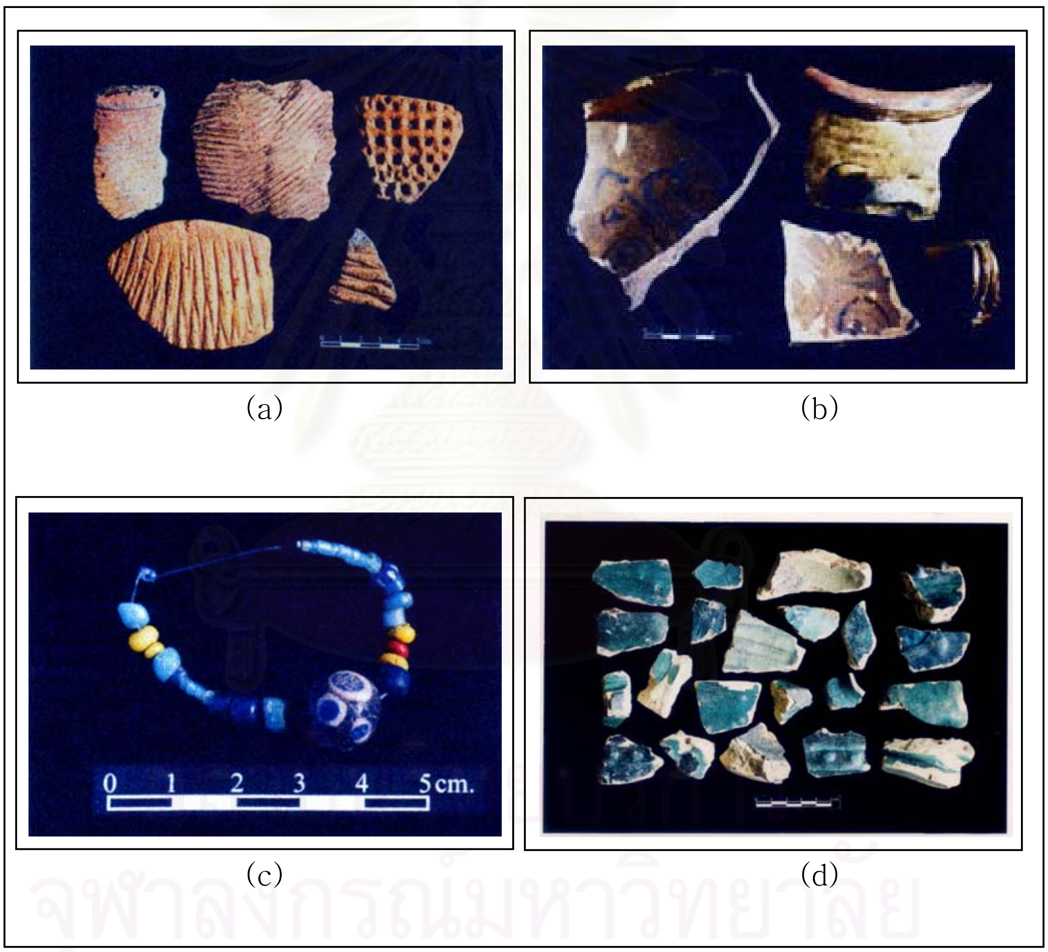



Figure 1.9 Some of ancient antiques that discovered in Thung Tuk archaeological site referred relative age; (a) Local earthenware, (b) Chinaware, (c) Bead, and (d) Persia pottery respectively (Chaisuwan and Naiyawatt, 2002).

The accessibility of Thung Tuk archaeological site can be conveniently done by the Highway no. 4032 from Amphoe Takua Pa, Phang Nga province to Phetchakasem- Ban Bang Muang road about 7 kilometers and turn left go to Ban Nam Khem (see Appendix-H) ferry crossing. From Ban Nam Khem ferry, take a ferry boat to get across to Ban Thung Tuk (Figure 1.10).

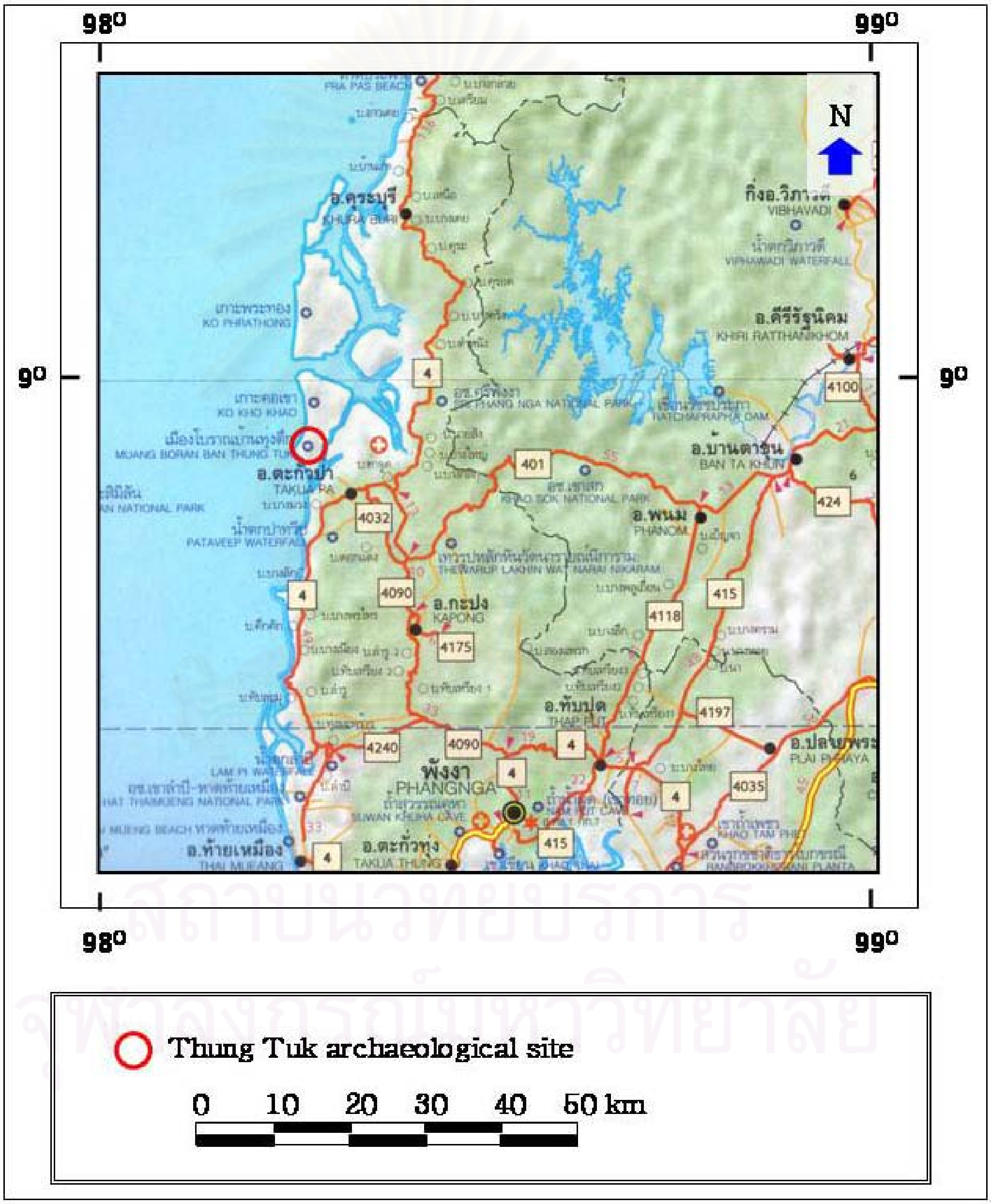



Figure 1.10 Route map of southern peninsular Thailand showing location and accessibility to Thung Tuk archaeological site in Phang Nga province.

The majority of archaeological expert (e.g. Wales, 1947; Srisuchart,1986) has resolved that Thung Tuk use to be a location of an ancient port town where Indians, Arabians, and Malayans were so well acquainted due to its being an important spice market situated on the west bank of the Malayan Peninsula (Srisuchart,1986). It is located in a suitable locality having appropriate natural circumstances to anchor in safety from big storms. Besides its perfect natural resources, it is situated nearby the deep open sea where big vessels can access conveniently and yet located on the mouth of Takua Pa River which is also the center of water communication (Chaisuwan and Naiyawatt, 2002).

At Thung Tuk archaeological site, the previous age data are from relative age with 1,500-1,200 years Tang dynasty pottery (Srisuchart, 1986) and conventional radiocarbon ages of 1,310 ± 230, 1,070±330 and 1,260±820 years (Chaisuwan and Naiyawatt, 2002).

## 1.4 Literature Reviews

Aitken (1985) studied TL dating in both of theoretical and practical terms, particularly with a strong background in physics. He proposed application of TL dating for archaeological objects including Quaternary sediments and introduced some phenomena about residual signal of sediments after 6-10 hours bleaching by natural light.

Berger and Eyles (1994) have reported 8 satisfactory TL ages of Quaternary sedimentary deposits in Toronto area, Canada. The samples are clayey lamina, silt and sand, from shallow water lacustrine deposits. They employed the partial bleach TL technique to separate the post-burial light-sensitive TL signal from the total signal and to measure the equivalent dose value. Almost all samples produced excellent plateau. The TL ages ranged between 20-80 ka and significantly contributed to the chronostratigraphic sequence of the Toronto area.

Zoller, Oches, and McCoy (1994) presented 41 TL dates from the stratigraphic ages of some well-known palaeosols in Austrian and Hungarian loess sections. Quartz mineral concentrates (size 90-200 μm) yield more reliable TL ages than the polymineralic fine grain fractions. The total bleach and regeneration techniques were applied for equivalent dose determination. Some ages were correlated and supported by amino-acid dating and biostratigraphical correlations.

Smith, Prescott, and Head (1997) used TL dating with sediment samples from Puritjarra rock shelter and compared with conventional radiocarbon dating from the same sedimentary layer. Total bleach and partial bleach technique were used for equivalent dose evaluation. The results of TL ages are older than conventional radiocarbon ages. They concluded the old TL ages were effect from disturbation from root plant and some of bioturbation. Moreover, they produced calibration curve between TL dating results versus radiocarbon dating results by using data from Prescott and Smith (1993) for the reliable TL dating. There is ample evidence that TL ages agree with calibrated radiocarbon ages.

Yeats et al. (1997) reviewed and classified technique for determining equivalent dose including regeneration, total bleach and partial bleach techniques and described the detail of processing in each technique.

Changkian and kaewtubtim (1999) applied TL dating with ancient stupa and brick pieces from Ban jalae number 3, Yarang historical site, Amphoe Yarang, Pattani province, southern Thailand. The samples were crushed into small fractions with grain size of 100-300 μm, etched with 48% of hydrofluoric acid before separated this contaminated crystal by precipitating in liquid of high specific gravity (Tetrabromoethane, Dipropylene glycol). The crystals were washed until clean quartz was obtained. The absorbed dose of radioactivity from environment of this quartz was then estimated using the TL reader with the maximum temperature of 400 °C. additive dose technique was proposed in these dating. From the glow curve obtained, it was found that the ancient radiation dose of the stupa and bricks were 810 rad and 753 rad, respectively. The annual dose of this historical site estimated using $CaSO_4$ crystals was 1.40±0.04 rad/year. The ages of stupa and brick piece was found to be 579±17 years and 538±15 years, respectively. These TL ages were in line with conventional radiocarbon age from Reotrit (1987) that determined the ages of Yarang historical site in 445±85 years.

Liritzis (2000) reviewed about TL dating on environmental nonburnt materials formed mainly during the past quarter of a million years. A special interest is placed on the applications on sedimentary deposits, including materials related to cultural activities. It also critically discussed the limitations and potential applications of these TL dating methods on solar set crystal clock.

Kusiak et al. (2002) present the TL dating results for 10 loess samples were taken from Zahvizdja loess profile, western Ukraine. They compared their TL ages obtained by using 2 methods of equivalent dose determination: regeneration and total-bleach. Both techniques from TL ages are then compared with those of paleomagnetic dates. The regeneration technique gave the results similar to Bun Matuyama paleomagnetic boundary more than those of the total bleach technique. They also concluded that the regeneration method was able to date sediment samples from 200 to 900 ka. When estimating the age higher than 900 ka, the result is difficult to evaluate because luminescence signals may reach to the saturation level.

Charusiri et al. (2003) dated 3 samples of sediments collected from Ban Pong Kom trench, Chiang Rai province, northern Thailand by using regeneration TL-dating technique and compared the TL dates with AMS radiocarbon dating (University of Oregon, USA).TL dates range from 765±200 years to 3,700±500 years and have a good correlation with the AMS radiocarbon dates.

Won-in (2003) proposed 3 TL dates of shell taken from Ban Phraek Sa Pit, Samut Prakarn province, central part of Thailand by additive dose method and compared TL ages with AMS radiocarbon dating of Bivalve genus *Chamys sp.* sample from Sato and Suzuki (1999). Both results are in good agreement with one another.

kawkeaw (2004) studied archaeological work in Tam Lod rock shelter, Mae Hong Sorn province, northern Thailand using results from TL dating of sediments and compared with those of the AMS radiocarbon dating of bone. Regeneration technique was applied to this research. The TL-dating results range from 9,980 to 22,257 years while those of the AMS radiocarbon dating vary from 12,100 years to 22,150 years.

## 1.5 Thermoluminescence Dating

Thermoluminescence (TL) dating is the one of absolute age dating method (Mahaney, 1984), which can determine ages with many kinds of materials such as volcanic materials (Wintle, 1973; Berger and Huntley, 1983), calcite and shells (Aitken, 1985; Ninagawa et al., 1992), quartz from sediments (Wintle and Huntley,1982).

In the case of application TL dating for quartz from sediments, the concept relies on the last exposure of the sediment grains to sufficient sunlight at the time of their deposition to greatly reduce the TL signal (Feathers, 2002). The age reflecting the time since the sediment grains were last exposed to sunlight (Wintle and Hunley, 1980). This application can now give credible ages from a few tens of years to 500 ka (Huntley and Prescott, 2001)

### 1.5.1 Thermoluminescence Process

Thermoluminescence is the thermally stimulated emission of light (TSL) (Singhvi and Wagner, 1986).The features of thermoluminescence can be discussed in terms of ionic crystal that comprise  a lattice of positive and negative ions (Figure 1.11a). Naturally, lattice can be defects that cause by rapid cooling from the molten state and damage caused by nuclear radiation etc. There are many types of defect can occur (Figure 1.11b). The defective lattice act as electron trap and attracts free electron to fill out (Figure 1.11c). Free electron is activated by ionizing radiation from environment particularly by uranium, thorium and potassium radiation. Some excited electrons are able to diffuse through the lattice and gets trapped at various lattice defects.

Whenever, an appropriate stimulation by way of heating can cause instantaneous evict of the electron, some of which are able to recombine with a luminescence centre and emitted energy in term of light (Figure 1.11d). The emitted light is called “thermally stimulated luminescence” or “thermoluminescence”.

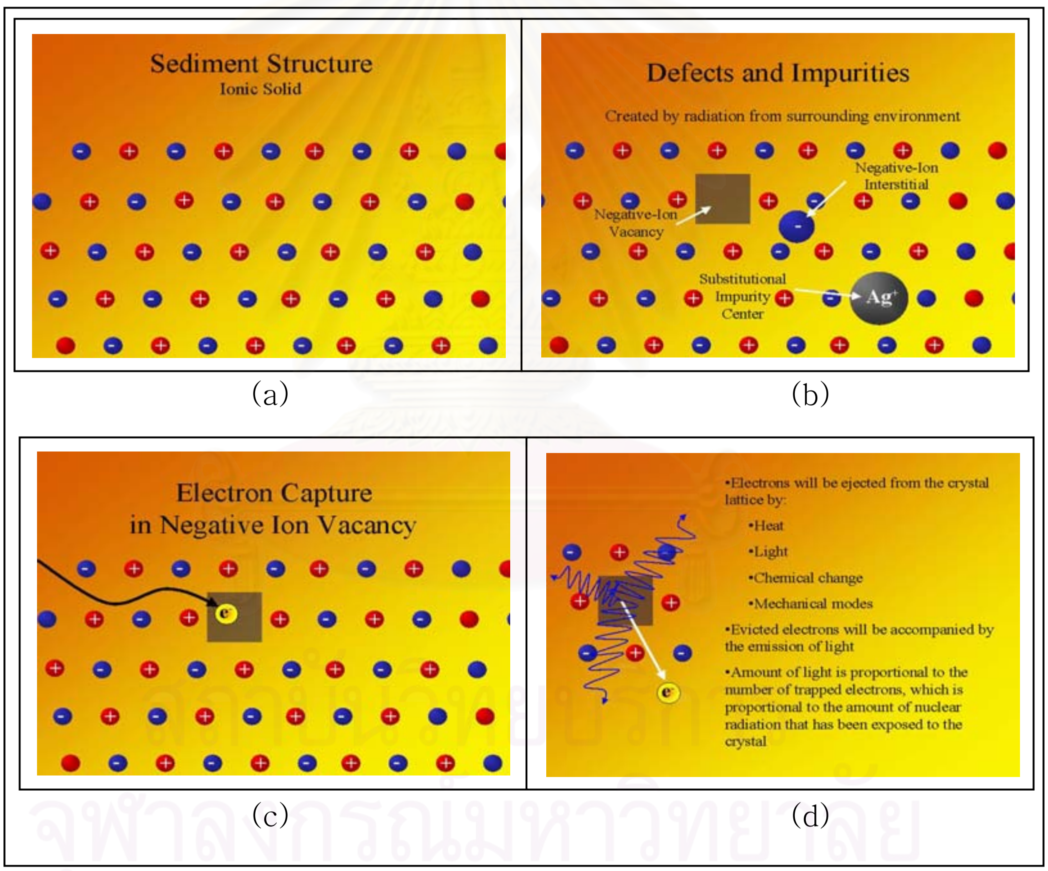



Figure 1.11 Schematic of thermoluminescence process; (a) Perfect ionic crystal pattern of ideal sediments, (b) Defect and impurities of natural sediments, (c) Electron capture in negative ion vacancy, and (d) Electron evict from electron trap by activating from heat or light (http://www.hope.edu/academic/physics/reu01html/ pp_presentations/ MJGoupell/sld001.htm).

A convenient way to represent the thermoluminescece process shows in Figure 1.12. Energy-level of thermoluminescence includes; (a) The defective lattices act as electron traps and attracts free electron to fill out. (b) Ionization due to exposure of crystal to nuclear radiation, with trapping of electrons in the traps and holes at defects, respectively. (c) Storage during antiquity; the lifetime is determined from amount of electrons that trapped in lattice. and (d) To observe thermoluminescence the sample is heated and there is a certain temperature at which the thermal vibrations of the crystal lattice causes eviction. Some of these evicted electrons reach luminescent centers and emitted energy in term of light.

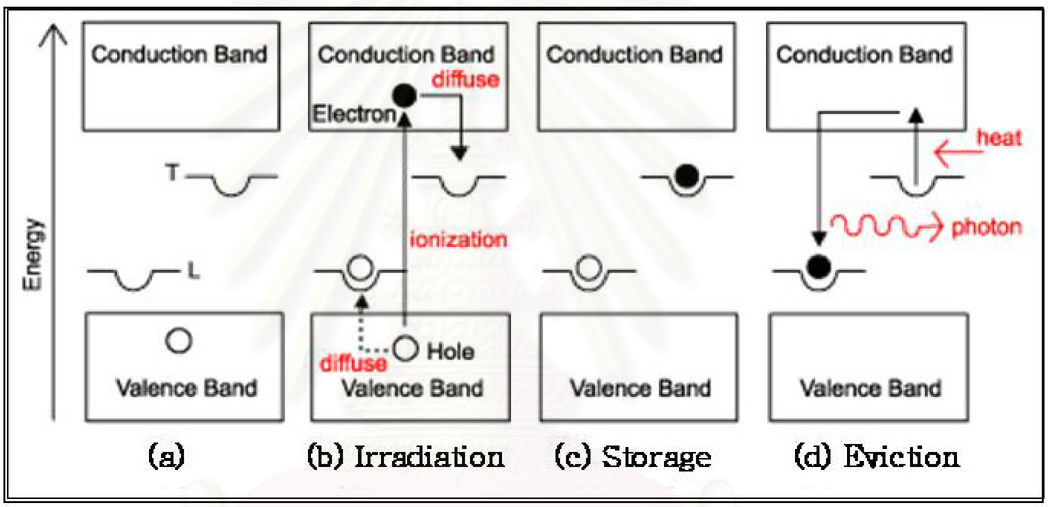



Figure 1.12 Energy-level representation of thermoluminescence; (a) Effective lattices stage, (b) Irradiation stage (c) Storage stage, and (d) Eviction stage (Aitken, 1985).

### 1.5.2 Applications of TL Dating for Quaternary Sediments

When the country rocks or sediments are weathered and transported prior to last deposition, the exposure to daylight causes bleaching of the TL signal. Afterward last deposition of the grains are burial under new sediment, TL signal accumulates again because they absorb the natural ionizing radiation that is emitted by the surrounding sediment (Figure 1.13). The ionizing radiation ($\alpha$-rays, $\beta$-rays and $\gamma$-rays) is produced by the very low concentrations of uranium ($^{235}U$, $^{238}U$), thorium ($^{232}Th$) and potassium ($^{40}K$) in the sediments. A small amount is cosmic radiation be included. Thus the present-day TL intensity of the sediment reflects both the environmental radiation level and the length of time since last deposition. The total radiation dose that is accumulated in this way is called the Equivalent dose and the rate of natural irradiation by sediments called Annual dose (Aitken, 1985).

However, the resetting of the TL signal by sunlight is less efficient than by heat. Because sunlight does not completely evict the electron from traps that produce TL signal (Wintle and Huntley, 1980; Huntley et al., 1985). In case of TL dating for sediments, optical bleaching experiments are essential (Aitken, 1985) because of residual contributions must be subtracted from the natural glow curves in order to date the last sedimentation event. For the dating method to be reliable there must be good reason to believe that the sediment grains were fully bleached before deposition.

### 1.5.3 The Age Equation for Dating Sediments

The TL age is simply calculated from the equivalent dose (ED) and annual dose (AD). Aitken (1985) proposed the simple equation of age determination as shown below.

$$\text{TL age (years)} = \frac{\text{Equivalent dose (Gy)}}{\text{Annual dose (Gy/year)}} \qquad \text{(Eq.1.1)}$$

Where

- Equivalent dose (ED): The total accumulated dose that received by irradiation from natural radioactivity and preserve this record through time. In the case of sediments, residual intensity (Io) from the bleaching experiment is considered herein.
- Annual dose (AD): Irradiation dose per year from natural radioactivity. Annual dose is calculated from the chemical data of radiogenic elements (uranium, thorium, and potassium) and comic ray evaluation.

Thus, TL dating involves the determination of 2 major parameters; equivalent dose and the annual dose.

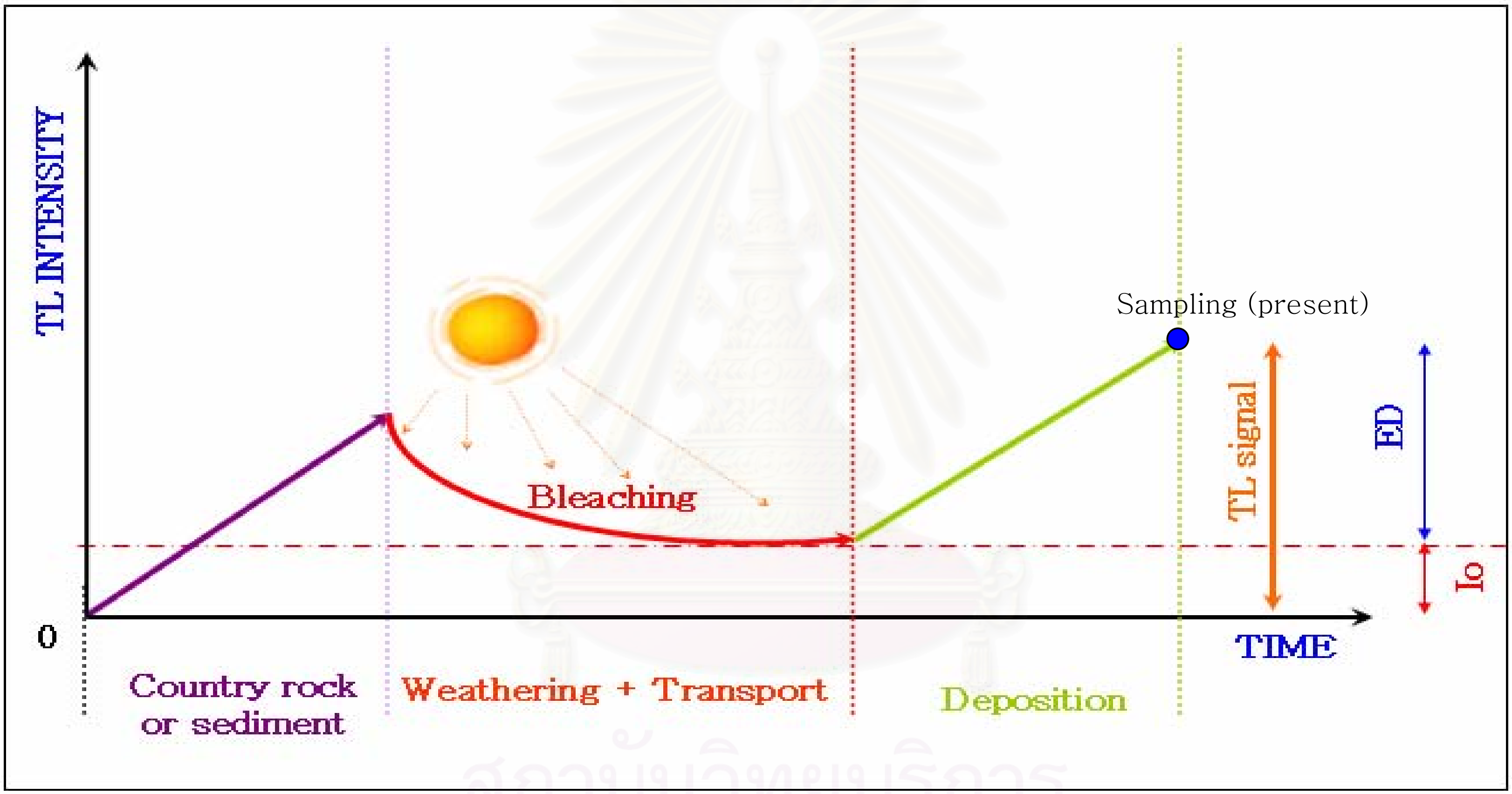



Figure 1.13 Hypothetical thermoluminescence level versus time. An event permitting the sediment to be exposed to sunlight reduces the captured electron causes thermoluminescence signal to a residual level (Io). Today's heating drains the sample and emit TL signal (modified from Won-in 2003).

# CHAPTER II

# METHODOLOGY

In this research study, the methodology is conducted to clarify advantage and disadvantage of total bleach and regeneration techniques for TL dating, and to determine effects of grain size (74-149 μm and 149-250 μm) on TL dating. Methodology can be subdivided into 3 consecutive steps (Figure 2.1), including:

- Planning and preparation;
- Field work investigation and sample collection; and
- Laboratory analysis.

## 2.1 Planning and Preparation

The first step of methodology starts from preparing information regarding theory of thermoluminescence dating and the study area data, such as literature reviews (see section 1.4 in chapter I), preliminary data of the two interesting study areas, select an appropriated study area. Two conditions are required for area selection, including:

- The areas being selected involve either appropriate geological or/and archaeological context.
- The study areas should have relevant data useful for age reference by independent ages. So the TL dating results and other independent age dating can be compared.

Based on the available and existing information, we selected Ban Bom Luang exploratory trench in Lampang province, northern Thailand and Thung Tuk archaeological site, Phang Nga province, southern Thailand for the detailed TL dating approach.

## 2.2 Field Work Investigation and Sample Collection

Detailed field investigation was undertaken during March,2003 and October,2004 and is regarded the best way for studying characteristics of sedimentary deposition. Understanding of stratigraphy and sedimentary deposition in the field lead bright conclusion and clear information on the history of the study area and nature of suitable samples being collected. Photographs or trench logs showing the locations of samples are included at this stage. Location of the site using GPS systems is also conducted.

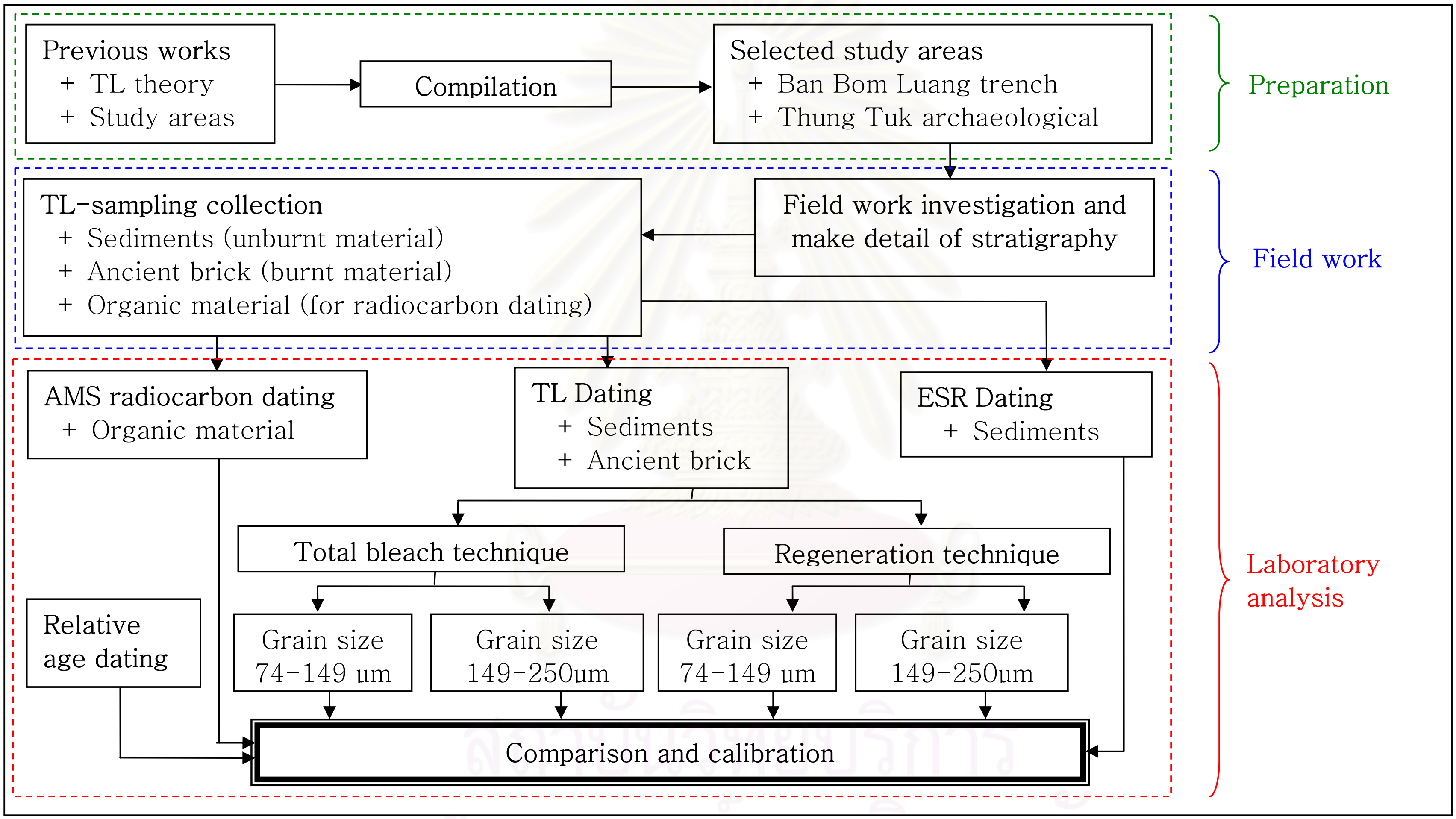



Figure 2.1 Simplified flow chart illustrating methodology procedure for this research study.

In sample collection, the primary consideration when selecting sedimentary samples for TL dating is whether the individual grains of the material received an adequate exposure to daylight at the time of deposition. Depending on the intensity of the daylight, exposures of between one day and one week are sufficient to reduce the intensity of the dating signal to its minimum level (Aitken, 1985). Sediments that are found to provide successful TL dates are described in details particularly in the trench. It is advisable to discussion on the details of different sedimentary environments before sample collection was also performed. Care must also be taken to ensure that the sample is taken from an undisturbed site and has not been subject to re-exposure by bioturbation.

Samples for the TL measurement were carefully collected at depth of 10 cm from surface in order to avoid sunlight and weathering processes. The samples were then kept carefully into a freshly cleaned back surface and wrapped in moisture-tight and light protect containers to prevent further exposure to light and to preserve the environmental moisture content for annual dose evaluation.

This section starts from field investigation and collection of the detailed stratigraphic data in both of the study areas for determining the appropriated sampling point.

### 2.2.1 Ban Bom Luang Trench

#### A) Mapping Stratigraphic Units and Description

The mappable units exposed in a Ban Bom Luang trench (Figure 2.2) are divided into 4 units.

- Unit A: Sandy silt, dark brown, gravelly

This unit is the topmost layer with thickness varying from 30 (southern part of trench) to 90 cm (northern part of trench). It is poorly sorted and mainly comprises coarse sand to medium gravels. The color of this unit is dark brown approximately. Rock fragments (up to 20 cm) are sparsely distributed, mostly they are polycrystalline and mono-crystalline quartz, quartzite and chert. Some of organic fragments can be found in this unit. Due to the unit lying at the topmost layer, it is easily disturbed by human activities and some by root plants. This unit is interpreted as the youngest layer in the trench.

- Unit B: Sand, coarse grained to fine silt, dark brown

This unit was found only in the northern side of trench. Thickness of this unit varying from 0 to 70 cm. Composition of sediments in this unit is mainly sand, with sub ordinal coarse-grained to fine silt. The color of this unit is similar to that of the unit A. This unit shows characteristic of high water content. Some of organic fragments were also observed in this unit.

- Unit C: Gravelly silt, dark brown, firm, clay rich at lower part

This unit is the thinnest sedimentary layer that shown in the trench. The layer is smooth and thickness is 20 cm approximately. Sorting is varied in the composition of gravel to clay. Displacement in the north side of this layer reveal faulting that continuously cut from lower unit. Organic fragments are rarely found in this unit.

- Unit D: Weathered white rhyolite, with high fractures, and strong alteration

This unit is represented by a large number of weathered rhyolite mixed up with trivial sediments from unit C. Exposed thickness of this unit from top surface to the bottom of trench is 1 m. The lower part of this layer shows characteristic of high alteration of rhyolite basement. At least 4 faults and fractures appear in this unit. Organic materials are not found in this unit.

B) Location of Collected Samples

Four quartz-rich sediment samples were collected in Ban Bom Luang trench for TL age determination while four organic fragments were collected for radiocarbon dating. All of them were collected in sediment units A, B and C from the west wall of the trench (Figure 2.2). Sediments in unit D is not appropriated for TL dating and lack of organic material for radiocarbon dating. The details of sample collection are shown below.

- Sample nos. BL5 (TL sample) and C5 (organic fragment) were collected from the same position in unit A (Figure 2.2).
- Sample nos. BL11 (TL sample) and C11 (organic fragment) were collected from the same position in the topmost layer of unit B (Figure 2.2).
- Sample nos. BL10 (TL sample) and C10 (organic fragment) were collected from the same position in lower part of unit B (Figure 2.2).
- Sample no. BL20 (TL sample) was collected from unit B (Figure 2.2).
- Sample no. C14 (organic fragment) was collected from unit C (Figure 2.2).

After selection of samples for TL dating, we aliquot each TL sample into 4 portions in order to get 4 dates relevant to total bleach and regeneration techniques and grain size ranges (74-149μm and 149-250μm). The details of divided sample and nomenclature of samples are show in Table 2.1a. (Appendix-A).

Four organic samples that were collected from Ban Bom Luang trench were sent to The NSF - Arizona Accelerator Mass Spectrometry (AMS) Laboratory, University of Arizona, Physics Building 81, 1118 East Fourth Street, Tucson, AZ 85721, USA for AMS radiocarbon dating.

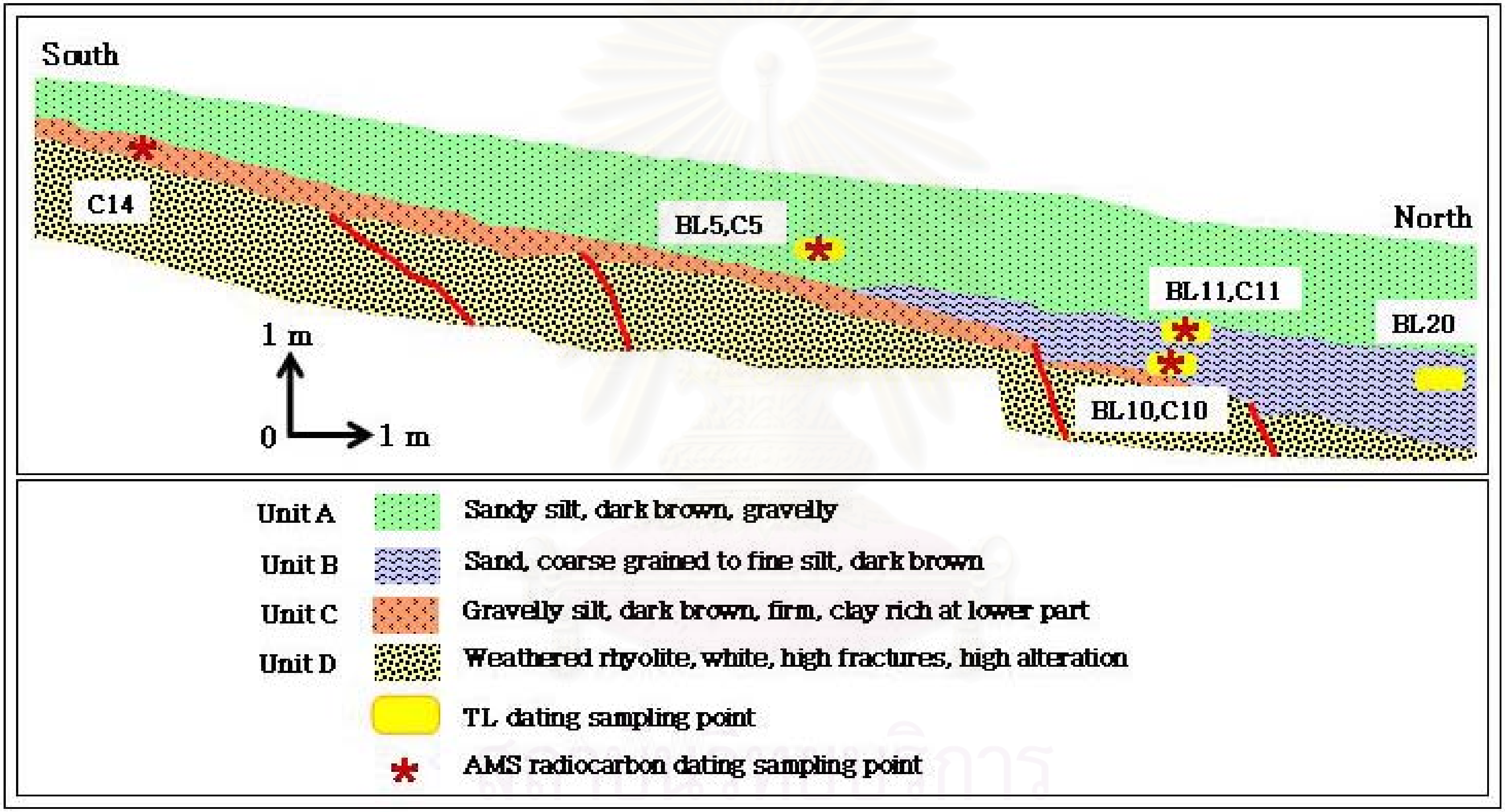



Figure 2.2 Stratigraphy of west wall from Ban Bom Luang trench illustrated characteristic of sediments deposition and sampling point (modified from Charusiri et al., 2003).

### 2.2.2 Thung Tuk Archaeological Site

According to the current field work investigation in Thung Tuk archaeological site, the boundary of Thung Tuk town plan is mapped and shown in Figure 2.3. There are 8 ancient remains, 1 trench and 2 pits in Thung Tuk town plan. In order to comprehend TL dating and history of this site, it is important to determine ages of some ancient remains. A total of 8 brick samples from the basement of ancient remains and 12 samples apart from sediments under ancient remains were collected from 6 locations of Thung Tuk archaeological site.

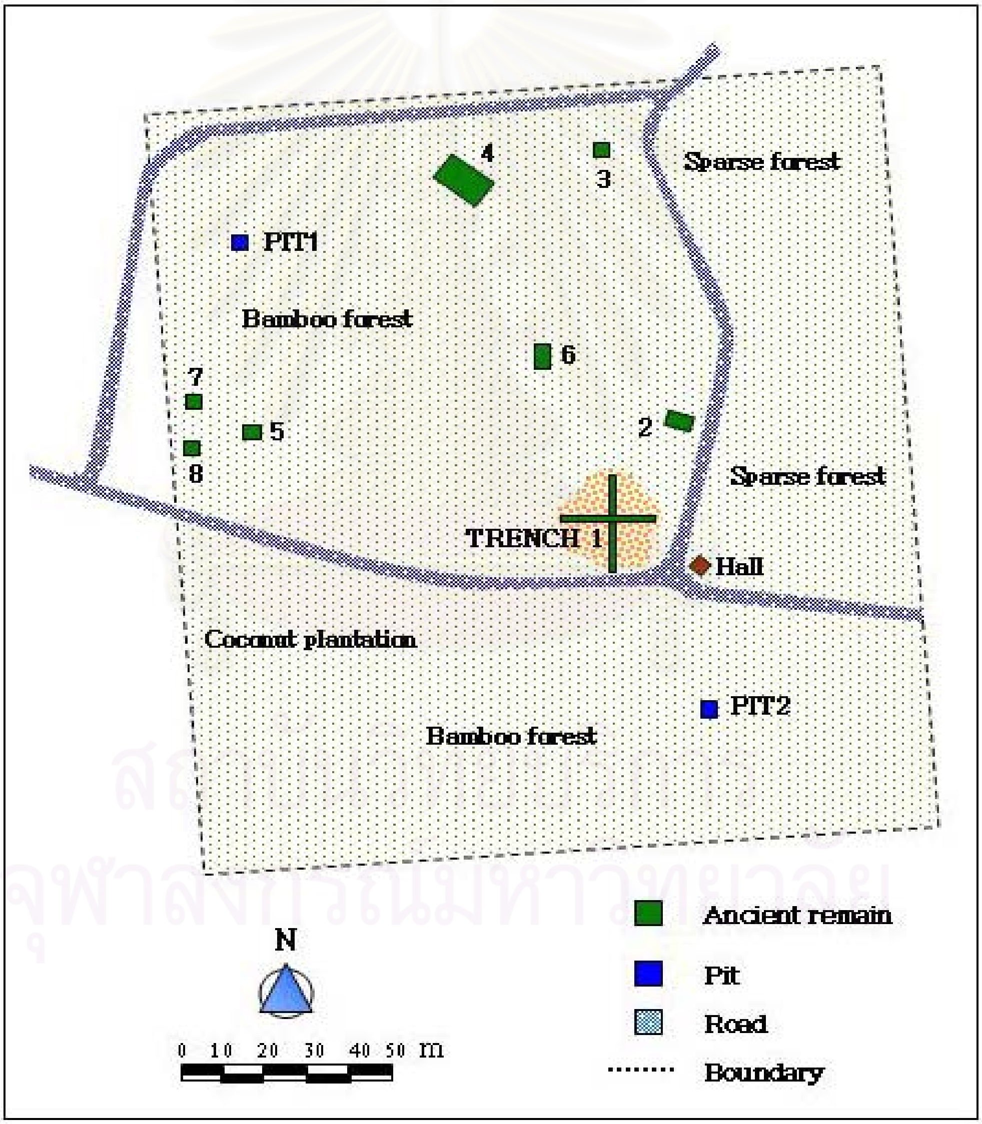



Figure 2.3 Town plan of Thung Tuk archaeological site showing boundary of site and location of 8 ancient remains, 1 trench and 2 pits in town plan (modified from Chaisuwan and Naiyawatt, 2002).

A) Trench 1

According to archaeological exploration by 15th Regional Office of Fine Arts, Phuket province, all of ancient remains were emerged excepted from the ground surface. Exception is for trench 1 that required some digging (Figure 2.4a). The shape of trenching is similar to “T “English letter with the 20-m long head in the east-west direction and the 20-m long tail in the north-south direction. The depth from surface to ancient remain basement is approximately 1.50 m. In this area, we collected a brick piece from the basement and also collected a sediment sample under the basement (Figure 2.4b) to evaluated the period of the ancient remain construction from the brick sample and the age of sediments under ancient remain. Detail of the TL samples at trench 1 is displayed in Table A.2 (Appendix-A).


(a) (b)

Figure 2.4 Trench 1 from Thung Tuk archaeological site; (a) A view during trenching (photo from Chaisuwan and Naiyawatt, 2002), and (b) TL sampling point of brick and sediments (red circle).

B) Ancient Remain 3

Ancient remain 3 is situated in the northeastern part of Thung Tuk town plan (Figure 2.3). This station shows the basement of ancient remain emerged from surface (Figure 2.5a). The size of this ancient remain is 6.80x8.55 meters. In this remain, we collected 3 pieces of brick samples from basement and a sediment sample under the basement (Figure 2.5b). In case of brick, the first brick seems homogeneous in composition as investigated by color changing. The second and the third bricks show the color change in mass of brick (Figure 2.6). We assume that the color of brick may indicate not entirely heating of brick mass in the past time. According to incompletely heating brick, it will effect to non-zeroing signal in inner part of brick mass. We were interested to evaluate equivalent dose both of inner and outer parts of brick to prove the possibility of dating brick in archaeological site. The detailed of sample dividing and nomenclature is shown in Table A.3 (Appendix-A).

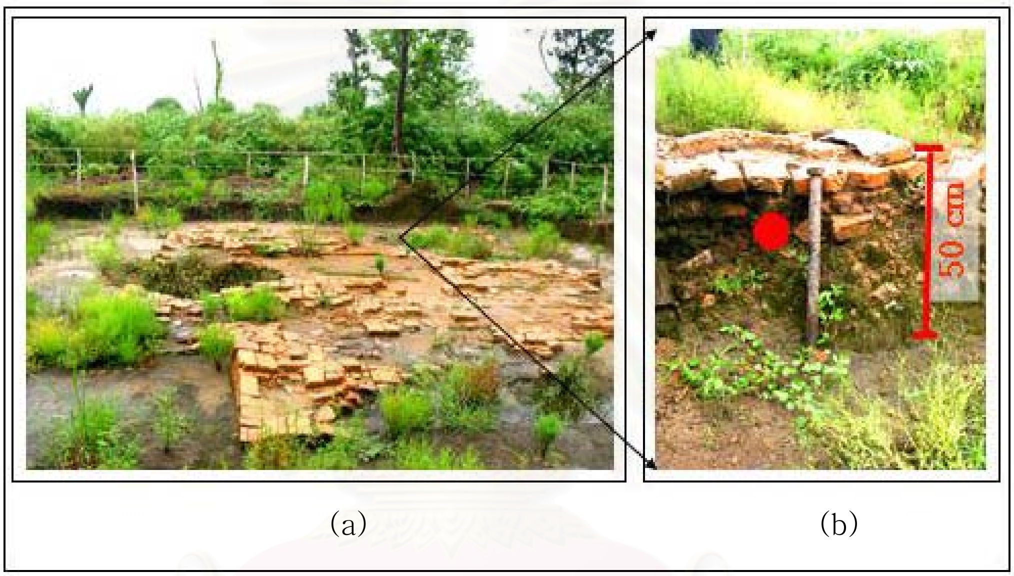



Figure 2.5 Ancient remain 3 from Thung Tuk archaeological site; (a) Characteristic of ancient remain and (b) TL sampling point of brick and sediments (red circle).


Figure 2.6 Brick sample from ancient remain 3, Thung Tuk archaeological site that reveal characteristic of different color within mass of brick.

C) Ancient Remain 4

Ancient remain 4 shows the basements of ancient remain emerging from surface (Figure 2.7a). Ancient remain 4 situated in the northern of Thung Tuk town plan (Figure 2.3). The size of this ancient remain is 9.00x20.50 meters. Except the basement of ancient remain, these are 2 strange objects on floor in ancient remain boundary. These objects look like the ancient burner (Figure 2.7b). The shape of these objects is a circular with 30-cm diameter. At this location, we collected a sediment sample under basement of ancient remain and also collected 2 brick pieces. The first brick was collect from the basement of ancient remain and the second brick collect from the object that look like burner. By technique and grain size separation of TL sample, the systematic of separation and nomenclature of samples are submitted on Table A.4 (Appendix-A).


(a) (b)

Figure 2.7 (a) Ancient remain 4, the yellow circle show location of ancient burner and (b) Ancient burner.

D) Ancient Remain 6

Ancient remain 6 situated in the center of Thung Tuk town plan (Figure 2.3). This shows the basement of ancient remain emerged from the land surface (Figure 2.8). The size of this ancient remain is 3.40X3.60 meters. In ancient remain 6, we collected only a brick piece from the remnant part of ancient remain to check/confirm the age of Thung Tuk archaeological site and compared with the age from the other stations. After collection of sample, the systematic of separation and nomenclature samples were undertaken (Table A.5) (Appendix-A).

Figure 2.8 A close-up view of ancient remain 6 showing brick sampling point for TL dating.

E) Ancient Remain 8

In ancient remain 8, the size of this station is 5.50X6.50 meters. We collected a brick piece from basement of ancient remain (Figure 2.9a) and also collected sediments under the basement of ancient remain (Figure 2.9b). The systematic of separation samples and nomenclature are submitted on Table A.6 (Appendix-A).

(a)


(b)

Figure 2.9 Ancient remain 8; (a) Sampling point of a brick sample for TL dating (red circle) and (b) Layer of sediments under ancient remain and sampling point of sediments sample for TL dating (red ellipse).

F) Pit 1

Except exploration of ancient remain that is the significant evidence of ancient community in Thung Tuk area, we also excavated 2 archaeological pit in undisturbed area for study ancient settlement and evaluated chronological data of archaeological site. Due to excavation in pit 1, there is no evidence of ancient remain except some antique from sediment layer. The size of the pit is 3.00X3.00 meters in lateral plan and 1 meter in depth. There are 5 separated sediment layers can identify in pit 1 (Figure 2.10). Sediment characteristic in this area is sand and shown variegated colors in each layer. The details of each sediment layer are:

- Unit A: Human activities

Sediment in this layer is black to brown and consists largely of loose sand and plant debris. Thickness of this unit is 20 cm approximately (Figure 2.10). This sediment layer reveals human activities and agriculture activities including disturbation from root plants from surface. We collected a sediment sample for TL dating from the east side of the layer.

- Unit B: Top soil

Sediment in unit B is mainly sand like unit A and the color is brown to white suggesting high organic content due to biological decomposition such as root plants. Thickness of this unit is approximately 20 cm (Figure 2.10). This layer shows evidence of some bioturbation such as root plants and borrows. We collected 2 sediment samples from the west and the east side in this layer to confirm the dates in the same sediments layer and to correlate with the upper and lower unit.

- Unit C: Pale gray sand

Characteristic of sediment in this unit is the abundance of quart-rich sand with pale gray color (Figure 2.10). Thickness of this unit is approximately 15 cm. Along excavation, we found some antiques in this unit such as Tang's dynasty pottery, Persia glassware, and local earthenware. Srisuchart (1986) determines the relative age of these antiques using historical evidence at 1,200-1,500 years. Moreover, Chaisuwan and Naiyawatt (2002) determined the ages of archeological site from 3 organic fragments found in this layer by conventional radiocarbon dating method. The ages from this dating method are show in Table 2.1.

Table 2.1 Conventional radiocarbon dates from organic fragments collected in sediment unit C in pit 1, Thung Tuk archaeological site (Chaisuwan and Naiyawatt, 2002).

| Sample number | Type of sample | Age (year) |
|---|---|---|
| OAP 2120 | Charcoal | 1,070±330 |
| OAP 2121 | Charcoal | 1,310±230 |
| OAP 2122 | Charcoal | 1,260±820 |

For this sediment unit, we decide to collect 2 sediment samples from the west and the east side in this layer to confirm the dates in the same layer. Comparisons of the TL with relative and radiocarbon dates are also considered.

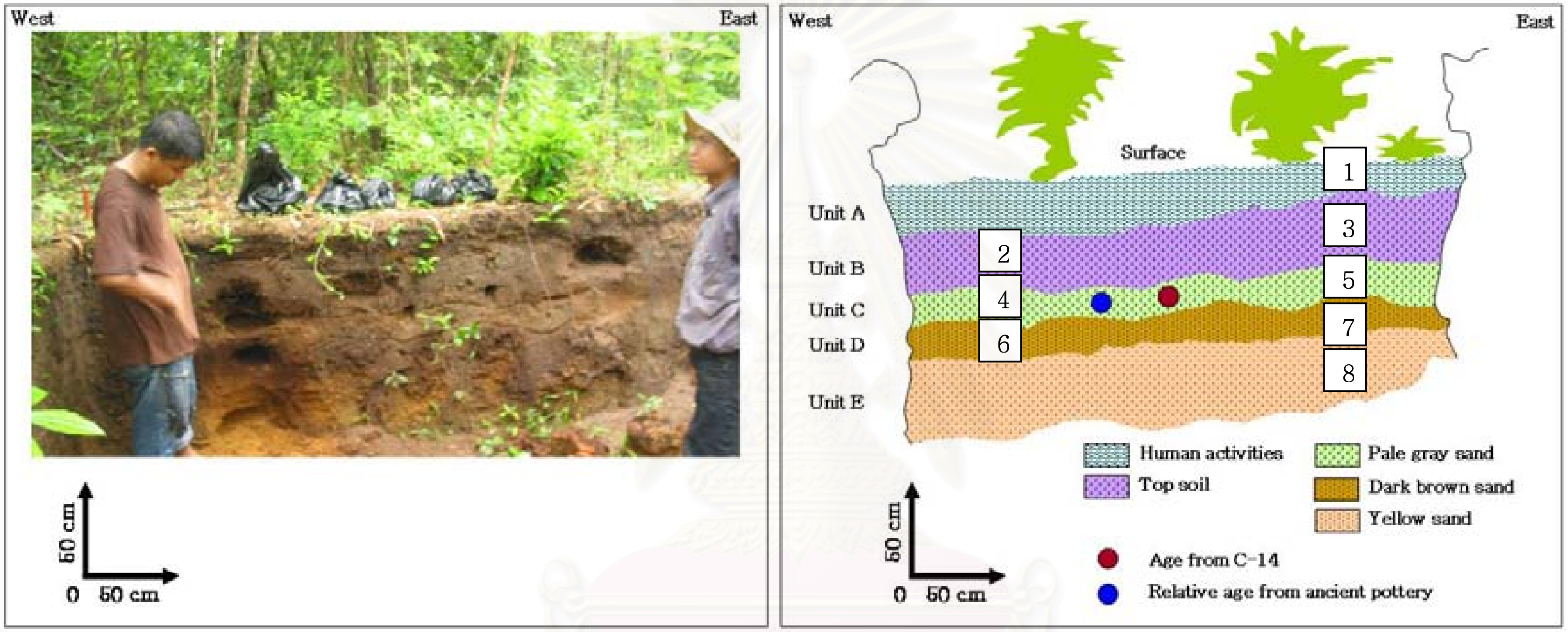
- Unit D: Dark brown sand

Sediment in this unit is dominated by quartz-rich sand with dark brown color. Thickness of this unit is approximately 15 cm. This sediment are quartz-rich, contain rather equal grains with good maturity not have disturbed by root plant or human activities. We collect 2 sediment samples from this sediment unit for TL dating (Figure 2.10).

- Unit E: Yellow sand

This sediment layer is the thickest layer from pit 1. Thickness of this layer from upper unit boundary to bottom of pit is 30 cm. Most of the sediments are sand with yellow color. There is no evidence of biological disturbance in this unit. We collected a sediment sample from east side of pit.

After sample collection, we separated each sample in 4 portions based on technique and grain size separation from Figure 2.1. The systematic sample separation and nomenclature are shown on Table A.7 (Appendix-A).




| Number | Sample name |
|---|---|
| 1 | = TTp 4-0.2 |
| 2 | = TTp 4-1.1 |
| 3 | = TTp 4-1.2 |
| 4 | = TTp 4-2.1 |

| Number | Sample name |
|---|---|
| 5 | = TTp 4-2.2 |
| 6 | = TTp 4-3.1 |
| 7 | = TTp 4-3.2 |
| 8 | = TTp 4-4.2 |

Figure 2.10 Quaternary stratigraphy of pit 1, Thung Tuk archaeological site and the sampling point for TL dating.

## 2.3 Laboratory Analysis

TL laboratory procedure proposed by Takashima and Honda (1989) is applied for this research study. The methodology of analysis is composed of 2 main procedures, including equivalent dose evaluation and annual dose evaluation (Figure 2.11).

### 2.3.1 Crushing and Sieving

Upon arrival in the laboratory, TL samples normally were dried by 40-50 °C bake in the dark room. Water content is also measured for all samples being dated because it is the one significant parameter for annual dose determination. The formula of water content calculation is;

$$\frac{\text{(weight of a wet sample- weight of a dried sample) X 100}}{\text{weight of a dried sample}} \quad \text{(Eq.2.1)}$$

After getting dried sample, each sediment sample was shattered by using a rubber-hammer and the material passed through sieves to isolate the grain size fraction in 2 parts. Sediments which grain size pass through a 20 mesh (<841μm) were collected about 300 g was separated to keep in plastic containers for annual dose determination. Remnant part from annual dose collection is carefully re-sieved and the material passed through sieves to isolate the grain size fraction between 60-100 mesh (149-250μm) and 100-200 mesh (74μm-149μm). Both of these portions were kept in beakers for purifying quartz grained and equivalent dose determination, respectively.

In the case of brick samples, a slice of several millimeters thickness was cut for eliminating the outer most part of bricks that might be exposed to light before arrival laboratory (Bailiff and Holland, 2000). After removing the outer rim, cut a segment for annual dose assessment. The remaining part of the slice is used for equivalent dose determination. The methodology of crushing and sieving sample size for each portion is similar to the routine method used in sedimentological study.

When complete this step, the cut slice was split into 4 portions including one portion for water content determination and the other 3 portions consisting of a portion for annual dose analysis (grain size<841μm, 300g) and two portions for equivalent dose analysis (grain size 74μm-149μm and 149-250μm) (Figure 2.12b). In the annual dose, a sample portion is ready and skips to the measurement step but in both of two portions for equivalent dose determination necessary to participate in chemical treatment.

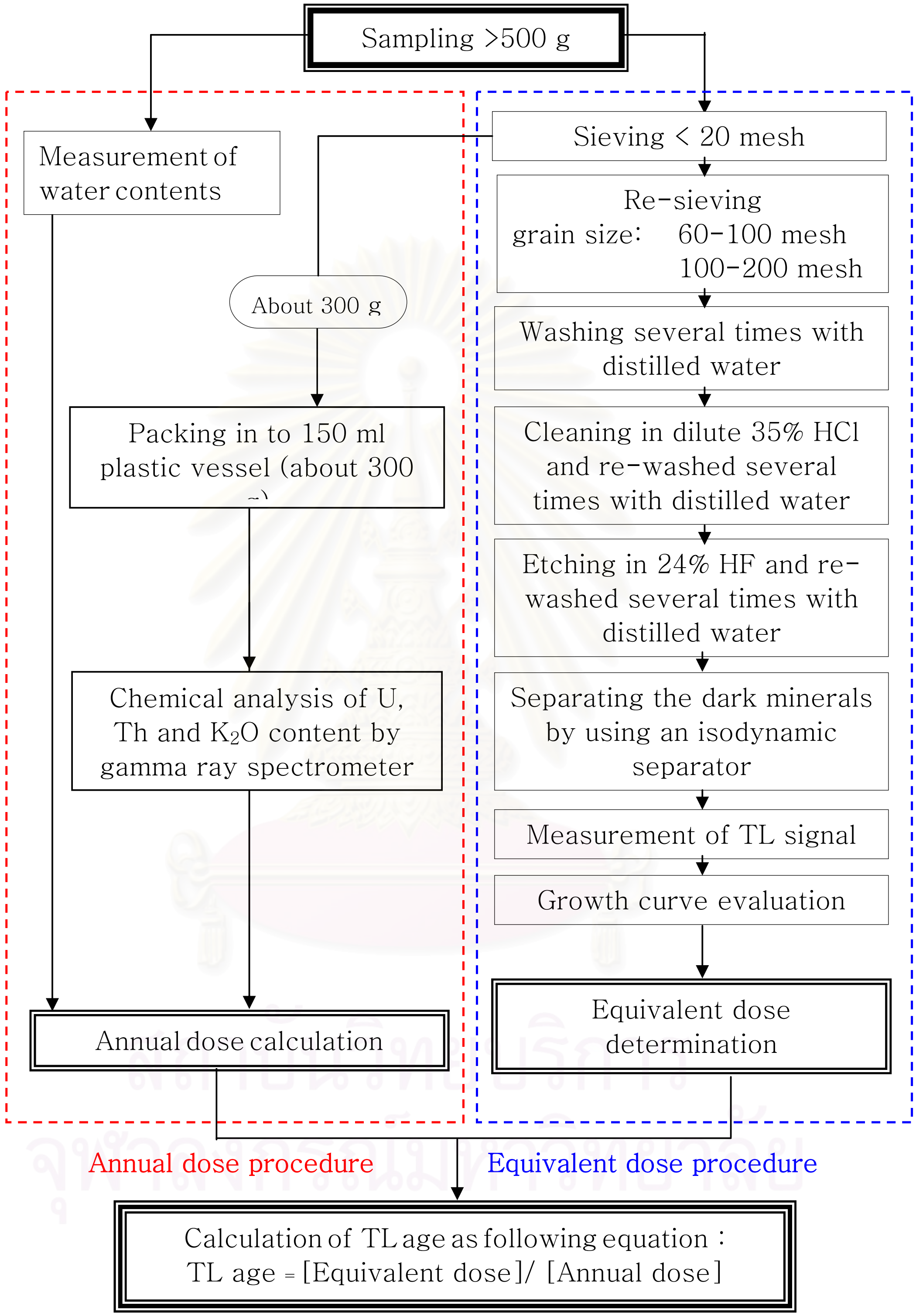



Figure 2.11 Simplified flow chart illustrating laboratory analysis use in this research study. The red dash line is the annual dose procedure and the blue dash line is the equivalent dose procedure (modified from Takashima and Honda, 1989).

### 2.3.2 Equivalent Dose Evaluation

#### A) Chemical Treatment

The main objective of chemical treatment is purification of quartz mineral in TL samples from the method that keeps off destroying the signal of sample. The detail of chemical treatment is show below.

a) Washing the sample by distilled water 10 times for remove some organic materials and clay particles (Figure 2.12a).

b) Chemically cleansed the sample in dilute 35% HCl at 50-60 °C in a period of 15-30 minutes and re-washed several times with distilled water for eliminating carbonates and deep-rooted organic material.

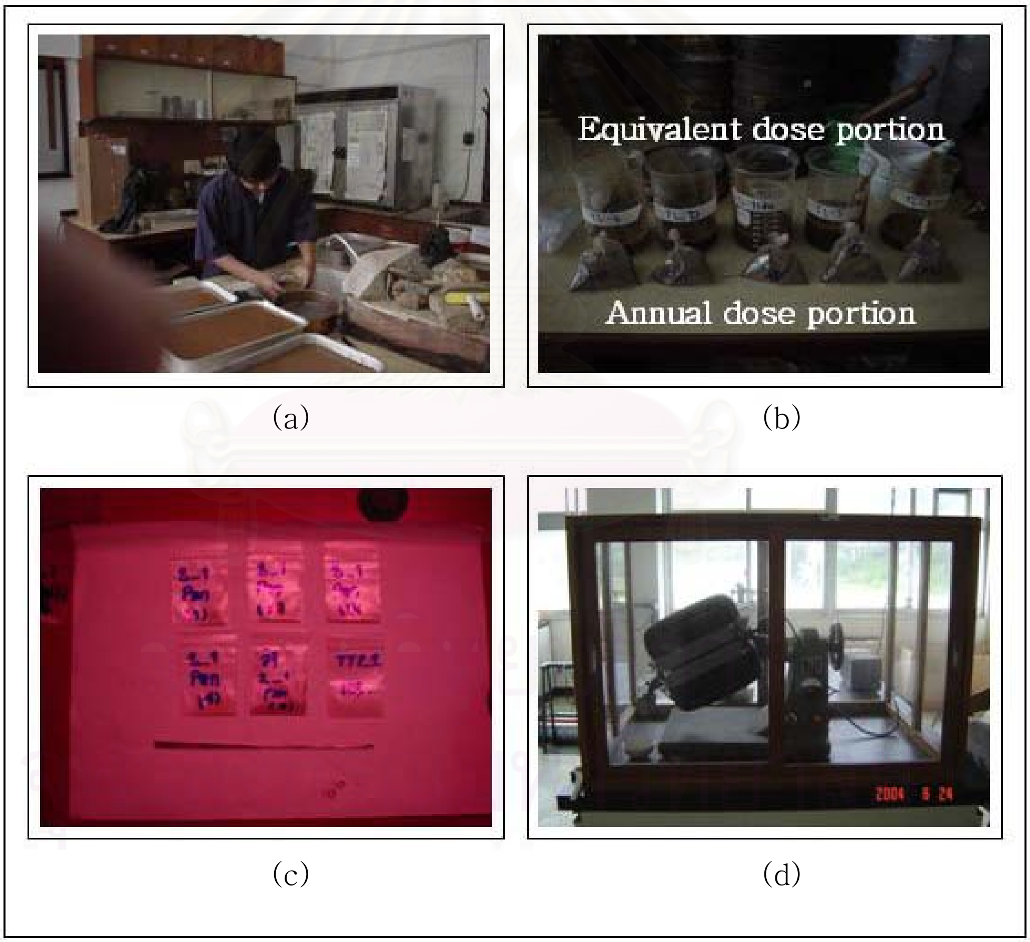



Figure 2.12 Sample treatment for TL dating method; (a) Washing by distilled water, (b) Two parts of grain size isolation consist of annual dose portion and equivalent dose portion, (c) Pure quartz concentrates in plastic bags, and (d) Frant'z isodynamic magnetrometer from Department of Mineral Resources (DMR) in Bangkok.

c) Etching the sample in 24% HF at 50-60 °C for 15-30 minutes and re-washed it several times with distilled water. HF was used to dissolve the plagioclase and outer layer of quartz grains to a depth sufficient for the core remaining to have a negligible component of alpha particle dosage.

d) After washing with water and drying in the dark room, the dried sample was then separated to remove out the dark minerals (e.g. zircon, garnet, and metallic minerals) by using an isodynamic separator from Department of Mineral Resources (Frant'z isodynamic magnetrometer; Figure 2.12d).

After finishing sample treatment, it is necessary to check purity of quartz sample by XRD analysis (Figure 2.13). If the quartz-rich samples contain less than 10% of the other minerals, the samples were supposed to contain pure quartz concentrates (Figure 2.12c). Then the sample was ready to determined equivalent dose in the next step.

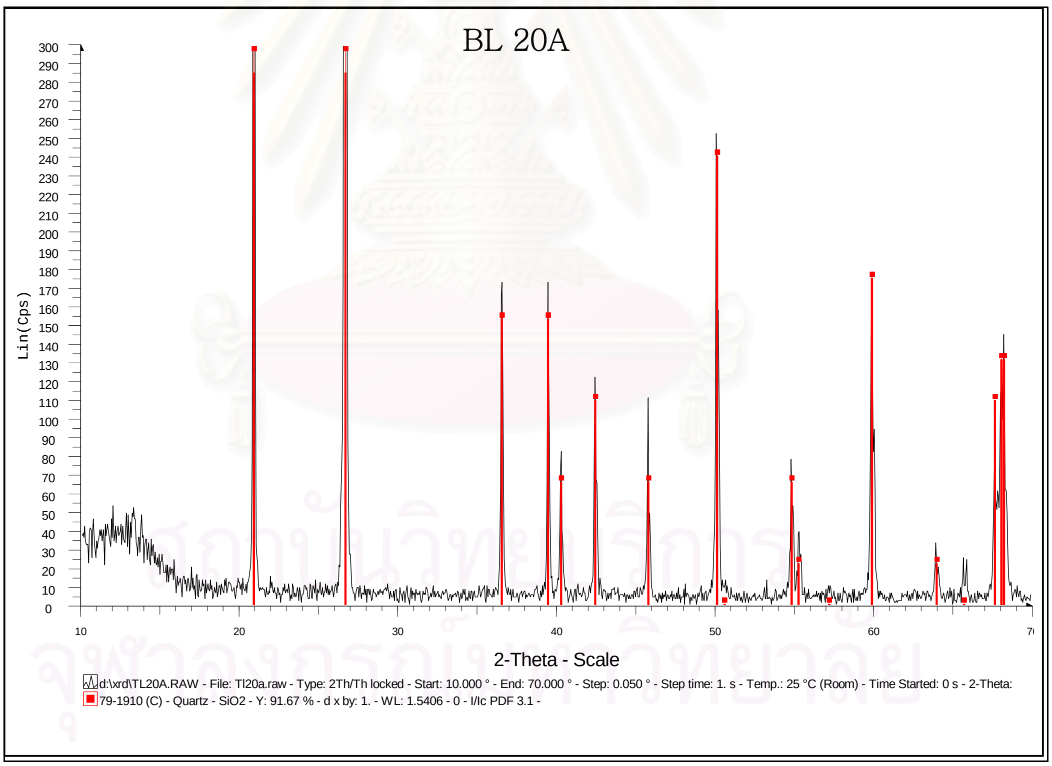



Figure 2.13 XRD result of sediment sample no. BL20A from Ban Bom Luang trench (Lampang province) after chemical treatment. Graph showing matching between sample peak (black line) and standard quartz peak (red line).

### B) Sample Preparation for Equivalent Dose Measurement

The pure quartz sample after chemical treatment is subdivided into 3 parts:

- Part1: Natural quartz sample used for evaluated natural sensitivities of previously acquired TL signal.
- Part2: Sample was exposed directly with natural sunlight for 12 hours (Aitken, 1985) to effectively remove all of the previously acquired TL leaving only what is termed as the unbleachable TL signal. This part used for determining residual levels.
- Part3: Sample used to find out the characteristic of quartz effective with artificial irradiation that amount of radioactive irradiation (in unit Grey) is known. The gamma ray source for artificial irradiation is a $^{60}Co$ from Office of Atomic Energy for Peace (OAEP), Bangkok. The details of artificial irradiation with TL sample in this research are shown in Appendix-B.

### C) Equivalent Dose Measurement

Evaluation of equivalent dose commences with measurement of TL intensities on 3 sample portions: 1) natural sample portion, 2) artificial irradiation sample portion and 3) residual sample portion (in case of sedimentary sample). The TL emission of quartz were measured by using the Kyokko 2500 TLD dosimeter (Figure 2.14) with the constant heating rate of 200 °C per minute with a well-equipped air condition at Akita University, Japan. About 20 mg of sample was filled in aluminum planchettes and placed on a molybdenum heater. The sample is heated on a molybdenum disk under nitrogen condition to 450 °C. Filter system applied in this research study is a blue filter (Toshiba IRA-10). The light emission is amplified and measured by photomultiplier and record simultaneously with the temperature of the sample. The graph shows a relationship between TL intensity and temperature which is called “glow curve” (Aitken, 1985). The term glow curve is given to plot intensities of emitted light versus temperature (Figure 2.15). The light is recorded and in this way it is possible to a establish TL growth curve which relates TL output and the absorbed radiation dose (Figure 2.17). Calculation of equivalent dose can be done by extrapolating natural signal intensity and residual signal intensity with a growth curve from artificial irradiated signal intensity. The result is assumed to be proportional to the equivalent dose of Eq.1.1 in Chapter I.


Figure 2.14 Kyokko 2500 TLD dosimeter at Akita University, Japan; that is used for TL glow curve measurement.

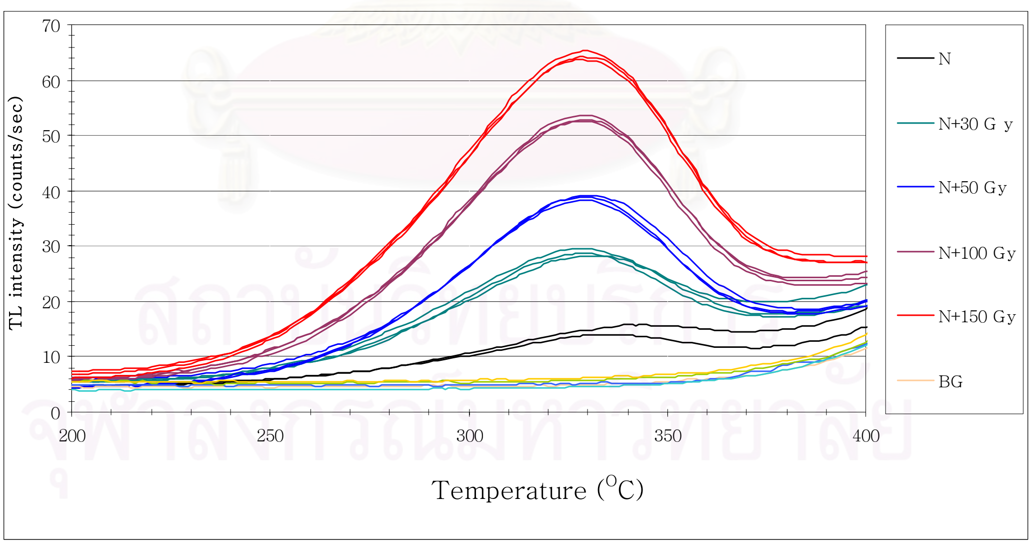



Figure 2.15 Glow curve of sample no. TT1-1AB, Thung Tuk archaeological site, Pang Nga province. The graph shows a graph relationship between TL intensity versus temperature. The graph measured from thermoluminescence detector (TLD) at Department of Mineral Resources (DMR), Thailand.

Although the glow curve shown in Figure 2.15 is smooth continuum, it is really composed of stable and unstable signal. The TL signal in a stable region of glow curve should be considered by the plateau test method (Aitken, 1985) (Figure 2.16). This procedure makes by compare the shape of the natural glow-curve (i.e. the glow-curve observed from a sample which has not received any artificial irradiation in the laboratory) with the artificial glow-curve observed as a result of artificial irradiation.

Thus a constant ratio between natural and artificial glow curves gives an indication that, throughout this plateau region, there has been negligible leakage of electrons over the centuries that have elapsed since all traps were emptied in the course of the stimulation by ancient environment.

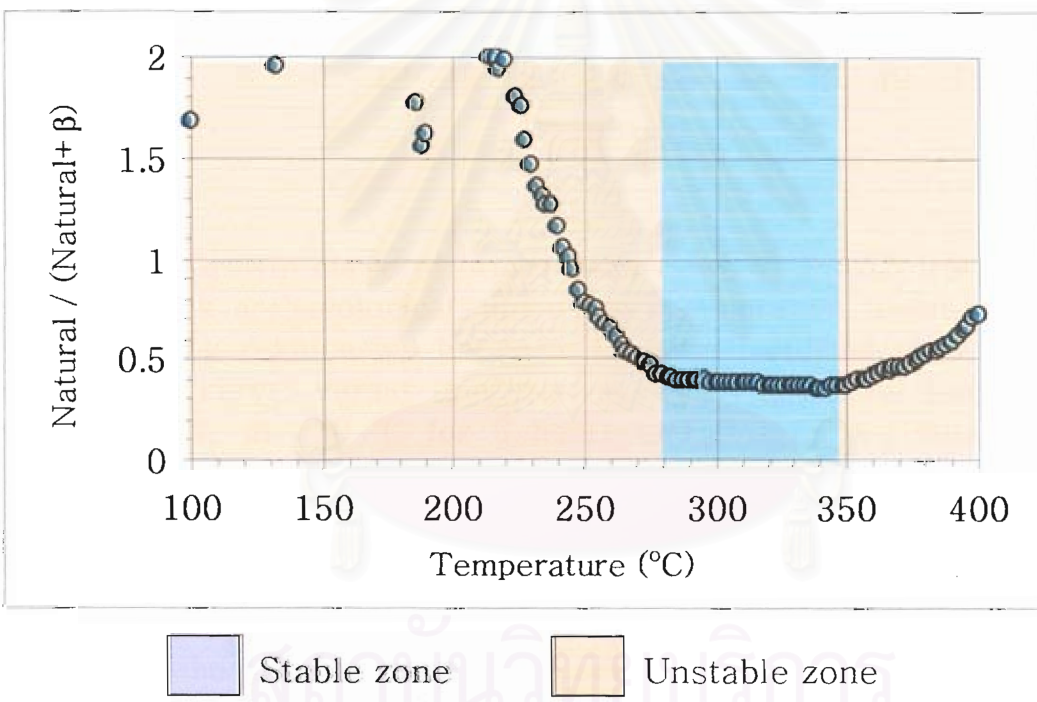



Figure 2.16 Plateau test of sample no. TT1-1 AB from Thung Tuk archaeological site showing a relationship between natural/artificial ratios from glow-curves versus temperature (°C)

The next step is for the construction of growth curve. This can be done by the increases of TL output with known amounts of additional radiation that induced the sample. The graph showing this relationship is called " growth curve" (Figure 2.17).

In this research 2 technique of equivalent dose evaluation are used-one is the total bleach technique (Yeats et al., 1997) and the other is the regeneration technique (Takashima and Honda, 1989).

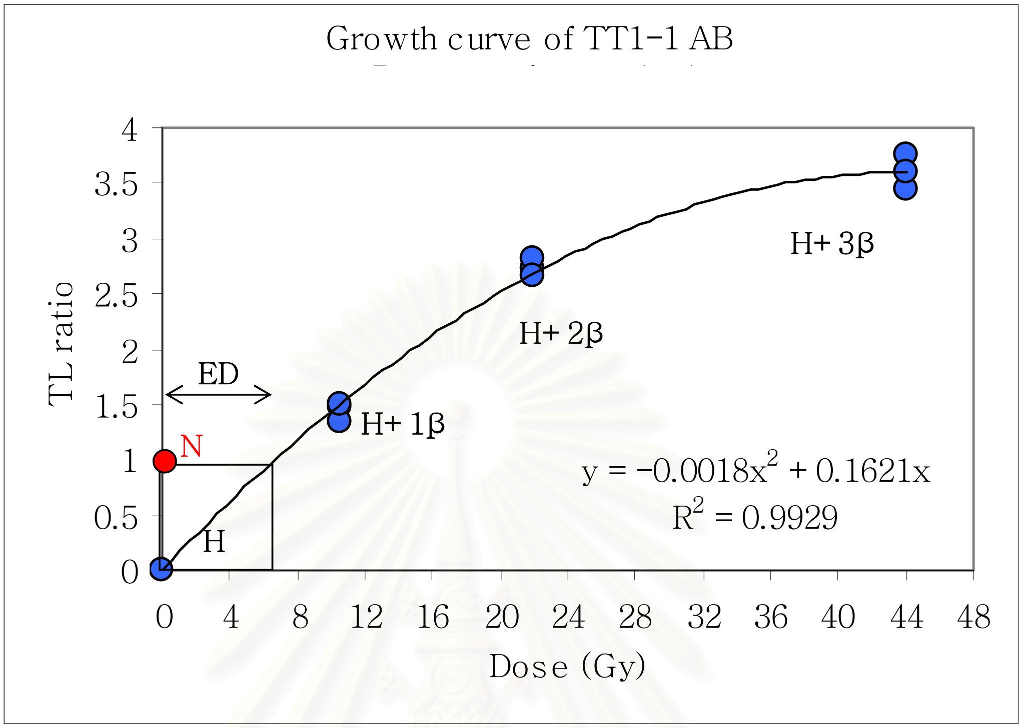



Figure 2.17 Growth curve of bricks sample no. TT1-1AB from trench 1, Thung Tuk archaeological site using regeneration technique. The curve showing relationship between TL ratio (artificial glow curves/ natural glow curve) versus temperature (°C). N is natural signal, H is heated sample at 320 °C for 5 hours and βis known dosage that irradiated sample.

- <u>Total bleach technique</u>

The total bleach technique was introduced by Yeats et al. (1997) is basically the similar procedure as additive dose technique that used for pottery (Aitken, 1985). This technique (Figure 2.18) starts from measuring TL intensity of a natural sample (N) compared with those of the artificial irradiated samples that set up from the same sample. The sample was exposed to artificial irradiation from radioisotope source, at known certain dosages (e.g. 30Gy, 100Gy, and 300Gy). The intensity of the natural sample (N) plus additive artificial irradiate dosage is shown as N+β (e.g. N+30Gy, N+100Gy, and N+300Gy). After irradiation, the unstable signals of the sample must be excluded by heating at 130 °C for 24 hours for eliminated effective from alpha particles. The equivalent dose is read from a starting point of horizontal line drawn at the level of the natural thermoluminescence.

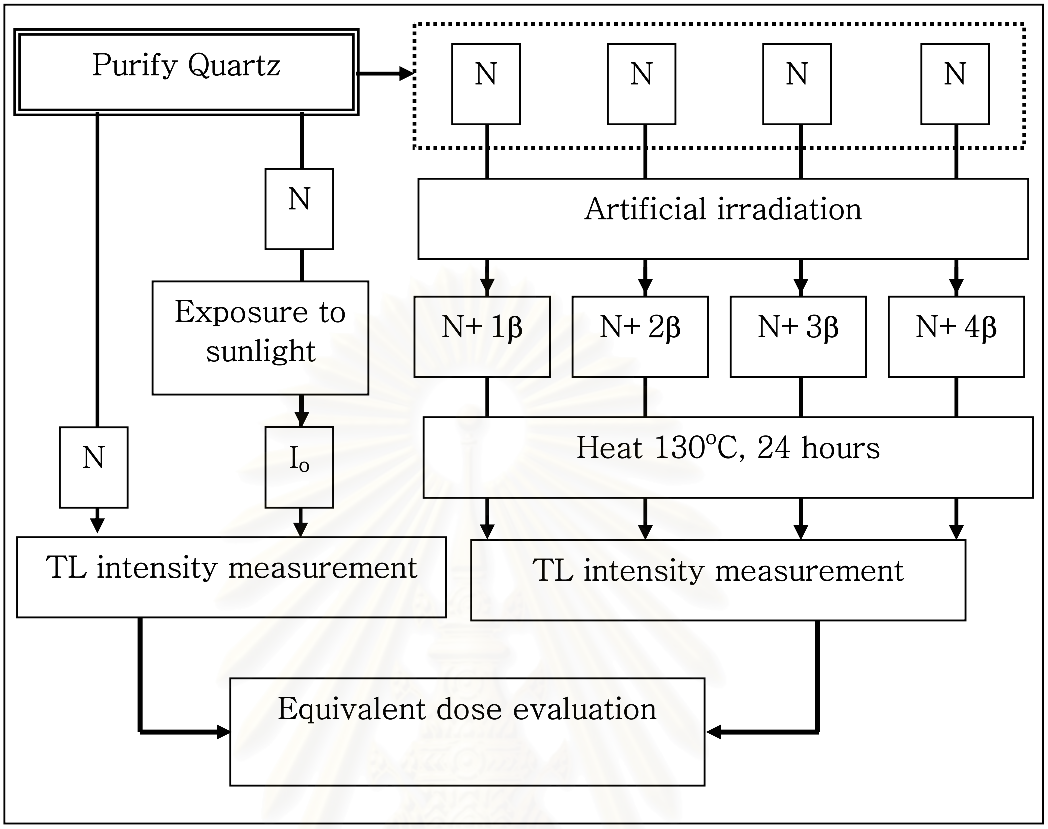



Figure 2.18 Schematic charts of total bleach technique frequently used in sediment dating. N is an intensity in a natural sample, Io is residual intensity from the same sample and β is known dosage that irradiated sample (Yeats, et al., 1997).

- <u>Regeneration technique</u>

In this technique, the simplest approach to the evaluation of equivalent dose is by the straight-forward procedure of measuring the natural TL intensity from a natural sample (N) and comparing it with the artificial TL intensity from the same sample that know certain dosage (artificial irradiate sample). The artificial irradiate sample was preheat in 320 °C and 5 hours duration which were enough to reset existing TL signals to zero level (Takashima et al., 1989). The preheated samples (H) were exposed to artificial irradiation from radioisotope source, which can control the certain dosage (e.g. 30Gy, 100Gy, and 300Gy). The preheat sample (H) adds artificial irradiate shows as H+β (e.g. H+30Gy, H+100Gy, and H+300Gy). After irradiation, the unstable signals of the samples must be excluded by heating at 130 °C for 24 hours (Figure 2.19). The equivalent dose is read from a starting point of horizontal line drawn at the level of the natural thermoluminescence.

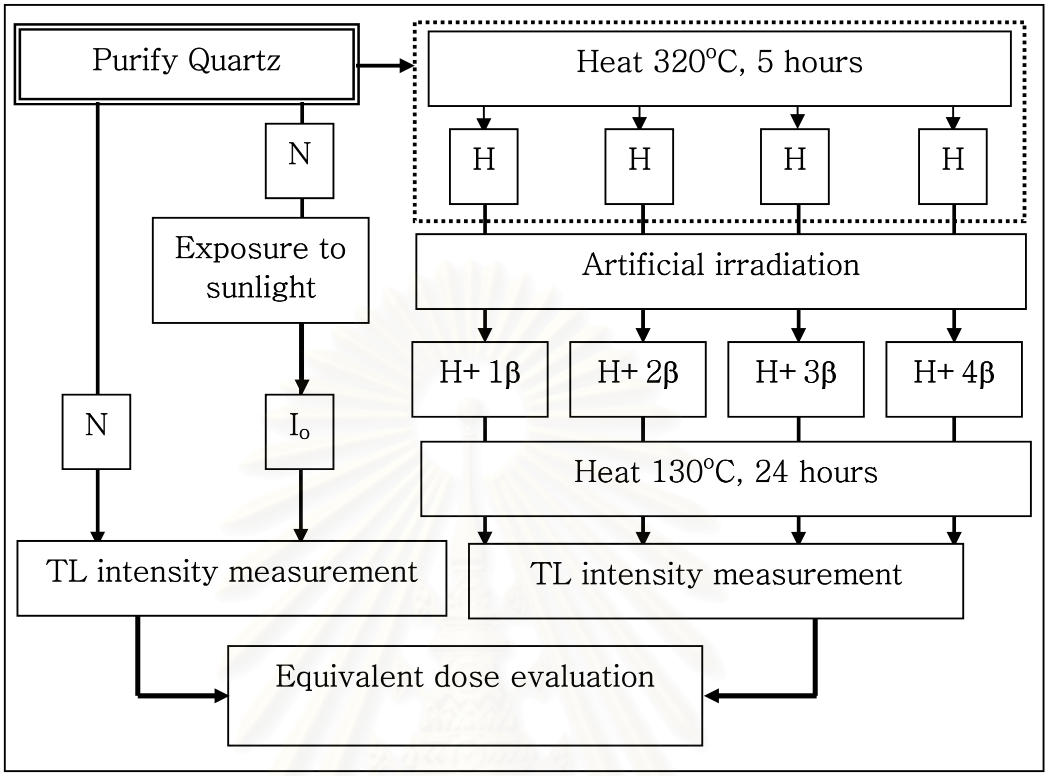



Figure 2.19 Schematic charts of regeneration technique (Takashima et al., 1989). Several portions are used for measurement of the TL intensity; N is natural sample, Io is residual intensity from sample, H is 350°C heated sample and β is known dosage that irradiated sample.

- Residual test

In case of sediment sample, evaluation of equivalent dose is complicated by the need to allow for the fact that the equivalent dose is composed of two components: the natural TL signal acquired since deposition and the residual signal that the sample had when it was deposited in the last time.

Many scientists (e.g. Wintle and Huntley, 1980; Tanaka et al., 1997) proposed several methods to simulate the light source exposures. Samples were exposed to some kinds of light sources. Natural sunlight, UV-ray lamp (365 nm) and xenon lamp were the important illumination sources for bleaching experiments (Won-in, 2003). In this research study, the naturally bleaching experiment by sunlight requires and depends significantly upon a long sunny day. For the artificial bleaching experiment, it is important to check the minimum of time that can completely bleach samples to the residual level and how much residual level in each sediment sample. The methodology of residual testing starts with bleaching sample and check TL intensity of sample in every 1 hour. Plotting graph showing a relationship between TL intensity and time use for bleaching reveal the minimum time that residual signal begin stable (unbleachable).

### 2.3.3 Annual Dose Evaluation

Generally sediments are exposed continuously to ionizing radiation which originates from their radioactive contents, plus a small fraction from cosmic rays (Aitken, 1985). There are essentially 3 radioactive elements which contribute to the natural dose rate (annual dose) i.e. uranium (U), thorium (Th) and potassium ($K_2O$). The decay of uranium and thorium results in α, β and ɣ radiation whereas potassium emits β and ɣ. Normally, the natural dose rate in most sediments is of the order of mGy/year.

For age determination it is necessary to evaluate the natural dose rate accurately. Several components are needed for an accurate annual dose is

1. Measurement of U, Th and K contents,
2. Calculation of environmental water content in field at time of sample collection, and
3. Cosmic ray component evaluation.

The annual dose to the sample is computed from the concentrations of K, U and Th by the method described by Bell (1979) and Aitken (1985).

| | |
|---|---|
| Annual dose (AD) = | $D_\alpha + D_\beta + D_\gamma + D_c$ ______________________ (Eq. 2.2) |
| Where | α= Alpha irradiation content,<br>β= Beta irradiation content,<br>ɣ= Gamma irradiation content, and<br>C = Cosmic ray irradiation content. |

#### A) Measurement of Uranium, Thorium and Potassium Contents

Figure 2.20 shows the schematic preparation and procedure for measurement U, Th and $K_2O$ contents by gamma ray spectrometer. The first step is to select equal grains of samples being dated by sieving with 20 mesh sample. The samples are contained in the plastic vessel (Figure 2.21). A plastic vessel with 300 g sample is put on 75 mm NaI sincirator unit with a multi-channel analyzer unit. Chemical analyses were performed by gamma ray spectrometry at Akita University, Japan

(Figure 2.22). The detector employed was a 76∅ x 76 mm NaI (T1) scintillator connected to a multichannel analyzer (Takashima and Watanabe, 1994). Standard samples employed were NBS samples for U and Th, and $K_2O_3$ chemical reagent for K. Each sample was measured for two days (Kalchgruber et al., 2002). The estimated standard errors were less than 10% for U and Th, and less than 3% for K using the fixed count error calculation method (Takashima and Watanabe, 1994).

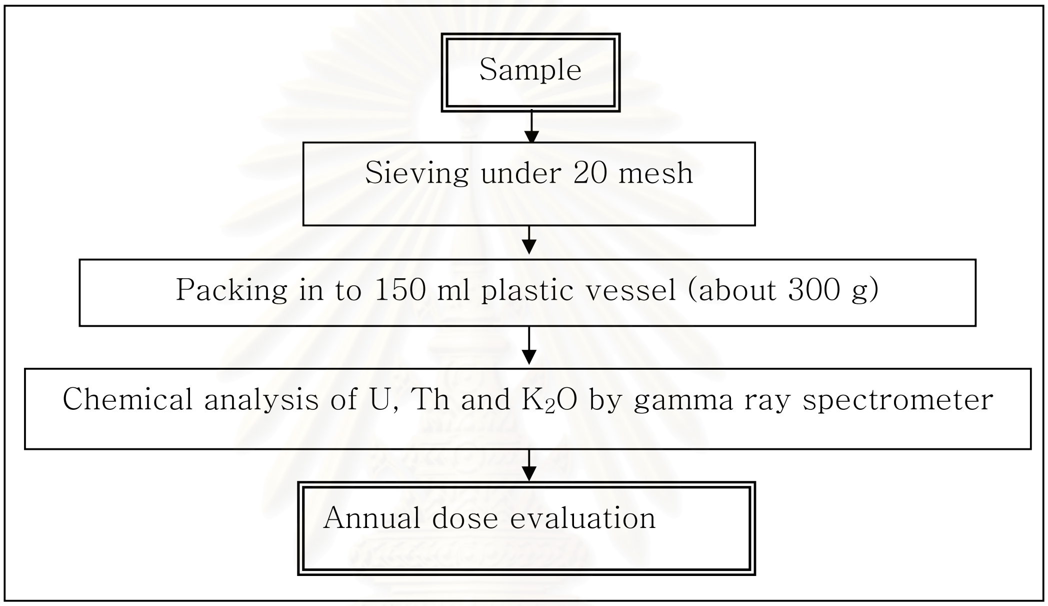



Figure 2.20 Summary of gamma ray spectrometry procedure with sample preparation and annual dose determination (Takashima and Watanabe, 1994).

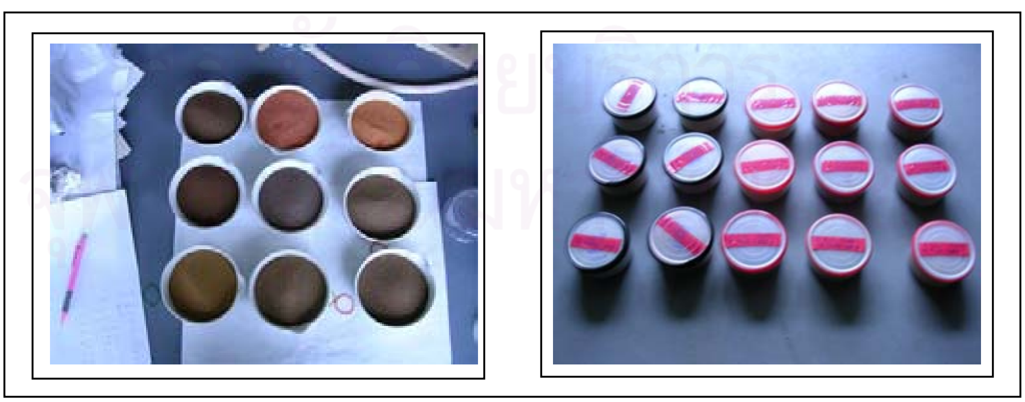


Figure 2.21 TL sample packing in plastic vessel for uranium, thorium and potassium measurement.

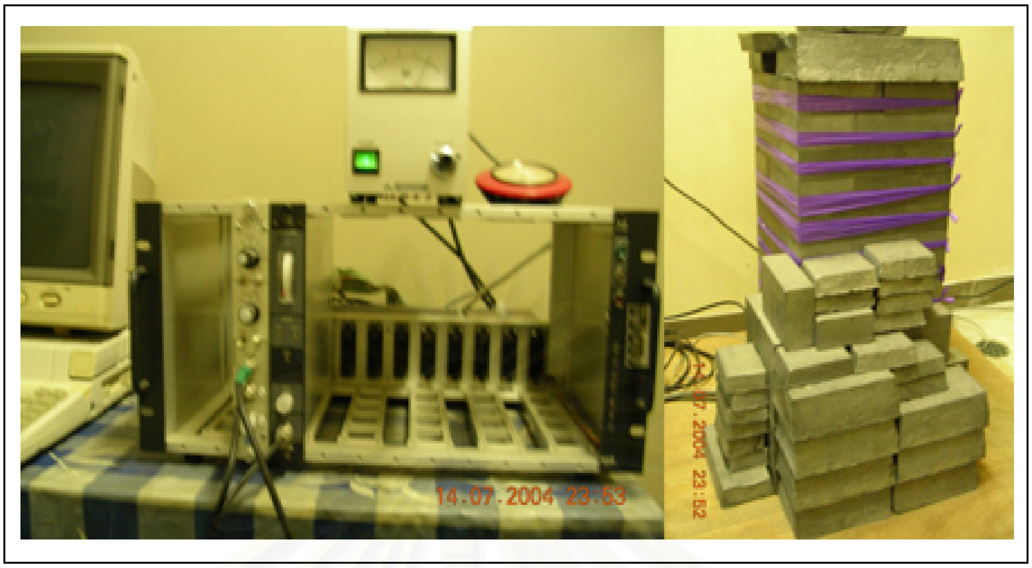



Figure 2.22 Gamma ray spectrometer at Akita University, Japan. This equipment is used for measure uranium, thorium and potassium contents.

B) Annual Dose Calculation

Annual dose is calculated from chemical data of U, Th and $K_2O$ contents with the equation proposed by Bell (1979) and Aitken (1985).

$$\begin{aligned} AD = \; & [0.15(2.783U + 0.783Th)/(1+1.50(W/100))]+ \\ & [(0.1148BU + 0.0514BTh + 0.2069BK)/(1+1.14(W/100))] + \\ & [(0.1462U + 0.0286Th + 0.6893K)K/(1+1.25(W/100))]+ \\ & 0.15 \qquad \text{(Eq. 2.3)} \end{aligned}$$

Where AD = Annual dose (mGy/year),
U = Concentration of uranium in ppm,
Th = Concentration of thorium in ppm,
K = Concentration of potassium oxide (%),
B = Beta coefficient in quartz grains, and
W = Water content (%).

# CHAPTER III

# RESULTS

Results of this research study can be divided into 3 main portions for convenient and comfortable discussion in the next chapter. They include thermoluminescence procedure results, dates from Ban Bom Luang trench and dates from Thung Tuk archaeological site and also electron spin resonance dating for some samples.

## 3.1 Thermoluminescence Procedure Results

According to the main objective of this research, it is essential to clarify TL dating particularly its behavior in the details of physical properties. Consequently, we ought to concentrate and realize in every procedure which involves in getting the TL dates. The advantages of understanding each procedure results will not only confirm the date's value of each sample but also visualize the technical problem are causes of dating error. The results of TL procedure includes XRD results, glow curve results, plateau test results, growth curve results, residual testing results and annual dose calculated from uranium, thorium and potassium content.

### 3.1.1 XRD Results

After completely chemical treatment of sample for extracting quartz mineral from unwanted minerals such as clay mineral, feldspar mineral, ferrous mineral and also organic material etc., the XRD test is conducted to check and ensure composition of treated sample comprising only quartz mineral or not. The results of XRD checking in this research reveal high peaks that can refer to peaks of quartz mineral and lack characteristics of other mineral peaks in most treated samples.

However, by detailed investigation, excepted quartz peak, all of the XRD results show a mixture with some awkward peaks. These awkward peaks cover approximately in 10 °-20 ° of 2 theta scales in XRD angle condition (Figure 2.13).

### 3.1.2 Glow Curve Results

In this research, the graph which traces the variation of the TL intensity with increasing temperature is known as the glow curve of the sample. Generally, TL glow curve exhibits one or more peaks (Aitken, 1985), which occur whenever the increasing thermal energy of the crystal becomes sufficient to release electrical charges from the various traps in which it is held.

Based on glow curve results (see Appendix-C), all of the samples show a set of glow curves exhibiting the single sharp peak at 280-350 °C approximately. In individual dates, several portions of the same sample were measured to obtain the series of glow curves. Some of the portions were given by artificial radiation doses before their measurement, while others were left unirradiated. The series of glow curves in each sample illustrate increasing the intensity of the TL peak grows as the radiation exposure increases (N+$\beta$ in case of total bleach technique, H+$\beta$ in case of regeneration technique). The TL emission produced by the unirradiated portions (the black grow curve in Appendix-C) is known as the natural TL signal (N), since it results from the radiation dose accumulated by the sample in the natural environment over geological time.

However, from the grow curve results in Appendix-C, there are some glow curves that are different from the other glow curves, such as a glow curve of brick sample no. TT3-3AB from Thung Tuk archaeological site (see Figures C.1.1 and C.1.2). These glow curves illustrate the strange glow curve when compared with the other. So, in selecting representative glow curve value for growth curve construction, we ought to consider it carefully. Moreover, we have to realize that the dates from these glow curves may be lower reliable ages.

### 3.1.3 Plateau Test Results

Since the low temperature part of the TL glow curve is subject to decay at normal environmental temperatures, its shape will be markedly different for an artificial irradiated dose read out immediately and for a natural dose accumulated over centuries. It is necessary therefore to use data only from a temperature range where the curves have the same shape. This may be found simply by dividing a natural glow curve by the artificial irradiated dose glow curve in every temperature, the so-called "plateau test".

As shown in Appendix-E, all plateau tests yield characteristic of parabolic curves and show flat curves between 280-360 °C approximately. These ranges from flat curves can be referred to stable zones that can be representative glow curve data for growth curve construction. The detailed plateau ranges in each sample are described in Appendix-E.

### 3.1.4 Growth Curve Results

The TL intensity of TL glow peak was chosen for representative intensity of each curve for constructing the TL growth curve. All of the intensities were divided by average natural intensity, and they were plotted on a graph showing relationship between TL ratio and added doses (Appendix-F).

The vertical axis was set by TL ratio, and horizontal axis was set by irradiated dose (Gy unit) which was added in the sample. The graph which records the growth of TL intensity versus increasing radiation dose is referred as its growth curve (Appendix-F). From the growth curves, natural dosage and residual dosage (including equivalent doses) can be measured if they are comfortably below the saturation dose. The results of equivalent dose in each sample are shown in Table 3.5 for Ban Bom Luang trench and in tables 3.6-3.11 for Thung Tuk archaeological site.

### 3.1.5 Residual Test Results

In this research, sample no. TTp4-2.1 from Thung Tuk archaeological site was selected for determining characteristics of bleaching in a coastal dune environment while sample no. BL10A from Ban Bom Luang trench was selected to represent colluvial or alluvial environment. From the residual testing experiment, these two samples were bleached by natural sunlight with sediment size of 149-250 μm. The results of TL intensity from sample nos. TTp4-2.1A and BL10A are shown in Table 3.1. The residual level of natural signal for sample no. TTp4-2.1A is 28% while that of the sample no. BL5A is about 58%.

### 3.1.6 Concentration of Uranium, Thorium and Potassium

In evaluating the annual dose which the thermoluminescence builds up, we need to know the rate at which ionization is being created in the crystals of the sample. The purpose of the radiation survey is to measure the concentrations of the naturally occurring radioactive elements; uranium, thorium and potassium, in the sedimentary deposits which surround the sampling location. The radioactive elements concentration determined by instrumental neutron activation analysis or performed with a portable gamma spectrometer which counts gamma rays emitted by the radioisotopes, and identifies their energies emitted. Samples of the burial deposits are collected for supplementary laboratory analyses of their radioactivity, and for measurement of their

Table 3.1 Remnant TL intensities of quartz concentrates with the size range 149-250 µm after bleaching by natural sunlight for each time. Sample no. TTp4-2.4A collected from pit 1, Thung Tuk archaeological site. Sample no. BL10A collected from Ban Bom Luang trench.

| Sample number \ Bleaching time | Natural signal | 1 hour | 2 hours | 4 hours | 6 hours | 8 hours | 10 hours | 12 hours | 14 hours | 16 hours | 18 hours |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TTp4-2.1 A | 260 | 115 | 99 | 75 | 65 | 65 | 68 | 73 | 70 | 70 | 85 |
| | 300 | 127 | 107 | 63 | 64 | 75 | 85 | 70 | 60 | 70 | 80 |
| | 250 | 101 | 75 | 70 | 68 | 81 | 65 | 66 | 70 | 70 | 65 |
| BL10 A | 64 | 47 | 44 | 35 | 32 | 30 | 29 | 24 | 24 | 26 | 25 |
| | 63 | 46 | 45 | 37 | 31 | 28 | 28 | 26 | 26 | 28 | 27 |
| | 61 | 48 | 45 | 35 | 31 | 30 | 24 | 27 | 30 | 30 | 26 |

water content. The radioactivity and water content value are shown in Table 3.2.

Table 3.2 Concentration of Uranium, Thorium, Potassium and water contents for the analyzed samples from Ban Bom Luang trench (sample no. BL) and Thung Tuk archaeological site (sample no. TT).

| Sample number | Uranium content (ppm) | Thorium content (ppm) | Potassium content (%) | Water content (%) |
|---|---|---|---|---|
| BL5 | 2.20 | 8.03 | 1.39 | 3.84 |
| BL10 | 2.10 | 8.45 | 1.25 | 12.95 |
| BL11 | 2.21 | 7.74 | 1.28 | 11.81 |
| BL20 | 2.27 | 8.41 | 1.34 | 15.51 |
| TT1-1 | 10.49 | 58.78 | 1.88 | 9.69 |
| TT1-2 | 5.10 | 21.34 | 0.72 | 18.94 |
| TT3-1 | 9.83 | 46.58 | 2.33 | 14.00 |
| TT3-2 | 3.02 | 7.34 | 0.13 | 8.74 |
| TT3-3 | 22.73 | 94.92 | 2.00 | 2.15 |
| TT3-4 | 22.35 | 62.57 | 1.93 | 1.55 |
| TT3-5 | 22.35 | 62.57 | 1.93 | 1.55 |
| TT4-1 | 9.18 | 44.06 | 2.32 | 14.00 |
| TT4-2 | 2.32 | 6.77 | 0.18 | 11.29 |
| TT4-3 | 6.99 | 40.50 | 1.93 | 10.77 |
| TT6-1 | 20.85 | 72.74 | 2.13 | 0.28 |
| TT8-1 | 19.58 | 85.44 | 2.51 | 1.09 |
| TT8-2 | 1.22 | 2.4 | 0.01 | 2.45 |
| TTp4-0.2 | 1.03 | 2.29 | 0.02 | 1.69 |
| TTp4-1.1 | 1.26 | 3.77 | 0.02 | 8.87 |
| TTp4-1.2 | 1.31 | 2.78 | 0.02 | 1.82 |
| TTp4-2.1 | 1.15 | 2.89 | 0.01 | 5.34 |
| TTp4-2.2 | 1.30 | 3.55 | 0.02 | 3.74 |
| TTp4-3.1 | 1.65 | 7.09 | 0.02 | 14.08 |
| TTp4-3.2 | 1.19 | 2.36 | 0.01 | 2.39 |
| TTp4-4.2 | 1.15 | 2.10 | 0.02 | 9.31 |

### 3.1.7 Calculation of Annual Dose

Actually, procedure of annual dose calculation is so complex due to the variety ranges (length of travel before stopping) of the different components of the radiation particle. The potential of radiation particle are varied in individual type of particle: alpha particles (20-50 µm), beta particles (1-3 mm) and gamma rays (0.3 m) (Aitken, 1985) together with the contribution from cosmic rays, which is a minor one.

In contrast to alphas and betas, the range of gamma rays is approximately 0.3 meters and therefore much greater than the dimensions of most TL samples. This means that the contribution to the total annual dose, which comes from gammas, is dependent mainly upon the radioactive content of the sediment surrounding the TL sample. Like the alpha and beta rays, gamma radiation derives from the decay of naturally occurring radionuclide standard per 1 unit of radioactive element (ppm unit for uranium and thorium, % unit for potassium) proposed by Bell (1979).

Table 3.3 Components of annual dose (in µGy/year) for the naturally occurring radionuclide (Bell, 1979).

| Radionuclide | Concentration | Concentration of annual dose (µGy/year) | | |
|---|---|---|---|---|
| | | Alpha | Beta | Gamma |
| Uranium series | 1 ppm $^{232}Th$ | 2783 | 146.2 | 114.8 |
| Thorium series | 1 ppm $^{238}U$ | 738 | 28.6 | 51.4 |
| Natural potassium | 1 %K | - | 830.3 | 249.2 |

After detailed derived equation, the effect of water content attenuation, and the effect of variety potential of radiation particle are eliminated. The detailed annual dose equation in each gain size range of quartz minerals are shown below.

+ Grain-size range 74-149 µm

$$AD = [((0.91*0.1462U)+(0.86*0.0286Th)+(0.97*0.8303K))/(1+1.25W)] + [(0.1148U+0.0514Th+0.2492K)/(1+1.14W)] + [0.15] \quad \text{(Eq.3.1)}$$

+ Grain-size range 149-250 µm

$$AD = [((0.87*0.1462U)+(0.79*0.0286Th)+(0.93*0.8303K))/(1+1.25W)] + [(0.1148U+0.0514Th+0.2492K)/(1+1.14W)] + [0.15] \quad \text{(Eq.3.2)}$$

+ Grain-size range 74-250 µm

$$AD = [((0.88*0.1462U)+(0.83*0.0286Th)+(0.95*0.8303K))/(1+1.25(W)] + [(0.1148U+0.0514Th+0.2492K)/(1+1.14W)] + [0.15] \quad \text{(Eq.3.3)}$$

The annual dose values in each sample are shown in Table 3.5 for Ban Bom Luang trench and in tables 3.6-3.11 for Thung Tuk archaeological site.

Due to the complex annual dose equations that are shown above, in this research, we proposed the comfortable way to calculate the annual dose.

We constructed "Annual dose calculation program (version 1.1)" that is improve from Visual Basic computer language version 6.0. All of algorithms in this program are referred to the equations that derive from annual dose equation by Aitken (1985; 1990). This program consists of annual dose calculator for coarse-grained technique (size range of 74-250 μm) and fine-grained technique (size<74 μm), particularly for archaeological object such as brick, pottery, and stupa etc.

Although accuracy of this program has not been statistically proved yet for detailed annual dose calculation, this program can reveal rapidly the preliminary information on annual dose value. The graphic interface feature of this program is shown in Figure 3.1. The detail of this program is shown in Appendix-G that consists of 3 sections, including (G.1) About annual dose calculation program, (G.2) Installation guide of annual dose calculation program, and (G.3) Processing of annual dose calculation program.

Except the manual of Annual dose calculation program that is proposed in this thesis, we also disseminate this program in the compact disc (CD) in this thesis, so interesting researcher can comfortably download and improve it independently.

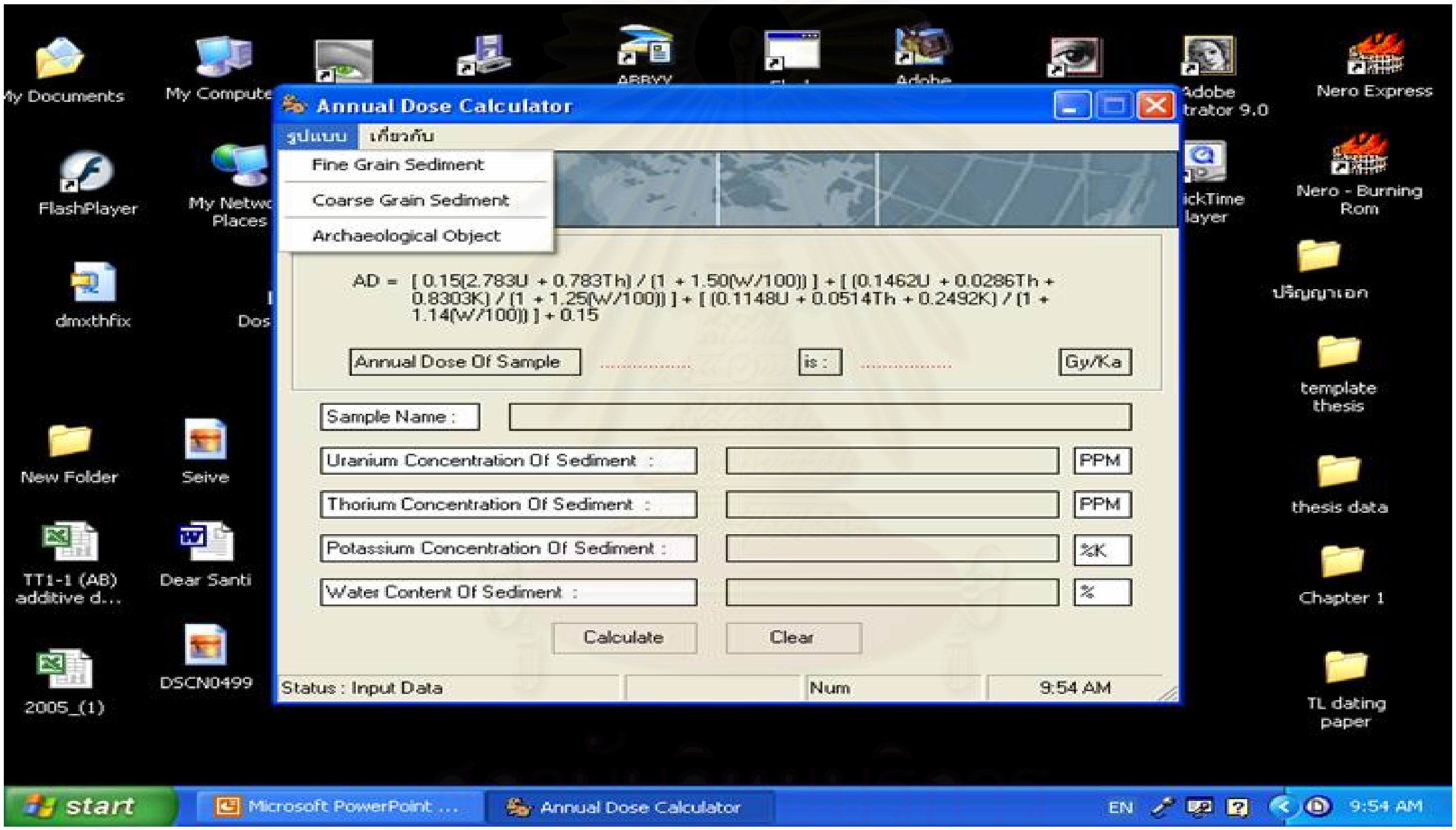



Figure 3.1 Feature of annual dose calculation program interface.

## 3.2 Ban Bom Luang Dating Results

For Ban Bom Luang trench, the results of TL dates are of two-folds. The first group belongs to AMS radiocarbon dates analyzed at University of Arizona and the second group is TL dates at Akita University. The detail of each dating results are shown below.

### 3.2.1 AMS Radiocarbon Dates

The radiocarbon dating of the organic-rich sediments in Ban Bom Luang trench is based on dating of charcoal fragments using accelerator mass spectrometry (AMS) processed by University of Arizona, USA. The selection of material from the sediment layer and the preparation for the AMS measurements is described based on suggestion  University of Arizona laboratory dating procedure, is shown below.

#### A) Sample Preparation

Before an AMS measurement can be made, the sample must be prepared. The nuclides of interest must be extracted from their geologic matrix and converted into a form suitable for AMS analysis (General aspects of sample preparation are covered in Finkel and Suter, 1993, Tuniz et al., 1998, and Gosse and Phillips, 2001.). The goals of sample preparation are (1) to prepare a chemical form that will optimize the formation of negative ions in the ion source, (2) to remove unwanted isobars (nuclei with the same total number of protons and neutrons, such as $^{14}C$ and $^{14}N$ because their mass difference is very small) from the sample, and (3) to minimize contamination of the sample.

#### B) $^{14}C/^{12}C$ and $^{13}C/^{12}C$ Measurements

After completely preparation procedure, 4 samples were placed in a cassette together with a blank sample and standards. All samples were measured in sequence for 500 seconds each. This measuring time was subdivided into 10 intervals of 50 seconds; all relevant information was stored in an on-line computer. For each cassette this sequence was repeated 3 times.

C) Determination of Radiocarbon Age

The $^{14}C/^{12}C$, as well as the determined $^{13}C/^{12}C$ ratios (both relative to the appropriate standards) used to calculate the age of each sample were the averages of the mean values for each of the three measurements (Bonani et al. 1987) . The AMS radiocarbon age was calculated for each sample by using the procedure suggested by Stuiver and Polach (1977). The organic-rich samples from Ban Bom Luang trench yield the AMS radiocarbon dates below.

- Sample no. C5 collected from layer A (see Figure 2.2) in the same point with TL sample no. BL5 give the AMS radiocarbon age 1,793±35 years.
- Sample no. C10 collected from layer B (see Figure 2.2) in the same point with TL sample no. BL10 give the AMS radiocarbon age 4,030±39 years.
- Sample no. C11 also collected from layer B (see Figure 2.2) in the same point with TL sample no. BL11 give the AMS radiocarbon age 1,940±35 years.
- Sample no. C14 collected from layer C (see Figure 2.2) give the AMS radiocarbon age 5,882±42 years.

The results of C-13 value, fraction of modern (FM) and AMS radiocarbon ages were shown in Table 3.4.

3.2.2 Thermoluminescence Dates

At Ban Bom Luang trench, 4 sediment samples were taken from the studied profile for TL dating- one sample from layer A and other three samples from layer B. TL of both regeneration and total bleach techniques were applied to samples of two grain-size ranges (74-149 μm- or finer grains and 149-250 μm- or coarser grains). The results of TL analysis are presented in Table 3.5. The TL date of the first layer from the top of the profile (sample no. BL5 from a depth of 0.70 m) obtained by the regeneration technique is 2,758±375 years for coarse-grained sample and 3,702±405 years for fine-grained sample. The TL date obtained by using the total bleach technique is 2,524±782 years for fine-grained sample. When we compared this series of dates with TL dates in the same layer of sediments from Charusiri et al. (2003), all of our dates are older than their dates. The AMS radiocarbon age of the same sampling point give 1,793±35 years. It is interesting that the AMS radiocarbon age is agreed with the TL age reported by Charusiri et al (2003) rather than ours TL ages.

In the second layer from the top, the TL ages of sample no. BL10 (from a depth of 1.50 m) obtained by using the regeneration technique

Table 3.4 Results of AMS radiocarbon dating evaluated from Accelerator Mass Spectromety Laboratory, University of Arizona, USA. The organic samples collected from Ban Bom Luang trench.

| Sample number | Depth (cm) | Fraction dated | Weight (g) | Treatment | fraction of modern (Fm ) | C-13 | C-14 (Year BP) | C-14 calibrated (Year BP) |
|---|---|---|---|---|---|---|---|---|
| C5 | 70 | Organic residue | 1.86 | AMS | 0.7999 ±0.0035 | -24.69 | 1,793 ± 35 | 1,758-1,828 |
| C10 | 150 | Organic residue | 1.24 | AMS | 0.6055 ±0.0029 | -26.45 | 4,030 ±39 | 3,991-4,069 |
| C11 | 120 | Organic residue | 2.65 | AMS | 0.7855 ±0.0035 | -27.77 | 1,940 ± 35 | 1,905-1,975 |
| C14 | 65 | Organic residue | 0.52 | AMS | 0.4809 ± 0.0025 | -26.25 | 5,882 ±42 | 5,840-5,924 |

Radiocarbon dating technique

AMS = Accelerator mass spectrometry

are 8,609±1,596 years for fine-grained sample and 3,868±649 years for coarse-grained sample. The TL dates obtained by using the total bleach technique are 8,595±2,236 years for fine-grained sample and 3,690±1,011 years for coarse-grained sample. The dates of sample no. BL10 evaluated from the finer grains are younger than those of the coarser grains. It is noted that for coarse-grained samples, the dates of 3,690±1,011 and 3,868±649 years obtained from both total bleach and regeneration techniques, respectively, are well consistent with the TL date of 3,500±80 years reported by Charusiri et al. (2003) and the AMS radiocarbon age of 4,030±39 years (this study).

In contrast, for the same sediment layer, from fine-grained samples always become older than those of the other methods previously mentioned.

The next sample is sample no. BL11 which was taken from a depth of 1.20 m above the sampling point of sample no. BL10. The TL date obtained by using the regeneration technique is 6,393±1,995 years for the coarser sediments. The TL date obtained by using the total bleach technique is 6,393±1,500 years for the coarser sediments. Sample no. BL11 yields the TL dates older than the date reported earlier by Charusiri et al. (2003) which 2,000±110 years for the same sample layer. However, dates from sample no. BL11 are geologically meaningless or fallacious and were interpreted as result of sediment redistribution due to bioturbation. However, the dates of 2,000±110 years show a good comparison with that of AMS radiocarbon age (1,940±35 year).

Finally, sample no. BL20, taken from a depth of 1.50 m, is in the same layer of sediments deposit with sample nos. BL10 and BL11. The TL date obtained by using the regeneration technique is 4,158±1,838 years for the coarse-grained sediments. The TL date obtained by using the total bleach technique is 5,011±1,403 years in finer sediments. Dates obtained by total bleach and regeneration techniques are similar to that of Charusiri et al. (2003) for the same sediment layer.

However, we cannot report dates from the finer sediments of sample nos. BL11 and BL20 due to their insufficient amount of TL dating.

### 3.3 Thung Tuk Archaeological Site Dating Results

For convenient description of the dates from Thung Tuk archaeological site, we describe the TL dates consecutively in each ancient remain (see also Figure 2.4-2.10 for a sample locations).

Table 3.5 TL dating results of sediment samples from Ban Bom Luang trench.

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range ($^{o}$C) | Equivalent dose | | | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| BL5 | Se | A | TB | 3.07 | 280-330 | 25.77 | 18.02 | 7.75 | 2,524±782 |
| | | | R | 3.07 | 280-330 | 28.17 | 19.70 | 8.47 | 2,758±375 |
| | | B | TB | 3.15 | 290-360 | 32.79 | 21.15 | 11.64 | 3,690±518 |
| | | | R | 3.15 | 290-360 | 32.89 | 21.22 | 11.67 | 3,702±405 |
| BL10 | Se | A | TB | 2.24 | 280-330 | 40.32 | 21.11 | 19.21 | 8,595±2,236 |
| | | | R | 2.24 | 280-330 | 41.11 | 21.87 | 19.24 | 8,609±1,596 |
| | | B | TB | 2.30 | 290-350 | 27.93 | 19.46 | 8.47 | 3,690±1,011 |
| | | | R | 2.30 | 290-350 | 29.19 | 20.31 | 8.88 | 3,868±649 |
| BL11 | Se | A | TB | 2.26 | 270-330 | 27.40 | 12.92 | 14.47 | 6,393±1,500 |
| | | | R | 2.26 | 270-330 | 27.40 | 12.92 | 14.47 | 6,393±1,995 |
| BL20 | Se | A | TB | 2.29 | 280-320 | 25.64 | 14.16 | 11.48 | 5,011±1,403 |
| | | | R | 2.29 | 280-320 | 21.28 | 11.75 | 9.52 | 4,158±1,838 |

Material of sample
Se = Sediment

Grain size
A = 74µm -149µm (fine grain)
B = 149µm-250µm (coarse grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

### 3.3.1 Trench 1

In trench 1, we evaluated TL dates from an ancient brick piece from the basement of ancient remain and a sediment sample beneath the brick sampling point (Figure 2.4). Both TL techniques (regeneration and total bleach) and grain size (74-250 μm) were investigated for individual samples. The TL-dating results are presented in Table 3.6. The TL date of sediment sample no. TT1-2 obtained by the regeneration technique is 11,830±1,722 years whereas that by the total bleach technique is 14,765±1,198 years.

In case of a brick sample (sample no. TT1-1), the TL date obtained by the regeneration technique is 1,142±119 years while that of the total bleach technique shows slightly lower the higher error, i.e., 994±394 years.

When we compared roughly both dates from bricks and sediments sample with 1,200-1,500 years relative ages from Srisuchart (1986) and series of conventional radiocarbon ages from Chaisuwan and Naiyawatt (2002) (see Table 2.1). It is essential to report that the TL dates of two brick samples give the ages in accordance with the reference ages and are older than those of the sediment sample.

### 3.3.2 Ancient Remain 3

We evaluated TL dates from 4 ancient brick samples from ancient remain3 and a sediment sample beneath ancient remain (Figure 2.5). The results of TL analysis are presented in Table 3.7. The TL date of a sediment sample no. TT3-2 obtained by the regeneration technique is 82,594±8,697 years and the TL date obtained using the total bleach technique is 125,781±55,783 years.

In case of brick, 4 brick samples reveal the date discrepancy. Sample no. TT3-1 gives the date of 3,518±463 years by the total bleach technique and 2,789±266 years by regeneration technique. Sample no. TT3-3 gives the date of about 632±685 years for total bleach technique while 239±90 years for regeneration technique. The last brick sample at this station is divided into 2 portions, sample no. TT3-4 is evaluated for equivalent dose from outer rim of brick mass and sample no. TT3-5 is evaluated for equivalent dose from inner rim of brick mass (Figure 2.6). Sample no. TT3-4 yields the date of about 6,070±7,137 years for the total bleach technique and about 1,267±368 years for the regeneration technique. Sample no. TT3-5 gives the date of about 6,245±7,960 years for the total bleach technique and about 1,545±656 years for the regeneration technique.

Table 3.6 TL dating results of sediment and brick samples from trench 1, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range ($^{o}C$) | Equivalent dose | | | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| TT1-1 | Bi | AB | TB | 5.83 | 280-350 | 5.80 | 0 | 5.80 | 994±394 |
| | | | R | 5.83 | 280-350 | 6.66 | 0 | 6.66 | 1,142 ±119 *100 |
| TT1-2 | Se | AB | TB | 2.88 | 280-400 | 74.62 | 32.16 | 42.46 | 14,765 ±1,198 |
| | | | R | 2.88 | 280-400 | 56.71 | 22.69 | 34.02 | 11,830 ±1,722 |

Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Se = Sediment
Bi = Brick

Grain size
AB = 74μm -250μm (mixed grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

Table 3.7 TL dating results of sediment and brick samples from ancient remain 3, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range (°C) | Equivalent dose | | | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| TT3-1 | Bi | AB | TB | 7.27 | 270-360 | 25.58 | 0 | 25.58 | 3,518 ±463 |
| | | | R | 7.27 | 270-360 | 20.27 | 0 | 207 | 2,789 ±266 *100 |
| TT3-2 | Se | AB | TB | 1.44 | 300-380 | 56.81 | 21.97 | 180.83 | 125,781 ±55,783 *100 |
| | | | R | 1.44 | 300-380 | 52.96 | 19.10 | 118.74 | 82,594 ±8,697 |
| TT3-3 | Bi | AB | TB | 11.67 | 300-350 | 7.38 | 0 | 7.38 | 632 ± 685 *100 |
| | | | R | 11.67 | 300-350 | 2.79 | 0 | 2.79 | 239 ± 90 |
| TT3-4 | Bi | AB | TB | 9.26 | 280-350 | 56.17 | 0 | 56.17 | 6,070 ± 7,137 *100 |
| | | | R | 9.26 | 280-350 | 11.73 | 0 | 11.73 | 1,267 ± 368 |
| TT3-5 | Bi | AB | TB | 9.26 | 290-350 | 57.80 | 0 | 57.80 | 6,245 ± 7,960 *100 |
| | | | R | 9.26 | 290-350 | 14.30 | 0 | 14.30 | 1,545 ± 656 |

Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Se = Sediment
Bi = Brick

Grain size
AB = 74μm -250μm (mixed grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

It is noted that the sediments at this station give terrifying old dates and that some dates from brick sample such as a regeneration and total bleach dates from sample no. TT3-1 and total bleach dates of sample nos. TT3-4 and TT3-5. In contrast, the brick sample no. TT3-3 gives the young ages.

### 3.3.3 Ancient Remain 4

We evaluated TL dates from a brick sample (no. TT4-1) from basement of ancient remain, a sample of brick fragment (no. TT4-3) from the ancient burner near ancient remain 4, and a sediment sample (no. TT4-2) beneath the brick sampling point (Figure 2.7). The results of TL analysis are presented in Table 3.8. The TL date of sediment sample (no. TT4-2) obtained by the regeneration technique is 26,849 ±1,740 years while TL date obtained by using the total bleach technique is 27,638 ±2,458 years.

In case of brick, sample no. TT4-1 gives the dates of about 886±194 years for the total bleach technique and about 1,080±263 years for the regeneration technique. Sample no. TT4-3 gives the dates 2,809±3,533 years for the total bleach technique and about 1,028±334 years for the regeneration technique. These 2 brick samples (i.e. sample nos. TT4-1 and TT4-3) reveal the well dated result when compared with reference ages. Exception is for the date of brick no. TT4-3 which shows the high errors.

### 3.3.4 Ancient Remain 6

In ancient remain 6, we selected only a brick piece for TL dating (Figure 2.8). The results of TL analysis are presented in Table 3.9. The TL date of brick sample (no. TT6-1) obtained by the regeneration technique is 1,102±438 years and that obtained by the total bleach technique is 6,374±8,158 years. It is likely that the date from the regeneration technique is in a good agreement with that of the inference age, while the dates from the total bleach technique give a chaotic date.

### 3.3.5 Ancient Remain 8

We evaluated TL dates from a sample of ancient brick piece and a sediment sample beneath ancient remain 8 (Figure 2.9). In case of the dated sediment, we separated grain size factor into 3 portions; grain size 74-149 μm, 149-250 μm and 74-250 μm. Grain-size separation is aimed to investigate the dates from individual grain size ranges.

Table 3.8 TL dating results of sediment and brick samples from ancient remain 4, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range ($^{o}C$) | Equivalent dose Natural (Gy) | Residual (Gy) | ED (Gy) | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| TT4-1 | Bi | AB | TB | 6.96 | 290-330 | 6.17 | 0 | 6.17 | 886 ±194 |
| | | | R | 6.96 | 290-330 | 7.52 | 0 | 7.52 | 1,080 ±263 |
| TT4-2 | Se | AB | TB | 1.26 | 300-330 | 56.81 | 21.97 | 34.85 | 27,638 ±2,458 |
| | | | R | 1.26 | 300-330 | 56.96 | 19.10 | 33.85 | 26,849 ±1,740 |
| TT4-3 | Bi | AB | TB | 5.34 | 290-330 | 14.99 | 0 | 14.99 | 2,809 ± 3,533 *100 |
| | | | R | 5.34 | 290-330 | 5.49 | 0 | 5.49 | 1,028 ± 334 |

Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Se = Sediment
Bi = Brick

Grain size
AB = 74μm -250μm (mixed grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

Table 3.9 TL dating results of brick sample from ancient remain 6, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range ($^{o}C$) | Equivalent dose | | | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| TT6-1 | Bi | AB | TB | 10.187 | 290-330 | 64.94 | 0 | 64.94 | 6,374 ± 8,158 *100 |
| | | | R | 10.187 | 290-330 | 11.22 | 0 | 11.22 | 1,102 ± 438 |

Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Bi = Brick

Grain size
AB = 74μm -250μm (mixed grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

The results of TL analysis are presented in Table 3.10. TL dates of a brick sample no. TT8-1 by the regeneration technique is 838±297 years and that using the total bleach technique is 2,422±2,730 years.

In case of the TL date for a sediment sample (no. TT8-2), dates from each grain-size range are shown below.

- For coarse-grained portion 149-250 μm, the date obtained by the regeneration technique is 35,714±12,693 years and that obtained by the total bleach technique is 188,192±82,954 years.
- For fine-grained portion 74-149 μm, the date obtained by the regeneration technique is 17,059±4,848 years and that obtained by the total bleach technique is 105,760±55,166 years.
- For mixed-grained size 74-250 μm, the date obtained by the regeneration technique is 25,339±6,738 years and that obtained by the total bleach technique is 152,853±82,054 years.

When we compared roughly between the dates of brick and the dates of sediments, sediment dates always give the older dates than the dates of brick sample. And also when compared TL dates of both dates from bricks and sediments sample with 1,200-1,500 years relative ages from Srisuchart (1986) and series of conventional radiocarbon ages from Chaisuwan and Naiyawatt (2002) (see Table 2.1), both regeneration and total bleach dates of a brick sample give the ages in line with these reference ages more than the dates from sediment sample.

### 3.3.6 Pit 1

Pit1 illustrates stratigraphy characteristic in 1-meter depth from surface. There are 5 sediment layers in pit 1. Eight sediment samples were selected from the studied profile for TL dating (Figure 2.10). The main aim of TL dating in this station is to provide the chronostratigraphic data beneath Thung Tuk area. The detailed results of TL analysis are presented in Table 3.11. For this station, both TL technique (regeneration and total bleach) and grain size between 74-149 μm and 149-250 μm were investigated for individual samples. The dates from the topmost to bottom are described below.

Table 3.10 TL dating results of sediment and brick sample from ancient remain 8, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range ($^{o}C$) | Equivalent dose (Gy) | | | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| TT8-1 | Bi | AB | TB | 11.28 | 280-340 | 27.32 | 0 | 27.32 | 2,422 ±2,730 *100 |
| | | | R | 11.28 | 280-340 | 9.45 | 0 | 9.45 | 838 ±297 |
| TT8-2 | Se | A | TB | 0.61 | 300-350 | 118.1 | 2.2 | 115.9 | 188,192 ±82,954 *100 |
| | | | R | 0.61 | 300-350 | 22.42 | 0.79 | 21.94 | 35,714 ±12,693 |
| | | B | TB | 0.63 | 285-325 | 68.01 | 1.63 | 66.38 | 105,760 ±55,166 *100 |
| | | | R | 0.63 | 285-325 | 11.09 | 0.38 | 10.71 | 17,059 ±4,848 |
| | | AB | TB | 0.468 | 270-340 | 72.99 | 1.41 | 71.58 | 152,853 ±82,054 *100 |
| | | | R | 0.468 | 270-340 | 12.22 | 0.36 | 11.87 | 25,339 ± 6,738 |

Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Se = Sediment
Bi = Brick

Grain size
A = 74μm -149μm (fine grain)
B = 149μm-250μm (coarse grain)
AB = 74μm -250μm (mixed grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

A) Dates from Unit A: Human Activities

At this layer, we collect a sediment sample from the east side (Sample no. TTp4-0.2) of a profile log (Figure 2.10). Sample no. TTp4-0.2 give the regeneration date of 10,150±2,921 years for coarse-grained portion and 8,042±2,508 years for fine-grained portion. The TL date obtained by the total bleach technique is 31,060±13,281 years for coarse-grained portion and 51,782 ±25,557 years for fine-grained portion.

B) Dates from Unit B: Top Soil

This layer shows evidence of some bioturbation such as root plants and borrows. We collected 2 sediment samples from the west side (sample no. TTp4-1.1) and the other from east side (Sample no. TTp4-1.2) in order to confirm the dates in the same sediment layer and to correlate with the upper and lower units. After collection, we split separated each sample into 4 portions based on technique and grain size separation (see Figure 2.1.)

The date of sample no. TTp4-1.1 obtained by the regeneration technique are 13,540±1,470 years for coarse-grained portion and 19,195±1,815 years for fine-grained portion. The TL dates obtained using the total bleach technique is 9,636±3,832 years for coarse-grained portion and 11,832±3,292 years for fine-grained portion.

The dates of sample no. TTp4-1.2 obtained by the regeneration technique are 10,081±3,479 years for coarse-grained portion and 6,622±2,040 years for fine-grained portion. The TL date obtained using the total bleach technique is 31,252±10,619 years for coarse-grained portion and 24,431±9,281 years for fine-grained portion.

C) Dates from Unit C: Pale Gray Sand

This sediment unit shows an evidence of ancient settlement as inferred from some antiques found in this layer upon excavation. We collected 2 sediments sample from this layer at the west side (sample no. TTp4-2.1) and the east side (sample no. TTp4-2.2) (Figure 2.10). Four portions of size ranges are performed similar to that of the unit B (see Figure 2.1)

For the regeneration technique, the sample no. TTp4-2.1 gives the dates of 29,716±6,401 years for coarse-grained portion and 58,220 ±5,590 years for fine-grained portion. The TL dates obtained by the total bleach technique is 18,405±3,624 years for coarse-grained portion m and 36,532±9,700 years for fine-grained portion.

Sample no. TTp4-2.2 yields the regeneration dates of 8,942±2,368 years for coarse-grained portion and 7,342±3,417 years for fine-grained portion. The TL dates obtained by the total bleach technique is 21,362±8,247 years for coarse-grained portion and 24,966±8,675 years for fine-grained portion.

D) Dates from Unit D: Dark Brown Sand

Based on our field work investigation, the unit D was not disturbed by root plants or human activities, similar to that suggested earlier by Chaisuwan and Naiyawatt (2002). We collected 2 sediment samples from this layer for TL dating- one on the west side (sample no. TTp4-3.1) and the other of east side (sample no. TTp4-3.2) (Figure 2.10). Similarly, four portions of sediments are prepared for both regeneration and total bleach techniques. However, due to small amount of sample collected only the coarse grain size with was unavailable for TL dating. The dates obtained using the regeneration techniques are 21,150±3,896 years and 26,693 ±3,407 years for total bleach technique.

In case of sample no. TTp4-3.2, the sample was separated into 3 portions of grain size range (74-149 μm, 149-250 μm and 74-250 μm). The dates obtained using the regeneration technique are 14,429±6,983 years, 12,423±6,940 years and 16,608±4,550 years for grain size range of 149-250μm, 74-149 μm and 74-250 μm, respectively.

The TL dates obtained using total bleach technique are 39,607±22,097 years, 52,719±47,969 years and 69,195±27,681 years for grain size range of 149-250 μm, 74-149 μm and 74-250 μm, respectively.

E) Dates from Unit E: Yellow Sand

This sediment unit is the lowest one in this stratigraphy. No evidence of bioturbation was observed in this unit. We collected only a sediment sample from the east side (sample no. TTp4-4.2) (Figure 2.10). Four portions of sediments were separated based on technique adoption and grain size separation (Figure 2.1). TL date of this sample obtained using the regeneration technique are 17,290±5,056 years for coarse-grained portion and 13,150±4,146 years fine-grained portion. The TL date obtained using the total bleach technique are quite higher 150,774±50,158 years for coarse-grained portion and 74,881±37,037 years for fine-grained portion.

Table 3.11 TL dating results of sediment samples from pit1, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range ($^{0}C$) | Equivalent dose | | | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| TTp4-0.2 | Se | A | TB | 0.58 | 290-330 | 19.47 | 1.44 | 18.03 | 31,060 ± 13,281 *100 |
| | | | R | 0.58 | 290-330 | 6.46 | 0.56 | 5.89 | 10,150 ± 2,921 |
| | | B | TB | 0.592 | 300-320 | 32.27 | 1.64 | 30.63 | 51,782 ±25,557 *100 |
| | | | R | 0.592 | 300-320 | 5.09 | 0.33 | 4.757 | 8,042 ±2,508 |
| TTp4-1.1 | Se | A | TB | 0.70 | 250-370 | 14.68 | 7.96 | 6.71 | 9,636±3,832 *100 |
| | | | R | 0.70 | 250-370 | 20.87 | 11.43 | 9.43 | 13,540 ±1,470 |
| | | B | TB | 0.71 | 290-380 | 15.74 | 7.33 | 8.41 | 11,832 ±3,292 *100 |
| | | | R | 0.71 | 290-380 | 26.45 | 12.81 | 13.64 | 19,195 ±1,815 |
| TTp4-1.2 | Se | A | TB | 0.68 | 285-325 | 21.94 | 0.73 | 21.21 | 31,252 ±10,619 *100 |
| | | | R | 0.68 | 285-325 | 7.12 | 0.28 | 6.84 | 10,081 ±3,479 |
| | | B | TB | 0.692 | 290-330 | 18.21 | 1.3 | 16.91 | 24,431 ±9,281 *100 |
| | | | R | 0.692 | 290-330 | 4.99 | 0.40 | 4.58 | 6,622 ±2,040 |

Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Se = Sediment

Grain size
A = 74µm -149µm (fine grain)
B = 149µm-250µm (coarse grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

Table 3.11 TL dating results of sediment samples from pit1, Thung Tuk archaeological site (cont.).

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range (°C) | Equivalent dose | | | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| TTp4-2.1 | Se | A | TB | 0.62 | 280-390 | 19.94 | 8.49 | 11.46 | 18,405 ±3,624 *100 |
| | | | R | 0.62 | 280-390 | 30.75 | 12.25 | 18.49 | 29,716 ±6,401 *100 |
| | | B | TB | 0.63 | 310-370 | 33.43 | 10.25 | 23.18 | 36,532 ±9,700 *100 |
| | | | R | 0.63 | 310-370 | 51.03 | 14.09 | 36.94 | 58,220 ±5,590 *100 |
| TTp4-2.2 | Se | A | TB | 0.722 | 270-325 | 16.13 | 0.7 | 15.43 | 21,362 ± 8,247 *100 |
| | | | R | 0.722 | 270-325 | 6.80 | 0.34 | 6.46 | 8,942 ± 2,368 |
| | | B | TB | 0.737 | 285-350 | 19.41 | 1.01 | 18.4 | 24,966 ±8,675 *100 |
| | | | R | 0.737 | 285-350 | 5.76 | 0.35 | 5.41 | 7,342 ±3,417 |
| TTp4-3.1 | Se | A | TB | 0.96 | 270-380 | 34.86 | 9.25 | 25.61 | 26,693 ±3,407 |
| | | | R | 0.96 | 270-380 | 28.05 | 7.75 | 20.29 | 21,150 ±3,896 |

Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Se = Sediment

Grain size
A = 74µm -149µm (fine grain)
B = 149µm-250µm (coarse grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

Table 3.11 TL dating results of sediment samples from pit1, Thung Tuk archaeological site (cont.).

| Sample number | Material | Grain size | Technique | Annual dose (Gy/ka) | Plateau range ($^{o}C$) | Equivalent dose | | | TL date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| TTp4-3.2 | Se | A | TB | 0.61 | 285-400 | 25.05 | 0.9 | 24.15 | 39,607 ±22,097 *100 |
| | | | R | 0.61 | 285-400 | 9.20 | 0.40 | 8.80 | 14,429 ±6,983 |
| | | B | TB | 0.621 | 280-400 | 33.75 | 0.99 | 32.76 | 52,719 ±47,969 *100 |
| | | | R | 0.621 | 280-400 | 8.05 | 0.33 | 7.72 | 12,423 ±6,940 |
| | | AB | TB | 0.466 | 285-350 | 33 | 0.77 | 32.23 | 69,195 ±27,681 *100 |
| | | | R | 0.466 | 285-350 | 7.98 | 0.24 | 7.74 | 16,608 ± 4,550 |
| TTp4-4.2 | Se | A | TB | 0.559 | 285-330 | 86.22 | 1.97 | 84.25 | 150,774 ±50,158 *100 |
| | | | R | 0.559 | 285-330 | 10.01 | 0.35 | 9.66 | 17,290 ± 5,056 |
| | | B | TB | 0.569 | 300-355 | 43.62 | 1 | 42.62 | 74,881 ±37,037 *100 |
| | | | R | 0.569 | 300-355 | 7.72 | 0.23 | 7.48 | 13,150 ±4,146 |

Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Se = Sediment

Grain size
A = 74μm -149μm (fine grain)
B = 149μm-250μm (coarse grain)
AB = 74μm -250μm (mixed grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

## 3.4 Electron Spin Resonance Dating Results

In order to report the age dating result more confidently and to confirm TL dates from the same sample with the exception of radiocarbon ages, which require the appropriate amount of in situ organic materials, methods utilizing radiation-defects in minerals. i.e. electron spin resonance (ESR) and optically stimulated luminescence (OSL) dating methods are often well suited for this purpose (Tanaka et al., 1995). Dating of unconsolidated sediments by the ESR method was first proposed by Yokoyama et al. (1985). ESR ages are determined by dividing the total dose of radiation that has affected a sample by the annual dose rate of acquisition of radiation (likely TL dating).

ESR dating of sediments is based on the assumption that paramagnetic centres in quartz grains are bleached when they are exposed to sunlight during the transport and deposition of these grains. After burial, paramagnetic centres are formed again by radiation emitted from natural radioactive elements and cosmic rays.

In this research, we selected 2 sediment samples from Ban Bom Luang trench (sample nos. BL5A and BL20A) and 2 sediment samples (sample nos. TTp4-1.1A and TT1-2AB) from Thung Tuk archaeological site in order to compare and confirm the reliability of TL dates in the study area.

### 3.4.1 ESR Measurement

In an ESR spectrometer concept, the sample is placed into a microwave cavity which is located in a strong external magnetic field. A paramagnetic centre (i.e. sites of the trapped electrons or holes) has a magnetic moment, and this has the same orientation as the magnetic field. In resonance, the magnetic moment is flipped into the opposite direction by absorption of microwave energy which is conducted to the sample from a microwave generator. The amount of absorbed microwave energy is directly proportional to the number of paramagnetic centres, and, in the end, to the age of the sample. In this research all samples were run in room temperature condition and the configuration of ESR spectrometer setting are as following:

| | | | | |
|---|---|---|---|---|
| C.FIELD: | 336.278 | mT | SLOW SWEEP time: | 1 m |
| SWP WID: | 5.0x1 | mT | MOD FREQ: | 100 kHz |
| MOD WID: | 0.25 | mT | PHASE: | 0 degree |
| AMPLITD: | 6.3x100 | | $Mg^{+}$-marker: | 555 |

### 3.4.2 ESR Results

After three time of measurement, the ESR spectrometer records the microwave absorption with respect to the magnetic field. The results of characteristic ESR spectra of samples and ESR sensitivity selection in this research are shown in Appendix-D.

Based on selected ESR sensitivity, we constructed growth curves of 4 samples (Figure 3.2) and evaluated equivalent doses from those growth curves. Finally, by dividing equivalent doses from ESR measurement to annual doses in each sample, the dates of ESR dating are shown in Table 3.12.

For Ban Bom Luang trench, ESR dates are 7,807±1,280 years for sample no. BL5A and 4,026±1,943 years for sample no. BL20A.

For Thung Tuk archaeological site, ESR date from sample no. TTp4-1.1A is 12,326±4,905 years and that of TT1-2AB is 612,057±92,350 years.

Table 3.12 ESR dating results of sediment samples from Ban Bom Luang trench and Thung Tuk archaeological site.

| Sample number | Location | Material | Grain size | Technique | Annual dose (Gy/ka) | Equivalent dose | | | ESR date (Year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Natural (Gy) | Residual (Gy) | ED (Gy) | |
| BL5 | BL | Se | A | TB | 3.07 | 287.61 | 263.64 | 23.97 | 7,808±1,280 |
| BL20 | BL | Se | A | TB | 2.29 | 89.02 | 79.80 | 9.22 | 4,026±1,943 |
| TTp4-1.1 | TT | Se | A | TB | 2.88 | 475.66 | 440.16 | 35.5 | 12,326±4,905 *100 |
| TT1-2 | TT | Se | AB | TB | 0.70 | 11,111.10 | 10,682.70 | 428.44 | 612,057±92,350 *100 |

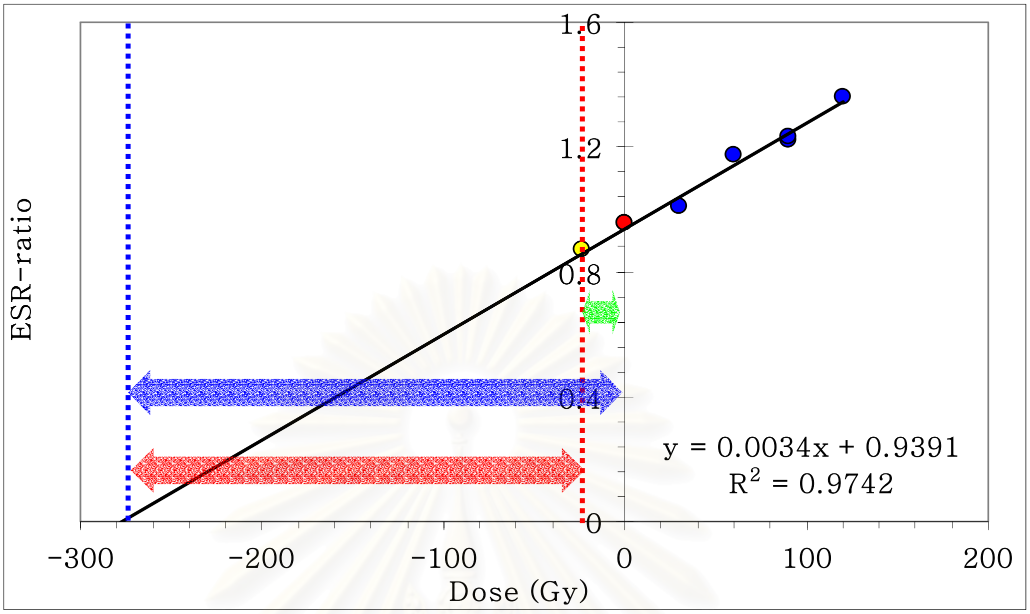
Remark: *100 = erroneous date are based on analyses of glow curves and growth curve, so the dates are not geologically meaningful.

Material of sample
Se = Sediments

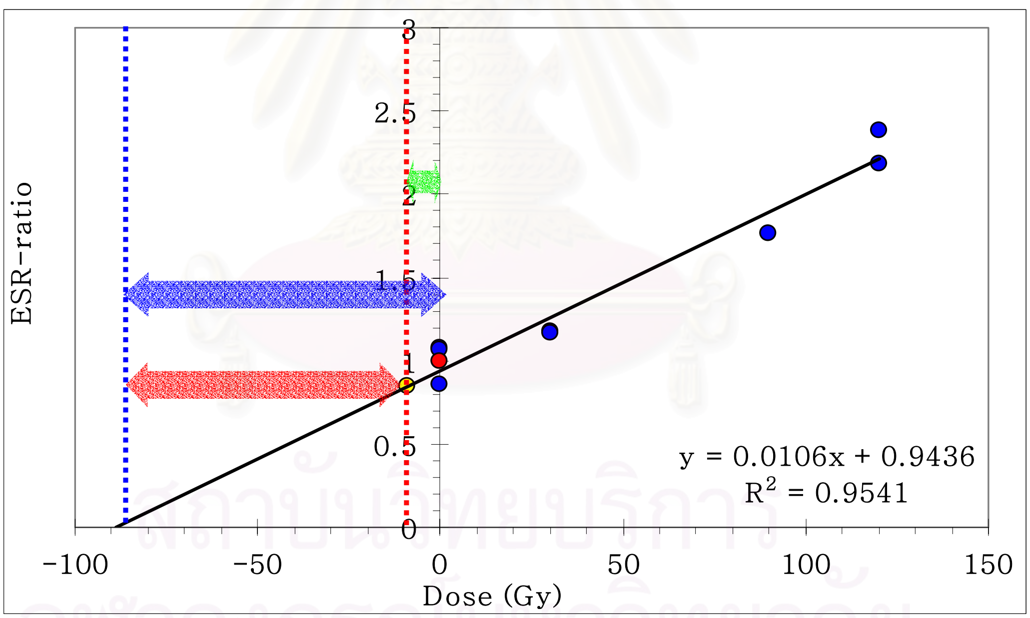
Grain size
A = 74μm -149μm (fine grain)
AB = 74μm -250μm (mixed grain)

TL-dating technique
TB = Total bleach technique
R = Regeneration technique

Location of sample
BL = Ban Bom Luang trench
TT = Thung Tuk archaeological site




(a) ESR growth curve of sample no. BL5A




(b) ESR growth curve of sample no. BL20A

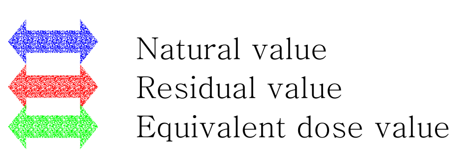
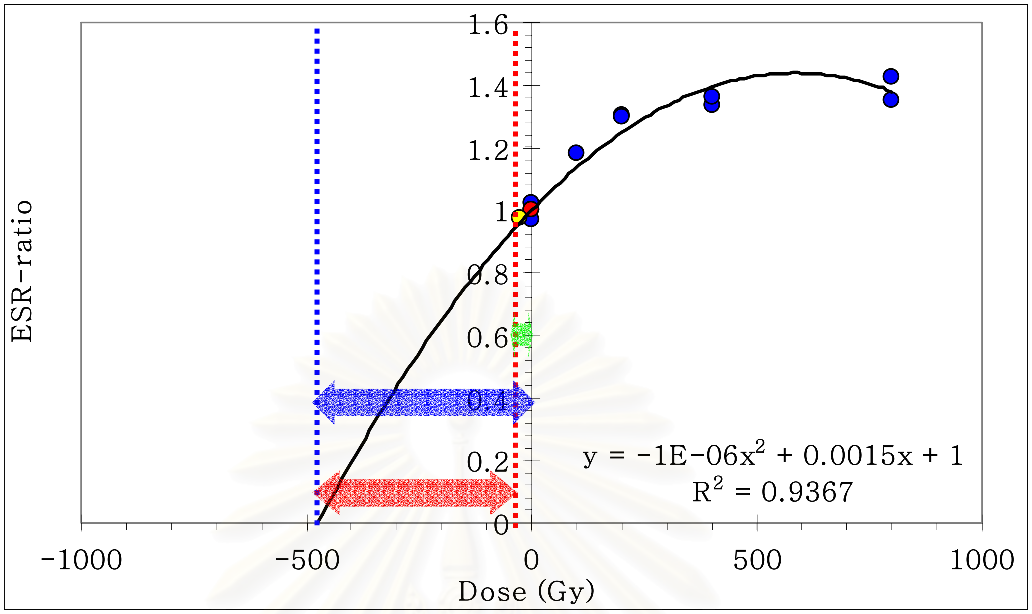
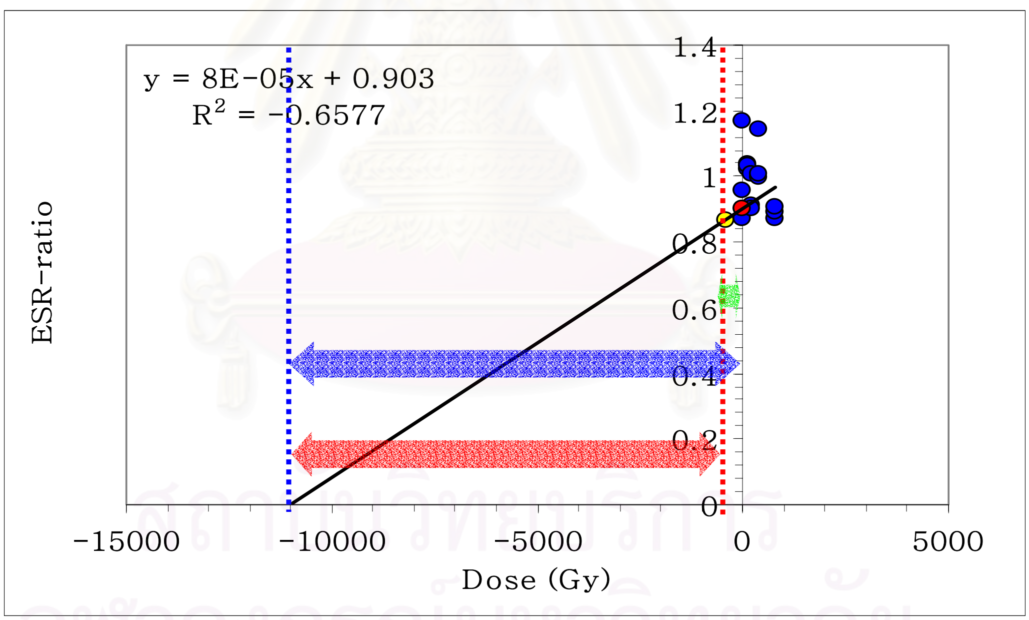



Figure 3.2 Growth curve constructed from ESR sensitivity; (a) Growth curve of sample no. BL5A, and (b) Growth curve of sample no. BL20A, Ban Bom Luang trench.




(c) ESR growth curve of sample no. TTp4-1.1A




(d) ESR growth curve of sample no. TT1-2 AB

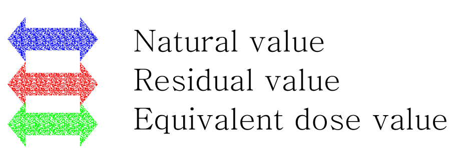



Figure 3.2 (cont.) (c) Growth curve of sample no. TTp4-1.1A, and (d) Growth curve of sample no. TT1-2AB, Thung Tuk archaeological site.

# CHAPTER IV

# DISCUSSION

In an attempt to understand TL dating method and evolution of sediment deposits in study area, all information in the past sections are analyzed and integrate in order to make a discussion part more feasible. Discussion in this research consists of 4 main sections:

1. Results on experiments;
2. Ages of Ban Bom Luang trench; and
3. Ages of Thung Tuk archaeological site.

Finally, all of the well-dated results were complied and analyzed by comparison with independent dating results to prove the reliability of TL dating method in Thailand. The details of discussion are described below.

## 4.1 Results on Experiments

We first tried to evaluate and discuss each continuous step for age determination. Discussing in the details of TL dating technique consists of:

1. XRD checking,
2. Glow curve ,
3. Plateau test,
4. Residual testing,
5. Uranium, thorium and potassium content,
6. Age comparison between grain size 74-149 μm and 149-250 μm,
7. Age comparison between total bleach and regeneration techniques, and
8. Electron spin resonance dating.

### 4.1.1 XRD Checking

Results from the XRD analysis on samples being dated show that some samples show awkward peak which can be mixed with peaks of quartz mineral. We interpret that those samples with unusual peaks are contaminated by impurities (Figure 4.1). This perhaps yield strange glow and growth curves. Consequently, the dates may be less reliable.

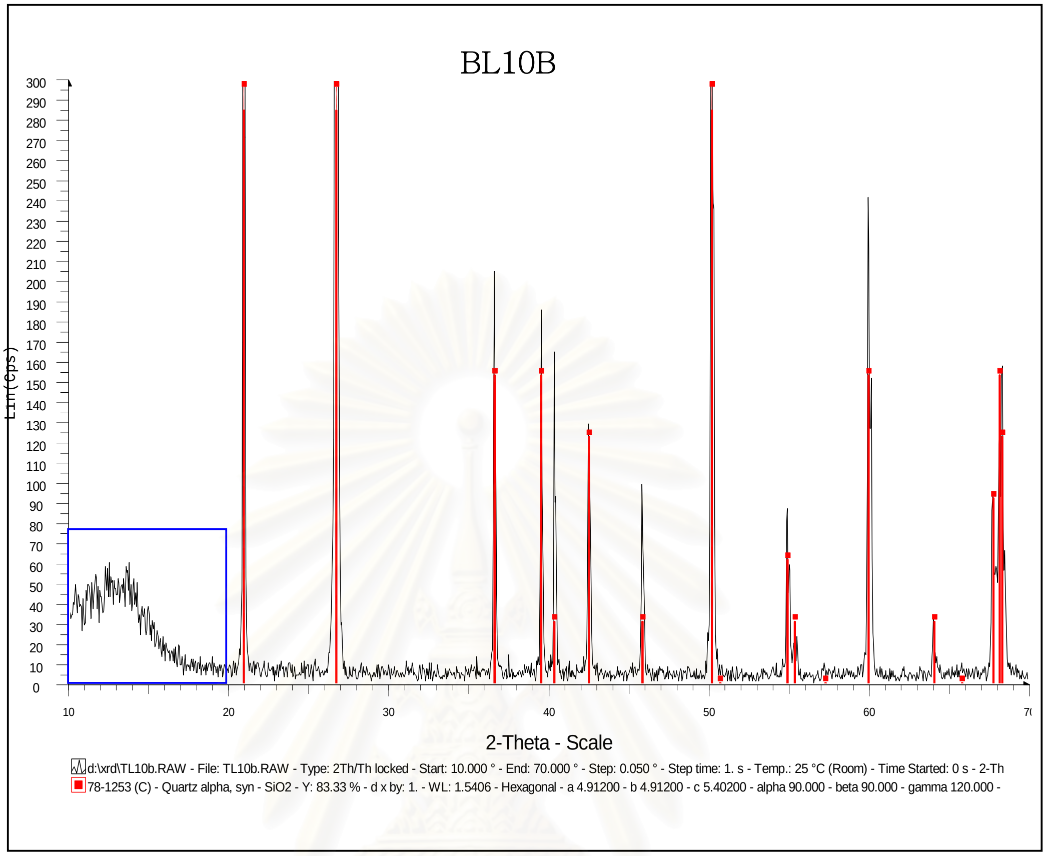



Figure 4.1 XRD results of sediment sample no. BL10B from Ban Bom Luang trench with pronounced awkward peak (in blue box) mixed up with characteristic of quartz's peaks (red line).

### 4.1.2 Glow Curve

Before measuring TL-glow curves, we must adjust and calibrate condition and/or configuration of TL-equipment to find out the stable and appropriated condition for our sample measurement. Based on trial and error procedure, the suitable condition for samples in this research study depends on voltage adjusting. The glow curves amplified signal with 1,500 voltage yield the best clear shape of glow curve (Figure 4.2 a) and better amplified signal than that of 1,250 voltage (Figure 4.2b) applied in the earlier research (see Krowchan, 2001; Kosuwan, Saithong, and Lumjuan, 2002).

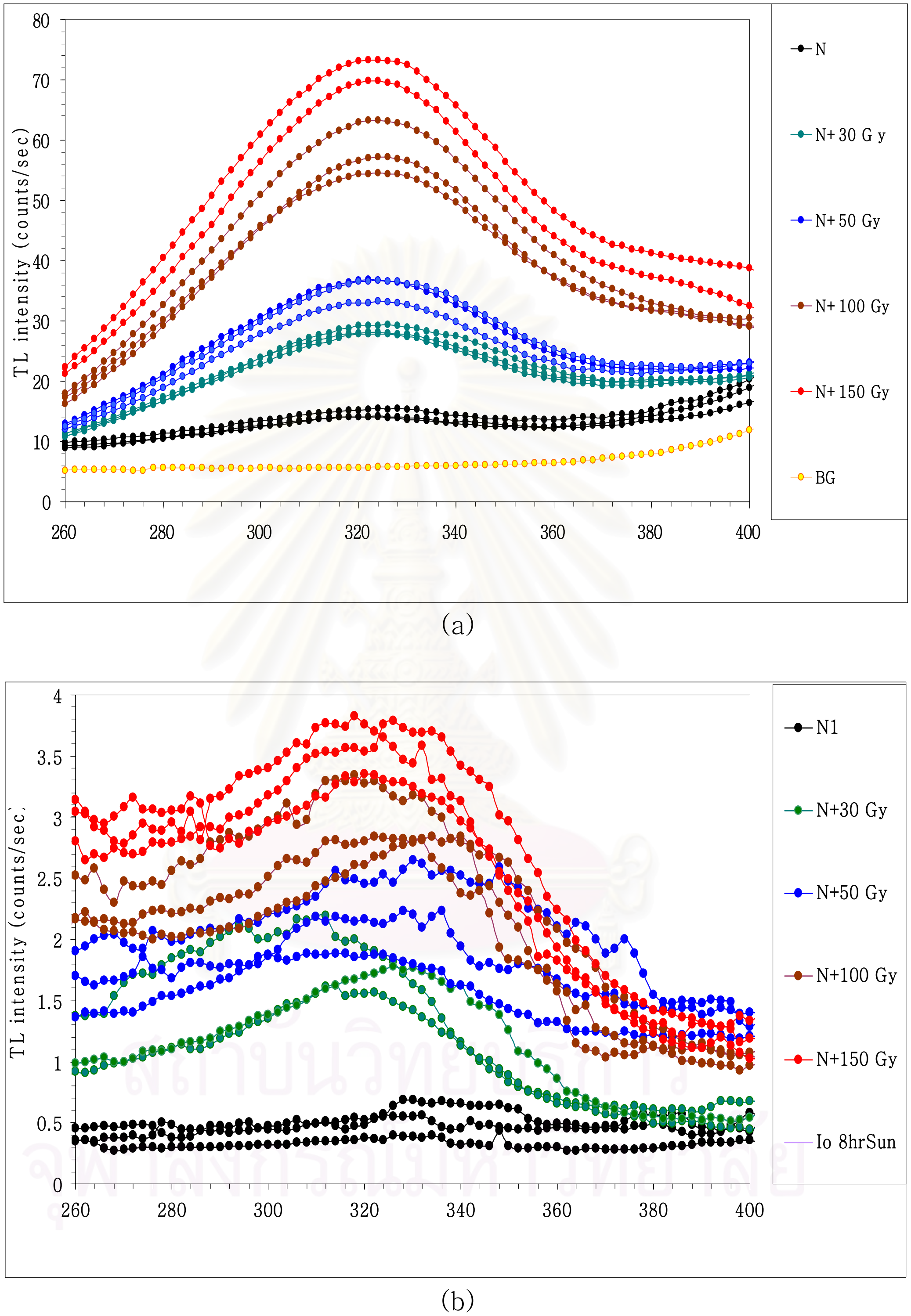



Figure 4.2 Glow curves of sample no. TT1-1AB from Thung Tuk archaeological site measured by thermoluminescence detector (TLD) at Department of Mineral and Resources, Bangkok; (a) amplified signal with 1,500 voltages (b) amplified signal with 1,250 voltages.

### 4.1.3 Plateau Test

From the results of plateau test, discussion can be divided into 3 sections, namely (A) Range of stable zone, (B) Characteristic of plateau shape, and (C) Stable plateau zone checking. The detailed discussions are described below.

#### A) Range of Stable Zone

An important difference exists between the natural glow curve and the TL signal induced by a laboratory irradiation. Because the TL emitted at low temperatures (typically below 200 °C) is unstable (Aitken, 1985; Vij, 1993), so in natural samples this TL signal has decayed away during burial time, and is therefore absent from the glow curve. In contrast, artificially dosed samples emit this low temperature TL signal because the interval between irradiation and measurement is too short for decay to have a significant effect. This difference forms the basis of the plateau test, which identifies the temperature region of the natural glow curve in which the TL intensity is unaffected by thermal decay during burial time. The name of the test derives from the constant height of the graph of equivalent dose values versus temperature in the region of the stable TL, as illustrated in Figures 4.3 and 4.4. The ability to recognize thermal instability in this way is a unique and valuable advantage of the TL dating method (Aitken, 1985).

From integration of the plateau test results (see Appendix-E), almost plateau results in this research indicate the stable temperature region of TL signal in range 280-360 °C approximately. These ranges correspond fairly well with that of Vij (1993) who propose the normally characteristic of stable silica's peak can observe at 300 °C.

#### B) Characteristic of Plateau Shape

From detailed investigation of plateau shape, all of plateau shapes in this research give different shape with the plateau shape in previous researchers (i.e. Aitken, 1985; Oczkowski and Przegietka, 1989). Their plateau testing give exactly plateau shape (Figure 4.3) while plateau test results in this research expose the shape of parabolic curve (Figure 4.4).

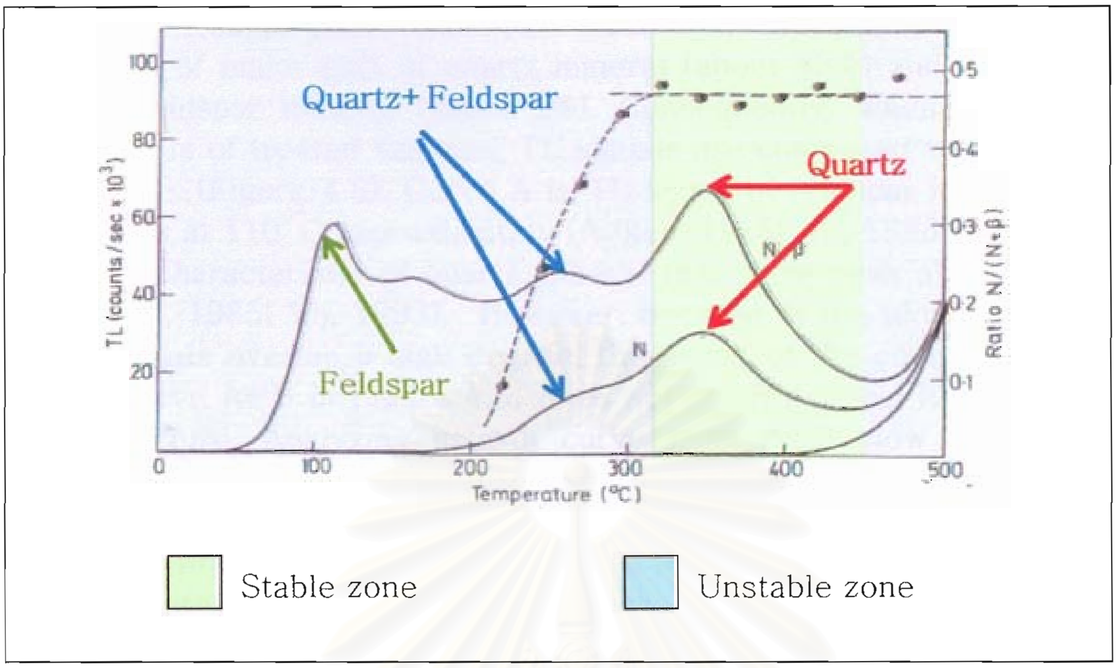



Figure 4.3 Theoretical plateau test of polymineral mixed technique (feldspar and quartz minerals) (Aitken, 1985)

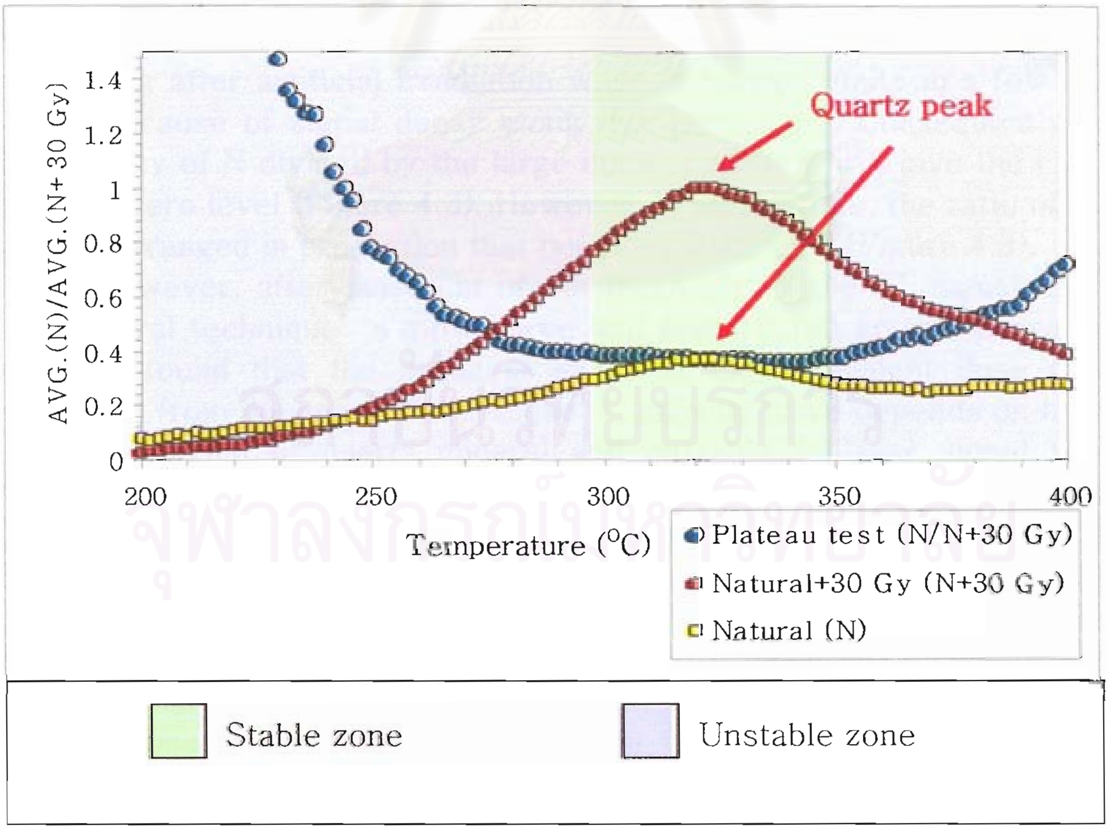



Figure 4.4 Plateau test of quartz inclusion technique from sample TT1-1AB, Thung Tuk archaeological site, yielding a parabolic curve.

Practically, after chemical treatment, treated samples are composed of major part of quartz mineral (about 95%) and a remnant part of feldspar mineral (about 5%). Consequently, when measuring glow curves of treated samples, TL signals are composed of largely of two signals (Figure 4.5). Curve A is TL signal of feldspar mineral that show peak at 110 °C approximately (Aitken, 1985; Vij, 1993) and curve B reveal characteristic of quartz mineral that show peak about at 300 °C (Aitken, 1985; Vij, 1993). However, because of the glow curves of these signals overlap a high degree, the shape of the composite glow curve (curve A+B in Figure 4.5) does not always reveal its individual true structure. Analyzing growth curve from A+B glow curve was called polymineral technique (see Abdel-Wahab et al., 1996; Kusiak et al., 2002) that comprises feldspar signal overlapped with quartz signal.

The first application of the plateau principle was to identify parts of the natural glow curve which had remained stable during the burial time of the sample. The plateau test is evaluated from plotting relationship between the ratio of N/ N+$\beta$ (Y-axis) versus temperature (X-axis), where N is natural TL signal and $\beta$ is artificial irradiation.

a) Plateau test of polymineral technique

In unstable plateau zone of polymineral technique (Figure 4.3), N+$\beta$ portion gives high quality of TL signal because promptly measuring after artificial irradiation while N portion emits in a few TL signal because of signal decay along the burial time. Consequently, a few quality of N divided by the large number of N+$\beta$ will give the ratio close to zero level (Figure 4.3). However, in stable zone, the ratio of N/ N+$\beta$ is arranged in proportion that becomes flat shape (Figure 4.3).

However, after selection of the thermally stable TL signal from polymineral technique's glow curve and constructed growth curve, it is often found that the apparent value of the equivalent dose that evaluated from polymineral technique's growth curve depends on both of stable signal of quartz mineral and unstable feldspar signal that overlap together. Consequently, equivalent dose gives the swing and varies values. To eliminate the risk of overlap peak, present knowledge does not allow the unstable signal to be calculated equivalent dose.

Not long after, some researchers improve extracting stable quartz signal from unstable feldspar signal. In order to eliminate the unstable signal from apparent TL signal, heating 130°C for 24 hours was proposed by Takashima and Honda (1989). After heating signal from feldspar (curve A from Figure 4.5) was eliminated and remain only stable signal from quartz mineral (curve B from Figure 4.5). This technique was called quartz inclusion technique (Fleming, 1970).

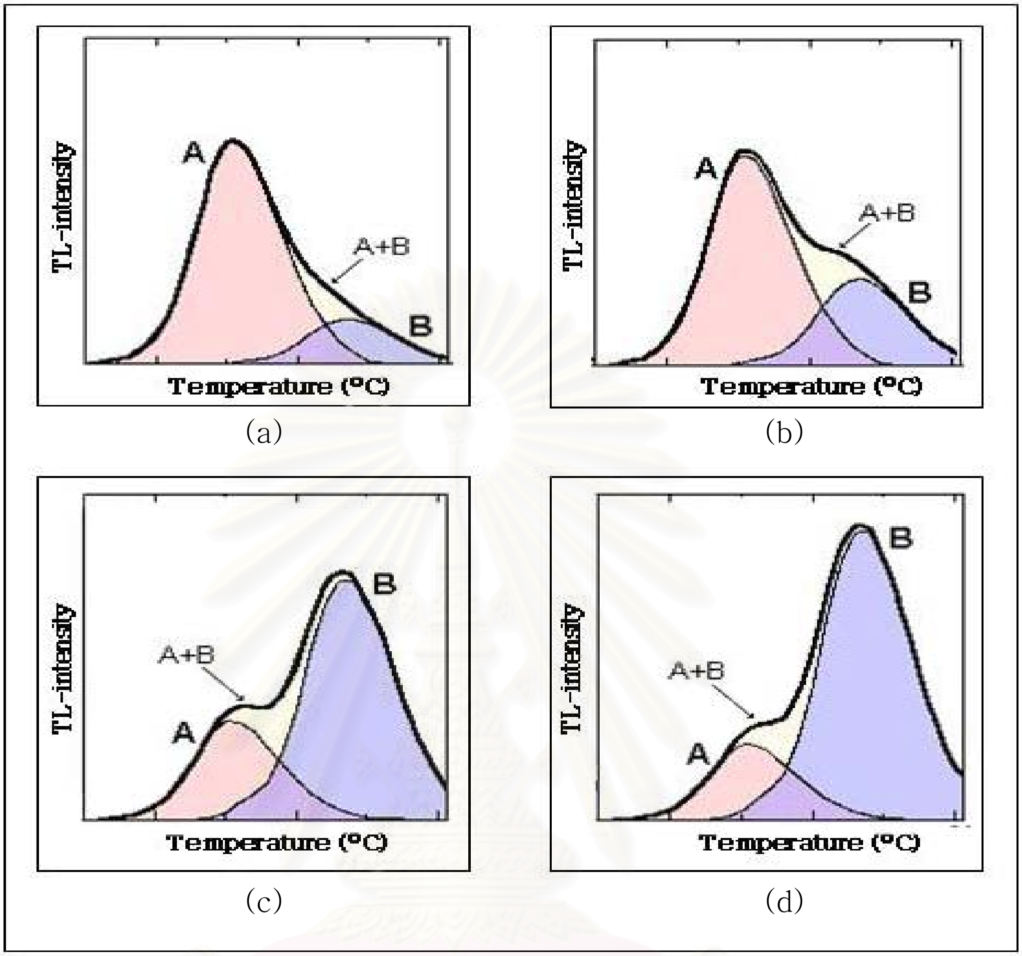



Figure 4.5 Variations of the natural glow curve shape obtained from one sample of sediment. TL signal composed of largely of two signals. Curve A is TL signal of feldspar mineral and curve B is characteristic of quartz mineral peak. Curve A+B is the signal that overlaps to a high degree between curve A and curve B (http://www.users.globalnet.co.uk/~qtls/).

b) Plateau test of quartz inclusion technique

In unstable plateau zone of quartz inclusion technique (Figure 4.4), when TL signals from both of N and N+β for plateau testing are measured, the plateau test of quartz inclusion technique reveals a few natural signal divided by a few of artificial irradiation effect from heating 130 °C for 24 hours. Consequently, a few quantity of N divided by a few quantity of N+β will increase the ratio abnormally. However, in the stable zone, the ratio of N/ N+β is arranged in proportion and becomes flat shape like stable plateau zone from polymineral technique (Figure 4.4).

Therefore, we can conclude that the primary cause of different plateau shape is effect from heating at 130 °C for 24 hours after artificial irradiation in quartz inclusion technique. However, both of plateau shape from polymineral technique and quartz inclusion technique give almost equal in the stable temperature range.

C) Stable Plateau Zone Checking

After complete plateau testing, the result of stable TL signal is in term of range, such as between 270-330 °C approximately. Most TL researchers (i.e. Aitken, 1985; Singhvi and Wagner, 1986) often select the glow curve data from only one representative temperature for construction of growth curves. It might give risk for determination the equivalent dose from those growth curves. In this research, we attempted to check and confirm the result of plateau test that the temperatures can be used to define a stable plateau range or not.

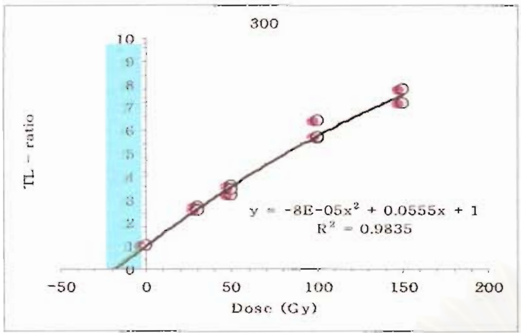
Based on plateau test, results of sample no. TT1-1AB from Thung Tuk archaeological site reveal the plateau range between 280 - 350 °C approximately (Figure 4.4), we selected glow curve data from 6 fixed temperatures within stable zone and constructed growth curves in each data series. The representative temperature range is 300 to 350 °C. The results of equivalent doses evaluation in all of the selected temperature data are in vicinity of this temperature range (Figures 4.6 a, b, c, d, e and f). Therefore, we ensure that every temperature selection along the stable plateau zone can be applied for growth curve construction.

### 4.1.4 Residual Test

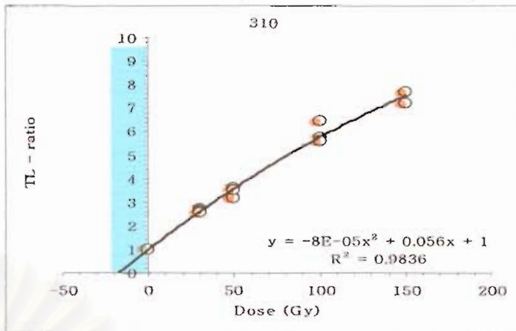
For a TL sample exposed to the natural sunlight, there is a certain probability that some electrons will be evicted from its trap but some cannot. This simple model leads to the expectation that the number of electrons remaining trapped at time will be exponentially dependent on time. However experiment indicates that as the bleaching proceeds the probability of eviction decreases (Aitken, 1985; Singhvi and Wagner, 1986).

From residual testing experiment in this research, the results reveal that expending of time consumed for complete bleaching is at least 4-8 hours to reset TL signal to residual level by natural sunlight (Figures 4.7a and 4.7b) and independent with started quantity of natural signal.

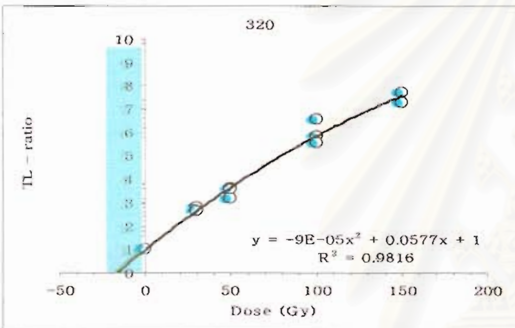
(a) Growth curve from 300 °C glow curve data, ED= 17.57 Gy



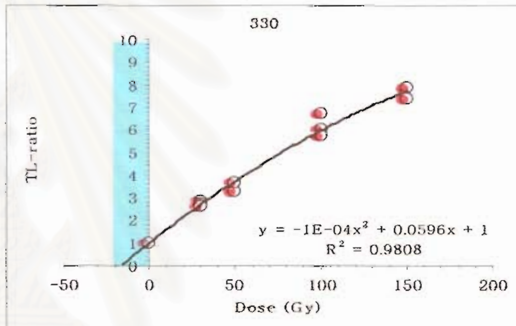

(b) Growth curve from 310 °C glow curve data, ED= 17.42 Gy



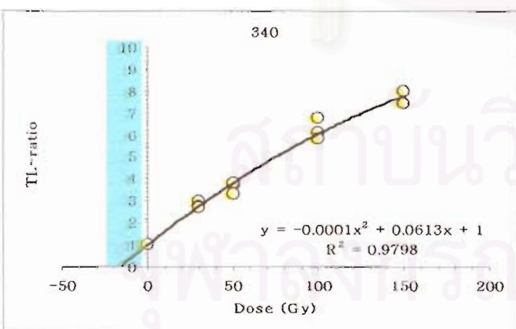

(c) Growth curve from 320 °C glow curve data, ED= 16.88 Gy



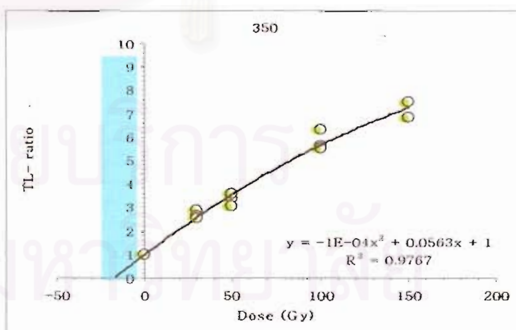

(d) Growth curve from 330 °C glow curve data, ED= 17.40 Gy




(e) Growth curve from 340 °C glow curve data, ED= 16.21 Gy

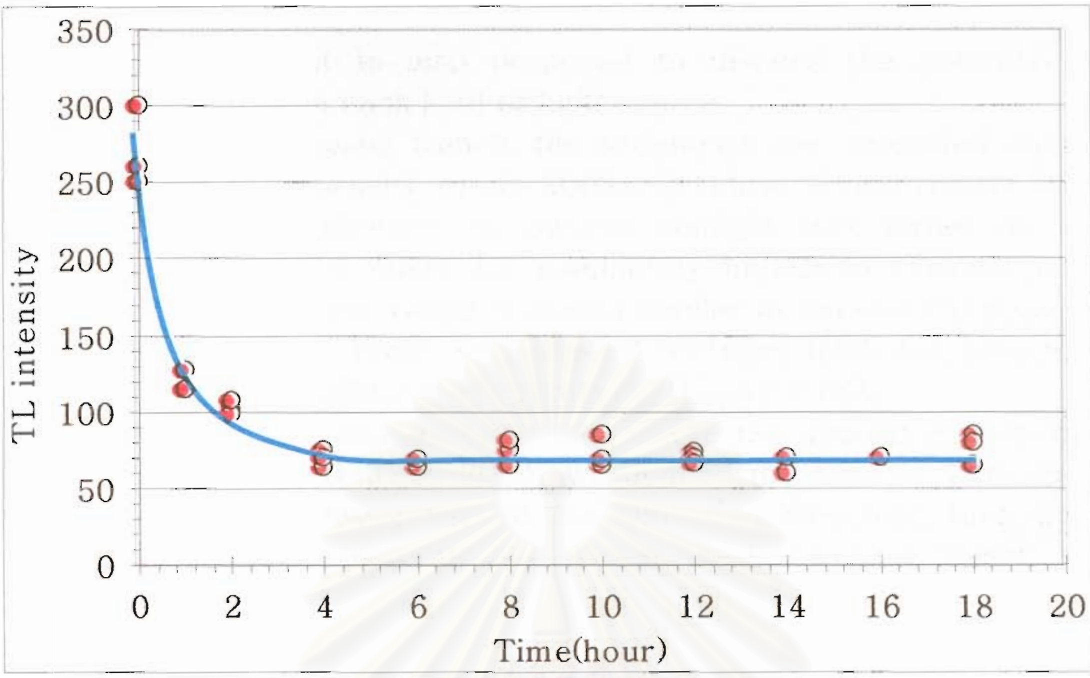



(f) Growth curve from 350 °C glow curve data, ED= 17.36 Gy

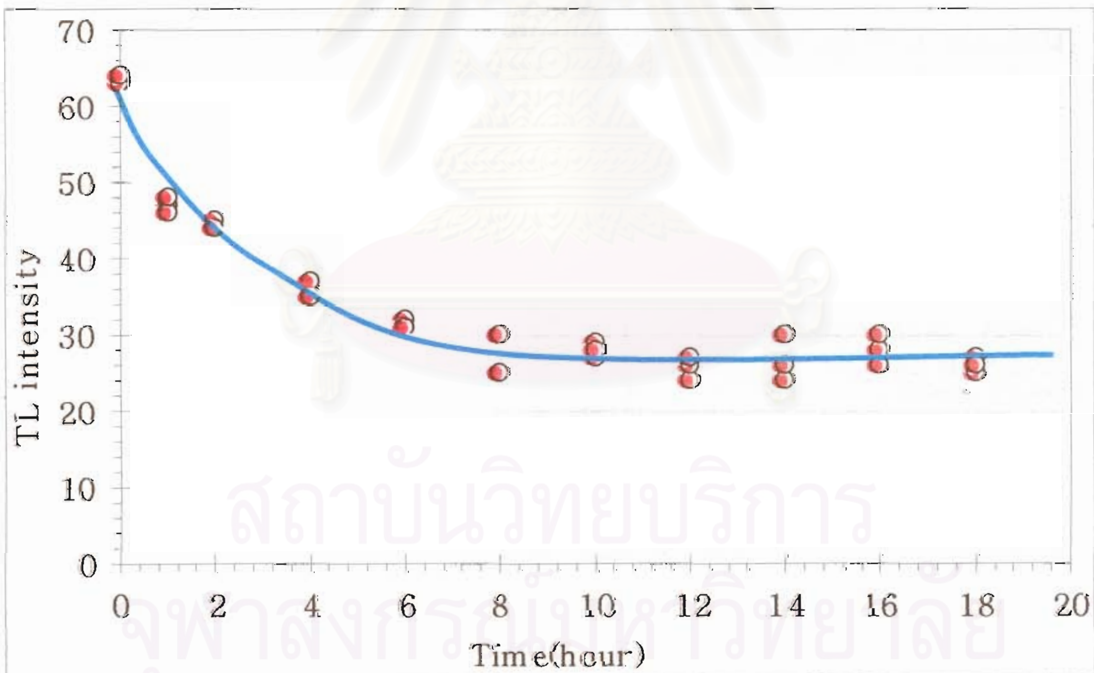



Equivalent dose value

Figure 4.6 Growth curves of brick sample (no.TT1-1AB) at different stable temperature. The representative temperatures are 300 °C, 310 °C, 320 °C, 330 °C, 340 °C and 350 °C, respectively.




(a)




(b)

Unbleachable zone (residual level)

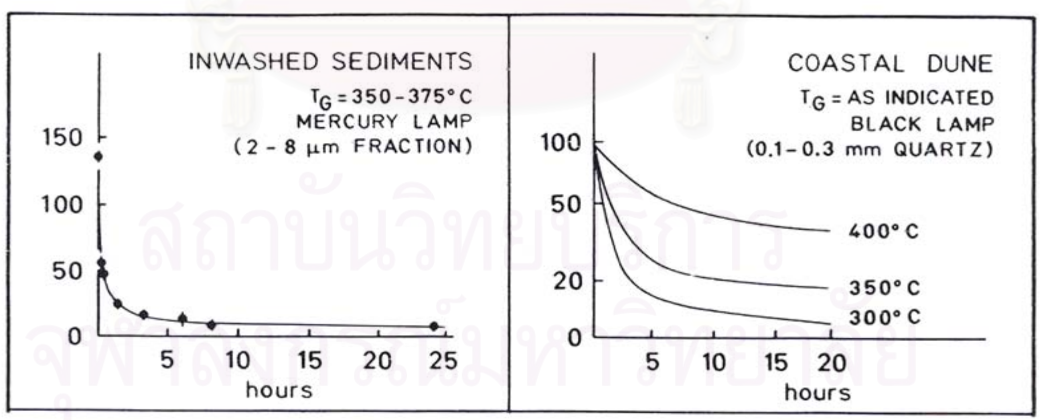
Figure 4.7 Residual testing by natural sunlight with; (a) Coastal dune sediment sample no. TTp 4-2.1A from Thung Tuk archaeological site, and (b) Colluvial sediment sample no. BL 10A from Ban Bom Luang trench.

Moreover, comparison between bleaching by natural sunlight with laboratory light is also proposed to discuss the potential of complete bleaching in each kind of light source.

At Ban Bom Luang trench, the sediments are regarded mainly colluvial deposit (Charusiri, et al., 2003). Residual testing results from Ban Bom Luang sediments by natural sunlight was based on the consuming times of 8 hours for completely bleach to residual level (Figure 4.8 b). This time range is almost similar to experiment done by Singhvi and Wagner (1986) who applied mercury lamb for bleaching inwashed sediments (Alluvial environment) (Figure 4.8a).

At Thung Tuk archeological site where the deposit is regarded as the coastal dune (Lunsai, 2004) we applied the time of 4 hours to complete bleaching using natural sunlight. The bleaching time from Thung Tuk archaeological site is less than the black-lamb bleach that use the time more than 20 hours for complete bleaching (Figure 4.8 b).

Although, the time consumed for complete bleaching using natural sunlight is similar to that of Singhvi and Wagner (1986) in case of inwashed sediments, sediment size range they applied to bleaching is 2-8 μm while our size range is 74-149 μm. Therefore, if we use grain size similar to their experiment, the possibility of times that expends to complete bleach by natural sunlight might decrease more than 8 hours. The result indicates that natural sunlight has a potential to bleach TL signal better than laboratory lamp in sense of the amount of time that use for complete bleaching.




(a) (b)



Figure 4.8 Reduction in TL levels measured at glow curve in response to a laboratory exposure to a sunlamp or like; for various sediments types (Singhvi and Wagner, 1986). (a) Bleaching inwashed sediments (Alluvial) by mercury lamp, and (b) Bleaching coastal dune sediments by black lamp.

Based on residual comparison between coastal dune sediments (Thung Tuk archaeological site) and colluvial sediments (Ban Bom Luang trench) (see Figure 4.9), the evidence indicated that residual percent of coastal dune usually remain 4-8% while residual percent of colluvial sediments is 50-70%. Moreover, residual level is independent from amount of started natural TL signal.

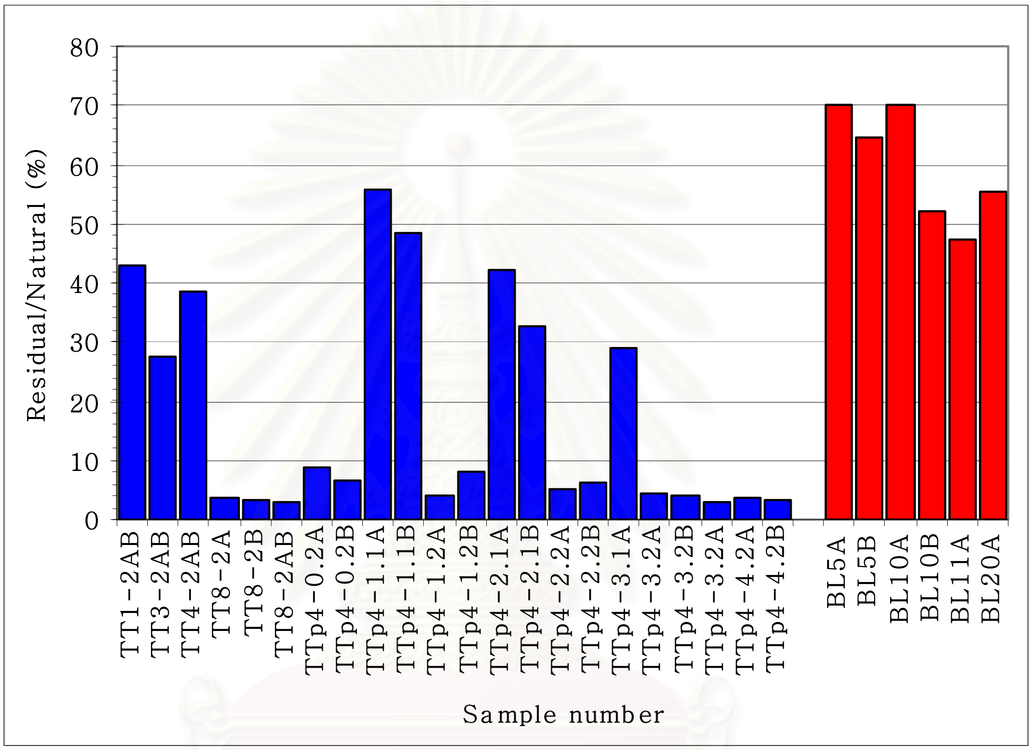



Figure 4.9 Ratio of residual TL signal/natural TL signal after bleaching sediment sample by natural sunlight 16 hours. The blue color is residual of sediment samples from coastal dune environment (Thung Tuk archaeological site) and the red color is residual of sediment samples from colluvial environment (Ban Bom Luang trench).

### 4.1.5 Uranium, Thorium and Potassium Contents

From the annual dose analysis based on contents of uranium, thorium and potassium results, all of brick samples from Thung Tuk archaeological site give large quantities of Uranium, Thorium and Potassium content more than sediments sample from both of Thung Tuk archaeological site and also Ban Bom Luang trench (Figure 4.10). These different of radioactive mineral content imply that brick samples are richer in clay minerals than sediments samples.

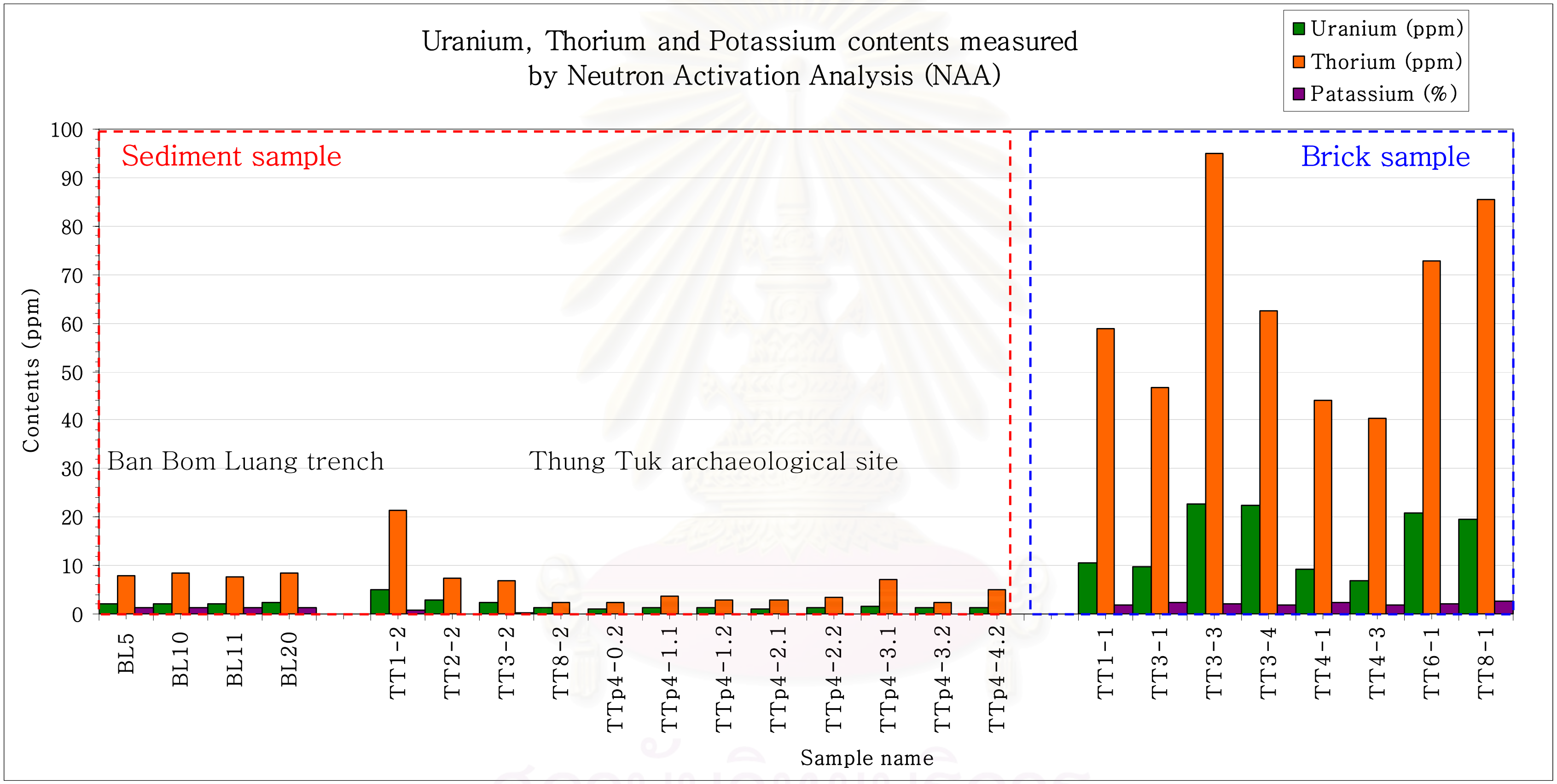



Figure 4.10 The quantities of Uranium, Thorium and Potassium measured by Neutron Activation Analysis from Office of Atomic Energy for Peace (OAEP), Bangkok. The red dash is a series of sediment samples and the blue dash is a series of brick samples. Sample no. BL collected from Ban Bom Luang trench while sample no. TT collected from Thung Tuk archaeological site.

### 4.1.6 Age Comparison between Fine and Coarse Size Ranges

In order to study the influence of grain size with the dates, in this study, the widely accepted grain size between 74-250 μm (60-200 mesh) (Takashima and Honda, 1989) were separated into 149-250 μm (60-100 mesh) or coarse-grain portion and 74-149 μm (100-200 mesh) or fine-grain portion, in each TL dating technique. The dates from both of 2 grain-size ranges are compared by constructing calibration curve between the dates of these 2 grain-size ranges. For detailed investigation on the size effect, we subdivided ages into 5 ranges namely 0-5 ka, 0-10 ka, 0-50 ka and 0-200 ka. The results of comparison are shown in Figure 4.11.

The results from calibration curves reveal tendency of the dates that evaluated from grain size 74-149 μm and 149-250 μm are almost equal for every range of the ages. However, a minority part of the dates yield the contrasting dates. Such age discrepancy mainly effect from incomplete bleaching or some technical problems.

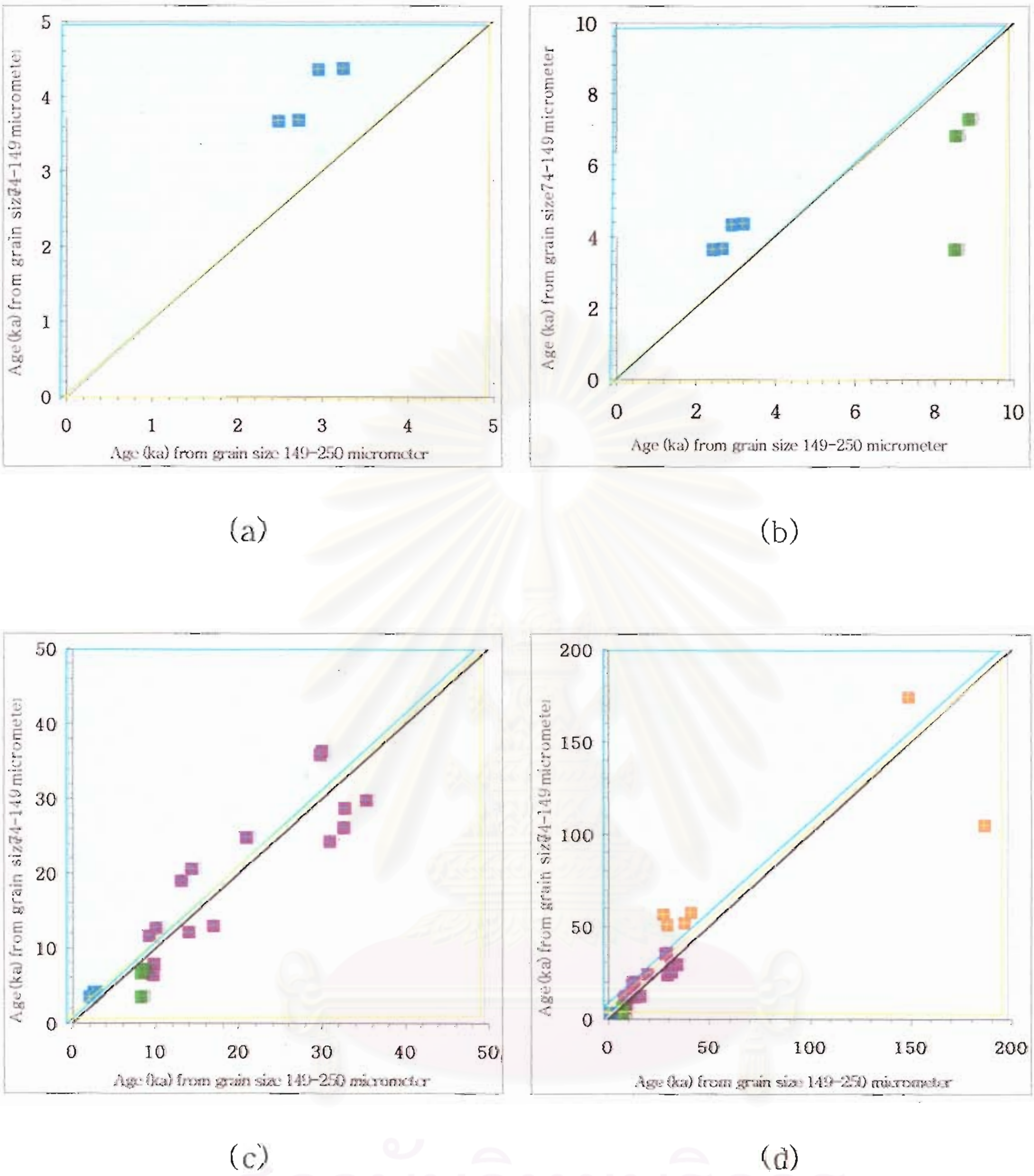
It is likely that for the age lower than 50 ka, the dates obtained from sediments of fine-size range (74-149 μm) are always lower than those of the coarser size range (149-250 μm). The dates are higher at about 60-70 ka for sediments of fine-size range (74-149 μm). For both size ranges, the dates seem to be almost similar within the range of 0-50 ka and become quite fluctuated at about >100 ka.

### 4.1.7 Age Comparison between Total Bleach and Regeneration Techniques

When considering the age (or date) results evaluated from both total bleach and regeneration techniques, calibration curves can clearly reveal the difference of the dates between these two techniques (Figure 4.11).

Subdivision of the age ranges is similar to that of section 4.16, including (a) range of 0-5 ka, (b) 0-10 ka, (c) 0-50 ka, and (d) 0-200 ka.

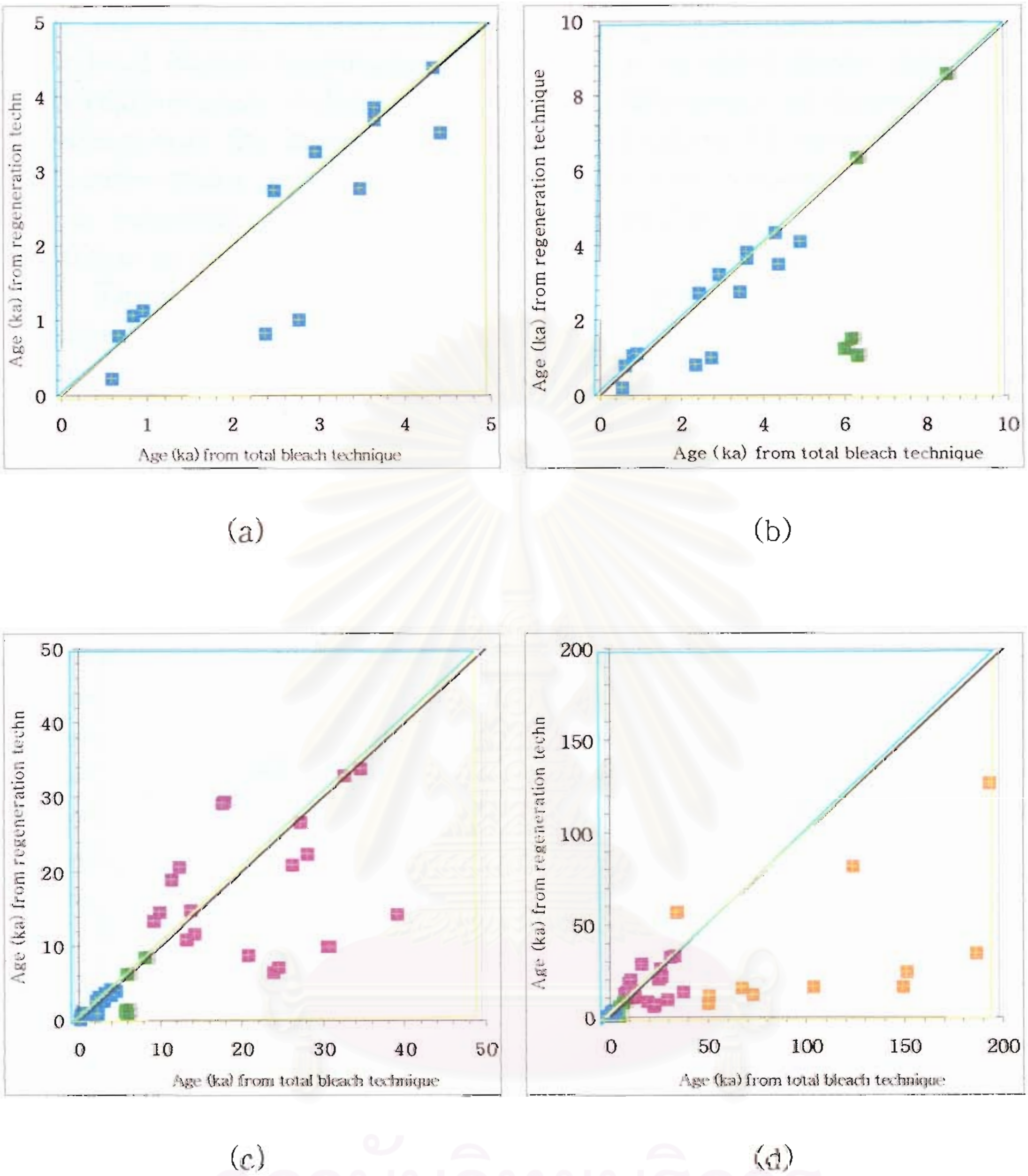
As shown in Figure 4.12a, at the TL age range 0-5 ka, dates obtained from the total bleach technique show similar values to those of the regeneration technique in the same sample. It is likely, as shown in Figures 4.12b and c that the dates from the total bleach technique are always higher than those of the regeneration technique at a range of 0-10 ka, and become much higher than those of the total bleach technique up to the age ranges of 0-50 ka and 0-200 ka.




Zone of age range which dates from grain size range 74-149 μm> those of the 149-250 μm.

Zone of age range which dates from grain size range 74-149 μm< those of the 149-250 μm.

Figure 4.11 TL-age comparisons of dated samples between grain size range of 74-149 μm and 149-250 μm. (a) at age range of 0-5 ka, (b) at age range of 0-10 ka, (c) at age range of 0-50 ka, and (d) at age range of 0-200 ka.




Zone of age range which dates from total bleach technique> those of the regeneration technique

Zone of age range which dates from total bleach technique< those of the regeneration technique

Figure 4.12 TL-age comparisons of dated samples between total bleach and regeneration techniques. (a) At the age range of 0-5 ka, (b) At the age range of 0-10 ka, (c) At the age range of 0-50 ka, and (d) At the age range of 0-200 ka.

From the above discussion, it is reliable that most of the results from total bleach technique give tendency of older dates than those from regeneration technique and that the difference of dates becomes increased with the increase of the dates obtained. However, in the low age range, minor portions of TL dates from total bleach technique have also a possibility to be less than those evaluated from regeneration technique in the same sample.

These specialties can refer to the TL growth curve characteristic proposed by Singhvi and Wagner (1986). They proposed the characteristics of TL growth curve both of in ideal (Figure 4.13a) and practical (Figure 4.13b) cases. In ideal growth curve, the curve shows relationship between TL signals versus increasing doses in term of linear curve (Figure 4.13a) while in practiced growth curve, show the curve shows the complex non-linear (Figure 4.13b).

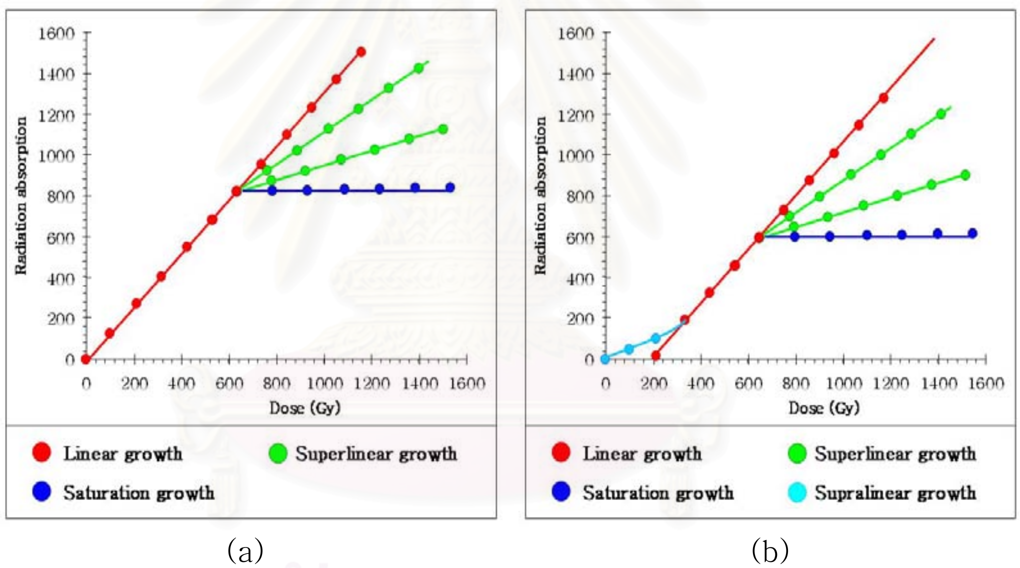



Figure 4.13 Characteristics of thermoluminescence growth curve; (a) An ideal TL signal versus dose growth curve, and (b) Schematic representation of practical growth curve illustrated a supralinear growth, superlinear growth and saturation of TL signals at high doses. (modified from Singhvi and Wagner, 1986)

From the complex characteristic of the currently obtained growth curve (Figure 4.13b), this is the significant problem of total bleach technique that, to some extent, can give over-estimated and under-estimated dates when compared with those of the regeneration technique at the low ages range (Figure 4.12a). In contrast, in the higher ages range (Figures 4.12b, c, and d), over ages from total bleach technique is more effect than under ages when compared with those of the regeneration technique. The details of over-estimation and under-estimation of total bleach technique when compared with those of the regeneration technique are described below.

A) Over Estimation of Total Bleach Technique Effect from Superlinear and Saturation Effect

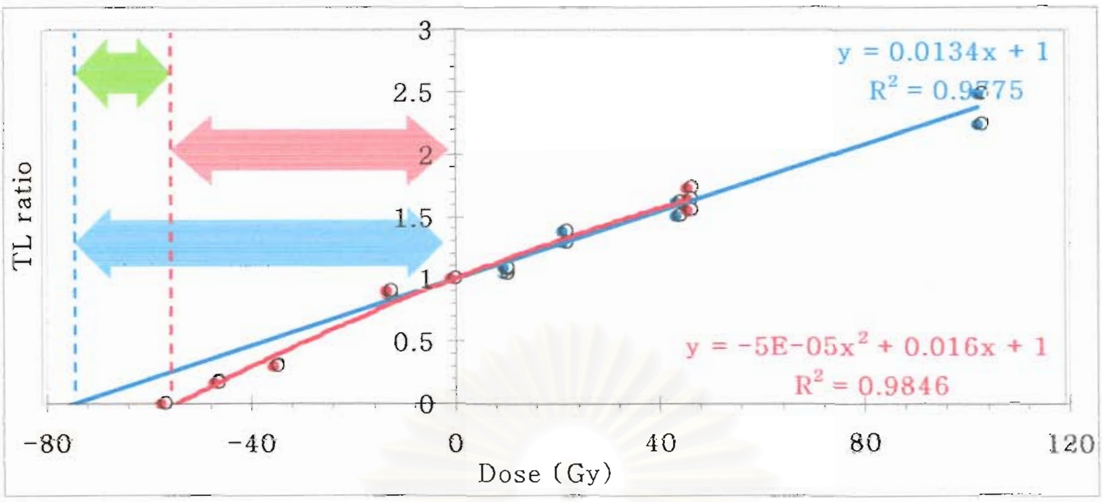
Normally, the question of the superlinear and saturation of TL signals is not always easily answered by researchers (see Singhvi and Wagner, 1986). In simple glow curves, the growth curve of each peak as the radiation dose to the sample is increased and can be clearly discerned. In contrast, almost growth curve of increasing TL intensity versus radiation dose (N+$\beta$) seldom bends into a horizontal line, showing that the TL material has reached its saturation dose. This level is called "superlinear phenomena" by Singhvi and Wagner (1986) (see Figure 4.13b).

Moreover, when irradiated the dose higher than superlinear level with TL sample, the quantity of TL emitted by a crystalline mineral cannot increase indefinitely with additional radiation doses (N+$\beta$). It eventually reaches a limit where further irradiation produces no increase of TL intensity and the growth curve becomes flat. Then the TL signal is said to be "saturated phenomena", and the dose at which this occurs is called the saturation dose (Figure 4.13b).

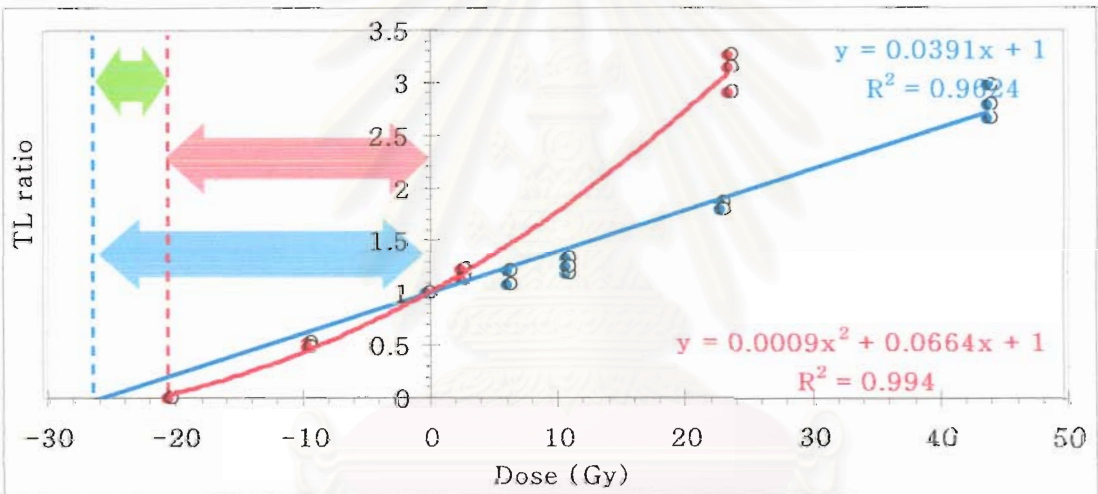
From total bleach processing, this technique started with plot increasing natural plus artificial irradiation (N+$\beta$) versus TL signal. Afterward, extrapolated back to zero level of TL signal, the equivalent dose read from a predicted starting point of a horizontal line drawn at the level of the natural TL signal. Therefore, every time when evaluating equivalent dose by prediction tendency back to zero, equivalent dose have a possibility to give the overestimation value effect by superlinear and/or saturation phenomena (Figure 4.14).

In this research, sediment sample exemplifies the problems of overestimate and this situation can been seen in total bleach technique better than regeneration technique. The characteristic of superlinear was shown in Figures 4.14a and b while saturation was shown in Figures 4.14c and d.

Practically, the superlinear growth and saturation growth are impossible to predict due to some limitation. However, as a general rule, it must be expected that materials subjected to high rates of artificial irradiation exposure will meet saturation earlier than those in low dose-rate of artificial irradiation.




(a) Sediment sample no. TT1-2AB, Thung Tuk archaeological site



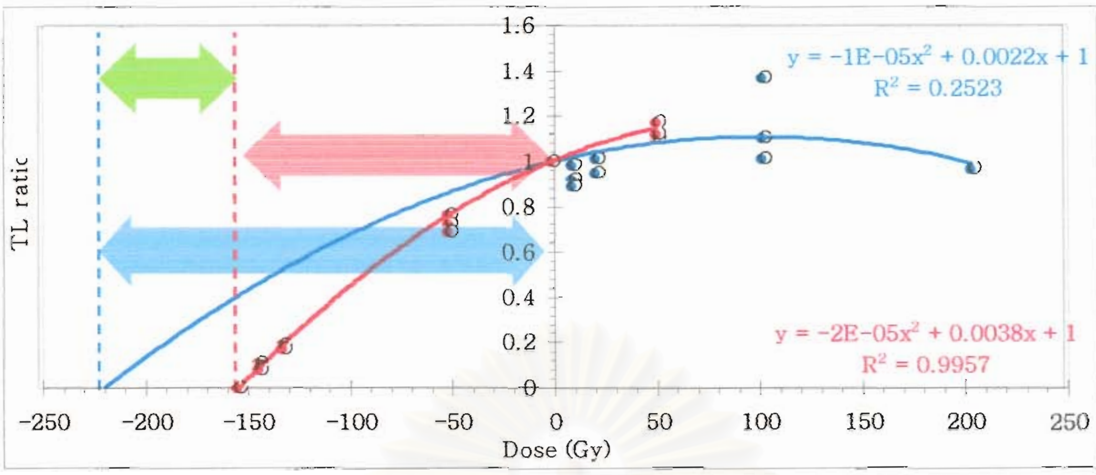

(b) Brick sample no. TT3-1AB, Thung Tuk archaeological site

Equivalent dose evaluate from regeneration technique

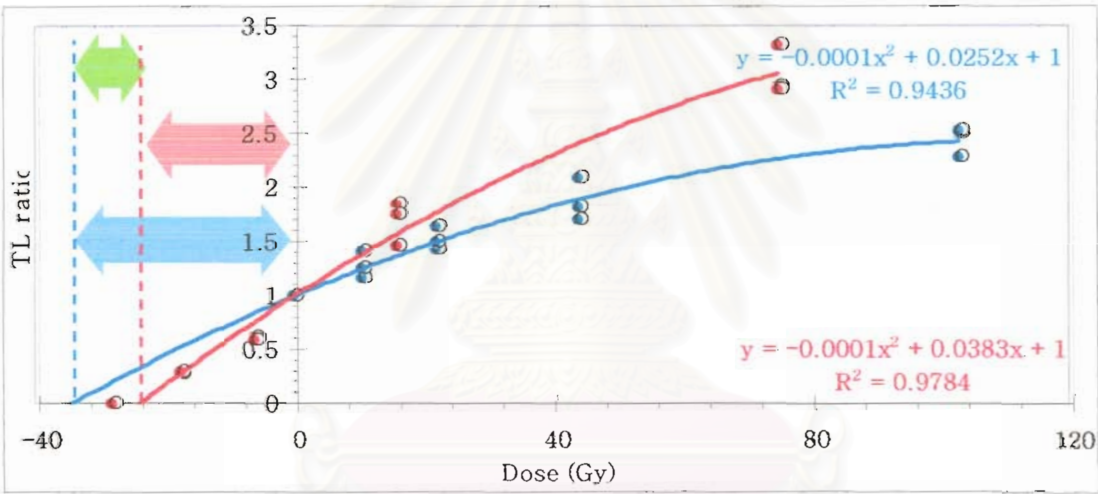
Equivalent dose evaluate from total bleach technique

Over estimated equivalent dose of total bleach technique

Figure 4.14 A case of superlinear phenomena (a and b) from total bleach glow curves showing the declining rate of TL-intensity growth as the sample from Thung Tuk archaeological site are irradiated with increasingly large doses. The blue line is total bleach growth curve and the red line is regeneration growth curve. Total bleach technique show tendency of growth curve by use linear function while regeneration technifque use polynomial function.




(c) Sediment sample no. TT3-2AB, Thung Tuk archaeological site




(d) Sediment sample no. TTp4-3.1A, Thung Tuk archaeological site

Equivalent dose evaluate from regeneration technique

Equivalent dose evaluate from total bleach technique

Over estimated equivalent dose of total bleach technique

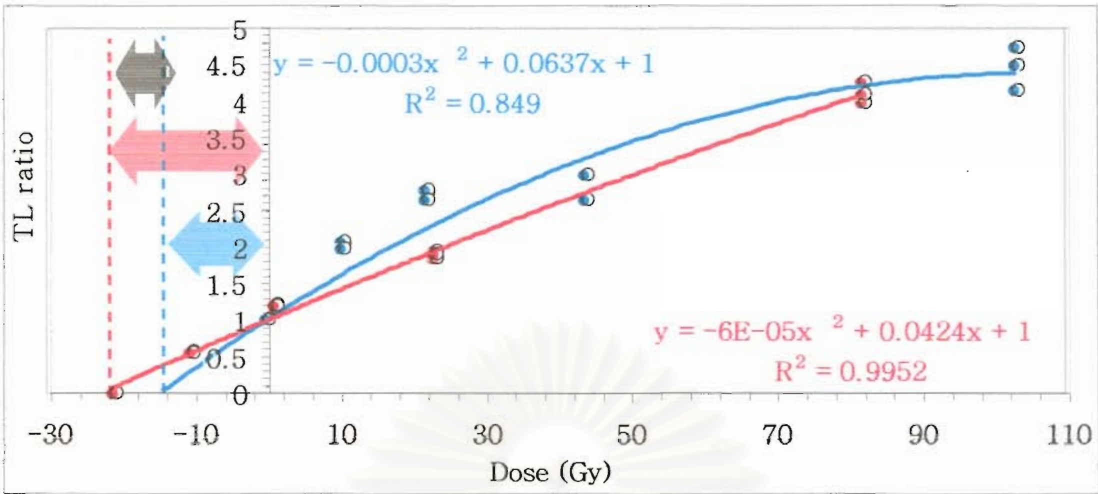
Figure 4.14 (cont.) A case of saturation phenomena (c and d) from total bleach glow curves showing the declining rate of TL-intensity growth as the samples from Thung Tuk archaeological site are irradiated with increasingly large doses. The blue line is total bleach growth curve and the red line is regeneration growth curve. Both of total bleach and regeneration techniques show tendency of growth curve by use polynomial function.

B) Under Estimation of Total Bleach Technique Effect from Supralinear Effect

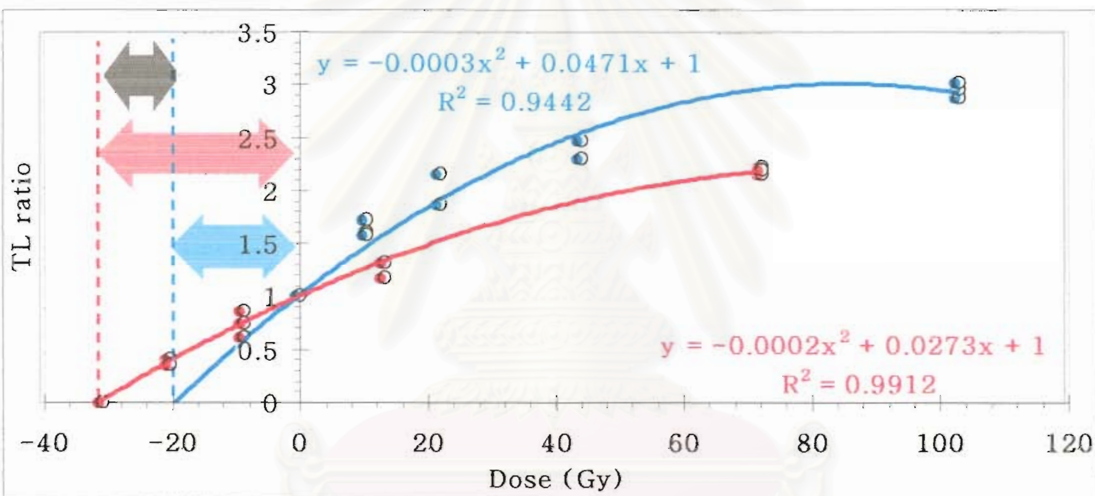
Except for overestimation by superlinear and saturation effect of TL signal, a minor part of error ages derived from total bleach technique is under estimation from supralinear effect. Although an ideal TL growth curve (Figure 4.13a) is a linear increase of TL signal with dose, but in practice, a higher TL sensitivity (dose) may expose a lower initial TL intensity. This phenomenon, called "supralinear phenomena"(Singhvi and Wagner, 1986), is due to competition between different sets of traps, some of which do not take part in the TL process. When evaluated equivalent dose by total bleach technique, this phenomena effects to underestimation when predicted back to zero level of TL intensity. In this research some growth curves from regeneration technique show supralinear characteristic (Figure 4.15).

In order to evaluate the accuracy of total bleach and regeneration techniques, comparison of both techniques with widely accepted radiocarbon ages should be investigated. The calibration curves between the dates from total bleach techniques versus radiocarbon dating and regeneration techniques versus radiocarbon dating reveal the difference in accuracy for total bleach and regeneration techniques. The dates obtained from regeneration techniques (Figure 4.16a) are more closely comparable with those of the radiocarbon dating than the ages from total bleach techniques (Figure 4.16b) when compared sample by sample.

To discussion about different date of each technique, a complication of total bleach technique arises because, in general, the growth curves are not straight lines (see Figures 4.14 and 4.15). When evaluating equivalent dose by total bleach techniques, it is possible to observe growth curve in lower or higher than the natural level. This problem can be answered by measuring a growth curve from regeneration technique, using portions of the sample in which the initial state of the TL has been recreated by heating 320 $^{\circ}$C for 5 hours (Takashima and Honda, 1989). The form of this regenerated growth curve is then taken as the correct line and fit with growth curve of sample that constructed in the past time.




(a) Sediment sample no. TTp4-1.1A, Thung Tuk archaeological site



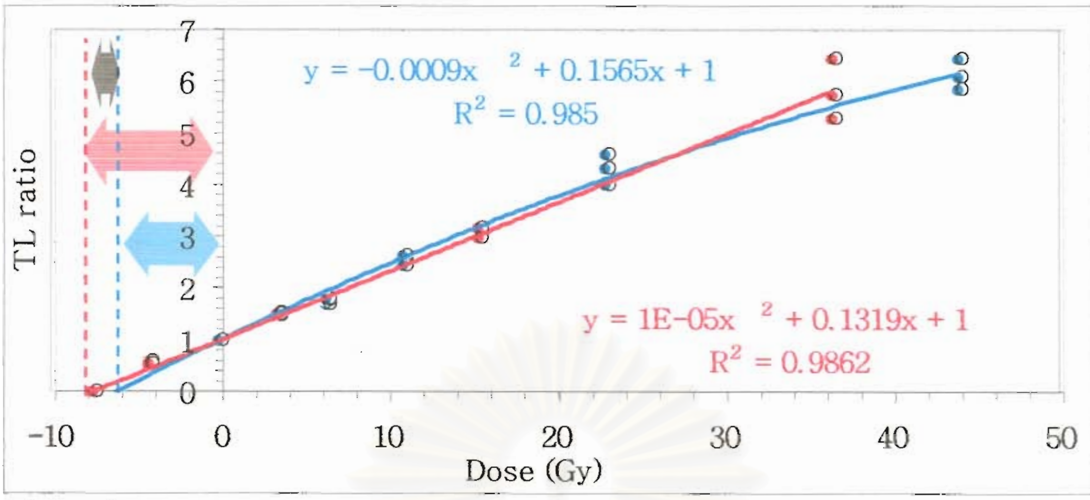

(b) Sediment sample no. TTp4-2.1A, Thung Tuk archaeological site

Equivalent dose evaluate from regeneration technique

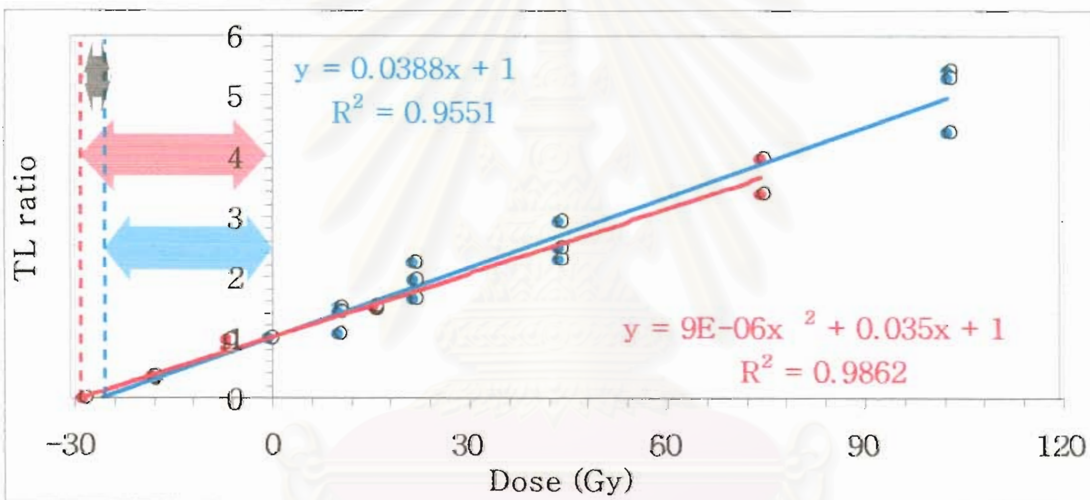
Equivalent dose evaluate from total bleach technique

Under estimated equivalent dose of total bleach technique because of supralinear phenomena

Figure 4.15 Supralinear characteristic from sediments samples from Thung Tuk archaeological site evaluated from regeneration technique. The blue line is total bleach growth curve and the red line is regeneration growth curve. Total bleach technique show tendency of growth curve by use polynomial function (Figure 4.15a and b) while regeneration technique use both of linear function (Figure 4.15a) and polynomial function (Figure 4.15b).




(c) Sediment sample no. TT4-1AB, Thung Tuk archaeological site



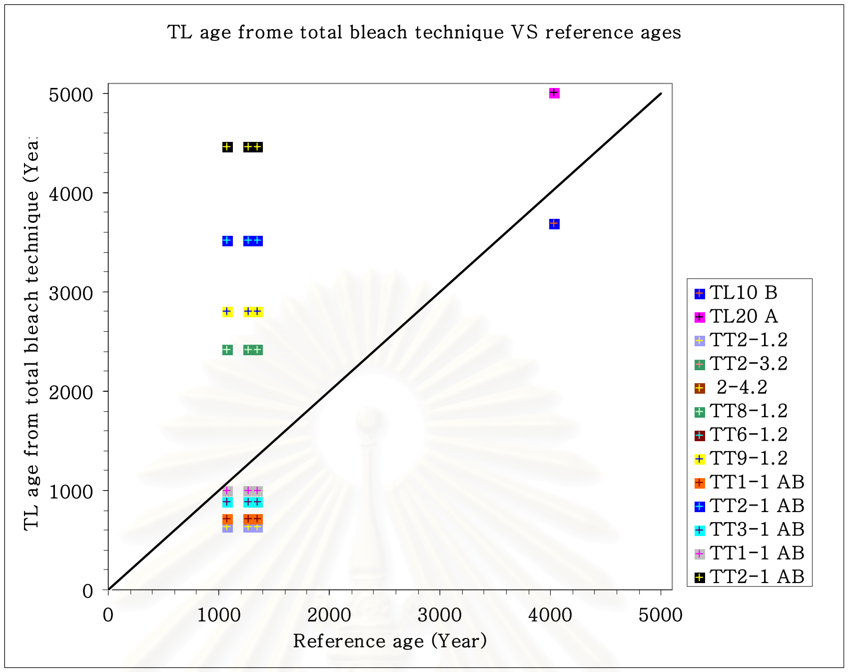

(d) Sediment sample no. BL5A, Ban Bom Luang trench

 Equivalent dose evaluate from regeneration technique

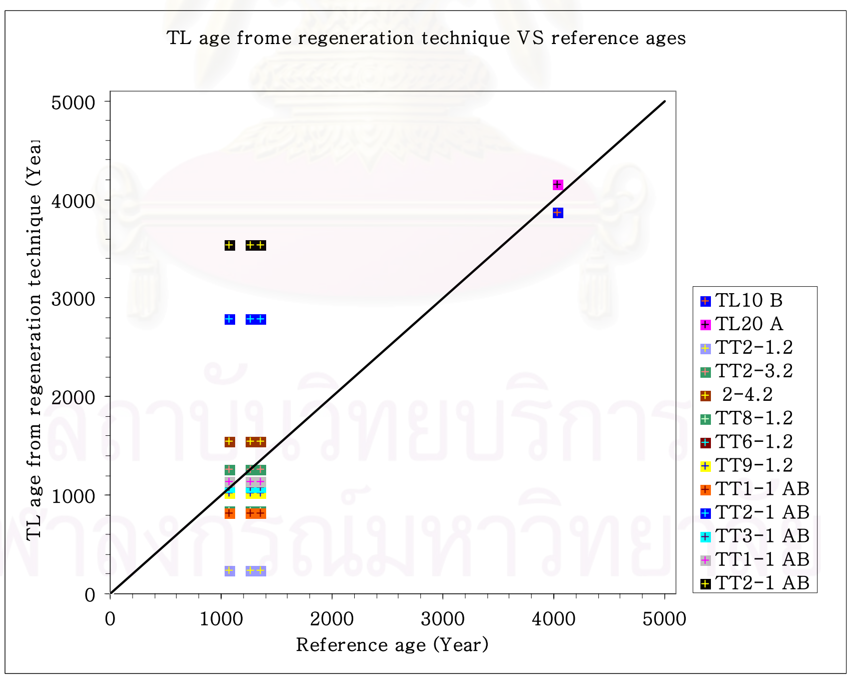
 Equivalent dose evaluate from total bleach technique

 Under estimated equivalent dose of total bleach technique because of supralinear phenomena

Figure 4.15 (cont.) Supralinear characteristic of sediment samples evaluated from regeneration technique. The blue line is total bleach growth curve and the red line is regeneration growth curve. Total bleach technique show tendency of growth curve by use polynomial function (Figure 4.15c) and linear function (Figure 4.15d) while regeneration technique use linear function (Figures 4.15c and d).




(a)




(b)

Figure 4.16 Comparison of TL age versus radiocarbon ages. (a) TL age from total bleach techniques versus radiocarbon ages, (b) TL age from regeneration techniques versus radiocarbon ages.

### 4.1.8 Electron Spin Resonance Dating

To ensure the reliability of TL dating, electron spin resonance (ESR) dating is performed to evaluate the age from the study areas. Based on comparison between TL dates with ESR dates, three from four samples (sample nos. BL5A, TTp4-1.1A and TT1-2AB) give the ESR dates older than TL dates. The significant point that causes of older dates for ESR dating is most ESR growth curves illustrate superlinear or saturation phenomena (Figure 4.17). The sensitivity of ESR dating shows the standing value when adds the higher artificial dose. This assumption is may be effect from unsuitable of ESR measurement condition such as room temperature condition etc.

Except for sample nos. BL5A, TTp4-1.1A and TT1-2AB, the ESR date (4,026±1,943 years) from sample no. BL20A seem agreed with TL dates of 4,158±1,838 years by regeneration technique. The ESR date is also compatible with TL dates of 4,200±120 years from Charusiri et al. (2003)

However, all ESR dates, 2 from 3 time residual measurement are eliminated in construction ESR growth curve because they (eliminated residual values) give more ESR signal than natural ESR signal. So, it likely that most of the ESR dates from this thesis are low reliable.

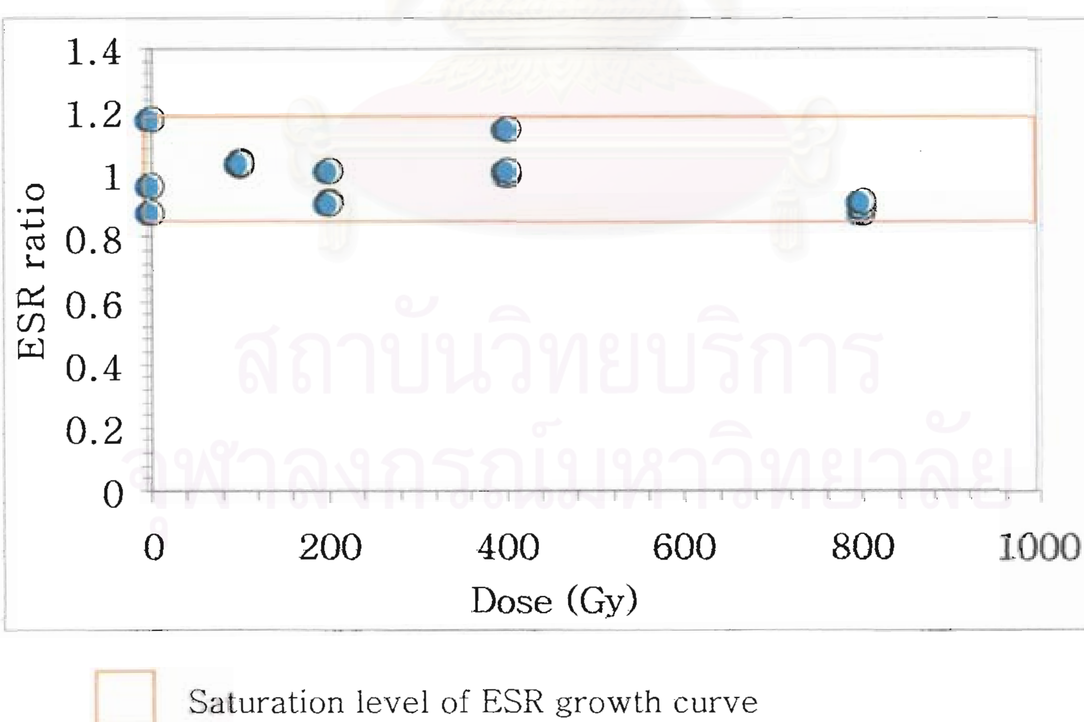



Figure 4.17 ESR growth curve of sediment sample no. TT 1-2AB from Thung Tuk archaeological site displaying saturation level of glowing ESR signal.

## 4.2 Ages of Ban Bom Luang Trench

### 4.2.1 Discussion of the Dates from Ban Bom Luang Trench

At Ban Bom Luang trench, 2 groups of TL dates were obtained for each sample. The TL dates of samples nos. BL10 and BL20 by regeneration and total bleach technique correspond well to TL ages evaluated by regeneration technique by Charusiri et al. (2003) and also agree with AMS radiocarbon age reported in this thesis. These results support that fine-grained sand and coarse-grained silt are the suitable size for TL dating (Figure 4.19C). Based on this comparison, it is ensured that TL dating method give the high precision and high accuracy particularly when fine-grained sediments (or sample) are applied.

The coarse fraction of the sample no. BL5 gives chaotic dating results, i.e., 3,702±405 and 2,524±782 years. The results are discrepancy with those of AMS radiocarbon and TL age reported by Charusiri et al. (2003). This implies that the coarse fractions are not suitable for TL dating method (Figure 4.18). However, TL ages reported by Charusiri et al. (2003) agree well with those of AMS radiocarbon dating in this sediments unit.

Figure 4.18 Sampling point no. BL5 (yellow circle) illustrating coarse-grained deposit from Ban Bom Luang trench. Two fingers indicate the top and bottom of coarse-sediment layer (Dr. Punya Charusiri as a scale).

Sample no. BL11 also gives the old dates when compared with TL ages of Charusiri et al. (2003) and AMS radiocarbon age in this study. Although stratigraphic description from previous log reveals sediment size of the layer is over sand size and down to silt size, it is not the appropriate size for TL dating approach. So, we interpret that the sample contains quartz concentrates which some are not completely bleach during the transportation period.

### 4.2.2 Evolution of Sediment Deposition in Ban Bom Luang Trench

In order to clarify evolution of sediment deposition in Ban Bom Luang area, the well-dated sediment layer and detailed trench logging information are systematically compiled and interpreted for constructing an evolutional model of sediment deposition in this area. Based on this information, five events are recognized as shown in Figure 4.19. They are:

(A) Event 1: In situ weathering of rhyolite and volcaniclastic with high fractures and high alterations that can be mixed up with trivial sediments in the upper part (Figure 4.19A). Thickness of sediment deposit at the study site is up to 1 m. Such deposition may have occurred prior to 6,100 years BP.

(B) Event 2: Colluvial deposition of 20-cm thick, dark brown gravelly silt that is rich in clay at the lower part. This deposition occured within the period of 5,900-6,100 years BP (Figure 4.19 A).

(C) Event 3: Deposition of dark brown silt to sand of alluvial origin with the thickness of 70 cm. This deposit may have occurred during 3,500-4,200 years BP in the lower part deposition continued to take place and possibly ceased after 1,900 years BP (Figure 4.19 C).

(D) Event 4: Fault-induced earthquake may have happened sometime within the age range of 1,800-1,900 years BP (Figure 4.19 D).

(E) Event 5: Deposition of dark brown gravelly to sandy silt by river process with the thickness of 30-90 cm such alluvial deposit may have occurred at about 1,500-1,800 years BP (Figure 4.19 E).

(A)
Event 1: Weathered rhyolite with high fractures, mixed up with trivial sediments in the upper part.

(B)
Event 2: Gravelly silt, dark brown, firm, clay rich at the lower part.

(C)
Event 3: Deposition of sand (coarse grained to fine silt, dark brown).

(D)
Event 4: Earthquake due to fault movements.

(E)
Event 5: Deposition of sandy (silt dark brown, gravelly).

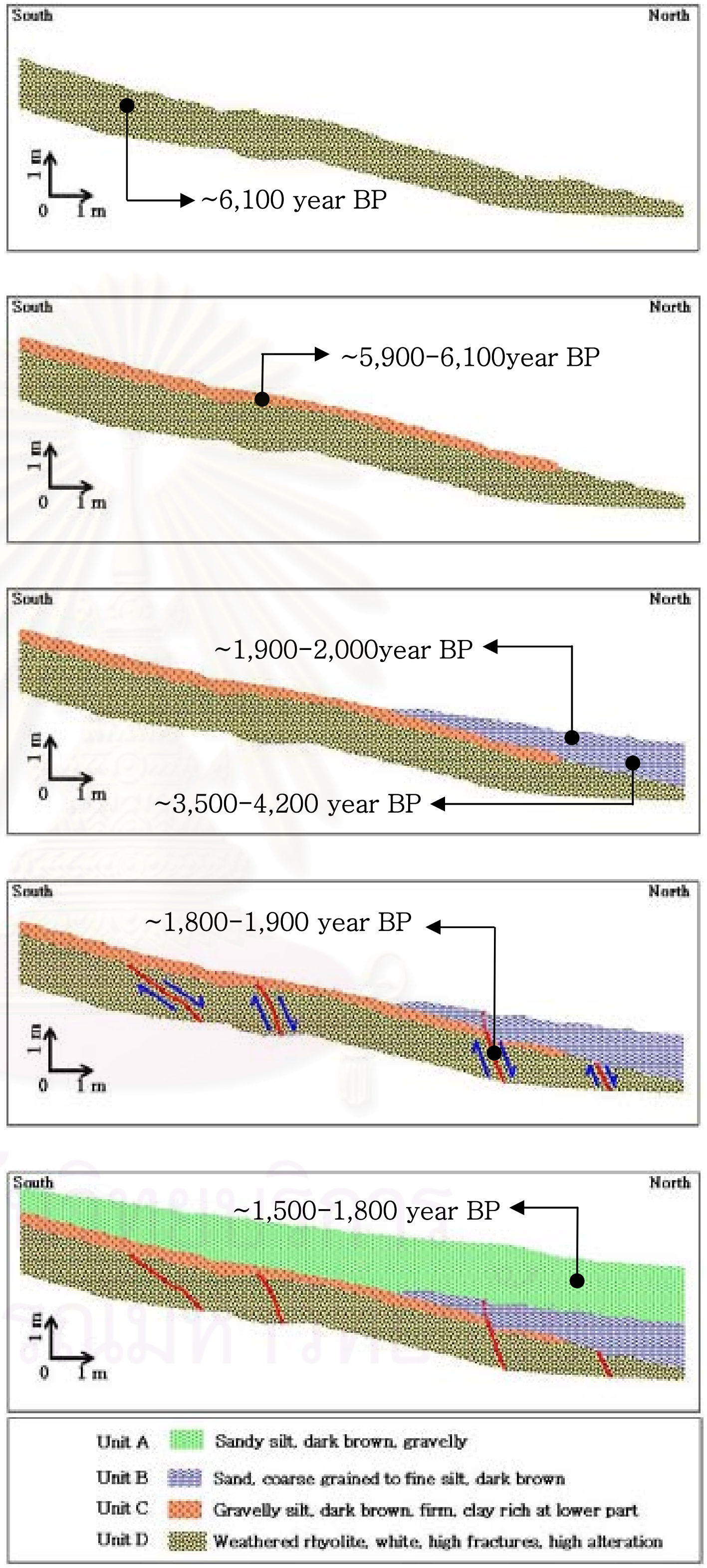



Figure 4.19 Evolutionary model of sediment deposition and earthquake activity based upon stratigraphic and structural data from Ban Bom Luang trench, Lampang province.

### 4.2.3 Rate of Fault Movement

Based on trench-log stratigraphy and virtual separation by fault movement, the rate of fault movement (or slip rates) which the rate of slip on a fault average over a time period involving several large earthquakes (Yeast et al., 1997) can be estimated using the cumulative offset of dated deposit. So, one can calculate the slip rate using such criteria (McCalpin, 1986)

In this study area, the fault from Ban Bom Luang trench which shows the obvious offset was used to calculate the slip rate. Field work investigation suggest the maximum slip length of sediments layer movement of about 30 cm. Based on our dating information, the most probable estimate time for the only single earthquake is about 1,800 years BP. Consequently, the rate of fault movement at the Ban Bom Luang trench in Lampang province is approximately 0.17 mm/ year.

## 4.3 Ages of Thung Tuk Archaeological Site

### 4.3.1 Thermoluminescene Dating with Sediments

In the case of sediment samples collected beneath ancient remain at Thung Tuk archaeological site, southern Thailand, all of them yielded very old dates when compared with the dates of brick samples collected from underneath the basement of ancient remain. We can interpret the dating result from Thung Tuk archaeological site into 2 cases. The first case is that ancient remain was settled onto the old sediment layer which emerged during that time. The second assumption is that the sediment layer might have been artificially graded as a flat basement before construction was made in the past time.

In case of TL dating of sediments in pit 1 it is demonstrated, based on the stratigraphic characteristic beneath Ko Kao Island that the TL dating method illustrates the different dates using total bleach regeneration techniques of the same sediment layer (Table 4.1 and 4.2) as shown in Appendix-F, all of growth curve by total bleach technique show characteristic of superlinear and saturation level (see Appendix-F). Consequently, all of the dated samples using total bleach technique invariable give the old and chaotic dates (Table 4.1). This leads us to eliminate series of dates in results from total bleach technique in pit1 and essentially concentrate to series of the dates from regeneration technique.

Field investigation indicates that sediment layer from units 1, 2 and 3 (Table 4.2) reveal re-sedimenting evidences due to human and agricultural activities including disturbance from root plants from surface (Figure 4.20). This means that the sediments of these layers are unnatural or artificial and also have a possibility to show incomplete bleaching. Consequently, all of TL dates in these units give relatively high uncertainty. Therefore, we cannot ensure whether or not the dates evaluated from units 1, 2 and 3 are the last deposition true ages.

However, as shown in Table 4.2, most of the TL results show a well arrangement on order of stratigraphic position. This means that TL dating on sediments has high potential and displays good reliability exception is for the sediments disturbed by human activity, agriculture activity and bioturbation (Smith et al., 1997). Such biological activities have much influence on TL dating and can contaminate the samples by up taking of older sediments. This could have happened due to animals burrowing in the soil strata and therefore mixing the dates.

Figure 4.20 Evidence of bioturbation clearly observed in unit D of the trench walls, pit 1, Thung Tuk archaeological site. Such bioturbation causes the older TL dates.

### 4.3.2 Evolution of Sediment Deposition in Thung Tuk Archaeological site

To clarify stages in the evolution of sediment deposition in Thung Tuk area, integration of the well dated (as much as possible) and detailed trench logging information are crucial to demonstrate the model of sediment deposition in this area. The deposition evolution event can be divided consecutively into 6 events in an ascending order below (see Figure 4.21).

(A) Event 1: Deposition of yellow sand sediment layer during 13,000-17,000 years BP. This is based upon the results from regeneration technique for fine-grained sediments as old as 17,080 years and as young as 13,000 years for coarse-grained sediments.

(B) Event 2: Deposition of dark brown sand during 12,400-14,400 years BP.

(C) Event 3: Bleach and coastal sediments deposited during the period 12,400 to 1,500 years BP.

(D) Event 4: Settlement of human community and oversea trade occurred in the period of 1,500 years BP.

(E) Event 5: Development of top soil after trade community was abandoned.

(F) Event 6: Recent human activity took place during the top soil development.

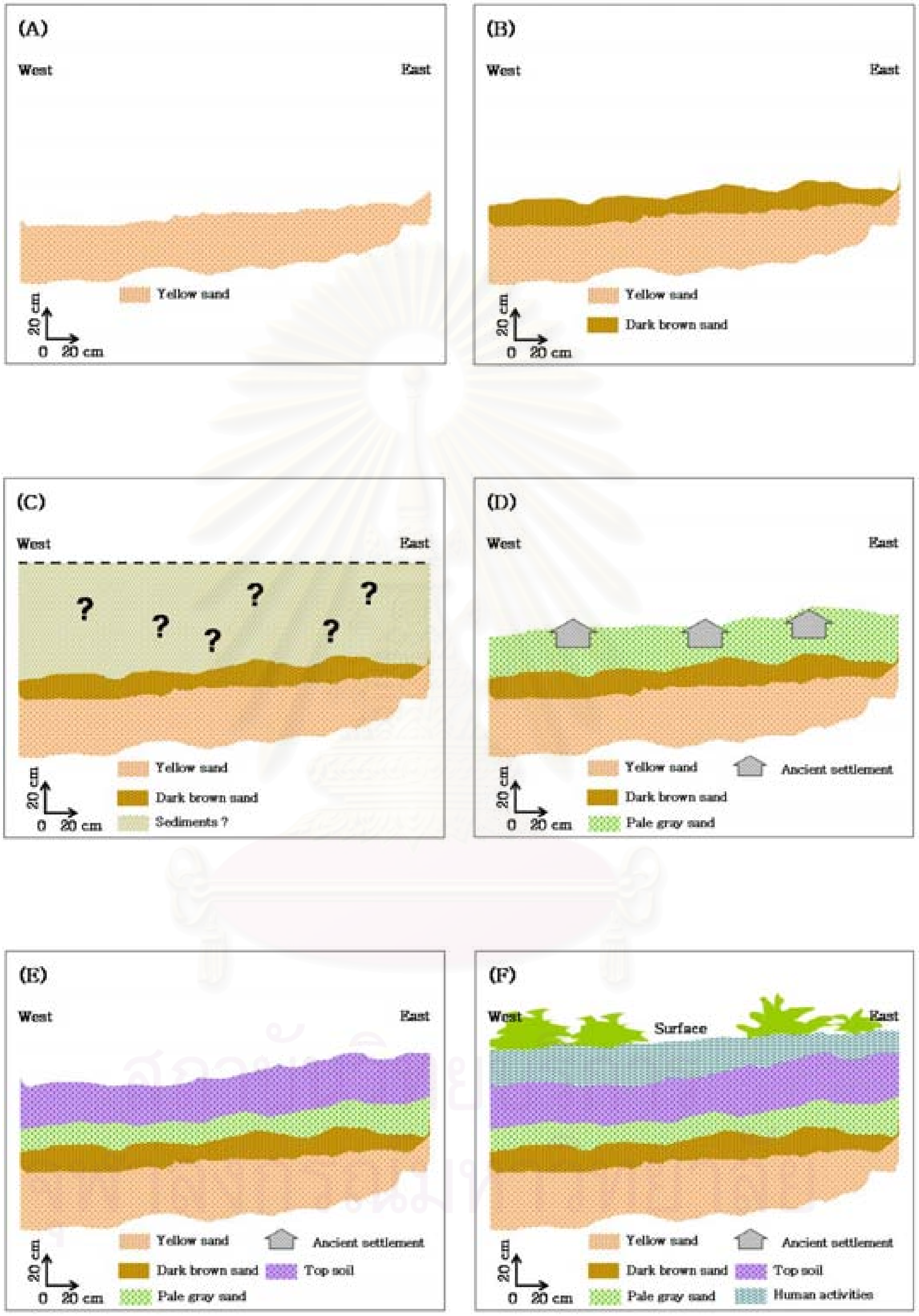



Figure 4.21 Evolution of sediment deposition at Thung Tuk archaeological site, based upon trench-log stratigraphy and TL dating result.

Table 4.1 TL dating with sediment samples from pit 1, Thung Tuk archaeological site by total bleach technique.

| Profile logging | Sample from the west side | | | | Sample from the east side | | |
|---|---|---|---|---|---|---|---|
| | Sample number | Total bleach technique | | | Sample number | Total bleach technique | |
| | | Grain size A | Grain size B | | | Grain size A | Grain size B |
| Unit 1 | - | - | - | | TTp 4-0.2 | 31,060 ± 13,281 | 51,782 ±25,557 |
| Unit 2 | TTp 4-1.1 | 9,636±3,832 | 11,832 ±3,292 | | TTp 4-1.2 | 31,252 ±10,619 | 24,431 ±9,281 |
| Unit 3 | TTp 4-2.1 | 18,405 ±3,624 | 36,532 ±9,700 | | TTp 4-2.2 | 21,362 ± 8,247 | 24,966 ±8,675 |
| Unit 4 | TTp 4-3.1 | 26,693 ±3,407 | - | | TTp 4-3.2 | 39,607 ±22,097 | 52,719 ±47,969 |
| Unit 5 | - | - | - | | TTp 4-4.2 | 150,774 ±50,158 | 74,881 ±37,037 |

Table 4.2 TL dating with sediment samples from pit 1, Thung Tuk archaeological site by regeneration technique.

| Profile logging | Sample from the west side | | | | Sample from the east side | | |
|---|---|---|---|---|---|---|---|
| | Sample number | Regeneration technique | | | Sample number | Regeneration technique | |
| | | Grain size A | Grain size B | | | Grain size A | Grain size B |
| Unit 1 | - | - | - | | TTp 4-0.2 | 10,150 ± 2,921 | 8,042 ±2,508 |
| Unit 2 | TTp 4-1.1 | 13,540 ±1,470 | 19,195 ±1,815 | | TTp 4-1.2 | 10,081 ±3,479 | 6,622 ±2,040 |
| Unit 3 | TTp 4-2.1 | 29,716 ±6,401 | 58,220 ±5,590 | | TTp 4-2.2 | 8,942 ± 2,368 | 7,342 ±3,417 |
| Unit 4 | TTp 4-3.1 | 21,150 ±3,896 | - | | TTp 4-3.2 | 14,429 ±6,983 | 12,423 ±6,940 |
| Unit 5 | - | - | - | | TTp 4-4.2 | 17,290 ± 5,056 | 13,150 ±4,146 |

Grain size

| | |
|---|---|
| A | = 74μm -149μm (fine grain) |
| B | = 149μm-250μm (coarse grain) |

### 4.3.3 Thermoluminescence Dating with Ancient Bricks

According to dating a structure built using burned bricks dates obtained from bricks can be the chronological image of construction if the site contains high mass of bricks. This leads us to use TL dating on brick samples within the framework of ancient remain at Thung Tuk archaeological site.

Our results based on two approaches of TL dating method clearly show that dates from the regeneration technique is better than those of total bleach technique and correspond well with 1,070±330, 1,310±220, and 1,260±820 years by conventional radiocarbon ages from organic fragment (Chaisuwan and Naiyawatt, 2002) and 1,200-1,500 years relative ages from antiques (Srisuchart, 1986). The TL dating by total bleach technique approach invariably give the older dates that were effect from superlinear and saturation level phenomena (see Appendix-F).

However, some of brick dates by the regeneration technique also give the confused and unreliable dates, such as that of sample no. TT3-3AB from ancient remain3 gives the younger ages when compared among other TL dates (Table 3.7). We consider, based on glow curve data, which the glow curve from sample no. TT3-3AB is different from those of the other glow curve (see Figures C.1.1 and C.1.2 in Appendix-C). It is therefore possible that the young date from sample no. TT3-1AB may have been affected from impurities in the quartz concentrate and from the defects of quartz mineral structure itself.

The other case is that sample no. TT3-1AB from ancient remain 3 also gave the dates older than independent dates. Based on our dating result, we interpret that the brick sample may have not been completely heat during construction period. So, when we compared this date with the others (such as sample no. TT3-4AB) that the inner part was removed from the brick for dating, the dating result gave the reliable age. Based on our confirmed result, it quite possible that TL dating from the inner rim of brick mass give fallacious dates which are older than that of the outer rim. We therefore propose the approach for brick sample treatment suitable for TL dating as explain below (Figure 4.22). The first step is to eliminate the outermost rim of the brick using low-speed saw machine because that part must be easily exposed to sunlight on arrival to laboratory (see also Bailiff and Holland, 2000). The second step is to save the middle portion of the brick for equivalent dose evaluation. Then peel off the middle part by sawing and save the inner portion for annual dose evaluation.

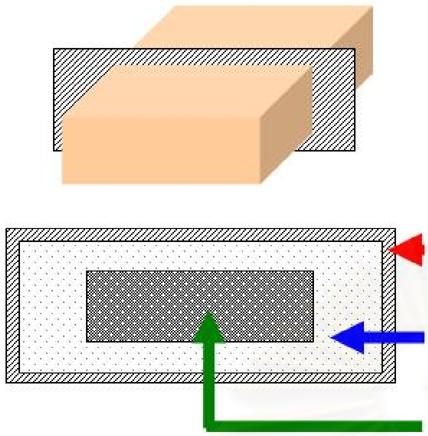



Figure 4.22 Schematic of brick sample separation use for each procedure in TL dating method.

## 4.4 Age Comparison between Thermoluminescence Ages and Other Ages

Because there are many kinds of Quaternary dating method applied to several geological/archaeological materials, comparison among the method are essential to constraint the ages we obtained. For example, Reneau et al. (1996) studies and determined age of buried soils by TL and radiocarbon analyses. The results show similar age and agree well with ESR dates analysis by Toyoda et al. (1995) who determined the age of soil in the same region. In addition, Smith, et al. (1997) produced calibration curve between TL dating results versus radiocarbon dating results by use of data from Prescott and Smith (1993) to reveal the reliable of TL dating. There is ample evidence that TL ages well agree with radiocarbon ages in the same sedimentary layer.

In Thailand, it is relevant to examine other published data where comparisons between TL and other ages can be made. In this research, we have collected a number of TL ages and other independent ages available all over Thailand (Table 4.4). We also included some of our own data to confirm the outcome. The TL ages are plotted against other scientific dating ages from the nearest stratigraphic level. In the case of the whole work, our TL ages are entered as obtained and the corresponding AMS radiocarbon versus TL age is interpolated. If AMS radiocarbon and TL dates corresponded exactly, they would fall on the red solid straight line (Figures 4.23a, b and c). It seems clear from Figures 4.23 a, b and c that our TL ages are compatible with the trend of the data as a whole.

Generally the calibration curve of TL and other dating results displays a good positive correlation with the linear regression of about 0.992 (see Figures 4.23a, b and c). This strongly advocates that our current TL-age dating result are more consistent with that of the AMS radiocarbon dating than that of the conventional radiocarbon dating. Moreover, as illustrated in Figure 4.23a, the TL dating method is more powerful than the AMS radiocarbon dating in a sense that the TL data are well applicable to the old terrestrial material of up to 2 Ma (Krowchan, 2001) and extraterrestrial-related samples (like tektite) of about 0.7 Ma (see Klongsara et al., 2002 and Panpate, 2004).

Table 4.3 Comparison between TL dating results and the other dating results from geological and non-geological materials in Thailand.

| Location | Material | TL technique | Age (year) | Error | Sources | Material | Other methods | Age (year) | Error | Sources |
|---|---|---|---|---|---|---|---|---|---|---|
| [1] | Se | R | 765 | 200 | Kosuwan,1998 | Ch | P- AMS | 515 | ? | Kosuwan,1998 |
| [1] | Se | R | 985 | 150 | Kosuwan,1998 | Ch | C-14 | 950 | 90 | Kosuwan,1998 |
| [1] | Se | R | 3,700 | 500 | Kosuwan,1998 | Ch | P- AMS | 3,745 | ? | Kosuwan,1998 |
| [2] | Se | R | 242 | ? | Kosuwan,2002 | Ch | C-14 | 230 | ? | Kosuwan,2002 |
| [3] | Sh | TB | 37,200 | 5,000 | Won-in, 2003 | Bi | AMS | 43,480 | 50 | Sato et al.,1999 |
| [3] | Sh | TB | 38,400 | 6,000 | Won-in, 2003 | Bi | AMS | 43,480 | 50 | Sato et al.,1999 |
| [3] | Sh | TB | 38,600 | 5,000 | Won-in, 2003 | Bi | AMS | 43,480 | 50 | Sato et al.,1999 |
| [4] | Se | R | 9,980 | 120 | Khaokhiew,2004 | Bo | AMS | 12,100 | 60 | Khaokhiew,2004 |
| [4] | Ca | R | 13,422 | ? | Khaokhiew,2004 | Ch | AMS | 13,160 | 75 | Khaokhiew,2004 |
| [4] | Se | R | 22,257 | ? | Khaokhiew,2004 | Sh | AMS | 22,150 | 60 | Khaokhiew,2004 |
| [5] | Se | R | 2,980 | 180 | Khaokhiew,2004 | Ch | AMS | 2,870 | 80 | Khaokhiew,2004 |
| [6] | B | TB | 538 | 15 | Changkian, 1999 | Ch | C-14 | 455 | 85 | Reotrit, 1987 |
| [6] | St | TB | 519 | 17 | Changkian, 1999 | Ch | C-14 | 455 | 85 | Reotrit, 1987 |
| [7] | Te | TB | 745,000 | 55,000 | Klongsara,2002 | Te | Fis | 670,000 | 40,000 | Gartner et al., 1992 |
| [7] | Te | TB | 745,000 | 55,000 | Klongsara,2002 | Te | Ar | 770,000 | 20,000 | Izett et al.,1992 |
| [8] | Te | TB | 650,000 | 160,000 | Orachon, 2001 | Te | K | 725,000 | 25,000 | Blum et al.,1992 |
| [9] | Se | R | 4,158 | 1,838 | *** | Se | TB | 5,011 | 1,403 | *** |
| [9] | Se | R | 3,868 | 649 | *** | Se | TB | 3,690 | 1,011 | *** |

Table 4.3 Comparison between TL dating results and the other dating results from geological and non-geological materials in Thailand (cont.).

| Location | Material | TL technique | Age (year) | Error | Sources | Material | Other methods | Age (year) | Error | Sources |
|---|---|---|---|---|---|---|---|---|---|---|
| [9] | Se | TB | 3,690 | 1,011 | *** | Se | R | 3,500 | 180 | Charusiri et al., 2003 |
| [9] | Se | R | 3,868 | 649 | *** | Se | R | 3,500 | 180 | Charusiri et al., 2003 |
| [9] | Se | R | 4,158 | 1,838 | *** | Se | R | 4,200 | 160 | Charusiri et al., 2003 |
| [9] | Se | TB | 5,011 | 1,403 | *** | Se | R | 4,200 | 160 | Charusiri et al., 2003 |
| [9] | Se | R | 3,868 | 649 | *** | Ch | AMS | 4,030 | 39 | University of Arizona, USA |
| [9] | Se | TB | 3,690 | 1,011 | *** | Ch | AMS | 4,030 | 39 | University of Arizona, USA |
| [9] | Se | R | 6,100 | 170 | Charusiri et al., 2003 | Ch | AMS | 5,882 | 42 | University of Arizona, USA |
| [9] | Se | R | 2,000 | 110 | Charusiri et al., 2003 | Ch | AMS | 1,940 | 35 | University of Arizona, USA |
| [9] | Se | R | 1,500 | 20 | Charusiri et al., 2003 | Ch | AMS | 1,793 | 35 | University of Arizona, USA |
| [9] | Se | R | 3,500 | 180 | Charusiri et al., 2003 | Ch | AMS | 4,030 | 39 | University of Arizona, USA |
| [10] | B | Ad | 886 | 194 | *** | Ta | Re | 1,150 | 50 | Chaisuwan et al., 2002 |
| [10] | B | R | 1,080 | 263 | *** | Ta | Re | 1,150 | 50 | Chaisuwan et al., 2002 |
| [10] | B | Ad | 712 | 282 | *** | Ta | Re | 1,150 | 50 | Chaisuwan et al., 2002 |
| [10] | B | R | 818 | 85 | *** | Ta | Re | 1,150 | 50 | Chaisuwan et al., 2002 |
| [10] | B | Ad | 994 | 394 | *** | Ta | Re | 1,150 | 50 | Chaisuwan et al., 2002 |
| [10] | B | R | 1,142 | 119 | *** | Ta | Re | 1,150 | 50 | Chaisuwan et al., 2002 |

Description of the abbreviation in Table 4.3

Location

[1] = Ban Pong Khom trench No.5, Chiang Rai province
[2] = Ban Hat Chom Phu trench No.3, Chiang Mai province
[3] = Ban Pheak Sa pit, Samut Prakarn province
[4] = Thamlod rock shelter, Mae Hong Son province
[5] = Pongmanow archaeological site, Lopburi province
[6] = Yarang archaeological site, Pattani province
[7] = Landfill, Ta Chang, Nakorn Ratchasima province
[8] = Landfill, Buntarik, Ubon Ratchatani province
[9] = Ban Bom Luang trench, Lampang province
[10] = Thung Tuk archaeological site, Phang Nga province

Material

B = Brick
Bi = Bivalve
Bo = Bone
Ca = Calcretes
Ch = Charcoal
Se = Sediments
Sh = Shell
St = Stupa
Ta = Tang's dynasty
Te = Tektites

Dating method

AMS = AMS radiocarbon dating
Ar = $^{40}Ar/^{39}Ar$ dating
C-14 = Conventional radiocarbon dating
Fis = Fission - track dating
K = K/Ar dating
P- AMS = Preliminary AMS radiocarbon dating
Re = Relative age dating
R = TL dating (regeneration technique)
T = TL dating (total bleach technique)

Sources

*** = Result from this research study

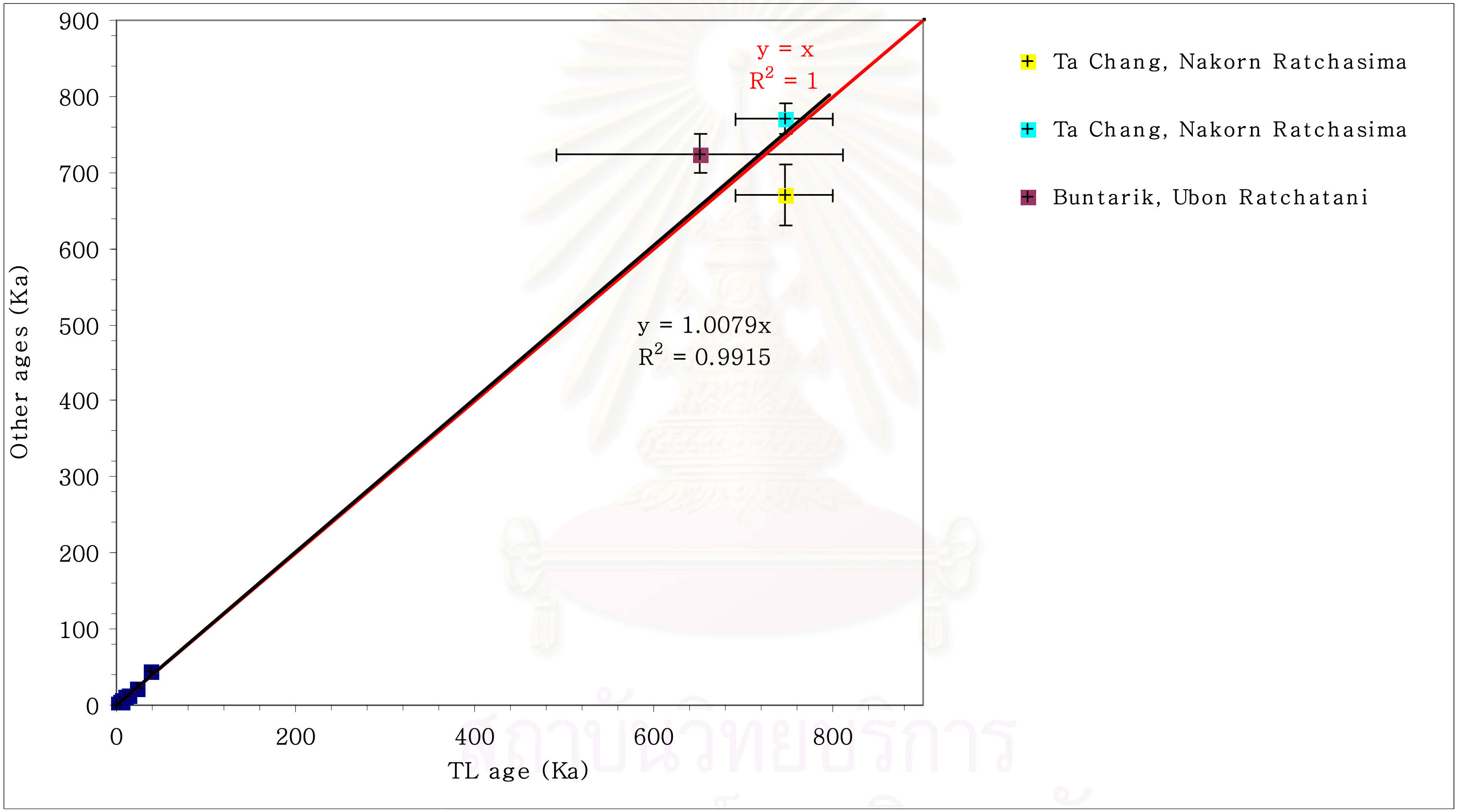



Figure 4.23a Calibration graph showing relationship between TL age (ka) and other independent ages (ka).

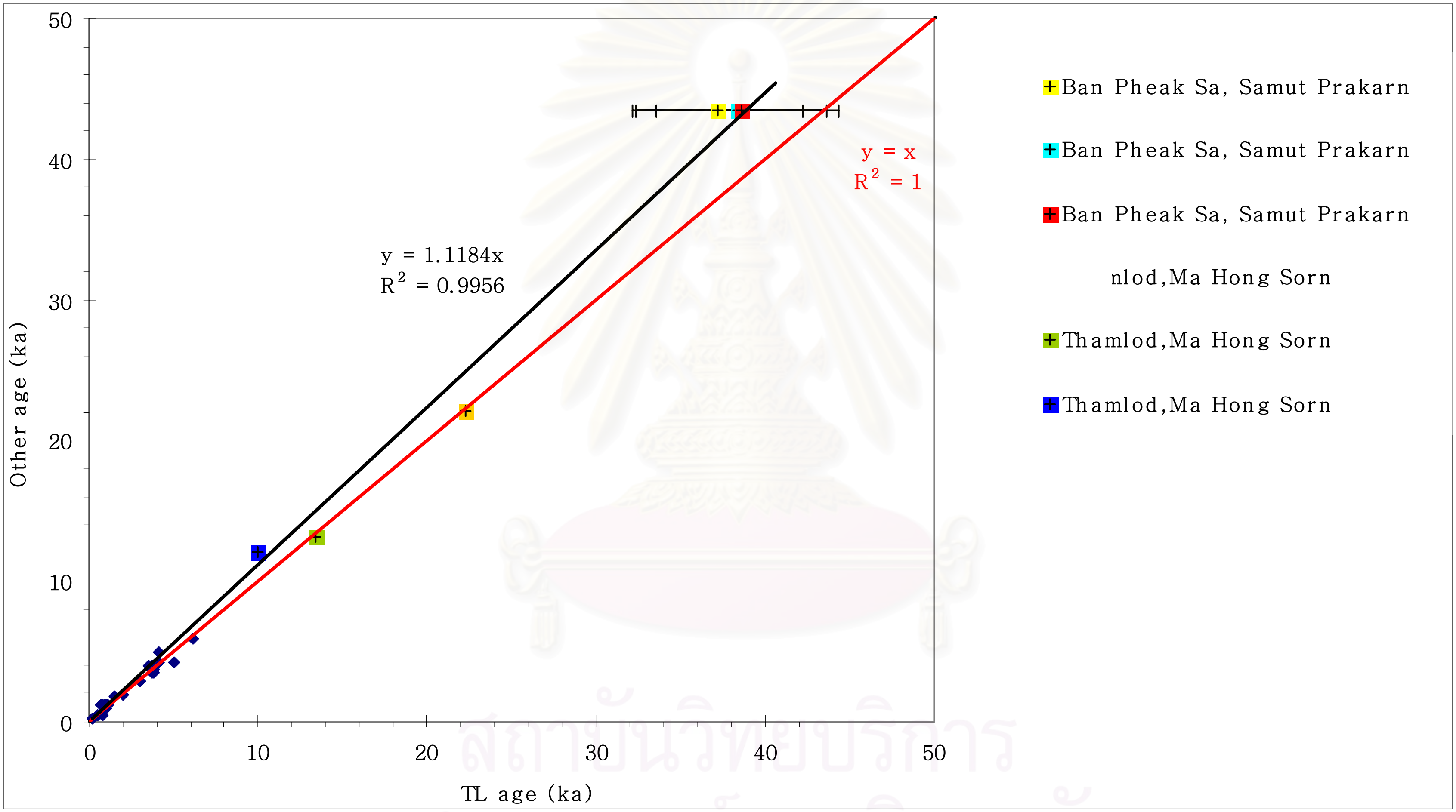



Figure 4.23b Calibration graph showing relationship between TL age (ka) and other independent ages (ka).

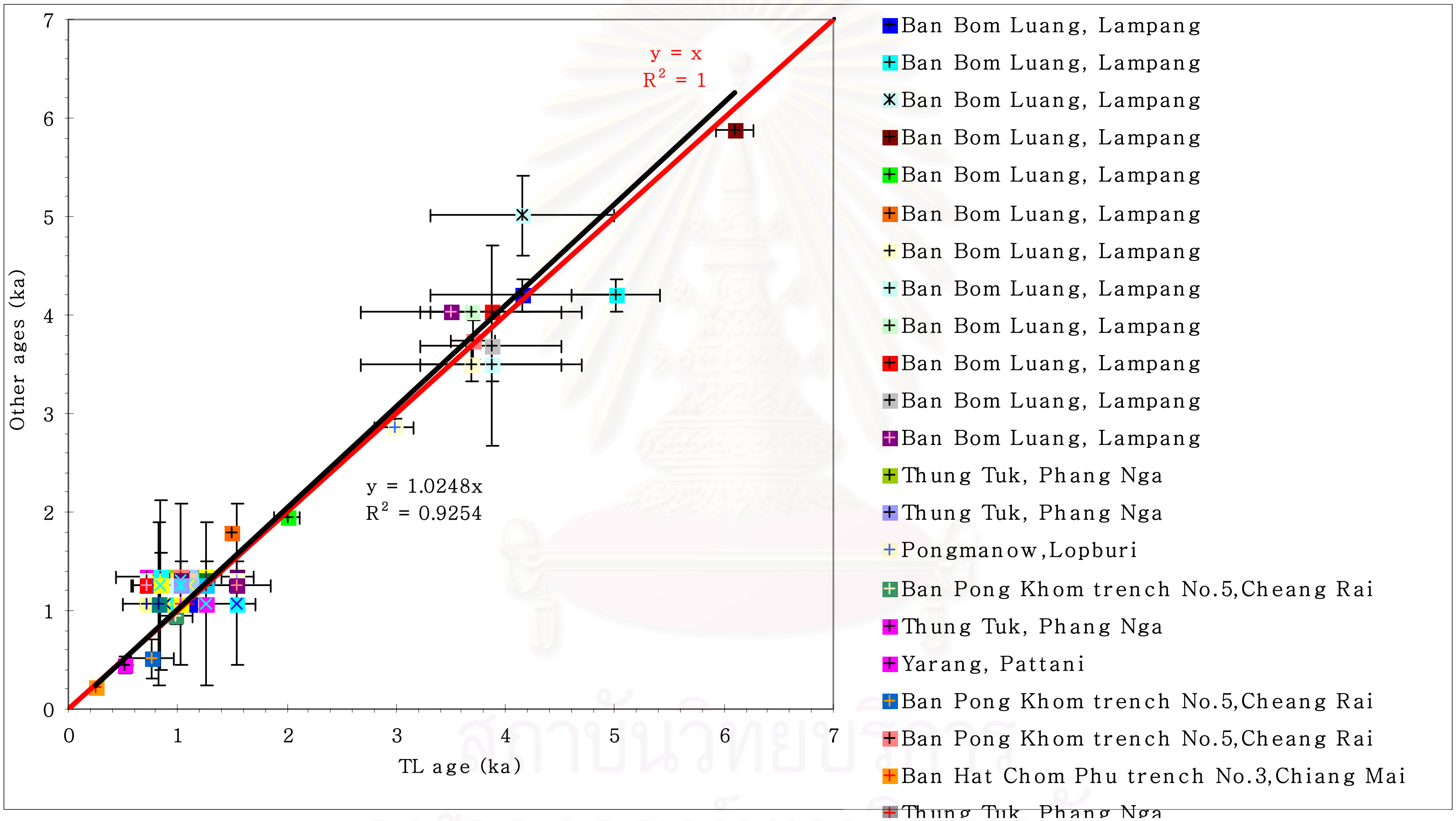



Figure 4.23c Calibration graph showing relationship between TL age (ka) and other independent ages (ka).

# CHAPTER V

# CONCLUSION

Based on the whole results of this research study including literature research, all of results are integrated and compiled to this chapter, the conclusion is shown in 4 main sections depending on objectives of this research. They are (1) Thermoluminescence dating technique, (2) Ban Bom Luang trench, (3) Thung Tuk archaeological site and (4) recommendation.

## 5.1 Thermoluminescence Dating Technique

(A) Measurement of TL glow curve from thermoluminescence detector with 1,500 voltage multiplier condition give the better and more clear sharp peak than 1,250 voltage condition.

(B) Stable temperature region of TL glow curve is checked by plateau test method. Generally quartz mineral gives a stable region of TL signal between 260-360 $^{\circ}$C, approximately.

(C) Glow curve of quartz mineral measured from extracted quartz inclusion technique give a single sharp peak at 300 $^{\circ}$C approximately and agree with characteristic of quartz peak that proposed by Vij (1993).

(D) Plateau test from quartz inclusion technique can yield different shapes of plateau analyzed from polymineral technique. However, both of them can be used potentially for representing stable region of glow curve.

(E) All of stable temperatures along plateau range can use potentially for fix and selected glow curve data for construct growth curve and evaluate equivalent dose.

(F) Bleaching by natural sunlight use 4-8 hours of the time for completely bleaching to residual level of sediments.

(G) For Bleaching experiment, bleaching by natural sunlight use the time to completely bleach less than laboratory light such as back lamp or mercury lamp.

(H) The standard residual levels of coastal dune usually remain 4-8% from natural TL signal while those of colluvial sediments are 50-70%.

(I) Thermoluminescence (or TL) dating with grain size 74-149 μm gives the equal to TL dating with grain size 149-250 μm.

(J) TL dating by total bleach technique risk for mistake prediction characteristic of TL growth effect from supralinear (under estimation), superlinear (over estimation), and saturation phenomena (over estimation).

(K) The TL ages obtained by regeneration technique proved to be more convincing for TL dating than total bleach technique when compared with reference ages. Dating by regeneration technique is planned for come to validate the technique completely. These properties would also be applicable to other types of materials containing quartz and not necessarily burned material such as sediments.

(L) Electron spin resonance (or ESR) dating by room temperature condition is not suitable for dating sediments sample.

(M) The calibration curve of TL and other dating results displays a good positive correlation with the linear regression of about 0.992. This strongly advocates that our current TL ages dating result are more consistent with that of the AMS radiocarbon dating than that of the conventional radiocarbon dating. Moreover, the TL dating method is more powerful than the AMS radiocarbon dating in a sense that the TL data are well applicable to the fine-grained quartz-rich sediments of up to 2 Ma (Krowchan, 2001) and tektite samples of about 0.7 Ma (Klongsara et al., 2002 and Panpate, 2004).



5.2 Ban Bom Luang Trench

(A) TL dating with colluvial deposit at Ban Bom Luang gives the age in line with the dates from AMS radiocarbon dating in the same sedimentary layer.

(B) The main fault in Ban Bom Luang trench move along the period 1,793-1,940 years BP.

(C) Rate of movement of main fault in Ban Bom Luang trench is 0.17 mm/ year.

5.3 Thung Tuk Archaeological Site

(A) TL dating can use potentially with ancient brick from archaeological site. The dates from ancient brick sample represent the dates of producing brick or imply that the ages of ancient community construction.

(B) TL dating with outer rim of brick mass after eliminated brick surfaces give the precision ages more than dates that evaluated from inner rim of brick mass because the inner rim of brick piece have a possibility to incomplete heating in a whole of brick mass along the brick production process.

(C) TL dating with sediments in archaeological site is difficult to date because of uncertainty in the extent of zeroing or because of mixtures of different aged deposits and effect from human activity in the past time.

(D) Ancient community settlement determined by brick dated results is in period 838 ±297 year BP. to 1,545 ± 656 year BP.

(E) Ancient remain constructed upon the sediment layer that last deposit in the period 12,423 ±6,940 to 14,429 ±6,983 year BP. (sediment dated data from pit1).

5.4 Recommendation

In the recommendation, we proposed that our results of the samples analysis show how great are the interpretation problems of the TL dating. Incompletely bleaching is the dangerous condition for TL dating with sediments. The researchers ought to carefully investigate before sampling in the field. Some appearance of sediments can be dated potentially by TL dating whereas other one can not.

# REFERENCES


Abdel-Wahab, M. S., El-Fiki, S. A., El-Fiki, M. A., Gomaa, M., Abdel-Kariem, S., and El-Faramawy, N. 1996. Annual dose measurements and TL-dating of ancient Egyptian pottery. Journal for Radiation Physics and Chemistry 47 (5): 697-700.

Aitken, M.J. 1985. Thermoluminescence dating. London: Academic Press.

Aitken, M. J. 1990. Science-based dating in archaeology. London: Longman.

Aitken, M.J. 1998. An introduction to optical dating. Oxford: Oxford University Press.

An introduction to Quaternary Geochronology [online]. Available from: http://www.rses.anu.edu.au/environment/eePages/eeDating/QuaternaryGeochronology/Quat_info.html [2004, May 22]

Bailiff, I. K., and Holland, N. 2000. Dating bricks of the last two millennia from Newcastle upon Tyne: a preliminary study. Radiation Measurements 32: 615-619.

Beck, J.W., et al. 2001. Extremely large variations of atmospheric C-14 concentration during the last glacial period. Science 292: 2453-2458.

Bell, W.T. 1979. Attenuation factors for the absorbed radiation dose in quartz inclusions for thermoluminescence dating. Ancient TL 8: 2-13.

Berger, G. W., and Eyles, N. 1994. Thermoluminescence chronology of Toronto area: Quaternary sediments and implications for extent of the midcontinent ice sheet. Geology 22: 31-34.

Berger, G. W., and Huntley, D. J. 1983. Thermoluminescence dating of volcanic ash. Council of Europe PACT Journal 9: 581-592.

Bird, M. I., Ayliffe, L. K., Fifield, L. K., Turney, C. S. M., Cresswell, R. G., Barrows, T. T., and David, B. 1999. Radiocarbon dating of "old" charcoal using a wet oxidation, stepped-combustion procedure. Radiocarbon 41: 127-140.

Blum, J. D., Papamastassiou, D. A., Koeberl, C. and Wasserberg, G. 1992. Neodymium isotope study of the Australasian tektites: New constrains on the provenance and age of target materials. Ceochim. Cosmochim. Acta 56: 483-492.

Bonani, G., et al. 1987. Fractionation, precision and accuracy in $^{14}C$ and $^{13}C$ measurements. Nuclear Instruments and Methods in Physics Research 29: 87-90.

Chaisuwan, B., and Naiyawatt, R. 2002. Thung Tuk ancient seaport. Phuket. Phuket: 15$^{th}$Regional Office of Fine Arts. (Unpublished Manuscript)

Chankian, S., and Kaewtubtim, P. 1999. TL dating of ancient pottery of Yarang historical site, Amphur Yarang, Pattani Province. Songklanakarin Journal of Science and Technology 21: 347-353.

Charusiri, P., Daorerk, V., Muangnoichareon, N., Lamjuan, A., and Kosuwan, S. 2003. Exploration of active fault in Kanchanaburi, Lampang and Prae province project. Bangkok: Department of Geology, Faculty of Science, Chulalongkorn University. (Unpublished Manuscript)

Colman, S. M., and Pierce, K. L. 2000. Classifications of quaternary geochronologic methods. In J. S. Noller, J. M. Sowers, and W. R. Lettis (eds.), Quaternary Geochronology: Methods and Applications, pp.2-5. Washington D.C.: American Geophysical Union.

Colman, S. M., Pierce, K. L., and Birkeland, P. W. 1987. Suggested terminology for quaternary dating methods. Quaternary Research 28: 314-319.

Debenham, N. and Feathers, J. K. (n. d.) Quaternary TL Surveys in Nottingham England [onlene] University of Washington [Distributor]. Available from http://www.users.globalnet.co.uk/~qtls/ [2004, June 15]

Dumitru, T. A. 2000. Fission-track geochronology. In J. S. Noller, J. M. Sowers, and W. R. Lettis (eds.), Quaternary Geochronology: Methods and Applications, pp. 131-155. Washington D.C.: American Geophysical Union.

Feathers, J. K. 2002. Luminescence dating in less than ideal conditions: case studies from Klasies River Mouth and Duinefontein, South Africa. Journal of Archaeological Science 29:177-194.

Finkel, R. C., and Suter, M. 1993. AMS in the Earth sciences: Techniques and applications, in M, Hyman, and M. W. Rowe (eds.), Advance in analytic geochemistry: Greenwich, Connecticut. JAI Prees 1: 1-114.

Fleming, S. J., 1970. Thermoluminescence dating; refinement of quartz inclusion method. Archaeometry 12:135-145.

Gartner, W., Kleinman, N., and Wagner, G. A. 1992. New Kr-dating and Fission track dating of Impact Glasses and Tektites. Earth and Planetary Science Letters 2: 82-86.

Gosse, J. C., and Phillips, F. M. 2001. Terrestrial cosmogenic nuclides: Theory and applications. Quaternary Science Reviews 20: 1475-1560.

Grün, R. 2001. Trapped charge dating (ESR TL OSL). In M. Pollard, and D. Brothwell (eds.), Introduction to Archaeological Sciences, pp. 47-62. London: Wiley.

Hedges, R. E. M. 2000. Radiocarbon dating. In E. Ciliberto, and G. Spoto (eds.), Modern Analytical Methods in Art and Archaeology Chemical Analyses Series, pp. 465-502. New York: Wiley.

Huntley, D. J., and Prescott, J. R. 2001. Improved methodology and new thermoluminescence ages for the dune sequence in south-east South Australia. Quaternary Science Reviews 20: 57-69.

Huntley, D. J., Godfrey-Smith, D. I., and Thewalt, M. L.W. 1985. Optical dating of sediments. Nature 313: 105-107.

Ikeya, M. 1993. New applications of electron spin resonance-dating: Dosimetry and microscopy. Singapore: World Scientific.

Ivanovich, M., and Harmon, R. S., eds. 1992. Uranium-series disequilibrium: Applications to earth, marine, and environmental sciences. Oxford: Clarendon Press.

Izett, G. A., and Obradovich J. D. 1992 Laser-fusion $^{40}Ar/^{39}Ar$ Tges of Australian Tektites. Lunar and Planetary Science 23: 593-594.

Kalchgruber, R., Göksu, H. Y., Hochhäuser, E., and Wagner, G. A. 2002. Monitoring environmental dose rate using Risø TL/OSL readers with built-in sources: recommendations for users. Radiation Measurements 35: 585-590.

Khaokhiew, C. 2004. Geoarchaeology of Tham Lod rock shellter, Changwat Mae Hong Sorn, Northern Thailand. Master's Thesis. Department of Geology, Graduate School, Chulalongkorn University.

Klongsara, N., 2002. Thermoluminescence dating of tektites from Ban Mai, Tambon Ta Chang, Amphoe Chalerm Phrakiet, Changwat Nakhon Ratchasima. An unpublished B.Sc. report, Department of Geology, Chulalongkorn University, 62 p.

Kosuwan, S., and Lumjuan, A. 1998. Neotectonics of the Mae Chan Fault in Mae Chan District, Chiang Rai Province. A Technical Report, Geological Survey Division, Department of Mineral Resources. (Unpublished Manuscript)

Kosuwan, S., Saithong, P., and Lumjuan, A. 2002. Paleoseismology of Mae Ai area, Changwat Chiang mai. An internal report, Department of Mineral Resources. (Unpublished Manuscript)

Krowchan, V., 2001. Quaternary tektites bearing sediments at Tambon Ta Chang, Amphoe Chalerm Phrakiet, Changwat Nakhon Ratchasima : Stratigraphy and TL dating. An unplublished B.Sc. report, Department of Geology, Faculty of Science, Chulalongkorn University, 75 p.

Ku, T. L. 2000. Uranium-series methods. In J. S. Noller, J. M. Sowers, and W. R. Lettis (eds.), Quaternary Geochronology: Methods and Applications, pp.101-114. Washington D.C.: American Geophysical Union.

Kuniholm, P. I. 2001. Dendrochronology and other applications of tree ring studies in archaeology. In M. Pollard, and D. Brothwell (eds.), Introduction to Archaeological Sciences, pp. 35-46. London: Wiley.

Kusiak, J., Anczont, M., Boguckyj, A., and Wojtanowicz, J. 2002. Divergence in the TL dating resulting from different methods of equivalent dose determination. Geochronometria 21: 27-32.

Liritzis, I. 2000. Advances in thermo- and opto-luminescence dating. Global Nest Journal 2: 29-49.

Lunsai, C. 2004. Coastal landfrom and its sediment stratigraphy of Pha Tong Island, Changwat Phang Nga. An unplublished B.Sc. report, Department of Geology, Faculty of Science, Chulalongkorn University, 60 p.

Mahaney, W. C., ed. 1984. Quaternary dating methods: Developments in Palaeontology and Stratigraphy. Elsevier Science 7: 62-65.

Matthew, J.G. (n.d.). Optically stimulated luminescence dating at Hope College [online]. Hope College [Distributor]. Available from: http://www.hope.edu/academic/physics/reu01/html/pp_presentations/ MJGoupell/sld001.htm [2003, June 21]

McCalpin, J. P. 1996. Paleoseismology. California: Academic press.

McDougall, I., and Harrison, T. M. 1999. Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method. 2nd ed. New York: Oxford University Press.

Miller, G. H., and Brigham-Grette, J. 1989. Amino acid geochronology: Resolution and precision in carbonate fossils. Quaternary International 1: 111-128.

Ninagawa, K., et al. 1992. TL dating of calcite shells in the Pectinidae family. Quaternary Science Reviews 11: 121–126.

Oczkowski, H. L., and Przegietka, K. R. 1998. TL dating of young Aeolian deposits from Kepa Kujawska. Radiation Measurements 29 (3-4): 435-439.

Orachorn, N., 2001. The construction of thermoluminescence equipment. An unplublished B.Sc. report, Department of Physics, Faculty of Science, Mahidol University, 83 p.

Panpate, N., 2004. The preliminary thermoluminescence dating of tektites in Amphoe Buntarik, Changwat Ubon Ratchatani. An unpublished B.Sc. report, Department of Geology, Chulalongkorn University, 73 p.

Prescott, J. R., and Hutton, J. T. 1995. Environmental dose rates and radioactive disequilibrium from some Australian luminescence dating sites. Quaternary Science Reviews 14: 439-448.

Prescott, J. R., and Smith, M. A. 1993. Comparison of TL and $^{14}C$ dates as an indicator of cosmic ray intensity variations. Contributed Papers. 23rd International Cosmic Ray Conference. 3. 838-841. University of Calgary. Calgary.

Reneau S. L., Gardner, J. N., and Forman, S.L. 1996. New evidence for the age of the youngest eruptions in the Valles caldera, New Mexico. Geology 24: 7-10.

Reotrit, S. 1987. Archaeological exploration in Yarang historical site, Amphur Yarang, Pattani Province. Pattani: Center of southern Thailand strudy, Songklanakarin University, a faculty Pattani. (Unpublished Manuscript)

Roberts, R. G., Jones, R., and Smith, M. A. 1994. Beyond the radiocarbon barrier in Australian prehistory. Antiquity 68: 611-616.

Royal Thai Survey Department. 1997. Map Information. Bangkok: Royal Thai Survey Department. (Mimeographed)

Sato, Y. and Suzuki, Y. 1999. Molluscan assemblages for reconstruction of late quaternary sea-level change, lower central plain, Thailand. In S. Sinsakul, N. Chaimanee, and S. Tiyapairach (eds.), Proceedings of the Comprehensive Assessments on Impacts of Sea-Level Rise, Phetchaburi, Thailand, pp. 110-122.

Schwarcz, H. P. 1997. Uranium series dating. In R. E. Taylor, and M. J. Aitken (eds.), Chronometric dating in Archaeology, pp. 159-182. New York: Plenum.

Singhvi, A. K., and Wagner, G. A. 1986. Dating Young Sediments. In A.J. Hurford, E. Jager, and I. A. M. Tencate (eds.), pp. 159–197. Bangkok.

Smith, M. A., Prescott, J. R., and Head, M. J. 1997. Comparison of $^{14}C$ and luminescence chronologies at Puritjarra rock shelter, central Australia. Quaternary Science Reviews 16: 299-320.

Srisuchart, T. 1986. Ta Kua Pa: Ancient town. Southern culture Encyclopedia 3. Center of southen culture study. Srinakharinwirot University, Song Khla province. p. 1217.

Stuiver, M. and Polach, H. A. 1977. Reporting of $^{14}C$ data. Radiocarbon 19: 355-363.

Takashima, I., and Honda, S. 1989. Comparision between K-Ar and TL dating results of pyroclastic flow deposits in the Aizutajima area, Northeast Japan. Joural of Geological Society 95: 807-816.

Takashima, I. and Walanabe, K. 1994. Thermoluminescence age determination of lava flows/domes and collapsed materials at Unzen volcano, SW Japan. Bulletin of the Volcanological Society of Japan 39: 1-12.

Tanaka, K., Hataya, R., Spooner, N. A., Questiaux, D. G., Saito, Y., and Hashimoto, T. 1997. Dating of marine terrace sediments by ESR, TL and OSL methods and their applicabilities. Quaternary Science Reviews 16: 257-264.

Tanaka, K., Machette, M. N., Crone, A. J., and Bowman, J. R. 1995. ESR dating of Aeolian sand near Tennant Creek, northern territory, Australia. Quaternary Science Reviews 14: 385-393.

Taylor, R. E. 1997. Radiocarbon dating. In R. E. Taylor, and M. J. Aitken (eds.), Chronometric dating in Archaeology, pp. 65-96. New York: Plenum.

Toyoda, S., Goff, F., Ikedo, S., Ikeya, M. 1995. ESR dating of quartz phenocrysts in the ElCajete and Battleship Rock members of Valles Rhyolite, Valles caldera, New Mexico. Journal of Volcanology and GeothermalResearch 67: 29–40.

Tuniz, C. Bird, J. R., Fink, D., and Herzog, G. F., 1998. Accelerator mass spectrometry: Ultrasensitive analysis for global science. Florida: CRC Press.

Vij, D. R. 1993. Thermoluminescent materials. New Jersey: Englewood Cliffs.

Wagner, G. A., and Van den haute, P. 1992. Fission track-dating. Dordrecht: Kluwer Academic.

Wales, D. C., and Wales, H. G. Q. 1947. Further work on Indian sites in Malaya. JMBRAS 5: 1-2.

Wehmiller, J. F., and Miller, G. H. 2000. Aminostratigraphic dating methods in quaternary geology. In J. S. Noller, J. M. Sowers, and W. R. Lettis (eds.), Quaternary Geochronology: Methods and Applications, pp. 187-222. Washington D.C.: American Geophysical Union.

Wintle, A. G. 1973. Anomalous fading of thermoluminescence in mineral samples. Nature 245: 143-144.

Wintle, A. G., and Huntley, D. J. 1980. Thermoluminescence dating of ocean sediments. Canadian Journal of Earth Sciences 17: 348-360.

Wintle, A. G., and Huntley, D. J. 1982. Thermoluminescecne dating of sediments. Quaternary Science Reviews 1: 31-53.

Won-in, K. 2003. Quaternary geology of the Phrae basin, northern Thailand and application of thermoluminescence technique for quaternary chronology. Doctoral dissertation. Graduate School of Mining and Engineering, Akita University, Japan.

Yeats, R. S., Sieh, K. E., and Allen, C. R. 1997. The Geology of earthquakes. New York: Oxford University Press.

Yokoyama, Y., Esat, T. M., Lambeck, K., and Fifield, L. K. 2000. Last ice age millenial scale climate changes recorded in Huon Peninsula corals. Radiocarbon 42: 383-401.

Yokoyama, Y., Falgueres, C., and Quaegebeur, J. 1985. ESR dating of quartz from Quaternary sediments: first attempt. Nuclear Tracks 10: 921-928.

Zoller, L., Oches, E. A., and McCoy, W. D. 1994. Towards a revised chronostratigraphy of loess in Austria with respect to key sections in the Czech Republic and in Hungary. Quaternary Science Reviews 13: 465-472.

# APPENDICES

# Appendix-A

List of samples for dating

Table A.1 List of collected samples from Ban Bom Luang trench.

| Sample number | Material | Grain size | Technique | Nomenclature |
|---|---|---|---|---|
| BL5 | Se | A | TB | BL 5 A (TB) |
| | | | R | BL 5 A (R) |
| | | B | TB | BL 5 B (TB) |
| | | | R | BL 5 B (R) |
| BL10 | Se | A | TB | BL 10 A (TB) |
| | | | R | BL 10 A (R) |
| | | B | TB | BL 10 B (TB) |
| | | | R | BL 10 B (R) |
| BL11 | Se | A | TB | BL 11 A (TB) |
| | | | R | BL 11 A (R) |
| BL20 | Se | A | TB | BL 20 A (TB) |
| | | | R | BL 20 A (R) |

Table A.2 List of collected samples from trench 1, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Nomenclature |
|---|---|---|---|---|
| TT1-1 | Bi | AB | TB | TT1-1 AB (TB) |
| | | | R | TT1-1 AB (R) |
| TT1-2 | Se | AB | TB | TT1-2 AB (TB) |
| | | | R | TT1-2 AB (R) |

Table A.3 List of collected samples from ancient remain 3, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Nomenclature |
|---|---|---|---|---|
| TT3-1 | Bi | AB | TB | TT3-1 AB (TB) |
| | | | R | TT3-1 AB (R) |
| TT3-2 | Se | AB | TB | TT3-2 AB (TB) |
| | | | R | TT3-2 AB (R) |
| TT3-3 | Bi | AB | TB | TT3-3 AB (TB) |
| | | | R | TT3-3 AB (R) |
| TT3-4 | Bi | AB | TB | TT3-4 AB (TB) |
| | | | R | TT3-4 AB (R) |
| TT3-5 | Bi | AB | TB | TT3-5 AB (TB) |
| | | | R | TT3-5 AB (R) |

Table A.4 List of collected samples from ancient remain 4, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Nomenclature |
|---|---|---|---|---|
| TT4-1 | Bi | AB | TB | TT4-1 AB (TB) |
| | | | R | TT4-1 AB (R) |
| TT4-2 | Se | AB | TB | TT4-2 AB (TB) |
| | | | R | TT4-2 AB (R) |
| TT4-3 | Bi | AB | TB | TT4-3 AB (TB) |
| | | | R | TT4-3 AB (R) |

Table A.5 List of collected samples from ancient remain 6, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Nomenclature |
|---|---|---|---|---|
| TT6-1 | Bi | AB | TB | TT6-1 AB (TB) |
| | | | R | TT6-1 AB (R) |

Table A.6 List of collected samples from ancient remain 8, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Nomenclature |
|---|---|---|---|---|
| TT8-1 | Bi | AB | TB | TT8-1 AB (TB) |
| | | | R | TT8-1 AB (R) |
| TT8-2 | Se | A | TB | TT8-2 A (TB) |
| | | | R | TT8-2 A (R) |
| | | B | TB | TT8-2 B (TB) |
| | | | R | TT8-2 B (R) |
| | | AB | TB | TT8-2 AB (TB) |
| | | | R | TT8-2 AB (R) |

Table A.7 List of collected samples from pit 1, Thung Tuk archaeological site.

| Sample number | Material | Grain size | Technique | Nomenclature |
|---|---|---|---|---|
| TTp4-0.2 | Se | A | TB | TTp4-0.2 A (TB) |
| | | | R | TTp4-0.2 A (R) |
| | | B | TB | TTp4-0.2 B (TB) |
| | | | R | TTp4-0.2 B (R) |
| TTp4-1.1 | Se | A | TB | TTp4-1.1 A (TB) |
| | | | R | TTp4-1.1 A (R) |
| | | B | TB | TTp4-1.1 B (TB) |
| | | | R | TTp4-1.1 B (R) |
| TTp4-1.2 | Se | A | TB | TTp4-1.2 A (TB) |
| | | | R | TTp4-1.2 A (R) |
| | | B | TB | TTp4-1.2 B (TB) |
| | | | R | TTp4-1.2 B (R) |
| TTp4-2.1 | Se | A | TB | TTp4-2.1 A (TB) |
| | | | R | TTp4-2.1 A (R) |
| | | B | TB | TTp4-2.1 B (TB) |
| | | | R | TTp4-2.1 B (R) |
| TTp4-2.2 | Se | A | TB | TTp4-2.2 A (TB) |
| | | | R | TTp4-2.2 A (R) |
| | | B | TB | TTp4-2.2 B (TB) |
| | | | R | TTp4-2.2 B (R) |
| TTp4-3.1 | Se | A | TB | TTp4-3.1 A (TB) |
| | | | R | TTp4-3.1 A (R) |
| | | B | TB | TTp4-3.1 B (TB) |
| | | | R | TTp4-3.1 B (R) |
| TTp4-3.2 | Se | A | TB | TTp4-3.2 A (TB) |
| | | | R | TTp4-3.2 A (R) |
| | | B | TB | TTp4-3.2 B (TB) |
| | | | R | TTp4-3.2 B (R) |
| | | AB | TB | TTp4-3.2 AB (TB) |
| | | | R | TTp4-3.2 AB (R) |
| TTp4-4.2 | Se | A | TB | TTp4-4.2 A (TB) |
| | | | R | TTp4-4.2 A (R) |
| | | B | TB | TTp4-4.2 B (TB) |
| | | | R | TTp4-4.2 B (R) |

Where

| Material | | TL-dating technique | |
|---|---|---|---|
| Se | = Sediments | TB | = Total bleach |
| Bi | = Brick | R | = Regeneration |

Grain size

| | |
|---|---|
| A | = 74µm -149µm (fine grain) |
| B | = 149µm-250µm (coarse grain) |
| AB | = 74µm-250µm (mixed grain) |

Appendix-B

List of artificial irradiation of TL samples

Table B.1 The detail of artificial irradiation with samples from Ban Bom Luang trench.

| Sample number | Total bleach | | | | Regeneration | | | |
|---|---|---|---|---|---|---|---|---|
| | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) |
| BL 5 A | 10.5 | 22 | 40 | 100 | 10.5 | 22 | 40 | 100 |
| BL 5 B | 10.5 | 22 | 40 | 100 | 10.5 | 22 | 40 | 100 |
| BL 10 A | 10.5 | 22 | 100 | 200 | 10.5 | 22 | 100 | 200 |
| BL 10 B | 10.5 | - | 100 | 200 | 10.5 | 22 | 100 | 200 |
| BL 11 A | 10.5 | 22 | 100 | 200 | 10.5 | 22 | 100 | 200 |
| BL 20 A | 10.5 | 22 | 100 | 200 | 10.5 | 22 | 100 | 200 |

Table B.2 The detail of artificial irradiation with samples from trench 1, Thung Tuk archaeological site.

| Sample number | Total bleach | | | | Regeneration | | | |
|---|---|---|---|---|---|---|---|---|
| | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) |
| TT1-1 AB | 6.73 | 10.5 | 22 | 40 | 3.73 | 10.5 | 22 | 40 |
| TT1-2 AB | 6.73 | 10.5 | 22 | 40 | 10.5 | 22 | 40 | 100 |

Table B.3 The detail of artificial irradiation with samples from ancient remain 3, Thung Tuk archaeological site.

| Sample number | Total bleach | | | | Regeneration | | | |
|---|---|---|---|---|---|---|---|---|
| | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) |
| TT3-1 AB | 6.73 | 10 | 20 | 40 | 3.37 | 10 | 20 | 40 |
| TT3-2 AB | 10.5 | 22 | 100 | 200 | 10.5 | 22 | 100 | 200 |
| TT3-3 AB | 30 | 40 | 50 | 60 | 30 | 40 | 50 | 60 |
| TT3-4 AB | 30 | 40 | 50 | 60 | 30 | 40 | 50 | 60 |
| TT3-5 AB | 30 | 40 | 50 | 60 | 30 | 40 | 50 | 60 |

Table B.4 The detail of artificial irradiation with samples from ancient remain 4, Thung Tuk archaeological site.

| Sample number | Total bleach | | | | Regeneration | | | |
|---|---|---|---|---|---|---|---|---|
| | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) |
| TT4-1 AB | 6.73 | 10 | 20 | 40 | 3.37 | 10 | 20 | 40 |
| TT4-2 AB | 10 | 20 | 40 | 100 | 10 | 20 | 40 | 100 |
| TT4-3 AB | 30 | 40 | 50 | 60 | 30 | 40 | 50 | 60 |

Table B.5 The detail of artificial irradiation with samples from ancient remain 6, Thung Tuk archaeological site.

| Sample number | Total bleach | | | | Regeneration | | | |
|---|---|---|---|---|---|---|---|---|
| | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) |
| TT6-1 AB | 30 | 40 | 50 | 60 | 30 | 40 | 50 | 60 |

Table B.6 The detail of artificial irradiation with samples from ancient remain 8, Thung Tuk archaeological site.

| Sample number | Total bleach | | | | Regeneration | | | |
|---|---|---|---|---|---|---|---|---|
| | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) |
| TT8-1 AB | 30 | 40 | 50 | 60 | 30 | 40 | 50 | 60 |
| TT8-2 A | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TT8-2 B | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TT8-2 AB | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |

Table B.7 The detail of artificial irradiation with samples from pit 1, Thung Tuk archaeological site.

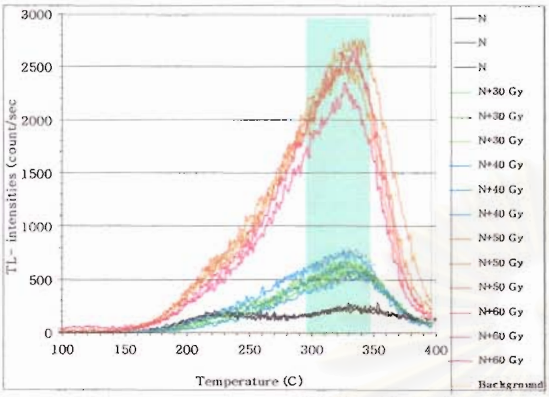
| Sample number | Total bleach | | | | Regeneration | | | |
|---|---|---|---|---|---|---|---|---|
| | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) | β1 (Gy) | β2 (Gy) | β3 (Gy) | β4 (Gy) |
| TTp4-0.2 A | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-0.2 B | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-1.1 A | 10.5 | 22 | 40 | 100 | 10.5 | 22 | 40 | 100 |
| TTp4-1.1 B | 10.5 | 22 | 40 | 100 | 10.5 | 22 | 40 | 100 |
| TTp4-1.2 A | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-1.2 B | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-2.1 A | 10.5 | 22 | 40 | 100 | 10.5 | 22 | 40 | 100 |
| TTp4-2.1 B | 10.5 | 22 | 40 | 100 | 10.5 | 22 | 40 | 100 |
| TTp4-2.2 A | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-2.2 B | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-3.1 A | 10.5 | 22 | 40 | 100 | 10.5 | 22 | 40 | 100 |
| TTp4-3.2 A | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-3.2 B | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-3.2 AB | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-4.2 A | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |
| TTp4-4.2 B | 30 | 40 | 60 | 80 | 30 | 40 | 60 | 80 |

# Appendix-C

Results of glow curve data for sediments and bricks

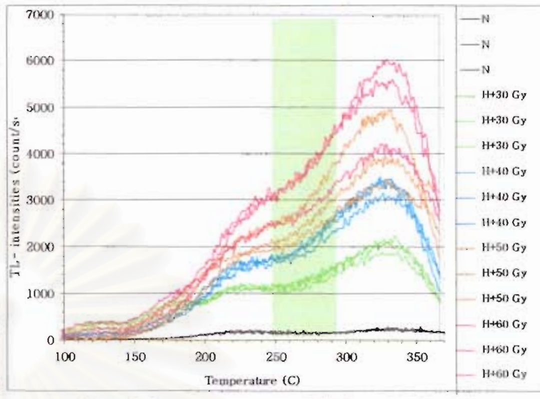
Figure C.1 Results of glow curve data for bricks of Thung Tuk archaeological site.

(C.1.1) TT3-3 AB (TB)



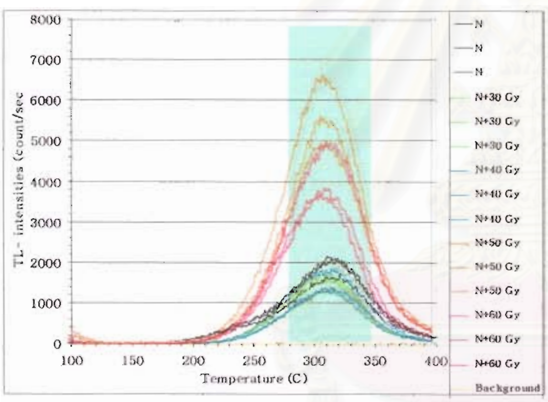

Stable zone = 300–350 °C

(C.1.2) TT3-3 AB (R)



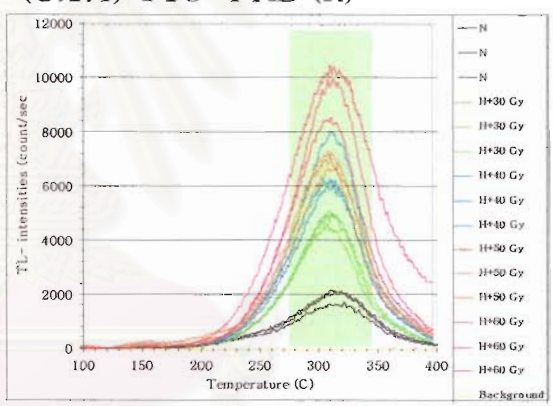

Stable zone = 300–350 °C

(C.1.3) TT3-4 AB (TB)



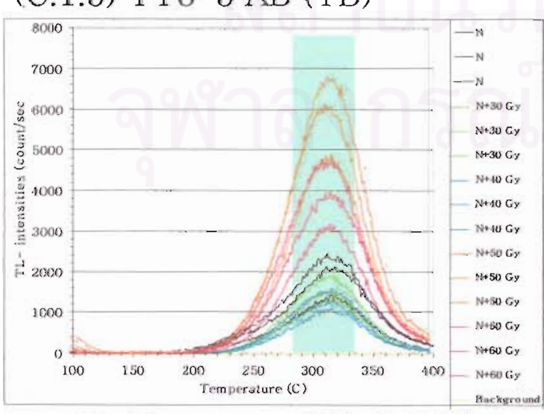

Stable zone = 280–350 °C

(C.1.4) TT3-4 AB (R)



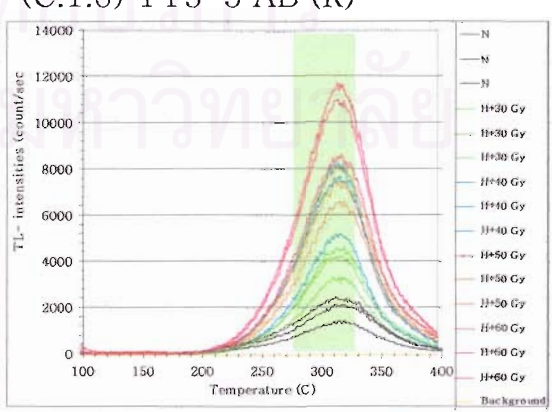

Stable zone = 280–350 °C

(C.1.5) TT3-5 AB (TB)




Stable zone = 290–340 °C

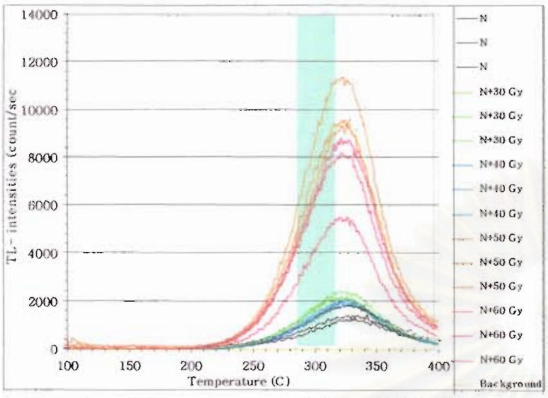
(C.1.6) TT3-5 AB (R)




Stable zone = 290–340 °C

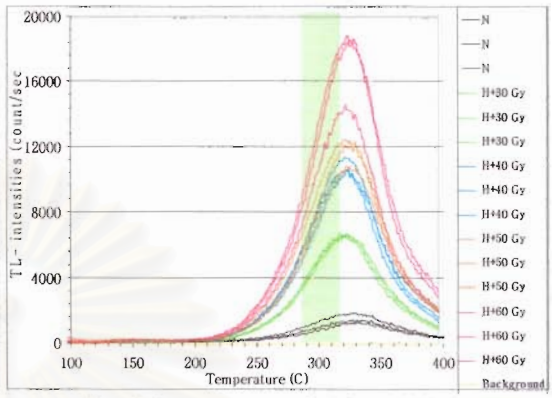
Figure C.1 Results of glow curve data for bricks of Thung Tuk archaeological site (cont.).

(C.1.7) TT4-3 AB (TB)



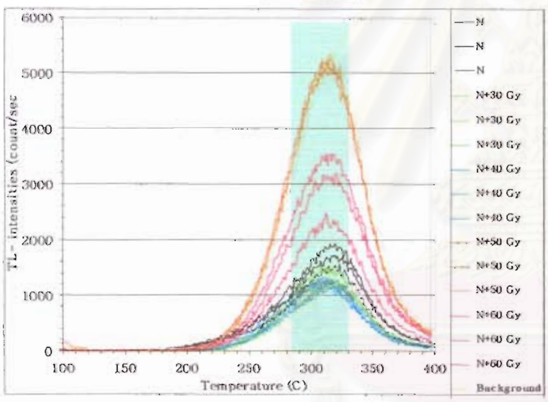

Stable zone = 290-330 °C

(C.1.8) TT4-3 AB (R)



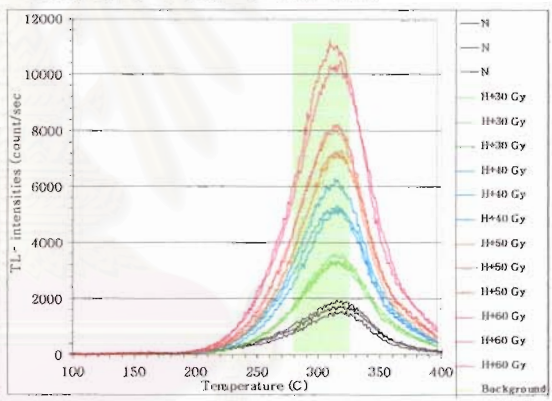

Stable zone = 290-330 °C

(C.1.9) TT6-1 AB (TB)



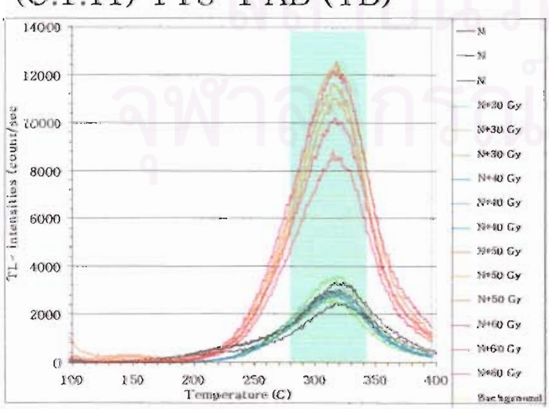

Stable zone = 290-330 °C

(C.1.10) TT6-1 AB (R)



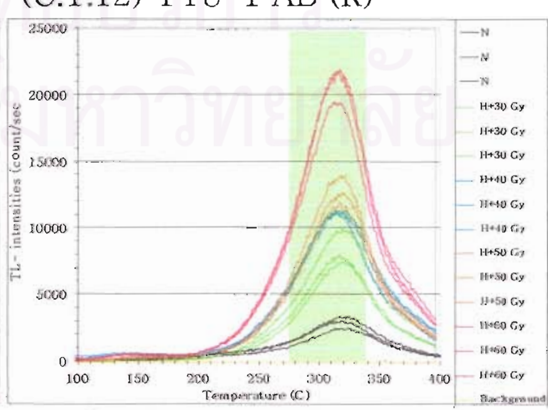

Stable zone = 290-330 °C

(C.1.11) TT8-1 AB (TB)




Stable zone = 280-340 °C

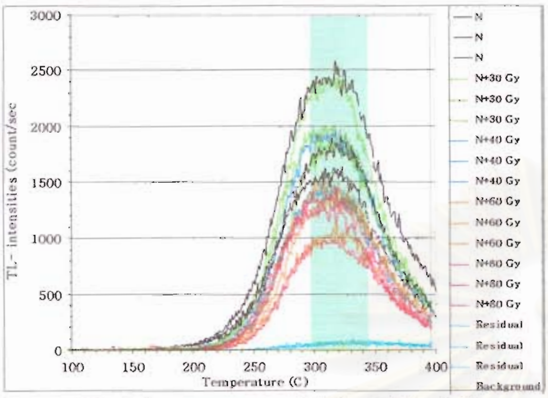
(C.1.12) TT8-1 AB (R)




Stable zone = 280-340 °C

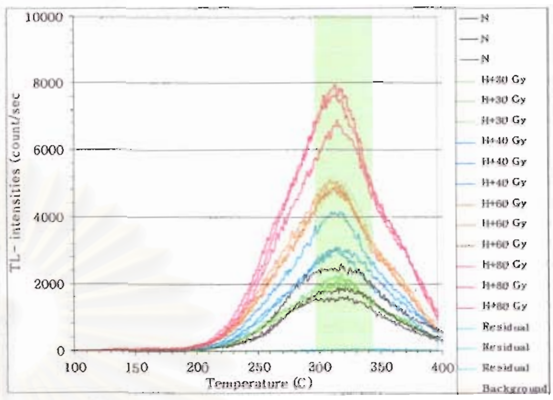
Figure C.2 Results of glow curve data for sediments of Thung Tuk archaeological site.

(C.2.1) TT8-2 A (TB)



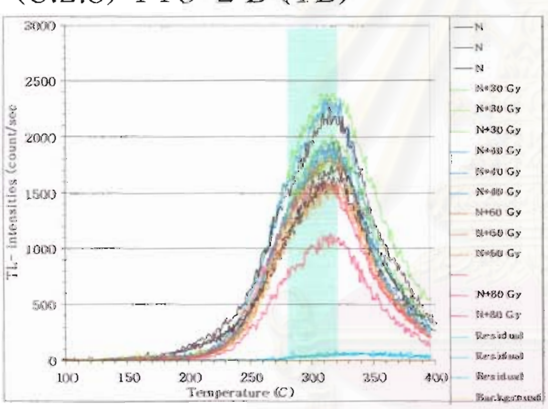

Stable zone = 300-350 °C

(C.2.2) TT8-2 A (R)



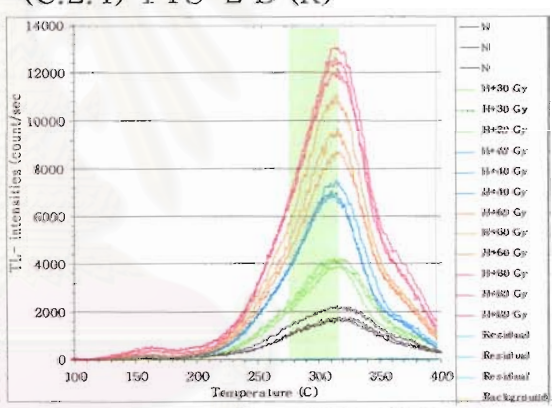

Stable zone = 300-350 °C

(C.2.3) TT8-2 B (TB)



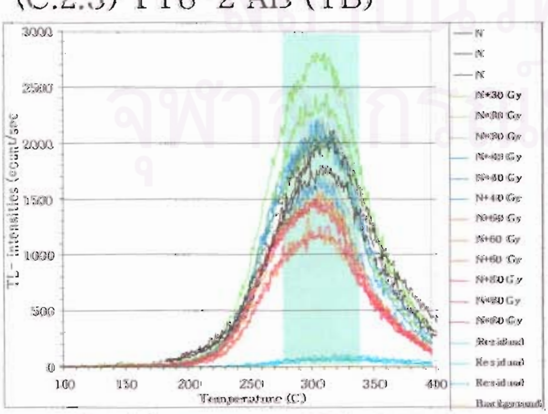

Stable zone = 285-325 °C

(C.2.4) TT8-2 B (R)



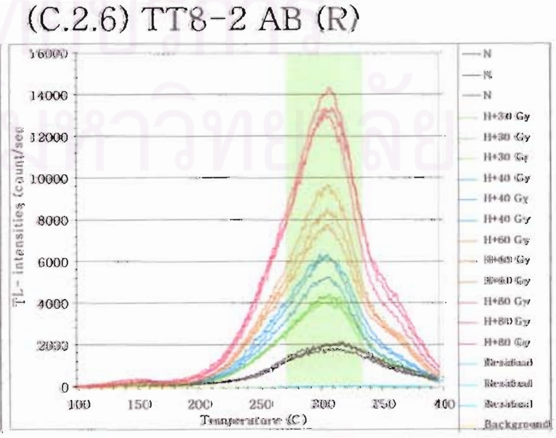

Stable zone = 285-325 °C

(C.2.5) TT8-2 AB (TB)




Stable zone = 270-340 °C

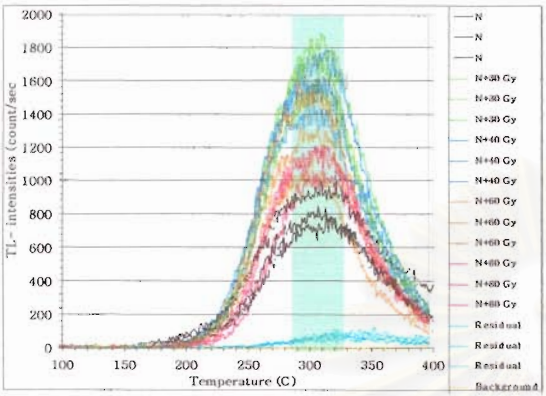
(C.2.6) TT8-2 AB (R)




Stable zone = 270-340 °C

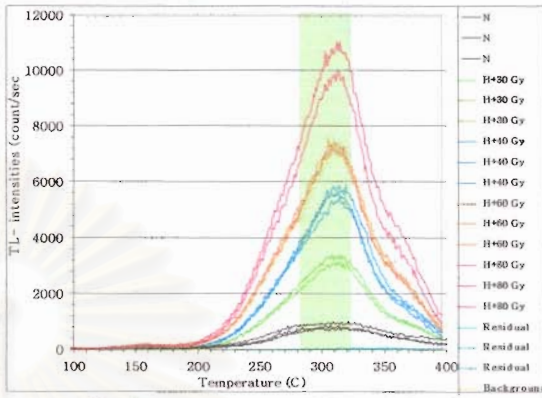
Figure C.2 Results of glow curve data for sediments of Thung Tuk archaeological site (cont.).

(C.2.7) TTp4-0.2 A (TB)



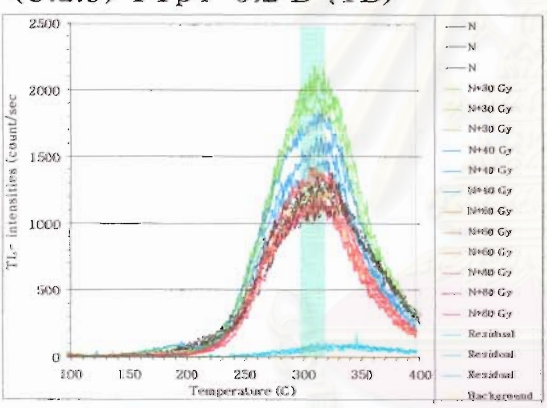

Stable zone = 290-330 °C

(C.2.8) TTp4-0.2 A (R)



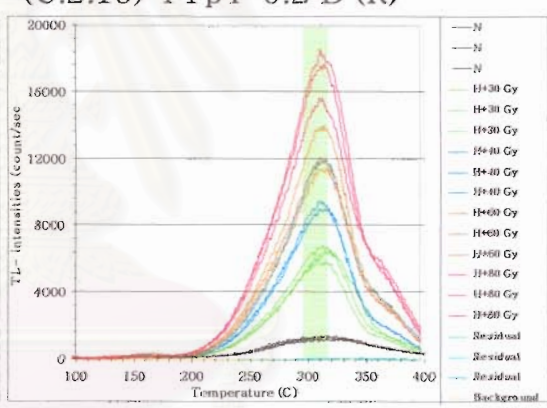

Stable zone = 290-330 °C

(C.2.9) TTp4-0.2 B (TB)



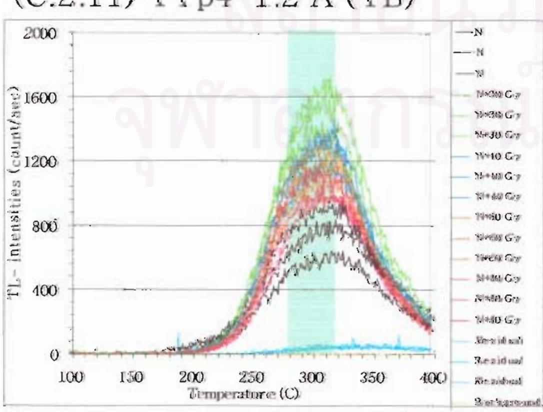

Stable zone = 300-320 °C

(C.2.10) TTp4-0.2 B (R)



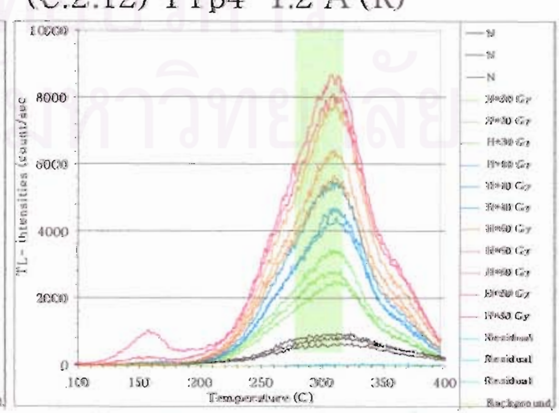

Stable zone = 300-320 °C

(C.2.11) TTp4-1.2 A (TB)




Stable zone = 285-325 °C

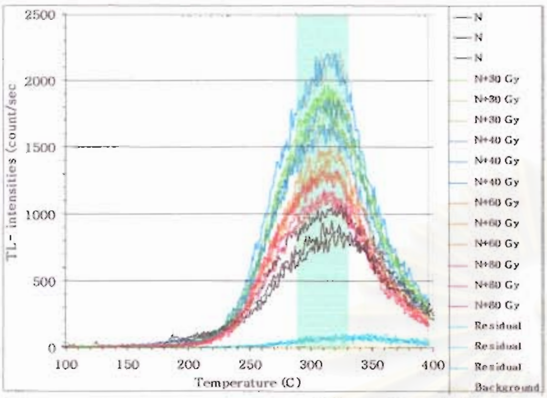
(C.2.12) TTp4-1.2 A (R)




Stable zone = 285-325 °C

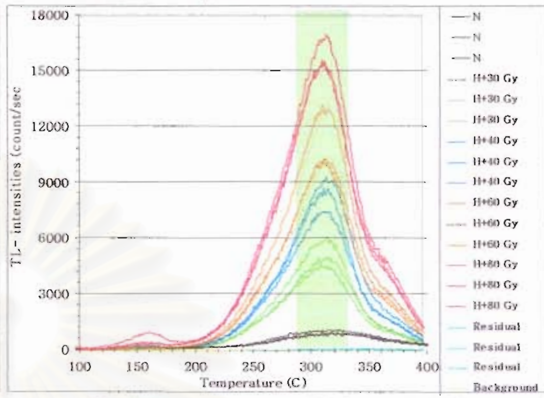
Figure C.2 Results of glow curve data for sediments of Thung Tuk archaeological site (cont.).

(C.2.13) TTp4-1.2 B (TB)



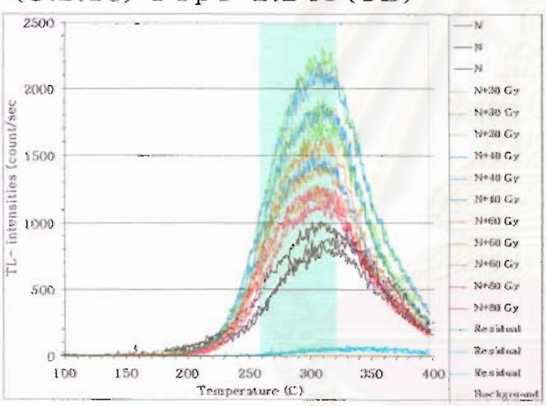

Stable zone = 290-330 °C

(C.2.14) TTp4-1.2 B (R)



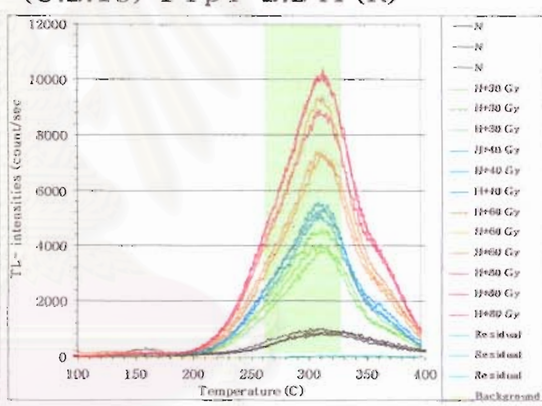

Stable zone = 290-330 °C

(C.2.15) TTp4-2.2 A (TB)



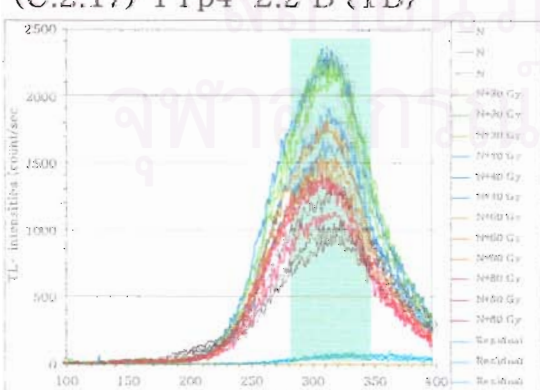

Stable zone = 270-325 °C

(C.2.16) TTp4-2.2 A (R)



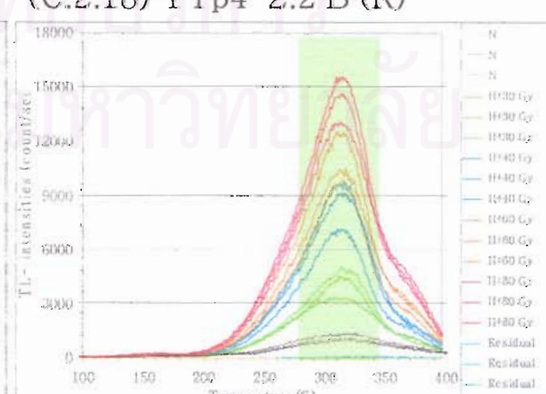

Stable zone = 270-325 °C

(C.2.17) TTp4-2.2 B (TB)



Stable zone = 285-350 °C

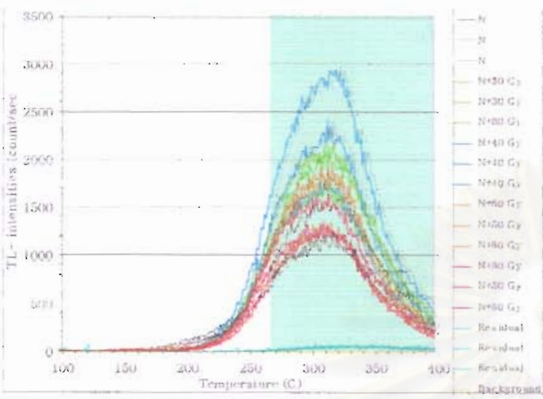
(C.2.18) TTp4-2.2 B (R)



Stable zone = 285-350 °C

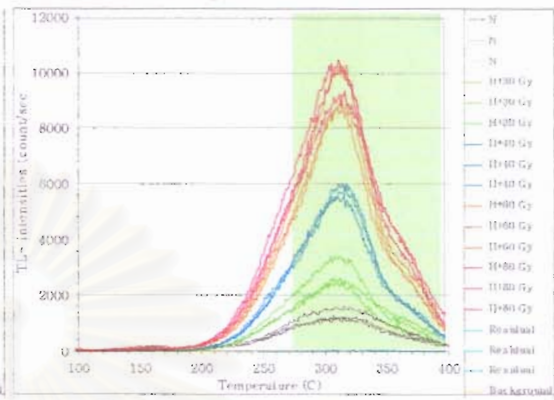
Figure C.2 Results of glow curve data for sediments of Thung Tuk archaeological site (cont.).

(C.2.19) TTp4-3.2 A (TB)



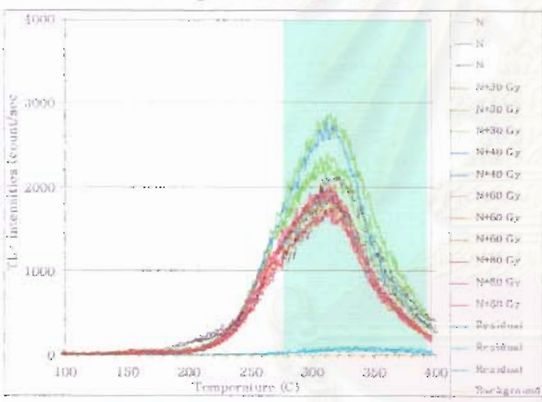

Stable zone = 285-400 °C

(C.2.20) TTp4-3.2 A (R)



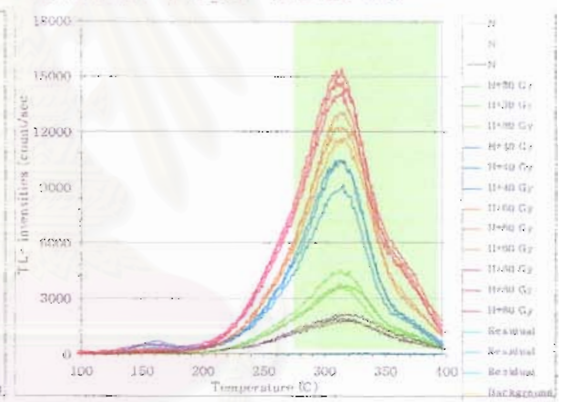

Stable zone = 285-400 °C

(C.2.21) TTp4-3.2 B (TB)



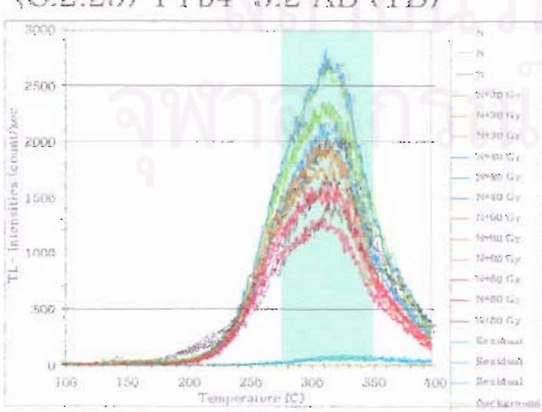

Stable zone = 280-400 °C

(C.2.22) TTp4-3.2 B (R)



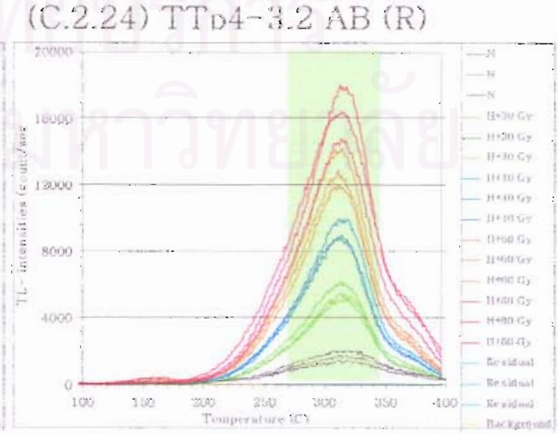

Stable zone = 280-400 °C

(C.2.23) TTp4-3.2 AB (TB)




Stable zone = 285-350 °C

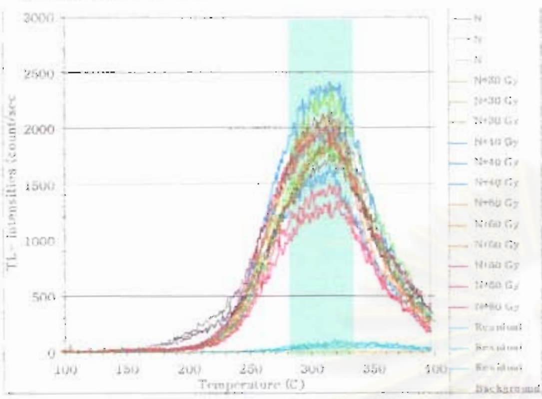
(C.2.24) TTp4-3.2 AB (R)




Stable zone = 285-350 °C

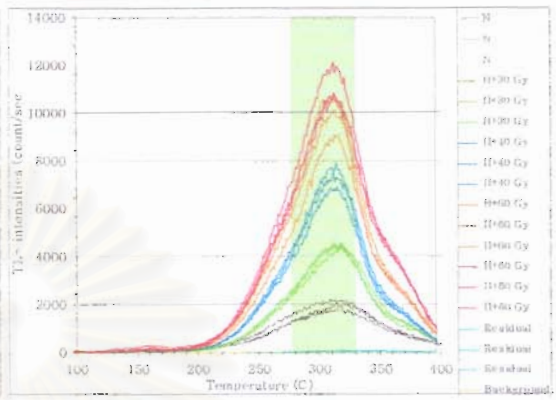
Figure C.2 Results of glow curve data for sediments of Thung Tuk archaeological site (cont.).

(C.2.25) TTp4-4.2 A (TB)



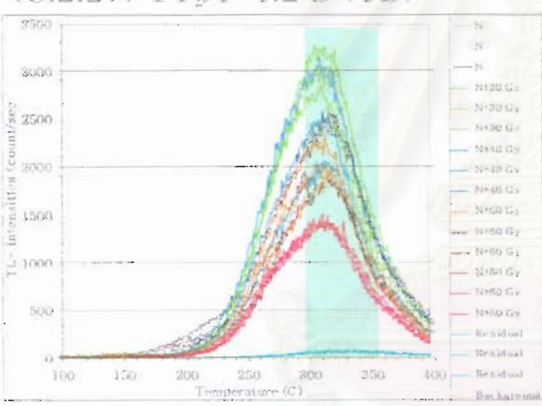

Stable zone = 285-330 °C

(C.2.26) TTp4-4.2 A (R)



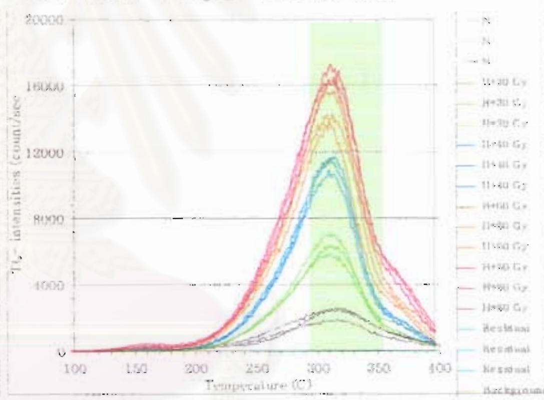

Stable zone = 285-330 °C

(C.2.27) TTp4-4.2 B (TB)




Stable zone = 300-355 °C

(C.2.28) TTp4-4.2 B (R)




Stable zone = 300-355 °C

Where

= Stable zone determine from plateau testing (see Appendix-E)

Remark:

Except these glow curves, the rest glow curves of this research show in term of digital file in the compact disc (CD) that proposed in this thesis.

# Appendix-D

Results of ESR glow curve data for sediments in Ban Bom Luang trench
and Thung Tuk archaeological site

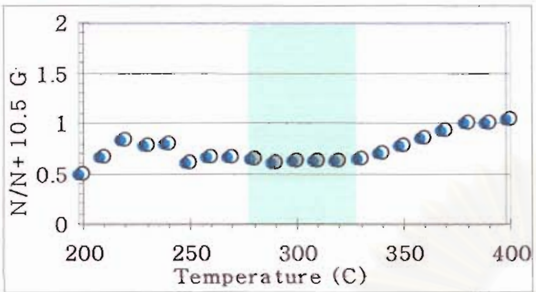
Because of a large number of ESR glow curves in this research, we compile all of them in term of digital file format. The researcher can comfortably accesses from the compact disc (CD) attached in this thesis.

Appendix-E

Results of plateau test for sediments and bricks

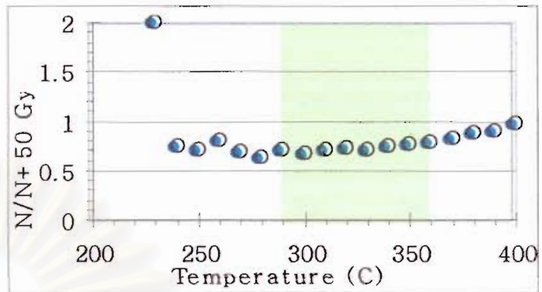
Figure E.1 Results of plateau test data for sediments of Ban Bom Luang trench.

(E.1.1) BL5 A



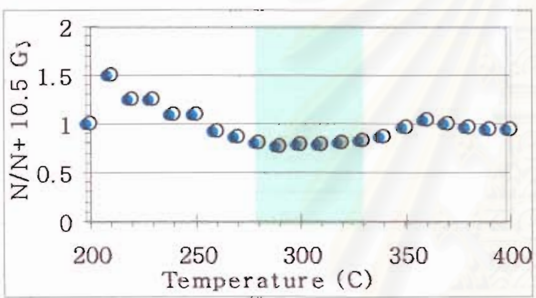

Stable zone = 280-330 °C

(E.1.2) BL5 B



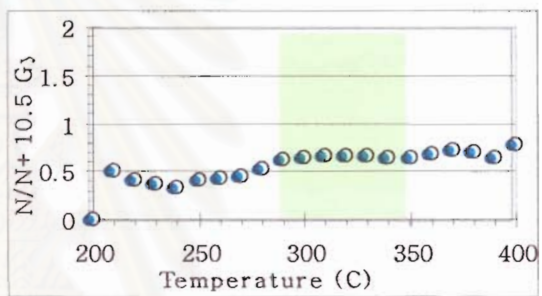

Stable zone = 290-360 °C

(E.1.3) BL10 A



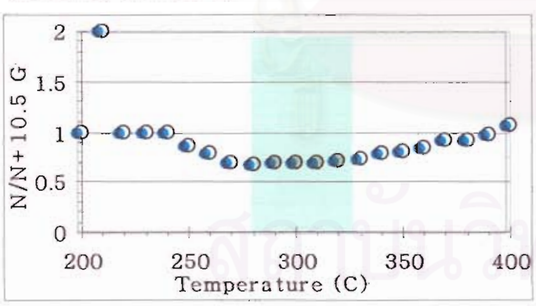

Stable zone = 280-330 °C

(E.1.4) BL10 B



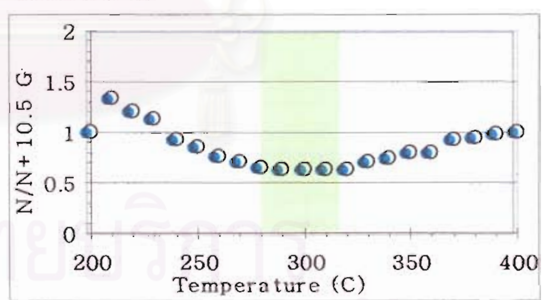

Stable zone = 290-350 °C

(E.1.5) BL11 A




Stable zone = 280-330 °C

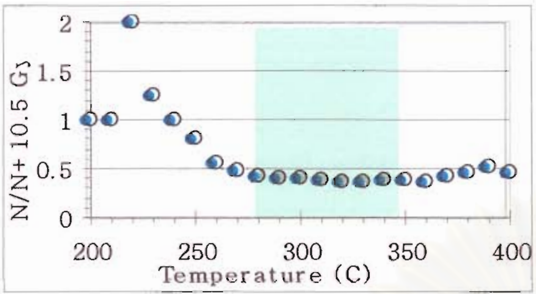
(E.1.6) BL20 A




Stable zone = 280-320 °C

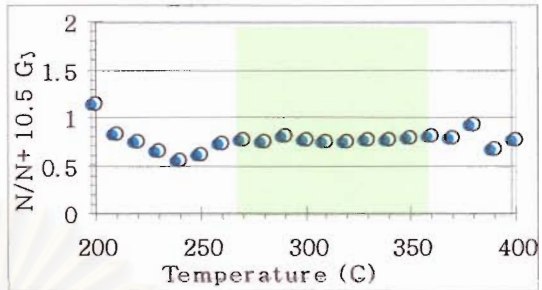
Figure E.2 Results of plateau test data for bricks of Thung Tuk archaeological site.

(E.2.1) TT1-1 AB



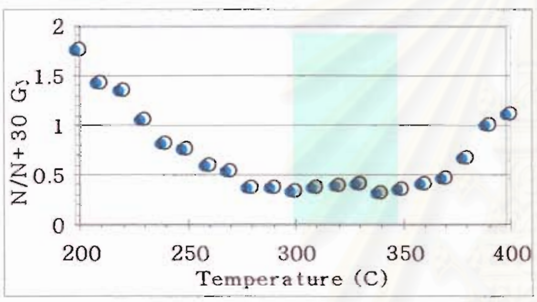

Stable zone = 280-350 °C

(E.2.2) TT3-1 AB



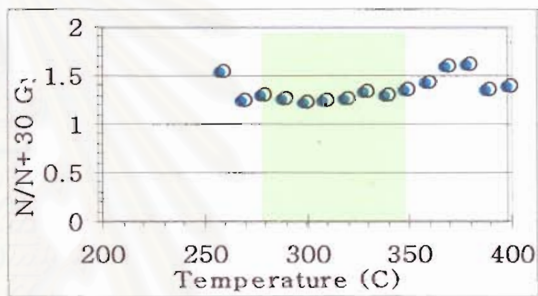

Stable zone = 270-360 °C

(E.2.3) TT3-3 AB



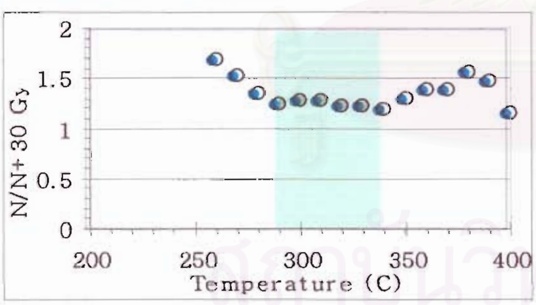

Stable zone = 300-350 °C

(E.2.4) TT3-4 AB



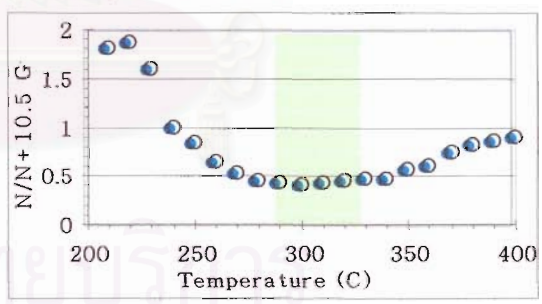

Stable zone = 280-350 °C

(E.2.5) TT3-5 AB



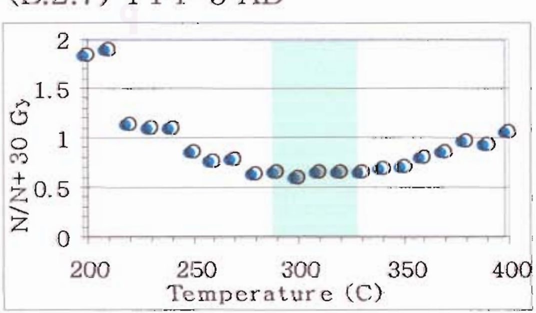

Stable zone = 290-340 °C

(E.2.6) TT4-1 AB



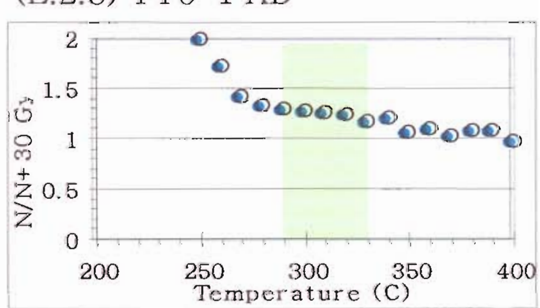

Stable zone = 290-330 °C

(E.2.7) TT4-3 AB




Stable zone = 290-330 °C

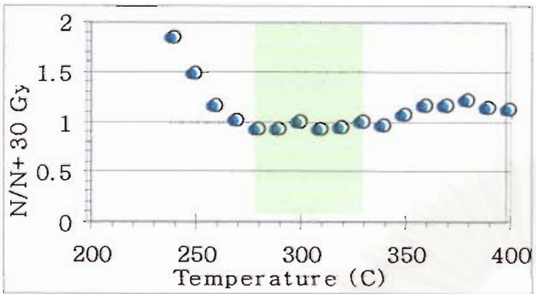
(E.2.8) TT6-1 AB




Stable zone = 290-330 °C

Figure E.2 Results of plateau test data for bricks of Thung Tuk archaeological site (cont.).

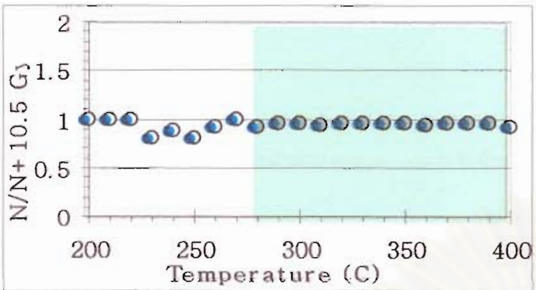
(E.2.9) TT8-1 AB




Stable zone = 280-340 °C

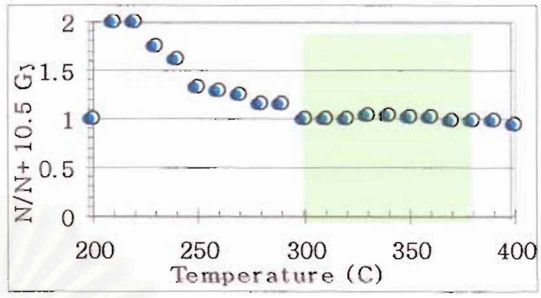
Figure E.3 Results of plateau test data for sediments of Thung Tuk archaeological site.

(E.3.1) TT1-2 AB



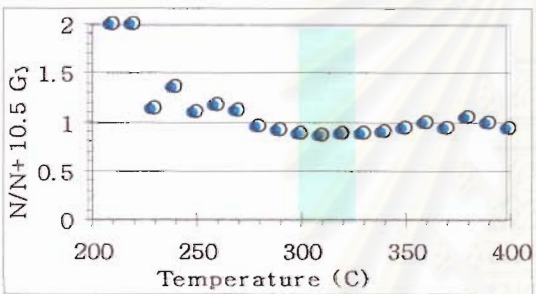

Stable zone = 280-400 °C

(E.3.2) TT3-2 AB



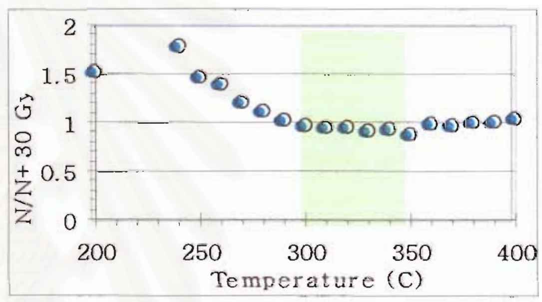

Stable zone = 300-380 °C

(E.3.3) TT4-2 AB



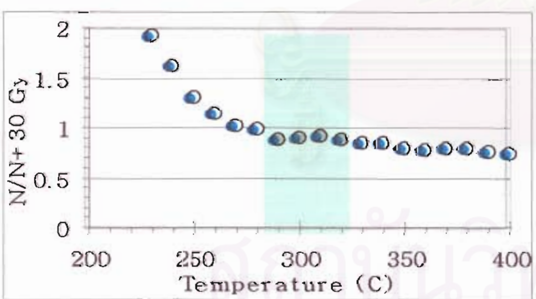

Stable zone = 300-330 °C

(E.3.4) TT8-2 A



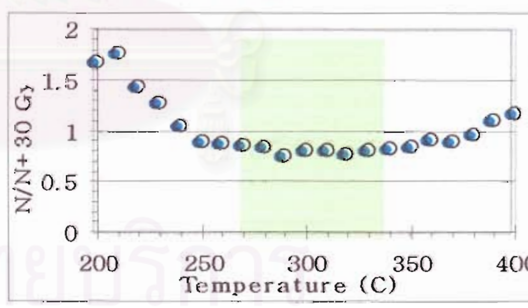

Stable zone = 300-350 °C

(E.3.5) TT8-2 B



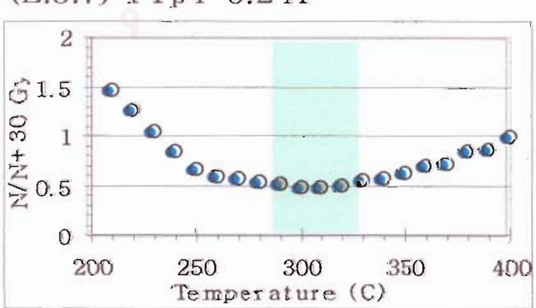

Stable zone = 285-325 °C

(E.3.6) TT8-2 AB



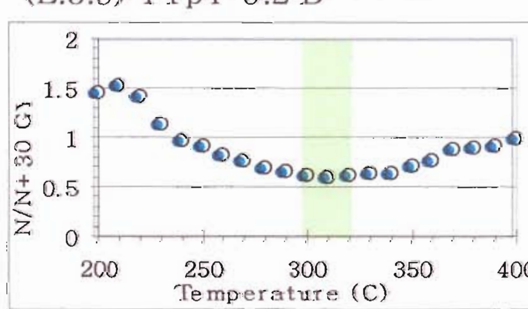

Stable zone = 270-340 °C

(E.3.7) TTp4-0.2 A




Stable zone = 290-330 °C

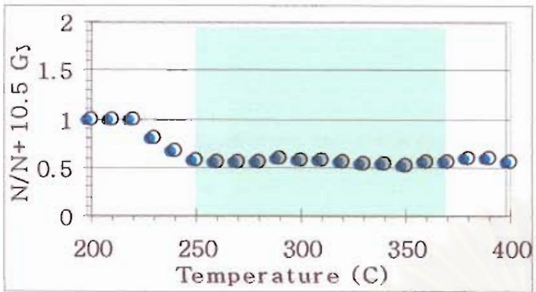
(E.3.8) TTp4-0.2 B




Stable zone = 300-320 °C

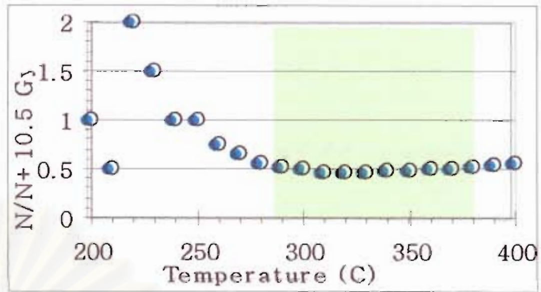
Figure E.3 Results of plateau test data for sediments of Thung Tuk archaeological site (cont.).

(E.3.9) TTp4-1.1 A



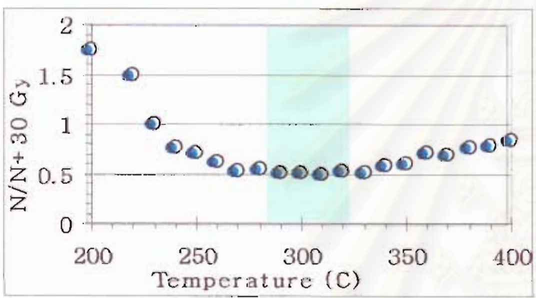

Stable zone = 250-370 °C

(E.3.10) TTp4-1.1 B



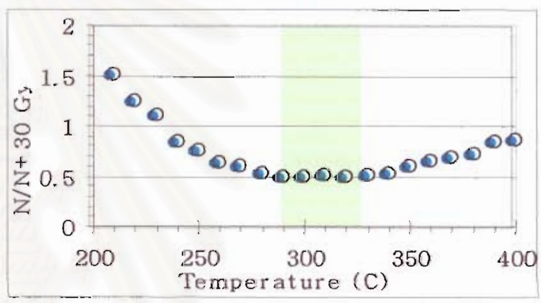

Stable zone = 290-380 °C

(E.3.11) TTp4-1.2 A



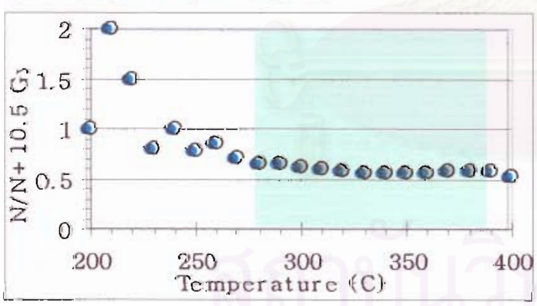

Stable zone = 285-325 °C

(E.3.12) TTp4-1.2 B



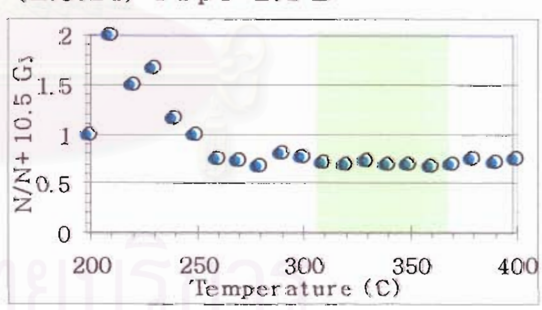

Stable zone = 290-330 °C

(E.3.13) TTp4-2.1 A



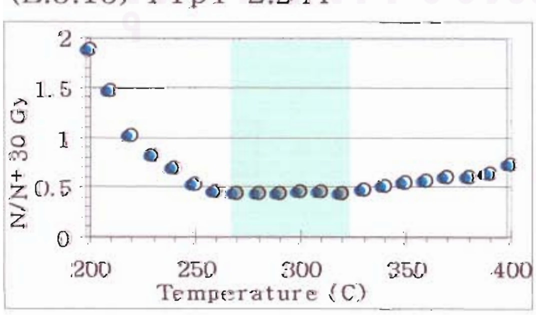

Stable zone = 280-390 °C

(E.3.14) TTp4-2.1 B



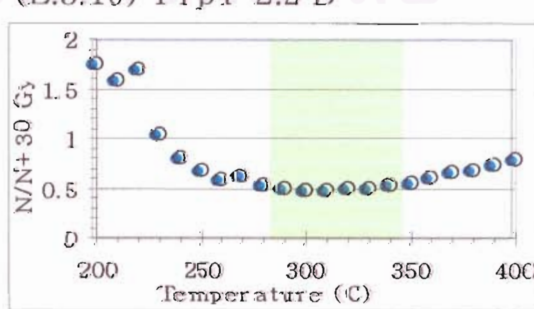

Stable zone = 310-370 °C

(E.3.15) TTp4-2.2 A




Stable zone = 270-325 °C

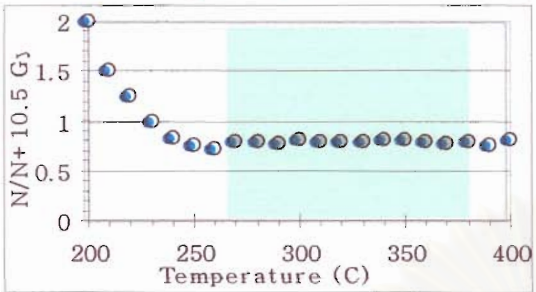
(E.3.16) TTp4-2.2 B




Stable zone = 285-350 °C

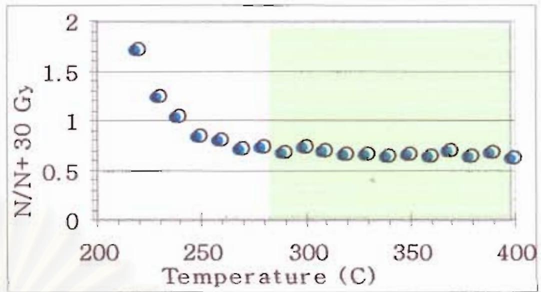
Figure E.3 Results of plateau test data for sediments of Thung Tuk archaeological site (cont.).

(E.3.17) TTp4-3.1 A



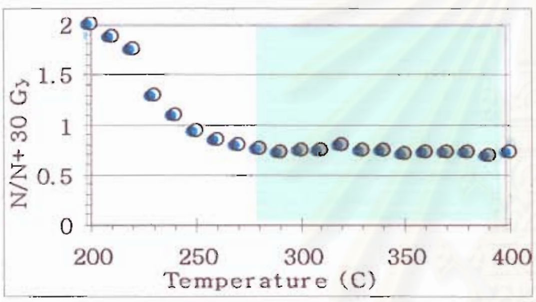

Stable zone = 270-380 °C

(E.3.18) TTp4-3.2 A



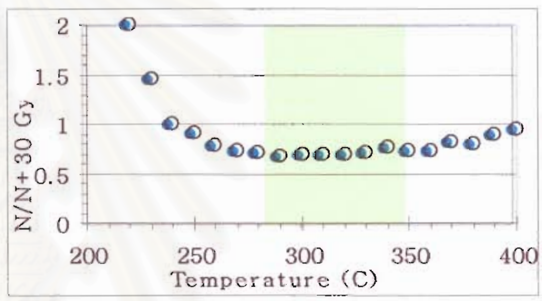

Stable zone = 285-400 °C

(E.3.19) TTp4-3.2 B



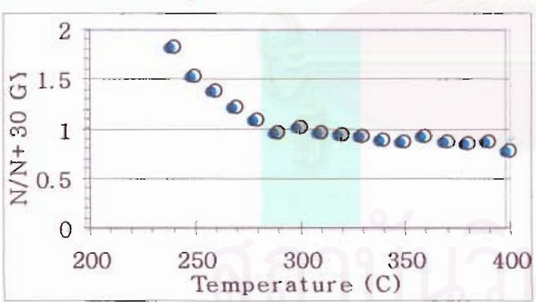

Stable zone = 280-400 °C

(E.3.20) TTp4-3.2 AB



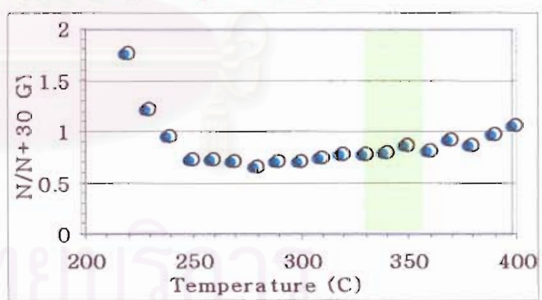

Stable zone = 285-350 °C

(E.3.21) TTp4-4.2 A




Stable zone = 285-330 °C

(E.3.22) TTp4-4.2 B




Stable zone = 300-355 °C



Where

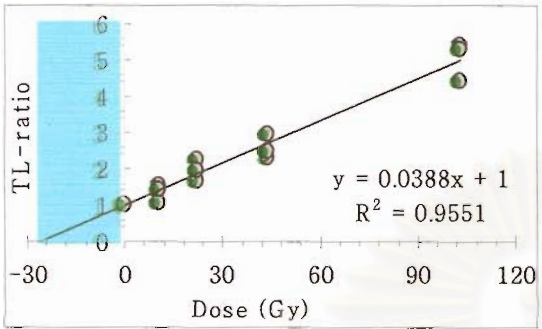
= Stable zone

# Appendix-F

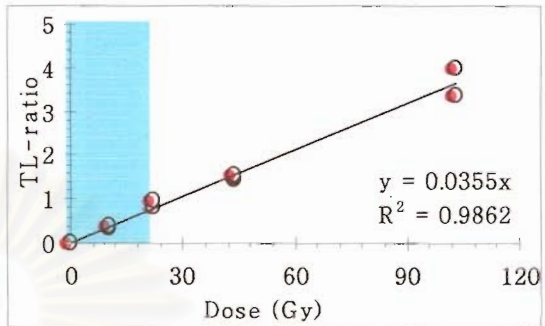
Results of growth curve data for sediments and bricks

Figure F.1 Results of growth curve data for sediments of Ban Bom Luang trench.

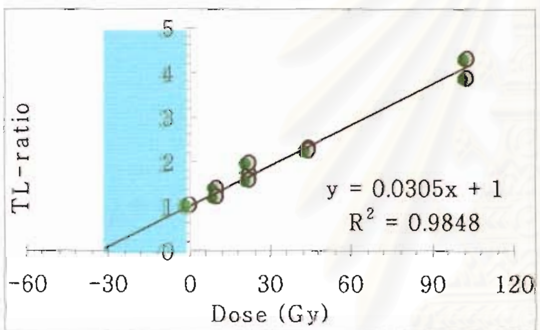
(F.1.1) BL5 A (TB)



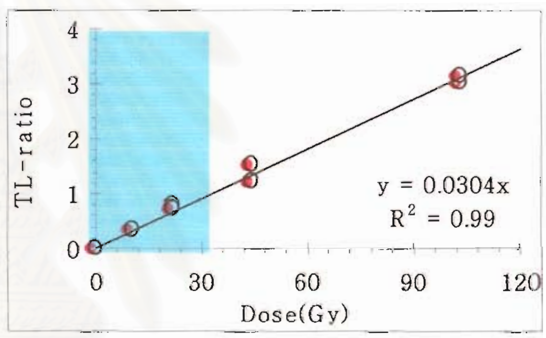

(F.1.2) BL5 A (R)



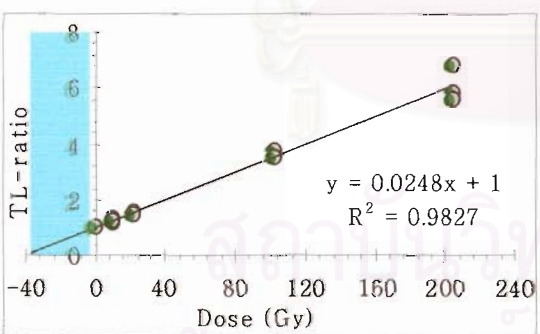

(F.1.3) BL5 B (TB)



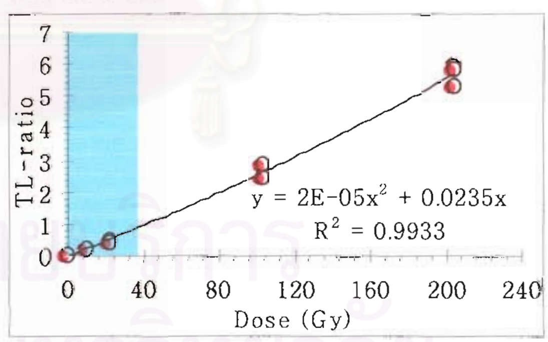

(F.1.4) BL5 B (R)



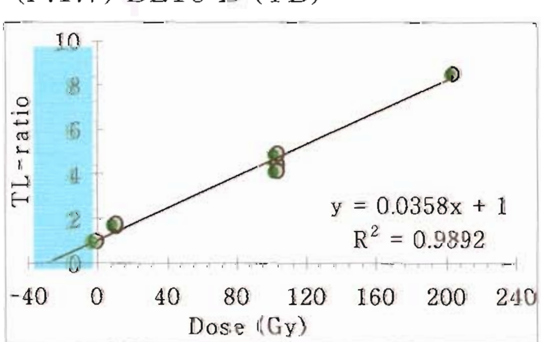

(F.1.5) BL10 A (TB)




(F.1.6) BL10 A (R)




(F.1.7) BL10 B (TB)




(F.1.8) BL10 B (R)

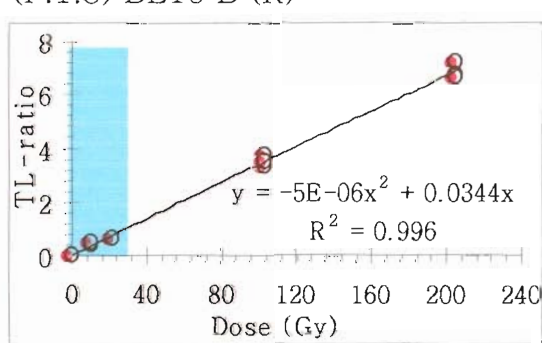
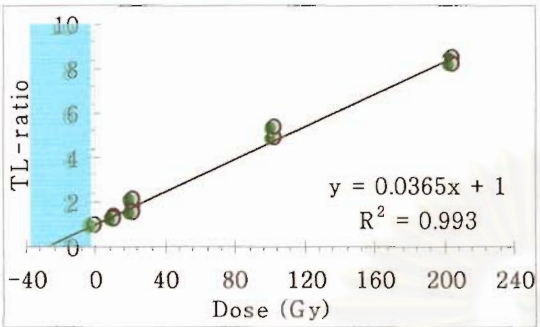
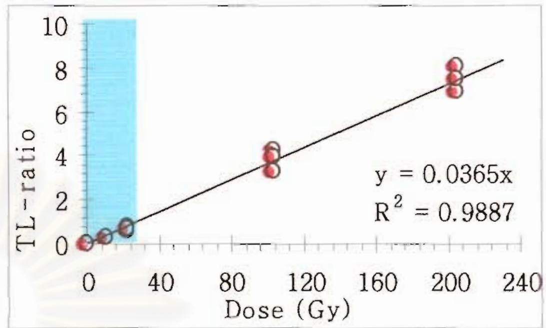


Figure F.1 Results of growth curve data for sediments of Ban Bom Luang trench (cont.).

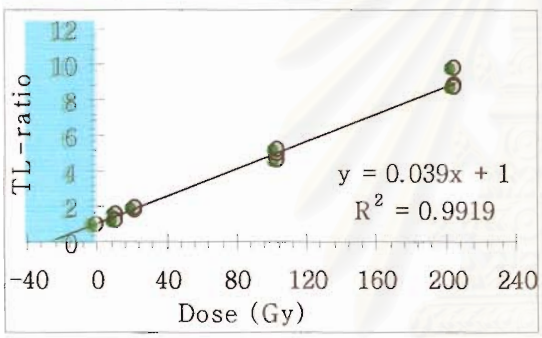
(F.1.9) BL11 A (TB)




(F.1.10) BL11 A (R)




(F.1.11) BL20 A (TB)




(F.1.12) BL20 A (R)

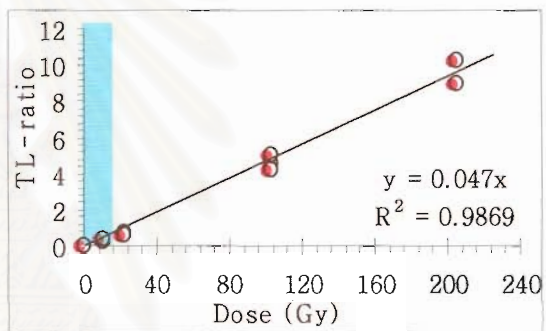
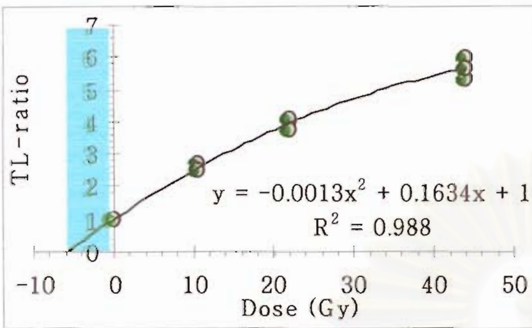
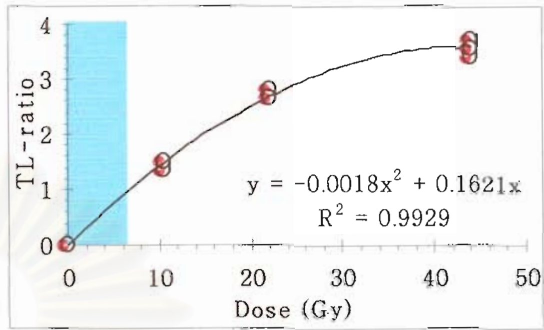


Figure F.2 Results of growth curve data for bricks of Thung Tuk archaeological site.

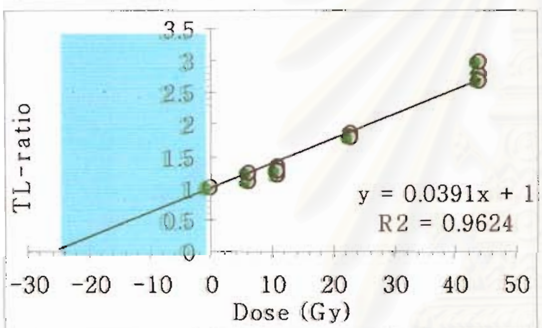
(F.2.1) TT1-1 AB (TB)



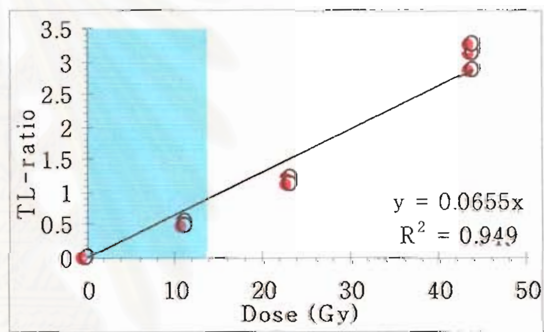

(F.2.2) TT1-1 AB (R)



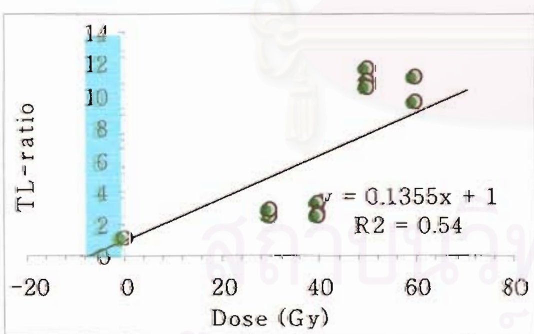

(F.2.3) TT3-1 AB (TB)



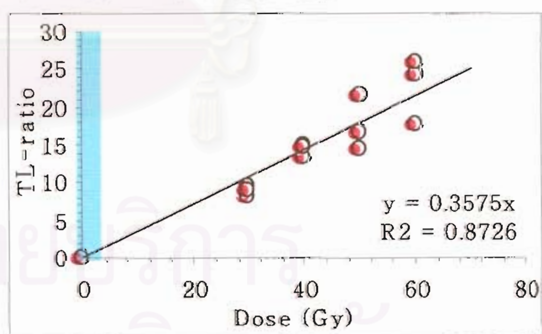

(F.2.4) TT3-1 AB (R)



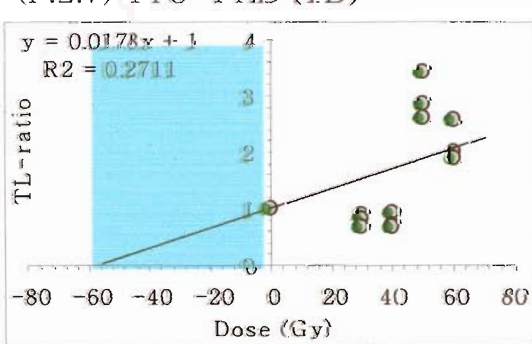

(F.2.5) TT3-3 AB (TB)




(F.2.6) TT3-3 AB (R)




(F.2.7) TT3-4 AB (TB)




(F.2.8) TT3-4 AB (R)

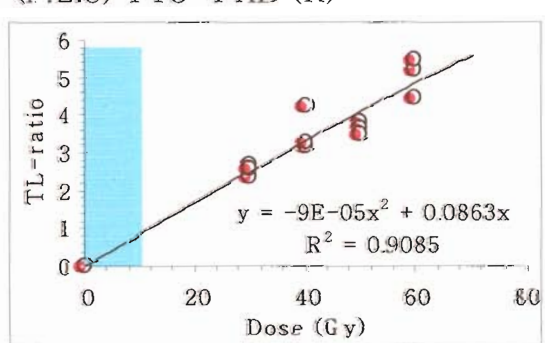
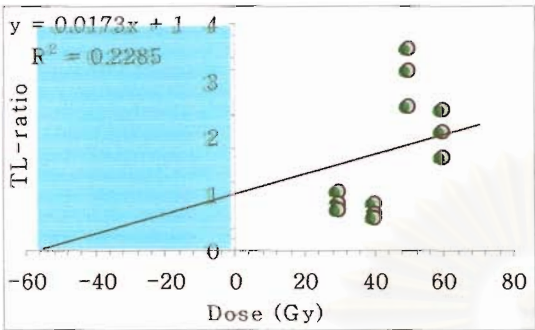
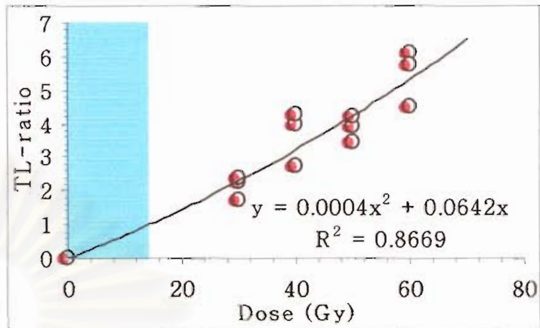


Figure F.2 Results of growth curve data for bricks of Thung Tuk archaeological site (cont.).

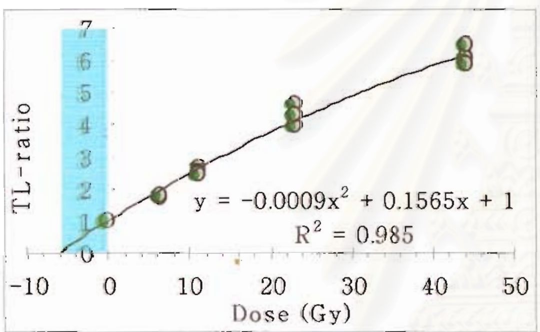
(F.2.9) TT3-5 AB (TB)



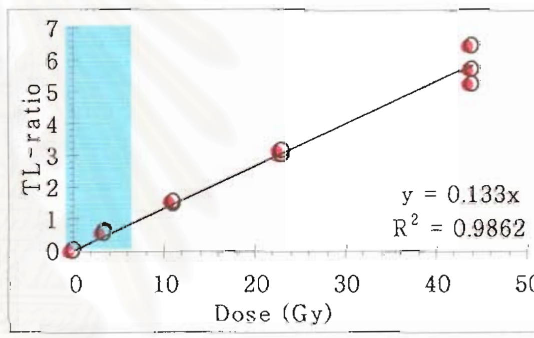

(F.2.10) TT3-5 AB (R)



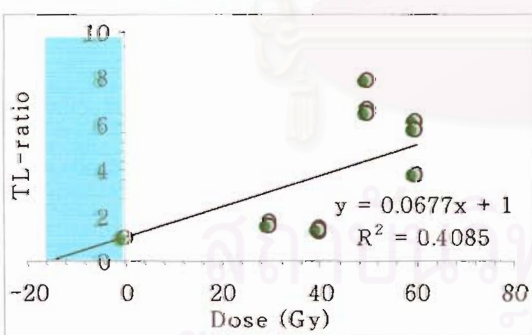

(F.2.11) TT4-1 AB (TB)



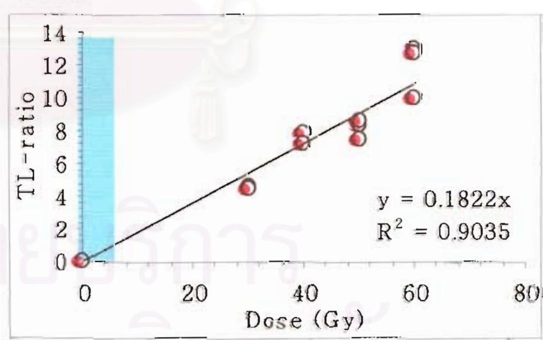

(F.2.12) TT4-1 AB (R)



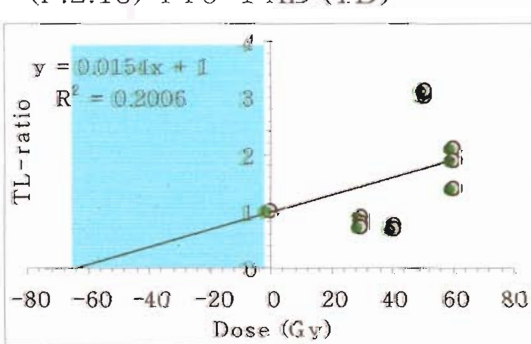

(F.2.13) TT4-3 AB (TB)




(F.2.14) TT4-3 AB (R)




(F.2.15) TT6-1 AB (TB)




(F.2.16) TT6-1 AB (R)

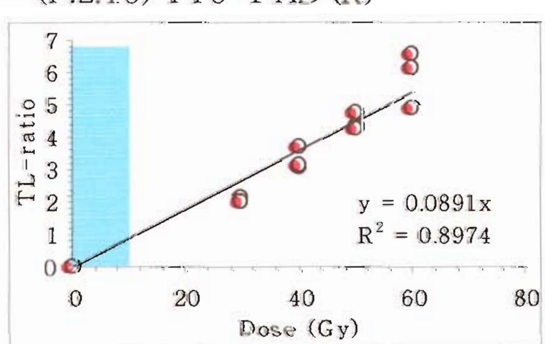
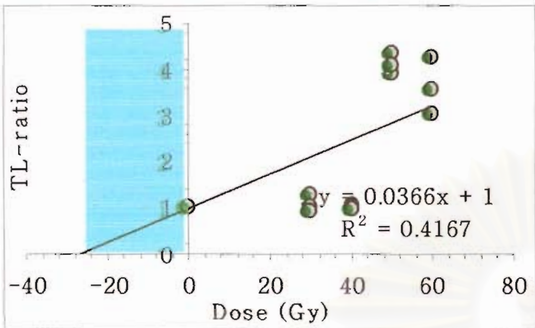


Figure F.2 Results of growth curve data for bricks of Thung Tuk archaeological site (cont.).

(F.2.17) TT8-1 AB (TB)




(F.2.18) TT8-1 AB (R)

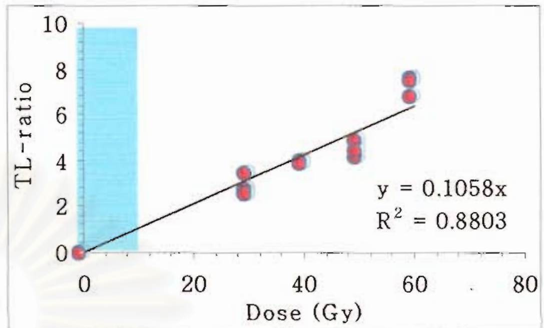
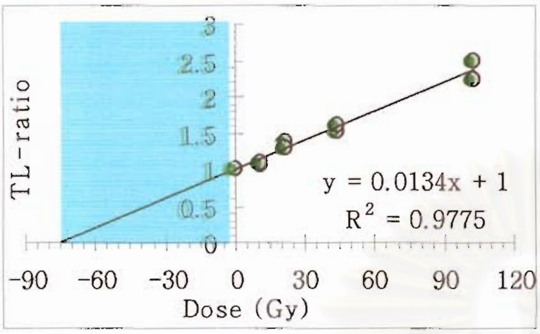
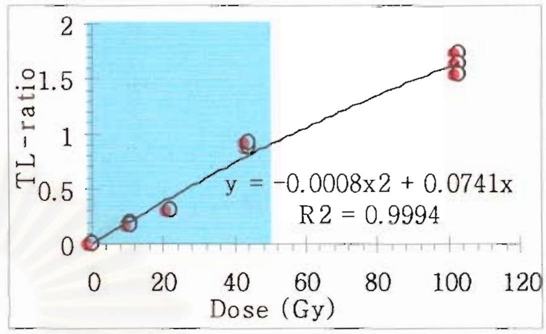


Figure F.3 Results of growth curve data for sediments of Thung Tuk archaeological site.

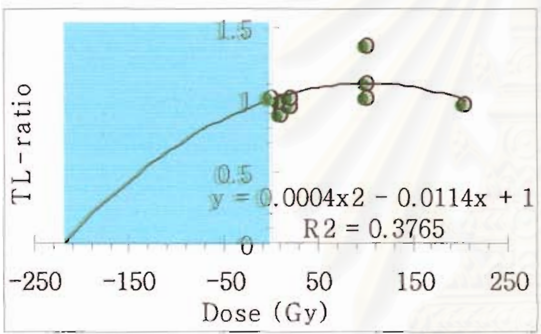
(F.3.1) TT1-2 AB (TB)



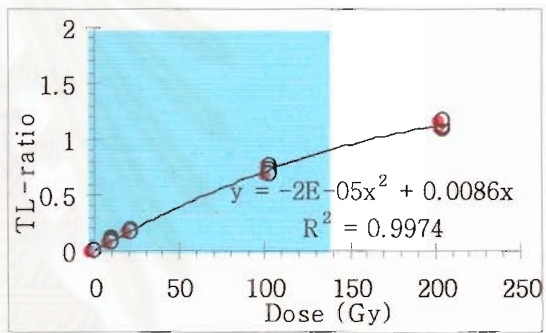

(F.3.2) TT1-2 AB (R)



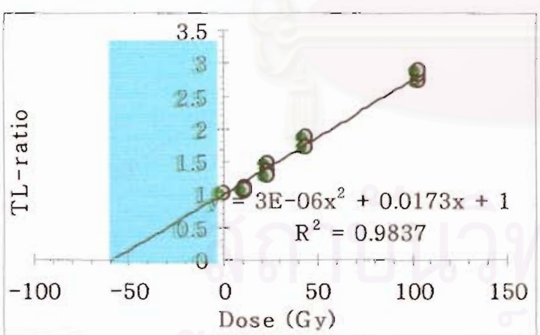

(F.3.3) TT3-2 AB (TB)



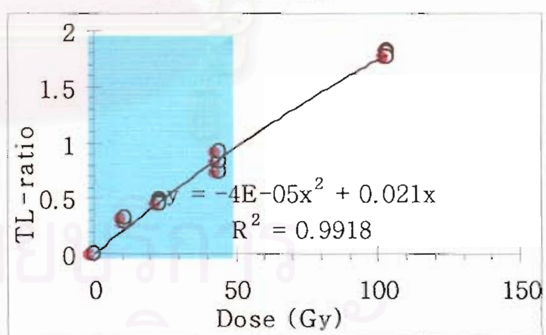

(F.3.4) TT3-2 AB (R)



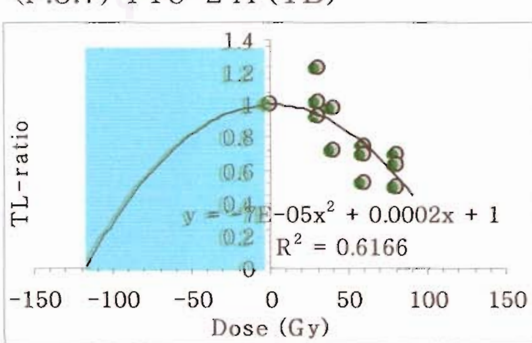

(F.3.5) TT4-2 AB (TB)




(F.3.6) TT4-2 AB (R)




(F.3.7) TT8-2 A (TB)




(F.3.8) TT8-2 A (R)

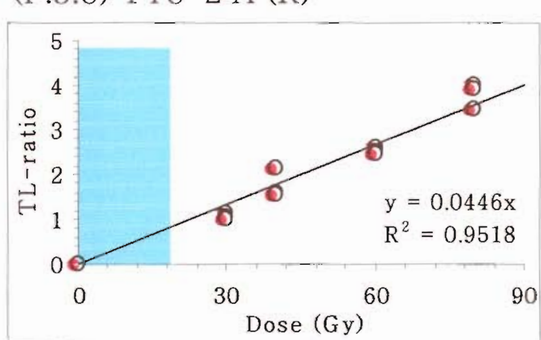
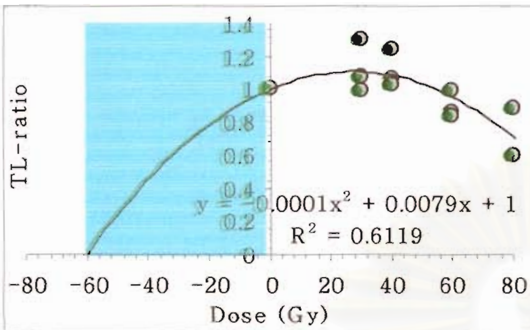
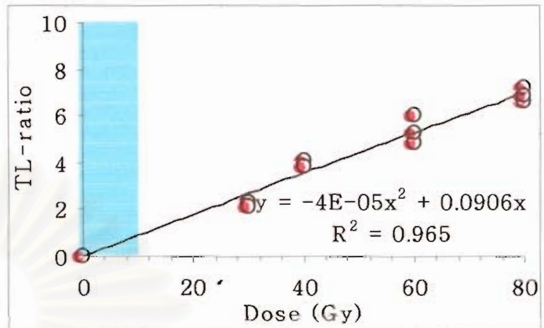


Figure F.3 Results of growth curve data for sediments of Thung Tuk archaeological site (cont.).

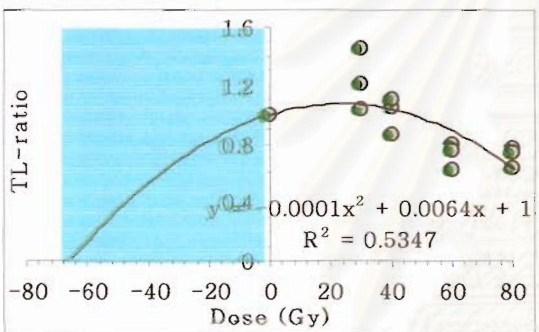
(F.3.9) TT8-2 B (TB)



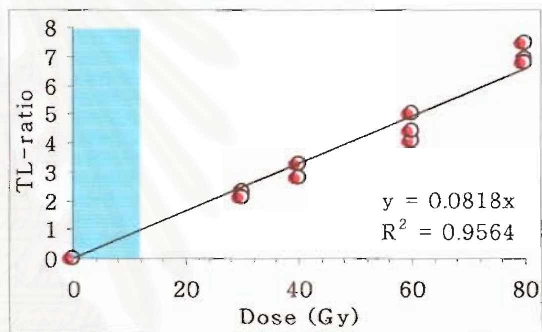

(F.3.10) TT8-2 B (R)



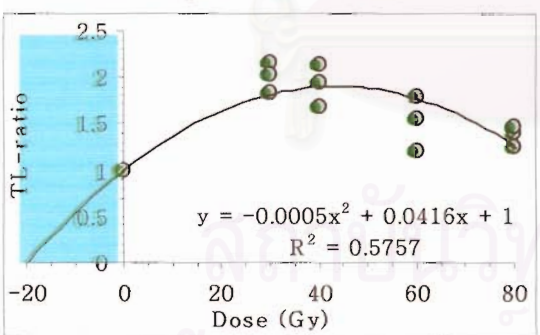

(F.3.11) TT8-2 AB (TB)



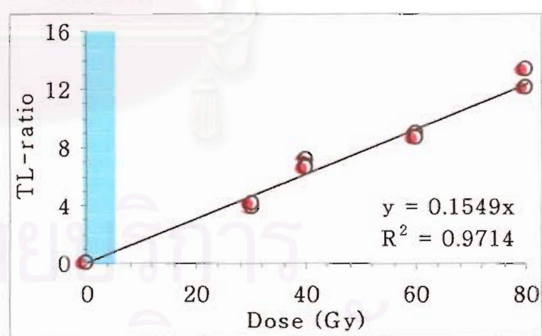

(F.3.12) TT8-2 AB (R)



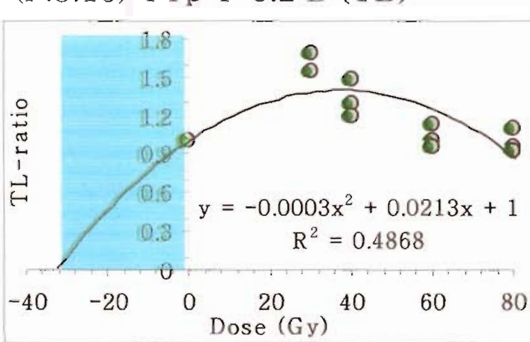

(F.3.13) TTp 4-0.2 A (TB)




(F.3.14) TTp4-0.2 A (R)




(F.3.15) TTp 4-0.2 B (TB)




(F.3.16) TTp4-0.2 B (R)

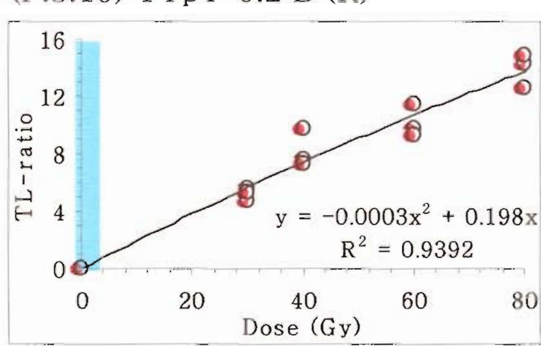
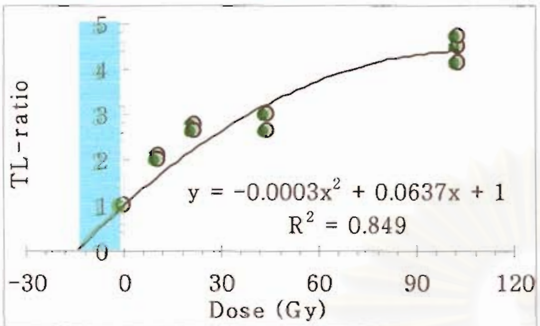
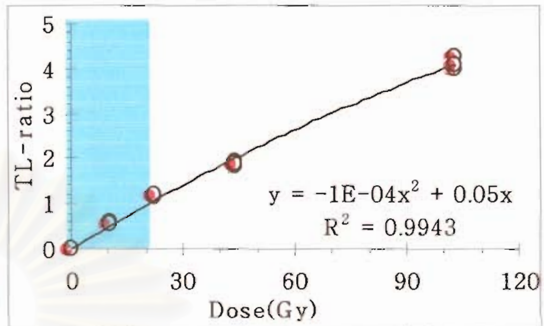


Figure F.3 Results of growth curve data for sediments of Thung Tuk archaeological site (cont.).

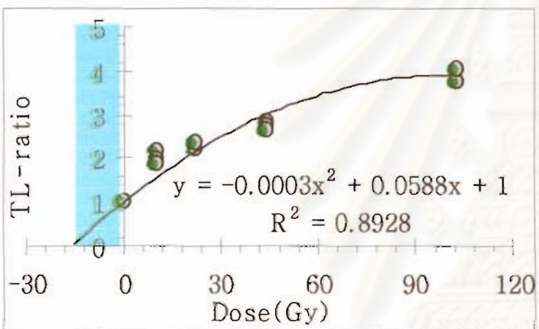
(F.3.17) TTp 4-1.1 A (TB)



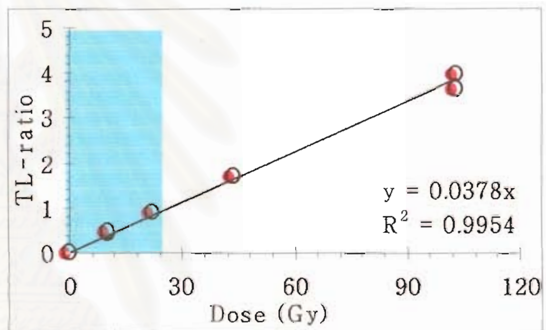

(F.3.18) TTp4-1.1 A (R)



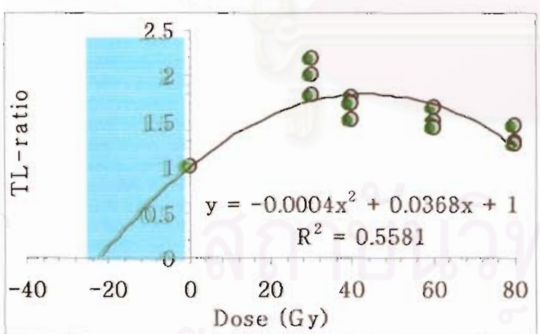

(F.3.19) TTp 4-1.1 B (TB)



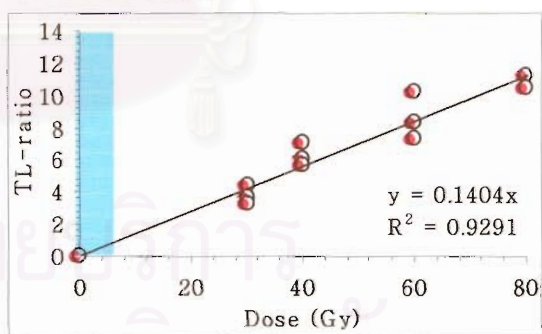

(F.3.20) TTp4-1.1 B (R)



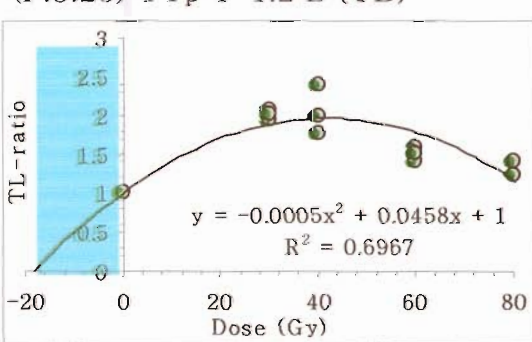

(F.3.21) TTp 4-1.2 A (TB)




(F.3.22) TTp4-1.2 A (R)




(F.3.23) TTp 4-1.2 B (TB)




(F.3.24) TTp4-1.2 B (R)

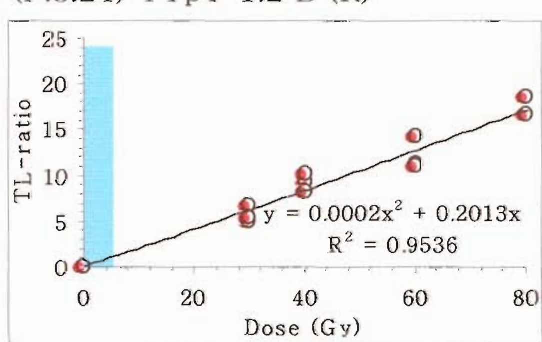
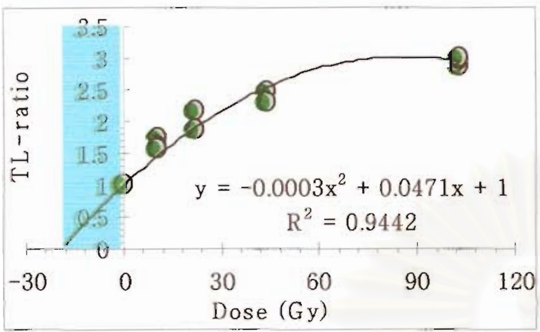
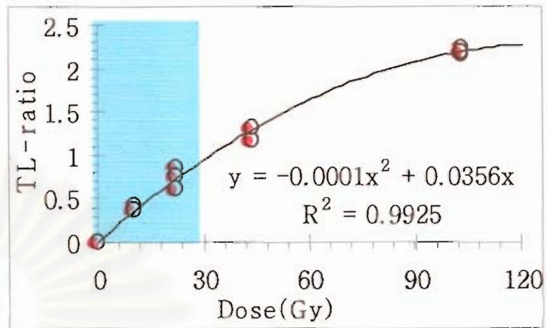


Figure F.3 Results of growth curve data for sediments of Thung Tuk archaeological site (cont.).

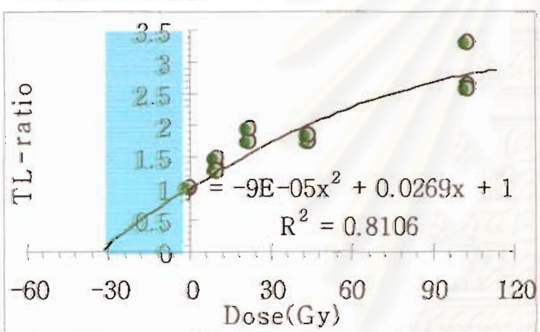
(F.3.25) TTp 4-2.1 A (TB)



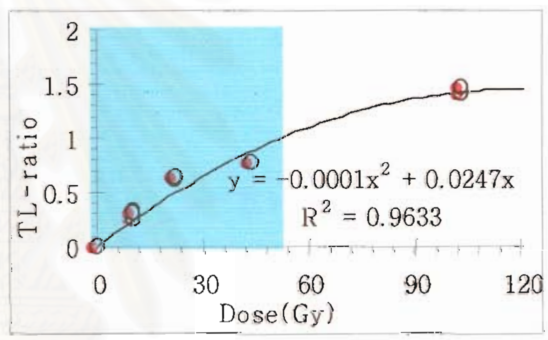

(F.3.26) TTp4-2.1 A (R)



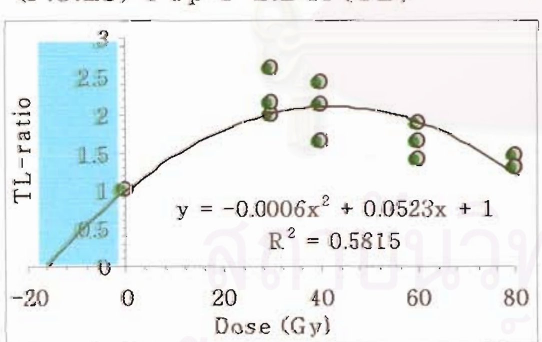

(F.3.27) TTp 4-2.1 B (TB)



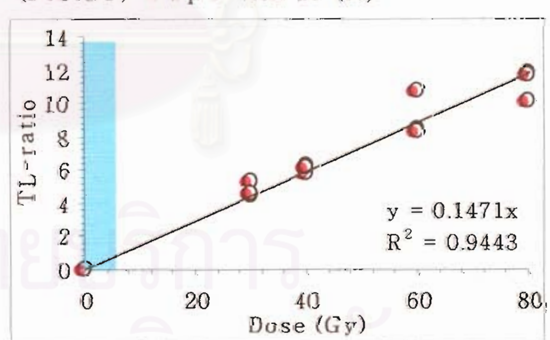

(F.3.28) TTp4-2.1 B (R)



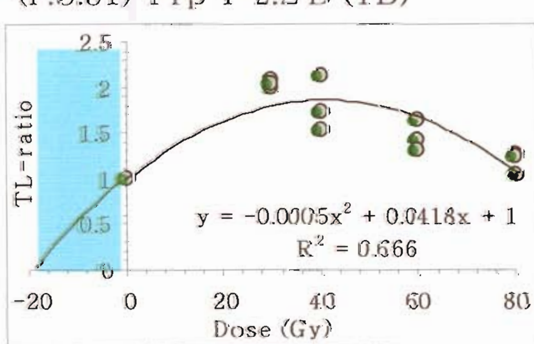

(F.3.29) TTp 4-2.2 A (TB)




(F.3.30) TTp4-2.2 A (R)




(F.3.31) TTp 4-2.2 B (TB)




(F.3.32) TTp4-2.2 B (R)

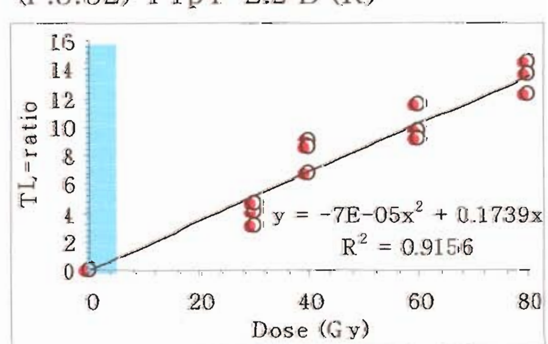
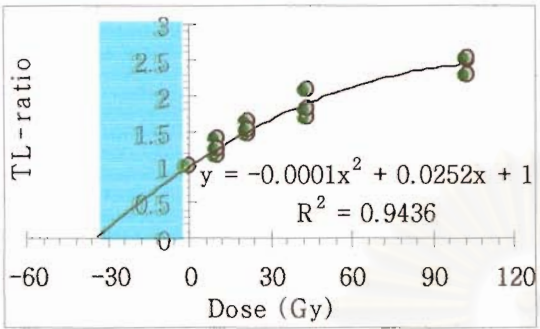
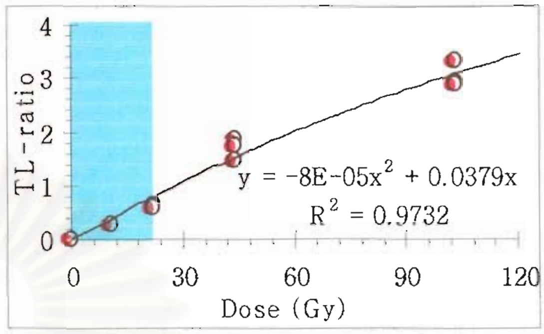


Figure F.3 Results of growth curve data for sediments of Thung Tuk archaeological site (cont.).

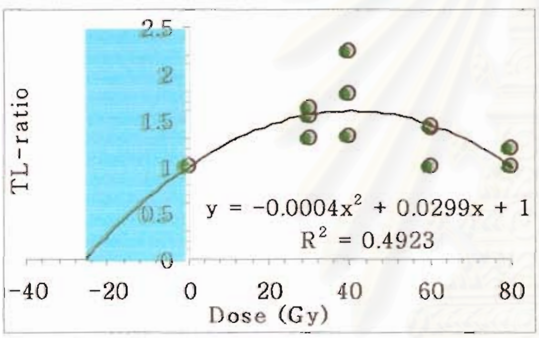
(F.3.33) TTp 4-3.1 A (TB)



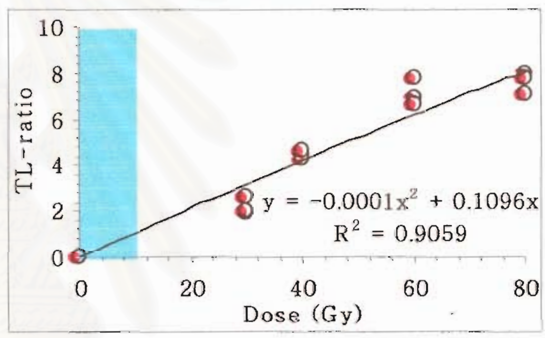

(F.3.34) TTp4-3.1 A (R)



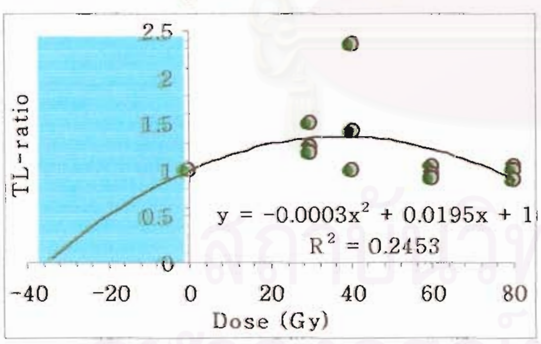

(F.3.35) TTp 4-3.2 A (TB)



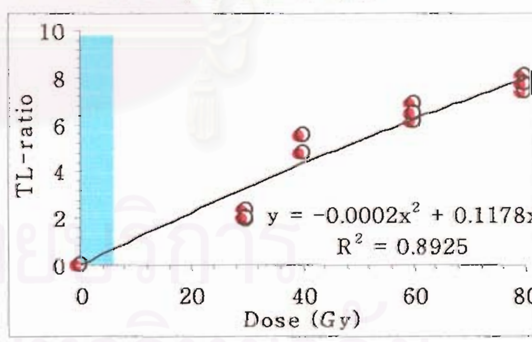

(F.3.36) TTp4-3.2 A (R)



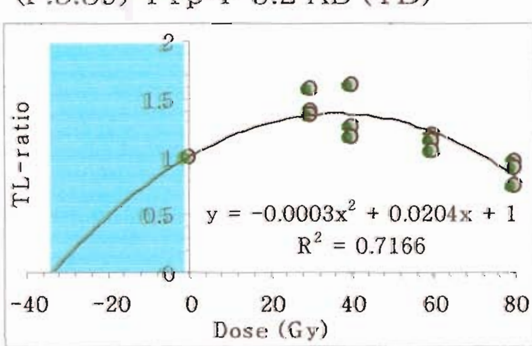

(F.3.37) TTp 4-3.2 B (TB)




(F.3.38) TTp4-3.2 B (R)




(F.3.39) TTp 4-3.2 AB (TB)




(F.3.40) TTp4-3.2 AB (R) (R)

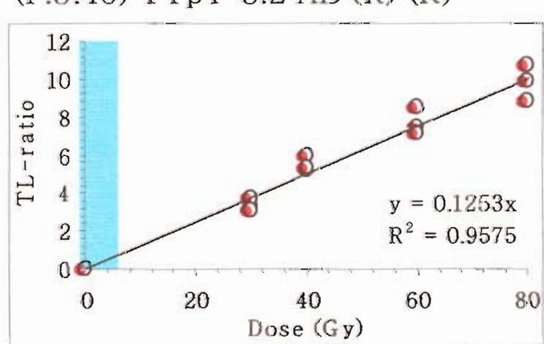
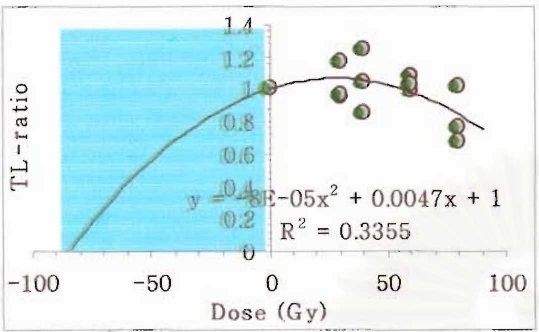
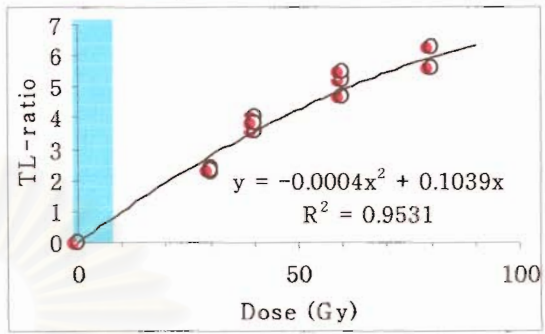


Figure F.3 Results of growth curve data for sediments of Thung Tuk archaeological site (cont.).

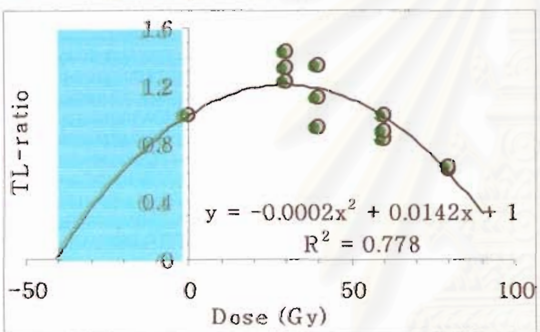
(F.3.41) TTp 4-4.2 A (TB)



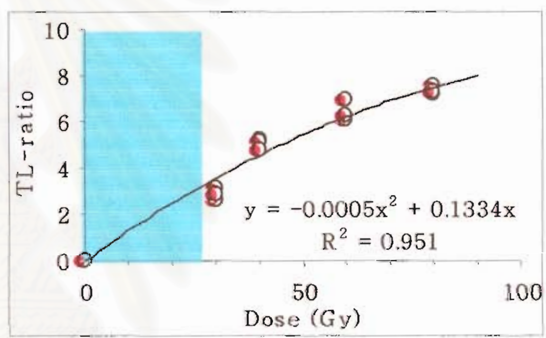

(F.3.42) TTp4-4.2 A (R)




(F.3.43) TTp 4-4.2 B (TB)




(F.3.44) TTp4-4.2 B (R)




Where

= Equivalent dose

Appendix-G

Manual of annual dose calculation program (version 1.1)

Manual of Annual Dose Calculation Program (Version 1.1)

## G.1. About Annual Dose Calculation Program

Evaluation of the annual dose has presented very complex and sophisticate calculation since it was first published (Aitken, 1985; Prescott and Hutton, 1995; Abdel-Wahab et al., 1996), the detailed evaluation has prompted a lot of significant discussion and interpretation in individual sites, particularly alpha and beta coefficient that depend on the whole grain size of sample. Moreover, attenuation factor from water content in environment around sampling point must be carefully considered.

Consequently, the construction of an annual dose calculation program (version 1.1) was taken as an opportunity to create a new and easy software package for the evaluation of annual dose value in TL-dating procedure. This software is designed primarily for calculate annual dose for samples of 2 different grain size; coarse grain technique (74-250 µm) and fine grain technique (grain size <74µm). This philosophy of separated grain size processing is similar to that applied by Aitken (1985).

This program was developed using the object orientated programming language "Virtual Basic version 6.0". Because it's visual programming interface allows the development of more user-friendly and fuzzy-logic applications than pure "Basic" programming language. It is also offers a powerful graphic platform. Moreover, the window and modular system provides convenient operation and flexibility in data management; manual input raw data (such as Uranium, Thorium and Potassium contents etc.) can be directly corrected, thus saving time and comfort for user.

An annual dose calculation program (version 1.1) developed by Pailople, S. and Charusiri, P. consists of two subprograms;

- Core of annual dose calculation program (version 1.1) that developed from Virtual Basic version 6.0 (Figure G.1). Researcher can access from compact disc (CD) that is proposed in this thesis. or down load free of charge at URL: http://pioneer.netserv.chula.ac.th/~cpunya/
- Supporting program (Microsoft.NET framework package) is in Basic language for window operation system (Figure G.1). This program can be down loaded from Microsoft Company's home page at URL:

  http://msdn.microsoft.com/netframework/downloads/framework1_1/

  or copy it directly from CD included in this thesis.

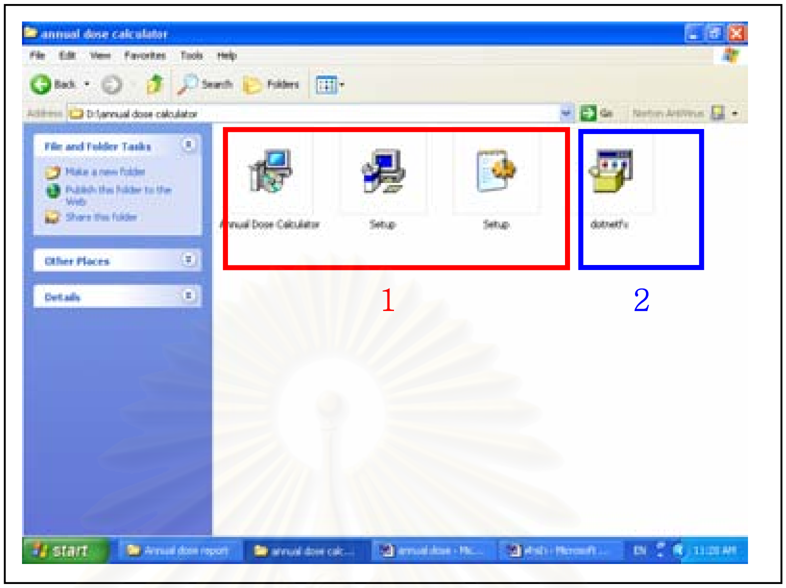



Figure G.1 Component of annual dose calculation program (version 1.1); (1) Annual dose calculation program (version 1.1) and (2) Microsoft.NET fame work package.

## G.2. Installation Guide of Annual Dose Calculation Program (Version 1.1)

G.2.1. “Double click Microsoft.NET framework package” to prepared suitable condition for program installation.

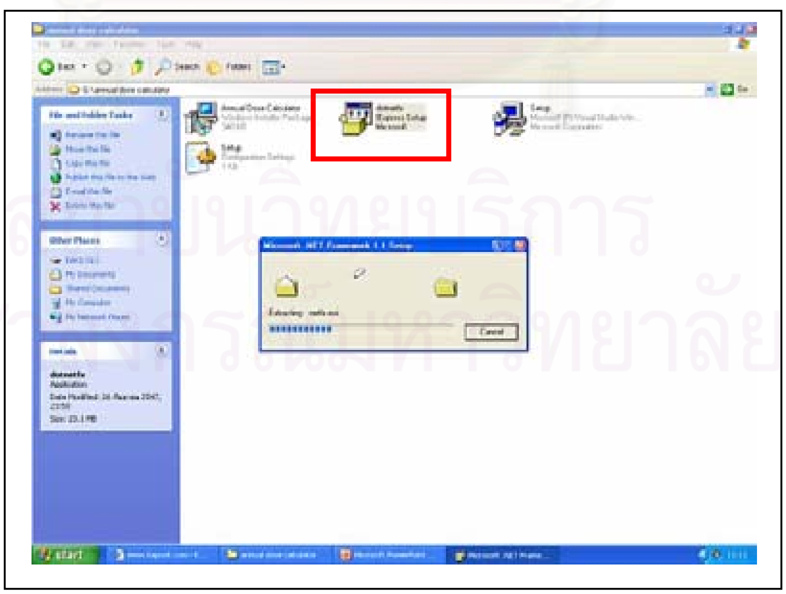


Figure G.2 Installation Microsoft.NET framework package.

G.2.2 "Double click icon SETUP" from subprogram annual dose calculation version 1.1 for installing full version program. Then the path of directory as one wish for dumping all programs in computer.

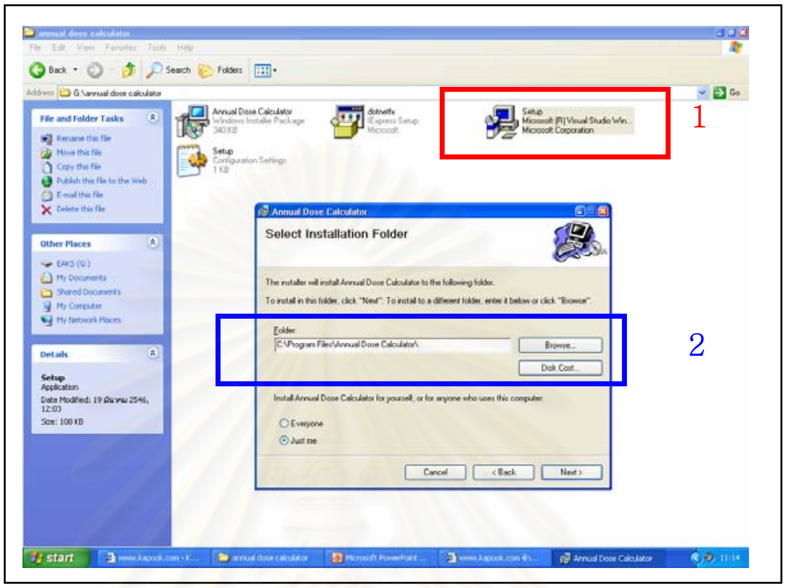



Figure G.3 Installation annual dose program (version 1.1); (1) Set up annual dose calculation program and (2) Select path of directory.

G.2.3. "Click FINISH" for confirm completely install annual dose calculation program.

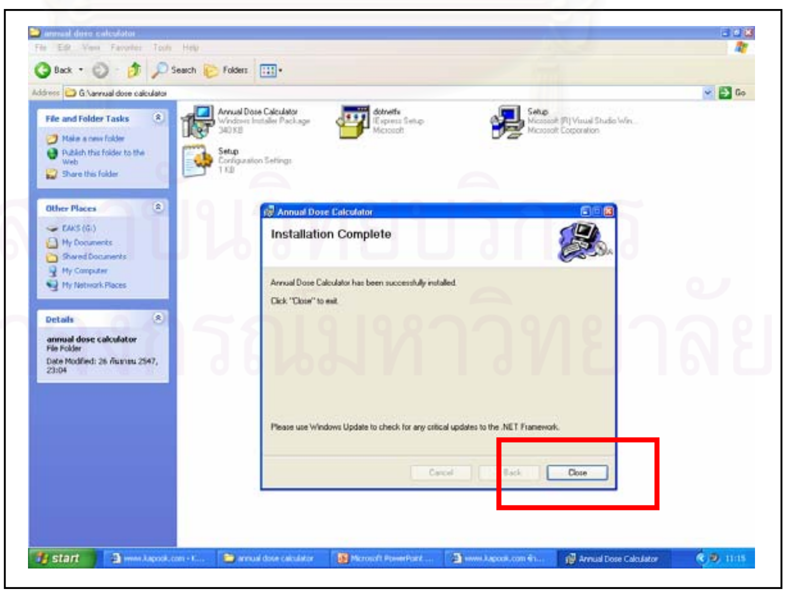



Figure G.4 Feature of complete installation of annual dose calculation program version 1.1.

## G.3 Processing of Annual Dose Calculation Program

The interface of "Annual dose calculation program (version 1.1)" consists of three mainly components:

- A component for the annual dose calculation of fine-grained sediments (grain size <74 μm);

$$AD = [0.15(2.783U+0.783Th)/(1+1.50(Wb/100))] + [(0.1462U+0.0286Th+0.8303K)/(1+1.25(Wb/100))] + [(0.1148U+0.0514Th+0.2492K)/(1+1.14(Wb/100))] + 0.15 \quad \text{(Eq. G.3.1)}$$

- A component for the annual dose calculation of coarse-grained sediments (grain size 74-250 μm);

$$AD = [0.9(0.1462U+0.0286Th+0.8303K)/(1+1.25(Wb/100))] + [(0.1148U+0.0514Th+0.2492K)/(1+1.14(Wb/100))] + 0.15 \quad \text{(Eq. G.3.2)}$$

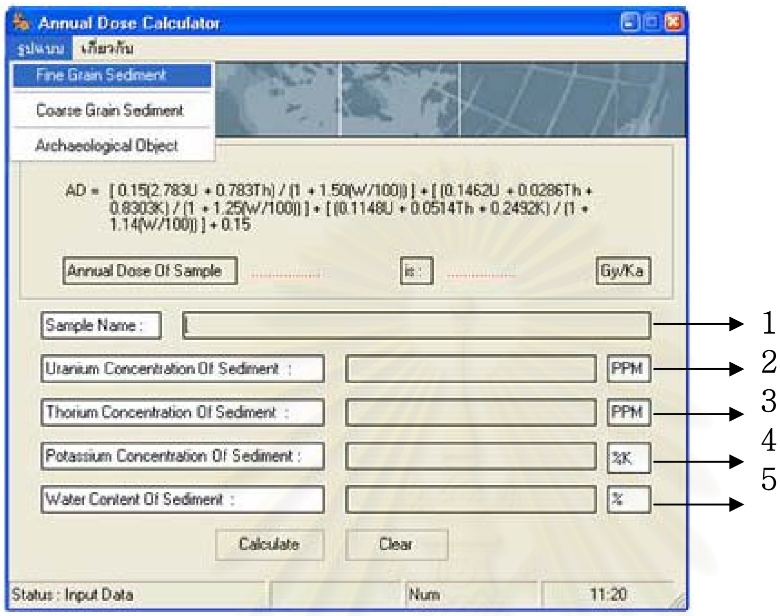
- A component for the annual dose calculation of archaeological object such as pottery, stupa and brick;

$$AD = [0.15(2.783U+0.783Th)/(1+1.50(Wa/100))] + [(0.1462U+0.0286Th+0.8303K)/(1+1.25(Wa/100))] + [(0.1148U+0.0514Th+0.2492K)/(1+1.14(Wb/100))] + 0.15 \quad \text{(Eq. G.3.3)}$$

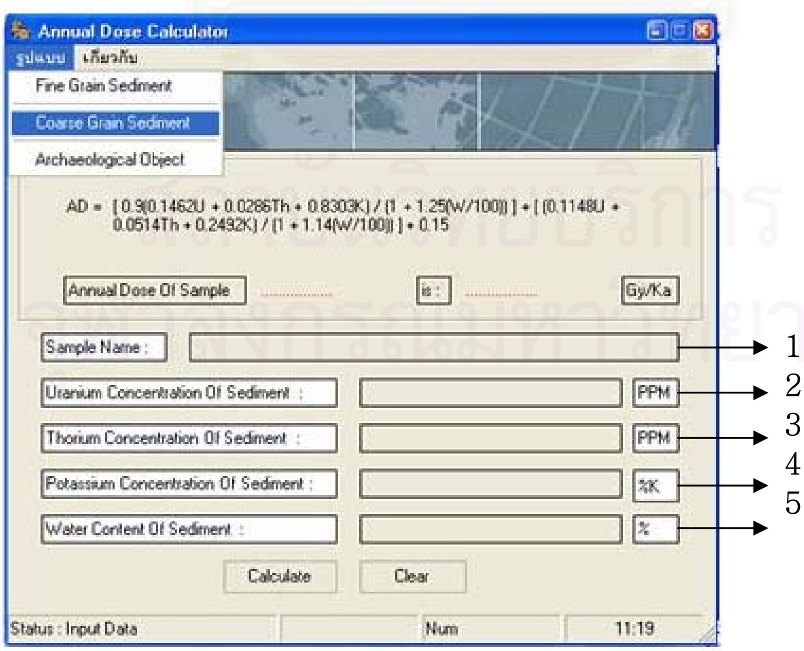
Where

AD = Annual dose (mGy),
U = Uranium content (ppm),
Th = Thorium content (ppm),
K = Potassium content (%),
Wa = Water content in sample (%), and
Wb = Water content in sediment (%).

G.3.1. Fine-Grained Technique
(For Sample with Grain Size of <74 μm Diameter)

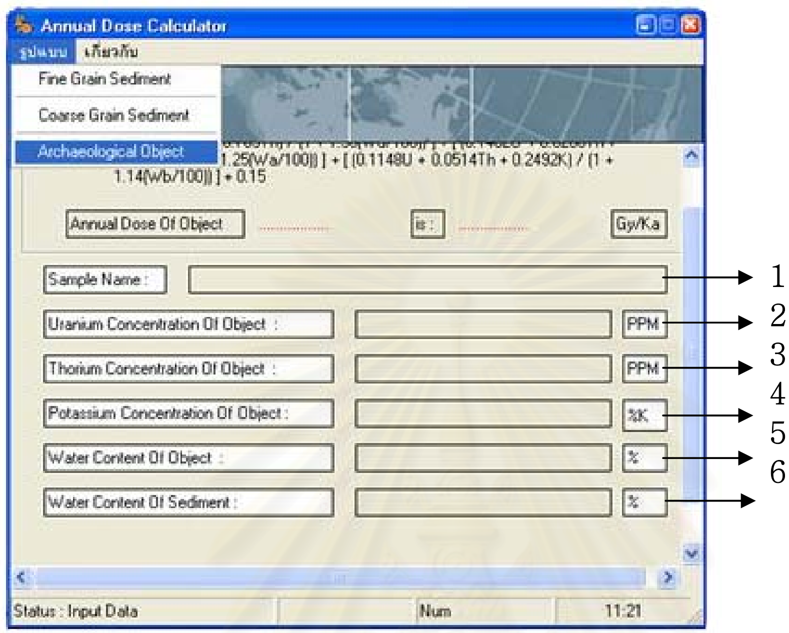



G.3.2 Coarse-Grain Technique
(For Sample with Grain Size of 74-250 μm)



G.3.3 Archaeological Objects

(Such as Pottery, Stupa and Brick etc.)




Where

1 = Sample name,
2 = Uranium content (ppm),
3 = Thorium content (ppm),
4 = Potassium content (%),
5 = Water content in sample (%), and
6 = Water content in sediment (%).

# Appendix-H

## Glossary of Thai geographical terms

Because Thai geographical terms are used in this thesis, the Thai-English equivalents are listed below:

| | | |
|---|---|---|
| Amphoe | = | Town, district, secondary administrative centre |
| Ban | = | Village, small community |
| Changwat | = | Province |
| Doi | = | Mountain or a prominent peak of a mountain (northern Thailand) |
| Khao | = | Hill, mountain |
| Khem | = | Salted, shrewed |
| Ko | = | Island |
| Muang | = | Mining |
| Nam | = | Water |
| Thong | = | Gold |
| Thung | = | Field, a pasture, a range |
| Tuk | = | A building, a brick work, a brick house, an edifice |

# BIOGRAPHY

Mr. Santi Pailoplee was born in Nakornrajsima province in 1978. He studied in a local elementary school in Burirum province for 6 years during 1985 to 1990. In 1990, his adventure was started. He decided to study and spend his life at King's College for the pre-university education in Nakornprathom province in 1990-1996. Later on, he attended to Department of Physics, Faculty of Science, Chulalongkorn University. He graduated with the bachelor degree of Science (B. SC.) in 2001 with the computer simulation and nuclear physic experience. After B.Sc. graduation, he ran a business with his parents in Burirum province for 1 year. Then, he studied a Master degree (Earth-sciences major) in Department of Geology, Chulalongkorn University. His thesis mainly focuses in application of thermoluminescnece (TL) dating for both geological and archaeological materials.