ลักษณะเฉพาะของชิ้นตะกอนโครเมียนสปิเนลในหินทรายจากหมวดหินน้ำดุก บริเวณอำเภอหล่มสักและน้ำหนาว จังหวัดเพชรบูรณ์

นาย วิชัย จูฑะโกสิทธิ์กานนท์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาธรณีวิทยา ภาควิชาธรณีวิทยา
คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2542

ISBN 974-333-708-3

CHARACTERISTICS OF DETRITAL CHROMIAN SPINELS IN SANDSTONES FROM THE NAM DUK FORMATION, AMPHOE LOM SAK AND AMPHOE NAM NAO, CHANGWAT PHETCHABUN

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A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Science in Geology

Department of Geology

Faculty of Science

Chulalongkorn University

Academic Year 1999

ISBN 974-333-708-3

Thesis Title	Characteristics of Detrital Chromian Spinels in Sandstones from the Nam Duk Formation, Amphoe Lom Sak and Amphoe Nam Nao, Changwat Phetchabun
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วิชัย จูฑะโกสิทธิ์กานนท์ : ลักษณะเฉพาะของชิ้นตะกอนโครเมียนสปิเนลในหินทรายจากหมวดหินน้ำดุก บริเวณอำเภอหล่มสักและน้ำหนาว จังหวัดเพชรบูรณ์ (CHARACTERISTICS OF DETRITAL CHROMIAN SPINELS IN SANDSTONES FROM THE NAM DUK FORMATION, AMPHOE LOM SAK AND AMPHOE NAM NAO, CHANGWAT PHETCHABUN) อ. ที่ปรึกษา : ผศ. ดร. ปัญญา จารุศิริ, อ. ที่ปรึกษาร่วม : รศ. ดร. เคน-อิชิโร ฮิซาดะ. 135 หน้า. ISBN 974-333-708-3.

ข้อมูลที่ได้จากการศึกษาในภาคสนามตลอดเส้นทางหล่มสัก-ชุมแพ ระหว่างหลักกิโลเมตรที่ 16.0 ถึงหลักกิโลเมตรที่ 42.0 ในเขตจังหวัดเพชรบูรณ์ สามารถแบ่งหมวดหินน้ำดุก ออกเป็น 6 หน่วยหินย่อย ได้แก่ หน่วยหินแทรกสลับชั้นหินทราย-หินดินดานชุดล่าง หน่วยหินแทรกสลับชั้นหินปูน-หินดินดาน หน่วยหินแทรกสลับชั้นหินทราย-หินดินดานชุดบน หน่วยหินแทรกสลับชั้นหินดินดาน-หินทราย หน่วยหินแทรกสลับชั้นหินทราย-หินดินดาน-หินปูน และหน่วยหินดินดาน หน่วยหินสามชุดแรกตั้งอยู่ในพื้นที่ตะวันตกของพื้นที่ศึกษาและชุดหินเหล่านี้แสดงลักษณะของการแปรสภาพที่รุนแรงกว่าและสภาพแวดล้อมของการสะสมตัวที่ลึกกว่าเมื่อเปรียบเทียบกับลักษณะของหน่วยหินที่ตั้งอยู่ในพื้นที่ตะวันออก ตลอดเส้นทางพบชิ้นตะกอนโครเมียนสปิเนลจำนวนมากเป็นแร่ประกอบหินในหินทรายชนิดลิทิเกรย์เวค (ในปริมาณที่น้อยกว่า 1 เปอร์เซ็นต์) ซึ่งสัมพันธ์อยู่กับสภาพแวดล้อมน้ำลึก ในการศึกษาลักษณะเนื้อหินชิ้นตะกอนโครเมียนสปิเนลมีสีน้ำตาลเข้มจนถึงเกือบดำ ซึ่งสัมพันธ์อยู่กับการแทนที่กันระหว่างธาตุโครเมียม ธาตุอะลูมิเนียม และธาตุเหล็ก ขนาดของชิ้นตะกอนมีขนาดตั้งแต่ 30-75 ไมครอน บางชิ้นมีขนาดใหญ่กว่า 100 ไมครอน ชิ้นตะกอนเกือบทั้งหมดค่อนข้างเหลี่ยม ถึงเหลี่ยม บางชิ้นแสดงลักษณะกึ่งรูปผลึก ถึงรูปผลึก ซึ่งบ่งชี้ถึงรูปผลึกเดิม ชิ้นตะกอนสปิเนลจำนวน 35 ตัวอย่าง ถูกคัดเลือกเพื่อทำการศึกษาและหาองค์ประกอบทางเคมีด้วยวิธีอิเลคตรอนไมโครโพรบ แร่สปิเนลเหล่านี้มีค่าโครเมียมค่อนข้างสูง ขณะที่มีค่าไททาเนียมไดออกไซด์ค่อนข้างแตกต่างกัน อัตราส่วนระหว่างอะตอมของธาตุโครเมียมกับธาตุอะลูมิเนียมค่อนข้างสูง มีค่ามากกว่า 0.5 สำหรับค่าเฟอร์ริกไอออนค่อนข้างต่ำและมีค่าอัตราส่วนระหว่างเฟอร์ริกไอออนต่อธาตุโครเมียมและอะลูมิเนียม ต่ำกว่า 0.2

เมื่อทำการบันทึกค่าหาความสัมพันธ์ระหว่างอัตราส่วนระหว่างอะตอมของโครเมียมกับอะลูมิเนียม และอัตราส่วนระหว่างอะตอมของแมกนีเซียมกับธาตุเหล็ก และค่าความสัมพันธ์ระหว่างไอออนที่มีประจุบวกสาม ของเศษชิ้นตะกอนของแร่โครเมียมสปิเนล พบว่าสามารถใช้เป็นตัวแบ่งสภาพการเกิดของหินอัลตราเมฟิกที่ดีในการศึกษาครั้งนี้ แร่โครเมียนสปิเนลในหมวดหินน้ำดุกมีค่าองค์ประกอบอยู่ในช่วงของแร่สปิเนลซึ่งพบในหินอัคนีที่มีความสัมพันธ์กับบริเวณที่เปลือกโลกมีการมุดตัว เมื่อวิเคราะห์ถึงรูปร่างของชิ้นตะกอนในบริเวณพื้นที่ศึกษาพบว่า ชิ้นตะกอนเล็กๆ ที่มีรูปร่างกึ่งรูปผลึก ถึงรูปผลึก ซึ่งพบมีมลทินอาจจะบ่งชี้ถึงหินเดิมที่เป็นหินภูเขาไฟ การมีอยู่และลักษณะรูปร่างของชิ้นตะกอนโครเมียมสปิเนลซึ่งพบมากในตะกอนน้ำลึกของหมวดหินน้ำดุก ชี้ถึงการมีอยู่จริงของหินอัลตราเมฟิกและหินเมฟิกในช่วงระหว่างที่มีการสะสมตะกอนของหมวดหินน้ำดุก ผลลัพธ์ที่ได้จากการศึกษาในครั้งนี้ พบว่าสภาพเทคโทนิคของพื้นที่ศึกษามีความสัมพันธ์กับบริเวณที่เปลือกโลกมีการมุดตัวในช่วงยุคเพอร์เมียนตอนกลาง ก่อนที่จะมีการเคลื่อนไหวของเปลือกโลกที่รุนแรงในช่วงเพอร์โมไตรแอสซิก

ภาควิชา ธรณีวิทยา ลายมือชื่อนิสิต ....

สาขาวิชา ธรณีวิทยา ลายมือชื่ออาจารย์ที่ปรึกษา ....

ปีการศึกษา 2542 ลายมือชื่ออาจารย์ที่ปรึกษาร่วม ....

3971672023 :MAJOR GEOLOGY
KEY WORD: DETRITAL CHROMIAN SPINEL / NAM DUK FORMATION / LOM SAK-CHUM PHAE / PHETCHABUN / PERMIAN / SANDSTONE
VICHAI CHUTAKOSITKANON : CHARACTERISTICS OF DETRITAL CHROMIAN SPINELS IN SANDSTONES FROM THE NAM DUK FORMATION, AMPHOE LOM SAK AND AMPHOE NAM NAO, CHANGWAT PHETCHABUN. THESIS ADVISOR : ASSIST. PROF. PUNYA CHARUSIRI, Ph.D. THESIS CO-ADVISOR : ASSOC. PROF. KEN-ICHIRO HISADA, Ph.D. 135 pp. ISBN 974-333-708-3.

Detailed field investigation along the Lom Sak-Chum Phae Highway along km 16.0 to km 42.0 in Phetchabun reveals Nam Duk Formation is subdivided into 6 associated rock units from older to younger, namely lower sandstone-shale alternation, limestone-shale alternation, upper sandstone-shale alternation, shale-sandstone alternation, sandstone-shale-limestone alternation, and shale units. The first three units are located in the west part of the study area and exhibit stronger deformation features and deeper environment than those of the units situated mostly in the east. Along the highway, numerous detrital chromian spinels are discovered as the accessory mineral in lithic graywacke (less than 1 percent) of mostly deep-water facies. Petrographically detrital chromian spinels are generally deep brown to almost opaque in transmitted light corresponding to their Cr-Al-Fe^{3+} substitutions. Their grains vary between 30 and 75 μm in size and some rise to 100 μm across. They are mostly sub-angular to angular. Some of them exhibit sub-hedral to euhedral habits suggesting the preservation of the original crystal shape. Thirty-five grains of detrital spinels were chosen for electron microprobe analysis (EMPA). Characteristically these spinels have relatively high Cr content and relatively vary in TiO_2 content. The atomic ratios Cr/(Cr+Al) or Cr# are almostly above 0.5. The Fe^{3+} values are consistently low. The atomic ratios $Fe^{3+}/(Cr+Al+Fe^{3+})$ in detrital spinels are below 0.2.

Composition plots between the Cr/(Cr+Al) and $Mg/(Mg+Fe^{2+})$ and ternary plots of the major trivalent cations (Cr, Al and Fe^{3+}) for the different chromian spinels, regarded powerful for discriminating mafic to ultramafic rocks of different sources, indicate that the Nam Duk detrital chromian spinels lie within the composition field of the arc-related source rocks. Considering petrographic investigation, the encountered sub-hedral to euhedral-shape spinels with a few inclusions probably suggests volcanic origin. Occurrence and morphology of detrital chromian spinels mostly in the deep-water sediments of the Nam Duk Formation point to the existence of exposed ultramafic-mafic rocks during sedimentation of the Nam Duk Formation. The result reveals that the arc-related tectonic setting may have developed in the region during Middle Permian prior to more violent subduction activity of Permo-Triassic period.

ภาควิชา ธรณีวิทยา	**ลายมือชื่อนิสิต** ......
สาขาวิชา ธรณีวิทยา	**ลายมือชื่ออาจารย์ที่ปรึกษา** ......
ปีการศึกษา 2542	**ลายมือชื่ออาจารย์ที่ปรึกษาร่วม** ......

ACKNOWLEDGEMENTS

The author would like to express his deeply grateful and sincere acknowledgements to his thesis advisors, Assistant Professor Dr. Punya Charusiri and Associate Professor Dr. Ken-ichiro Hisada, for their invaluable supervisions, suggestions, encouragement and contributions, especially their kind-heartedness to make this research well achieved. Greatly sincere acknowledgements to Assistant Professor Dr. Somchai Nakapadungrat and Dr. Pol Chaodamrong for critical reading and suggestions the thesis manuscripts. Deeply sincere gratitude is extended Professor Dr. Shoji Arai, Associate Professor Dr. Katsumi Ueno, Assistant Professor Sompop Vedchakanchana, Assistant Professor Pongsak Phongprayoon, Assistant Professor Veerote Daorerk, and Associate Professor Dr. Visut Pisutha-Arnond, who made the available time to help and suggest him.

The author is highly indebted to Mr. Suvapak Imsamut, Geological Survey Division, Department of Mineral Resources for his generous help and many facilities in field investigation that create this research more convenient. Special recognition and thanks are also due to Archan Montri Choowong and Miss Titima Charoentitirat for their help and suggestions. The help and friendship of Mr. Sone Bhongaraya, Mr. Khamawat Siritheerasas, Mr. Krit Won-in, Miss Shizuka Takashima, Miss Takami Sugiyama and Miss Kiriko Kubo were greatly appreciated. Thank is also made to Miss Wilasinee Kongsumrit for being a good assistant in the field mapping.

The author would specially like to express his sincere thanks to the Institute of the Promotion of Teaching Science and Technology (IPST) for the scholarship of the Development and Promotion of Science and Technology Talents (DPST) during his education in Chulalongkorn University.

Furthermore, the financial support is partly contributed by the research grant of the Graduate School of Chulalongkorn University. Also thanks to the Department of Geology, Faculty of Science for providing all research facilities and some financial support. Several persons whose names can not be entirely listed but concern and assist in this study, are also deeply thanked.

Finally, the author's mother and father, sisters and brothers are thanked sincerely for their moral and financial encouragement for him to get through this difficult and hard research. The author would like to dedicate this thesis to all members of the Chutakositkanon family.

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CHAPTER I

INTRODUCTION

1.1 General statement

Thailand, central part of mainland SE Asia, tectonically comprises two major continental blocks, the Shan-Thai (or Sibumasu) on the west and the Indochina on the east (Fig 1.1). which were completely joined together in the Late Triassic (Bunopas, 1981; Charusiri, 1989; Bunopas and Vella, 1992; Bunopas, 1994; and Metcalfe, 1997). Their continent-continent collision zones called the Nan-Uttaradit suture had, however, been well studied in the type locality. Their suture zone in central Thailand is not easily recognizable since there are not any outcrops of ophiolite remnants available in this region.

During the last three decades, the rather narrow mountain belt that extends along the western edge of the gigantic Khorat Plateau played as a key area for decoding the tectonic evolution of central Mainland SE Asia. Chonglakmani and Sattayarak (1978) first introduced the name of uppermost Paleozoic geosynclinal deposit in this region as the Nam Duk Formation. Later on, this incredible formation has been interesting as the main theme leading a large number of published papers discussing the paleogeography and plate tectonics of SE Asia, especially during 1978-1989. However, tectonic evolution of this region is still questionable. The knowledge derived from previous studies is too a little to provide the exact history of this rather narrow mountain belt and the evolution of suture between the Shan-Thai and the Indochina in the central Mainland SE Asia.

From several geochemical researches, chromian spinel is believed to be one of appropriate indicators in accordance to the physico-chemical conditions of ultramafic-mafic rocks

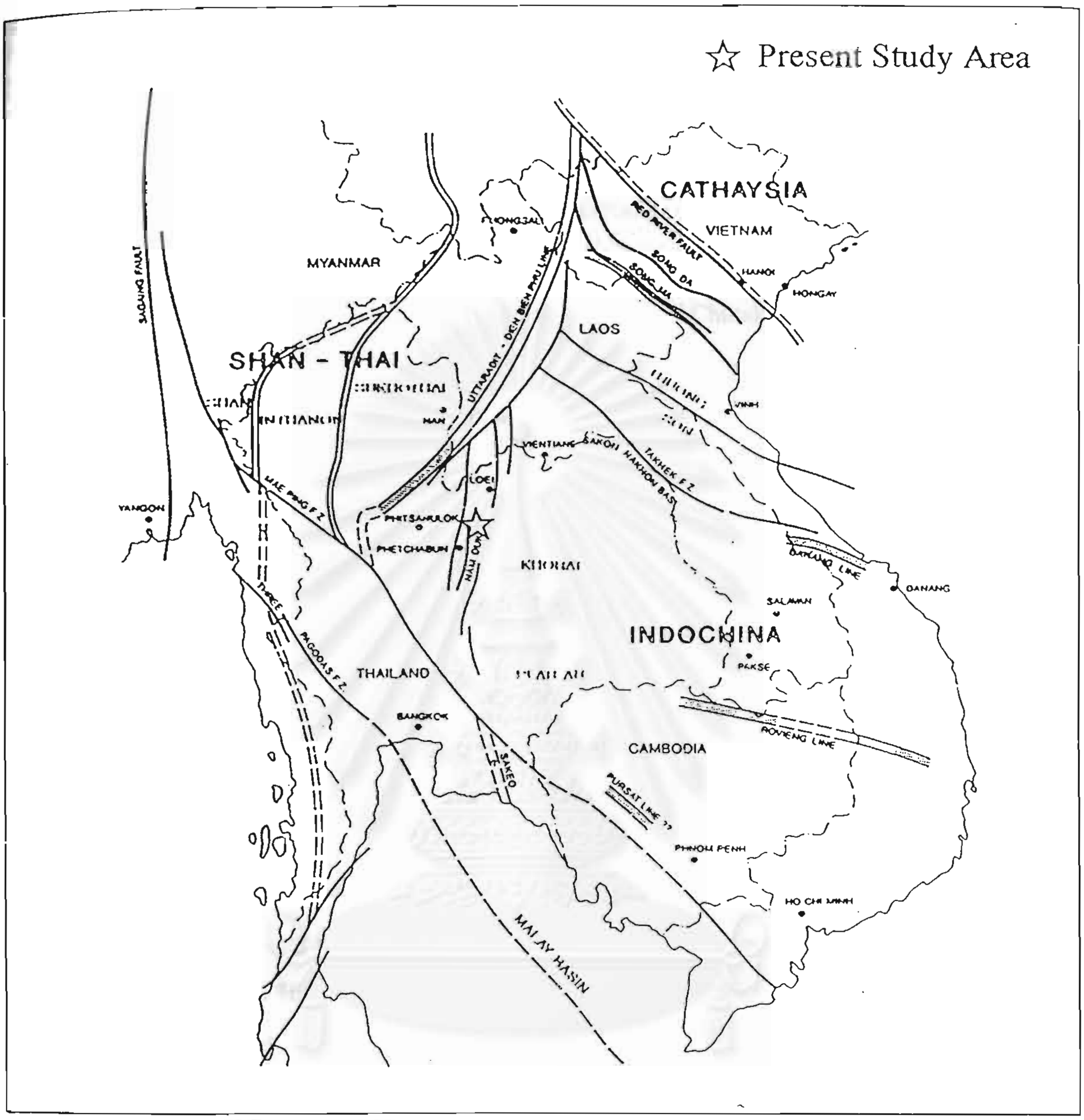

Fig.1.1 Regional geotectonic setting of the study area (Muoret, 1994) show the location of the study area related with the major plate in Southeast Asia

(Irvine, 1965; Dick and Bullen, 1984; Haggerty, 1991). In particular, chromian spinels in volcanic rocks can be the potential discrimination for magma chemistry (Arai, 1992). The recent chemical data accumulation of chromian spinels in ultramafic and mafic rocks expedites the precise comparison between detrital grains in clastic rocks and their parent source rocks. Since then, the determination of tectonic setting by using detrital chromian spinel chemical data has been studied widespreadly during the last decade such as Arai and Okada (1991), Arai and Hisada (1991), Hisada and Arai (1993, 1994), Cookenboo et al. (1997), and Chutakositkanon et al. (1997, 1999a, 1999b). In addition. detrital chromian spinels from the Nam Duk Formation in this study area were first recognized by Dr. Hisada, but without any detailed analysis, both petrographically and chemically.

Regarding to the suture zones between Shan-Thai and Indochina, the so-called Nan-Uttaradit suture (Bunopas, 1981), one of the inferred geosutures (Charusiri et al., 1997), its appearance in this mountain belt was in question (Barr and Macdonald, 1991; Ueno, 1999). In addition, the occurrence of deep-water sediments (Chonglakmani and Sattayarak, 1978) in the study region (north-central Thailand) during Middle Permian or even younger (Chutakositkanon et al., 1997) lead the author to consider that the Nan-Uttaradit suture (northern Thailand) may be very distal for the major site of collision tectonic setting. Therefore a great care has to be taken to explain tectonic setting of the study region. To tackle with this tectonic scenario, the electron microprobe analysis (EMPA) of detrital chromian spinels in sandstones is applied to determine the composition and tectonic provenance of their ultramafic-mafic rocks. (Hisada et al., 1998). This method is quite updated and is expected to be available for elucidating tectonic setting of Thailand as well.

The application of detrital chromian spinel analysis has just been proposed in Thailand for only a few years ago. Studies of detrital chromian spinel here are therefore in an early stage. Hopefully their application will be useful not only for the progress on knowledge of the composition and tectonic setting of the ultramafic-mafic sources of the Nam Duk Formation, but also a key to the geological history of Thailand as well as the conceptual development of geological studies in Thailand as the case study.

1.2 The study area

1.2.1 Location

The study area is located along the Highway 12 (Lom Sak-Chum Phae) between km 16.0 to 21.5 and km 34.0 to 42.0 in part of Amphoe Lom Sak and Amphae Nam Nao, Changwat Phetchabun, north-central Thailand. It comprises geographically 2 sub-areas, western (km 16.0–21.5) (Fig 1.2) and eastern (km 34.0–42.0) parts (Fig 1.3). Both sub-areas are bounded by the latitudes $16^{\circ}43'$N and $16^{\circ}47'$N and the longitudes $101^{\circ}20'$E and $101^{\circ}34'$E. The total area is covered by the 1:250,000-scale, series 1501S topographic map, namely sheet NE 47-16 (Changwat Phetchabun) and the 1:50,000-scale, series L7017 topographic maps, namely sheet 5242 I (Ban Tha Chang), sheet 5242 II (Ban Nam Duk Nua), sheet 5342 III (Ban Plaek) and sheet 5342 IV (Amphoe Nam Nao), of the Royal Thai Survey Department (RTSD).

1.2.2 Accessibility

The study area (along the Route 12, Lom Sak-Chum Phae Highway), east of Lom Sak township, is about 410 kilometers north of Bangkok. The most convenient route to the study area is using the Highway 1 (Paholyothin) from Bangkok via Saraburi and then joining and following the Highway 21 to Chai Badan, Si Thep, Bung Sam Phan, Nong Phai and Phetchabun. The area is about 50 kilometers far to the north of Phetchabun township, whenever travelling by car, it needs to turn right at the joined junction and follows the Highway 12 about 16 kilometers to get there.

The topography of the study area is generally very steep and rugged mountain range with the average elevation of 600-900 meters above the mean sea level. Most of study area is covered by dense subtropical vegetation with bushes and high trees. Therefore, it is difficult to enter and reach the exposures.

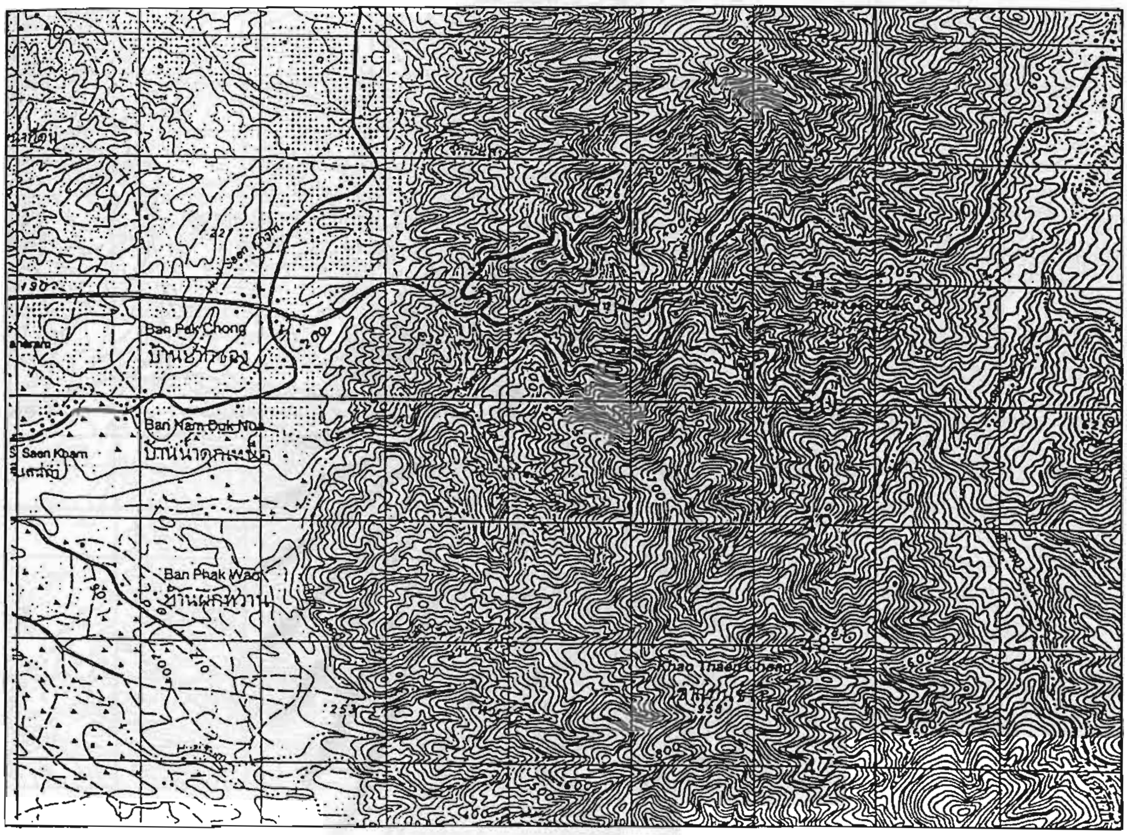

Fig.1.2 The topographic map showing the Highway 12 and the study area in the western part of Nam Duk Formation

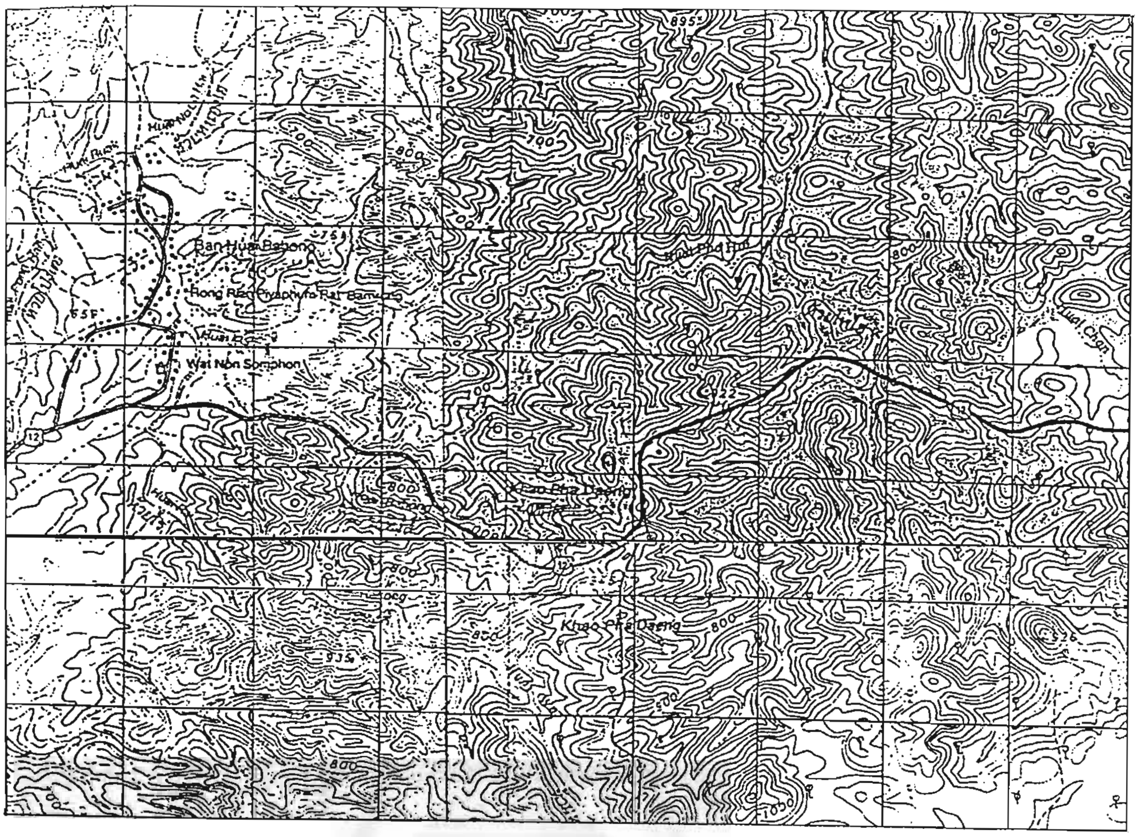

Fig.1.3 The topographic map showing the Highway 12 and the study area in the eastern part of Nam Duk Formation

The Highway 12 represents the only route that passes through the lithologic sequences of Nam Duk Formation. Both sides of this road cuts show properly excellent exposures for geological studies although other exposure may consider that the other candidate for the type locality is the exposure that follows the Huai Nam Duk stream (D. Helmcke and C. Chonglakmani, per. comm.).

1.3 Objectives

The Phetchabun region is of interest in term of tectonic setting of Thailand since the complex region called Phetchabun Fold and Thrust Belt (PFTB) has been mentioned (Wielchowsky and Young, 1985; Altermann, 1989). Although some geologic and paleontological data from previous studies on this complicated belt exist, there are seemingly very few details available to clarify tectonic evolution. Therefore, the detailed studies of the geology, stratigraphy, petrology and tectonic setting of the Nam Duk Formation, most closely related to the unit with the Shan-Thai and Indochina collision, is critically required in central Thailand.

The purposes of this investigation, with the emphasis on detrital chromian spinels along the Highway 12, Lom Sak-Chum Phae, are:

(1) To study the geology and stratigraphy of the Nam Duk Formation;
(2) To study the appearance, distribution, morphology and composition of detrital chromian spinels in sandstones;
(3) To determine chemical compositions and provenance of possible parent rocks of detrital chromian spinels; and
(4) To serve as a case study for future studies of detrital chromian spinels.

1.4 General approach and research methodology

The endeavors at interpretation of sediments are generally directed toward reconstruction of the environment of deposition at a particular time and place. Broad arrays of techniques of the sandstone provenance studies conceptually fall into three approaches. Firstly, the basic detailed stratigraphic studies on the related strata and field mapping. The second is involving characterization of the bulk composition of the sandstone, typically by point-count determination of modes for detrital framework grains (Dickinson and Suczex, 1979; Dickinson et al., 1983; Lash, 1985). Lastly the third approach is to quantifying characteristics of a single-mineral analysis to increase confidence in provenance interpretation and simultaneously add the detail unavailable from the first and second approaches (Basu et al., 1975; Trevana and Nash, 1981; Cookenboo et al., 1997).

Detrital chromian spinel studies, a single-mineral analysis, are applied to determine tectonic setting of the source. In addition, the electron probe microanalysis of detrital chromian spinels in the sandstone is used to supply the basic geological studies of this research. Detailed studies of basic geological approach and geochemistry of the detrital chromian spinels are desirable in order to evaluate geological processes for tectonic evolution along the collision zone.

In order to fulfill the objectives and scopes of the study, the method of investigation (Fig. 1.4) has been systematically performed as explained below:

(1) The first stage involves the literature review of theories and related case studies of basic geology and chromian spinel studies together with the review of geological setting of the study area from previous investigations. Detailed field and laboratory studies have been subsequently formulated and carried out.

(2) The second stage is the detailed field investigation includes the geological mapping and collecting proper samples for further investigation in the laboratory of the Nam Duk Formation (Chonglakmani and Sattayarak, 1978; Helmcke and Kraikhong, 1982; Helmcke et al., 1985). The rock distribution along the Highway 12 is described and measured. Each geological section is examined and measured in detail for the available lithostratigraphy of the rock units.

(3) The third stage commences with laboratory investigation. The sedimentary structures, textures, and compositions have been studied by petrographic techniques.

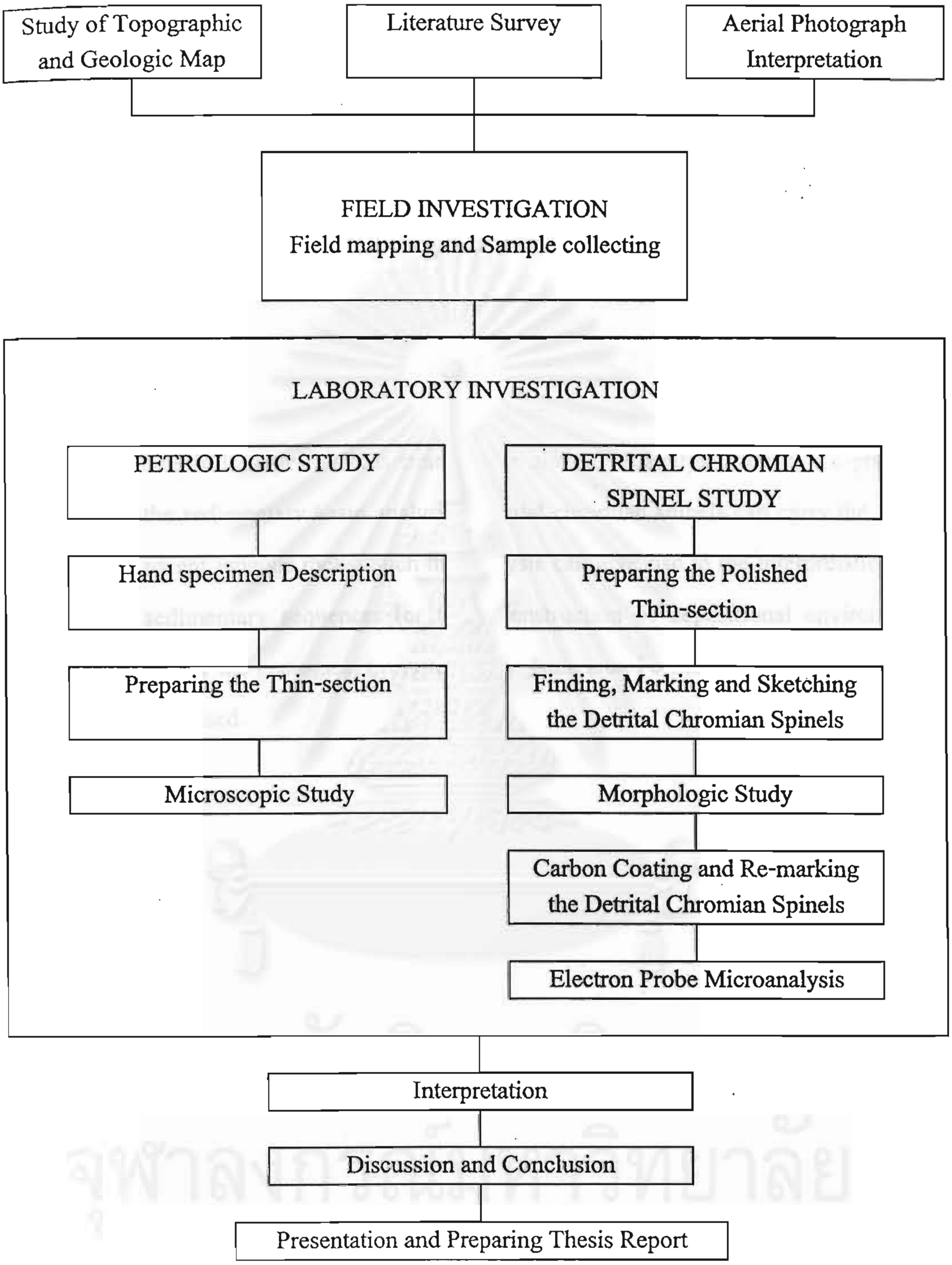

Fig. 1.4 Flow chart of method of investigation performed in this study

Subsequently, the appearance, distribution, morphology and composition of detrital chromain spinels usually found in sandstones are petrographically identified, and later on are geochemically analyzed. The quantitative major element analysis of detrital chromian spinels is carried out by the Electron Probe Microanalysis (EPMA) at the Chemical Analysis Center, the University of Tsukuba, Japan.

(4) The forth stage is to prepare and to manipulate all the geological and geochemical data obtained from the previous stages in such a manner that they can be appropriately utilized for lithostratigraphic and facies analyses. Numerous graphic representations are finally prepared, notably geological map, detrital chromian spinel distribution-map, geological sections, and road-cut profiles along the route.

(5) The fifth stage involves stratigraphic and facies analysis which is a prerequisite of the sedimentary basin analysis. Detrital chromian spinels can carry the data of their parent igneous rocks. Such the analysis can give rise to the interpretation of ancient sedimentary sequences (or the reconstruction of depositional environment). And finally the geological evolution of the Nam Duk Formation has been synthesized and proposed.

CHAPTER II

REGIONAL GEOLOGY

2.1 General statement

To fully understand the geological setting of the study area, it is considered that regional geology of the area should be familiarized as well. The Upper Paleozoic rock in the present study area are in the approximately north-south trending, steep and rugged mountain range which extents southward at least 400 km from central Laos (Workman, 1975; Lovatt Smith et al., 1996), across Mekhong River into Loei, northeast Thailand, and follows the western border of the Mesozoic Khorat Plateau. The study area itself lies within the central part of Phetchabun Fold and Thrust Belt or PFTB (Wielchowsky and Young, 1985; Altermann, 1989, 1991) (Fig. 2.1). As stated by Altermann (1989), this complex belt plays as the topical subject decoding the paleogeography and tectonic evolution of Thailand.

Creditably Chonglakmani and Sattayarak (1978) discovered and mentioned a complex Permian sequence of Nam Duk Formation. The Nam Duk Formation was deliberately proposed to distinguish these deformed clastic geosynclinal deposits from the more calcareous sequences of the same age. Their description was the first article of geosynclinal sediments of Permian age in Thailand and the whole of Southeast Asia which brought a lot of studies into being such as Helmcke and Kraikhong (1982), Helmcke and Lindenberg (1983), Helmcke et al. (1985), Wielchowsky and Young (1985), Altermann (1983, 1989, 1991), Chutakositkanon et al. (1997, 1999a, 1999b) and Hisada et al. (1998).

Perhaps the most acceptable geological and stratigraphical work which covers the regional area of this study pointing at the rock units, is that of Chonglakmani and Sattayarak

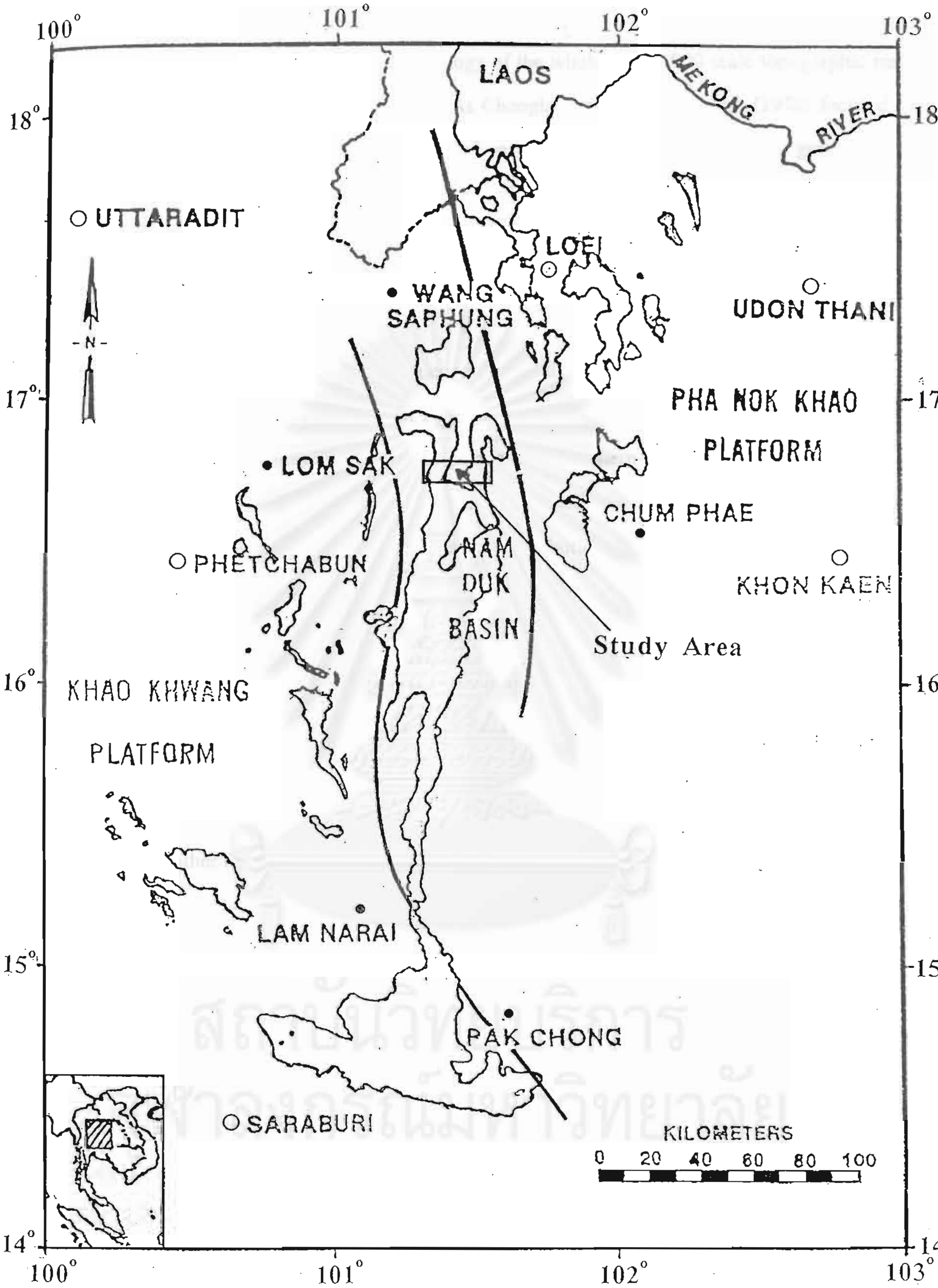

Fig. 2.1 The paleogeography of the Upper Paleozoic rocks in The Phetchabun fold and thrust Belt (Wielchowsky and Young, 1985).

(1984) who systematically compiled the geology of the whole 1: 250,000 scale topographic map sheet of NE 47-16 (Changwat Phetchabun). As Chonglakmani and Sattayarak (1978) focused to the Huai Hin Lat Formation, which is regarded on the oldest formation in Khorat group in this region; this work described in general detail on the lithology, stratigraphy and geological structure of the regional geology of the area.

Based on the Upper Paleozoic rocks, Wielchowsky and Young (1985) directed a series of reconnaissance field studies of upper Paleozoic units that crop out in the PFTB. Their studies focused on regional facies variations in Permian rocks in this fold and thrust belt. Three Early through Middle Permian paleogeographic provinces, a western carbonate platform, a central mixed siliciclastic-carbonate basin, and an eastern mixed carbonate siliciclastic platform, are established based on both the lateral and vertical distribution of facies in the area of the PFTB. They proposed the name Khao Khwang platform, Nam Duk basin, and Pha Nok Khao platform for these provinces, respectively. Both carbonate platforms separated by a siliciclastic-carbonate basin were present during the Early Permian and early Middle Permian. However siliciclastics were periodically shed onto the Pha Nok Khao platform from at least one bordering landmass causing temporary cessation of carbonate deposition. By insignificant thickness of terrigenous clastics on the Khao Khwang platform, the Nam Duk basin was suggested as a barrier to clastic influx from other high areas to the east on the Pha Nok Khao platform (Wielchowsky and Young, 1985). Probably it was no other emergent source areas nearby to the north, west, or south of the Khao Khwang platform.

2.2 Stratigraphy

Chonglakmani and Sattayarak (1978, 1984) previously studied regional geology of the study area. An attempt had been made hereto compile the geological map of Phetchabun region (Fig. 2.2). Generally the study and neighboring areas are covered by Upper Paleozoic marine deposits and Mesozoic Khorat continental sedimentary rocks. Tertiary sediment as well as Quaternary alluvial deposits are spread throughout the Phetchabun intermontane basin (Remus et

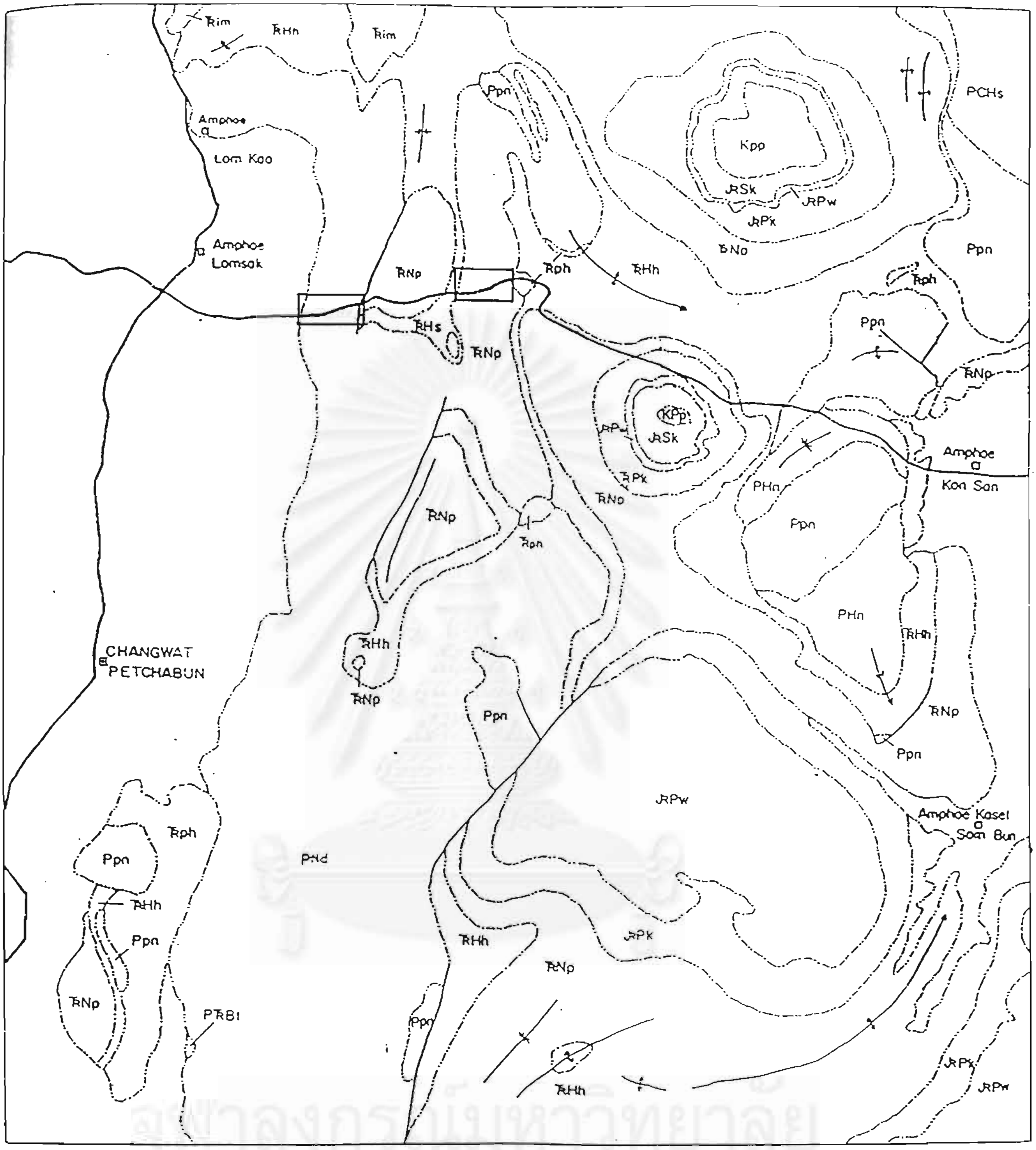

Fig. 2.2 Geological map of the study area and the vicinity showing the locations of the study area (inserted blocks) and the distribution of rock types in this region (Chonglakmani and Sattayarak, 1978)

		Member	Formation	Group		Age
Qa	Alluvial deposit					QUATERNARY
Qt	Terrace gravel, Talus, Colluvial deposit					
	UNCONFORMITY					
KPp	Sandstone, white, pale orange, pebbly, pebbles of quartz, chert and red siltstone, sandstone, white, cross-bedded, with some shale and conglomerate beds.		PHU PHAN			LOWER-MIDDLE CRETACEOUS
JSk	Sandstone, reddish brown, micaceous siltstone, gray, brown, reddish brown, lime-noduled conglomerate shale, purplish brown, brick red.		SAO KHUA			MIDDLE-UPPER JURASSIC
JPw	Sandstone, white, pink, orthoquartzite, cross-bedded, massive, pebble layering in the upper bed with some reddish brown and gray shale.		PHRA WIHAN			LOWER-MIDDLE JURASSIC
JPk	Shale, brown, reddish brown, purplish red, micaceous siltstone, sandstone, brown, gray, micaceous, cross-bedded with some lime-noduled conglomerate.		PHU KRADUNG	KHORAT		LOWER JURASSIC
TRNo	Sandstone, reddish brown, brown, cross bedded, laminated conglomerate, pebbles of red siltstone, quartz, quartzite, chert with brown to reddish brown shale and siltstone.		NAM PHONG		RHAETIAN	TRIASSIC
TRim	Shale, sandstone, limestone, gray diorite, tuff and agglomerate.	I MO				
TRhh	Basal conglomerate, sandstone, gray, reddish brown, shale, gray to black, reddish brown, calcareous, limestone, agillaceous.		HUAI HIN LAT		CARNIAN-NORIAN	
TRph	Tuff, agglomerate, rhyolite andesite. With some sandstone and conglomerate beds.	PHO HAI				
	UNCONFORMITY					
PNd	Shale, gray to black Sandstone, yellowish brown, fine-grained, limestone, lense and bedded. Highly disturbant.		NAM DUK			LOWER-MIDDLE PERMIAN
PHn	Shale, gray, sandstone, yellowish brown, limestone, lense and bedded.		HUA NA KHAM	RATBURI		
Ppn	Limestone, gray, massive, chert, black, noduled or thin bedded, with some shale.		PHA NOK KHAO			
PCHs	Sandstone, shale, gray, yellowish brown, chert, black, red, milky, pink, bandded to massive, limestone, gray, thick bedded.		HUAI SOM			LOWER PERMIAN-CARBONIFEROUS
	IGNEOUS ROCKS					
PTRbt	Diorite, andesite, stock, dyke.		BO THAI INTRUSIVES			PERMO-TRIASSIC

SYMBOLS

Fault

Anticline

Syncline

☐ Present Study Area

al., 1993). The sedimentary rocks are herein documented in the order of ages from the oldest to the youngest below.

2.2.1 Upper Paleozoic

Geographically the Phetchabun area is dominated by a series of parallel mountain chains an approximate north-south trend. These mountain trends are characteristics of Upper Paleozoic rocks of the PFTB (Wielchowsky and Young, 1985). The strata exposed on this belt were classified into five units namely Dok Du, Huai Som, Pha Nok Khao, Hua Na Kham and Nam Duk Formations in ascending order (Chonglakmani and Sattayarak, 1984).

The Dok Du Formation consists of the Lower to Middle Carboniferous chert with massive limestone, sandstone and shale. The next younger Huai Som Formation is proposed by Chonglakmani and Sattayarak (1978, 1984). The lithology of this formation is characterized by dark gray shale, sandstone and conglomerate with limestone and nodular chert. The age of this formation from previous works is considered to be Upper Carboniferous on stratigraphic position.

The Permian rocks in the regional area are recognized as the majority of the PFTB. The Pha Nok Khao Formation mainly consists of less deformed massive fossiliferous limestone with subordinate bedded chert and nodular chert. These strata are interpreted as a carbonate shelf facies. From the faunal evidence the age of this formation ranges from Lower to Middle Permian. The Younger Hua Na Kham Formation is more clastic. This unit comprises dominantly grey shale, sandstone, and bedded and lenticular limestone of Middle Permian. Rocks of both the Pha Nok Khao and the Hua Na Kham Formations are distributed in the eastern part of the regional area under consideration. On the other hand, the Nam Duk Formation extends as the north-south trending belt passing the western part. Its lithology is characterized by shale, sandstone and well-bedded limestone. Age of the Nam Duk Formation is proposed as the Middle Permian (Chonglakmani and Sattayarak, 1984) as well as the Lower to Middle Permian (Chonglakmani and Sattyarak, 1978; Helmcke and Kraikhong, 1982; Helmcke and Lindenberg, 1983; Helmcke, 1983; Winkel et al., 1983; Helmcke et al., 1985; Altermann, 1989).

2.2.2 Mesozoic

Mesozoic rocks are dominantly fluviatile, deltaic and lacustrine sediments. They have been grouped into the Khorat Group (Ward and Bunnag, 1964; Iwai et al., 1966), of which its structure is characterized by mesa, plateau and cuesta forming broad simple synclinal and anticlinal structures. Based on the Lexicon of Stratigraphic Names of Thailand (1992), the Khorat Group is classified into eight formal formations as Huai Hin Lat, Nam Phong, Phu Kradung, Phra Wihan, Sao Khua, Phu Phan, Khok Kruat and Mahasarakham Formations in the ascending order ranging from Upper Triassic to Cretaceous (Fig. 2.3).

Huai Hin Lat Formation

Huai Hin Lat Formation was first recognized by Iwai et al. (1966) as the basal conglomerate of Khorat Group. It lies unconformably on the Permian limestone. The unit consists of dark gray to black shale, sandstone and limestone including limestone conglomerate at the base. This Formation ranges in age from Carnian to Norian (Upper Triassic).

Nam Phong Formation

Nam Phong Formation consists of a sequence of siltstone, sandstone and conglomerate (Ward and Bunnag, 1964). The siltstones are soft, reddish gray to pale red, and make up approximately 70% of the formation. The sandstones are conglomeratic, medium-to fine-grained and fine-to very fine-grained, pale red to pale yellowish-brown, thick bedded, well-cemented to friable and slightly calcareous. The conglomerates contain pebble of quartz, chert and siltstone. The Formation conformably overlies the Huai Hin Lat Formation and underlies the Phu Kradung Formation. The Nam Phong Formation is considered as the Rhaetian (Upper Triassic).

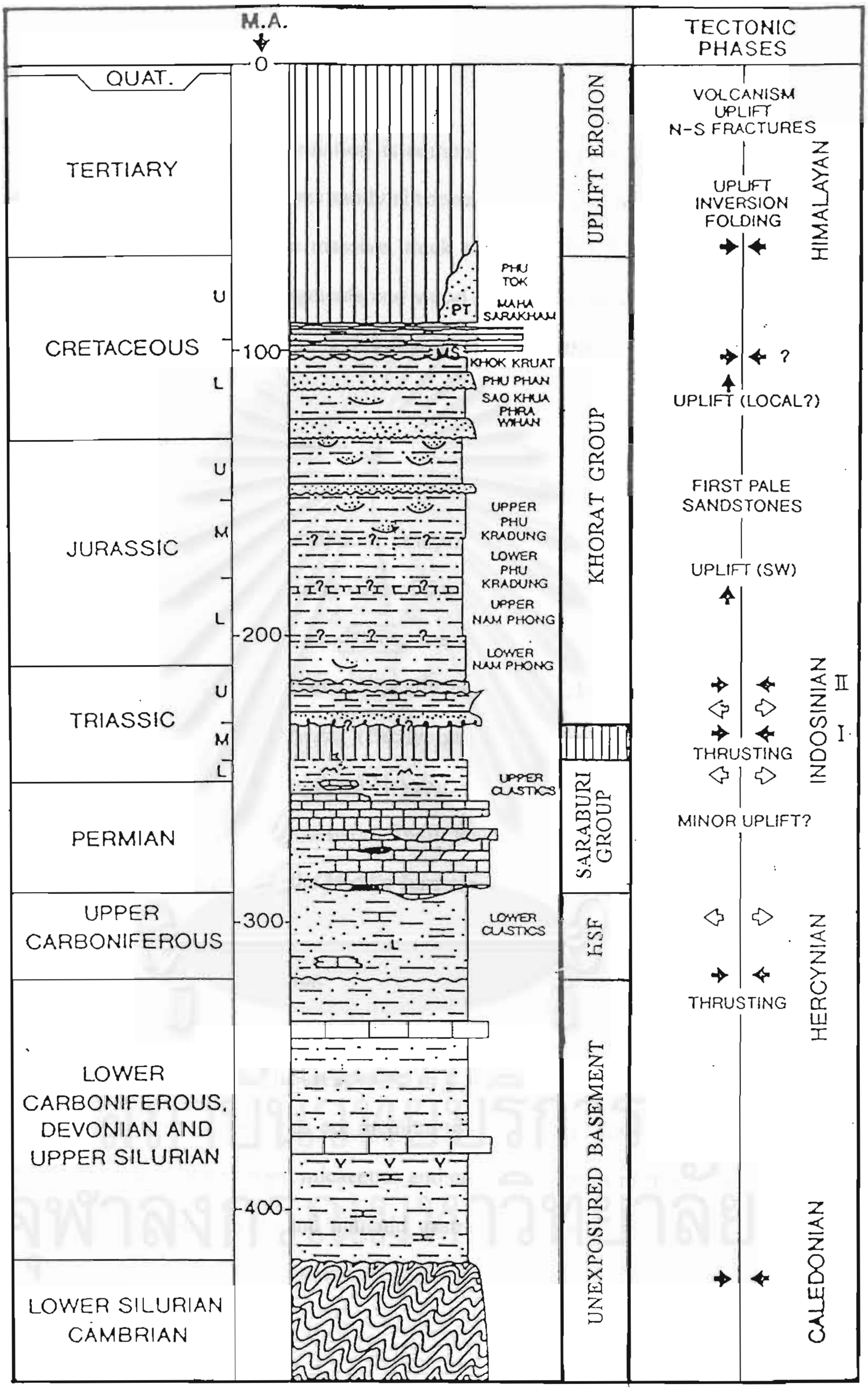

Fig. 2.3 The stratigraphy of the western border of Khorat Plateau

Phu Kradung Formation

Phu Kradung Formation is composed of purplish gray to reddish gray fine-to coarse-grained sandstone, micaceous sandy siltstone and siltstone (Ward and Bunnag, 1964; Iwai et al., 1966). The sandstones are massive, thick to flaggy bedded, and cross-laminated. This formation yield silicified bone fragments and wood stems. The only identified fossil is a striated tooth, which belongs to a plesiosaur. It is probably referred to the Lower Jurassic in age.

Phra Wihan Formation

Phra Wihan Formation comprises resistant sandstones with interbedded siltstones that cap the boundary escarpments of the Khorat plateau (Ward and Bunnag, 1964; Iwai et al., 1966). Characteristically the sandstones are white-coloured, quartzose, conglomeratic with small pebbles of quartz and gray cherts. The siltstones are reddish gray. This formation contains molluscan fossils identified as *Mytilus* (Pachymytilus?) *rectangularis* Kobayashi and Hayami, and *Cardinioides magnus* Kobayashi and Hayami, a tooth of Ichtyosauria, a naticoid gastropod, fragments of silicfied bone, and contain fossil leaves identified as *Brachyphyllum* sp. And *Sphenopteris* sp. The age given is the Middle Jurassic.

Sao Khua Formation

Sao Khua Formation consists of a sequence of siltstones and sandstones (Ward and Bunnag, 1964). The sandstones are medium-to very fine-grained, well cemented to friable, thick bedded to flaggy, calcareous, micaceous and conglomeratic with fragments of siltstones and shales. The unit contains shells and naticoid gastropod, thick-shelled pelecypods, ichthyosaur tooth and bone fragments. These fossils are considered to be Upper Jurassic in age.

Phu Phan Formation

Phu Phan Formation comprises sandstones and conglomerates (Ward and Bunnag, 1964; Iwai et al., 1966). Most of the sandstone are orthoquartzites, white gray, gray, very coarse-to fine-grained, generally well sorted, massive, thick and flaggy bedded, and cross bedded. The conglomerates are mainly composed of well-rounded granules to small pebbles of clear, white and light pink quartz, locally with minor amounts of white to pink feldspar and chert. The age of the Phu Phan Formation is given as Lower Cretaceous.

Khok Kruat Formation

Khok Kruat Formation consists of a section of siltstones and sandstones with thin characteristic beds of gypsum in the upper part (Ward and Bunnag, 1964). The sandstones are pale red to reddish brown, thick bedded to flaggy, cross-bedded, friable, medium-to very fine-grained, conglomeratic with pebbles of siltstone. The siltstones are frequently soft, slightly mottled, streaked, or spotted light, greenish gray, calcareous and micaceous. Both sandstones and siltstones form the main part of the formation. Its age is referred to the Upper Cretaceous in age.

2.2.3 Cenozoic

Generally the Cenozoic rocks in the regional area are deposited in the Phetchabun intermontane basin (Remus et al., 1993) located in the westernmost part. The basin is a composite of several north-south trending half and full graben. Sedimentation commenced in the Late Oligocene with syn-rift fluvial deposits and associated rift volcanics. Overlying the initial rift deposits is a Late Oligocene to Middle Miocene sedimentary sequence of dark, organic-rich fluvial and lacustrine deposits. Unconformity reflecting period of regional tectonism in the Middle Miocene is characterized by a change in palynological assemblages, from a diverse tropical swamp and forest flora throughout the Early and Middle Miocene to a temperate/montane flora in the Late Miocene. Lacustrine conditions were re-established following the Mid- Miocene event and persisted until the Pliocene. After that the basin was replaced by oxidizing fluvial/alluvial sediments during the Pliocene to Pleistocene.

2.3 Ancient volcanic rocks in the Loei-Phetchabun volcanic belt

Volcanic rocks, especially mafic volcanic rocks, are particularly useful for tectonic terrane analysis. Their petrology and chemical characters can be related to tectonic provenance. The study area is totally covered in the Phetchabun Volcanic belt (Barr and Macdonald, 1991) or the Loei-Phetchabun volcanic belt (Intasopa, 1993; Intasopa et al., 1994), which extends from Loei through Phetchabun, Lop Buri and Chantaburi (Fig. 2.4). This Loei-Phetchabun volcanic belt (LPVB) have been interpreted to be Permo-Triasic in age and to form above an eastward dipping subduction zone (Bunopas, 1981). From the recently Sr isotopic ages, the Loei volcanic province in the northern part of this volcanic belt (Intasopa, 1993), it provide convincing evidence that the volcanism in the northern LPVB extended from Devonian to Permo-Triassic (Fig. 2.5). The volcanic rocks are Devonian rhyolite, Middle Devonian-Lower Carboniferous basalt and Permo-Triassic andesite in Loei (Intasopa, 1993; Intasopa and Dunn, 1994).

The volcanic rocks in the Loei volcanic province are distributed in three nearly north-south belts along the eastern, western and central parts of the Loei area, corresponding with their lithology, provenance and ages. The oldest volcanic rocks in the east of Loei area are mostly rhyolites and associated pyroclastic rock. The resulting Rb-Sr isochron age is 374±33 Ma for these rhyolites (Intasopa, 1993). The geochemical signature of the rhyolites strongly suggests that the rhyolites were derived by partial melting of continental crust (Intasopa, 1993). The second volcanic rocks are in the central part of Loei area. They form as a narrow north-south trend of massive basalts and pillow lavas. Fossils associated with these pillows and associated tuffs that the basaltic magmas erupted in the marine environments. Intasopa (1993) reported that the isochron age of these basalts is 361±11 Ma. This age is Upper Devonian and is very similar to the age determined from guide fossils and the stratigraphic correlation age. The geochemical data for Loei basalts indicate that they are ocean floor tholeiites that represent magma generated at a spreading center in the ocean basin. The enrichment in radiogenetic Sr and the isotopic variability

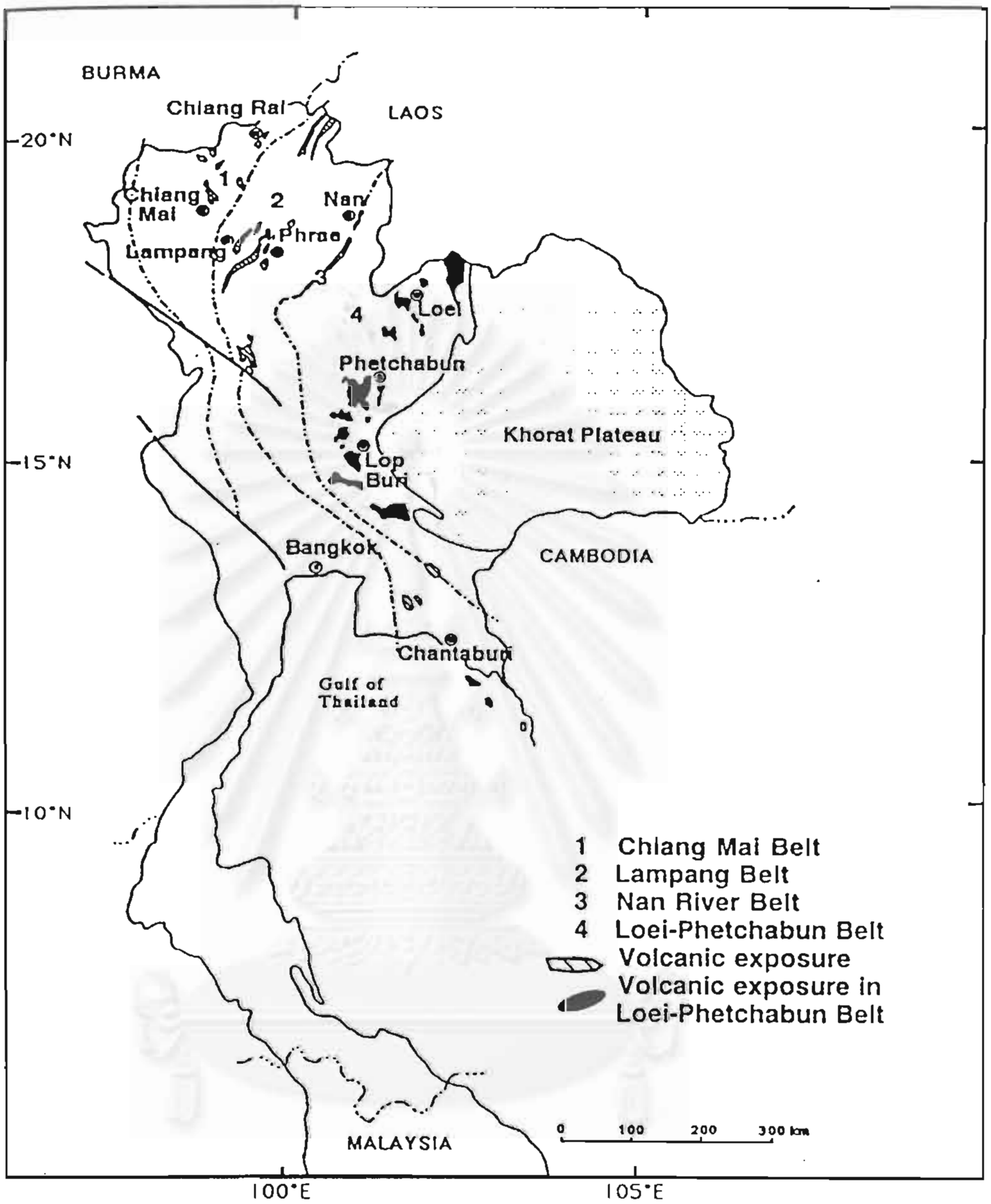

Fig. 2.4 The distribution of volcanic belts in Thailand. The Loei-Phetchabun volcanic belt is referred to as the Central Thailand volcanic belt (Intrasopa and Dunn, 1990).

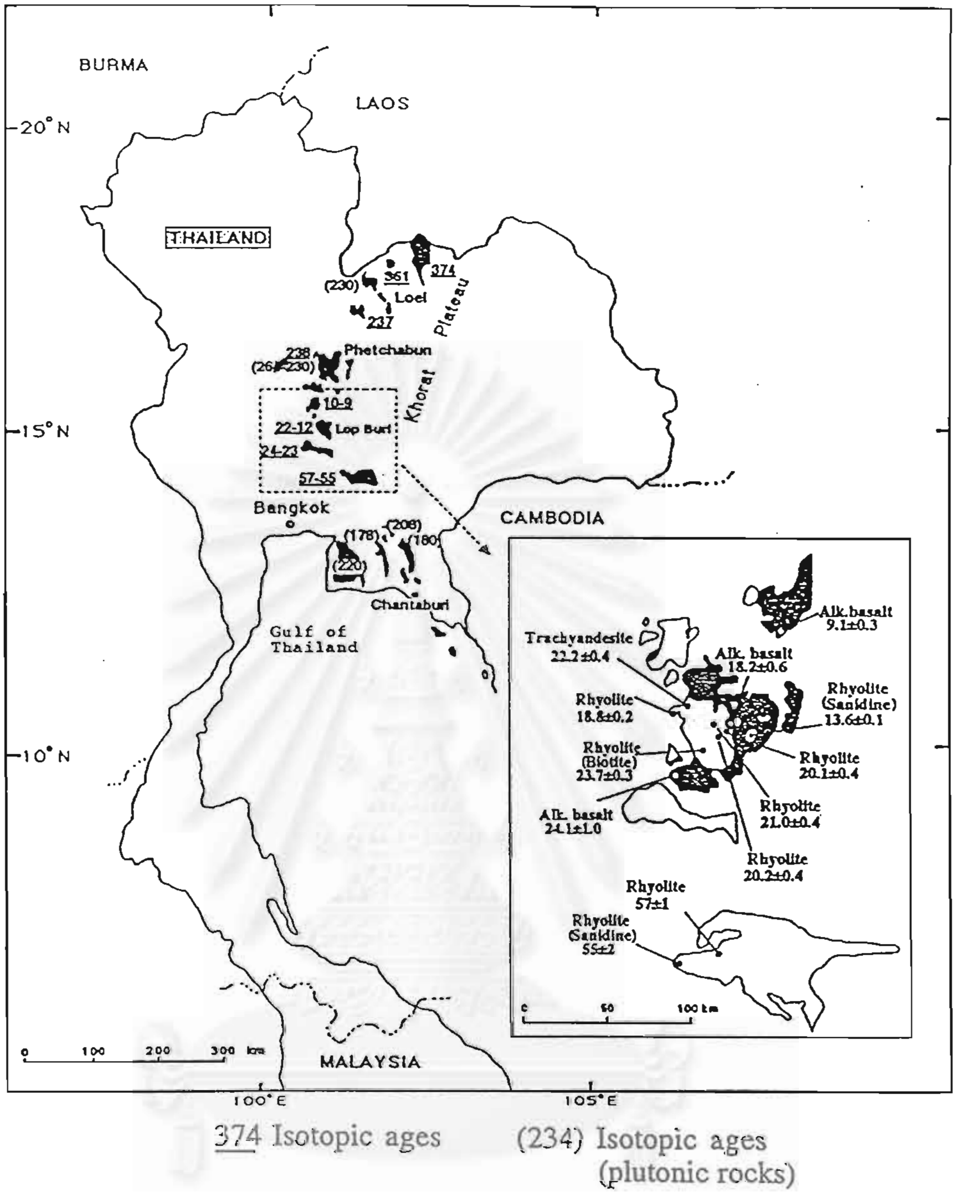

Fig. 2.5 Distribution and isotopic ages of the volcanic rock along the Central Thailand Volcanic Belt (Intasopa, 1993)

of the basalt could be explained by heterogeneity of the mantle source. The youngest volcanic rocks in Loei are the predominantly andesitic and dacitic volcanic rocks in the western region. Stratigraphically they are underlain by upper Permian sedimentary rock and are overlain unconformable by the Jurassic-Cretaceous non-marine clastic rocks of is approximately Triassic (Intasopa, 1993) or Permo-Triassic (Bunopas, 1981).

It is valuable to note that Intasopa (1993, 1995), and Intasopa and Dunn (1994) suggested two magmatic episodes at approximately 374±33 Ma and 361±11 Ma in the northern part of the LPVB. The volcanic rocks in the LPVB are not part of a contemporaneous volcanic arc as was previously thought.

CHAPTER III

GEOLOGICAL SETTING OF THE NAM DUK FORMATION

3.1 Previous works-Geological setting

The geological setting of the sedimentary rocks along the Highway 12 (Lom Sak-Chum Phae) between km 16.0 to 21.5 and km 34.0 to 42.0 in Changwat Phetchabun, north-central Thailand were reported previously by several authors. Because this area contains a variety of rock basements, tectonism, and geological setting in this area becomes significantly important. At the moment, geological features in this area show particular evidences to use as a key area for solving the geological history of Thailand during the Permian time.

Chonglakmani and Sattayarak (1978) first recognized a complex marine sequence exposed along the Highway 12. The name Nam Duk Formation was intentionally proposed to define these high-deformed geosynclinal deposits from the more calcareous units that were interpreted as shelf deposits of the same age. The Nam Duk Formation became the first Permian geosynclinal sediment mentioned in Thailand and SE Asia. The description, since then, brought a large number of subsequent and further detailed studies.

Special attention was paid to the studies of Helmcke and his co-workers (see Helmcke and Kraikhong, 1982; Helmcke and Lindenberg, 1983; Helmcke, 1983, 1984) who published various pioneer papers containing descriptions of lithology, stratigraphy and tectonics of the Nam Duk Formation. Then several authors (Altermann. 1983, 1989; Winkel et al., 1983) in the German-Thai team re-studied the Nam Duk Formation along the Highway 12 in detail and largely confirmed the results of Helmcke and his co-authors.

Helmcke and his co-authors (Helmcke and Kraikhong, 1982; Helmcke and Lindenberg, 1983; Helmcke, 1983, 1984) pioneerly studied the Nam Duk Formation along the Highway 12. They suggested that the Nam Duk Formation formed during Permian orogenic sequence of pelagic sediments, flyschs, and molasses (Fig. 3.1). It is interesting to note that the term Nam Duk Formation of Chonglakmani and Sattayarak (1978) was generally eluded to mention in their papers. With the variety of sedimentary environments, the Nam Duk Formation possibly seeks to be different and less defined for the entire Permian successions along the Highway 12 between km 16.0 to 42.0 in the Phetchabun region.

The oldest pelagic sediment unit exposed only in the western part contains mainly cherts, shales and allodapic limestones. Generally cherts are banded and varied in colors. Typical shales in this unit reveal gray to greenish gray in colors. Allodapic limestones are proposed to have originated by turbidity current in near-reef sedimentary basins. The age of this unit was limited by the poor-and ill-preserved allochthonous fusulinid fauna. It referred either as Early Permian to early Middle Permian (Helmcke, 1983) or early Early Permian to late Middle Permian (Helmcke, 1984).

Typical flysch-type sediments represent the second unit. This graywacke/shale alternating sequence displays all the characteristics of Bouma-cycle (Fig. 3.2), distinguishing them as turbidites. Judging from the bottom-marks, the direction of transportation could be parallel to the N-S strike direction of the mountain chains. This sequence was interpreted as syn-orogenic sediments based on its sedimentary facies and thickness. The age of strata was given as Middle Permian on the basic of the appearance of *Agathiceras* sp. (Helmcke, 1984).

The third unit of rocks comprises a very thick sequence of clastic rocks. Sandstones and shales are dominant. In the upper part of this succession, intercalations of autochthonous limestone beds are investigated. Usually these limestones are fossiliferous. They are generally rich in foraminifers and sometimes contain corals. Towards the east the limestone intercalation becomes thicker and more prominent. Large specimens of the genus *Pseudodoliolina* sp. occur together with *Schwagerina* sp. and very rare fragment of *Sumatrina* sp. are the majority of fossil

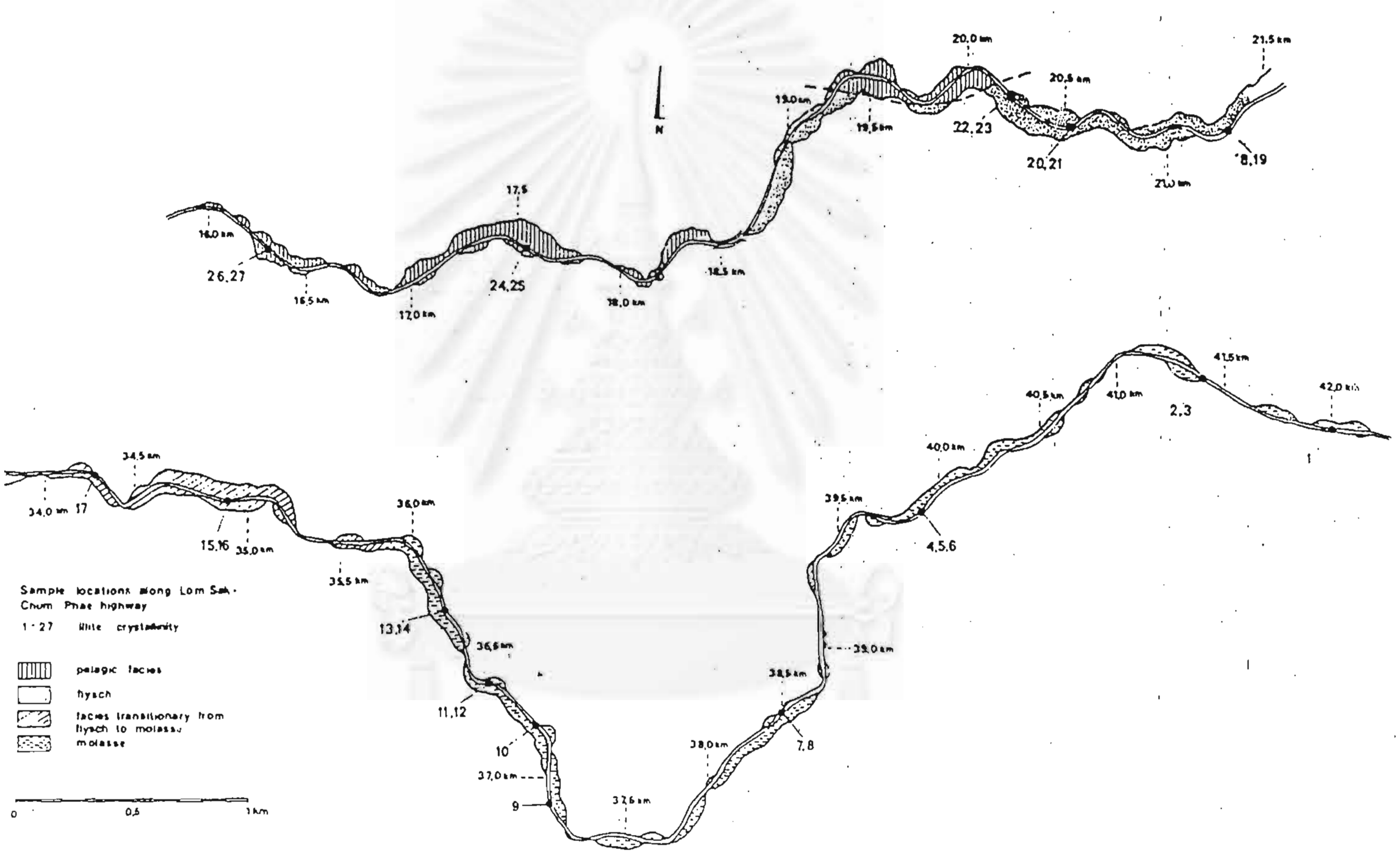

Fig. 3.1 Permain orogenic sequence of palegic sediment, flyschs and molasses along the Highway 12.

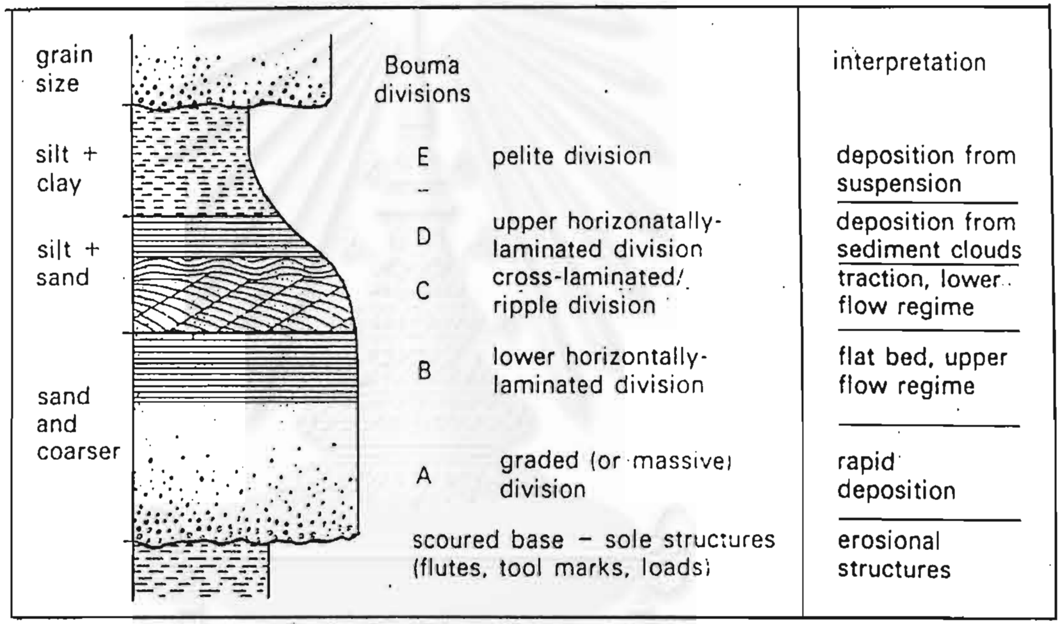

Fig. 3.2 The characteristics of Bouma-cycle (Bouma, 1962).

fauna in this unit. The smaller foraminifera, *Tetrataxis* sp. is the most conspicuous among a number of Endothyranid genera. On the other hand, some limestone layers contain a different fauna with a large *Verbeekina* sp. associated with rare *Pseudodoliolina* sp. and *Schwagerina* sp. These faunas can be assigned to a late Middle Permian to early Late Permian (Helmcke, 1984). Both lines of sedimentary and paleontological evidence suggest this unit deposited in shallow marine environment. A typical molasse-type sucession was proposed corresponding with pelagic sediments and flysical-type sediments.

Both paleontological and lithological features in this area allowed explaining the tectonic evolution of central Mainland SE Asia. The pelagic sediments of Lower Permian age in this area were recommended as the pre-orogenic phase. The presence of the flysch sedimentation indicated a sudden onset of orogenic activity probably occurred during the Middle Permian. In late Middle Permian the main orogenic phase stagnated and passed into a molasse basin in the post-orogenic phase.

Winkel et al. (1983) re-interpreted the pelagic sediments of the Nam Duk Formation along the Highway Lom Sak-Chum Phae. They performed a detailed sedimentological work on the pelagic phase based upon the works of Helmcke and Kraikhong (1982), and Helmcke and Lindenberg (1983), especially from km 15.95-18.5 and km 19.285-20.120. They confirmed the interpretation of a pelagic basin and gave a great amount of up-to-date details. Based on sedimentology, paleontology, and physiography, they revised the pelagic sediment along the Highway 12 into four sections as briefly described below.

The oldest strata expose generally in the westernmost part, at approximately km 15.950-16.400. This section is characterized predominantly by light gray siltstone and gray to greenish psammitic rocks. The psammitic rocks consist mainly of biogenic clasts and volcanic fragments in various portions. Black shales and dacitic tuffites as well as sittstones and claystones, and some thin layers of allodapic limestones distinguish the eastern part of this section. No fossils are recognized through these strata. Their ages were ascribed relatively older than Asselian.

Between km 16.400 and km 17.050, the second section was recognized as a typical pelagic sequence of Early Permian age, possibly Asselian to Sakmarian. The rocks consist of light to medium gray allodapic limestones alternating with black shales and cherts. Generally these allodapic limestones display the features of turbidity currents. Judging from the foraminifera, this section was of Asselian to Sakmarian age (early to middle Early Permian).

The third section was found within a sequence, which built up the area between km 17.050 and 18.500. Gray allodapic limestones alternating with light gray shale were predominately recognized in this section. Whilst the sedimentation by turbidity currents reached a maximum, individual layers of allodapic limestones with a thickness up to 240 cm were deposited. This sequence was deposited during the Bolorian to Kubergandian age (early to middle Middle Permian) due to the fauna of foraminifera here.

The last section of the pelagic sediments is situated eastward of the Tong River approximately between km 19.360 and km 20.120. Characteristically the rocks also composed of allodapic limestones alternating with dark gray shales similar to the third section. Most rocks in this sequence show strongly deformed. Also, foraminifera were strongly re-crystallized. It was thus not available to limit the age of the sequence. In short, Winkel et al. (1983) believed that this pelagic sequence occupied the currently investigated area also lie within the PFTB with the probable width of 100 to 200 km.

Altermann (Alterman, 1983, 1989, 1991) turned to study the Permian marine deposits again along the Highway 12, particularly in the Middle Permian molasse-type sediments. The outcrops along the highway between km 34.095 and km 42.180 were investigated once again in order to describe their petrology. Molasse-type strata were encountered and interpreted. The name Nam Nao Formation was proposed and divided into three members, the Huai Rahong, Huai Wa, and Khao Pha Daeng Units.

a) Huai Rahong Unit represents a transition between flysch and molasse and is composed of the alternations of graywackes and dark gray shale. The layers vary from 1 cm to 1 m thick. Based on sedimentology, graywackes are generally characterized by graded bedding, cross bedding and lamination. Sandstones also show typical bottom marks as flute casts. These sole marks indicate the trend of transportation either from SSW to NNE or from south to north (Altermann, 1989). Except some plant remains, no fossils were found in the graywackes and shales of the Huai Rahong Unit. The Huai Rahong Unit is visible from km 34.095 to km 36.700.

b) Huai Wa Unit extends from km 36.700 to km 40.900. This second unit is composed of yellowish sandstones alternating with gray siltstone, shale and autochtonous limestones. The Huai Wa sandstones are petrologically similar to the Huai Rahong sandstones. They both are classified as lithic graywacke. Limestones are up to several meters thick, and contain abundant fossiliferous. All limestones are biointramicrudites and biosparrudites with variation in quartzitic clasts. Brachiopods, coral colonies, crinoid stems, unbroken and unidentified algae and abundant foraminifera were found in the carbonates. The appearance of these fossils, together with the sedimentary structure of the clastic rocks of the Huai Wa Unit, provide a good evidence for the rather warm, shallow and quiet marine environment (Altermann, 1983, 1989). On the basis of the foraminifera in limestone layers, the sequences range from Kubergandian to Midian (middle Middle Permian to early Late Permian).

c) Khao Pha Daeng Unit is a typical dominion of dark shales extending from km 40.900 to km 42.180. Only a few ichnofossil and several millimeters of small plant remains were found in these shales. The Khao Pha Daeng Unit was thought to belongs to the molasse strata like the former units. However, this unit occurred in shallower depositional environment than both formers and had been suggested that its environment of the deposition might be in lacustrine.

Following the works of Helmcke and the co-workers along the Highway 12, Altermann (1983, 1989) confirmed that the pelagic facies is older and contemporaneous with the flysch (Asselian to Murgabian) and the flysch is older and time equivalent to the molasse (Kubergandian to Midian) according to foraminifera age determinations. Correspondingly, the sedimentological and environmental characters of the Nam Nao Formation support a general younging of the strata in the eastward direction as mentioned by Helmcke and his co-authors.

3.2 Detailed stratigraphy of the Nam Duk Formation from route map

The Nam Duk Formation itself is a part of the PFTB (Wielchowsky and Young, 1985; Altermann, 1989, 1991). Generally the topography of the study area is very steep and rugged mountain range with covered by high dense subtropical bushes and high trees. The Highway 12 or the Lom Sak-Chum Phae Highway is a good way to investigate because it cuts crosswise the attitude of strata of the Nam Duk Formation and exhibits excellent exposures.

In this study, a detaiked mapping was performed based upon the topographic maps at a scale of 1:50,000 (Ban Tha Chang, Ban Nam Duk Nua, Ban Plaek, and Amphoe Nam Nao) of the Royal Thai Survey Department (RTSD). In addition, geological maps reported by Helmcke et al. (1985) and Phaobpet (1994) were used as guide lines for the detailed structural and strtigraphic data. Stratigraphic investigations were done mainly along the Highway 12 (Lom Sak-Chum Phae). GPS data were recorded for the precise stratigraphic location, together with the mile poles set up along the highway. The entire exposures along the Highway and in some localities along off-roads were visited by walking and described for field data in detail.

The sandstone classification (Fig. 3.3) comes from Folk (1974). Sediment maturity, both compositional and textural, of sandstones was recognized after petrographic studies. The compositional maturity is after Pettijohn (1975) as the textural maturity is received from Folk (1951). Two of the most popular limestone classifications are of Folk (1959, 1962) and Dunham (1962). However, several additional classification of Adam et al. (1984), and Embry and Klovan (1972) are also used for more detailed petrographic data.

A detailed stratigraphy of this present study was made from km 16.0 to 21.5, and km 34.0 to 42.0, along the Lom Sak-Chum Phae Highway (Figs. 3.4 and 3.5). The area was described

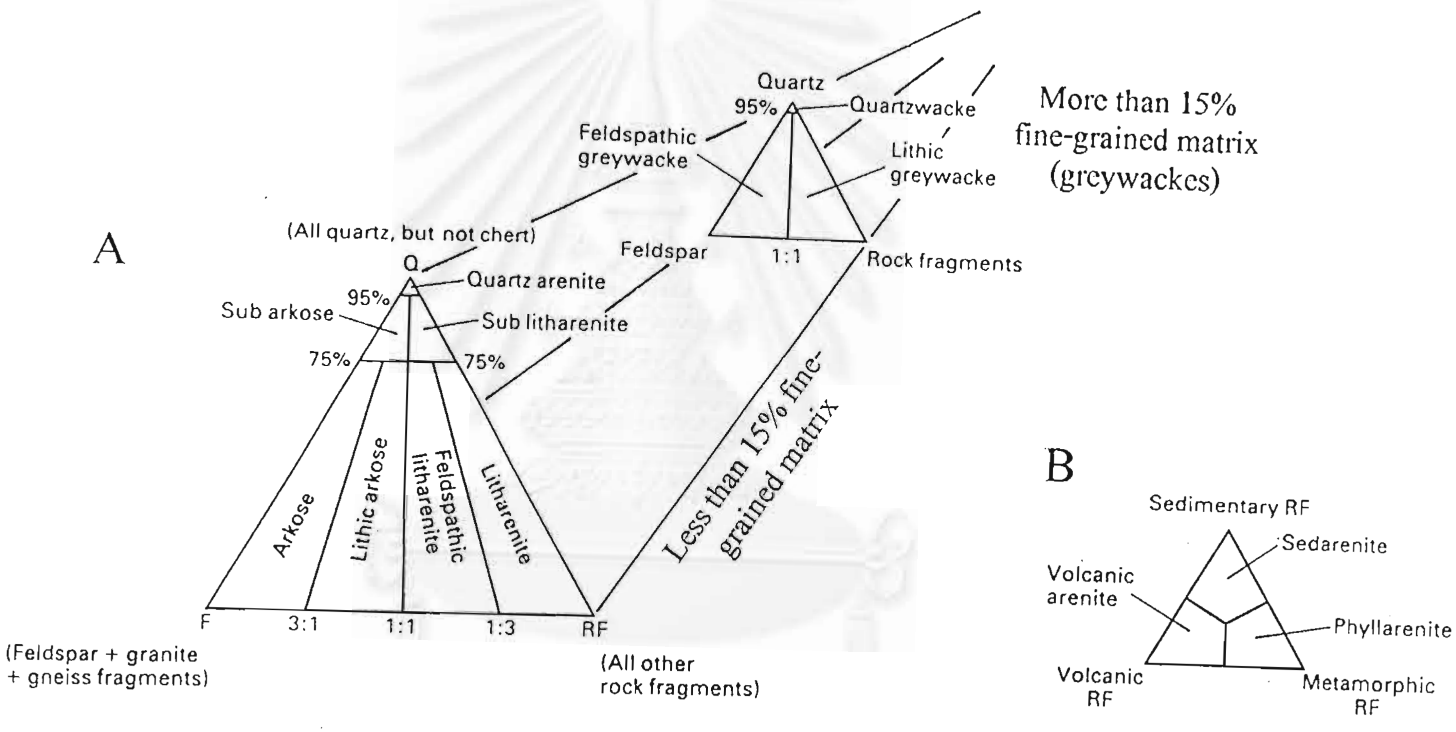

Fig. 3.3 Diagram of most famous classification of sandstone (after Folk, 1974).

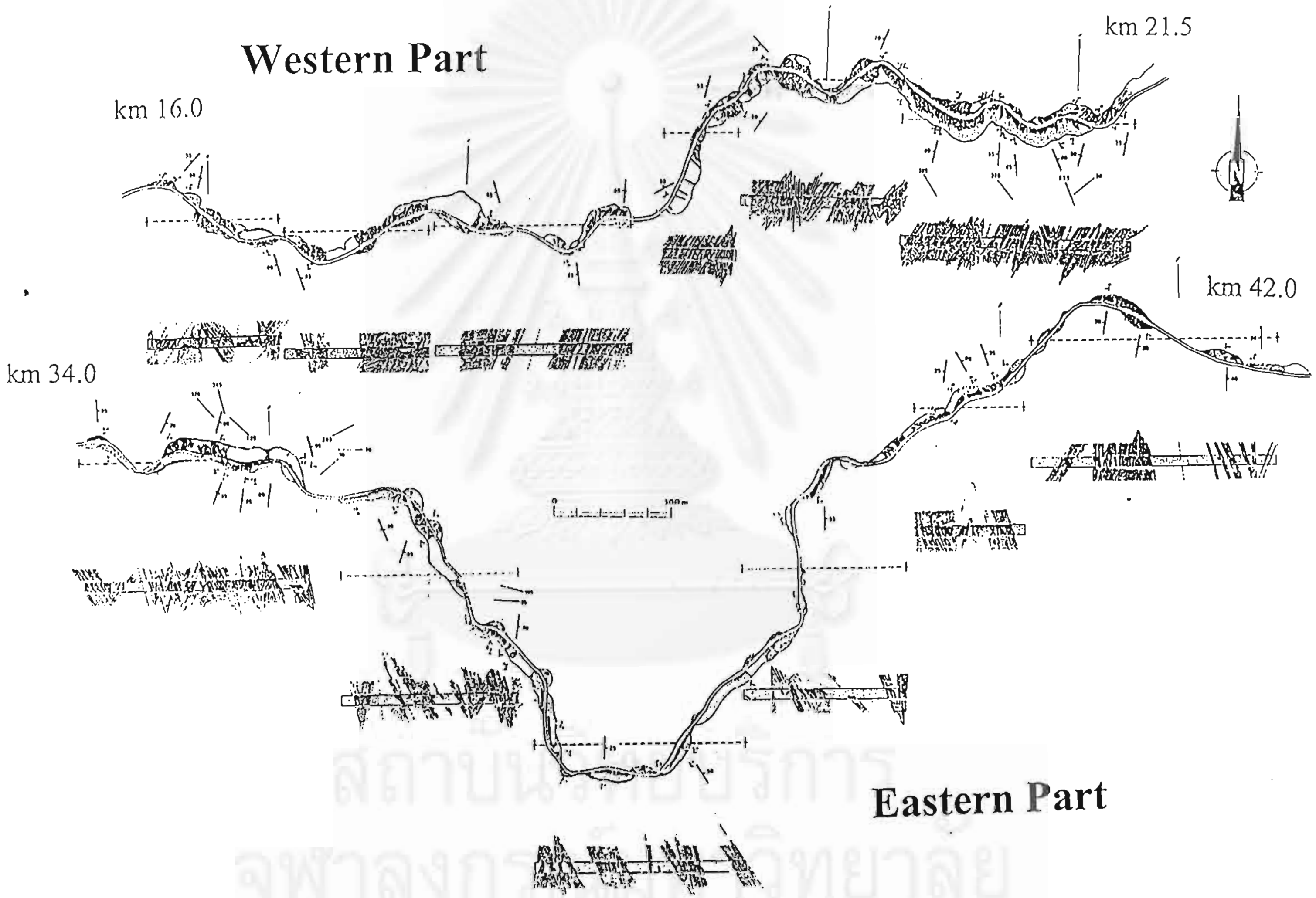

Fig. 3.4 Geological sketch of the exposures along the Highway 12, between km 16.0-km 21.5 and km 34.0-km 42.0 showing the profiles of the road-cut exposures and attitudes of bedding of strata.

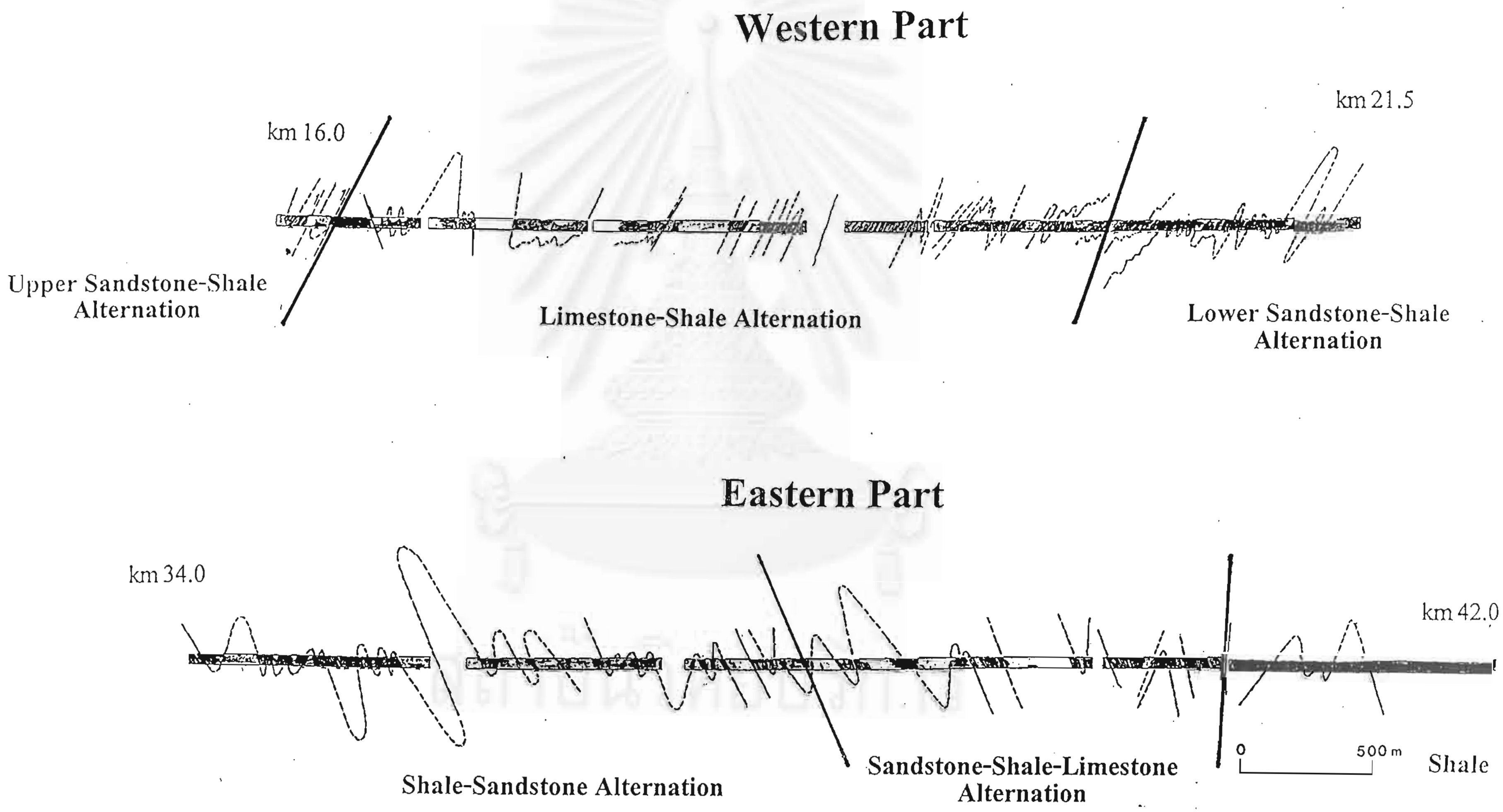

Fig. 3.5 Simplified-composite cross-section along the Highway 12 displaying the regional structures of the Nam Duk Formation.

geographically into 2 parts as the western part and the eastern part. The exposures concrete at some places due to the unstable topography. Detailed descriptions on geology and stratigraphy in this research study are shown below.

3.2.1 The western part

Outcrops in the western part between km 16.0 and km 21.5 are more widely exposed along the highway than those of the eastern part between km 34.0 and km 42.0. However the geology is much more complicated than that of the eastern part. Folds and faults of various sizes were encountered. Both field and photo-interpretation strongly support the occurrence of tectonic structures. In general, the attitude of the rocks strikes varying from NNW-SSE to NNE-SSW, with the average in the N-S trend. Dipping ranges from moderately steep (about 55°) to nearly vertical (85°). In some places, the dips are upright.

Folding becomes prominent throughout the western part. Almost all kinds of folds are recognized here. Tight and overturned folds are quite dominant, especially in limestone-shale alternation at km 17.000-17.400 and km 19.500-19.650 (Fig. 3.6). However in a local scale open folds are also recognized, but they are much less common. The axial plane mostly developed in approximately 190°-220° strike and 55° dip into the west, contrasting with the east direction mentioned by Helmcke and Kraikhong (1982: 58). Their fold axes have the average 200° trend and 45° plunge in the south direction (Fig. 3.7). It is valuable to note that the folding was more clearly observed in carbonates and calcareous sandstones than the shale units.

Faulting are more common to the west and occur intensely with the various spacing. In general, faults are also observed frequently. The thrust faults exhibit their planes varying from NNW-SSE to NNE-SSW with the west dipping. In some places, evidences of faults are recognized by repeated sequence, slicken sides, and offset strata. Displacements of major faults are difficult to determine, however in some place particularly for the minor ones, they range from 20 to 40 cm.

Fig. 3.6 Road-cut exposures of limestone/shale alternation unit showing overturned folded and faulted well bedded strata along the Lom Sak-Chum Phae Highway, at km 17.060.

Fig. 3.7 Very tight folded strata of limestone-shale alternation, Nam Duk Formation, whose fold axis plunges to the south (view to the north), at km 19.916 of Lom Sak-Chum Phae Highway.

In some parts of the western succession, a few index fossils such as smaller foraminifera were identified from the allodapic limestones assigned in pelagic sequence. Their ages of fusulinids, which are justified on few spot-locations, are early-middle Early Permian and early-middle Middle Permian (Winkel et al., 1983). However the age of deposition of the western succession must be younger than the ages of fusulinids in allodapic limestones which are associated with the other shallow marine fossils. The fusulinids and other shallow marine fauna were probably deposited in the shelf or platform environment before being transported by turbidity currents and deposited again in the deeper environments. The stratigraphic interpretations performed by Helmcke and Kraikhong (1982), Helmcke and Lindenberg (1983), Helmcke (1983, 1984), and Winkel et al. (1983), which were based primarily on only ages of reworked shallow marine fauna, is possibly inefficient for the turbiditic deposits of the Nam Duk Formation in the western part. Since the ages of these fauna are not the exact ages of turbidites. The major structures of west-dipping folded strata with common normal beds, and fault planes are the important factors in stratigraphic determination in this study (see Fig. 3.8). Based upon the structural relation and paleontology, the western part can be stratigraphically divided into 3 parts from bottom to top, as described below.

(1) Lower sandstone-shale alternation;

(2) Limestone-shale alternation; and

(3) Upper sandstone-shale alternation

3.2.1.1 Lower sandstone-shale alternation

The most probable oldest unit in the western part of the Nam Duk Formation is that of the sandstone-shale alternation (Fig. 3.8). The unit is exposed from km 20.120 to km 21.475, with the unclear fault-boundary contacts. The typical characteristic of the unit is the well-defined sandstone-shale alternations (Fig. 3.9) which crop out through the distance of about 1.3 km along the highway. Quite dominantly, sandstones are fine-grained to very fine-grained lithic graywackes following to Folk (1974)'s classification system. Weathered surfaces are pale gray to yellowish gray, and fresh surfaces are mostly black to deep chocolate brown. Each sandstone beds varying from 2 cm up to 50 cm.

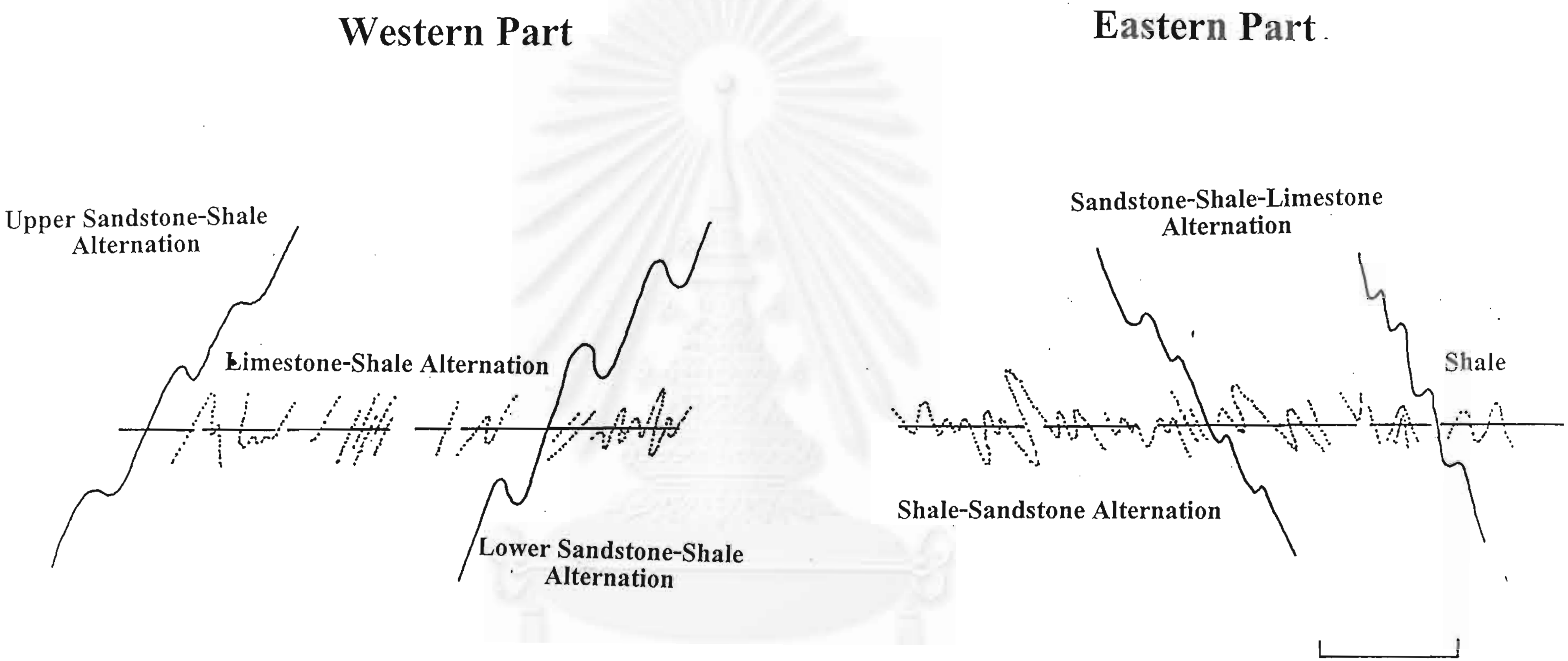

Fig. 3.8 Ideal cross-section of the Nam Duk Formation along the Highway 12 explaining the major structures of the west-dipping folded strata in the western part and the east-dipping folded strata in the eastern part.

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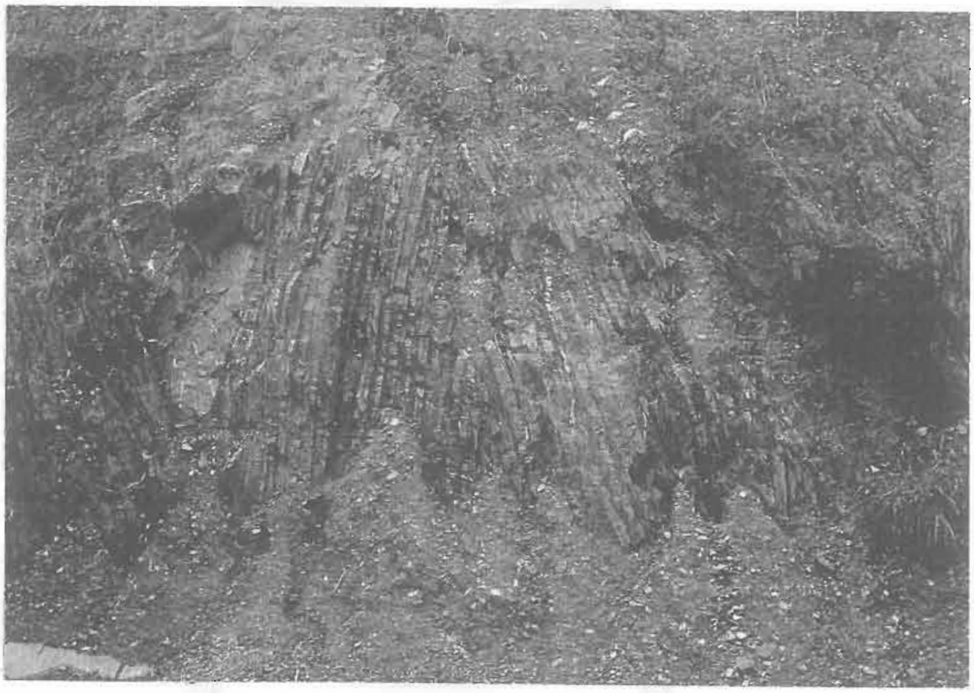


Fig. 3.9 Exposure of well-defined sandstone-shale alternation showing symmetrical folding, at km 20.360 of Lom Sak-Chum Phae Highway.

Shale belonging to this unit is recognized as soft and friable beds alternating with sandstones. Weathered colour ranges from pale gray to dark gray, and on fresh colour, the shale is dark gray to black. In general, shale beds are varied from 2 cm to 80 cm. Some of shale rise to 2 m. Limestones (10-30 m thick) are intercalated in some part of the unit-particularly.

The sequences exhibit almost characteristics of turbidite deposits. Sandstones and shales are monotonously alternated through several tens or hundreds of meters of stratigraphic sections. Sandstone layers show typical sole marks as load cast, flute casts, and groove casts (Fig. 3.10). Within the sandstone beds, the strata have sharp abrupt bases, and tend to grade upward into finer sand, silt, and mud as well as cross-lamination. Some sequence display almost complete Bouma sequence (Bouma, 1962) which comprises: a graded A division; a lower horizontally laminated B division, sometimes with parting lineation; a cross-laminated C division, frequently with stoss preservation; an upper horizontally laminated D division, and a pelitic E division (Fig. 3.11). However, the BDE turbidites are more common than the complete ABCDE turbidites of ideal Bouma sequence. The transportation of sediments is concluded from the sole marks of the sandstone strata, especially flute casts and groove casts. Directions of currents are various and ranging from SE to NW, and SSE to NNW. A few of them is SW to NE. It is possible to report the oblique bimodal for the paleocurrent of this sandstone-shale alternation.

In some sandstone beds, large carbonate fossil debris are rarely found in the lower parts of strata, especially in the interval A. The recognized fossils are mainly crinoid stems. Almost the rock unit, bryozoa, calcareous algae, and a few fusulinids are found as phenoclasts or fossil fragments in the sandstones. Locally plant remains as well as unidentified shell fragments are discovered in black shales, which alternated with sandstones.

Consideringly to the detrital chromian spinels, the Lower sandstone-shale alternation unit yields detrital spinels in the lithic graywacke, which alternated with shale in this investigation especially in km 21.09. Detrital chromian spinels are discovered as one of the

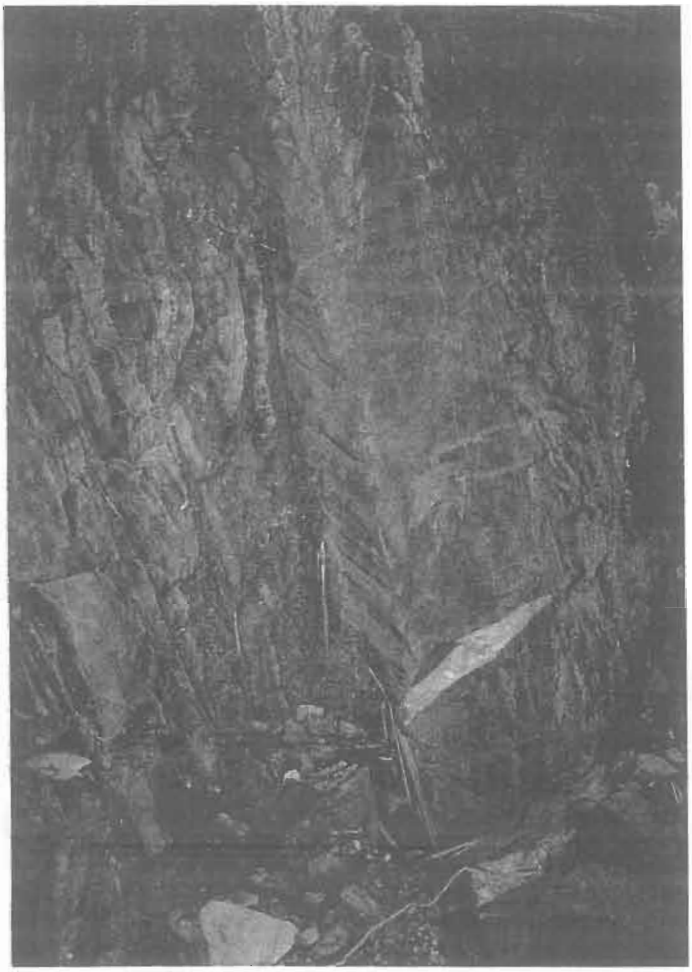


Fig.3.10 Outcrop of sandstone and shale , showing groove casts and flute casts at the bottom of Sandstone bed with the measured paleocurrent 145°-325° (view to the south at km 20.39 of Lom Sak-Chum Phae Highway.

Fig.3.11 Well-defined Bouma sequence showing interbedded shale-sand alternation, cross beds, and grade beds, at km 20.5 of Lom Sak-Chum Phae Highway.

accessory minerals in sandstones (less than 1 %). They are wide varied in size from 20 to 190 μm and display reddish brown to deep brown under the transmitted light.

3.2.1.2 Limestone-shale alternation

The second sequence is the Limestone-shale alternation (Figs. 3.4 and 3.5) unit that is presented at km 16.210 to km 20.120. The rock unit covers all limestone-shale alternations in the western part of the Nam Duk Formation, which extend nearly 4 km along the highway. It is valuable to note that this Limestone-shale alternation is the most outstanding unit because it was very strong deformed. Generally visitors can be easily recognized. Its characteristics brought into the naming the term Nam Duk Formation for defining these high-deformed geosynclinal deposits (Fig. 3.12) from the other carbonates in the Permian age in Thailand. With the great variety of sedimentary deposit along the Highway between km 16.0–42.0, however, it is possibly observed that the term Nam Duk Formation is different and less defined for all the successions in the study area.

Characteristically this unit is constituted of well-beded micritic limestone whose thickness appears to be similar to that of shale. The rock unit can be straitigraphically separated into 7 sub-units:- Lower limestone-shale, Chert, Lower shale-limestone with locally sandstone, Lower shale, Upper limestone-shale, Upper shale-limestone, and Upper shale units following the highway.

However, this research is concerning the detrital chromian spinels in sandstones, and the characteristics and lithology of each sub-unit in the Limestone-shale alternation are almost similar. The detailed description seems to be unnecessary in this chapter or in the study.

The limestone in the Limestone-shale alternation unit is pale gray to dark gray on weathered surface, and dark gray to black when fresh. It plays as the minor rocks in this alteration comparing with shale, which sometimes deposited in a little bit deeper environment

Fig.3.12 Strongly deformed and steep–dipping alternated strata of the Limestone-shale alternation.–a very characteristic of the Nam Duk Formation at km 17.060-17.400 of the Highway 12.

associated with siliceous shale. The beds of limestone vary from 2 cm to 20 cm and up to a few meters in some parts of the Upper limestone-shale sub-unit. Almost limestones are interbedded with shale. They are much more folded than rocks of the Sandstone-shale alternation unit. There are several sedimentary structures, which recognized during the field investigation. Such as the normal graded bedding (Fig. 3.13) as well as sole marking that be good indicators for the direction of the sequences in numerous locations. Clasts or allochems of the grading limestones at the bottom of beds are sometimes up than sand-sizes. Fauna fragments can be observed in hand specimens too. The recognized fossils are fusulinids and crinoid stems.

Petrographically the limestones are classified as the intramicrite (Folk, 1959, 1962) based mainly on the composition which be defined that allochem of intraclasts is more than 50 to 80 percent with minor carbonate mud as well as packstone (Dunham, 1962) or packstone to rudstone (Embry and Klovan, 1972). Almost allochems in the rock are limestone fragments with some of broken fossils, crinoid stems and fusulinids. The allochems of intraclasts are widely ranging in sizes. Considering to the poor sorting of limestone intraclasts, the lithology, sedimentary structure of whole rock, and the rhythmical alternation with shale, it is possible to interpret the sedimentary processes of limestones as the slump deposits by turbidity currents. This process suggests that fauna found were re-deposited in the limestone. The age of the rock unit is possible younger than the relatively ages of re-worked fossils. No detrital grains are recognized in the carbonate rocks. Dissemination of pyrite grains can be observed in both hand specimens and thin sections.

Some of thick-to very thick-bedded limestones (1-5 m thick) are locally exposed especially between km 17.200 and km 17.400. They are dominantly conglomeritic limestones. Clasts are rock fragments and fossil fragments, ranging 3-5 mm and up to 1-2 cm in sizes. In several beds, they display grading of allochems from 0.8-1 cm at the bottom to 3 mm at the top of beds. Observed fossils are also fusulinids and crinoid stems.

Black shale in the Limestone-shale alternation unit is exposed in all rock sub-units. They can be divided into 2 group, one formed as interbedded shale (Fig. 3.12) in the

Fig.3.13 Large exposure of limestone (light-colored) with graded bedding in alternation with laminated shale (dark-colored) along the Lom Sak-Chum Phae Highway at km 16.595.

alternation of limestone and shale, and the other one formed in shale units (Fig. 3.14). Interbedded shales in the alternation of limestone and shale are greenish gray to dark gray on the weathered surface, and black in the fresh surface. Their beds are measured and studied together with limestone beds. The layers of shale are ranging from 1-2 cm up to 40-60 cm. Some of them might rise to a few meters in the shale-dominant units.

Characteristically shales in the alternation of limestone and shale are not fossiliferous, however, fossiliferous shales are locally discovered between km 18.375 to 18.400. Thickness of fossiliferous shale is about 20 cm to half the meter. Anyway they occurred in thick lense-shap, not well extending like the normal bed which is more dominant. The observed fossils are predominantly fusulinids (Fig. 3.15).

The other shales are formed in shale or siliceous shale units (Fig. 3.16) which are not influenced by carbonate comparing with the former alternated shales. Characteristically they are shale and siliceous shale. Sometimes they are formed as chert, depending to the content of silica or quartz. The outcrop of this shale and siliceous shale usually formed as the alternation of hard beds of more siliceous layer and soft beds of less siliceous layer. The thickness of shale is ranging from 2 cm to 8 cm. Hard and brittle beds are well defined as siliceous shale, or frequently cherts.

About km 19.300-19.400 along the highway, banding cherts are exposed with the interbedding of dark and light-colored cherts (Fig. 3.16). The layer is 3 cm to 50 cm thick. Some of them show grading of clasts, especially in light-colored cherts which usually have crinoid stems and rock fragments in their texture. Anyhow this outcrop shows light gray limestones overlying the layering chert sequence in the north side of the highway with probably fault contact. Nearby, volcanic rocks are defined as basalts under the microscope.

Sandstones are also locally interbedded in the limestone-shale alternation between km 18.250 and km 19.300. However, no well-exposed sandstone beds can be observed. Some loose blocks along the highway interpret the presence of sandstone. The

Fig.3.14 Alternation of black shale with well-bedded siliceous shale (light-colored) of the Nam Duk Formation, at km 16.210 of the Lom Sak-Chum Phae Highway. Hand and brittle beds (light-colored) are well-defined as siliceous shale, or frequently cherts, depending to the content of silica.

Fig.3.15 Fusulinid fossils observed in a black shale lense of the Limestone-shale unit, the Nam Duk Formation, at km 18.381 of the Lom Sak-Chum Phae Highway.

Fig.3.16 Banded cherts (Both dark and light colored) exposed as natural exposure at km 19.356 of the Lom Sak-Chum Phae Highway. Some layers show grading of phenoclasts of crinoid stem and rock fragments, especially in light-colored.

sandstones are very fine-grained texture with dark gray to black colors, and calcareous cement. Considering to their lithology, these sandstones are very difficult be recognized from the dark gray limestones.

3.2.1.3 Upper sandstone-shale alternation

The westernmost unit in the western parts of the Nam Duk Formation is defined for a sequence, which built up the area between km 15.950 and km 16.210 (Figs. 3.4. 3.5 and 3.8). This rock unit is predominantly characteristic by the sandstone-shale alternation with interbedding of micritic limestone (5-7 cm thick). Sandstones (Fig. 3.17) are generally pale greenish gray on weathered surface and greenish gray when fresh. The thickness of sandstone beds is thicker than the former Lower sandstone-shale alternation unit about 5-10 cm to half the meter and up than a few meters. The grading of clasts are observed in sandstone layers. Their clasts are varied in sizes, ranging 0.5-2 mm diameter. However a large piece of black shale rip-up clast is also found with the cobble size about 6 cm in diameter and 2 cm thick. In this study, the sandstones are microscopically re-classified as feldsparthic graywacke following to Folk (1974)'s system. Until now, no detrital chromian spinels are defined in these feldsparthic graywackes of the Upper sandstone-shale alternation unit.

Shales in this unit are not sought different from shale in the former unit. Some of them are siliceous shale. The thickness ranges from 5-10 cm. The carbonates are micritic limestone. They are ranging from 5-10 cm thick in each beds. No fossils are observed in these shales.

3.2.2 The eastern part

The eastern part the Nam Duk Formation is found within a sedimentary sucession which exposed between km 34.0 and km 42.0 along the Highway 12. Comparing with the western part, the geology and structures in the eastern part are less complicated. Generally the

Fig.3.17 Pale greenish gray rather coarse–grained graywacke with deformed and contorted calcite veins, exposed at km 16.050 of the Lom Sak-Chum Phae Highway.

bedding planes are very sleep to precipitous (about 30° to 85°) inclined to the east-northeast to east-southeast directions with north-northwest to north-northeast trending.

Folding and faulting in the eastern part are less complex than the western part. Tight to open fold is quite dominant. However, overturned folds are recognized in the succession by the presence of several overturned beds or fold heads. Their major axial planes and fault planes are dipping to the east. Both normal and thrust faults can be observed in the eastern succession.

Several faunas are well recognized from fossiliferous limestone. They are foraminifers, brachiopods, coral colonies, calcareous algae, bryozoa, and crinoid stems. Comparing with the turbiditic limestones in the western succession, these fossiliferous limestones are more abundant and various in fauna. The environments of these limestones are probably shallower than those of the western limestones. The ages of fusulinids and smaller foraminifera are late to latest Middle Permian (Chutakositkanon et al., 1997).

The eastern part of the Nam Duk Formation can be stratigraphically sub-divided into 3 units (Fig. 3.8) from oldest to youngest, as described below.

(1) Shale-sandstone alternation;

(2) Sandstone-shale-limestone alternation; and

(3) Shale

3.2.2.1 Shale-sandstone alternation

The oldest unit of eastern part of the Nam Duk Formation is the westernmost rock unit exposed from km 34.095 to km 37.200 (Figs. 3.4, 3.5 and 3.8), with the unclear fault boundary. Characteristically this rock unit consists of all the shale-sandstone alternations (Fig. 3.18) which cover the exposures along the highway about 3 km. Consideringly to the presence of the detrital chromian spinel, the majority of detrital chromian spinels discovered in the study area is from the eastern part of the Nam Duk Formation in this shale-

Fig.3.18 Overall thicker layers of black shale alternated with bedded sandstone (light-colored), typical of the Nam Duk Formation, showing with steepy-dipping strata, at km 34.870 of the Lom Sak-Chum Phae Highway.

sandstone alternation. The sandstone in this alternation are fine-grained to very fine-grained lithic graywackes (Folk, 1974). Their weathered surfaces are pale gray, and the fresh surfaces are generally dark gray to black. The thickness of individual sandstone beds is varying from 2 cm up to 70 cm. Based upon field observation, it is observed that though the general appearance of this unit is similar to those of the previous sandstone-shale alternation unit to the west, sandstone beds of this unit become thicker and appear in a close space than those of the west.

Shale alternated with sandstone in this unit is recognized as soft and friable beds. The weathered colors are pale gray to dark gray, and on fresh color, shale is dark gray to black. Alternated shale beds are commonly varied from 2 cm to 80 cm. Some of them frequently rise to 2-3 m. It is valuable to note that no limestone beds are intercalated in the shale-sandstone alternation.

Regarding to the absence or less abundance of the interbedded limestone beds in the shale-sandstone alternation unit in the eastern part of the Nam Duk Formation, this unit is recognized for less influence of carbonate sediment than the western sandstone-shale unit. However, there are many biogenetic clasts formed as carbonate sediments in the sandstones. Microscopically, these biogenetic clasts were fragments of shallow marine fauna such as bryozoa, calcareous algae, and fusulinids.

The alternation sequences of sandstone and shale display almost the characteristics of turbidite. Sandstone beds exhibit typical sole mark (Fig. 3.19) as load casts, flute casts, and groove casts, as well as cross-lamination, lamination and graded bedding. Several layers of sandstone contain elongated clay galls. These characteristics are recognized that the shale-sandstone alternation belongs to the Bouma sequence same as the Lower sandstone-shale alternation unit in the western part, some successions of this shale-sandstone alternation demonstrate almost complete Bouma sequence (Fig. 3.20). Generally the defined BDE turbidites are more common than the complete ABCDE turbidites of ideal sequence.

Fig.3.19 Loose block of sandstone with fluate mark structure from the shale-sandstone alternation in the eastern part of the Nam Duk Formation, at km 34.7 of the Lom Sak-Chum Phae Highway.

Fig.3.20 A close-up view of a characteristic of complete Bouma sequence, comprising a grade A division; a lower horizontally laminated B division; a cross-laminated C division, an upper horizontally-laminated D division and a pelitic E division of the Sandstone-shale alternation in the Nam Duk Formation at km 35.165 of the Lom Sak- Chum Phae Highway.

The directions of transportation are measured from the flute casts (Fig. 3.21), groove casts and cross-laminations in the sandstone beds. Paleocurrent directions are very diverse and widely ranging between ENE to WSW and SSE to NNW along the highway. Multi-model pattern is recognized for the paleocurrents of this rock unit. However, their transportation directions are consistency in each the locality. Such as at km 34.756, transportation current is SSE-NNW direction, the current at km 35.165 is ENE-WSW direction, and at km 36.660 the current is WNW-ESE direction.

Carbonate fossil debris is also found in thin sections of graywacke sandstones of this rock unit. They are mainly bryozoa, calcareous algae, and a few of fusulinids forming as bioclasts in sandstones.

Chromian spinels, which are found in this rock unit, are pioneerly discovered in the study area. They are generally found in lithic graywacke. Their sizes are rather small and varying from 20 μm to 100 μm. The color is ranging from reddish brown or brown to black under the microscope. They are admitted as an accessory mineral in the sandstones (less than 1 %).

3.2.2.2 Sandstone-shale-limestone alternation

The second succession in the eastern part of the Nam Duk Formation is exposed at km 37.200 to km 40.700. The rock unit is named here as the sandstone-shale-limestone alternation (Figs. 3.4, 3.5 and 3.8). This unit contains mainly fine to very fine sandstone in alternation with dark gray shales and limestones. The sandstone-shale-limestone alternation unit can be subdivided into 2 sub-units, the western or lower part that exposed from approximately km 37.200 to km 40.000 and the eastern or upper part that exposed from km 40.000 to km 40.700 by the occurrence of limestones. The first sub-unit is the alternation of sandstones and shales associated with massive limestones (Fig. 3.22). In other hand, the second sub-unit is the alternation of sandstones and shale associated with bedded limestones (Fig. 3.23).

Fig.3.21 An example of flute casts, typical structure usually observed in sole of sandstones of the Sandstone-shale alternation of the Nam Duk Formation, showing direction to NE, at km 35.185 of the Lom Sak-Chum Phae Highway.

Fig.3.22 Natural outcrop of massive limestone found within the sandstone-shale-limestone unit at km 39.240 along the Highway Lom Sak-Chum Phae.

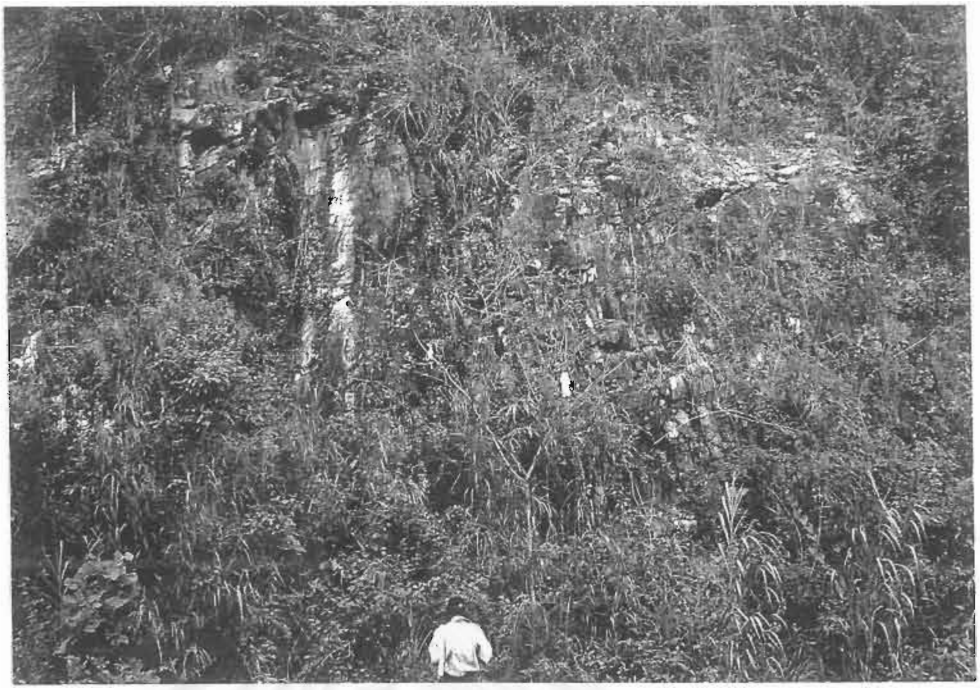


Fig.3.23 Alternation of sandstone and shale sandwiched locally by bedded fasulinid-rich limestone (brown–colored to the left) expose at km 40.460 of the Lom Sak-Chum Phae Highway

Fig.3.24 Black chert nodules in massive limestone exposed of the Highway Lom Sak-Chum Phae

The sandstones are mainly fine-to very fine-grained, of gray to yellowish gray color. The layers are ranging from 2 cm to 60 cm, frequently up more than a few meters. Several beds are very rich in fossils. Beds of dissolved foraminifera tests or brachiopod shells are found by recognition of extremely high moldic porosity. Some of them display variety of bed thickness, and sometimes form as lens-shape. The sandstones of this rock unit resemble those of the former shale-sandstone alternation under the microscope. They belong to the class of lithic graywacke (Folk, 1974).

Shale of this unit are mostly of dark gray to black color. They usually alternate with sandstones or limestones. Their layer is very wide-ranging in thickness from a few centimeters to a few meters. Some of them rarely exhibit laminae rich in detrital muscovite. Plant remains and organic matters are also common in this shale.

Generally the carbonates in this rock unit are fossiliferous limestones. It is possible to separate the limestone in this unit to massive limestone and bedded limestone along the Highway. Massive limestone is relatively older than bedded limestone by stratigraphic correlation. They crop out at the western part along approximately km 37.200 to km 40.000 Characteristically the limestones are up to several meters thick, of gray to dark gray colors, and fossiliferous. Brachiopods, coral colonies, crinoid fragments, and calcareous algae are found in the limestone. Several beds of massive limestone contain some of chert nodules (Fig. 3.24). Commonly chert nodules are dark gray to black. In the other hands, bedded limestones that exposed at km 40.000 to km 40.700 generally associated with shale and sandstone. The beds are ranging from 5 cm to 40 cm thick. They are also fossiliferous. Several kinds of shallow marine fauna are observed such as coral colonies, crinoid stems, calcareous algae, bryozoa, and foraminifera.

In several locations, limestone beds are abundant in foraminifera. Based upon the work of Chutakositkanon et al. (1997), *Pseudodoliolina pseudolepida* (Depart) and *Verbeekina verbeeki* (Geinitz) identified from the samples at km 40.3 are very good indicators for late Middle Permian (Murgabian and Midian) in Tethyan province. They are reported in many sections of Western Tethys such as Japan, South China, and Indochina. The samples here also yield *Abadehella* cf. *coniformis* (Okimura and Ishii), and *Sumatrina* sp., both strongly indicate a Midian age rather than Murgabian (Ueno, per. comm.).

3.2.2.3 Shale

Typically the rocks in the shale unit (Figs. 3.4, 3.5 and 3.8) is exposed between the km 40.700 to km 42.180. Characteristically this unit comprises dark shale. The layer are several cm thick and laminated. Shales are usually loose and brittle when weathered. They often contain black, elongated clay galls. Rarely sandstones are intercalated in some localities. Only small plant remains are discovered in these shales. It is valuable to note that no limestone occur in this rock unit.

Comparing with shales in the western succession, these shales are easily distinguished. Those shales in western succession usually deposited in deeper environments. They are the alternation of shale and siliceous shale occurred as the alternation between soft and hard beds. Some of them are chert.

3.3 Petrography of sandstones

Generally the Nam Duk Formation included a marine succession of pelagic sediments, flyschs and molasses (Helmcke and Kraikhong, 1982; Helmcke and Lindenberg, 1983). Anyhow, this study is pointed of investigating the detrital chromian spinels in sedimentary rocks. Regarding to the literature reviews of detrital chromian spinel studies and petrographic studies in this present area, the detrital chromian spinels usually associated with sandstones in turbiditic sequences, especially in graywacke (Hisada and Arai, 1993, 1994; Cookenboo et al., 1997; Chutakositkanon et al., 1999b). The petrography of spinel-bearing sandstones seems to be necessary for the detrital chromian spinel studies, especially for the understanding of the sedimentary environments when detrital spinels deposited. In thin-section investigation, sandstones are recognized in several locations, but they can be subdivided by the rock units and locations as the below.

3.3.1 The western part

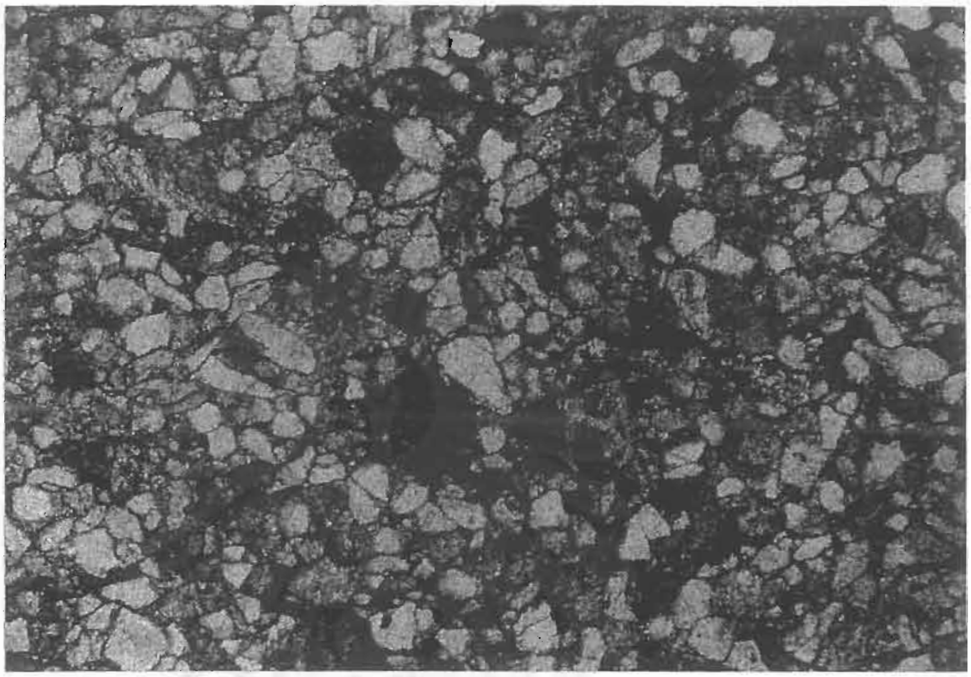
Sandstone in the Western parts of the Nam Duk Formation can be separated into 2 groups following their associated rock units. They are sandstones from lower-and upper-sandstone-shale alternation units. Both are quite different in the lithology

3.3.1.1. Lower sandstone-shale alternation

The sandstones in Lower sandstone-shale alternation unit are fine-to very fine-grained graywacke. They are alternated with black shale. Petrologically the graywackes exhibit that all of them belong to the class "lithic graywacke" of Folk (1974). They contain 15% to 50% clayish, sericitic, and ferritic matrix, 20% to 50% quartz (monocrystalline grains), 30% to 50% rock fragments (including polycrystalline quartz grains), less than 5% feldspar, and up to 3% detrital mica (mostly muscovite) (Figs. 3.25a and 3.25b). Almost the sandstones contain the fragment of bioclasts up to 15%. The recognized faunas are bryozoa, calcareous algae, crinoid stems, and fusulinids. Commonly opaque minerals are magnetites or pyrites. Observed hard minerals, turmaline, hornblende, rutile, and zircon are also found as accessory minerals. All the lithic graywackes are fine-to very fine-grained, poorly sorted, and of immature stage (Folk, 1951). The particle roundness is angular to sub-rounded but mainly angular.

Several detrital chromian spinels are discovered in these sandstones. The detrital spinels are also occurred as an accessory mineral in these lithic graywackes (less than 1%). However, the presence of detrital chromian spinels in one thin section can rise to 3-5 grains (e.g. the thin sections VC-29 and VC-29(3) at km 21.090). Generally chromian spinels display reddish brown to deep brown and ranging from 20 μm to 190 μm in size. Some of them contain a few inclusions.

a) without nicols



b) under crossed nicols

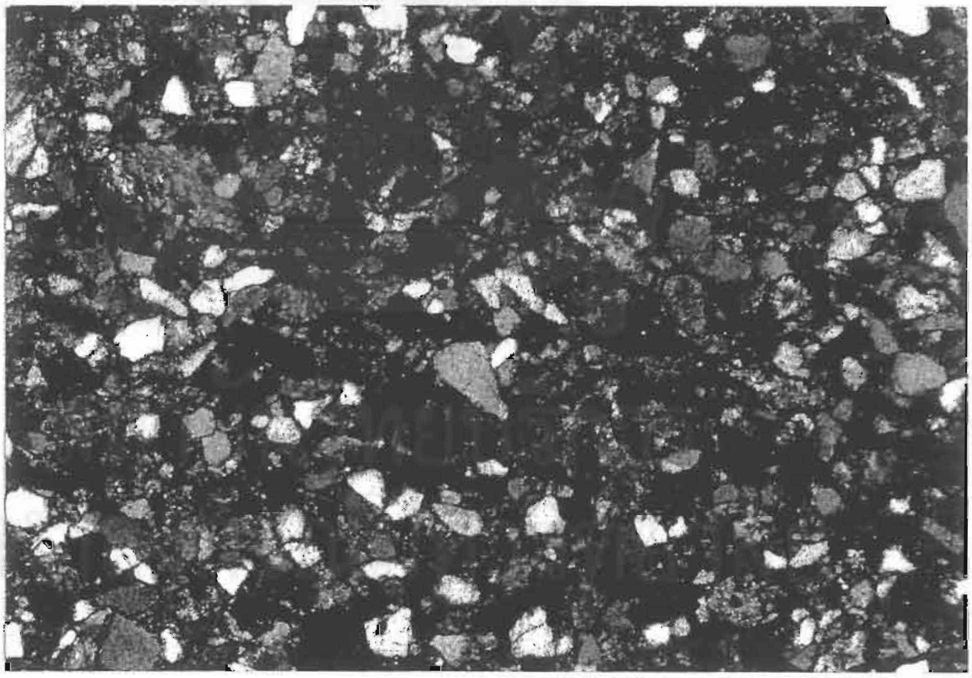


Fig.3.25 Photomicrograph of poorly-sorted, fine-to medium grained lithic graywacke of the Lower sandstone-shale alternation unit (km 20.4) in the western part of the Nam Duk Formation showing clasts of quartz, chert, calcite, and lithic fragments with fusulinid. The long axis of photograph is about 4 mm.

3.3.1.2 Upper sandstone-shale alternation

The sandstones of Upper sandstone-shale alternation are fine-to medium-grained graywacke. They are commonly pale greenish gray on fresh surfaced. These sandstones are exposed between km 15.950 and km 16.210. Under the microscope (Figs. 3.26a and 3.26b), these sandstones are defined as feldsparthic graywacke following to Folk (1974)' system. Generally they contain 15% to 50% clayish, and ferritic matrix, 30% to 60% feldspar, 15% to 20% quartz (monocrystalline grains), and 15% to 20% rock fragments (included polycrystalline quartz grains). Opaque minerals are usually magnetites or pyrites. The sandstone are fine-to medium-grained, poorly sorted, and of immature stage (Folk, 1951). The particle roundness of clast is mostly angular to sub-angular.

No detrital chromian spinels are observed in these feldsparthic graywackes. The absence of detrital chromian spinels and the lithology of sandstones of this rock unit are the outstanding characteristics of feldsparthic graywackes that distinguish from the other graywackes in the other units. It is possible to conclude that these feldsparthic graywackes have a different history and parent source.

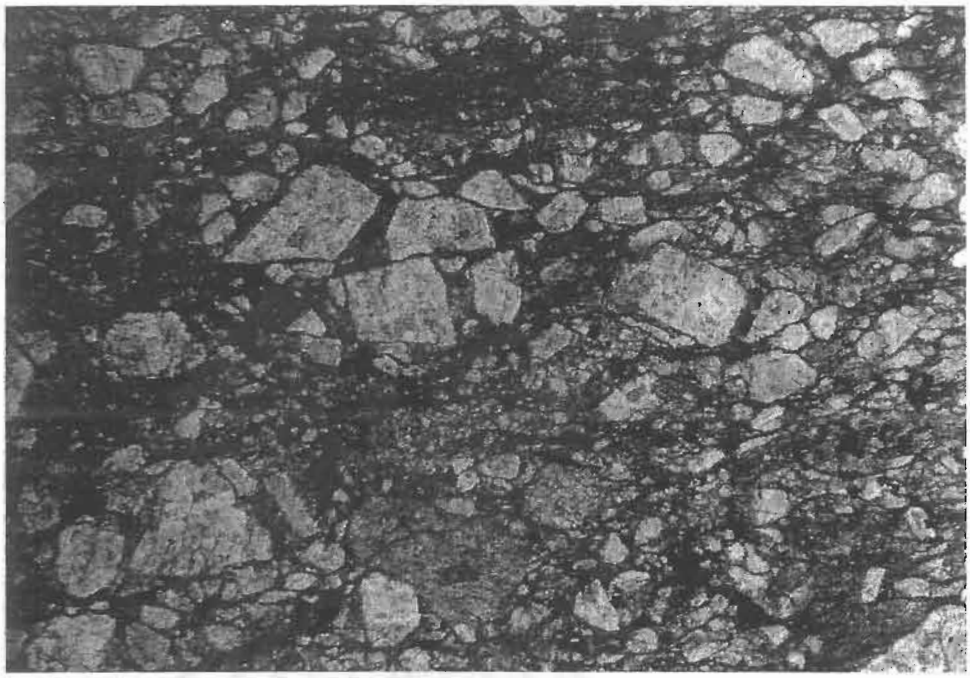
3.3.2 The eastern part

Sandstone in the eastern parts of the Nam Duk Formation can be divided into 2 groups following their associated rock units. Both groups are the shale-sandstone alternation and the sandstone-shale-limestone alternation.

3.3.2.1 Shale-sandstone alternation

In this unit, sandstones are usually associated with shale and form the alternation between sandstone and shale liked the Lower sandstone-shale alternation in the Western part. These sandstones are microscopically defined as lithic graywacke of Folk (1974). Compositionally they contain 15% to 70% clayish, sericitic, and ferritic matrix, 10% to 30%

a) without nicols



b) under crossed nicols

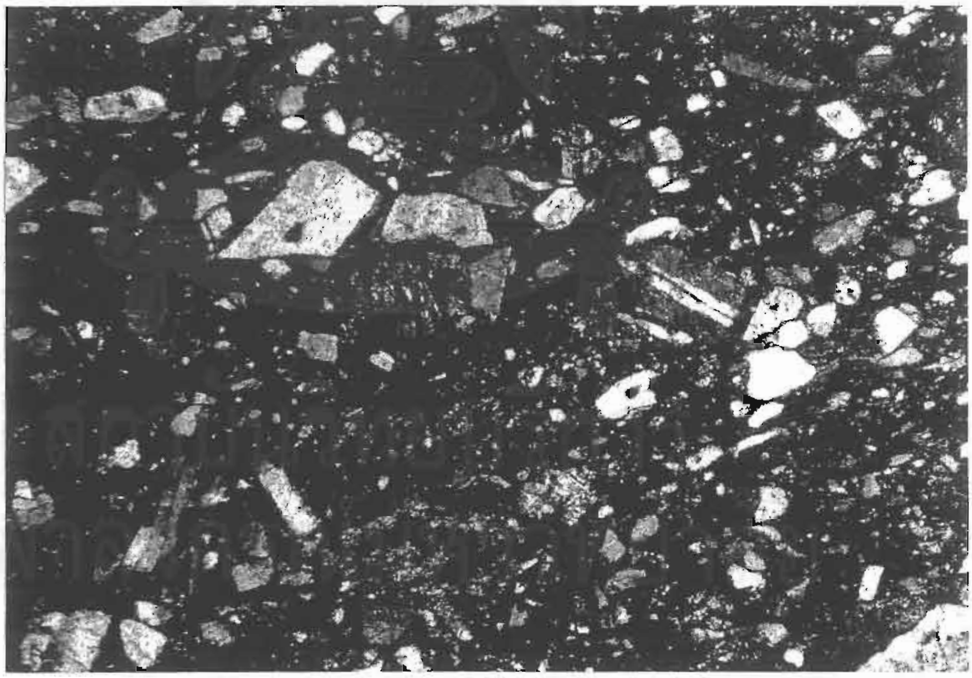


Fig.3.26 Photomicrograph of deformed and poorly-sorted feldsparthic graywacke of the Upper sandstone-shale alternation unit (km 16.025) in the western part of the Nam Duk Formation showing clasts of quartz, feldspar, chert, and rock fragments. Feldspar can be easily recognized in crossed polars, by their twins. The long axis of photograph is 4 mm.

quartz (monocrystalline grains), 10% to 30% rock fragments (including polycrystalline quartz grains), less than 5% feldspar, and up to 5% detrital mica (mostly muscovite) (Figs. 3.27a and 3.27b). The recognized fossils are bryozoa and calcareous algae. Opaque minerals are generally magnetites or pyrites. All the lithic graywackes are fine-to very fine-grained sandstones. Poorly sorting and immature stage can be observed in these lithic graywackes. A characteristic of particle roundness is mainly angular. but in several grains exhibit sub-rounded.

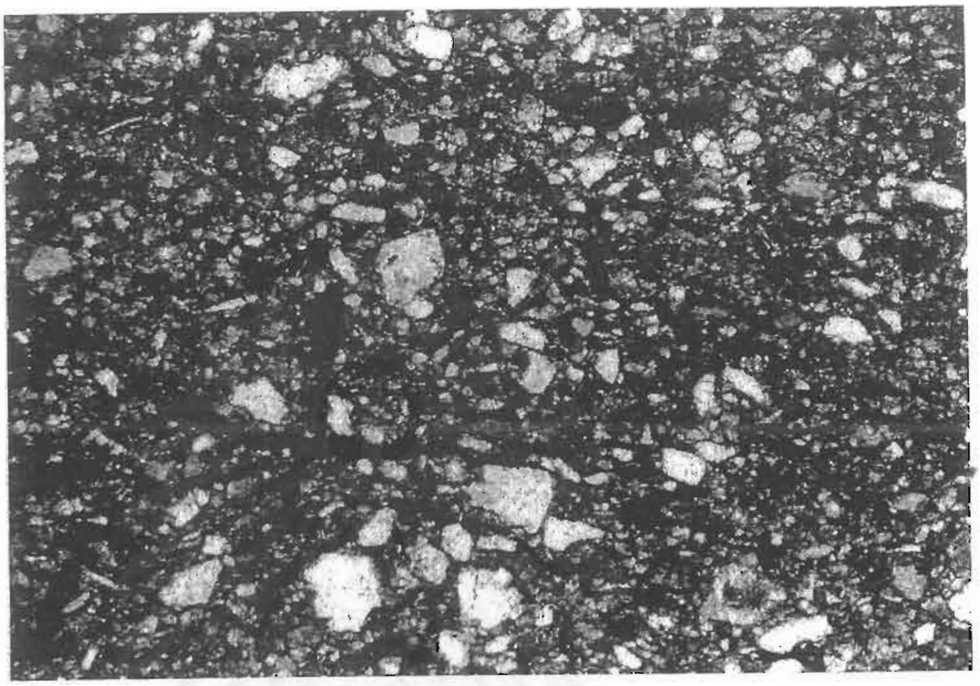
The majority of chromian spinels which are discovered in the Nam Duk Formation comes from this lithic graywackes. The detrital chromian spinels display themselves as an accessory mineral in the graywackes (less than 1%). Detrital spinels in this lithic graywackes can rise to 5-8 grains in some thin sections, e.g. the thin sections VC-34(3) and VC-35(4). Generally chromian spinel in this unit are rather small and varying 20 μm to 100 μm in size. They are mostly reddish brown to deep brown under the microscope as well as black or opaque.

3.3.2.2 Sandstone-shale-limestone alternation

Along the highway between km 37.200 to km 40.000, the sandstones are alternated with shales and limestones. Characteristically sandstones are fine-to very fine-grained, of gray to yellowish gray color. Their beds are ranging from 2 cm to 60 cm. Regarding to microscopic studies, the sandstones in this unit are classified as lithic graywacke (Folk, 1974). Compositionally they contain 15% to 50% clayish, sericific, and ferritic matrix, 20% to 55% quartz (monocrystalline grains), 30% to 50% rock fragments (including polycrystalline quartz grains, less than 3% feldspar, and up to 3% mica (mostly muscovite) (Figs. 3.28a and 3.28b). Almost sandstones contain the biogenic fragments up to 30%. The recognized fossils are bryozoa, calcareous algae, brachiopods, and fusulinids. Opaque minerals are mainly magnetite or hematite. Fine-to very fine-grained lithic graywackes are poorly sorted, and of immature stage (Folk, 1951). Their particles are angular to sub-rounded.

The occurrence of detrital chromian spinels in the sandstone of the sandstone-shale-limestone alternation is very interesting. This suggests that detrital chromian

a) without nicols



b) under crossed nicols

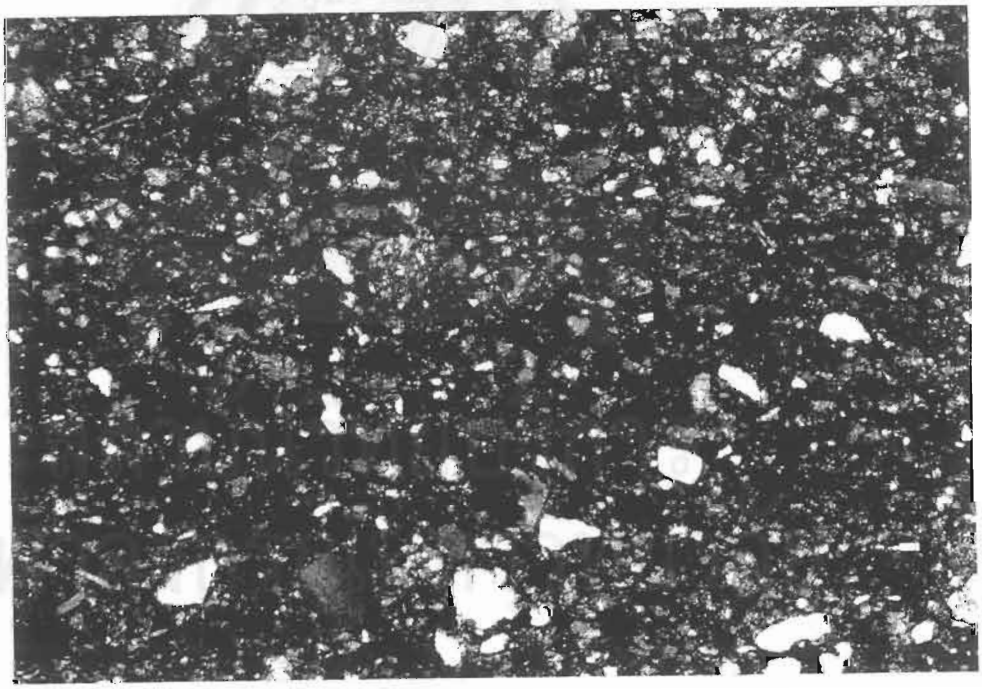
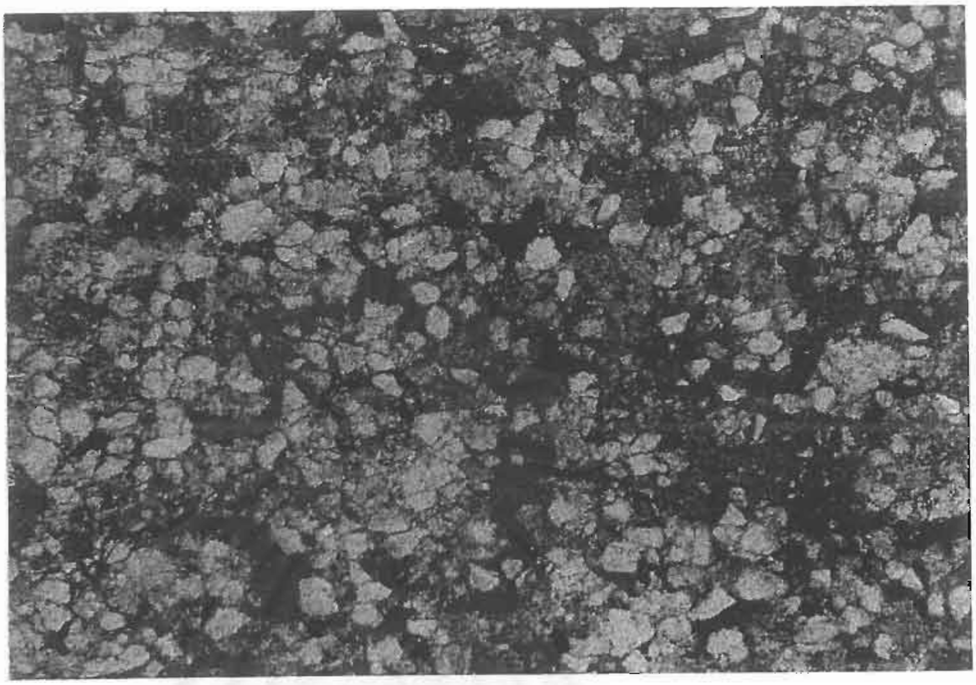


Fig.3.27 Photomicrograph of lithic graywacke with the clasts of quartz, chert, and biogenetic fragments in the shale -Sandstone alternation in the eastern parts of the Nam Duk Formation. Note that matrix is mainly clay minerals, and cementing material is calcareous, Specimen from the locality km 34.863. The long axis of photograph is 4 mm.

a) without nicols



b) under crossed nicols

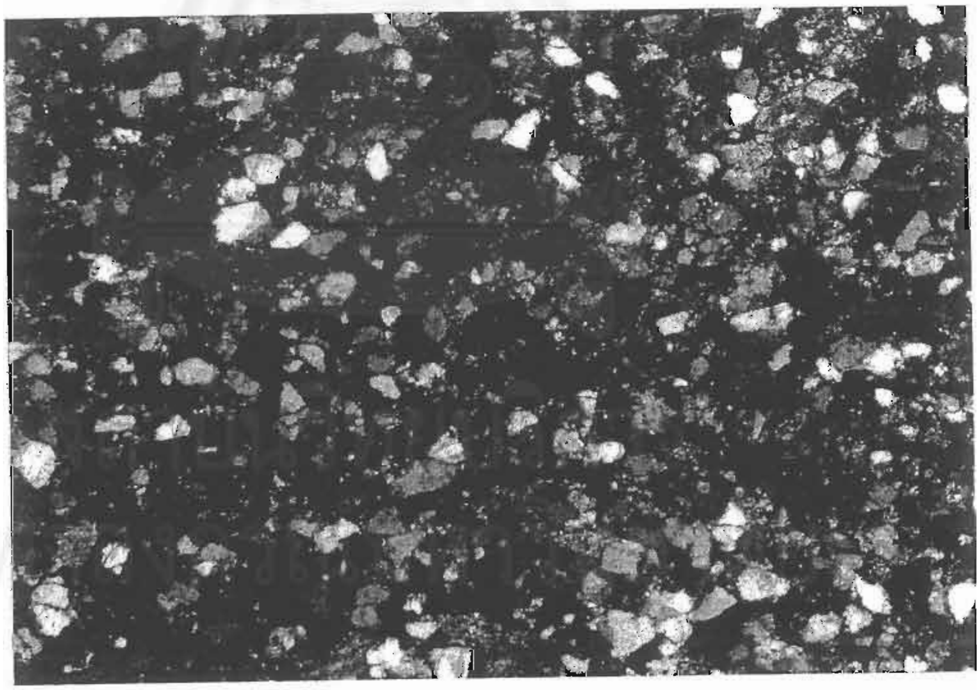


Fig.3.28 Photomicrograph of fine–grained lithic graywacke with moderately good sorting and containing clasts of quartz, chert, biogenetic, and rock fragments of the Sandstone-shale-limestone alternation unit (km 40.460) in the Eastern parts of the Nam Duk Formation. The long axis of photograph is about 4 mm.

spinels was not only deposited in turbiditic sandstone-shale successions, but also extend to more shallow environment which can be associated with limestone. Numerous detrital spinels, nearly ten grains were recognized under the microscope. They usually reveal deep brown to opaque with ranging sizes from 65 μm to 100 μm. Grain shapes of detrital grain are anhedral to euhedral.

Comparing with both spinel-bearing sandstones in the western part and eastern part, it is possible to make some recognition about lithology of sandstones which carrying chromian spinels. The lithology of lithic graywackes in this sandstone-shale-limestone alternation is more similar with those of lower sandstone-shale alternation in the western part than those of lithic graywacke in shale-sandstone alternation in the eastern part. Grain sizes of both are a little bit larger than of sandstones in shale-sandstone alternation in the eastern part. According to their composition of both samers, both also contain more biogenic fragments than of shale-sandstone alternation in the eastern part.

CHAPTER IV

DETRITAL CHROMIAN SPINELS

4.1 General statement

In the sandstone provenance studies, the approaches of single-mineral analysis are extremely diverse, such as the petrographic classification of detrital quartz (Basu et al., 1975), the compositional analysis of detrital feldspars (Trevena and Nash, 1981), or heavy minerals (Helmold, 1985; Cawood, 1991; Basu and Molinaroli, 1991; Morton, 1991), and the advanced laboratory methods of radiogenic decay or fission-track dating of detrital zircons (Kröner et al., 1987; Smith and Gehrels, 1991; Ross and Parrish, 1991). In spite of their restrictions, each of these approaches can increase important detail and confidence in provenance interpretation based on bulk composition techniques such as detrital-modes analyses.

Compositional analysis of chromian spinels is customarily applied for the petrological studies of spinel-bearing mafic and ultramafic rocks (such as Irvine, 1965, 1967, 1977; Dick and Bullen, 1984; Haggerty, 1991; Arai, 1992, 1994a, 1994b; Arai and Matsukage, 1996). Since the composition of chromian spinels is a sensitive indicator of physico-chemical condition of the parent melt during the crystallization (Irvine, 1965; Dick and Bullen, 1984). Furthermore, chromian spinel is also chemically more durable than other ultramfic minerals, which are invariably always major phases in the parent rocks. Chromian spinel is regard as the only mineral unaltered by the sub-greenschist facies serpentinization common in sea-floor environment (Hekinian, 1985; Arai and Okada, 1991) as olivine and most other mafic minerals are altered swiftly at near-surface.

Regarding to electron microprobe analyses of detrital chromian spinels for the provenance determination of sources, such theme has wide-spreadly researched during this decade. Detrital chromian spinels are important to provenance studies as same as common application of spinels in petrologic studies of parent ultramafic-mafic rocks (Arai and Okada, 1991; Arai, 1992; Hisada and Arai, 1993, 1994; Cookenboo et al., 1997; Hisada et al., 1998). Recent chemical data accumulation of chromian spinels in ultramafic-mafic rocks facilitates the precise comparison between detrital grains in clastic rocks and their parent source rocks. Despite the widespread use of chromian spinels in petrologic studies, the application of detrital chromian spinels in provenance studies has been limited and is now in progress.

4.2 Previous works- Significance of chromian spinels

Previous application of chromian spinel chemistry to support the provenance interpretation includes a study by Press (1986), who used the morphology and composition of detrital chromites to relate the sediments of the Rhenish Massif to an Alpine-type ophiolite instead of mid-oceanic ridge or stratiform intrusion. Pober and Faupl (1988) used spinels from heavy-mineral stream concentrates from a large area in the Eastern Alps, and on the basis of spinels in lherzolites and harzburgites established that the greatest population of spinel data is in the abyssal harzburgite field, equivalent to Dick and Bullen (1984). Similarly, Arai and Okada (1991) used chemistry of detrital chromian spinels to compare the petrologic characteristics of the lost peridotite mass with those of currently exposed peridotite, and to discuss a tectonic history of the serpentine belt itself. Hisada and Arai (1993, 1994) studied the chemical compositions of detrital chromian spinels in the Cretaceous Sanchu sandstone in Japan to relate serpentinite protrusion in the fore-arc region, and to determine the tectonic history of the Kanto Mountains. Recently Cookenboo et al. (1997) compared the composition of detrital chromian spinels in volcanic lithic sandstones from the Bowser Basin with the compositional range of spinels from the literature on ultramafic rocks. Bowser Basin spinels are compositionally matched those from Alpine-type peridotites emplaced by obduction of marginal-basin crust and island-arc complexes. This provenance interpretation was in a good agreement with earlier interpretation that related chert pebbles in the Bowser Basin and fitted in the detrital model analysis of sandstone, which called for obducted oceanic crust and island arc-source terrane.

4.3 Characteristics of detrital chromian spinels in sandstones

Detrital chromian spinel study is regarded as a single-mineral analysis applied to determine tectonic provenance. The study can increase tremendous confidence in provenance interpretation and simultaneously add the detailed secrets unavailable from normal approaches. The electron probe microanalysis (EPMA) of detrital chromian spinels in the sandstones from the Nam Duk Formation is adopted to unravel the geological history of the Nam Duk Formation in this research. Detailed studies of basic geological approach and geochemistry of the detrital chromian spinels are aimed to evaluate tectonic evolution of the Phetchabun fold and thrust belt (PFTB).

4.3.1 Definition of chromian spinels

Spinel, in general, means an isometric mineral that has the general formula $MgAl_2O_4$. The mineral spinel ($MgAl_2O_4$) is also an end-member of the spinel group in the oxides, which have two non-equivalent metal atom sites (AB_2O_4). The minerals of the spinel group usually show extensive solid solution between the various end-member compositions. There is, for example, the extensive solid solution between magnetite (Fe_3O_4) and ulvöspinel ($Fe^{2+}{}_2TiO_4$). Furthermore, there are substitution between chromite ($FeCr_2O_4$) and magnesiochromite ($MgCr_2O_4$), between spinel ($MgAl_2O_4$) and hercynite ($FeAl_2O_4$), and so on. The complexity of the chemical substitutions in this spinel group makes it very difficult to use triangular composition diagrams for expression of the various solid solutions extends; instead, a "spinel prism" (Fig. 4.1) is used for such chemical representations.

Following the general literature on the chromian spinel studies, "chromian spinel" as define in this study is a term used in the broadest sense to denote composition which are Cr-rich but which extensive solid solubility among members on the base of the so-called

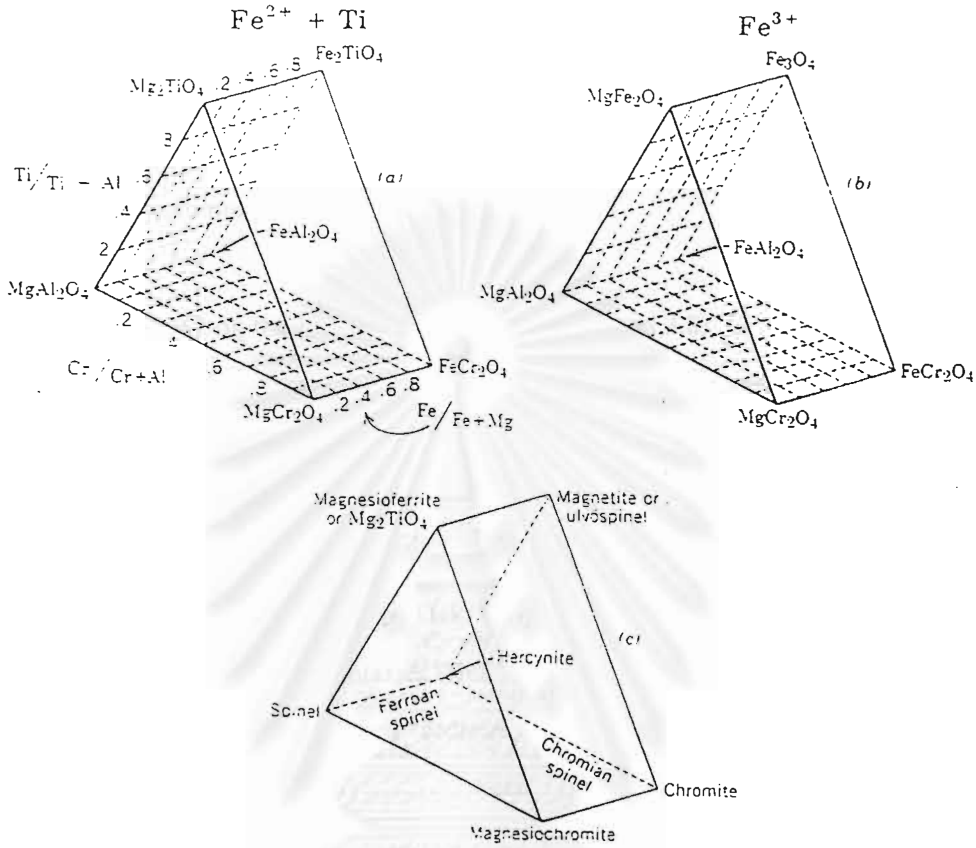


Fig. 4.1 End member compositions in the spinel group as represented in a spinel prism

spinel prism defined by the vertices of the (Mg, Fe^{2+})(Cr, Al, Fe^{3+})$_2O_4$ composition space (Irvine, 1965, 1967; Haggerty, 1976, 1991; Dick and Bullen, 1984; Sack and Ghiorso, 1991). Generally chromian spinel occurs in the intermediate mode among hercynite ($FeAl_2O_4$), spinel ($MgAl_2O_4$), and chromite ($FeCr_2O_4$) at or near the base of the spinel prism (Kerr, 1977; Klein and Hurlbut, 1993).

4.3.2 Accumulation and contribution

Along the Highway 12 (Figs. 3.4, 3.5 and 3.8), Lom Sak-Chum Phae, numerous detrital chromian spinels are discovered as one of the accessory minerals in sandstones from the Nam Duk Formation, forming as a part of PFTB. Such a discovery can provide the first and pioneering information for the chromian spinel studies in Thailand.

Generally the Nam Duk Formation included a Permian orogenic sequence of pelagic sediment, flyschs and molasses (Helmcke and Kraikhong, 1982; Helmcke and Lindenberg 1983) with the great variety of sedimentary rocks corresponding to their depositional environments. Although sandstones are collected from the entire Nam Duk Formation along the Highway 12 between km 16.0-21.5 and km 34.0-42.0, the detrital chromian spinels are usually found in the flysch-type sediments, or sandstone-shale alternation units under the microscope, both the western (km 20.120-21.500) and the eastern (km 34.095-37.200) areas. It is important to note that these sandstones have been documented as turbidites. These sandstones usually alternate with shales. Several indicators for deposition by turbidity currents can be observed. The successions often reveal graded bedding, cross-bedding, lamination and sole marking. Directions of currents, as measured from the flute casts, groove casts and cross-lamination for the probable source location of the detrital chromian spinels, varies from SE to NW ranging to S to N, and SW to NE ranging to WSW to ENE. It is noted that the detrital chromian spinels in alternated shale should be very smaller to observe under the microscope.

Detrital chromian spinels are also discovered in the molasse-type sedimentary rocks reported between km 37.200 and km 40.700, but in less concentration. The sedimentary sequences comprise mainly sandstones, shales and fossiliferous limestones. Detrital chromian spinels are documented during the microscopic studies on the sandstones, which associate with shale. As the Middle Permian fusulinacean fauna including *Verbeekina verbeeki* (Geinitz), *Psuedodolilina psuedolepida* (Deprat) and other shallow marine fossils are reported in the associated well-bedded limestones (Chutakositkanon et al., 1997).

4.3.3 Petrography of detrital chromian spinels

Chromian spinel grains discovered in this study area are generally deep brown to almost opaque in transmitted light corresponding to their Cr-Al-Fe^{3+} composition (Bernier, 1990). These detrital chromian spinels are the most abundant in fine to very fine sandstones in turbidite sequences, especially in the western and eastern sandstone-shale alternation unit. Comparing with the detrital chromian spinels of the Alpine-type peridotite origin in the Bowser Basin in the Canadian Cordillera (Cookenboo et al., 1997), the detrital chromian spinels in the Nam Duk Formation are rather small. Their grains are varied between 20 μm to 75 μm in size. Some of them rise to more than 100 μm across especially in the Western part of the Nam Duk Formation. Considering to the grain sizes of detrital chromian spinels, however, they are too small to observe and identify in the hand specimens.

To completing the studies of physical properties of small-sized chromian spinels that can not be noticed from hand specimens, literature review was carefully performed. The physical properties of chromian spinels are intermediate between spinel and chromite. They resemble chromite but are more transparent. The minerals, spinel-chromite, are isometric. They are hard, brittle minerals. The physical feature varies from them of chromite and spinel depending on their compositions. The hardness is about 5.5-8.0 as the specific gravity is about 3.6-4.8. Chromian spinels are usually black minerals with brown streak. Some of them are translucent to transparent minerals with varied colors. Luster is sub-metallic. Weakly magnetic feature usually in granular masses that are frequently associated with serpentine is sometimes recognized (Vanders and Kerr, 1967)

In transmitted light, the occurrence of detrital chromian spinels in this study (Figs. 4.2-4.9) as small, high refractive index (n=1.72-2.16) grains that are either opaque or deeply brown colored serves to distinguish them from other minerals in sandstones. The translucent grains are usually deep brown with the darker thin edges. It is very valuable to explain that translucent spinels are easier to be microscopically recognized for chromian spinels than opaque spinels. Both of them are mostly sub-angular to angular. Several grains exhibit sub-hedral to euhedral suggesting the preservation of original crystal shape. Grains are generally homogeneous and show no obvious signs of zoning or twinning. Some of larger grains show very weak birefringence. Several spinel grains contain inclusions with unknown composition. As in reflected light, high Cr-spinels are often black or opaque with a sub-metallic to metallic luster in reflected light depending on the content of Cr and thickness of thin sections.

4.3.3.1 The western part

After the discovery of detrital chromian spinels in the eastern part of the Nam Duk Formation around km 34.875, special attention was paid to the new locations that extend from the first location. Detrital chromian spinels in the Western sandstone-shale alternation (km 20.120-21.475) are probably new data for the characteristics of chromian spinel in the Nam Duk Formation. Chromian spinels are found in fine-to very fine sandstones interbedded with shale. Generally they display reddish brown to deep brown under microscope. Their grains are varied from 20 μm to 190 μm in size. Petrographically, the relationship between grain shape and grain size is recognized and can be divided into two groups, smaller and larger sizes. The smaller-sized group commonly ranges from 20 μm to 70 μm, and exhibits anhedral while the other group is sub-hedral to euhedral and ranges in size from 110 to 190 microns. Inclusions are sometimes found in both groups.

4.3.3.2 The eastern part

It is the fact that the shale-sandstone alternation unit in eastern part where chromian spinels were firstly found contains the majority of detrital chromian spinels of

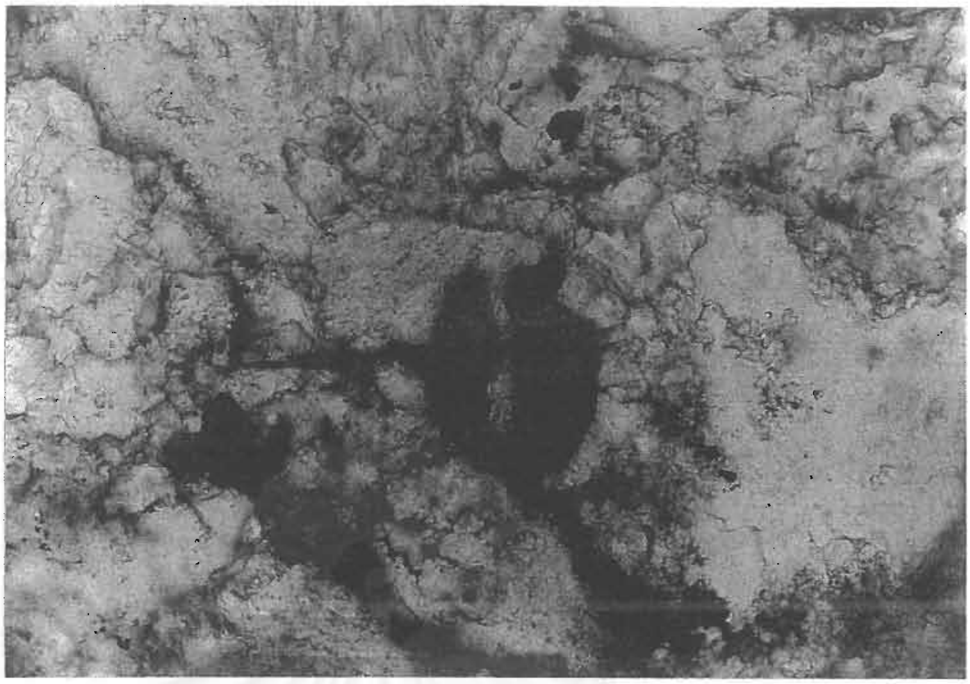


Fig. 4.2 Photomicrograph of detrital chromian spinel in Nam Duk sandstone showing deep brown color and subhedral habit. Polished--thin section without nicols.The long axis of photograph is about 4 mm.

Fig. 4.3 An example of detrital chromian spinel in sandstone, Nam Duk Formation, showing brown--colored, anhedral habit. Polished--thin section without nicols. The long axis of photograph is about 4 mm.

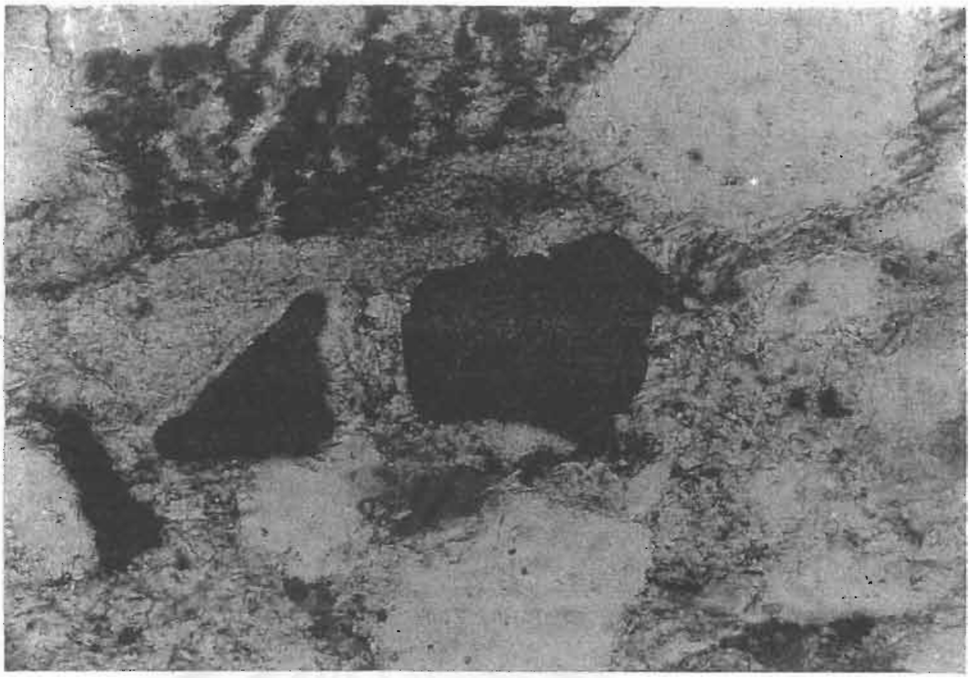


Fig. 4.4 An example of detrital chromian spinel detected in sandstone, Nam Duk Formation, showing brown–colored, subhedral to euhedral habits. Polished-thin section without nicols. The long axis of photograph is 4 mm.

Fig. 4.5 An example of detrital chromian spinel observed in sandstone, Nam Duk Formation, displaying a sharp crystal face with rather dark brown color. Polished-thin section without nicols. The long axis of photograph is 4 mm.

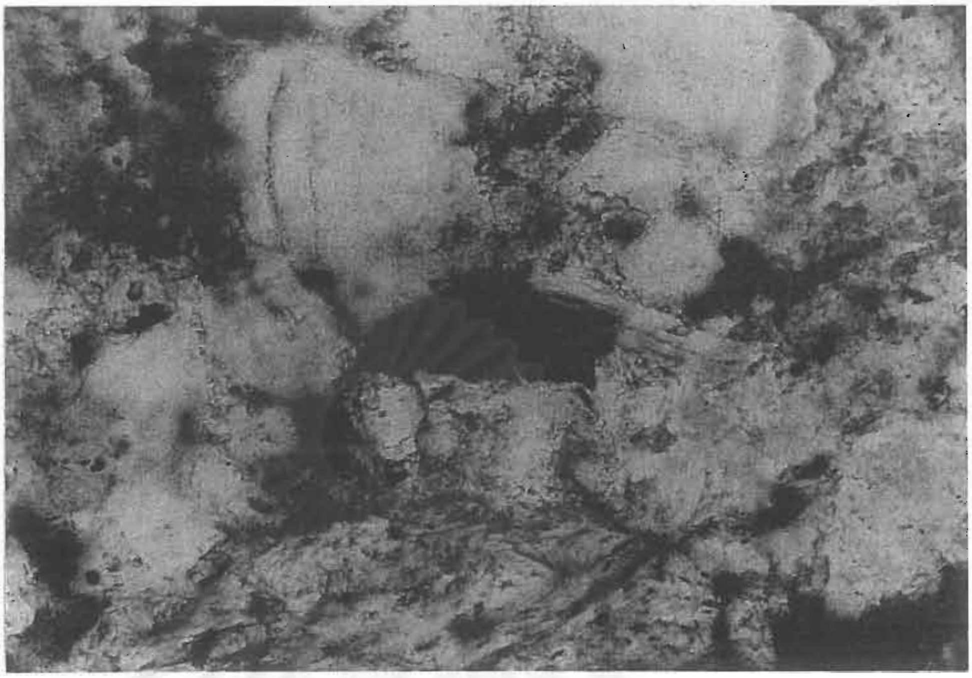


Fig. 4.6 An example of detrital chromian spinel in sandstone, Nam Duk Formation, displaying one–sharp crystal side and brown color

Fig. 4.7 An example of detrital chromian spinel occuring in sandstone, Nam Duk Formation, showing deep brown colored and euhedral crystal form. Polished-thin section without nicols. The long axis of photograph is 4 mm.

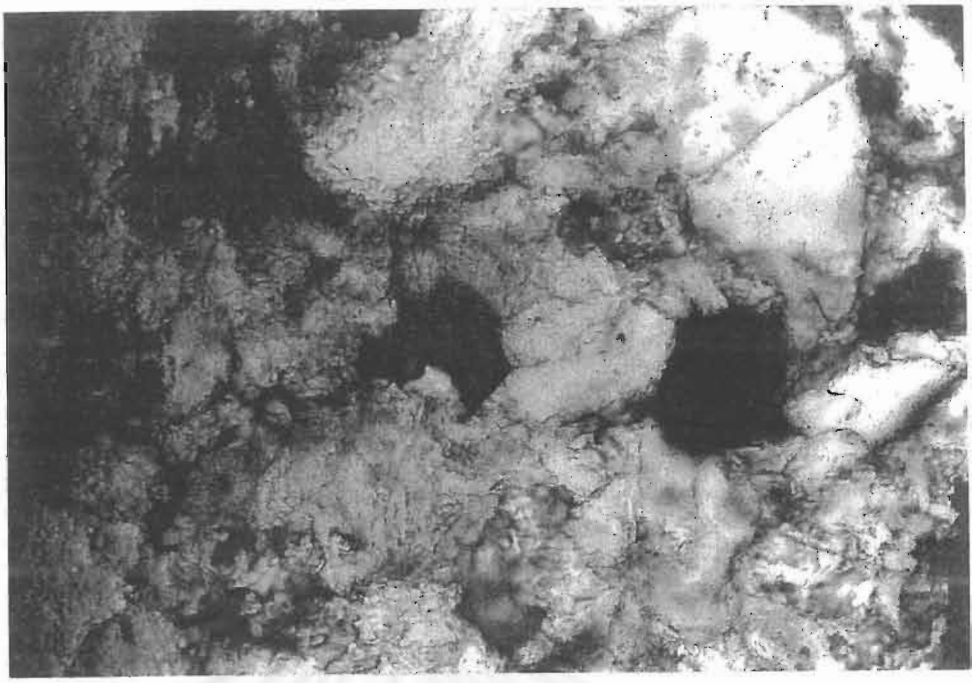


Fig. 4.8 An example of rather small spinel occuring in sandsstone, Nam Duk Formation, showing light–brown colored and subhedral grain shape. Polished-thin section without nicols. The long axis of photograph is about 4 mm.

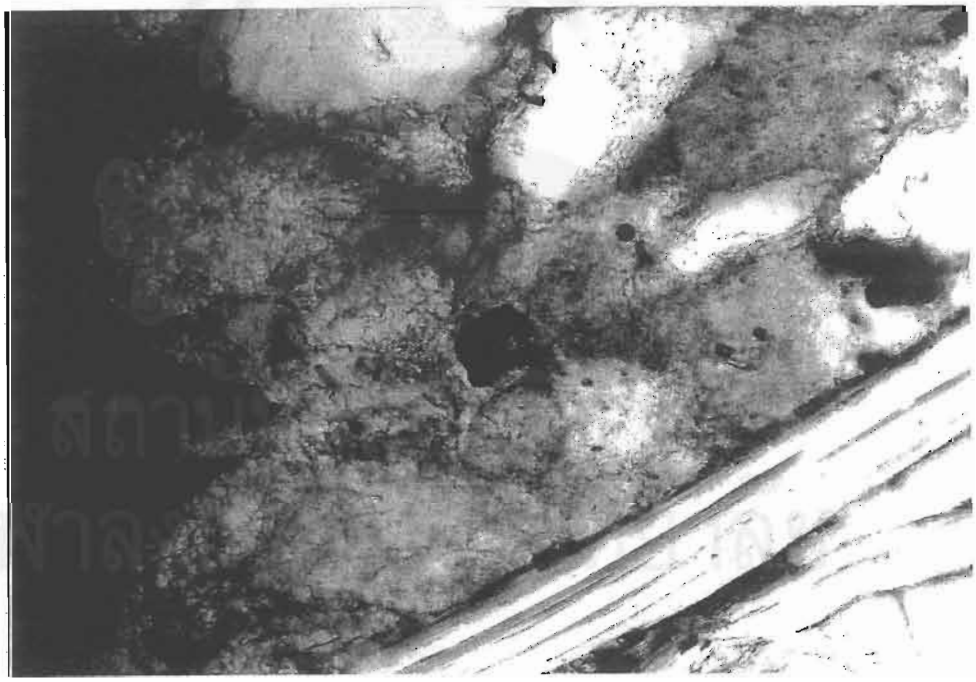


Fig. 4.9 An example of rather fine–grained spinel occuring in sandstone, Nam Duk Formation, showing light–brown subhedral habit. Polished-thin section without nicols. The long axis of photograph is about 4 mm.

the Nam Duk Formation. Up to 80 grains of detrital chromian spinels were found in the sandstones from turbidite sequence of this alternation. Characteristically the detrital chromian spinels grains are rather small in size ranging from 20 μm to 100 μm. Regarding the color of chromian spinels under microscope, two kinds of chromian spinels grains observed are reddish to dark brown and black (or opaque) spinels. The black spinel type displays euhedral and more variation in grain size (20-100 μm) compare to the dark brown spinels.

There is interesting relationship between color of chromian spinels and their type localities in this rock unit. Reddish to dark brown chromian spinels are dominant in the lower part of this unit, while to the east of km 35.168, opaque spinels are commonly found in very fine-grained sandstone. However, it is unable to correlate this relationship throughout the Nam Duk Formation due to the limited presence of chromian spinels.

Regarding the literature reviews, the detrital chromian spinels are usually associated with sandstone-shale alternation in turbiditic sequences, especially in graywacke which alternates with shale (Hisada and Arai, 1993, 1994; Cookenboo et al., 1997). Their environment of deposition is interpreted as deep-marine environments. The occurrence of detrital chromian spinels in this sandstone-shale-limestone alternation unit (km 37.800-40.700) reflecting the provenance of the spinel-bearing sandstones is firstly observed and recorded in this study. The author can also realize that chromian spinels are not associated only with turbiditic sandstone-shale sequences but also extend in more shallower environment like one of this sandstone-shale-limestone alternation succession.

About ten grains of detrital chromian spinels were recognized under the transmitted light. Spinels in this unit show deep brown to opaque, vary in grain shapes from anhedral to euhedral. With comparison to the former rock units, detrital chromian spinels in this succession are slightly larger. They range from 65 μm to 100 μm. Anyhow the detrital chromian spinels in this alternation unit can be loosely divided into two groups by their sizes, smaller and larger. The smaller sized group, ranging between 60 μm and 75 μm, is relative with euhedral or subhedral shapes, as the larger-sized group, ranging in particle sizes around 100 μm, is usually related with anhedral.

4.3.4 Geochemical characteristics

4.3.4.1 Sampling and analytical techniques

Thin-section examination indicates that chromian spinels are the accessory mineral (less than 1%) in the sandstone strata. Samples containing relatively higher concentrations of chromian spinels and distributing from several locations were selected during thin-section analysis for microprobe study. Several sandstones were chosen to represent all the sandstone strata from each rock unit exposed in the study area. More than 100 grains were identified for the representatives of chromian spinel for microprobe studies. Due to the constraints on available working time, only representative 35 grains from the flysch-type and molasse-type sandstones were analyzed.

Geochemical data on major and minor elements of these detrital chromian spinels were obtained from polished thin sections using the electron probe microanalysis (EPMA). EPMA is a technique for chemically analyzing small selected areas of solid samples, in which X-rays are excited by a focused electron beam. The X-rays spectrum contains lines which are characteristic of the elements present, hence a qualitative analysis is easy to obtain by identifying the lines from their wavelengths. By comparing the intensities of these lines with those emitted from standards it is also possible to determine the concentration of element (quantitative analysis).

The preparation procedure is that for normal thin sections in the early stages but, because of the high stress of polishing, a strong adhesive (e.g. epoxy resin) should be used for attaching the rock slice to the glass slide. The rock slice was ground to a thickness greater than the 30 μm final thickness required, before starting the polish in the next step.

For X-ray analysis it is extremely desirable to avoid topographic effects, therefore the specimens made are flat and well polished. Starting with a flat ground surface, polishing is carried out with progressively finer grades of abrasive (carborundum or emery in the coarser grades and diamond in the late stage). Woven nylon lap is preferable to clothe with a nap, since it is has fewer tendencies to produce surface relief between minerals of different hardness.

As most geological samples being nonconductors of electricity, chromian spinels require a conductive coating to prevent charging under electron bombardment. For X-ray analysis, carbon is the preferred coating element in this study, since it has a minimal effect on the X-ray spectrum. The method of carbon coating is to place thin sections in a vacuum chamber with a current of around 100 Å passed through a carbon evaporation source consisting of carbon rods in contact under light pressure (should be less than ~10^{-4} torr). The optimum thickness of carbon is about 20 nm (Reed, 1996). This thickness can be controlled approximately by using a fixed current and evaporation time.

The quantitative major and minor element analyses were carried out by a JEOL, model no. JXA-8621 Superprobe at the Chemical Analysis Center, the University of Tsukuba. Analysis of standards as unknowns was done at the beginning and the end of analytical runs to ensure proper calibration throughout. All Fe are expressed as FeO. In this investigation cationic ratios were calculated, assuming spinel stoichiometry.

It is visualized that the Cr-rich spinel grains are the solid solutions of the chromian spinel component, (Mg, Fe^{2+})(Cr, Al, Fe^{3+})$_2O_4$, and the ulvöspinel component, $Fe^{2+}{}_2TiO_4$. All Mn was added to total Fe before the calculation. All Ti was combined with Fe as the ulvöspinel component ($Fe^{2+}{}_2TiO_4$). After that, the cation fraction of Mg, Fe^{2+}, Al, Cr and Fe^{3+} were calculated for the chromian spinel component following Arai and Hisada (1991), Arai (1992), Hisada and Arai (1993), Arai and Matsukage (1996), and Arai et al. (1997).

Regarding the analyzing resolution of the probe (10 μm), many detrital spinels were much smaller than detection limit. Only chromian spinel grains that have polished flat surface larger than 10 μm diameter could be investigated. Total 35 representative chromian spinel grains were selected for geochemical data of detrital chromian spinels in the Nam Duk Formation.

4.3.4.2 Quantitative major element compositions

The result of the quantitative electron microprobe analysis (Table 4.1) was expressed in first instance as element mass concentrations (weight percent). The concentration of unanalyzed elements of O was obtained by computer calculation from the assumed valencies of the cations. The analyses, carried out by a JEOL Superprobe, were reported as both "weight percent oxide" and "number of atoms".

Detrital spinels measured in this study vary widely in major-element concentrations. Compositionally chromian spinels have high values of Cr_2O_3 about 43.0% to 56.0%. Some of them have Cr_2O_3 content less than 40.0%. The other major oxides of the chromian spinels are Al_2O_3 ranging from 7.3% up to 34.6%, FeO (total Fe) ranging from 12.8% to 39.3%, and MgO ranging from 4.5% to 17.3%. As the important minor oxides, TiO_2 ranging 0.015% to 1.159%; NiO ranging less than 0.001% to 0.196%; and MnO ranging 0.168% to 0.757%, make up only trace amounts.

Numbers of atoms derived from quantitative electron microprobe analysis were computer-normalized to 4 oxygens (which is appropriate for chromian spinels). The cation total is close to the theoretical value of three for chromian spinels. Detrital chromian spinels of the Nam Duk Formation have high Cr cation about 0.542 to 1.540, averaging about 1.261. The Al cations are ranging from 0.305 to 1.243 and averaging about 0.604. The other major element is the Mg cations within the range of 0.236 to 0.772 and average about 0.505. The Fe cation is the only element present that has dual valency, the proportions of Fe^{2+} and Fe^{3+} can be recalculated assuming ideal spinel stoichiometry following Arai and Hisada (1991) as previous metioned. Recalculated iron cations, Fe^{2+} and Fe^{3+}, are ranging from 0.232 to 0.766 and less than 0.001 to 0.389, respectively. Their averages are 0.497 for Fe^{2+} and 0.148 for Fe^{3+}.

Table 4.1 The representatives of detrital chromian spinels in the Nam Duk Formation

Sample No	VC-28(3)-1	VC-29-1-A	VC-31(2)-1-E	VC-34(3)-3	VC-35(2)-1	VC-39(2)-1	VC-39(2)-2	VC-40(3)-1	VC-40(3)-3
ocality (km n	20.8	21.09	34.863	35.165	35.168	40.46	40.46	40.46	40.46
SiO2	0.134	0.009	0.022	0.017	0.101	0.082	0.039	0.114	0.083
Al2O3	9.529	10.925	14.37	8.368	10.608	11.38	14.406	22.45	13.94
TiO2	0.427	0.015	0.46	0.26	0.264	0.924	1.034	1.159	0.54
Cr2O3	56.906	58.037	44.603	54.863	51.463	43.501	50.925	44.005	45.751
FeO	26.462	20.657	27.323	24.809	30.01	39.307	25.049	20.642	27.42
NiO	0.013	0.037	0	0.079	0.127	0	0.109	0.154	0.085
MnO	0.356	0.362	0.42	0.423	0.474	0.275	0.315	0.757	0.393
MgO	8.628	10.083	7.876	10.045	5.35	6.058	6.345	14.3	8.947
CaO	0.344	0	0.138	0.019	0.015	0.015	0.494	0.055	0.109
Na2O	0	0.112	0.04	0.011	0	0	0.058	0.015	0.057
K2O	0.036	0.015	0	0	0.041	0.005	0.045	0.017	0
Total	102.835	100.252	95.252	98.894	98.453	101.547	98.819	103.668	97.325
Cation	4 O	4 O	4 O	4 O	4 O	4 O	4 O	4 O	4 O
Si	0.0044	0.0003	0.0008	0.0006	0.0035	0.0028	0.0013	0.0034	0.0029
Al	0.3715	0.4259	0.5934	0.3388	0.4387	0.4649	0.5714	0.7941	0.5631
Ti	0.0106	0.0004	0.0121	0.0067	0.007	0.0241	0.0262	0.0262	0.0139
Cr	1.4881	1.5176	1.2355	1.4898	1.4276	1.1919	1.3548	1.0442	1.2396
Fe	0.7319	0.5714	0.8006	0.7126	0.8806	1.1393	0.7049	0.5181	0.7858
Ni	0.0003	0.001	0	0.0022	0.0036	0	0.0029	0.0037	0.0023
Mn	0.01	0.0101	0.0125	0.0123	0.0141	0.0081	0.009	0.0193	0.0114
Mg	0.4254	0.4971	0.4113	0.5143	0.2798	0.313	0.3183	0.6397	0.457
Ca	0.0122	0	0.0052	0.0007	0.0006	0.0006	0.0178	0.0018	0.004
Na	0	0.0072	0.0027	0.0007	0	0	0.0038	0.0009	0.0038
K	0.0015	0.0006	0	0	0.0018	0.0002	0.0019	0.0007	0
Total	3.0559	3.0316	3.0741	3.0787	3.0573	3.1449	3.0123	3.0521	3.0838
Fe total	0.7419	0.5815	0.8131	0.7249	0.8947	1.1474	0.7139	0.5374	0.7972
Fe*	0.7207	0.5807	0.7889	0.7115	0.8807	1.0992	0.6615	0.485	0.7694
Fe2+	0.5765	0.51	0.5984	0.50383333	0.72913333	0.71	0.65036667	0.34796667	0.5527
Fe3+	0.1442	0.0707	0.1905	0.20766667	0.15156667	0.3892	0.01113333	0.13703333	0.2167
TiO2	0.427	0.015	0.46	0.26	0.264	0.924	1.034	1.159	0.54
Cr#	0.80022586	0.78085927	0.67554268	0.81472164	0.76493597	0.71939884	0.70335375	0.56802481	0.68763521
Mg#	0.42459327	0.49359547	0.40734872	0.50514013	0.27732258	0.30596285	0.32859601	0.64768815	0.45260969
Cr3#	0.74263899	0.7534505	0.61181539	0.73163305	0.70747985	0.58255132	0.69931177	0.52861964	0.6138457
Al3#	0.18539774	0.21144871	0.29384966	0.16638292	0.21740782	0.22722385	0.2949415	0.4020081	0.2788452
Fe3+3#	0.07196327	0.03510078	0.09433495	0.10198402	0.07511233	0.19022483	0.00574673	0.06937226	0.1073091

After calculating the cation fraction of major-element for the chromian spinel component, (Mg, Fe^{2+})(Cr, Al, Fe^{3+})$_2O_4$, of each sample grains, atomic ratios are used herein for the chromian spinel component, unless weight percent oxide is specified. The notation Cr# is used for atomic ratios of Cr/(Cr+Al), and Mg# is used for atomic ratios of Mg/(Mg+Fe^{2+}), following common practice in petrologic literatures (e.g., Dick and Bullen, 1984; Arai and Matsukage, 1996; Cookenboo et al., 1997). Characteristically these spinels have high Cr content and relatively vary in TiO_2 content. The atomic ratios Cr/(Cr+Al) or Cr#s vary considerably from 0.304 to 0.825, mostly above 0.5 with the average about 0.677. Only three out of thirty-three grains measured had Cr# less than 0.4, they belong to the detrital chromian spinels which are discovered in the Eastern sandstone-shale alternation unit. The atomic ratios Mg/(Mg+Fe^{2+}) or Mg#s range widely from 0.236 to 0.769 and average about 0.504, with Mg concentration generally decreasing as Fe increases. The Fe^{3+} concentration is consistently low. The atomic ratios Fe^{3+}/(Cr+Al+Fe^{3+}) in detrital spinels are mostly below 0.15 with the average about 0.073. Only two out of thirty-three grains analyzed had the atomic ratios Fe^{3+}/(Cr+Al+Fe^{3+}) almost rise to 0.2.

4.3.4.2.1 The western part

Detrital spinels discovered in the Lower sandstone-shale alternation unit (km 20.120 to km 21.475) in the western part have high values of Cr_2O_3 about 54.387% to 58.037%. The other major oxides recognized are Al_2O_3 ranging from 9.529% to 10.925%; FeO (total Fe) ranging from 20.052% to 26.462%; and MgO ranging from 8.628% to 10.083%. The minor oxides are TiO_2 ranging 0.015% to 0.856%; NiO ranging 0.007% to 0.039%; and MnO ranging 0.214% to 0.362%.

Based on appropriately 4 oxygens, chromian spinels of this group have high averaged Cr cations about 1.505 within the range of 1.488 to 1.518. The Al cations are ranging from 0.372 to 0.426 and averaging about 0.404. The Mg cations are ranging 0.425 to 0.497 with the average about 0.472. Recalculated Fe^{2+} and Fe^{3+} cations are ranging from

0.507 to 0.577 and 0.063 to 0.144, respectively. The averages of recalculated ferrous iron and ferric iron cations are 0.526 for Fe^{2+} and 0.086 for Fe^{3+}.

Considering to the cation fractions, detrital chromian spinels from this unit are generally high in Cr# with the average about 0.789. The Cr#s are ranging from 0.781 to 0.800. As the Mg#s range from 0.425 to 0.494 and average about 0.473. The atomic ratios $Fe^{3+}/(Cr+Al+Fe^{3+})$ are ranging from 0.032 to 0.072 with the average about 0.043.

Only one spinel, VC-29(3)-2, out of the others has a little bit lower value of Cr and Fe contents (Cr_2O_3 44.86%; FeO 12.786%) and higher value of Al and Mg contents (Al_2O_3 22.368%; MgO 16.734%). Its cations Cr, Al, Mg, Fe^{2+}, and Fe^{3+} based on 4 oxygens are 1.098, 0.816, 0.772, 0.232, and 0.094, respectively. VC-29(3)-2 has Cr# about 0.574 and Mg# about 0.769.

4.3.4.2.2 The eastern part

In the Eastern part of the Nam Duk Formation, detrital chromian spinel are discovered in two kinds of alternations, both shale-sandstone alternation (km 34.095 to km 37.200) and sandstone-shale-limestone alternation (km 37.200 to km 40.700) units.

Compositionally detrital chromian spinels in the shale-sandstone alternation (km 34.095 to km 37.200) have the values of Cr_2O_3 about 22.515% to 58.485%, probably very wide range. Al_2O_3 ranging from 7.303% to 34.632%; FeO (total Fe) ranging from 13.482% to 31.490%; MgO ranging from 4.468% to 17.316% are measured as the major components of these spinels. As the minor oxides are TiO_2 ranging from 0.016% to 0.670%; NiO ranging from less than 0.001% to 0.196%; and MnO ranging from 0.174% to 0.571%.

After calculating based on 4 oxygens, the spinels have high Cr cation ranging from 0.542 to 1.540 and averaging about 1.240. The other major cations are Al ranging from 0.305 to 1.243 and averaging about 0.622; Mg ranging from 0.236 to 0.742 and averaging about 0.511; Fe^{2+} ranging from 0.265 to 0.766 and averaging about 0.492; and Fe^{3+} ranging from less than 0.001 to 0.378 and averaging about 0.156.

Generally detrital chromian spinels from this group have the atomic ratios Cr/(Cr+Al) or Cr#s range widely from 0.304 up to 0.825 and average about 0.667. The atomic ratios $Mg/(Mg+Fe^{2+})$ or Mg#s are about 0.236 to 0.737 with the average about 0.509. Both atomic ratios are very wide range comparing with those of Lower sandstone-shale alternation in the western part. The atomic ratios of $Fe^{3+}/(Cr+Al+Fe^{3+})$ are also widely ranging from less than 0.001 to 0.184, with the average about 0.077.

Characteristically detrital chromian spinels in the sandstone-shale-limestone alternation (km 37.200 to km 40.700) have the values of major components of Cr_2O_3 about 43.501% to 50.925%; Al_2O_3 about 11.380% to 22.450%; FeO about 20.364% to 39.307%; and MgO about 6.058% to 14.300%; As the minor components are TiO_2 ranging from 0.037% to 1.159%; NiO ranging from less than 0.001% to 0.154%; and MnO ranging from 0.275% to 0.757%.

Based on appropriately 4 oxygens, chromian spinels in this group have averaged Cr cation about 1.202 within the range of 1.044 to 1.355. The Al cations are ranging from 0.465 to 0.794 and averaging about 0.629. The Mg cations are ranging 0.313 to 0.640 with the average about 0.450. Iron is recalculated as Fe^{2+} ranging from 0.348 to 0.710 with the average about 0.549, and Fe^{3+} ranging from 0.011 to 0.389 with the average about 0.167.

Detrital chromian spinels from the Eastern sandstone-shale-limestone alternation yield the atomic ratios of Cr/(Cr+Al) or Cr#s about 0.568 to 0.719 with the average about 0.658, and of $Mg/(Mg+Fe^{2+})$ or Mg#s about 0.306 to 0.648 with the average about 0.451. Both atomic ratios are realized that they are ranging in the narrower scale than the shale-sandstone alternation. The atomic ratios $Fe^{3+}/(Cr+Al+Fe^{3+})$ are about 0.006 to 0.190 with the average about 0.083.

CHAPTER V

TECTONIC SETTING - DISCUSSIONS

Based upon field investigation and petrochemical studies on the detrital chromian spinels stated in previous chapters, a discussion on deposition environment for the Nam Duk Formation and its relevant tectonic settings can be made as in details below:

5.1 Depositional environments of the Nam Duk Formation

The occurrence of thickly bedded sandstones, thin-bedded shales, and limestones, and the prolific organism in gray limestones from km 37.200 to km 40.700 in the eastern study area, point to the shallow marine environment. This conclusion is rather similar to that mentioned earlier as molasse by Altermann (1983, 1989). However, based upon the index fossils such as *Pseudodoliolina pseudolepida* (Depart), *Verbeekina verbeeki* (Geinitz), *Abadehella* cf. *coniformis* (Okimura and Ishii), and *Sumatrina* sp. (see Chutakasitkanon et al., 1997), the age of this shallow-marine carbonate/clastic sequence is limited only in latest Middle Permian (Midian). So this sequence may have formed in a more restricted age than that reported earlier by Helmcke (1984) who proposed early Early Permian to early Late Permian for the age of the Nam Duk Formation.

Considering to the chromian spinel-bearing sandstones, lithological associations of both routes at km 20.120 to km 21.475 and km 34.095 to km 37.200 are characterized by the presence of thickly bedded graywacke sandstone with interbedded dark-colored shale. These rock sequence in conjunction with the presence of sedimentary structures including graded beddings, flute casts, groove casts, load casts, and cross bedding, and the occurrence of marian fossils are typical for sediments deposited by turbidity current in the deeper water environment. These rocks associations lead Helmcke and his co-workers (see Helmcke and Kraikhong, 1982; Helmcke and Lindenberg, 1983; Altermann, 1983, 1989) to assign these rock clans as flysch sequences. However, the discovery of fragments of index fossils, as crinoids, calcareous algae, and fusulinids in those rock sequences, points to the shallow-water condition. This perhaps indicate that the source of sediments deposited may have come from the shelf sedimentary facies. Based upon the paleocurrent patterns from flute casts, groove casts, and cross-beddings, the source may have situated to the south and the southeast of the area. Another word, the source rocks may have been those of the shallower marine limestone/clastic to the east, e.g. from km 37.200 to km 40.700 which is located in the eastern study area. It is not sure at present if the deposit occurred either as distal parts of turbidite sequences described as Bouma sequences by Altermann (1989), or as parts of submarine fans interpreted by Chutakosikanon et al. (1999a, 1999b). However, for convenience in interpretation of tectonic setting of the study, the latter is preferred herein (Fig. 5.1).

The appearance of allodiapic limestone beds with some shallow marine fauna and unidentified fusulinid fragments at km 16.210 to km 20.120 may support the sedimentary deposit accumulated in the deeper-water environment due to turbidity current as the displaced (or alloctonous) slump unit from the continental slope. The rock sequence is characterized by the mudstone/siliceous shale/limestone interbeds. The well-laminated, black-colored, thinly-bedded nature of mudstone, shale, and limestone, the devoid of fossils, the disappearance of thick sandstone beds and the appearance of radiolaria in siliceous shale (Sashida, per. comm.) in this limestone-shale alternation support that these marine rock association units may have formed in the environments deeper than that of the sandstone/shale unit.

Although Helmcke and his co-authors (see Helmcke and Kraikhong, 1982; Helmcke and Lindenberg, 1983) assigned this rock sequence as pelagic facies, the lack of "true" chert and the presence of thin-bedded sandstone in this unit lead to the author to disagree with Helmcke's idea for the pelagic facies. However, it is true that this rock clearly represent relatively deep marine environments.

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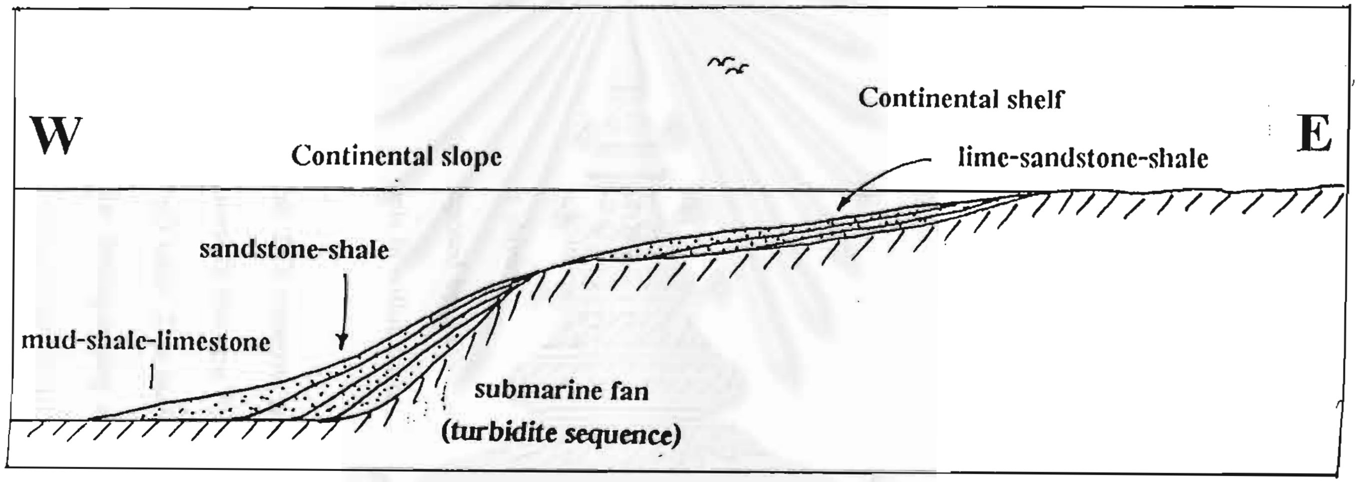

Fig. 5.1 Display the schematic diagram for the depositional environment of Nam Duk Formation

5.2 Tectonic setting using detrital chromian spinels

Compositional variation of chromian spinel is due to an apparent differentiation process of magma which may integrate crystallization differentiation, magma mixing (Sakuyama, 1978), inequilibrium crystallization of spinel (Thy, 1983), magma assimilation, etc. Therefore as stated by Arai (1992), the geochemical results obtained from chromian spinels can be applied to assessment of spinel-bearing igneous rocks and to estimate the provenance of detrital spinel particles which are of igneous affinity. As described clearly in previous chapters, it is obvious that though the chemical results strongly indicate mafic source component for chromian spinel-bearing sandstones, the petrographic results point to the provenance of basaltic nature. Therefore, the chemical data correspond fairly well with the petrographic results. Detrital spinels from the Nam Duk Formation are herein regarded as having the source potentially from basaltic environment.

In this study, three main groups of magma are considered - arc magmas (basalts and andesite), ocean-floor basalts (MORB), and intraplate basalts (see Glassley, 1974; Arai, 1992). It is quite obvious that chromian spinels from arc magma usually have a wide spread of Cr#. Chromian spinels in arc magmas show an inter-volcano variation of the Cr#, from 0.2 to 0.7 (Fig. 5.2). Based upon the results proposed by Arai (1992), it is clear that the range of Cr# from the Nam Duk detrital chromian spinels fit within those of the fore-arc and cratonic environments.

Wilson (1989) noted that TiO_2 contents can be used to distinguished different kinds of magmas. The TiO_2 contents frequently increase from island arc magma to intraplate basalts via MORB on a significant FeO/MgO ratio. This indicates a high potential usefulness of the TiO_2 contents of chromian spinels for distinguishing among those different magma origins (Arai, 1992). Spinels from the intraplate basalts are clearly discriminated from other ones by their high Ti contents. Spinels from boninites and high-Mg basalts/andesite are also characterized by quite higher Cr# and lower TiO_2 contents. The spinels of the MORB origin, are, however, undistinguished form those in the arc magmas and those in the back-arc basin basalts in terms of the Cr#-TiO_2 relationships (see Fig. 5.3). The relationship between Cr# and TiO_2 content of data

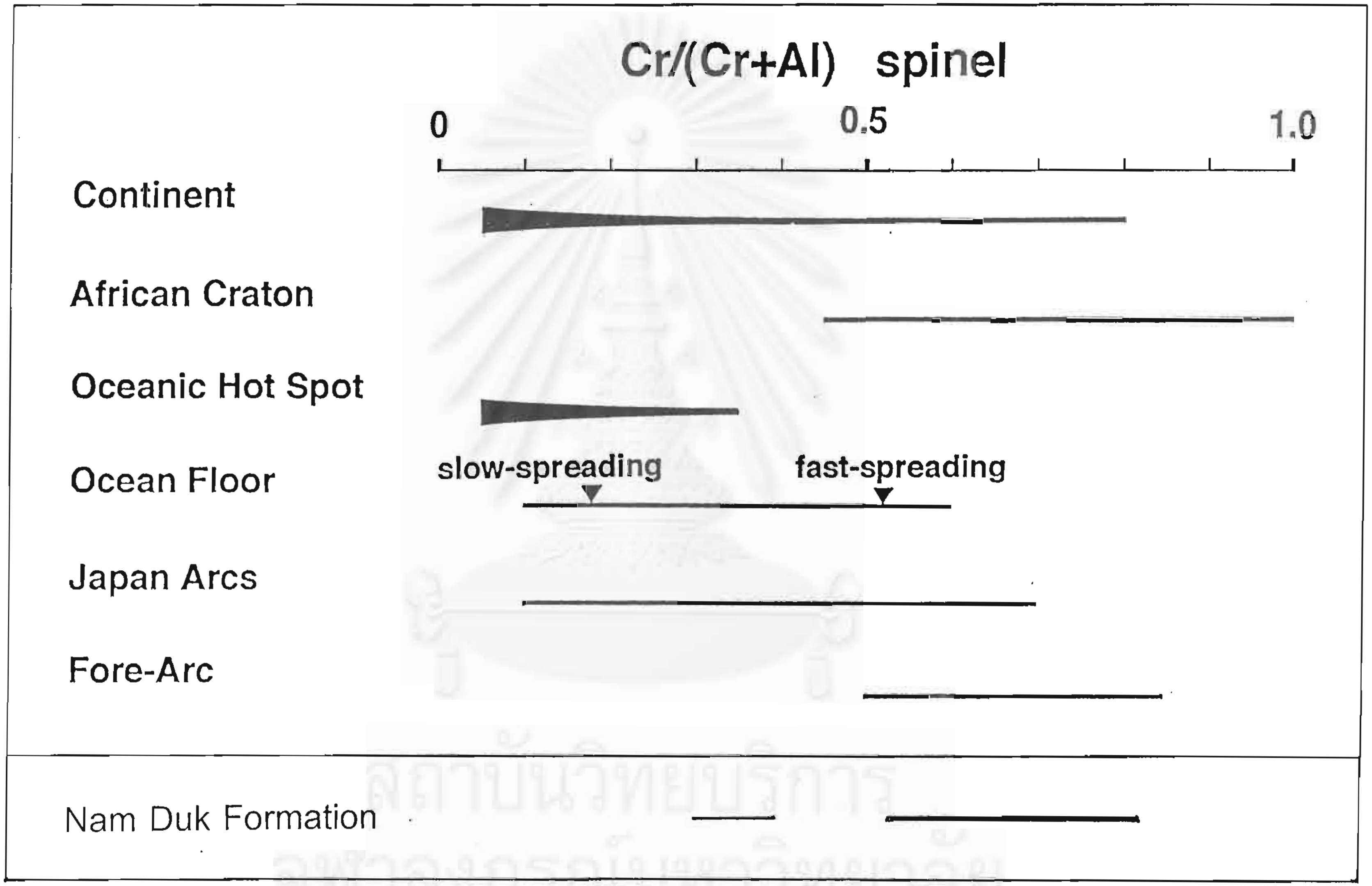

Fig. 5.2 Bar graphs showing ranges of Cr/(Cr+Al) ratios (or Cr#) of chromain spinels in various provenance (modified from Arai, 1994) as compared with that of Nam Duk Formation

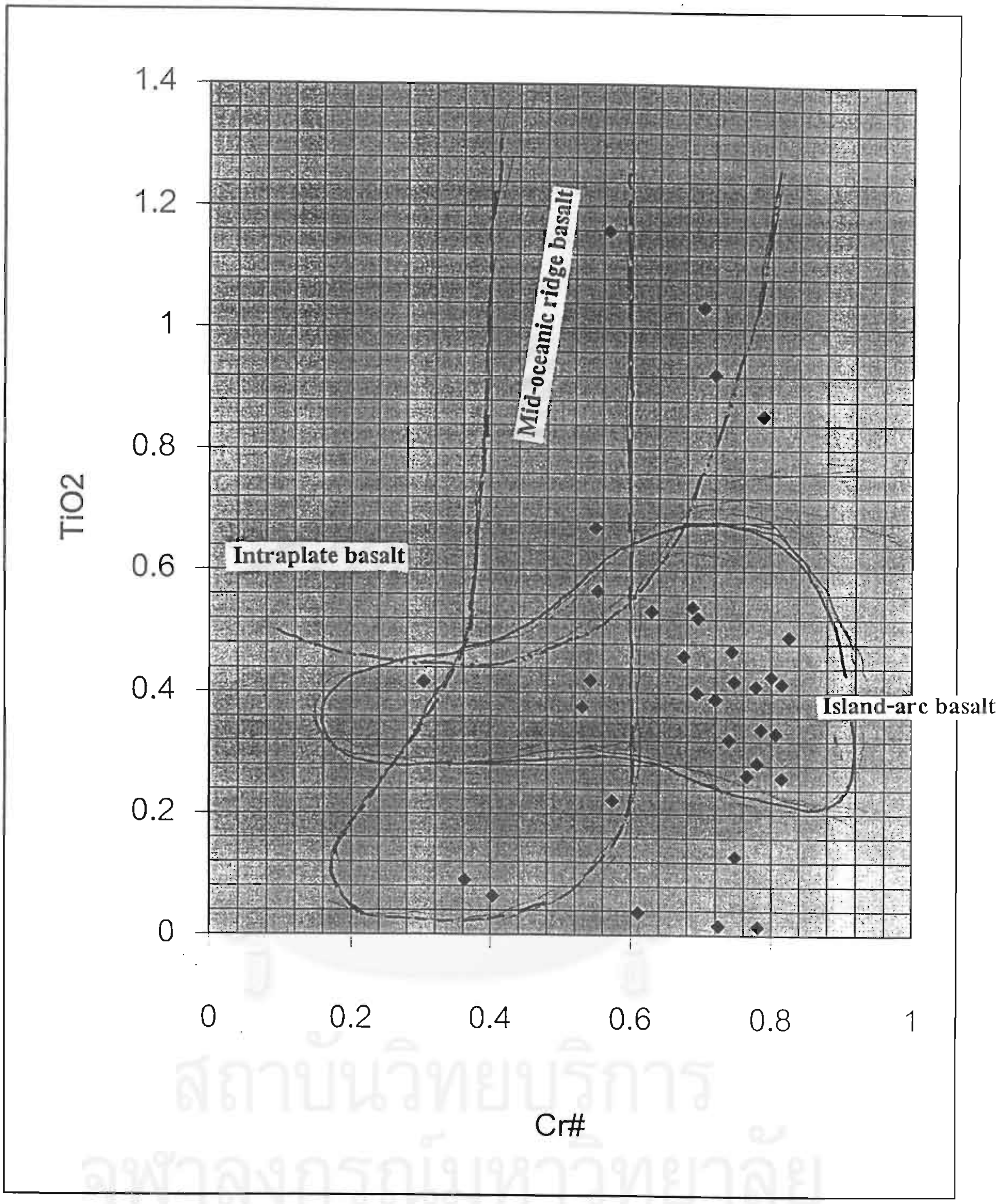

Fig. 5.3 Relationships between Cr^{3+}# and TiO_2 content of chromian spinels of Nam Duk Sandstones in comparison with fields of intraplate basalt, MORB (Mid-oceanic ridge) and are magmas proposed by Arai (1992).

plots of detrital chromian spinels from the Nam Duk sandstones indicate the trend of spinels corresponding to the island arc-related field of Arai (1992)'s diagram.

In addition, Arai (1992) also found that at a certain range of Cr, between 0.3 and 0.6, there exists a relationship of Fe^{3+}#-TiO_2 for chromian spinels. He also recognized that Fe^{3+}# of the MORB spinel is very low which is partly due to the less fractionated character of the MORB relative to the other magmas. Spinels in an arc-related alkaline basalt occupy a high-Ti portion of the arc-magma region on the Fe^{3+}#-TiO_2 diagram (see Fig. 5.4). The MORB spinels are intermediate, although not so clearly, between the arc-magma and intraplate-basalt spinels in their proportions between TiO_2 content and Fe^{3+}#. Low Fe^{3+}# is very characteristic for MORB spinel. Additionally, spinels in back-arc basin basalt are intermediate in TiO_2 content; they are similar to the MORB spinels in this sense but extend more towards a high Fe^{3+}# region. The relationship between Fe^{3+}# and TiO_2 of chromian spinels in three main magma groups was proposed by Arai (1992). Plots of the detrital chromian spinels in the Nam Duk Formation seems to correspond to the arc-related trend of Arai (1992).

One may agree that coincidence of detrital spinels chemistry with any one field does not necessarily imply a similar origin, because individual grains consider only selected aspects of the total chemical diversity of the spinels. Overlapping among fields on some plots is expected even though the chemistry may be relatively distinct on other plots. Therefore, one may agree that the spinel grains may have been derived from ultramafic source region. A ternary plot of Cr^{3+}, Al^{3+}, and Fe^{3+} is herein considered useful for discriminating the ultramafic provenance of detrital chromian spinel-bearing sandstones. Based upon criteria proposed by Cookenboo et al. (1997), the ternary plot of the major cations in chromian spinels can be applied for such discrimination (see Fig. 5.5). The Cr^{3+}, Al^{3+}, and Fe^{3+} data from the Nam Duk spinel-bearing sandstone are plotted in the discrimination diagram, it is obvious that most values fall within the field of Alpine-type peridotite and stratiform-complex ultramafics, although the former is more suitable. However, the Cr# and Mg# for the Nam Duk spinels are plotted (Fig. 5.6) compared with Alpine-type periditite and stratiform-complex ultramafics (fields from Irvine, 1978). It is discovered that the Nam Duk's values correspond very well with Alpine-type peridotitie. According to Bloomer

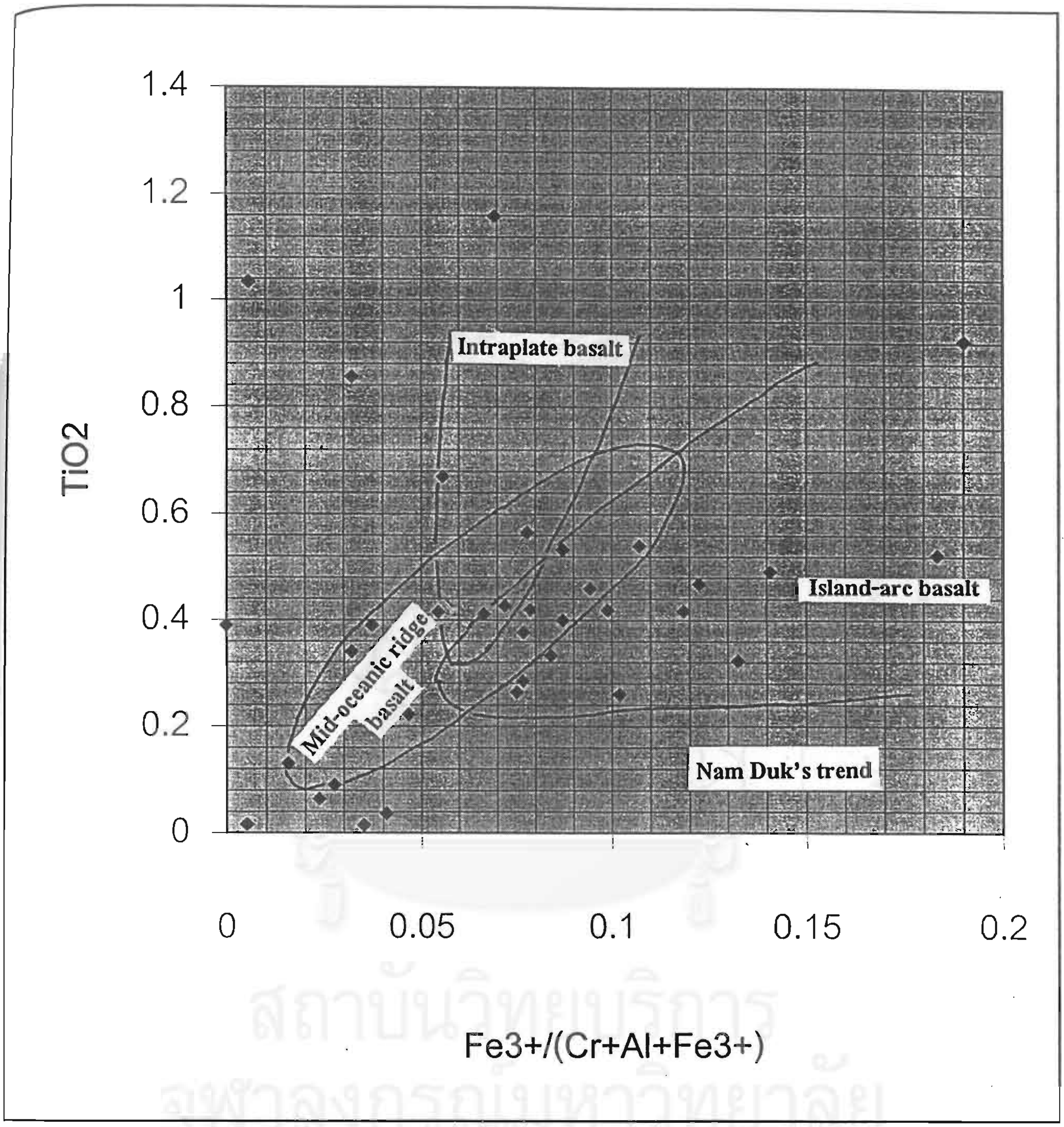

Fig. 5.4 Relationships between $Fe^{3+}/(Cr+Al+Fe^{3+})$ and TiO_2 content of chromian spinels of Nam Duk Sandstones in comparison with fields of intraplate basalt, MORB and are magmas proposed by Arai (1992).

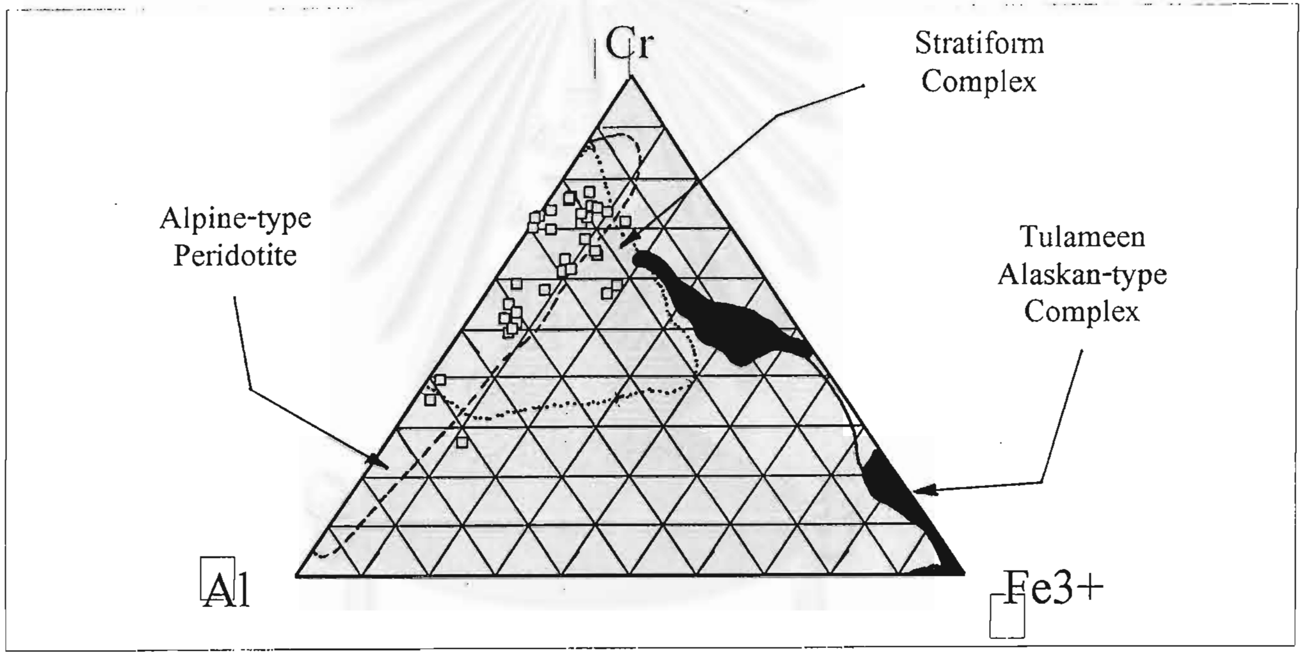

Fig. 5.5 Ternary plot of Al^{3+}, Fe^{3+}, and Cr^{3+} values in chromain spinels in comparision with fields of stratiform mafic/ultra mafic complexes, Alpine-type peridotites and Alaskan-type peridotites quoted by Cookenboo et al.(1987)

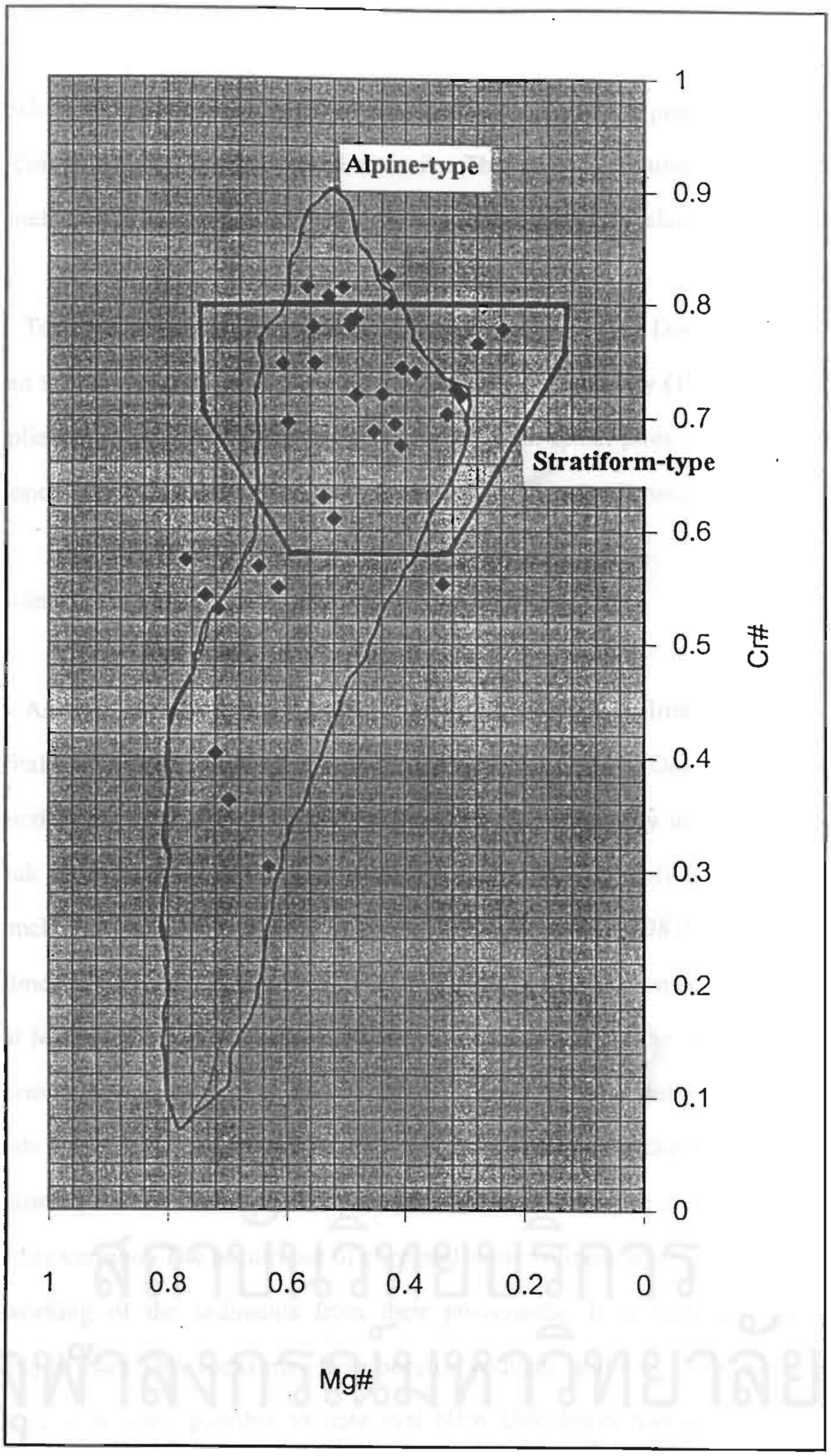

Fig. 5.6 Plots of Cr# versus Mg# of detrital chromian spinels of Nam Duk Formation in comparison compositional field of Alpine-type peridolite and statiform complexes propossed by Dick and Bullen (1984).

and Hawkins (1987), and Cookenboo et al. (1997), such the Alpine-type peridotite rocks are always common in the modern island-arc suite. Therefore, it is strongly believed that the Nam Duk spinels may have derived from the provenance dominated by island-arc tectonic setting.

To confirm the most probable tectonic setting of Nam Duk Formation using detrital chromian spinels data, the model based upon the work of Haggerty (1991) using Cr# and Mg# is also applied (Fig. 5.7), it is visualized that the chromian spinel plots of the Nam Duk Formation correspond fairly well to the type 3 ophiolites which is generated within the arc-related region.

5.3 Tectonic history of the study area

As noted in earlier sections in this chapter, it is rather confirmed from petrochemical data of detrital chromian spinels that its provenance of the Nam Duk graywacke sandstone is dominated by arc tectonic setting. Although mentioned previously in Chapters 2 and 3 that the Nam Duk Formation was formed during early Early Permian to early Late Permian as recognized by Helmcke and Kraikhong (1982), Helmcke and Lindenberg (1983), Altermann (1983, 1989), and Helmcke (1984), the index fossils as quoted by Chutakositkanon et al. (1997) indicate the age of latest Middle Permian. This leads the author to argue against the wide age range of the Nam Duk Formation reported by Helmcke and his co-workers. Additionally, fragments of fossils, e.g., fusulinids and crinoids, and fossil-bearing clasts found in graywacke sandstones in deeper-water environment point to the fact that they may have derived from the shallower marine regions due to turbidity currents. The occurrence of chert and some volcanic fragments in graywackes support the reworking of the sediments from their provenance. It is therefore considered that the formation of Nam Duk rocks may have become younger, and Late Permian is herein preferred. Therefore, it is quite possible to note that Nam Duk Formation may have occurred in the subduction-related tectonic setting after latest Middle Permian.

Considering the direction of subduction, structural data from Nam Duk area are required at this stage. Since the western part is more complicated tectonically than the east, the stress of deformation should have come from the west, implying that the occurrence of Late Paleozoic

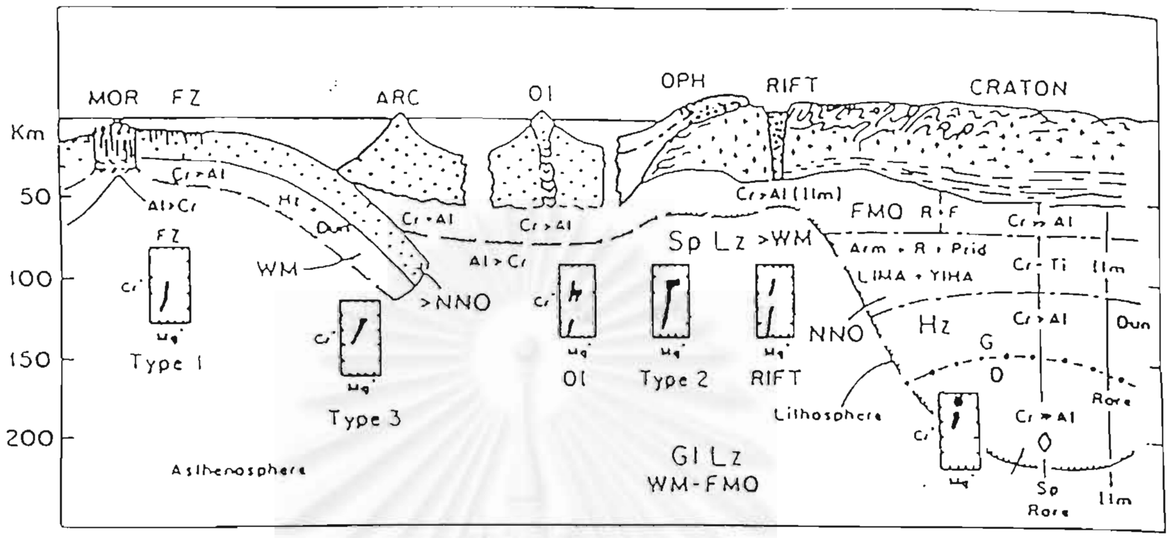

Fig. 5.7 Simplified tectonic settings band upon Cr# and Mg# for mafic and ultramafic rocks from mid-ocean ridge (MOR) and fracture zones (FZ), to arc, ocean islands (OI), ophiolite (OPH) complexes, continental rifts and stable cratons (Haggerty, 1979). Type 1 and 3 refer to oceanic setting for MOR and arc generated ophiolites (Dick and Bullen,1984); Type 2 is transitional and is of uncertain origin. Spinels are present in all setting.

oceanic crust from the west. Subsequently, probably during Permo-Triasic such basaltic crust may have subducted to the east, collided with the terrane in the east, and pushed that terrain to be folded and faulted. The occurrence of Nam Duk Formation as estimated from its thin venire of thickness compared to its folded and long length of formation strata, is considered to be widespread. However, due to the pushing of paleo- oceanic crust, herein representing Paleo-Tethys, the Nam Duk rocks show severe deformation from the west to the east.

This compression style gave rise to the tectonic uplift in several regions. The occurrence of chert fragments in graywacke presumably indicate the reworks of earlier-formed pelagic sediments which may have been tentatively uplifted. In addition, well-preserved sub-hedral chromian spinels may have been transported in a short distance from their arc-related provenance (i.e., basaltic layer). As a result of continuing subduction, older marine sediments of both shallow-and deep- marine origins may have been transported down slope along the continental slope. Submarine fan deposition may have occurred, and as a result the Nam Duk Formation may have formed prior to the advent of more violent subduction which have caused calc-alkaline volcanism during Permo-Traissic Period (Jungyusuk and Khositanont, 1992). The occurrence of dikes cutting the Nam Duk Formation may support this evidence. After Permo-Triasic, the study region became closed and almost the study area was exposed. The site of deeper marine environment was shifted southward and westward. During Middle Triassic, submarine fans sediments was deposited in eastern Thailand (Chantaburi and Srakaew) as clastic sediments of Pong Nam Ron Formation and northern Thailand as carbonates/clastics of Lampang Group (Chaodumrong, 1992, 1994; Chaodumrong and Rao, 1992 ; Chaodumrong and Burrett, 1997).

5. Numerous detrital chromian spinels are discovered as rather small grains of the accessory minerals only in sandstones documented as turbidites. Their grains are varied between 20 μm and 75 μm in size. Some of them rise more than 100 μm across. They display reddish to dark brown and black (or opaque) under microscope. Both of them are mostly sub-angular to angular. Several grains exhibit sub-hedral to euhedral habits suggesting the preservation of original crystal shape, and some grains contain inclusions with unknown composition.

6. Characteristically these spinels have high Cr content and relatively vary in TiO_2 content (0.015-1.159%). The atomic ratios Cr/(Cr+Al) or Cr#s vary considerably from 0.304 to 0.825, mostly above 0.5 with the average of 0.677. The atomic ratios $Mg/(Mg+Fe^{2+})$ or Mg#s range widely from 0.236 to 0.769 and average about 0.504, with Mg concentration generally decreasing as Fe increases. The Fe^{3+} concentration is consistently low. The atomic ratios $Fe^{3+}/(Cr+Al+Fe^{3+})$ are mostly below 0.15 with the average of 0.073.

7. Considering the notable appearance of small grains, sub-angular to angular shape and inclusions, Detrital chromian spinels probably indicate the provenance from basaltic volcanics for the Nam Duk chromian spinels. Evidences from geochemical as well as petrographical investigations reveal that the detrital chromian spinels of the Nam Duk Formation occurred in response to arc-related tectonic setting.

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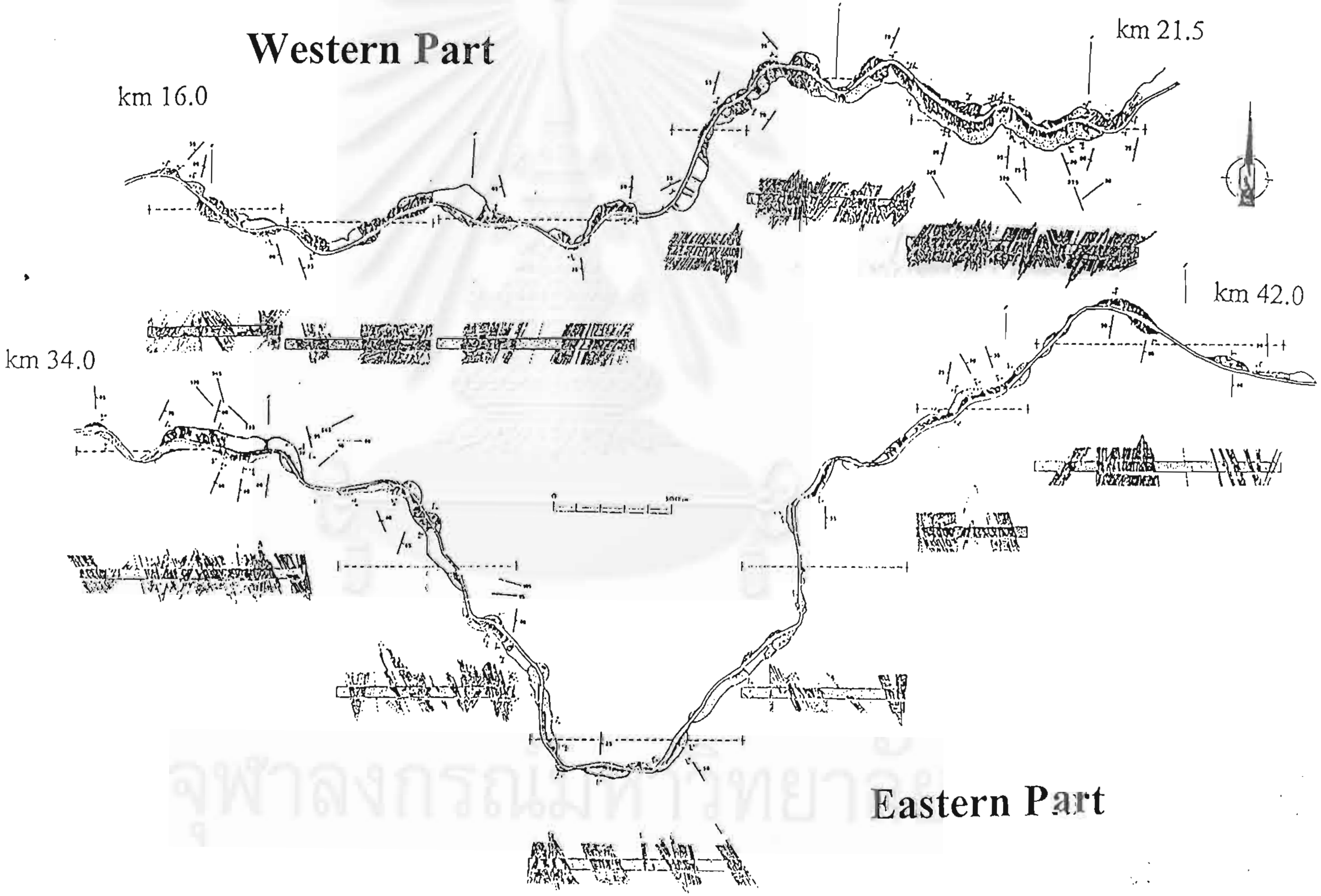
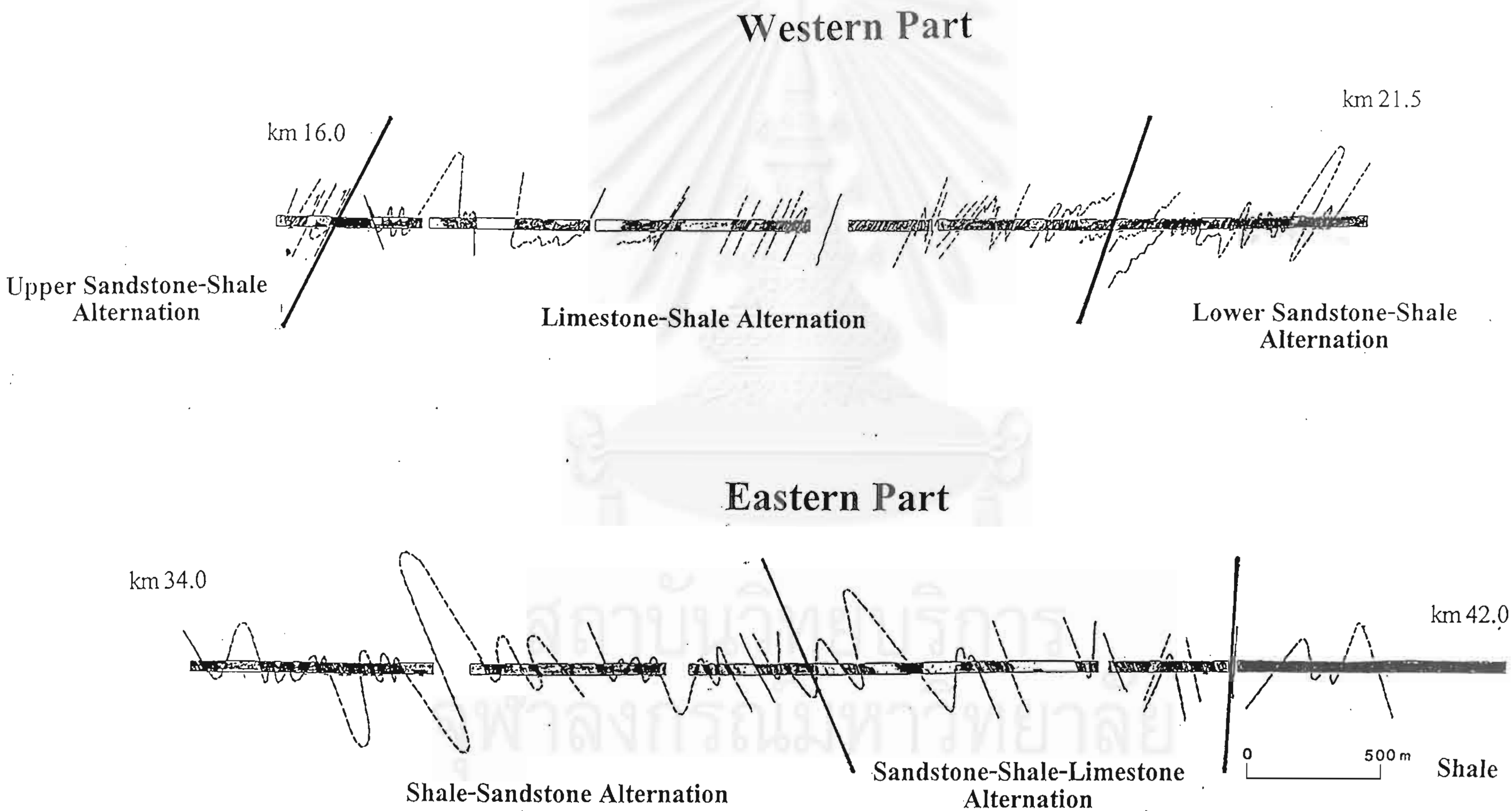
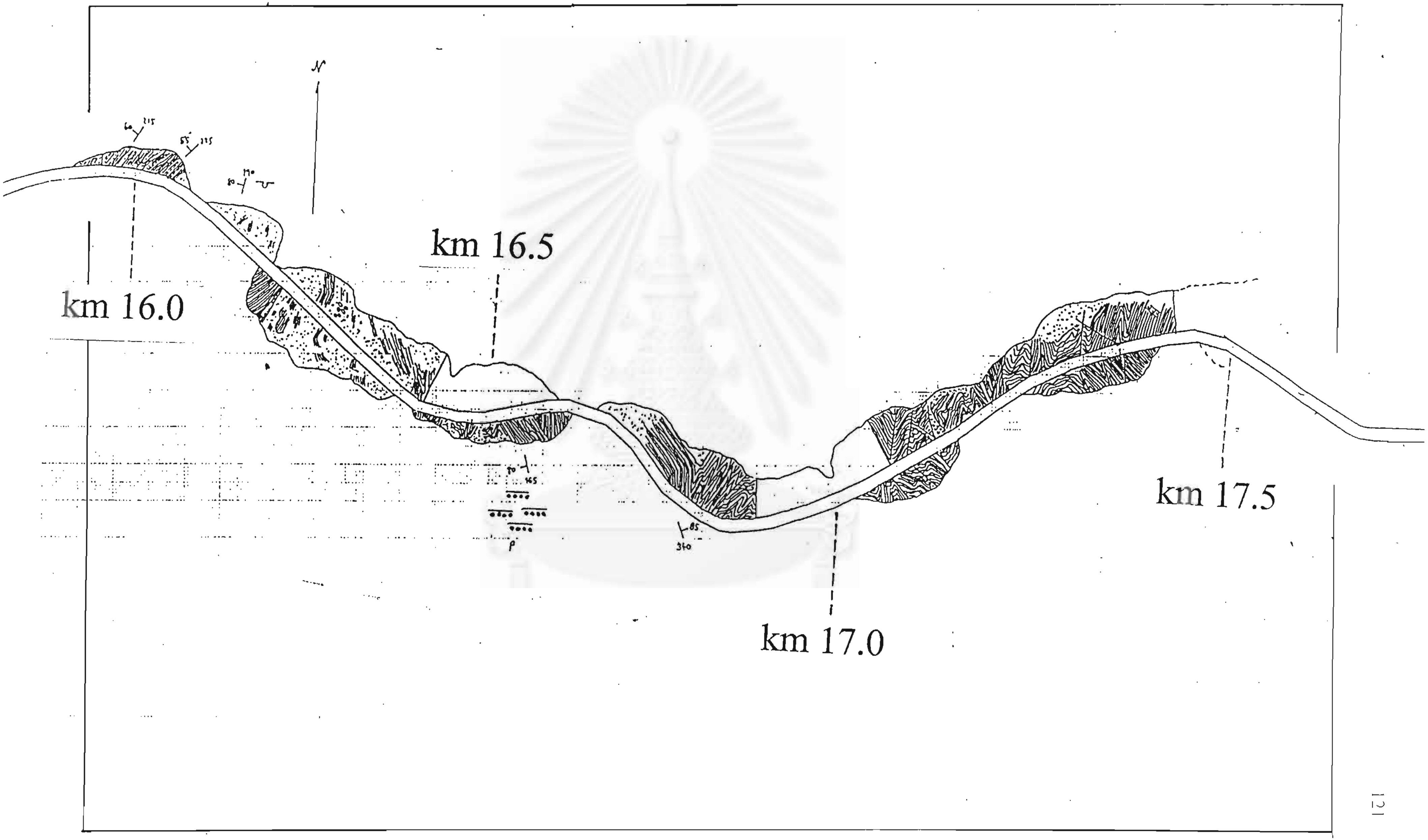
APPENDICES

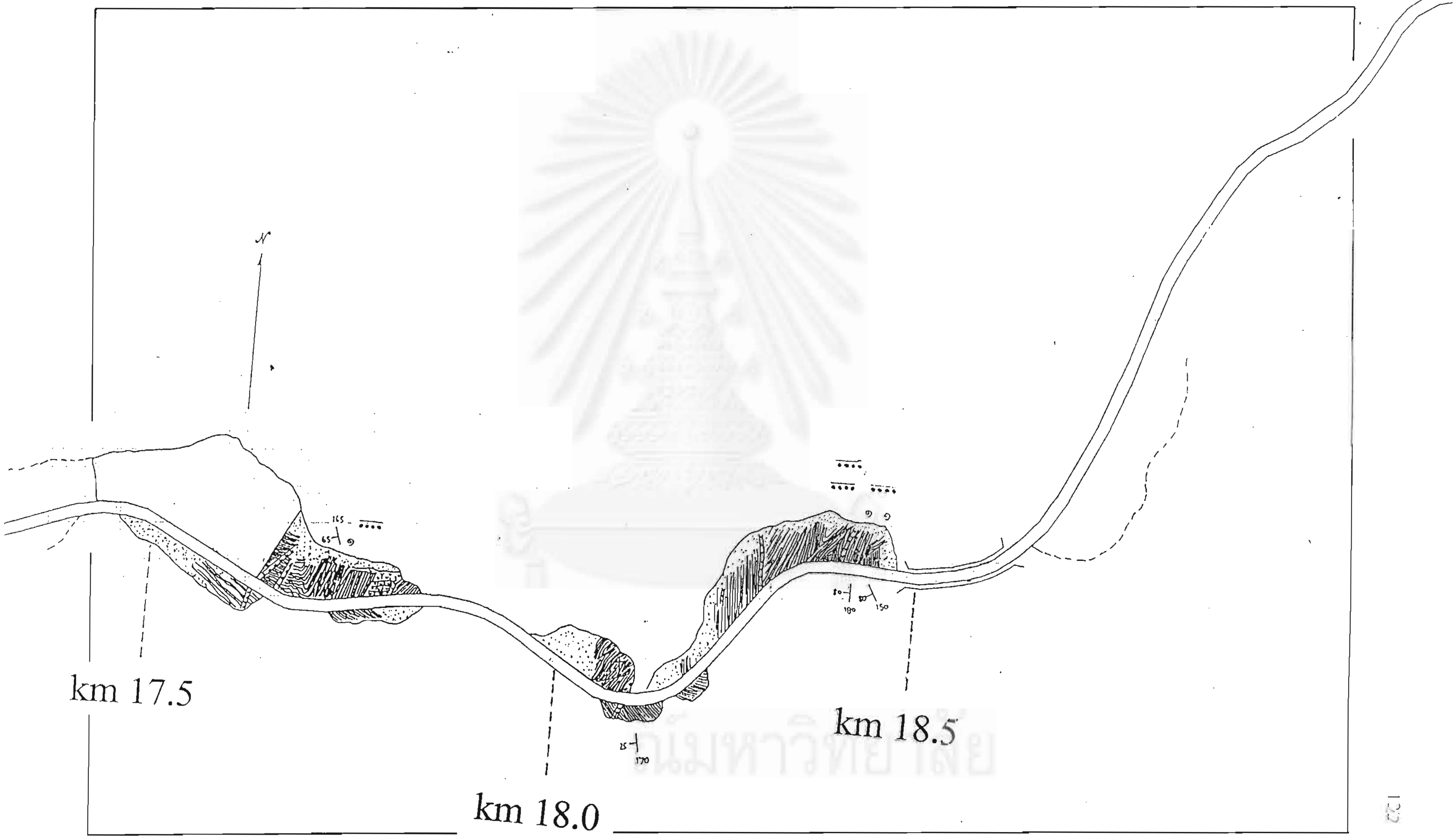
APPENDIX A

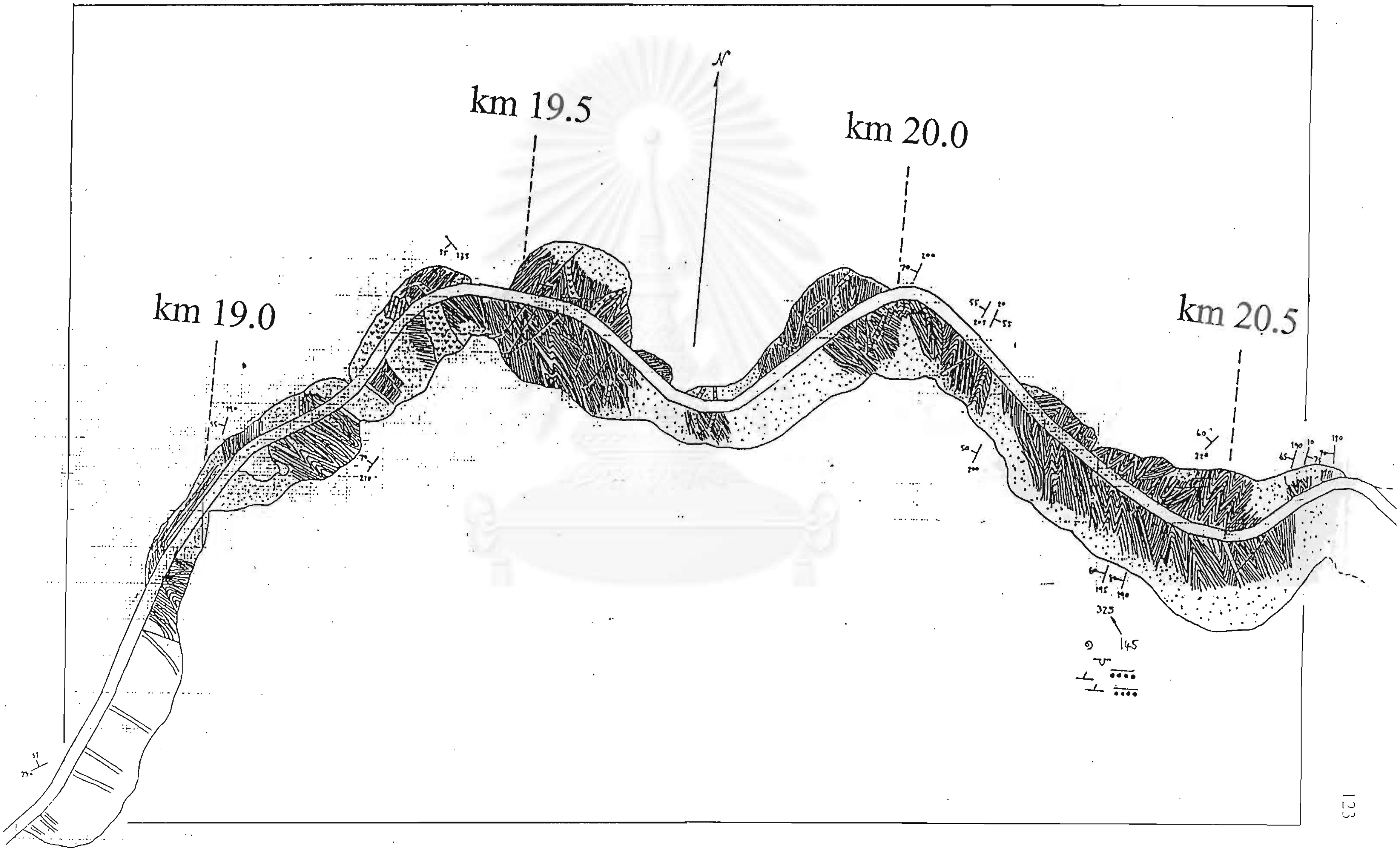
The Geological Sketch of the Exposures of the Nam Duk Formation Along the Highway 12 between km 16.0 to km 21.5 and km 34.0 to km 42.0


Western Part
km 16.0
km 21.5
km 34.0
km 42.0
Eastern Part

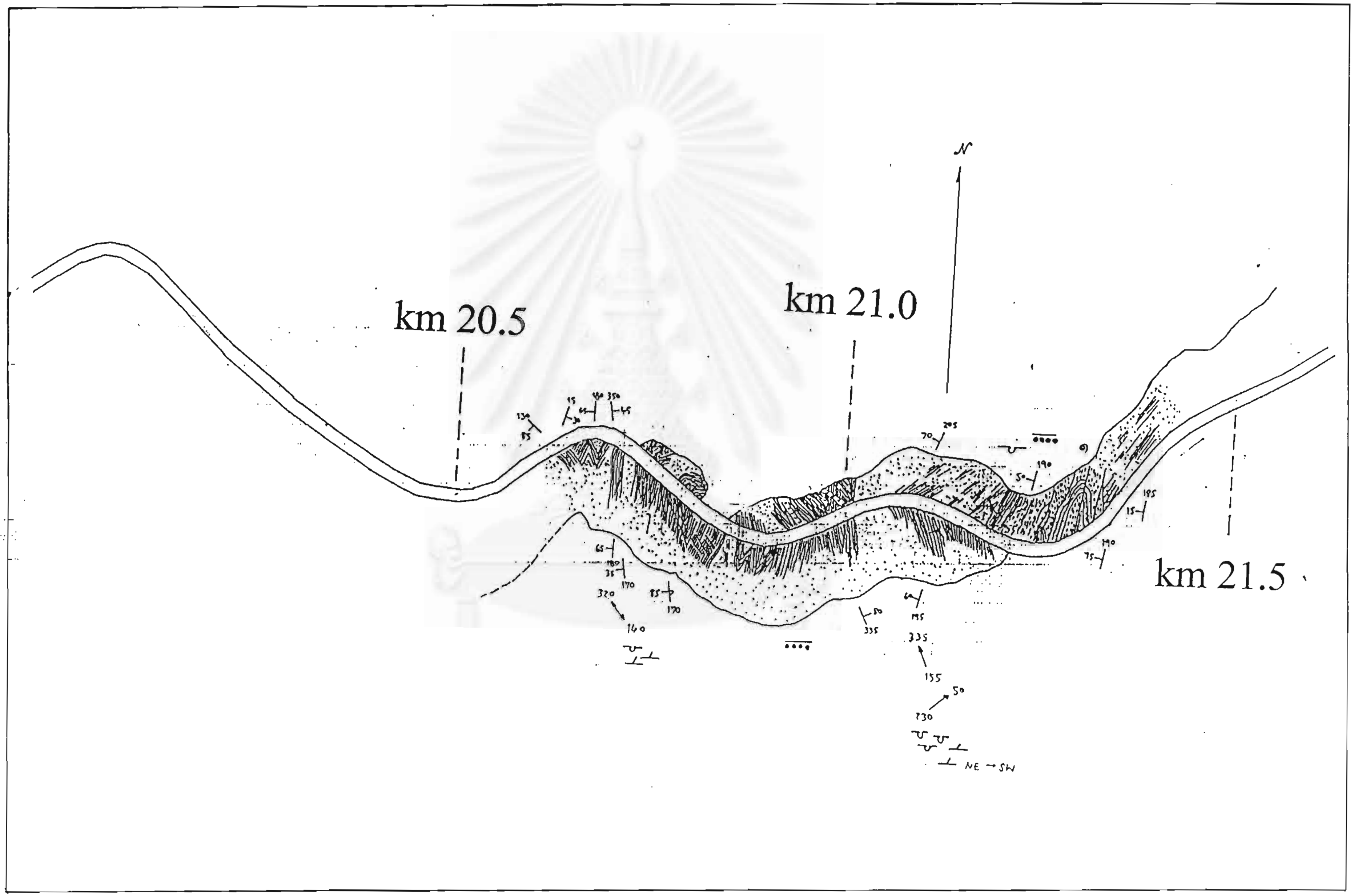

Western Part
km 16.0
km 21.5
Upper Sandstone-Shale Alternation
Limestone-Shale Alternation
Lower Sandstone-Shale Alternation
Eastern Part
km 34.0
km 42.0
0
500 m
Shale-Sandstone Alternation
Sandstone-Shale-Limestone Alternation
Shale

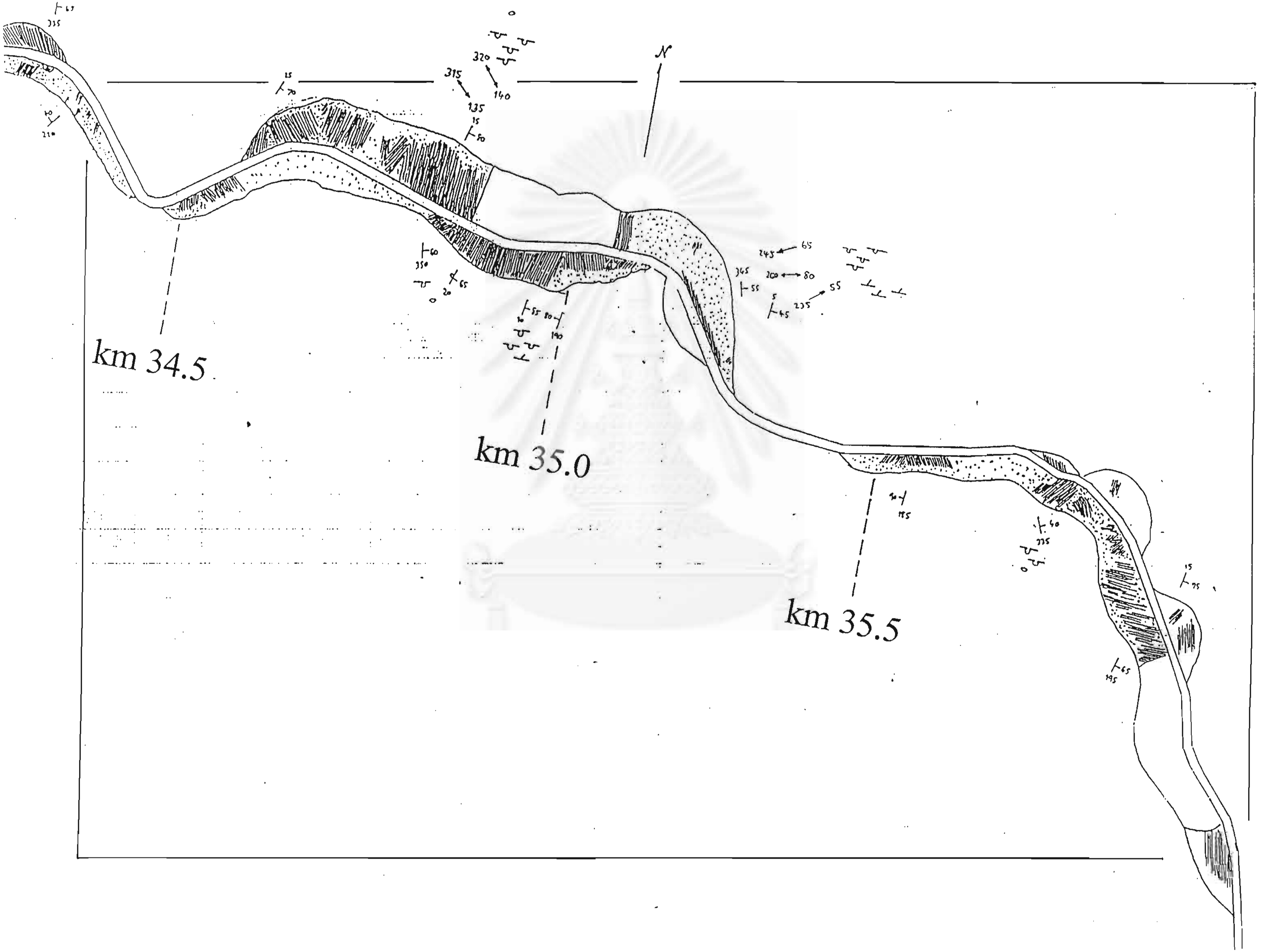

N
km 16.0
km 16.5
km 17.0
km 17.5

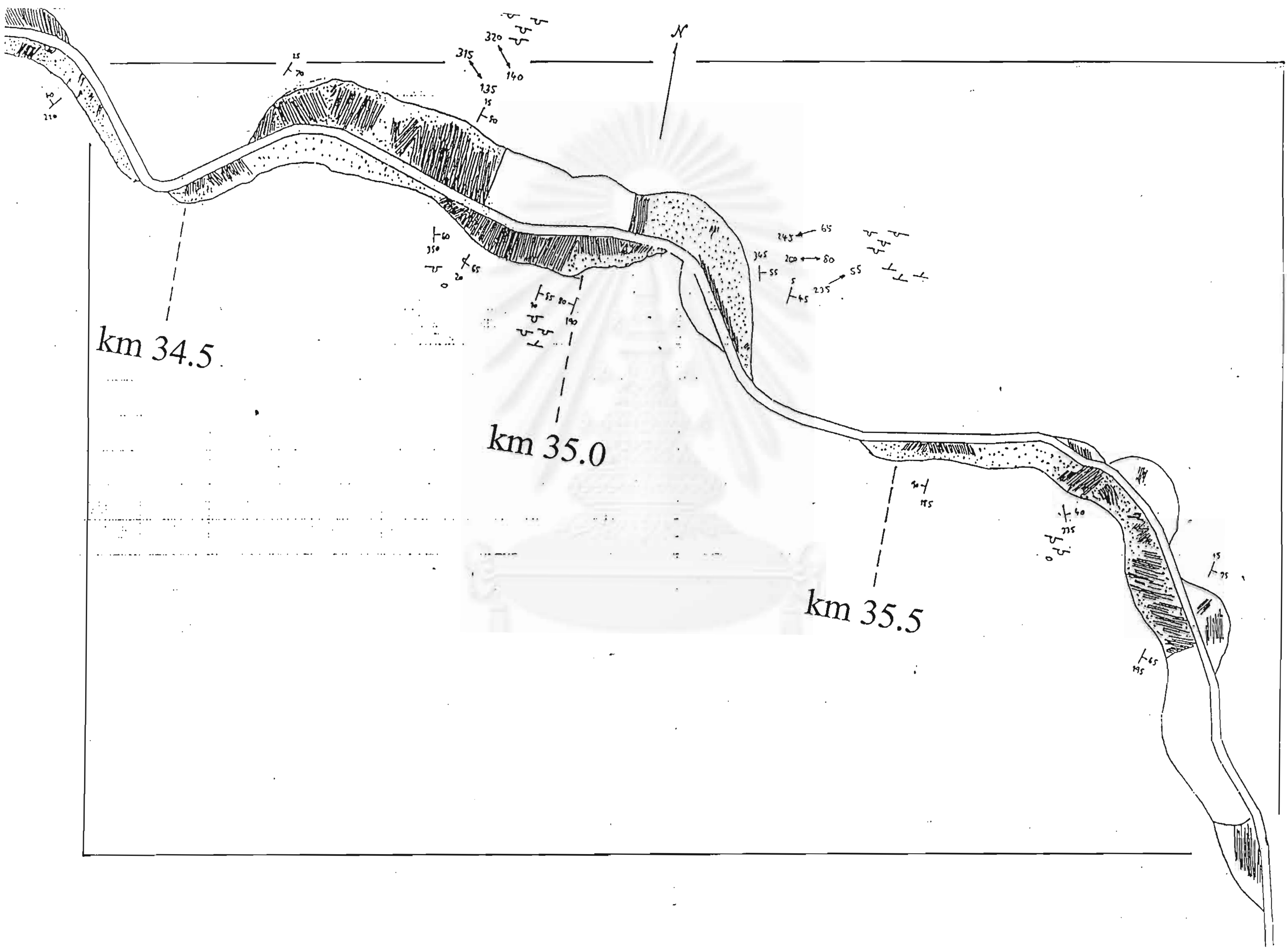

N
km 17.5
km 18.0
km 18.5

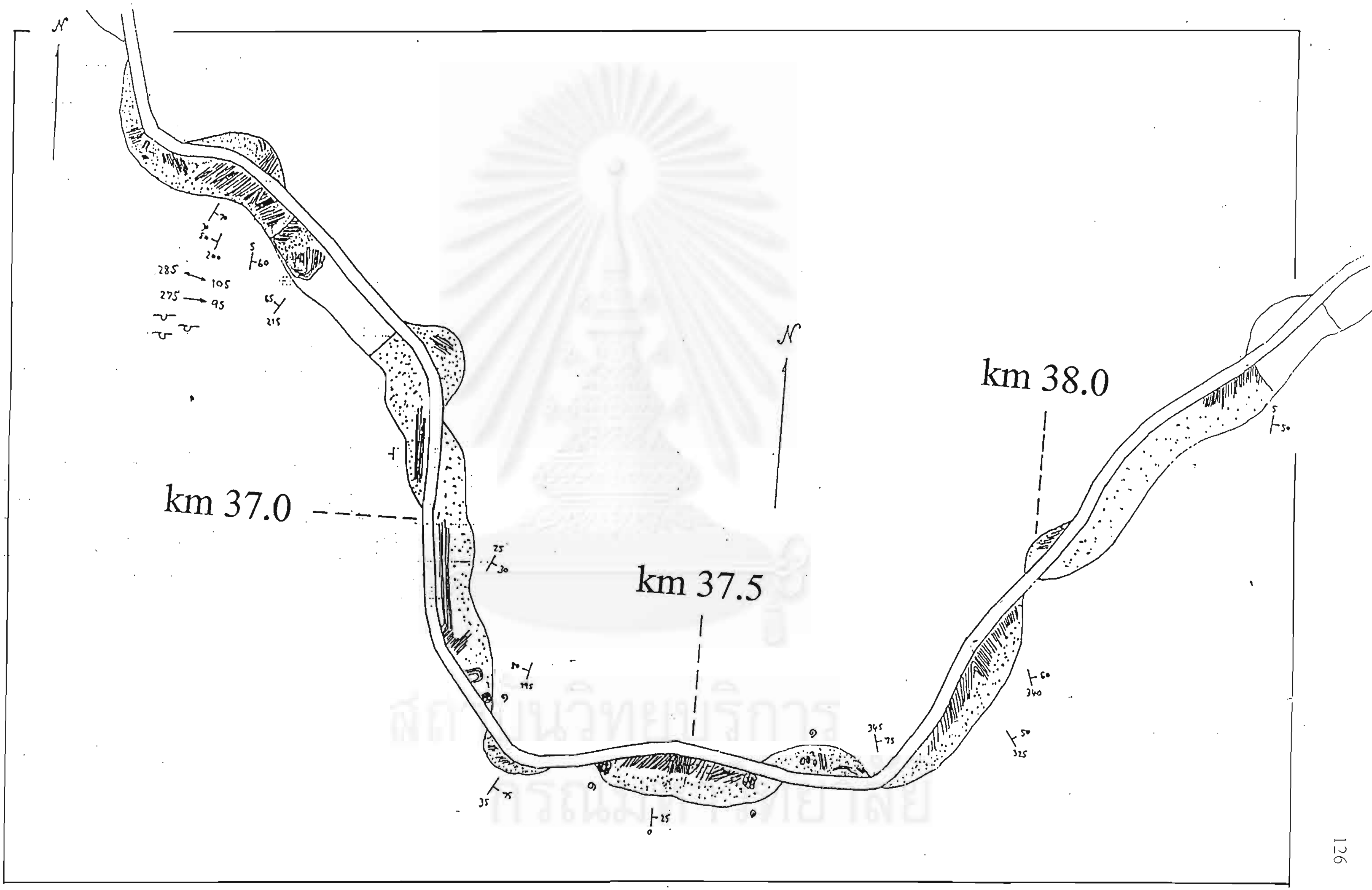


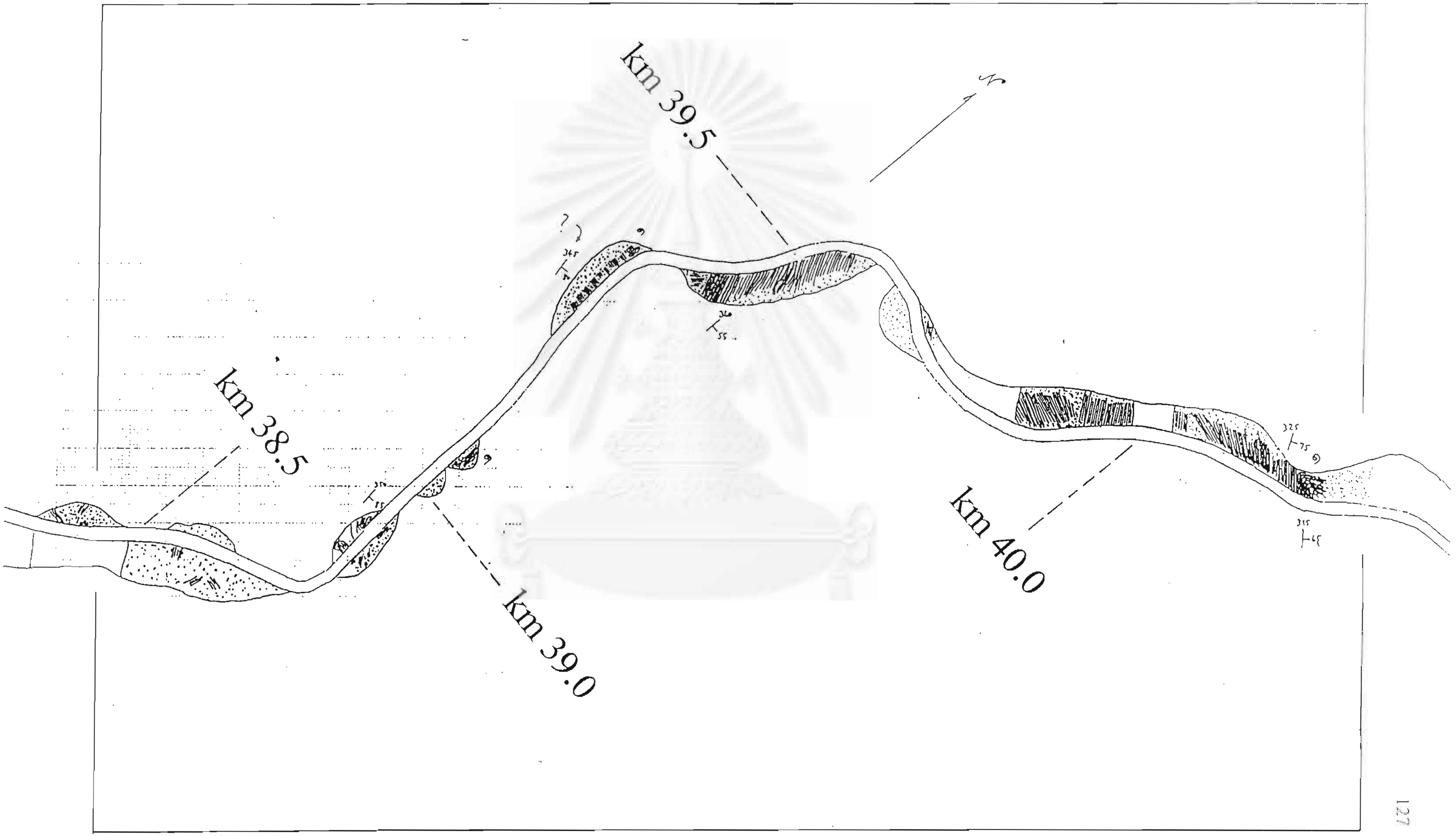
km 19.5
N
km 20.0
km 19.0
km 20.5

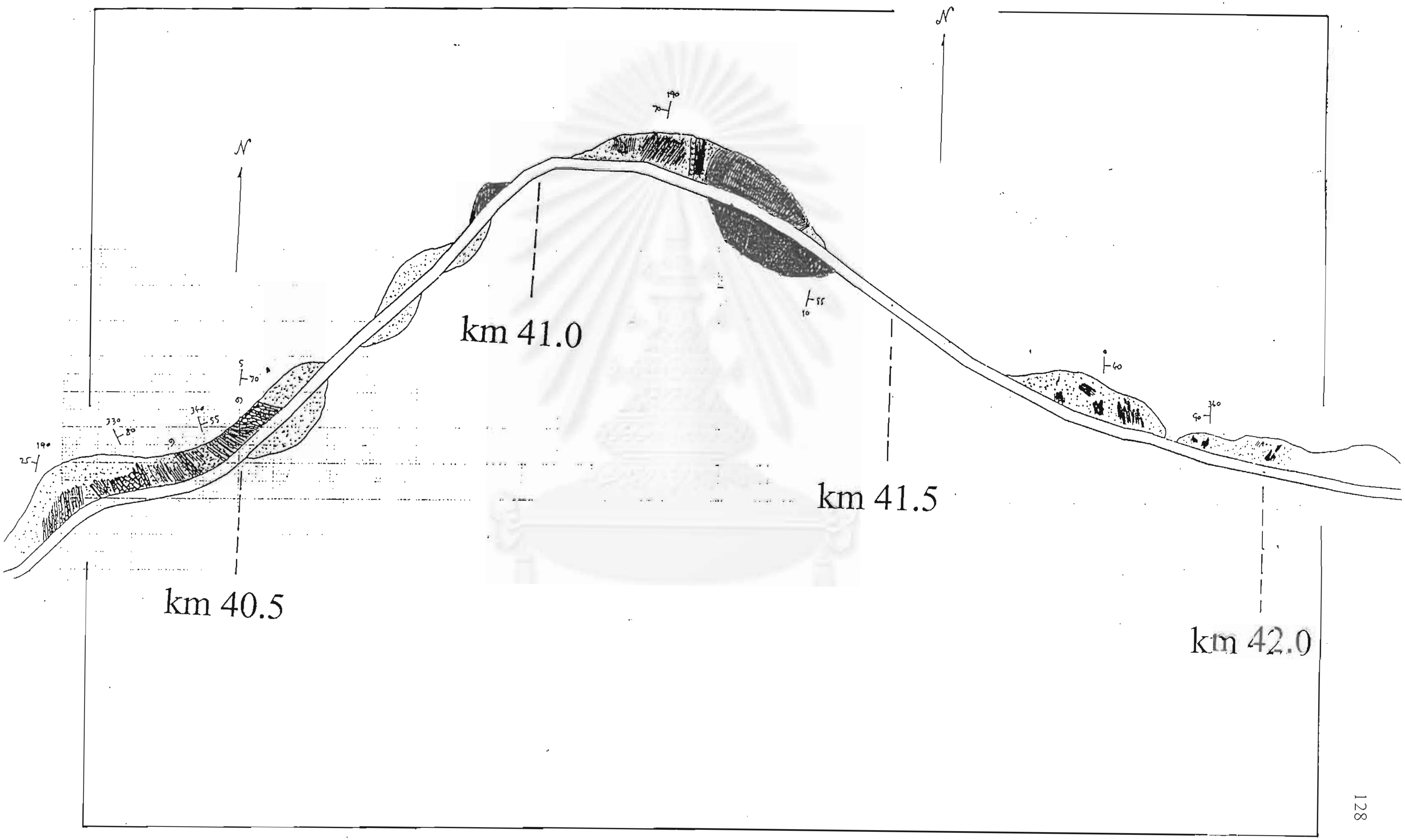

N
km 20.5
km 21.0
km 21.5
NE → SW


N
km 34.5
km 35.0
km 35.5


N
320
140
315
135
km 34.5
km 35.0
km 35.5


N
N
km 37.0
km 37.5
km 38.0


km 38.5
km 39.0
km 39.5
km 40.0


N
N
N
km 40.5
km 41.0
km 41.5
km 42.0

APPENDIX B

The Geochemical data of the Quantitative Electron Probe Microanalysis of Detrital Chromian Spinels in the Nam Duk Formation

Sample No Locality (km no.)	VC-28(3)-1 20.8	VC-29-1-A 21.09	VC-29-2* 21.09	VC-29(3)-1 21.09	VC-29(3)-2 21.09	T6 34.7	T7 34.7
SiO2	0.134	0.009	0.109	0.067	0.099		
Al2O3	9.529	10.925	9.827	10.183	22.368		
TiO2	0.427	0.015	0.856	0.34	0.222	0.67	0.09
Cr2O3	56.906	58.037	54.387	55.52	44.86		
FeO	26.462	20.657	20.954	20.052	12.786		
NiO	0.013	0.037	0.007	0.039	0.166		
MnO	0.356	0.362	0.214	0.343	0.168		
MgO	8.628	10.083	9.122	9.507	16.734		
CaO	0.344	0	0	0.031	0		
Na2O	0	0.112	0.011	0.079	0		
K2O	0.036	0.015	0.015	0	0.005		
Total	102.835	100.252	95.502	96.161	97.408	0.67	0.09
Cation	4 O	4 O	4 O	4 O	4 O	4 O	4 O
Si	0.0044	0.0003	0.0038	0.0023	0.0031		
Al	0.3715	0.4259	0.4039	0.4143	0.8162	0.8481	1.243
Ti	0.0106	0.0004	0.0225	0.0088	0.0052	0.0159	0.0019
Cr	1.4881	1.5176	1.4995	1.5154	1.0981	1.0346	0.7073
Fe	0.7319	0.5714	0.6111	0.5789	0.3311	0.5213	0.3599
Ni	0.0003	0.001	0.0002	0.0011	0.0041		
Mn	0.01	0.0101	0.0063	0.01	0.0044	0.0061	0.0028
Mg	0.4254	0.4971	0.4742	0.4893	0.7723	0.6124	0.6994
Ca	0.0122	0	0	0.0011	0		
Na	0	0.0072	0.0007	0.0053	0		
K	0.0015	0.0006	0.0007	0	0.0002		
Total	3.0559	3.0316	3.0229	3.0265	3.0347	3.0384	3.0143
Fe total	0.7419	0.5815	0.6174	0.5889	0.3355	0.5274	0.3627
Fe*	0.7207	0.5807	0.5724	0.5713	0.3251	0.4956	0.3589
Fe2+	0.5765	0.51	0.509133333	0.507466667	0.2316	0.3845	0.303466667
Fe3+	0.1442	0.0707	0.063266667	0.063833333	0.0935	0.1111	0.055433333
TiO2	0.427	0.015	0.856	0.34	0.222	0.67	0.09
Cr#	0.800225855	0.780859275	0.787800778	0.785303415	0.573630048	0.54952993	0.362662155
Mg#	0.424593273	0.493595472	0.482237288	0.490887202	0.769299731	0.614304343	0.697400784
Cr3#	0.742638986	0.753450501	0.762457627	0.760157844	0.546917024	0.518908617	0.352639101
Al3#	0.185397744	0.211448714	0.205372881	0.207821958	0.406514593	0.425368643	0.619723459
Fe3+3#	0.07196327	0.035100784	0.032169492	0.032020199	0.046568383	0.05572274	0.027637439

Sample No	T8	T9	T10	T11	KH(1)-R-1*	ND24(3)-1	ND24(3)-3
Locality (km no.)	34.7	34.7	34.7	34.7	34.7	34.86	34.86
SiO2					0.086	0.059	0.146
Al2O3					23.32	22.158	8.901
TiO2	0.13	0.39	0.4	0.39	0.377	0.566	0.415
Cr2O3					39.263	40.86	58.485
FeO					17.114	31.49	20.006
NiO					0.123	0.095	0.067
MnO					0.174	0.571	0.274
MgO					15.216	7.143	11.368
CaO					0.034	0.006	0.153
Na2O					0	0	0
K2O					0	0	0
Total	0.13	0.39	0.4	0.39	95.707	102.948	99.815
Cation	4 O	4 O	4 O	4 O	4 O	4 O	4 O
Si					0.0027	0.0019	0.0049
Al	0.4951	0.5386	0.5637	0.5726	0.8739	0.8281	0.3493
Ti	0.0031	0.0098	0.01	0.0098	0.009	0.0135	0.0104
Cr	1.4695	1.3818	1.2793	1.4743	0.987	1.0243	1.5395
Fe	0.4754	0.6005	0.7716	0.4576	0.4551	0.835	0.557
Ni					0.0031	0.0024	0.0018
Mn	0.0095	0.009	0.0128	0.0136	0.0047	0.0153	0.0077
Mg	0.5503	0.4817	0.4212	0.4282	0.7211	0.3376	0.5642
Ca					0.0012	0.0002	0.0054
Na					0	0	0
K					0	0	0
Total	3.0029	3.0214	3.0586	2.9561	3.0578	3.0583	3.0402
Fe total	0.4849	0.6095	0.7844	0.4712	0.4598	0.8503	0.5647
Fe*	0.4787	0.5899	0.7644	0.4516	0.4418	0.8233	0.5439
Fe2+	0.447566667	0.515633333	0.588333333	0.4516	0.286833333	0.666833333	0.434766667
Fe3+	0.031133333	0.074266667	0.176066667	0	0.154966667	0.156466667	0.109133333
TiO2	0.13	0.39	0.4	0.39	0.377	0.566	0.415
Cr#	0.747989413	0.719537596	0.694139989	0.720259905	0.530388522	0.552958324	0.815067768
Mg#	0.551476483	0.482987968	0.417222479	0.486701523	0.715424301	0.336109913	0.56478361
Cr3#	0.736320818	0.692747326	0.633609589	0.720259905	0.489615715	0.50988949	0.770546231
Al3#	0.248079236	0.270020053	0.279188404	0.279740095	0.433510814	0.41222248	0.174830658
Fe3+3#	0.015599947	0.03723262	0.087202008	0	0.07687347	0.07788803	0.054623111

Sample No	VC-31(2)-1-B	T1	T2	T3	T5	VC-34(3)-1	VC-34(3)-2
Locality (km no.)	34.863	34.875	34.875	34.875	34.875	35.165	35.165
SiO2	0.022	0.079	0.186	0.144	0.393	0.039	0.004
Al2O3	14.37	13.891	11.703	12.882	34.632	9.098	34.275
TiO2	0.46	0.016	0.419	0.523	0.417	0.333	0.064
Cr2O3	44.603	54.46	51.537	43.843	22.515	56.447	34.547
FeO	27.323	24.431	21.848	28.733	24.66	23.342	13.482
NiO	0	0.03	0.062	0.059	0.196	0.076	0.079
MnO	0.42	0.449	0.304	0.294	0.181	0.33	0.208
MgO	7.876	6.296	12.309	12.235	14.08	10.73	16.747
CaO	0.138	0.097	0.216	0.06	0.126	0.006	0.025
Na2O	0.04	0	0	0	0.015	0	0.004
K2O	0	0.024	0.016	0.035	0.058	0	0.022
Total	95.252	99.773	98.6	98.808	97.273	100.401	99.457
Cation	4 O	4 O	4 O	4 O	4 O	4 O	4 O
Si	0.0008	0.002666667	0.006233333	0.004866667	0.011966667	0.0013	0.0001
Al	0.5934	0.547266667	0.459866667	0.512533333	1.2421	0.359	1.1693
Ti	0.0121	0.0004	0.0105	0.013266667	0.009533333	0.0084	0.0014
Cr	1.2355	1.439233333	1.358433333	1.170133333	0.541666667	1.4942	0.7906
Fe	0.8006	0.682966667	0.609133333	0.811166667	0.627533333	0.6536	0.3264
Ni	0	0.0008	0.001666667	0.0016	0.0048	0.002	0.0018
Mn	0.0125	0.0127	0.008566667	0.0084	0.004666667	0.0094	0.0051
Mg	0.4113	0.3137	0.611733333	0.615633333	0.638666667	0.5355	0.7225
Ca	0.0052	0.003466667	0.007733333	0.002166667	0.0041	0.0002	0.0008
Na	0.0027	0	0	0	0.000866667	0	0.0002
K	0	0.001033333	0.000666667	0.0015	0.002266667	0	0.0008
Total	3.0741	3.004233333	3.074533333	3.141266667	3.088166667	3.0636	3.019
Fe total	0.8131	0.695666667	0.6177	0.819566667	0.6322	0.663	0.3315
Fe*	0.7889	0.694866667	0.5967	0.793033333	0.613133333	0.6462	0.3287
Fe2+	0.5984	0.684655556	0.397177778	0.414811111	0.373188889	0.476133333	0.2812
Fe3+	0.1905	0.010211111	0.199522222	0.378222222	0.239944444	0.170066667	0.0475
TiO2	0.46	0.016	0.419	0.523	0.417	0.333	0.064
Cr#	0.675542676	0.72450709	0.747089772	0.69540412	0.30366453	0.806281027	0.403387928
Mg#	0.407348717	0.314216712	0.606330257	0.597444468	0.631183634	0.529341988	0.719836605
Cr3#	0.611815391	0.720801985	0.67321755	0.567780893	0.267660074	0.738508682	0.393842782
Al3#	0.293849658	0.274084049	0.227902469	0.248695277	0.613773376	0.17743583	0.582494769
Fe3+3#	0.094334951	0.005113965	0.098879981	0.18352383	0.11856655	0.084055488	0.023662449

Sample No	VC-34(3)-3	VC-35(2)-1	VC-35(2)-2*	VC-35(2)-3*	VC-35(4)-1	VC-35(4)-2-B	VC-35(4)-4
Locality (km no.)	35.165	35.168	35.168	35.168	35.168	35.168	35.168
SiO2	0.017	0.101	0	0.366	0.073	0	0.181
Al2O3	8.368	10.608	11.319	17.376	10.793	11.454	25.079
TiO2	0.26	0.264	0.323	0.533	0.285	0.469	0.42
Cr2O3	54.863	51.463	47.867	44.05	56.901	49.47	44.25
FeO	24.809	30.01	31.256	23.689	22.536	30.488	18.115
NiO	0.079	0.127	0	0.102	0.071	0.067	0.181
MnO	0.423	0.474	0.484	0.334	0.386	0.446	0.253
MgO	10.045	5.35	7.564	10.928	11.603	8.161	17.316
CaO	0.019	0.015	0.018	0	0.09	0.049	0.023
Na2O	0.011	0	0	0	0.034	0	0
K2O	0	0.041	0	0.009	0.02	0.008	0.002
Total	98.894	98.453	98.831	97.387	102.792	100.612	105.82
Cation	4 O	4 O	4 O	4 O	4 O	4 O	4 O
Si	0.0006	0.0035	0	0.0121	0.0024	0	0.0052
Al	0.3388	0.4387	0.4636	0.6772	0.411	0.4585	0.8497
Ti	0.0067	0.007	0.0084	0.0133	0.0069	0.012	0.0091
Cr	1.4898	1.4276	1.3151	1.1516	1.4535	1.3284	1.0056
Fe	0.7126	0.8806	0.9083	0.6551	0.6089	0.8659	0.4355
Ni	0.0022	0.0036	0	0.0027	0.0019	0.0018	0.0042
Mn	0.0123	0.0141	0.0142	0.0093	0.0106	0.0128	0.0061
Mg	0.5143	0.2798	0.3918	0.5386	0.5588	0.4132	0.7419
Ca	0.0007	0.0006	0.0007	0	0.0031	0.0018	0.0007
Na	0.0007	0	0	0	0.0021	0	0
K	0	0.0018	0	0.0004	0.0008	0.0003	0.0001
Total	3.0787	3.0573	3.1021	3.0603	3.06	3.0947	3.0581
Fe total	0.7249	0.8947	0.9225	0.6644	0.6195	0.8787	0.4416
Fe*	0.7115	0.8807	0.9057	0.6378	0.6057	0.8547	0.4234
Fe2+	0.503833333	0.729133333	0.6336	0.463133333	0.450866667	0.605066667	0.264966667
Fe3+	0.207666667	0.151566667	0.2721	0.174666667	0.154833333	0.249633333	0.158433333
TiO2	0.26	0.264	0.323	0.533	0.285	0.469	0.42
Cr#	0.814721645	0.76493597	0.739360207	0.629702537	0.779565567	0.743410376	0.542014769
Mg#	0.505140126	0.277322585	0.382094792	0.537668042	0.553449983	0.405787613	0.736840363
Cr3#	0.731633054	0.707479847	0.641261947	0.574803674	0.719792011	0.652284929	0.499370986
Al3#	0.166382923	0.217407823	0.226058124	0.338014109	0.203532519	0.225137489	0.421952592
Fe3+3#	0.101984023	0.07511233	0.13267993	0.087182217	0.07667547	0.122577583	0.078676422

Sample No	VC-35(4)-5	VC-35(4)-6	VC-40-1	VC-39(2)-1	VC-39(2)-2	VC-40(3)-1	VC-40(3)-3
Locality (km no.)	35.168	35.168	40.46	40.46	40.46	40.46	40.46
SiO2	0.171	0.156	0.03	0.082	0.039	0.114	0.083
Al2O3	7.303	9.952	19.398	11.38	14.406	22.45	13.94
TiO2	0.492	0.411	0.037	0.924	1.034	1.159	0.54
Cr2O3	51.469	51.909	45.38	43.501	50.925	44.005	45.751
FeO	29.871	30.641	20.364	39.307	25.049	20.642	27.42
NiO	0.145	0.048	0.093	0	0.109	0.154	0.085
MnO	0.317	0.435	0.285	0.275	0.315	0.757	0.393
MgO	8.236	4.468	10.676	6.058	6.345	14.3	8.947
CaO	0.02	0.052	0.157	0.015	0.494	0.055	0.109
Na2O	0.042	0	0.005	0	0.058	0.015	0.057
K2O	0	0.075	0	0.005	0.045	0.017	0
Total	98.066	98.147	96.425	101.547	98.819	103.668	97.325
Cation	4 O	4 O	4 O	4 O	4 O	4 O	4 O
Si	0.0061	0.0055	0.001	0.0028	0.0013	0.0034	0.0029
Al	0.3054	0.4156	0.7517	0.4649	0.5714	0.7941	0.5631
Ti	0.0131	0.011	0.0009	0.0241	0.0262	0.0262	0.0139
Cr	1.4438	1.4543	1.1796	1.1919	1.3548	1.0442	1.2396
Fe	0.8863	0.908	0.5599	1.1393	0.7049	0.5181	0.7858
Ni	0.0041	0.0014	0.0025	0	0.0029	0.0037	0.0023
Mn	0.0095	0.0131	0.0079	0.0081	0.009	0.0193	0.0114
Mg	0.4356	0.236	0.5232	0.313	0.3183	0.6397	0.457
Ca	0.0007	0.002	0.0055	0.0006	0.0178	0.0018	0.004
Na	0.0029	0	0.0003	0	0.0038	0.0009	0.0038
K	0	0.0034	0	0.0002	0.0019	0.0007	0
Total	3.1075	3.0503	3.0325	3.1449	3.0123	3.0521	3.0838
Fe total	0.8958	0.9211	0.5678	1.1474	0.7139	0.5374	0.7972
Fe*	0.8696	0.8991	0.566	1.0992	0.6615	0.485	0.7694
Fe2+	0.582533333	0.765666667	0.483633333	0.71	0.650366667	0.347966667	0.5527
Fe3+	0.287066667	0.133433333	0.082366667	0.3892	0.011133333	0.137033333	0.2167
TiO2	0.492	0.411	0.037	0.924	1.034	1.159	0.54
Cr#	0.8254059	0.777742125	0.610780303	0.719398841	0.703353754	0.568024806	0.687635214
Mg#	0.427841802	0.235607321	0.519649065	0.305962854	0.328596008	0.647688154	0.452609686
Cr3#	0.709042693	0.7259401	0.585797053	0.58255132	0.699311769	0.528619642	0.613845697
Al3#	0.149980356	0.207454243	0.373299123	0.227223851	0.2949415	0.4020081	0.278845202
Fe3+3#	0.140976951	0.066605657	0.040903824	0.190224829	0.005746731	0.069372258	0.107309102

BIOGRAPHY

Mr.Vichai Chutakositkanon was born in Bangkok, central part of Thailand, on August 3, 1973. In 1992, he was chosen to study in Chulalongkorn University where he has received the scholarship of the Development and Promotion of Science and Technology Talents (DPST) from the Institute for the Promotion of Teaching Science and Technology (IPST) since 1992. After graduating in B.Sc. in Geology from the Department of Geology, Faculty of Science, Chulalogkorn University in 1996, he studied the M.Sc. program in Geology at the Graduate School, Chulalongkorn University. At present, his respect covers the stratigraphy and tectonic evolution of Thailand especially in chromian spinel studies.