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Geophysical Investigations at Khao Nang Klu Lead Deposit, Ban Kli Ti, Kanchanaburi, Western Thailand: Implications for Tectonic Structures Ore Locallization and Exploration

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ABSTRACT: Kli Ti area in Thong Pha Phum District, Kanchanaburi was selected in an attempt to search for a new and highly potential area of lead ores. On the basis of the proximity to the currently operated, low-grade Pb mine, we discovered Khao Nang Klu as a very promising target area for this investigation. Ground geophysical surveys were conducted using resistivity and induced polarization methods. The survey consisted of six investigated lines with a total length of 7.6 km, comprising 1 base line and 5 traverse lines. There were a total of 111 data points collected in the surveyed area characterized by steep-slope topography, and all the data were processed and enhanced using the Surfer6 and related programs. Field investigation revealed that the survey area is dominated by Ordovician limestones with the isoclinal folded strata whose major axis aligns in the northwest direction. Some sulfide ores are locally present in a few outcrops and in the exploratory trench. The geophysical result revealed 5 anomalous zones with the average thickness of 25 m and at the average depth of about 20 m. Two linear zones viz. those of the northeast and northwest directions were interesting for further detailed investigation. However, the northwest-trending geophysical anomalous zones corresponding to those of the near-surface geochemical anomalies in the southwestern part of the study area, were regarded as non-significant anomalies due to occurrence of discarded slags. The current investigation advocated that the northeast-trending Pb sulfide ores and isolated Cu ores formed as irregular to lens-shaped epigenetic bodies along the northeast-trending extensional fracture zones. Field investigation also revealed that Pb ores may not be temporally and spatially related to Cu ores. The latter may have formed as a result of ore fluids related closely with differentiation of I-type granitoids. Maximum stress developed as a result of tectonomagmatic interaction of the Western Burma block against the Shan Thai block may have caused open fractures responsible for channel ways for Pb(±Zn) ore precipitation in Ordovician carbonates.

KEYWORDS: tectonics, lead ores, Kanchanaburi, resistivity, induced polarization.

INTRODUCTION

Nowadays, industries widely use lead ores in various categories such as electric, electronic and chemical. Based on mineral statistics,[1] Thailand produced approximately 20,000 tons/year of lead ores and consumed about 40,000 tons/year of metal lead during 1994 to 2000. However, lead seems not to be adequate because many high-grade ores were mined out.[1] The major exploitation of lead ores in Thailand has been produced continuously and principally from the Thong Pha Phum area in Kanchanaburi since 1949 (Fig 1). Major ores are galena and cerussite, whereas silver and zinc ores are essential by-products.

At present, only the low-grade ores (<10%) are exploited and almost exhausted. Surface high anomalies of lead occurrences, however, have been subsequently discovered using geochemical soil surveys in Thong Pha Phum District and in nearby areas. A further investigation particularly a ground geophysical survey is important, and subsurface data required for those promising occurrences. Additionally, results from this geophysical survey will be helpful for interpreting subsurface structures related to tectonic setting of the study area.

The aims of this research are to delineate potential ore bodies at depth using ground geophysical data in the promising site of Thong Pha Phum District area in Kanchanaburi, and to apply the results for disclosing relevant tectonic structures both locally and regionally.

Location and Setting

The study area is located at Khao Nang Klu (about latitudes 14° 57' 42" N to 14° 58' 48" N and longitudes

98° 56' 36" E to 98° 58' 18" E), in Ban Kli Ti (village), Tambon Cha Lae, Thong Pha Phum District, in the northern part of Kanchanaburi Province (Fig 1). It is approximately 300 km west of Bangkok and encompasses 6 square km. Accessibility to the study area is not very difficult since it is situated about 2 km south of the Boh Ngam Pb mine area - the largest village in the study area. The study area is dominated by a high mountain with steep slopes. Tectonically, the study area is situated within the so-called Shan Thai[2] or Sibumasu[3] block with the Western Burma block to the west and the Indochina and related blocks to the east. Regionally, the study area comprises deformed and metamorphosed Ordovician carbonate - dominated sequences and Cambro-Ordovician clastic dominated sequences (Fig 1). The Ordovician rock sequences, which are widely distributed in the study area, include massive to well-bedded carbonates, dolomitized limestones, and alternated clastic rocks. These rock strata mostly oriented in the northwest trend, following the regional structure. There are several Pb-Zn mines in the regional area of Kanchanaburi, e.g., Bon Ngam, Kli Ti, Song Tho and Bo Yai mines.

Lead deposits at the Thong Pha Phum District area have been the topic of interest for several decades, particularly for their genesis. However, there is no doubt that the primary Pb ores took place at low temperatures within the Ordovician carbonates.[4-6] Stratabound origin for Pb-Zn ores was proposed by Yokart[4] and Diehl and Kern.[5] These ores belong to the Mississippi- Valley type and occur in fault – opened spaces by epigenetic hydrothermal fluids.

On the contrary, some workers, i.e., Permthong,[6] Yimyai,[7] Pedal,[8] and Putheang *et al*,[9] favor a diagenetic origin for ore deposition in the Thong Pha Phum area. Ores may have been either formed penecontemporaneously by chemical precipitation as clastic concentration at an interface of lime/mud during early diagenetic stage, or squeezed along with hydrothermal fluids from the underlying Cambro-Ordovician fine-grained clastics and deposited in fractures of deformed overlying Ordovician carbonates.

Due to the decrease in Pb ore production in Kanchanaburi, Department of Mineral Resources[10,11] conducted geochemical surveys to cover regional mine areas in the Thong Pha Phum District area. However, no research papers have ever been reported for controls of ore formation, whether or not they were associated with any tectonic structures.

Materials and Methods

Methodology

In this research the method of study was divided into 6 steps as follows.

The first step was to compile previous works and relevant data of the study area including geochemical data, geology of mineral deposits and unpublished/ published field reports. The second stage was to review geophysical field techniques and instruments, and to select the geophysical techniques appropriate for this study, which were the induced polarization and resistivity methods. The third step was to perform field geophysical data acquisition, which included a) designing survey lines to cover pre-existing geochemical anomaly; b) field-mapping along the survey lines; c) measuring time domain-induced polarization and resistivity using Wenner configuration array; and d) pitting in the promising target zones of high geophysical anomalies. The fourth step was to process and analyze data, involving the analog-to-digital data conversion and the construction of anomaly maps using commercial software programs. The fifth step was to generate the mineralization model and ore geometry at depths. This step also involved interpretation of all relevant data and creation of the subsurface ore model related to results of geophysical interpretation. The last step involved the discussion on paleostress in the area, probable ore origin, and further detailed exploration.

Survey Planning Design

Our field investigation result indicated that the Ordovician carbonate strata in the study area align in the northwest-southeast direction which, to some extent, is parallel with the mountain ridges and lineament pattern. Results from soil survey using ridge and spur method[10] showed high lead and copper anomalies oriented in the northeast trend. Our field data revealed that there are several ore deposits located near the study area (e.g. Song Tho, Boh Yai, Boh Noi, see also Fig 1). Most of these deposits occur along crests of anticlines and troughs of synclines where small open fractures are frequently present. Theoretically, survey lines should be perpendicular to the main trend of the geological units and structures. The main structures of the study area were overturned to recumbent folds with axes oriented in the northwest-southeast direction (Fig 2). In general, beds of rocks dip to the southwest direction, which enabled the design traverse lines in the northeast-southwest direction. Therefore the survey lines were assigned following high geochemical anomaly patterns (Fig 3). Consequently, the baseline was setup in the northeast-southwest direction, and 5 traverse lines in the northwest-southeast direction. Fig 3 and Table 1 show details of the entire survey lines.

In the current study we applied time-domain current switch on and Wenner configuration electrode

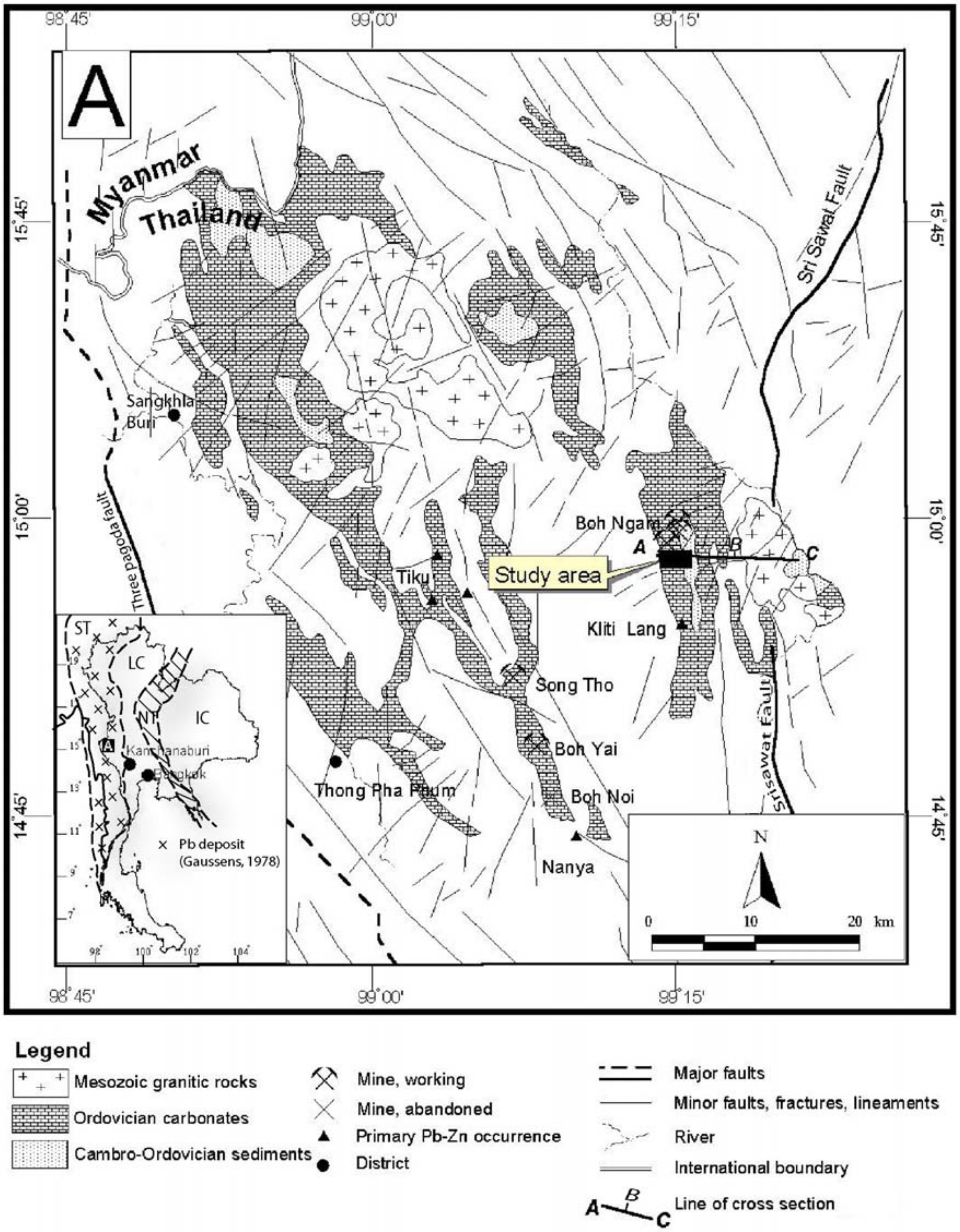

Fig 1. A) Simplified geological map showing major-rock distribution, geological lineaments and mineral occurrences of Thong Pha Phum and nearby areas, Kanchanaburi, western Thailand.
B) Map of Thailand and eastern part of Myanmar with distribution of Pb deposits in Myanmar. WB = Western Burma block, ST = Shan Thai block, LC = Lampang Chiang Rai block, NT = Nakhon Thai block, and IC = Indochina block.

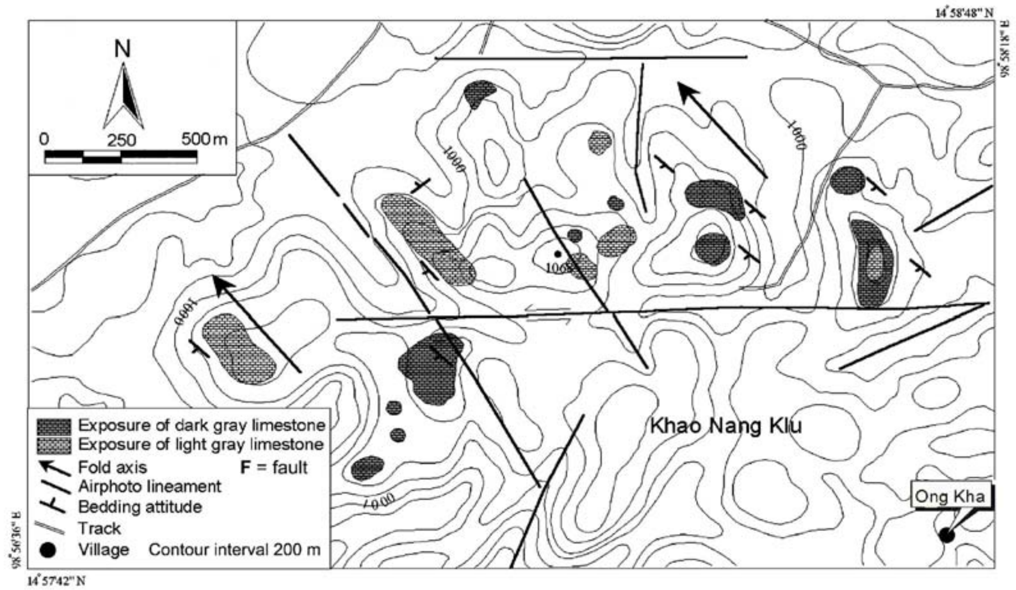

Fig 2. Map of the Kaho Nang Klu study area, Kliti, Kanchanaburi, showing limestone exposures, bedding attitudes, and fractures.

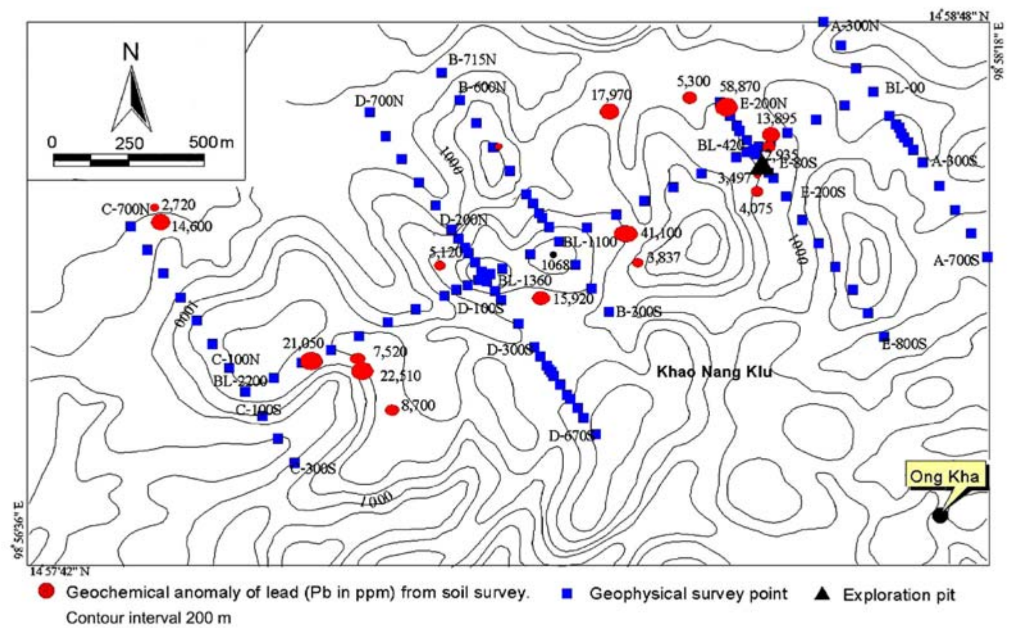

Fig 3. Topographic map showing orientation and spacing of geophysical survey lines with selected high anomaly of lead (modified after, DMR.[10,11]

array (see Fig 4A). Detail of the method follows the work described by Bertin and Loeb.[12] Chargeability and resistivity were measured at the depths A=2, 3.2, 5, 6.5, 8, 10, 12, 15, 17, 20, 22, 25, 27, 30, 32, 35 and 40 m. The array was defined by the length MN=A and AB=3A in such a way that AM=MN=NB. The depth of investigation increases with the spacing depth and approximates A (see Fig 4A).

Results and Discussion

Maps and Coutours

Geophysical contour maps were constructed from digital database using Surfer6 software package. Eight layers were made at depths of A=6.2, 10, 15, 20, 25, 30, 35 and 40 m with the contour interval of 2 m. In order to focus on the high chargeability anomaly, color and size of 14 m-sec contour and 20 m-sec contour

Table 1. Detail of survey lines used in the study area (see map locations in Fig 2).

Line	Cross-base line	Azimuth (°)	Distance (m)	Starting point	Terminal point
Base line		60°-240°	2200	BL-00	BL-2200
Line A	BL-00	150°-330°	1000	A-300N	A-700S
Line B	BL-1100	150°-330°	1000	B-700N	B-300S
Line C	BL-2200	150°-330°	1000	C-700N	C-300S
Line D	BL-1360	150°-330°	1400	D-700N	D-700S
Line E	BL-420	150°-330°	1000	E-200N	E-800S

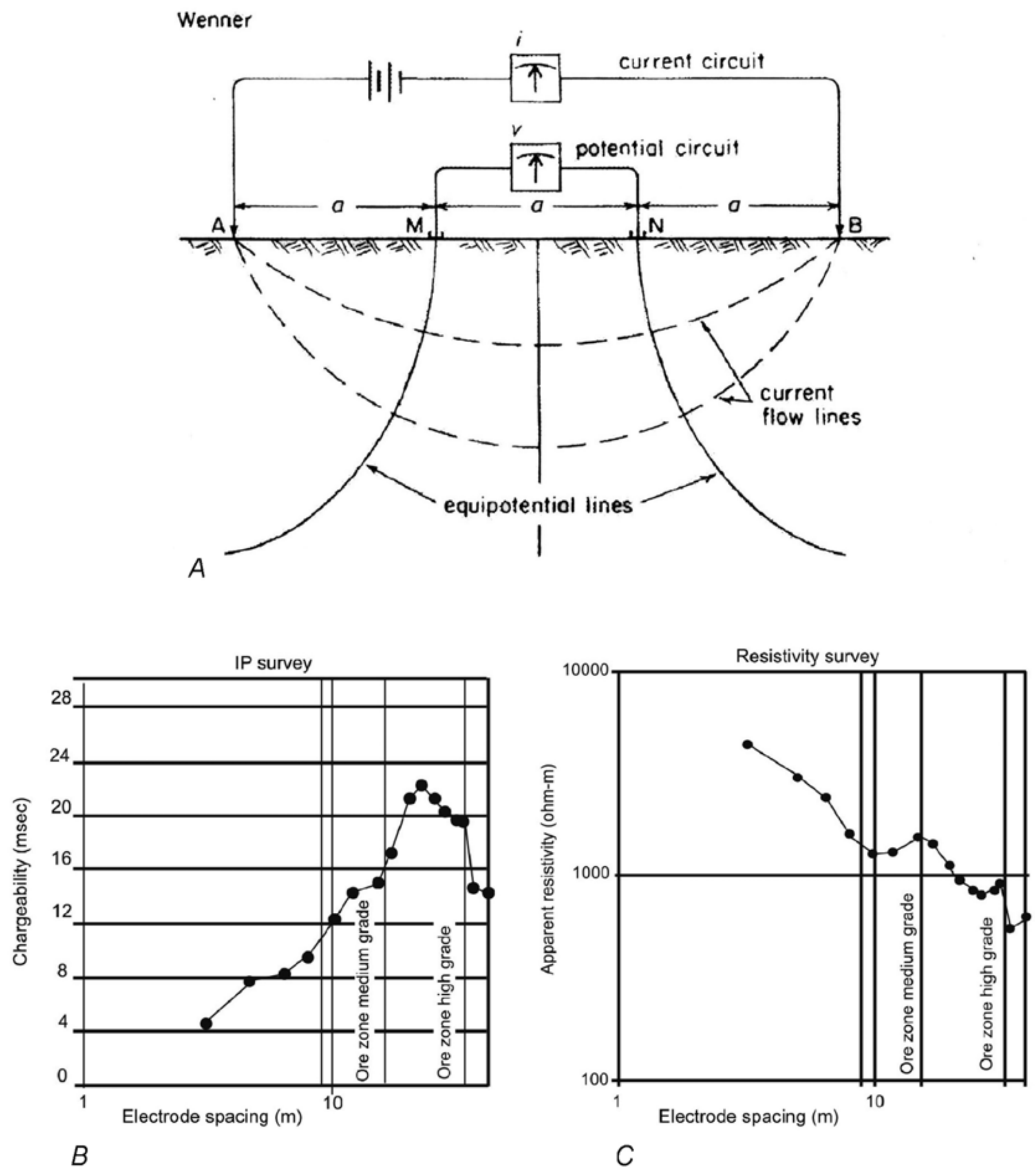

Fig 4. A) The Winner electrode system with four equally spaced electrodes showing current flow lines. Chargeability at various depths is measured by arranging distances of electrode (Robinson[14]).
B) Results from time domain induced polarization (left) and resistivity (right) surveys at the Boh Ngam mine.

were designed to be different from the other contours. In our study, the chargeability of the high-grade ore zone was higher than 15 m sec as defined at the Boh Ngam mine test site (Fig 4B). With this method size and shape of anomaly can be easily modified. Color shades filled between contours were chosen such that they change from pale to dark or dark to pale gray. This can enhance the sharpness of anomaly, which made it easy to notice.

As the contour maps are two-dimensional, they poorly represent the chargeability relief (Fig 5). Therefore, a three-dimensional surface map was constructed for selecting the promising mineralized zones or sub-areas using relief and surface features. The resistivity data and the induced polarization (IP) data were collected, and use in the construction of both contours and surface maps. The low resistivity zone probably indicates a potential area for sulfide mineralization. The combined use of both IP and resistivity data can increase level of confidence in defining potential areas. Sulfide mineral potential area normally exhibits high-induced polarization and low-resistivity anomalies.

In order to relate between the geophysical anomaly and depth, all the processed maps were orderly overlain. Chargeability and resistivity survey maps are illustrated in Figs 5, 6, respectively. Additionally, the data from IP and resistivity methods were combined with those of DMR soil survey[10,11] and our detailed geological mapping.

Interpretation

From chargeability and resistivity measurements of the currently mined ore body at the Boh Ngam mine, the ore body reflects distinctive chargeability. Chargeability of galena-bearing layers varies from 12 m-sec to over 22 m-sec, depending on its ore grades. In addition, resistivity values are also high, but not enough to separate ores from rock strata, and topography has a significant effect to resistivity. In order to explore metal sulfide ores in Boh Ngam area, it is important that we apply the IP method for further detailed investigation.

Data from soil survey revealed that the anomalies of Pb and Cu are high and aligne densely in the northern part of line E as well as on the baseline to the east of line C, and are slightly high close to lines B and D. The mineralized zone may represent the sulfide deposit of lead and copper ores. In the regional scale, the high chargeability anomaly mainly conforms with the high resistivity anomaly. This conflicts to the theory of geophysics, which states that both chargeability and resistivity values should be inverse to each other[12-14] such that high chargeability should lead to low resistivity, and low-grade ores should show the reverse. Only some anomaly points conform with the theory, and these anomalies are not very high, such as those of B200N, E300S, D300N and BL1900 points. Besides, the average resistivity shows relatively high value. One reason is that a local resistivity at the Boh Ngam mine is also high even in rock strata, and similar to those of overburden above the ore-bearing units, i.e., about 900-6,500 ohm-m. The results from the strata orientation, lineaments and structures in the vicinity suggested that the geological structures of the area are quite intricated with the fold axis striking in the northwest-southeast direction (Fig 2).

Zone A (Fig 7) is approximately at the approximate depth from 6.5 m to 10 m (see also Figs 5, 6), and the ore-bearing layers should not exist because of low chargeability and high resistivity. However, ore-bearing layers may exist from the depth of approximately 15 m where it clearly exhibits the increased chargeability and decreased resistivity. In deeper layers, the chargeability increases until it reaches the layers situated at about the depth of 35 m where it becomes decreasing to the depth about 40 m. Besides, resistivity decreases continuously from 15 m to the last depth. Ore bearing layers should therefore exist until the layer 40 m, implying that ore grades may decrease.

For zones B and C (Fig 7), the interesting depths are from 10 m to 25 m because of high chargeability and low resistivity. Grades of ores are possibly lower at the depths from 30 m to 40 m as it exhibits low values of chargeability and high values of resistivity. It is interesting that the linear zone between point E140N and E200S indicates crucial targets body due to high geochemical and geophysical (IP) values. A continuation of high chargeability values from A to D is about 2 km, and the body aligns in the northeast direction, giving rise to a high potential target underneath. Furthermore, our field information from 7-m deep test pit at E80S point indicates prominent stockwork-like small quartz veins and veinlets with disseminated pyrite, chalcopyrite, covellite and bornite.

Zone D at the depth about 15 m to 30 m yields the other interesting result. The rock strata should contain high-grade ores at the depth of 15 m and low-grade ores are located between at the depth between 30 m and 40 m.

The ore body of zone E may be located at the same depth as that of zone D, but ore grades probably decrease downward from the depth of about 25 m following the interpretation by Bertin and Loeb[12]. Therefore, we infer that the northwest-trending, 1-km long high chargeability along the D and E zones does not represent a concealed large ore body. High resistivity in zones D and E may be the result of thick overburdens, particularly along the hill slopes with

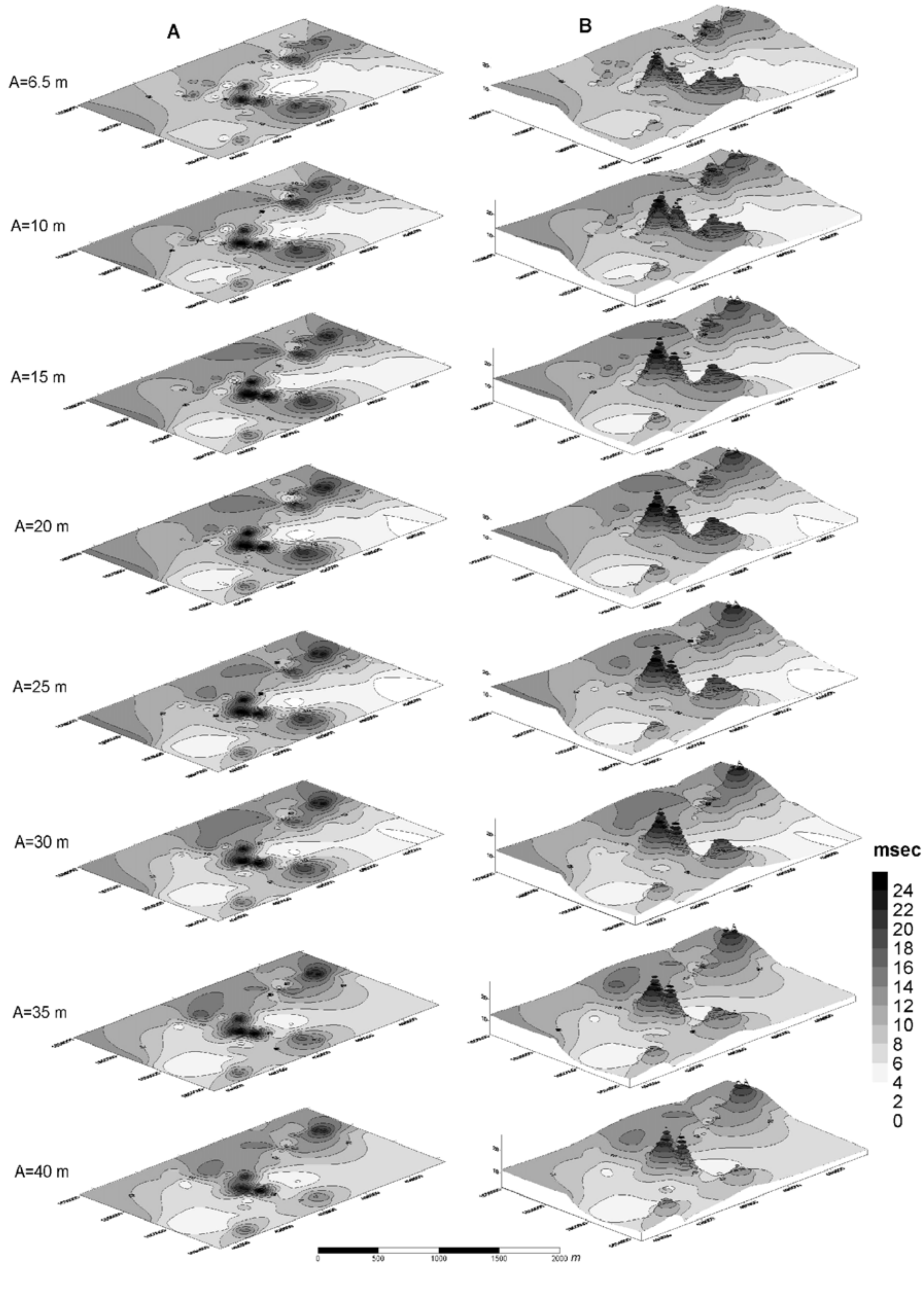

Fig 5. Overlays of chargeability contour (A) and surface (B) maps at the different depth A=6.5 m to A=40 m, Khao Nang Klu, Kli Ti, Kanchanaburi. Note that point 0 indicates the projected Ong klu village of Fig 3.

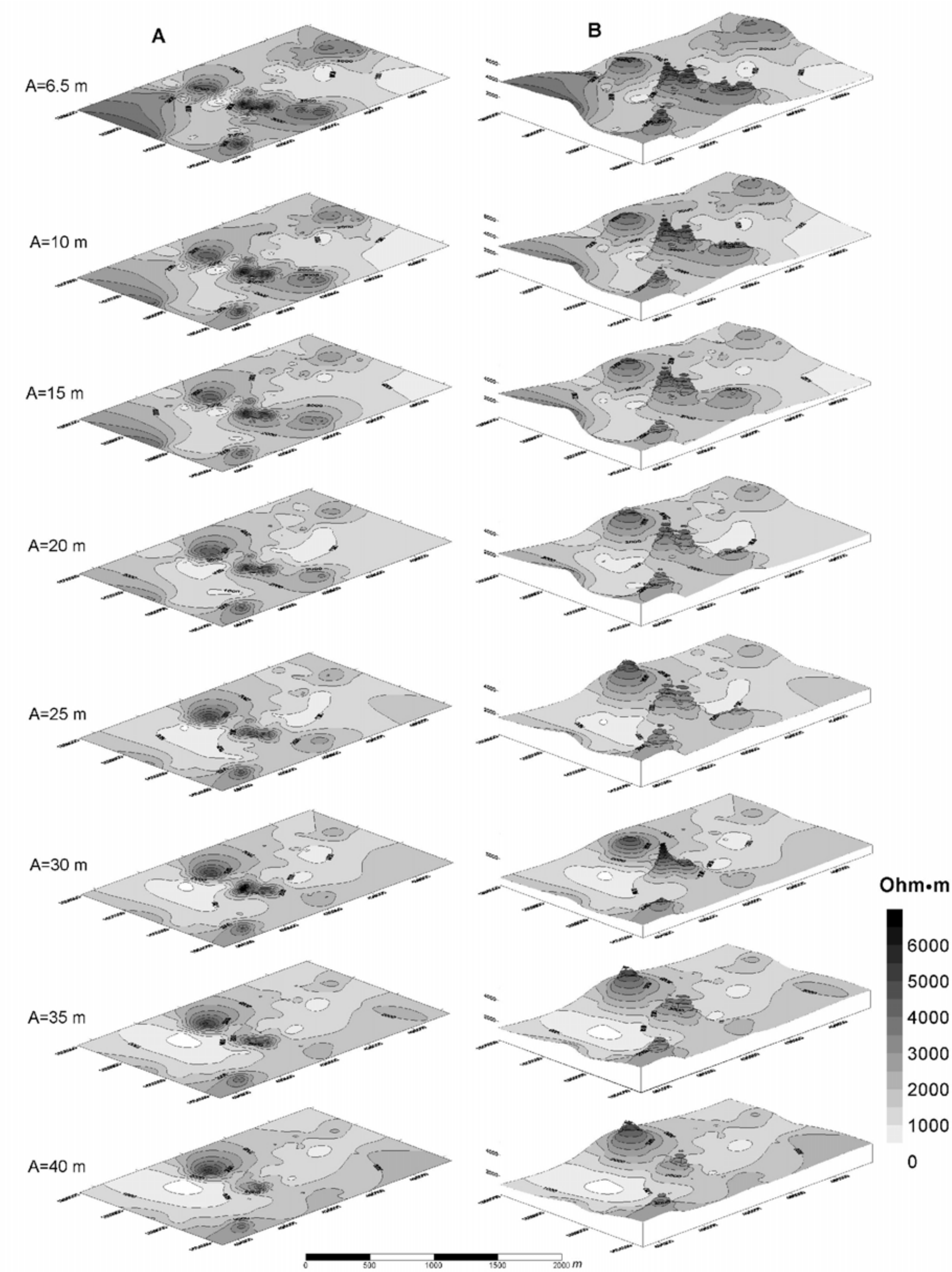

Fig 6. Overlays of resistivity contour (A) and surface (B) maps at the different depth A=6.5 m to 40 m, Khao Nang Klu, Kli Ti, Kanchanaburi. Note that point 0 indicates the projected Ong klu village of Fig 3.

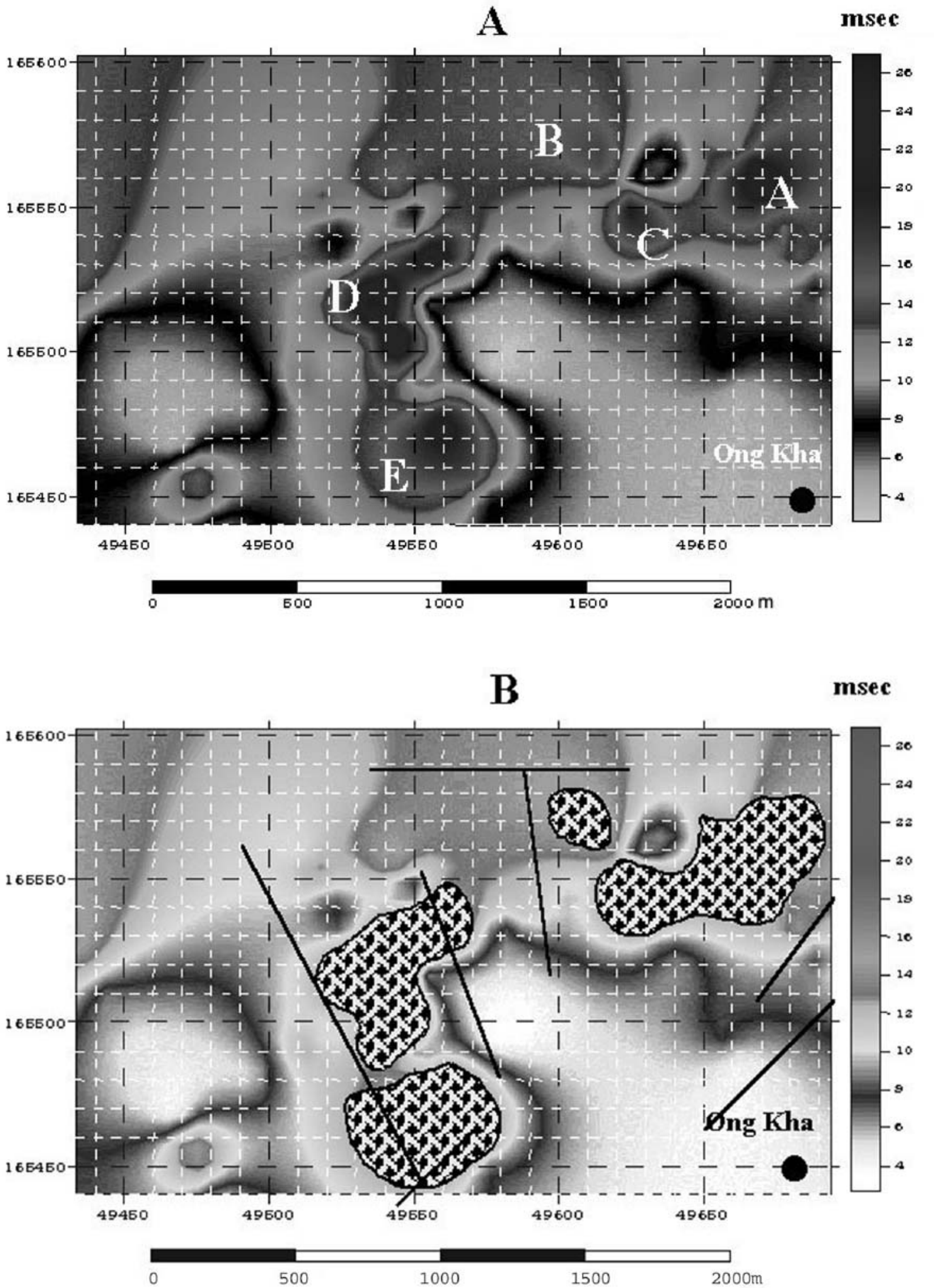

Fig 7. A) Induced polarization spectrum map at the depth A=20 m showing five zones of high chargeability (A, B, C, D and E), Khao Nang Klu, Kli Ti, Kanchanaburi.
B) Delineated metal sulfide mineralized bodies created using chargeability relief at the depth of about 20 m (darker tones) Khao Nang Klu, Kli Ti, Kanchanaburi.
Note that the major ore zone following the northwest-trending fracture (dark line).

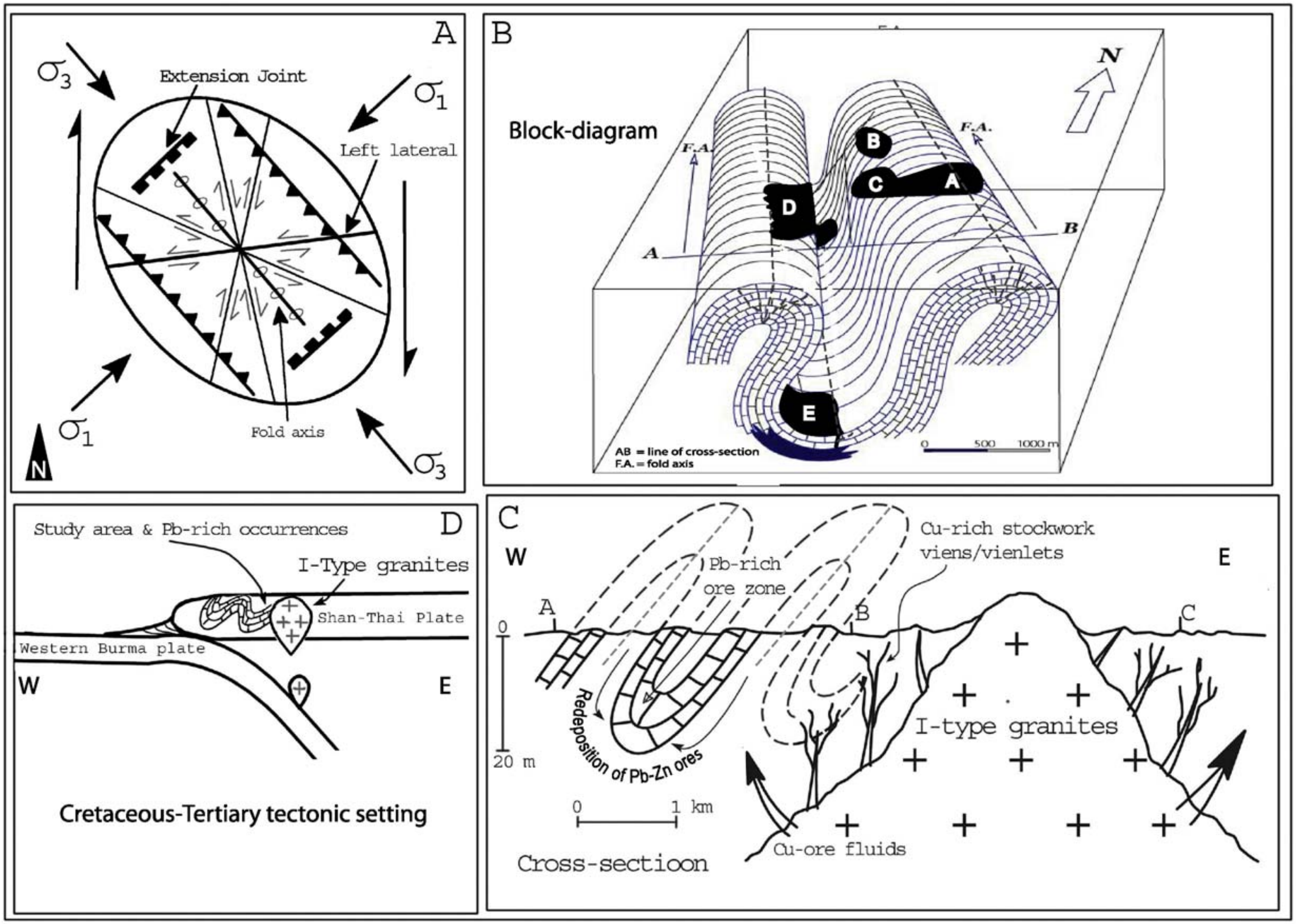

Fig 8. A) Strain-ellipsoid with σ_1 in the northwest - southeast direction extension joint, left-lateral fault and fold axes (data from figure 2).
B) Plan view showing the interpreted isoclinal structure due to compressive tectonics.
C) Simplified geological cross-section from A to C in figure 2, interpreted based on field mapping and ground geophysical results.
D) Plate-tectonic reconstruction of the Kli Ti study and nearby regions during Cretaceous-Tertiary.

thick deposits of unconsolidated and poorly-sorted sediments. From the 7 m-deep pitting, thickness of overburdens attains up to 8 m. The additional reason is that outcrops of carbonates in the area are partly silicified and crosscut by ore-bearing quartz veins and veinlets. When these veins become oxidized, secondary ores, such as those of carbonates, silicates, oxides, hydroxides and sulfates, have been formed in association with remnant primary ores. This possibly results in high values of resistivity.

Localization of Pb±Zn Ore Deposit and Probable Origin

It is important to note herein that due to intricated isoclinal fold structures and limited outcrop exposures in the study area, the data interpretation from this study is therefore inconclusive. Besides, our survey lines and point measurement are insufficient to visualize reliable ore zones at depth due to the limitation of times and budget. Under this circumstance a focus is placed upon localization and dimension of the ore body.

Geochemical soil survey results[10,11] showed that anomalies of Pb and Cu elements are more distinct than those of the Zn. Our field investigations in and around Thong Pha Phum area indicated that massive galena (PbS) ores are quite common, and chalcopyrite ($CuFeS_2$) ores are observed in much smaller amount. At the Boh Ngam mine, boulders of galena ores are sporadically distributed in eluvial deposits without the appearance of zinc ores. Two lines of possibility need to be discussed herein.

1) In the regional scale,[15] the area under survey is located in the Pb-Zn-Sb metallogenic province,[16,17] or in the Sn-W-Pb-Zn-Sb province.[18] However, in a relatively small scale, major exploited ores belong to the Pb group with minority of the Cu ores and without zinc ores. The ore localization may give rise to high Pb and Cu anomalies from geochemical results of soil and stream sediment surveys[10,11] (see Fig 2). However, occurrence of Cu ores elsewhere is not genetically related to that of the Pb ores.[19] The former are always associated with quartz veins and veinlets cutting the Ordovician carbonate host strata, as evident by an exploration pit at E80S (Fig 2). Chalcopyrite and covellite are observed in quartz veins/veinlets without any Pb±Zn mineralization. The most likely localization of Cu ores in the study area may have been influenced by I-type granite intrusions,[20] which are well exposed northeastward to the study area (see also Fig 1). Also, Pb±Zn ores may have been derived from contrasting sources of ore metals which is presumably related more or less to low-temperature epigenetic hydrothermal fluids from underlying older source rocks, and unrelated genetically to any granite origin.[9] Our conclusion is dissimilar to those of Diehl and Kern[3] who suggested the igneous-related, Alpine-type strata-bound origin for Pb±Zn deposits of Kanchanaburi, but it is similar to those of Yokart[4] and Putheang et al.[9] High geochemical values of Pb,[11] which show a distinct trend in the NW direction, are partly controlled by abundant slags and are considered to represent non-significant anomalies. Even though northwest-southeast-striking bedding planes can serve also as channel ways for fluid precipitation, they become so tight by deformation that fractures cannot be developed.

2) It is crucial that our geophysical anomaly points to localization of the sulfide ore body at depth and that there exists a few Zn deposits to the north of the study area (e.g. Pha Daeng mine of the Mae Sod area,Tak). However, due to the relatively higher mobility of Zn than Pb, it is possible that Zn may have almost entirely leached out from the area. As a result, there is no zinc anomaly detected from the surface. In order to prove the existence of zinc ores at depth, an exploration drilling is required for further detailed investigation.

Strain Ellipsoid and Further Exploration

Our geophysical result indicated that the anomalous bodies align mainly in the northeast-southwest and northwest-southeast directions (Fig 7A). It is widely accepted that signals or chargeability values achieved from IP can reflect sulfide ore deposits better than other methods. However, based upon our chargeability result, anomalies in the northwest direction can be traced in a short distance with alternated high and low values. As recognized in the field, fold is the main geological structure of the area with its fold axis trending in the northwest direction. Such synclinal and anticlinal structures may have been formed by the principal stress[21] along the northwest-southeast direction (Fig 8A). The compressive stress (s_1) in this northeast direction resulted in extension fractures in the northeast-southwest direction. Consequently, ore fluids may have migrated along these northeast-trending fracture planes where compressive stress (s_3) is minimum, giving rise to the continuity of mineralized body (Fig 7B). It is therefore inferred that the northward to northeastward shearing stress is responsible, as expressed in strain ellipsoid displayed in Fig 8A, for the fracture-filling ore deposit. In a more regional scale, the probable oblique subduction of oceanic slab of the Western Burma block[22] beneath the Shan-Thai block during Late Cretaceous to Early Tertiary,[23] may have caused the generation of I-type granites providing weak Cu-mineralization (Fig 8D) and NE-trending open fractures in Ordovician carbonate strata (Figs 8B, C). Heat provided and generated by the I-type magmas may have caused remobilization and reconcentration of Pb±Zn ores from the carbonates. Then Pb±Zn ores may have moved to redeposit in open fractures of folds, faults and bedding contacts in secondary pore spaces. Thus the northeast-trending, highly anomalous zones at about 20-m depth (A and B in Fig 7A) are most likely to be proved by further exploration drilling. Our interpretation on genetic relationships between ores and host rock potential is not new and seems to be similar to those of Permthong,[6] Yimyai[7] and Putheang *et al*.[8] Our results are based chiefly on ground field and geophysical investigations and can suggest a subsequent drilling exploration in the follow-up evaluation stage.

Conclusions and Recommendations

Both IP and resistivity methods were applied to Ordovician carbonate terrain in the Kli Ti area of Kanchanaburi province. Results from six survey lines indicated two major geophysical anomalies oriented in the northwest and northeast directions. The results revealed that the northwest-trending, 1- km long zone that conforms with bedding strata is absent at depth more than 10 m, suggesting non-significant anomaly in geophysical senses. The northeast-trending, 2 km long, anomalous zone with the thickness of 25 m and at the average depth of 20 m, becomes significant. This promising zone occurs in the major fracture planes, which developed in the northeast direction. This fracture-controlled ore zone is regarded as the epigenitic Pb±Zn ore body, which took place in the NE-trending vein/veinlets. The essential sources of ore fluids may not be related to that of the Cu ores, as supported by the separated ore-bearing vein/veinlets. The Cu ores was probably derived from I-type granites of the late Cretaceous (to Tertiary) age. The magmato-tectonic regime of this episode may have subject to the northeast-trending maximum stress axis, corresponding to the northward movement of the Western Burma block and interaction with the Sibumasu (or Shan-Thai) block in western Thailand. Results from ground geophysical surveys can delineate ore geometry and orientation, which then can be applied in the design of further drilling exploration assigned in the highly anomalous zones (Fig 7) in the future.

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