Kinematic history of the thrust fault-related calcite veins at the Indochina margin, Thailand

Ausa Nonthason[1,2], Pitsanupong Kanjanapayont[1,2*], Sukonmeth Jitmahantakul[1,2]

[1] Basin Analysis and Structural Evolution Research Unit (BASE RU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
[2] M.Sc. Program in Petroleum Geoscience, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

* Correspondence: pitsanupong.k@hotmail.com

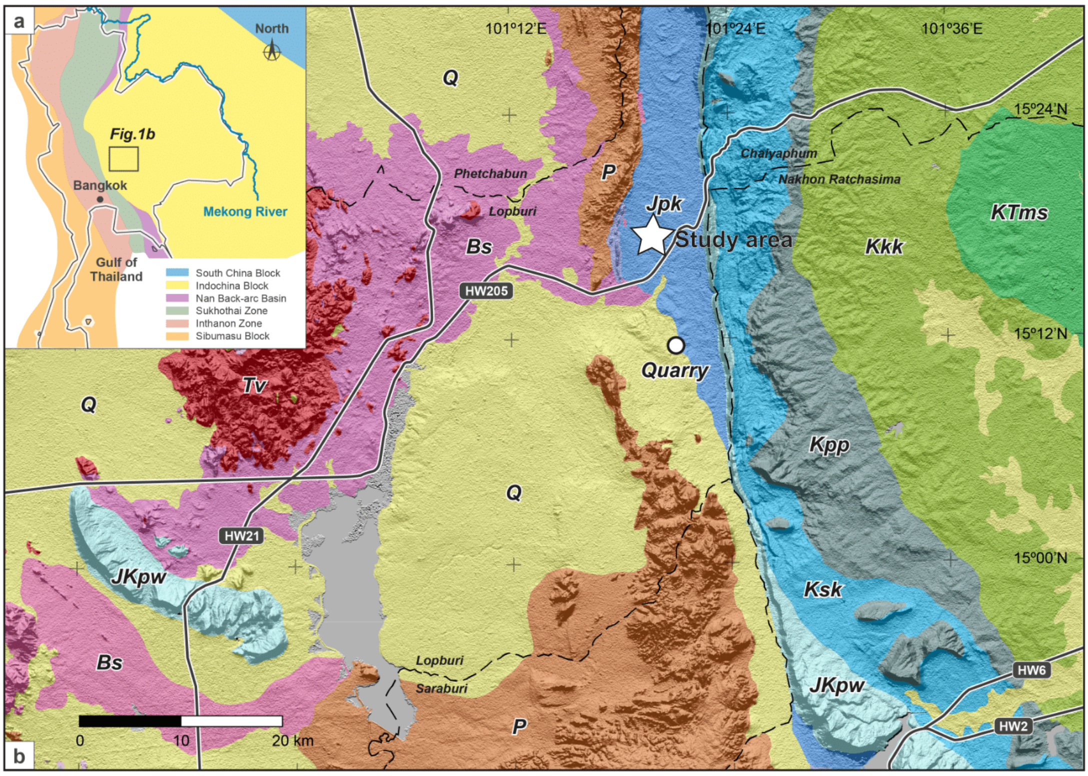
Abstract

Calcite veins in Mesozoic sedimentary rock localities are found in the southern part of Lam Sonthi District, Lopburi Province, in central Thailand, near the Loei-Phetchabun fold belt regions. The vein's host rock are siliciclastic rocks, primarily mudstone and sandstone. The main aim of this study is to learn more about calcite vein geometry and development, as well as the structural evolution of calcite veins in the Phu Kradung Formation in the Lam Sonthi area of Lopburi Province. A petrographic and structural analysis of the veins was performed to examine the kinematics and geological structures of the calcite vein in the host rock. The findings show three basic variants of the orientation of calcite veins, including east-dipping calcite veins, west-dipping calcite veins, and steep-dip-angle calcite veins. The majority of the calcite veins in the study area show common characteristics of fibrous crystals. So, most of them are considered antitaxial veins. The formation of the calcite vein is divided into four stages, including the formation stage of the host rock Phu Kradung Formation, the deformation stage, which causes the formation to show a gentle fold with the east-dipping veins and the west-dipping veins generated by the E-W compression. As a result, the host rock develops multiple thrust faults, resulting in the formation of fault-related veins. The final stage is the opening of the steep-dip-angle vein over each geologic stratum in the study area. The deformations of the veins were influenced by the escape tectonics and the creation of the Tertiary extensional rift basin in Southeast Asia.

Keywords: calcite veins, thrust fault, Phu Kradung Formation, Indochina, Thailand

1. Introduction

The research is being conducted in the Lam Sonthi district of Lopburi province in central Thailand. Information about the structural and tectonic history of the Lam Sonthi area remains unclear, as the region's geology has not been consistently mapped and described. Consequently, this study aims to use the investigation of veins in the study region to comprehend the structural and tectonic history (e.g., Abaab et al., 2021; Warren et al., 2014). To investigate the formation mechanism of the fibrous calcite vein in the host rock, structural and microstructural analyses of the veins were performed in this study. This method will be applied to the calcite veins in the host rock of the veins, which is the Phu Kradung Formation in the southern part of the Lam Sonthi area, which is part of the Indochina margin (Figure 1).



Jpk = Jurassic Phu Kradung formation
Q = Quaternary sediment
JKpw = Cretaceous to Jurassic Phra Wihan formation
Tv = Tertiary porphyritic Rhyolite
Bs = Tertiary basalt
Kkk = Cretaceous Khok Kruat formation
Kpp = Cretaceous Phu Phan formation
Ksk = Cretaceous Sao Khua formation
KTms = Cretaceous Maha Sarakham formation

Figure 1 . (a) An illustration of Thailand and surrounding regions shows the location and approximate boundaries of the tectonic blocks. (b) Geological map of Lopburi Province including the location of study area, scale 1:250,000 (Department of Mineral Resources, 2009a; 2009b; 2012).

2. Tectonic setting

In Thailand and the surrounding regions, there are two main tectonic blocks. While the western portion is a part of the Sibumasu Block (or part of what was formerly known as Shan-Thai (Bunopas, 1981b), the eastern portion is a member of the Indochina Block. The Sukhothai Fold Belt (SFB) on the west side and the Loei – Phetchabun fold Belt on the east side (LFB) divide these two blocks (Metcalfe, 2011; Sone & Metcalfe, 2008; Zaw et al., 2014). The Loei-Phetchabun fold belt is primarily dominated by Paleozoic Indochina Block rocks beneath the Khorat Group, where Triassic-Jurassic calc-alkaline plutons associated with Fe-Cu and Au-Ag mineralization has intruded upon deformed sedimentary and volcanic rocks of the Silurian, Devonian, Carboniferous, and Permian ages, whereas the Sukhothai fold belt is primarily dominated by post-Triassic rock (Khositanont, 2008; Nualkhao et al., 2018; Shi et al., 2021; Ueno & Charoentitirat, 2011; Zaw et al., 2014). The Jurassic-Cretaceous terrestrial Khorat Group is uncomfortably overlain by this sequence in the southern segment. From the Silurian through the Tertiary, extensively formed igneous rocks cover a wide age range (Racey and Goodall, 2009). The vein geometries and the occurrence of several thrust faults in the study area including the growth of veins associated with faults, which is part of the western margin of the Khorat Plateau, are interpreted to relate to this tectonic event. As an example of vein variants observed in the Mesozoic Khorat group, such as quartz veins in the Phu Phan Formation (Racey et al., 1996) and calcite veins in the Phu Kradung Formation observed in this study.

3. Geology of Lam Sonthi and the surrounding regions

Based on pre-existing geology maps (Department of Mineral Resources, 2007) and this study, the geology of the southern part of the Lam Sonthi was compiled (Figure 3). The geology of the study area consists of the rocks from the lowest member of the Mesozoic Khorat Group, which is the Phu Kradung Formation (Figure 2). It consists predominantly of fine-grained calcareous sandstone interbedded with mudstone, which is the host rock of the calcite veins in our study, lime-noduled conglomerate can occasionally be found (Minezaki et al., 2019). Based on recent vertebrate fossils discoveries and palynological data, the depositional age of the Phu Kradung Formation ranges from the Late Jurassic to the Early Cretaceous, while the majority of it was most likely deposited in the Late Jurassic (Racey and Goodall, 2009). Also, based on geochronological data, sandstone from the Phu Kradung Formation, which is rich in lithic volcanic rock pieces, has a deformational age of 180 Ma. This age is Early Jurassic and is significantly older than the Late Jurassic– Early Cretaceous depositional age of the Phu Kradung Formation estimated from fossil data, excluding palynological data. This older age implies that the Phu Kradung Formation does not contain syn-depositional zircons (Hara, 2024). The Formation is considered to have been deposited in floodplain settings, alluvial and fluvial fans, and meandering river systems with paleosols (Heggemann et al., 1994; Meesook, 2000). Numerous vertebrate fossils have been found in the Phu Kradung continental formation of northeastern Thailand, particularly in the Phu Phan Mountain Range. Most significantly, Upper Phu Kradung's sandstone beds alternate with silty to sandy claystone pedogenetic horizons, and their composition occasionally resembles the massive quartzitic sandstone body of the Phra Wihan Formation. The rest of the surrounding area consists of gravel, sand, silt, and mud from alluvial and terrace deposits, tertiary basalt, and limestone interbedded with shale from the Permain Khao Khwang Formation (Department of Mineral Resources, 2007; Liard & Martin, 2011).

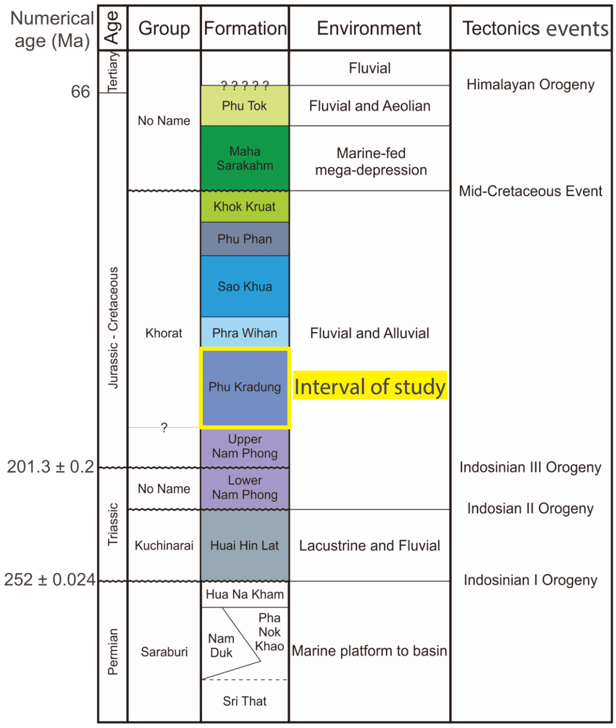


Figure 2. Stratigraphic units of the Khorat Plateau in northeastern Thailand including environment of deposition and major tectonic events (compiled from Racey, 2009; Booth & Sattayarak, 2011; Warren et al., 2014).

4. Material and method

We conducted a field investigation of the calcite veins from the outcrop in the research area, intending to determine the distribution of the calcite veins in the Phu Kradung Formation bed (Figure 4). To better understand the geometry and structural evolution of calcite veins in the host rock, structural analysis was performed on the outcrop at the study area and microstructural examination were performed on samples taken from calcite veins in the host rocks, which are the Mesozoic sedimentary rocks of the Phu Kradung Formation, which are dominated by sandstone and mudstone.

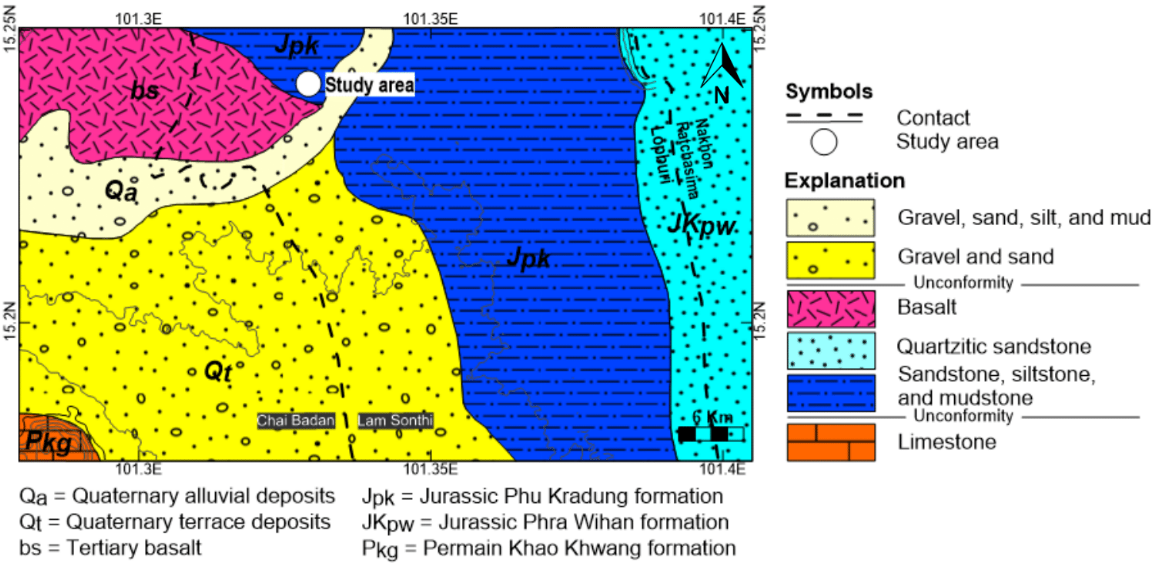


Figure 3. Geological map of the southern part of the Lam Sonthi area, Lopburi province, scale 1:250,000 (Department of Mineral Resources, 2007; 2010).

Nine samples of calcite veins were oriented and collected from various locations within the outcrop of Mesozoic sedimentary of the Phu Kradung Formation in the study area.

Additionally, information regarding the deformation events of the host rock was gathered to investigate the variations among the calcite vein varia tions in the study area.

4.1 Structural analysis

Structural investigation in the outcrop was carried out to better understand the characteristics of the variety of calcite veins as well as the fault geometry and pattern. The orientation of calcite veins, faults, and bedding planes were measured and plotted in the stereographic nets to characterize the geometry of calcite veins in the study area. The cross-cutting relationship will be applied to the structural evolution of the study area.

4.2 Petrography and microstructural analysis

Representative samples of calcite veins will be oriented and collected from the Phu Kradung Formation. All microstructure observations have been made with a polarizing microscope.

5. Results

5.1 Structural style

The considerable number of calcite veins in the research area can be observed owing to the Phu Kradung Formation's extensive exposure in the study area in the southern part of the Lam Sonthi area. They are distributed unevenly throughout the host rock's succession, usually clustered around the mud and sand layers, and have the same N-S trend orientation as the host rock beds, with the exception of the steep-dip-angle vein, which cuts through the outcrop's top conglomerate.

Additionally, we noted that in the research area, calcite veins are seen near minor discontinuities, such as thrust faults. Most of the calcite veins that are observable in the research region are oblique to the host rock strata (Figure 4). The orientation of calcite veins can be classified into three basic variants: 1) east-dipping calcite veins; 2) west-dipping calcite veins; and 3) steep-dip-angle veins. The westernmost part presents the west- and east-dipping veins, which are cut by the steep-dip-angle vein (Figure 5A). Some west- and east-dipping veins are connected (Figure 5C). The west- and east-dipping veins with the steep-dip-angle vein and thrust faults were illustrated in the easternmost part (Figure 5F). The calcite veins are abundant in the brown sandstone and shale lithology of the Phu Kradung Formation, which typically have a width of 2-4 cm but occasionally can reach over 30–40 cm. Most of the calcite veins have typical characteristics of fracture-fill veins, which are characterized by an extensive network of veins created by one vein set typically cutting through another older vein set (Figure. 5).

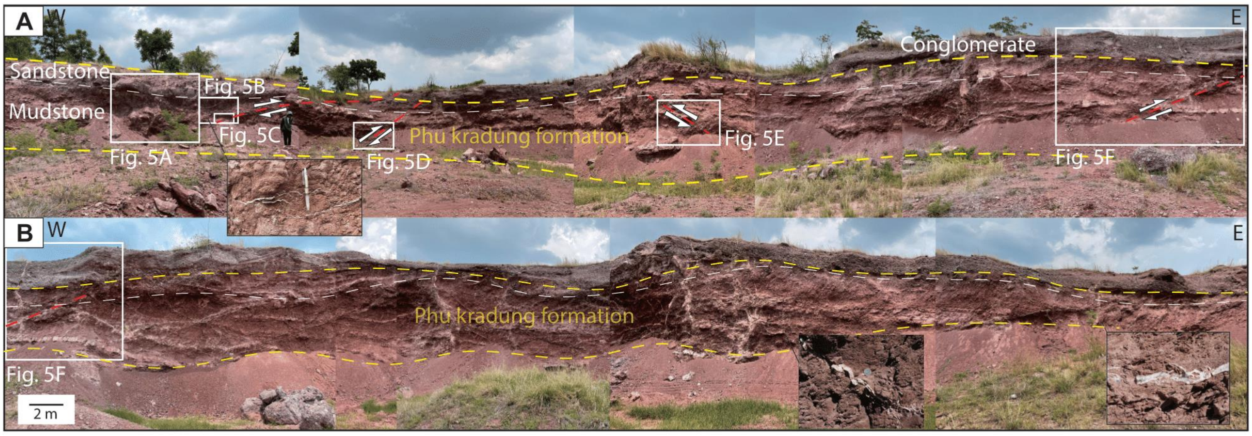


Figure 4. An overview cross-section with thrust faults distribution along the Phu Kradung Formation.

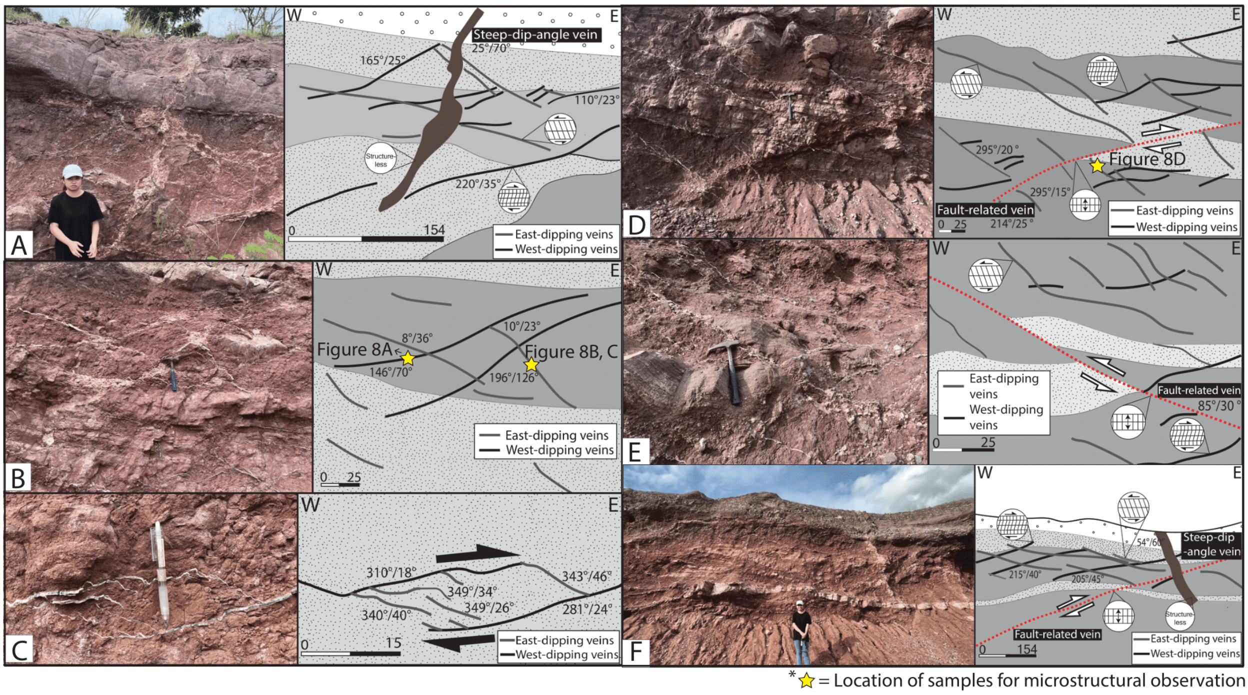


Figure 5. Photographs showing the common morphologies of calcite veins related thrust fault at the Indochina margin. (A) Relationship of the calcite veins between east- and west-dipping veins and the steep-dip-angle vein in the western part of an outcrop. (B) Continuous east- and west-dipping calcite veins cut by east-dipping thrust fault. (C) East-dipping calcite veins developed between two west-dipping calcite veins indicating a thrust component to the east. (D) West-dipping thrust fault cuts both east- and west-dipping calcite veins. (E) East- and west-dipping calcite veins within mudstones and sandstones cut by east-dipping thrust fault. (F) East- and west-dipping calcite veins and thrust fault cut by the steep-dip-angle vein.

Bedding planes of the Phu Kradung Formation in the study area are very gentle (~ 30°) and it is oriented in the NW -SE direction (Figure 6A). The calcite veins variation varies greatly. The east-dipping calcite veins show the variation from NE to SE (Figure 6B). The west-dipping calcite veins, which are dominantly found in the study area, show more stick together to the NW (Figure 6C). Thrust faults dip to the east and west which are parallel to the east- and west-dipping veins, respectively (Figure 6D). The steep-dip-angle veins are oriented in the NE-SW direction (Figure 6E).

Certain veins exhibit characteristics typical of tension veins, such as en-échelon arrays (Fig. 5C). They frequently have a sigmoidal (S or Z) form in these arrays. Conventionally, these arrays are interpreted as simple shearing parallel to the vein array in the opposite direction as the vein tips point (Fig. 7A) (Bons, 2000).

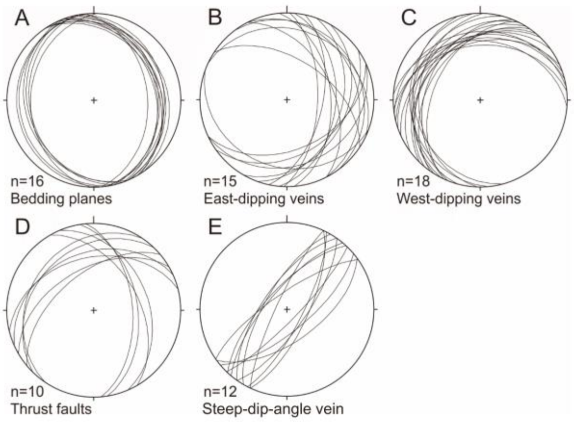


Figure 6. Stereographic projection of the structural measurement (A) bedding planes, (B) east-dipping veins, (C) west-dipping veins, (E) thrust faults, and (E) the steep-dip-angle vein.

5.2 Vein morphology

Calcite veins are frequently found throughout the area under investigation, both continuously and discontinuously. A broad network of calcite veins may be observed on occasion, indicating that these veins were probably formed simultaneously and were related to the others. The vein's branching at the vein's tip is a common observation (Figure 7B). Sometimes the branching of the calcite veins characterizes the structure of the en-échelon (Figure 7A). The en-échelon structure connected the calcite veins and their branching veins together. They are especially present in the layers of sandstone and mudstone.

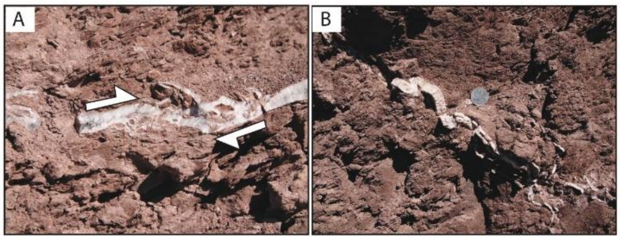


Figure 7. Photographs of the vein morphologies of calcite (A) En-échelon structure, (B) The calcite vein and their branching veins.

5.3 Petrography and microstructures

The petrographic observations of the calcite veins have been performed on nine samples of calcite veins located in the southern part of Lam Sonthi district, Lopburi province. The location where each sample was taken in each zone is shown in Figures 5A–F. All the results (Figure 8) were obtained using cross-polarization microscopy. According to the results, the calcite fiber's orientation provides helpful information about the kinematics of calcite growth. The west- and east-dipping calcite veins show fibrous calcites that grow continuously toward the edges. The west-dipping calcite veins can be divided into two zones based on the orientation of the calcite fiber: one zone has oblique growth directions due to the shear components, and the other zone has perpendicular growth directions. The growth direction of the east-dipping calcite vein was only detected in one orientation, and that orientation was slightly inclined. As seen in figures 8B and C, the calcite veins can be separated into two zones based on their growth direction patterns. Certain east-dipping veins (Figure 8D) are distinguished slightly from the others in that they have a single zone of oblique growth orientations resulting from the shear component.

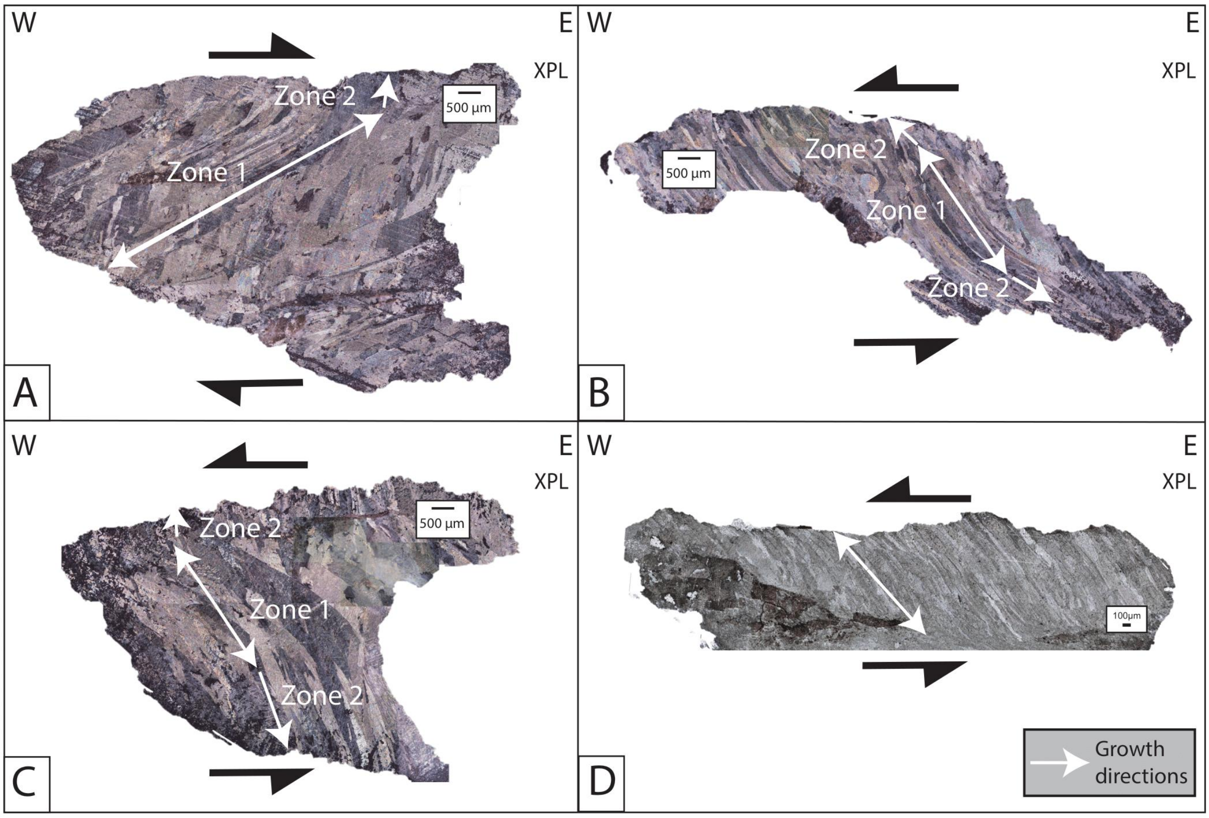


Figure 8. Microstructural characteristics of the calcite veins. Calcite of both (A) west-dipping veins and (B and C) east-dipping veins can be subdivided into 2 zones resulting from a shear component. (D) Sme calcites of the east-dipping vein show only 1 zone.

6. Discussion

6.1 Vein classification

Vein types, including syntaxial veins, stretching veins, and antitaxial veins, are classified according to their crystal growth mechanisms, crystal morphology, and directions of crystal growth (Bons et al., 2012; Bons & Montenari, 2005; Durney and Ramsay, 1973). Systematic vein populations are typically understood to be the result of regional (such as far-field stress transmission) or local (such as fault- or fold-related) tectonic evolution (Beaudoin et al., 2018). Syntaxial veins are veins in which the minerals that fill the vein grow out of the vein's wall rock. Usually, crystals grow toward the center of the vein from both sides, yet occasionally this fails to be the case and only one side grows that way. Their crystal shapes are typically blocky or elongated, and their growth competition is usually strong. Stretching veins are veins that are formed by crack-sealing. Systematic growth direction and growth competition are absent. Their crystal shapes are stretched crystals and only show the overall displacement of the vein walls. Antitaxial veins appear to grow from a median line towards the walls and are usually characterized by fibrous crystals. A median line, or median zone, is a characteristic that makes antitaxial veins distinguishable. The antitaxial veins have two growth planes that are situated on the vein's outside, whereas the syntaxial and stretching veins only have one growth plane at a time. The antitaxial veins typically show symmetry across the median zone (Bons et al., 2012; Bons & Montenari, 2005). Since most of the calcite veins in the research region commonly show typical characteristics of fibrous, a large majority of them are antitaxial.

6.2 Structural evolution

As a potential outcome, we propose that the calcite veins are primarily formed by a confluence of different mechanisms, including the tectonic stress that impacted the Phu Kradung Formation in the past and had a significant impact on the veins within it, as well as the natural sedimentary crack opening increments of the rock strata.

As illustrated in Figure 9A-D, we have separated the formation of the calcite vein into four stages. Based on our synthetic model, the initial stage is the formation of the Late Jurassic to Early Cretaceous Phu Kradung Formation, which is part of the Khorat Plateau (Figure 9A). The second stage is the deformation stage of the Phu Kradung Formation shows the gentle fold with the east-dipping veins and the west-dipping veins, that are formed by the E-W compression (Figure 9B). As a result, the host rock develops several thrust faults, which leads to the formation of fault-related veins (Figure 9C). The opening of the steep-dip-angle vein across each geologic stratum in the study area is interpreted to be the last stage (Figure 9D).

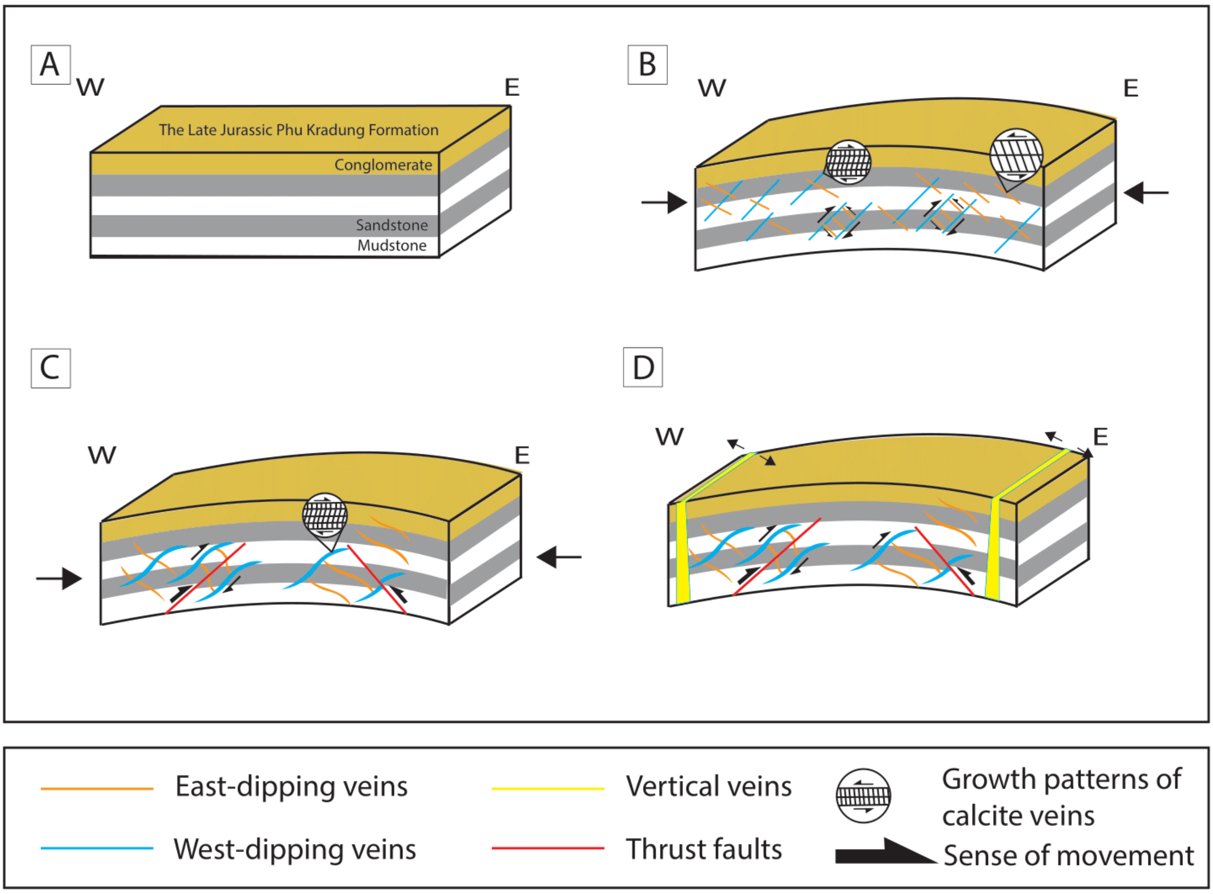


Figure 9. Schematic model of generation of calcite veins in the Indochina margin. (A) Initial stage of the Phu Kradung Formation. (B) The deformation stage: generation of east- and west-dipping calcite veins. (C) The inversion stage: continuous generation of east- and west-dipping calcite veins and thrust faults. (D) The last stage: generation of the steep-dip-angle vein.

6.3 Tectonics implication

Following a thorough analysis of the data and a review of the literature, the deformation in the study may integrated to the tectonic implication in the Southeast Asian region. After the sedimentary deposition of the Khorat Group in the Triassic to Cretaceous in the initial stage, the major tectonic in Southeast Asian region is the escape tectonics which concerns about the primary collision between India and Eurasia during the Eocene-Oligocene (Morley & Wang, 2023; Morley, 2012), and complex interaction of plate boundary forces, and some intra-plate sources (Morley & Wang, 2023). It drove the Indochina block to the northwest and provided the various deformations in Thailand. The strike-slip systems of the Three Pagodas, Mae Ping, Ranong, and Klong Marui faults were developed in the Sibumaru block (Morley, 2012), while folds and fractures were dominant in the Indochina block. The results of the Paleogene deformation also include strike-slip faults, folds, thrusts, and inversion structures, triggering the Khorat Group and time-equivalent formations to fold, elevate, and erode (Lamont et al., 2021; Morley & Wang, 2023; Morley, 2012; Veeravinantanakul et al., 2018). The deformation of the second and third stages may be affected by the collision of the Indian and Eurasian tectonic plates during the Cenozoic (Cooper et al., 1989; Racey et al., 1996) and forming the early stage of the escape tectonic (Morley, 2002; Morley & Wang, 2023). The vein geometries and the occurrence of several thrust faults in the study area including the growth of veins associated with faults, which is part of the western margin of the Khorat Plateau, are interpreted to relate to this tectonic event. As an example of vein variants observed in the Mesozoic Khorat group, such as quartz veins in the Phu Phan Formation (Racey et al., 1996) and calcite veins in the Phu Kradung Formation observed in this study.

The Tertiary extensional rift basin is the extensional rift basin during the Tertiary that was involved with the late stage of the escape tectonic in Thailand (Morley, 2001, 2002). According to our outcrop data, the orientation of the steep-dip-angle veins appears to be caused by the pulling in the NW-SE direction. So, we suggest that the Tertiary extensional basin opening (Morley & Wang, 2023) is the main tectonic events that have influenced the development of the steep-dip-angle calcite veins in the study area.

7. Conclusions

Throughout this research, the calcite veins related thrust faults are widespread and clearly observable in the Phu Kradung Formation in the Lopburi province of Thailand which is a part of the Indochina margin. The major geological structures in the study include the east- and west-dipping veins, thrust faults, and the steep-dip-angle vein. After the deposition of the Phu Kradung Formation in the study area in the first stage of our model, the Phu Kradung Formation, in the Khorat Plateau has undergone deformation, that was affected by the collision of Indian and Eurasian tectonic plates or the early stage of the escape tectonic during the Cenozoic (Hansen et al., 2016; Morley & Wang, 2023; Racey et al., 1996). This allowed the creation of the majority of calcite veins within the sedimentary host rock in the region under investigation of the second stage. The third stage is continuously driven by escape tectonics, which causes thrust faults to form in the host rock, which leads to the formation of fault-related veins in the study area. Microstructural analysis of the calcite vein samples from the Phu Kradung formation in the study area show that the majority of the calcite veins in the study area show common characteristics of fibrous crystals. So, most of them are considered antitaxial veins.

The final stage is the opening of the steep-dip-angle vein in the study area that related to Tertiary rift basin that was involved with the late stage of the escape tectonic (Morley, 2001, 2002; Morley & Wang, 2023). Hence, the E-W compression forces and the sedimentary crack opening increments of the host rock strata plays a significant role on the formation of weakness planes that allow the fluid that carried calcite minerals to flow into the open space within the sedimentary host rock and precipitate and create the majority of calcite veins in the Phu Kradung Formation in the study area. The escape tectonics and the creation of the Tertiary extensional rift basin are considered to be the most significant tectonic influences of the deformations of the veins in the study area.

Acknowledgments

The authors would like to thank Department of Geology, Chulalongkorn University, Thailand for the facilities to enable this research. Thanks are also extended to the editor and anonymous reviewers for constructive comments which improved this manuscript.

References

Abaab, N., Zanella, A., Akrout, D., Mourgues, R., & Montacer, M. (2021). Timing and distribution of bedding-parallel veins, in evaporitic rocks, Bouhedma Formation, Northern Chotts, Tunisia. *Journal of Structural Geology*, 153, 104461.

Beaudoin, N., Lacombe, O., Roberts, N. M., & Koehn, D. (2018). U-Pb dating of calcite veins reveals complex stress evolution and thrust sequence in the Bighorn Basin, Wyoming, USA. *Geology*, 46(11), 1015-1018.

Booth, J., & Sattayarak, N. (2011). Subsurface Carboniferous–Cretaceous geology of NE Thailand.

Bons, P. D. (2000). The formation of veins and their microstructures. *Journal of the Virtual Explorer*, 2, 12.

Bons, P. D., Elburg, M. A., & Gomez-Rivas, E. (2012). A review of the formation of tectonic veins and their microstructures. *Journal of structural geology*, 43, 33-62.

Bons, P. D., & Montenari, M. (2005). The formation of antitaxial calcite veins with well-developed fibres, Oppaminda Creek, South Australia. *Journal of structural geology*, 27(2), 231-248.

Bunopas, S. (1981). Paleogeographic history of Western Thailand and Adjacent Parts of South-east Asia-A plate tectonics interpretation.

Canham, A., Love, M., Racey, A., & Polachan, S. (1996). Stratigraphy and reservoir potential of the mesozoic Khorat group, NE Thailand: Part 2: diagenesis and reservoir quality. *Journal of Petroleum Geology*, 19(3), 321-338.

Cooper, M., Herbert, R., & Hill, G. (1989). The structural evolution of Triassic intermontane basins in northeastern Thailand. International symposium on intermontane basins: geology and resources.

Department of Mineral Resources (2007). Geological Map of Changaz Lopburi, Scale 1:250,000.

Durney, D. (1973). Incremental strains measured by syntectonic crystal growths. *Gravity and tectonics*, 67-96

Department of Mineral Resources (2009a). Geological Map of Changwat Kalasin, Scale 1:250,000.

Department of Mineral Resources (2009b). Geological Map of Changwat Udon Thani, Scale 1:250,000.

Department of Mineral Resources (2010). Geological Map of Changwat Nakhon Ratchasima, Scale 1:250,000.

Department of Mineral Resources (2012). Geological Map of Changwat Sakon Nakhon, Scale 1:250,000.

Hansen, B. T., Wemmer, K., Eckhardt, M., Putthapiban, P., & Assavapatchara, S. (2016). Isotope dating of the potash and rock salt deposit at bamnet narong, NE-Thailand. *Open Journal of Geology*, 6(08), 875-894.

Hara, H., Charoentitirat, T., Tokiwa, T., Kurihara, T., Suzuki, K., & Sardsud, A.

(2024). Record of the Indosinian Orogeny from conglomerates and detrital zircon U–Pb ages of the western Indochina Block, central Thailand. *Gondwana Research*, 128, 368-389.

Heggemann, H., Helmcke, D., & Tietze, K. (1994). Sedimentary evolution of the Mesozoic Khorat basin in Thailand. *Zentralblatt für Geologie und Paläontologie*, 1, 1267-1285.

Khositanont, S. (2008). Gold and iron-gold mineralization in the Sukhothai and Loei-Phetchabun Fold Belts (Doctoral dissertation, Chiang Mai: Graduate School, Chiang Mai University, 2008).

Lamont, T., Searle, M., Hacker, B., Htun, K., Htun, K. M., Morley, C., Waters, D., & White, R. (2021). Late Eocene-Oligocene granulite facies garnet-sillimanite migmatites from the Mogok Metamorphic belt, Myanmar, and implications for timing of slip along the Sagaing Fault. *Lithos*, 386, 106027.

Liard, R., & Martin, J. E. (2011). Relative position of the Mesozoic vertebrate localities in the Phu Kradung Formation of the Phu Phan uplift, Northeast Thailand. World Conference on Paleontology and Stratigraphy program and abstract,

Meesook, A. (2000). Cretaceous environments of northeastern Thailand. In *Developments in Palaeontology and Stratigraphy*

Metcalfe, I. (2009). Late Palaeozoic and Mesozoic tectonic and palaeogeographical evolution of SE Asia. *Geological Society, London, Special Publications*, 315(1), 7-23.

Metcalfe, I. (2011). Tectonic framework and Phanerozoic evolution of Sundaland. *Gondwana Research*, *19*(1), 3-21.

Metcalfe, I. (2011). Paleozoic–Mesozoic history of SE Asia. *Geological Society, London, Special Publications*, 355(1), 7-35.

Metcalfe, I. (2017). Tectonic evolution of Sundaland.

Minezaki, T., Hisada, K.-i., Hara, H., & Kamata, Y. (2019). Tectono-stratigraphy of Late Carboniferous to Triassic successions of the Khorat Plateau Basin, Indochina Block, northeastern Thailand: initiation of the Indosinian Orogeny by collision of the Indochina and South China blocks. *Journal of Asian Earth Sciences*, 170, 208-224.

Morley, C. (2001). Combined escape tectonics and subduction rollback–back arc extension: a model for the evolution of Tertiary rift basins in Thailand, Malaysia and Laos. Journal of the Geological Society, 158(3), 461-474.

Morley, C. K. (2002). A tectonic model for the Tertiary evolution of strike–slip faults and rift basins in SE Asia. Tectonophysics, 347(4), 189-215.

Morley, C. K. (2012). Late Cretaceous–Early Palaeogene tectonic development of SE Asia. Earth-Science Reviews, 115(1-2), 37-75.

Morley, C., & Wang, Y. (2023). The Cenozoic hyper-oblique collision zone of Indochina: A re-appraisal of escape tectonics. Earth Science Reviews, 243, 104453.

Nualkhao, P., Takahashi, R., Imai, A., & Charusiri, P. (2018). Petrochemistry of granitoids along the Loei Fold belt, northeastern Thailand. Resource Geology, 68(4), 395-424.

Racey, A. (2009). Mesozoic red bed sequences from SE Asia and the significance of the Khorat Group of NE

Thailand. *Geological Society, London, Special Publications*, 315(1), 41-67.

Racey, A., & Goodall, J. G. (2009). Palynology and stratigraphy of the Mesozoic Khorat Group red bed sequences from Thailand. *Geological Society, London, Special Publications*, 315(1), 69-83.

Racey, A., Love, M. A., Canham, A. C., Goodall, J. G. S., Polachan, S., & Jones, P. D. (1996). Stratigraphy and reservoir potential of the Mesozoic Khorat Group, NE Thailand: Part 1: Stratigraphy and Sedimentary Evolution. *Journal of Petroleum Geology*, 19(1), 5-39.

Shi, M., Zaw, K., Liu, S., Xu, B., Meffre, S., Cong, F., Nie, F., Peng, Z., & Wu, Z. (2021). Geochronology and petrogenesis of Carboniferous and Triassic volcanic rocks in NW Laos: Implications for the tectonic evolution of the Loei Fold Belt. *Journal of Asian Earth Sciences*, 208.

Sone, M., & Metcalfe, I. (2008). Parallel Tethyan sutures in mainland Southeast Asia: new insights for Palaeo-Tethys closure and implications for the Indosinian orogeny. Comptes Rendus Geoscience, 340(2-3), 166-179.

Warren, J., Morley, C.K., Charoentitirat, T., Cartwright, I., Ampaiwan, P., Khositchaisri, P., Mirzaloo, M., and Yingyuen, J. (2014). Structural and fluid evolution of Saraburi Group Sedimentary carbonates, central Thailand: A tectonically driven fluid system. *Marine and Petroleum Geology*. 55, 100–121.

Ueno, K., & Charoentitirat, T. (2011). Carboniferous and Permian.

Veeravinantanakul, A., Kanjanapayont, P., Sangsompong, A., Hasebe, N., & Charusiri, P. (2018). Structure of Phu Phan Range in the Khorat Plateau: Its Apatite Fission Track Ages and Geological Syntheses. *Bulletin of Earth Sciences of Thailand*, 10(1), 8-16.

Zaw, K., Meffre, S., Lai, C.-K., Burrett, C., Santosh, M., Graham, I., Manaka, T., Salam, A., Kamvong, T., & Cromie, P. (2014). Tectonics and metallogeny of mainland Southeast Asia—a review and contribution. Gondwana Research, 26(1), 5-30.