Petrography and Microstructural Analysis of Kinematics along the Klaeng Fault Zone, Eastern Thailand: Insights from Ductile and Brittle Deformation Zones

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Abstract

The Himalayan orogeny, resulting from the collision of the Indian and Eurasian plates during the Cenozoic, has significantly influenced the tectonic structures of Southeast Asia. This study examines the Klaeng fault zone, an NNW-SSE to N-S strike-slip fault zone extending from Nong Yai gneiss to the Khao Chamao fault, through microstructural analysis and petrography. Key features such as bulging, subgrain rotation, grain boundary migration, S-C and S-C' fabrics, mica fish, myrmekites, and 'V'-pull-apart structures reveal dynamic recrystallization and kinematics. The Khao Yaida metagranite and Ban Tha Cham pluton deformed under low to intermediate temperatures and moderate stress during extensional exhumation. While the Khao Chamao experienced high to low temperatures during the cooling phase of exhumation. Most of the ductile deformation coeval to the sinistral movement of the Klaeng fault zone during the Eocene and later overprinted by late Eocene dextral motion, influenced by the Himalayan orogeny.

Keywords: Klaeng fault zone, deformation mechanism, ductile deformation, brittle deformation, Cenozoic tectonic

1. Introduction

The Himalayan orogeny, resulting from the collision of the Indian and Eurasian plates during the Cenozoic, has significantly influenced the complex tectonic structures in Southeast Asia(e.g. Lacassin et al., 1997; Morley, 2002; Watkinson et al., 2011). Major strike-slip faults in the region include the Ailao Shan–Red River fault zone, Mae Ping fault zone (MPFZ), Three Pagodas fault zone (TPFZ), Ranong fault zone (RFZ), and Khlong Marui fault zone (KMFZ). The NW-striking fault systems (MPFZ and TPFZ) experienced sinistral movement at least from the late Eocene to early Oligocene, while the NE-striking systems (RFZ and KMFZ) exhibited dextral movement during the same period. These movements occurred simultaneously, followed by a reversal of motion in a later phase (Charusiri, 2002; Kanjanapayont et al., 2012a; Kanjanapayont et al., 2013; Kanjanapayont et al., 2018; Kongsukkho & Kanjanapayont, 2022a; Lacassin et al., 1997; Nantasin et al., 2012; Palin et al., 2013; Rhodes et al., 2005). The Klaeng fault zone (Figure 1) is an NNW-SSE to N-S strike-slip fault zone, extending from the Nong Yai gneiss to the Rayong low-angle normal fault (LANF) of the Khao Yaida metagranite in the west, and the Khao Chamao fault of Khao Chamao granite in the east, passing through Klaeng town of Rayong in Eastern Thailand.

Despite the structural significance of Thailand's major strike-slip faults, few studies have addressed the structure of the Klaeng fault zone or another area in Eastern Thailand ,(e.g. Kanjanapayont et al., 2013; Ridd, 2012), particularly through microstructural analysis. This study aims to examine and describe the deformation in the ductile and brittle deformation zones using microstructural analysis and petrography. The results reveal the kinematics of deformation within the Klaeng fault zone.

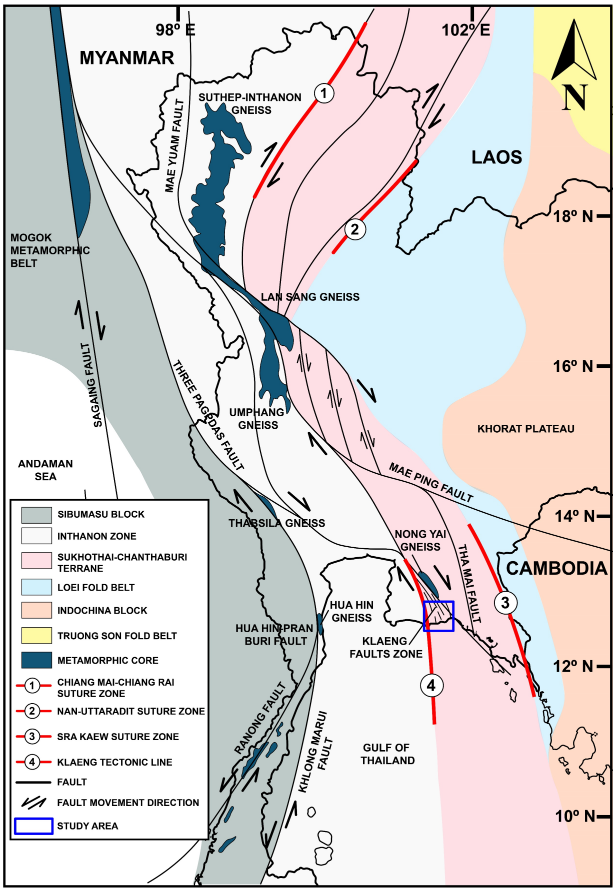

Figure 1 Major tectonic terranes map of Thailand illustrating the latest Neogene–Quaternary fault displacement. The location of Figure 4, eastern Thailand, is shown in the blue box.

1. Geological background

The geology within the Klaeng area exhibits a diverse range of rock types from the late Palaeozoic–Mesozoic (Vimuktanandana & Munchai, 2008). The western side features S-type granite from the Ban Tha Cham pluton (north) and the Khao Yaida pluton (south; KL-06/1G, 06/2G) (Figure 2). The Ban Tha Cham pluton includes Khao Khun-In (KL-25G), Khao Suan (KL-26G), and Khao Nguang Chang (KL-28G). Classified as part of the Central Granitoid Belt (Cobbing, 2011)was previously mapped as the Precambrian gneiss (Nakinbodee et al., 1976). U-Pb zircon dating indicates that these granites are Late Triassic ages of 215.7 ± 1.5 Ma and 216.9 ± 3.8 Ma, and from sphene, 218 ± 11 Ma by, indicating the Late Triassic granite. Apatite fission track (AFT hereafter) shows an age of 31 ± 3 Ma (Upton, 2000) and from Khao Yaida at 44.5 ± 5.7 Ma (Nachtergaele et al., 2019). Field observation reveals that the Ban Tha Cham pluton outcrops exhibit top-to-the-E ductile shearing (S-C fabrics) with a steep dip angle. At the same time, Khao Yaida displayed S-C' fabrics.

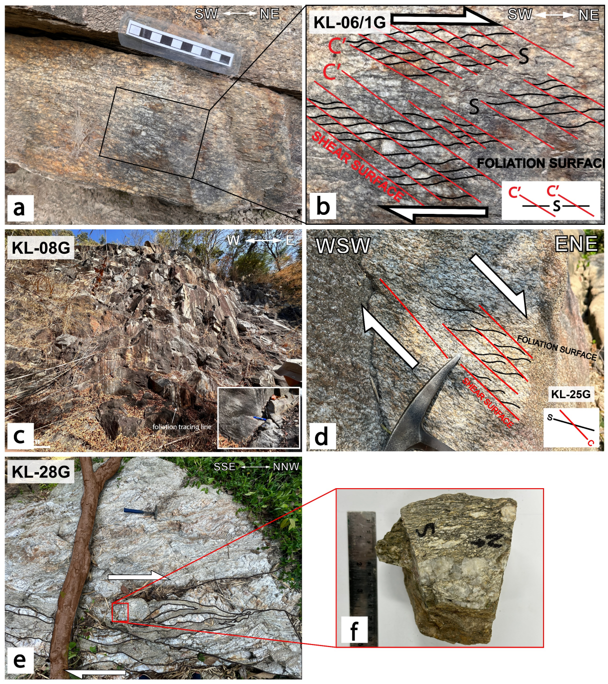

Figure 2 Outcrop from field observation at Khao Yaida **(a-b)**, south of Khao Yaida **(c)**, Khao Khun-In **(d)**, and Khao Nguang Chang **(e-f)**.

The eastern side of Klaeng features I-type granite at Khao Chamao (KL-21G), displaying sinistral ductile shearing in a strike-slip motion. Recent U-Pb magmatic zircon ages from Khao Chamao granite are 47.2 ± 1.4 Ma, 47.87 ± 0.63 Ma (Geard, 2008), 43.3 ± 0.2 (Veeravinantanakul et al., 2021), and 55.02 ± 0.34 Ma (Uchida et al., 2022). AFT indicates exhumation ages of 32.8 ± 2.1 Ma in the north and 26.1 ± 1.6 Ma in the southwest.

These data suggest a complex thermal history, with initial high-temperature deformation followed by subsequent cooling and exhumation. However, the relationship between ductile shearing and exhumation remains unclear.

Brittle deformation is observed in the Mesozoic redbeds (KL-10S) at Laem Pak Khlong Klaeng in central Klaeng, characterized by normal faulting oriented 335°/54°E, with striations at 36°/059° measured from field observation in this study. Thick quartz beds dominate this area, making the original redbeds show as a metasandstone. The origin of this brittle deformation and its relationship to the ductile deformation in the Khao Chamao granite are not well understood.

Table 1 Representatives samples from the Klaeng area with locations and rock types.

Sample	Location (Lat/Long)	Rock type
KL-06/1G	N12°39’6.1"/E101°25’9.6"	Metagranite
KL-06/2G	N12°38'56.8"/E101°24'51.3"	Metagranite
KL-08G	N12°38'47.9"/E101°25'25.8"	Granite
KL-25G	N12°55'37.9"/E101°27’1.9"	Granite
KL-26G	N12°53'31.8"/E101°25’2.1"	Granite
KL-28G	N12°48'20.5"/E101°25’49.4"	Granite
KL-21G	N12°55'3.0"/E101°44'27.8"	Granite
KL-10S	N2°38’40.1"/E101°30'55.8"	Metasandstone

2. Methodology

Oriented hand specimens with low weathering rates were collected from the Klaeng fault zone's ductile and brittle deformation zones to study deformation kinematics and mechanisms (Table 1 and Figure 3). Following, thin sections were prepared perpendicular to foliation and parallel to lineation. These sections were examined under a Nikon polarizing microscope with a high-resolution digital camera at Chulalongkorn University. Dynamic recrystallization, indicated by deformation mechanisms such as bulging (BLG), subgrain rotation (SGR), and grain boundary migration (GBM), helped evaluate the temperature and stress conditions during the deformation (Stipp et al., 2002).

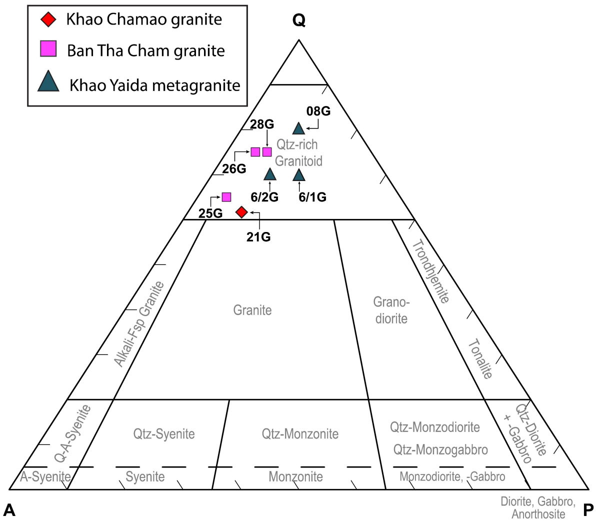

Figure 3 Classification of granitoids from granites within the Klaeng area based on modal estimation of quartz (Q), alkali feldspar (A), and plagioclase (P) (basic diagram is after Streckeisen, 1976).

3. Results

3.1. Khao Yaida (KL-06/1G and KL-06/2G)

The Khao Yaida metagranite sample displays strong foliation, with 70% quartz, 10% feldspar (K-feldspar and plagioclase), 15% biotite, and 5% of other minerals, categorizing it as quartz-rich granite (Figure 3). Foliation is characterized by biotite alignment and elongated quartz and feldspar. High biotite content indicates visible deformation (Figure 5). S-C’ fabrics suggest a top-to-the-E shear sense. Quartz mainly deforms through BLG and SGR with undulatory extinction. K-feldspar exhibits SGR deformation and perthite structures, while plagioclase shows undulatory extinction and multiple twins.

The lower section of Khao Yaida (Figure 5) shows high weathering. The KL-06/2G specimen, examined under a polarizing microscope, is composed of 65% quartz, 20% feldspar (K-feldspar and plagioclase), 10% biotite, and 5% other minerals, classifying it as quartz-rich granite. Foliation is marked by biotite alignment and elongated quartz and feldspar. S-C' fabrics indicate a dextral, top-to-the-right shear sense. The sample has medium to coarse grains of K-feldspar, plagioclase, and quartz, with finer grains of biotite, muscovite, and quartz. Quartz and K-feldspar megacrysts primarily deform through BLG and SGR, with common undulatory extinction.

3.2. South of Khao Yaida (KL-08G)

The steeply inclined foliation in the southern part of Khao Yaida granite (KL-08G) reveals fine to medium-grained granite (Figure 5) with 75% quartz, 15% feldspar (K-feldspar and plagioclase), 7% mica, and 3% other minerals. The groundmass is predominantly fine-grained quartz, K-feldspar, and mica. Megacrysts include quartz and K-feldspar. Foliation is defined by biotite alignment and the elongation of quartz and feldspar. Quartz mainly deforms by SGR and BLG, while K-feldspar shows SGR and perthite texture. S-C' fabric indicates dextral shear to the east, with strain shadows. Kink bands in mica are common.

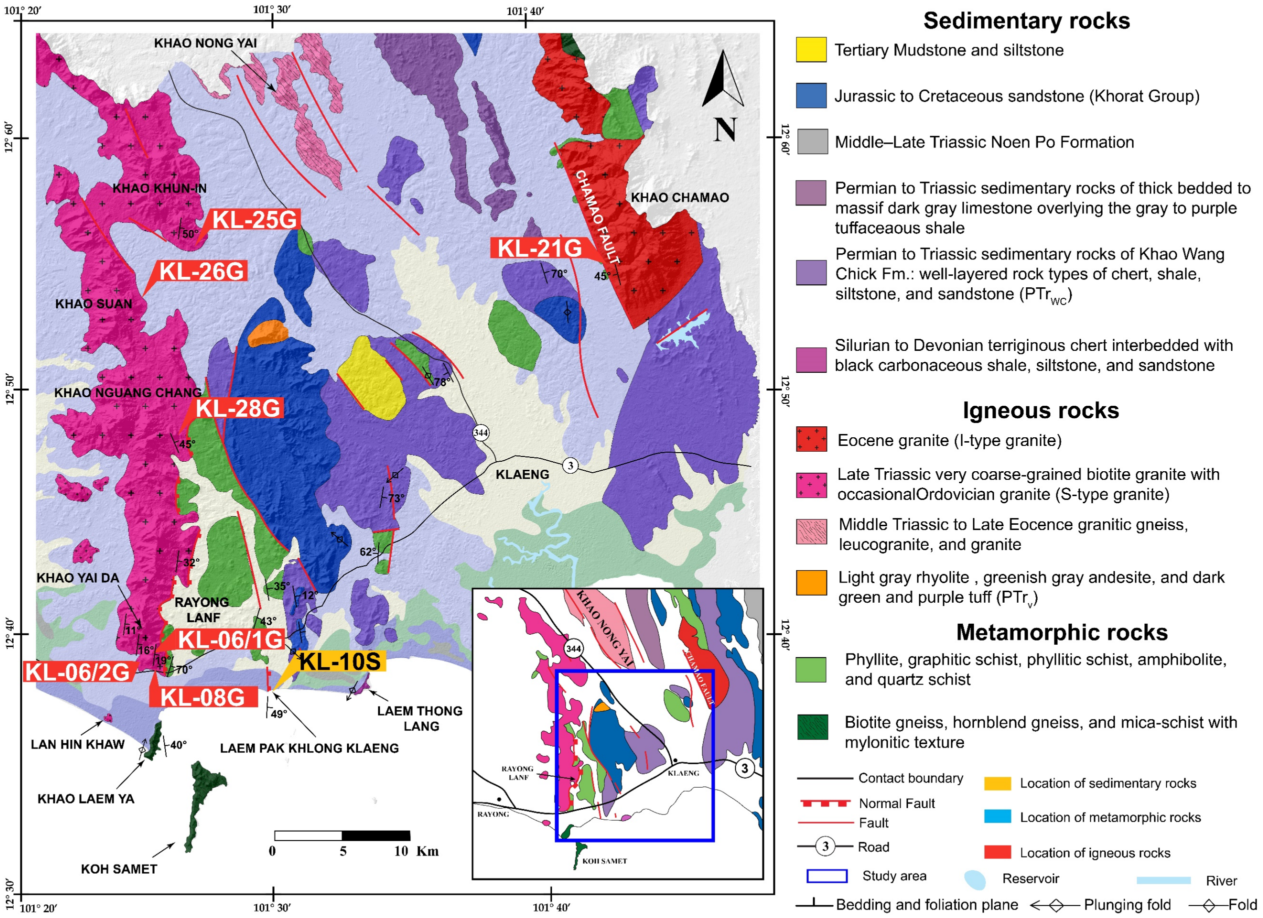

Figure 4 Geological map of the Klaeng area and adjacent area, indicating the location of thin section samples (modified after Vimuktanandana and Munchai, 2008)

3.3. Khao Khun-In (KL-25G)

A sample from Khao Khun-In (KL-25) (Figure 6) revealed essential minerals with an estimated composition of 60% quartz, 20% feldspar (K-feldspar and plagioclase), 15% biotite, and 5% other minerals such as zircon and chlorite. This classifies it as biotite quartz-rich granite. Foliation is identified by the alignment of biotite and elongated quartz crystals. S-C fabrics indicate a dextral, top-to-the-east shear sense. Medium to coarse grains comprise K-feldspar, plagioclase, and quartz, with finer grains of biotite, muscovite, and quartz. K-feldspar megacrysts exhibit minor myrmekite texture. Quartz and feldspar primarily deform through BLG and SGR, with common undulatory extinction in both.

3.4. Khao Suan (KL-26G)

Sample from Khao Suan (KL-26G) (Figure 6) comprises 65% quartz, 25% feldspar (K-feldspar and plagioclase), 5% biotite, and 5% other minerals, classified as quartz-rich granite. Foliation is mildly defined by biotite alignment. S-C fabrics are challenging to identify. Medium to coarse grains include K-feldspar, plagioclase, and quartz, with finer grains of biotite, muscovite, and quartz. Most megacrysts are K-feldspar, orthoclase, and microcline with perthite and grid twin. Quartz primarily deforms through BLG and SGR, with common undulatory extinction. Feldspar deforms mainly by SGR.

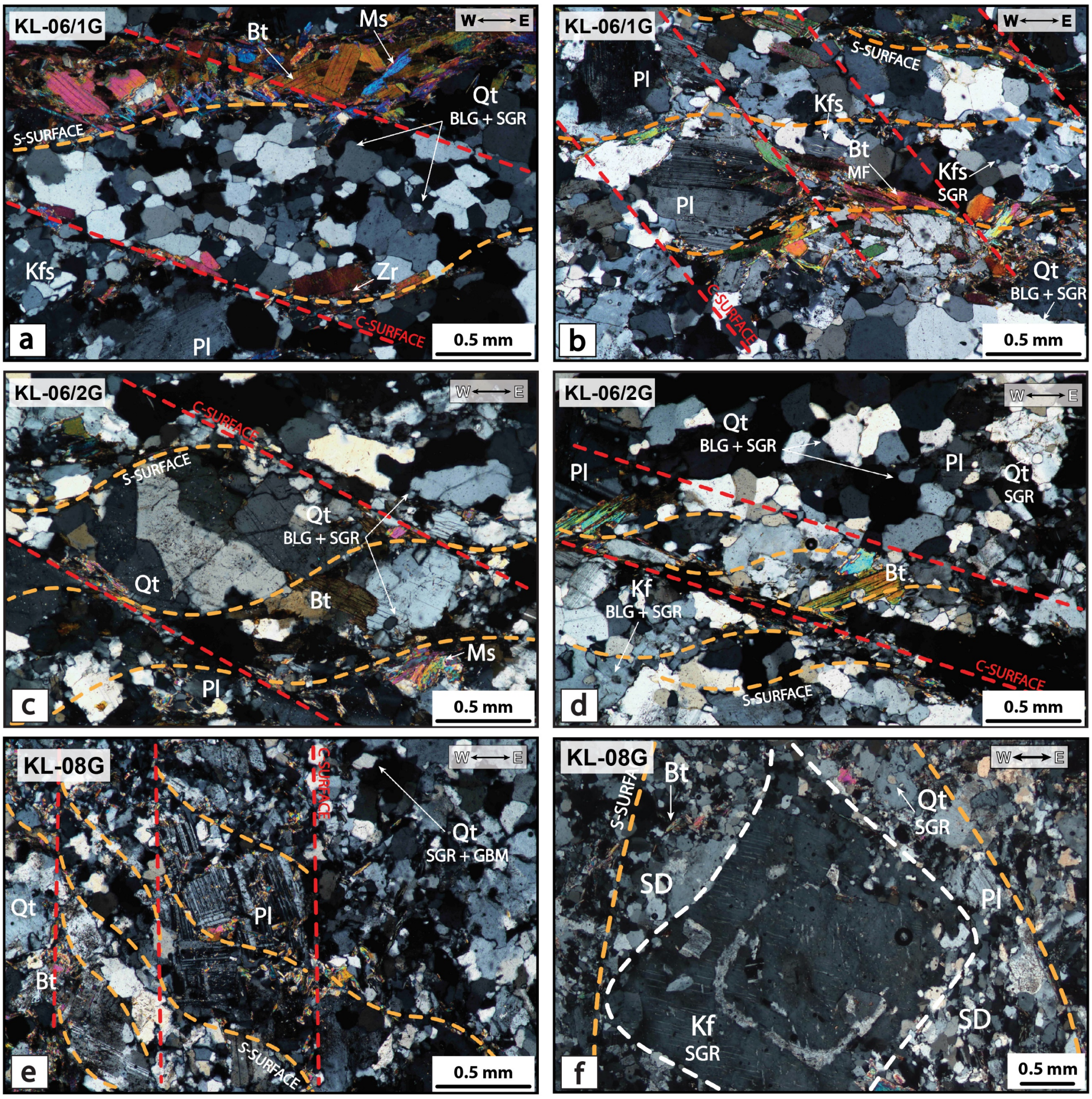

Figure 5 The 5x microphotograph showing a microstructure and petrographic relationship of KL-06/1G **(a-b)** and KL-06/2G **(c-d)** with observable S-C' fabric structure. The 5x **(e)** and 2x **(f)** of

KL-08G with observable steep S-C fabric structure. Bt-biotite; Chl-chlorite; Kfs-K feldspar; Ms-muscovite; Mf-micafish; Pl-plagioclase; Zr-zircon; BLG-bulging; SGR-subgrain rotation recrystallization.

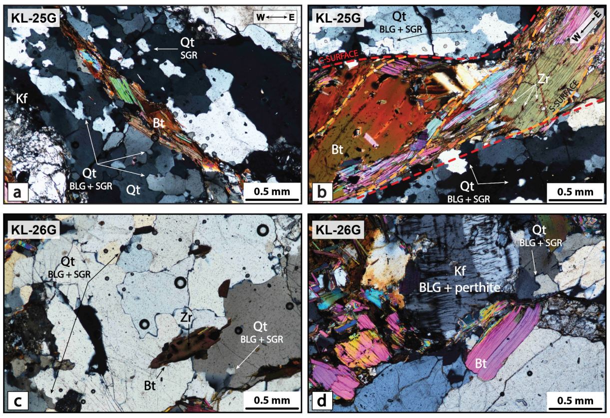

Figure 6 The 5x microphotograph showing a microstructure and petrographic relationship of KL-25G **(a-b)** and KL-26G **(c-d)**

3.5. KhaoNguang Chang (KL-28G)

The dextral ductile sample (KL-28G) exhibits a porphyritic texture (Figure 7) with K-feldspar phenocrysts. Mineral composition analysis shows quartz (60%), feldspar (20%) (both K-feldspar and plagioclase), mica (15%), and other minerals (5%), indicating biotite quartz-rich granite. Foliation is defined by biotite alignment and elongated quartz and feldspar crystals. Quartz deforms mainly through BLG, SGR, and GBM, with undulatory extinction. K-feldspar porphyroblasts show sigma-type augen and mantled clast structure, primarily deformed by SGR with perthite texture and simple twin. Overall, the texture resembles mylonitic granite. Features like porphyroblasts, augen, S-C fabric, and mica fish indicate dextral shear to the north.

3.6. Khao Chamao (KL-21G)

The sinistral ductile sample (KL-21G) of Khao Chamao granite (Figure 8) shows a porphyritic texture with feldspar phenocrysts. Mineral composition analysis reveals quartz (55%), feldspar (30%) (both K-feldspar and plagioclase), mica (10%), and other minerals (5%), indicating granite. The foliation is defined by biotite alignment and elongated quartz and feldspar crystals. Feldspar phenocrysts exhibit myrmerkite texture. Quartz deforms mainly through BLG, SGR, and GBM with undulatory extinction, while K-feldspar mainly deforms via SGR with perthite texture. Features like phenocrysts, augen, 'V'-pull-apart structure, and mica fish indicate a sinistral shear sense to NNW.

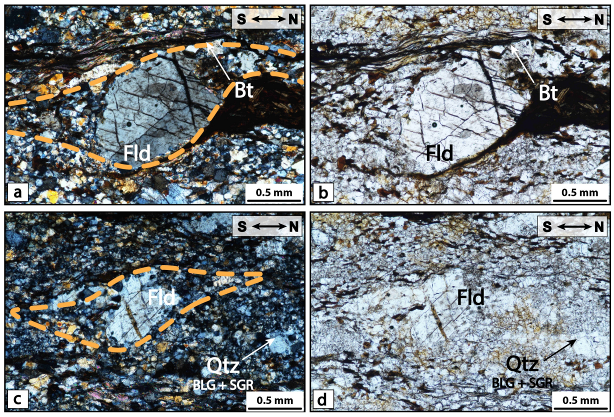

Figure 7 The 5x microphotograph showing a microstructure and petrographic relationship of Feldspar clasts exhibiting mantled clasts from KL-28G outcrop **(a-d)**. Feldspar clasts showed as a sigma-type augen with a mantle. Cross polarizing on the left and plane polarizing on the right side.

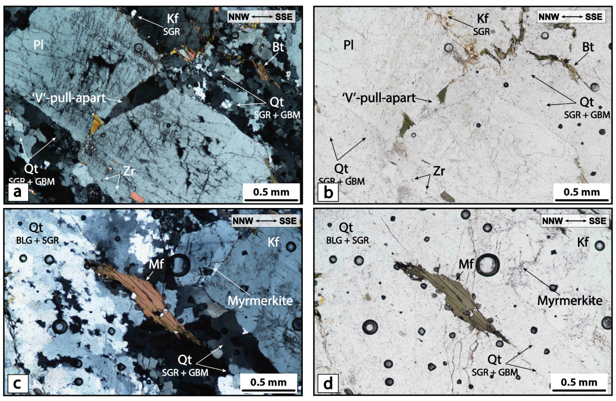

Figure 8 The 5x microphotograph showing the deformation of high strain indicated by myrmerkite and the exhibition of GBM in

quartz. Augen structure, 'V'-pull-apart **(a-b)** indicates the low-temperature deformation (Kanjanapayont et al., 2012a), and micafish indicates the sinistral movement **(c-d)**.

3.7. Laem Pak Khlong Klaeng (KL-10S)

The high-strain area in Mesozoic sedimentary rock exhibits normal faulting with folding. Samples from the upper section (KL-10S.1) (Figure 9) contain mainly quartz, mica, and clay, with fine-very fine grain size. Clay content is high between layers. Undulatory extinction in quartz is common, with kink banding and S-C structures indicating a shear sense to NE. Microscopic evidence suggests the folding resulted from eastward movement associated with normal faulting, later cut by minor quartz veins (0.2-0.4 mm wide).

In the adjacent area, the main thick quartz vein with a very steep inclination was cut to observe the microstructure (KL-10S.3) (Figure 10). This section has less clay content than the earlier one but more quartz grains. Most sizes of quartz are in fine to very fine grain and exhibit undulatory extinction. Mica is found between layers, comprising approximately 10% of the sample. Very fine quartz grains are generally displayed in the high-strain zone. In thin section, kink folds and fault propagation folds indicate dextral movement of fault propagation caused by normal faulting to the NE.

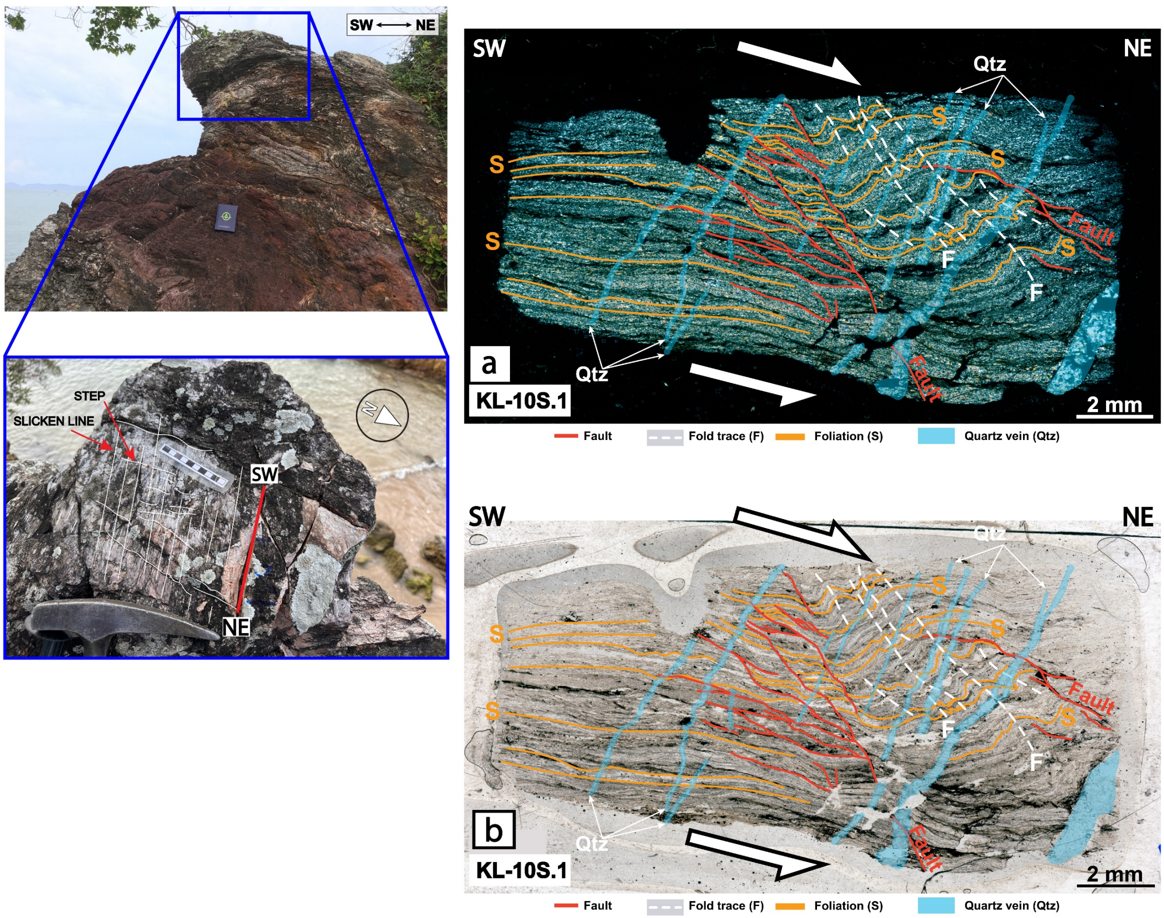

Figure 9 The overview microphotograph showing a microstructure under the microscope of KL-10S.1 on the fault plane of Mesozoic redbeds. **(a)** Cross polarizing and **(b)** plane polarizing showing the normal faulting to NE and cut by minor quartz vein.

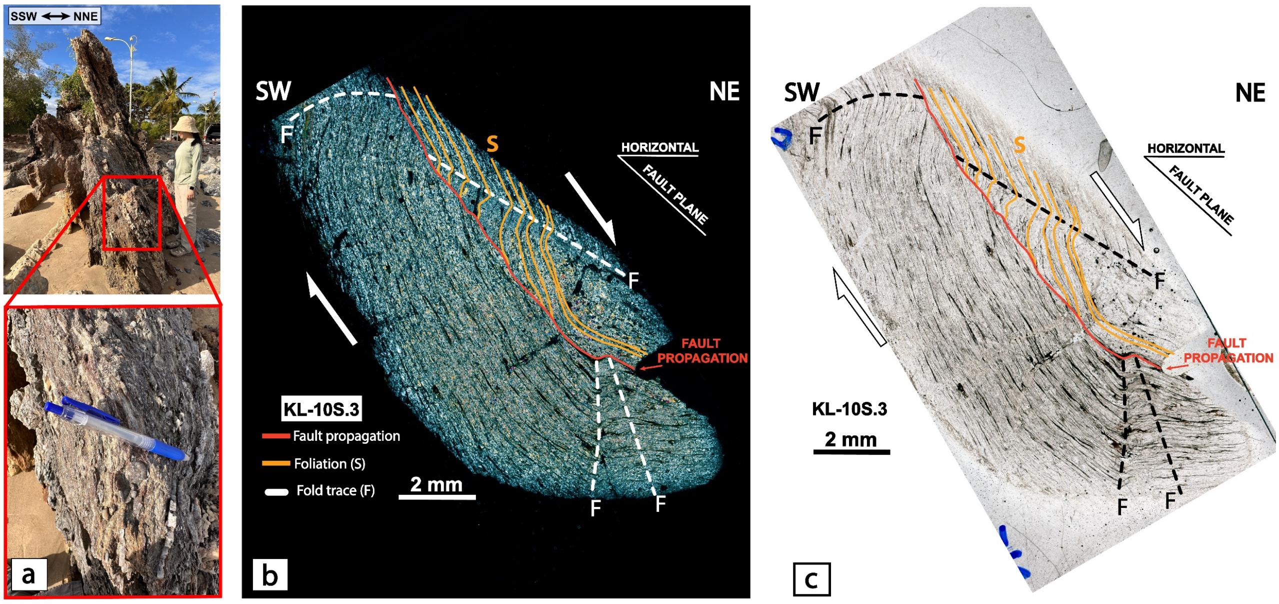

Figure 10 (a) The overview microphotograph showing a microstructure under the microscope of KL-10S.3 from the main thick quartz vein near the Mesozoic redbeds outcrop on the fault plane section. **(b)** Cross polarizing and **(c)** plane polarizing showing the normal faulting to NE as a fault propagation and kink fold.

4. Discussions

4.1. Deformation mechanism

Our structural observations on samples from the Klaeng fault zone show that the deformation mechanisms vary with rock type and deformation conditions. On the western side of the Klaeng area, Khao Yaida metagranite (KL-06/1G, KL-06/2G, KL-08G), and Ban Tha Cham pluton, including with Khao Khun-In (KL-25G) and Khao Suan (KL-26G), quartz deformation is primarily through BLG and SGR, indicating low-intermediate temperatures (300-500 °C) and moderate stress (Stipp et al., 2002). K-feldspar deforms through SGR and shows perthite texture, suggesting similar conditions. The presence of S-C' fabrics in these samples indicates a top-to-the-E shear sense, consistent with normal faulting. Whereas in Khao Suan, the less defined foliation suggests lower strain.

The deformation mechanisms observed in the Khao Yaida granite are consistent with those reported in other studies of granitic rocks in extensional settings, such as the exhumation of a gneiss dome (e.g. Huang & Yeh, 2020) during the exhumation of gneiss dome in an extensional setting. The presence of perthite texture in K-feldspar, as observed in the Khao Yaida granite, is also consistent with deformation under moderate to high temperatures (Md Ali et al., 2016). The AFT reported by Nachtergaele et al. (2019)Field indicates the exhumation of Khao Yaida at 44.5 ± 5.7 Ma, suggesting that it might be associated with the S-C' fabrics and ductile deformation of normal faulting. The low-intermediate temperatures resulting in BLG imply that it may have deformed during the cooling process (Watkinson et al., 2011).

Khao Nguang Chang (KL-28G) exhibits a mylonitic texture with feldspar porphyroblasts showing mantled and sigma-type augen structures. Quartz deformation includes BLG, SGR, and GBM, indicating higher temperatures (>500°C) and stress (Stipp et al., 2002). The presence of S-C fabrics and mica fish confirms dextral shearing, which can be interpreted to occur by the miner fault during the dextral movement of the Klaeng fault zone.

The Khao Chamao granite, showing feldspar porphyroclasts and recrystallized quartz ribbons, is indicative of high-strain deformation under sinistral ductile conditions with occasional brittle deformation. The presence of mantled and sigma-type augen structures in feldspar porphyroclasts suggests that the deformation occurred under high temperatures and pressure (Passchier & Trouw, 1996). The occurrence of GBM in quartz in these samples further supports the interpretation of the high-temperature deformation (Kanjanapayont, 2015; Watkinson et al., 2011), then followed by the BLG and SGR during the lower temperature.

The brittle deformation observed in the Mesozoic redbeds, characterized by normal faulting and folding, is consistent with deformation in the upper crust under low temperature and pressure conditions. The presence of undulatory extinction and kink bands in quartz indicates that the deformation was accommodated by the dislocation creep (Passchier & Trouw, 1996). The normal faulting and associated folding are interpreted to have formed due to E-W extension, which is consistent with the regional stress regime during the Cenozoic (Morley & Wang, 2023).

4.2. Tectonic implications

The dynamic recrystallization and kinematics of the ductile and brittle shear zones within the Klaeng fault zone are revealed through microstructural analysis. Top-to-the-E ductile shearing in normal faulting, dominant in most granitoid samples, and the sinistral shearing in Khao Chamao granite suggest that the deformation took place during the emplacement of this granite. These suggest that the occurrence of deformation may be linked to the sinistral motion within the main area of the Klaeng fault zone at the Khao Nong Yai gneiss (Kanjanapayont et al., 2013; Nachtergaele et al., 2019).

Geochronological data, including AFT ages from the Nachtergaele et al. (2019)Field and U-Pb ages Geard (2008), Uchida et al. (2022), and Veeravinantanakul et al. (2021), constrain the timing of ductile shearing and exhumation events within the fault zone. The exhumation of Khao Yaida and emplacement of Khao Chamao granites coeval to sinistral movement during late Eocene along the TPFZ and MPFZ (Kanjanapayont et al., 2013; Nachtergaele et al., 2019).

The sinistral shearing in the Klaeng fault zone is related to the kinematic deformation due to the India-Eurasia collision during the Eocene-Recent, which is found in most major strike-slip faults in Thailand (Kanjanapayont, 2015; Kanjanapayont et al., 2013; Kongsukkho & Kanjanapayont, 2022a; Rhodes et al., 2005; Upton, 2000).

Brittle deformation overprints earlier fabrics, suggesting a shift to E-W extension after the deposition of Mesozoic redbeds (Ridd & Morley, 2011). Reactivation of the TPFZ, with a shift in strain from E-W to N-S, is evident from U-Pb and AFT ages during the late Eocene-Oligocene, implying a kinematic reversal to dextral strike-slip movement (Kongsukkho & Kanjanapayont, 2022a; Nantasin et al., 2012; Rhodes et al., 2005), which resulted in brittle deformation in the Klaeng fault zone. This multi-stage evolution reflects the interplay of regional tectonics and local fault zone complexities that were influenced by the collision of India and Eurasia during Himalayan orogeny.

5. Conclusions

The microstructural analysis of the ductile and brittle deformation zones within the Klaeng fault zone reveals dynamic recrystallization and kinematics through features such as bulging, subgrain rotation, grain boundary migration, augen structures, S-C and S-C’ fabrics, mica fish, myrmekites, and 'V'-pull-apart structures observed under the microscope. The Khao Yaida metagranite and Ban Tha Cham pluton predominantly deformed under low to intermediate temperatures and moderate stress during exhumation in an extensional setting. The sinistral movement in Khao Chamao developed during the sinistral motion of the Klaeng fault zone in the Eocene before being overprinted by late Eocene dextral motion, which resulted in brittle deformation through normal faulting. Both sinistral and dextral motions of the Klaeng fault zone were influenced by the Himalayan orogeny.

Acknowledgments

The authors would like to express gratitude to the Department of Geology at Chulalongkorn University, Thailand, for providing all the necessary facilities for this research. KC appreciates the support from the Development and Promotion of Science and Technology Talents Project (DPST). PK acknowledges funding from the Thailand Science Research and Innovation Fund at Chulalongkorn University.

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