

Deformation styles and structural history of the Paleozoic limestone, Kinta Valley, Perak, Malaysia

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Abstract: The Paleozoic limestone of Kinta Valley formed a narrow deformed strip between the Late Triassic - Early Jurassic batholiths of the northern Peninsular Malaysia. Because of the advanced stage of karstification, it is difficult to understand the deformation events that affected the limestone. We use outcrop remote sensing mapping, outcrop examples and hand specimens to unravel the tectonic evolution from syn-sedimentary to Recent events. We identify (i.) an early extensional event marked by very penetrative micro-normal faults, possibly due to compaction underneath the sea bottom, which occurred when bedding was still horizontal, (ii.) an early compression indicated by a set of conjugate originally strike-slip faults, (iii.) a well-marked compression with thrusts and tight folds which tilted the previously formed structures, (iv.) ductile high temperature (HT) normal shear located near the contact with the granites, and (v.) late extensional event marked by subsequent large normal faults. We interpret the evolution as intra-basin extension during Permian-Triassic times followed by a continuum of high strain coeval with the late stages of granite emplacement including compression and gravitational extension on the edge of the intrusion. The late extension is undated but may be linked to the Tertiary basins formation of Malaysia or the Late Miocene to Quaternary uplift.

Keywords: structural geology, limestone, Kinta Valley

INTRODUCTION

Kinta Valley is located in the middle of the Perak state. It elongates in ~N-S direction for around 50 km, with width of 30 km at the south and narrow down to 10 km at the north. The valley is bounded to the west by the Kledang Range and to the east by the Main Range. Limestone hills are outcropping in the valley. The basement of the valley is believed to be mainly composed of limestone that is currently covered by superficial unconsolidated sediments. Many geological studies have been carried out in the Kinta Valley over the past century (e.g. Ingham & Bradford, 1960; Suntharalingam, 1968; Pierson *et al.*, 2009). The studies were however, not focused on structural deformations and to explain in detail neither the deformation of the Paleozoic limestone, nor the relationship between granite intrusion and limestone. The urban developments in the city of Ipoh have exposed new outcrops and satellite imagery draped on digital elevation model (DEM) have improved significantly and allowing the study of structures in more detail and be able to come to a regional structural models. The objectives of this study are: (1) to determine the deformation styles represented by the fracture sets occurring in the Paleozoic limestone and; and (2) understand the relationships with the granite intrusion. This study will not only provide better understanding of the regional geology, but cross-cutting fractures may also throw light on how the Paleozoic sequence of Peninsular Malaysia could be a potential candidate as a fractured reservoir.

GEOLOGICAL SETTING

Ingham & Bradford (1960) grouped the rocks of the Kinta Valley into several units i.e. calcareous and arenaceous series, granite and alluvium. The calcareous series are

composed mainly of limestone with some clastic sedimentary and metamorphic rocks; whereas the arenaceous series are composed of quartzite intercalated with schist bands. Ingham & Bradford (1960) assigned a Carboniferous age to the limestone; whereas Suntharalingam (1968) studied the fossils contained in the limestone in West Kampar, and proposed a Middle Devonian to Middle Permian age. The paleo-depositional environment of the limestone of the Kinta Valley has been interpreted as a slope associated with a large platform, located in relatively deep water during Late Paleozoic (Pierson *et al.*, 2009). This interpretation was based on frequent presence of thinly bedded/laminated micritic limestone bands indicative of low energy environment, and slumping structures formed at the bottom of the slope near to the deep sea.

The sedimentary rocks of the Kinta Valley have been tilted, with strikes generally following the boundary of the nearby granite (Ingham & Bradford, 1960). Isoclinal folds and overfolds are present mainly in the eastern half of the valley (Ingham & Bradford, 1960), and are sometimes difficult to distinguish from syn-sedimentary structures or slumps (Pierson *et al.*, 2009).

Joints in the limestone and granite are too irregular to allow for a solid interpretation (Ingham & Bradford, 1960). In the early seventies, lineament studies on aerial photography of the Kinta Valley done by Gobbett (1971) identified a consistent pattern of fracture orientation. The dominant fracture sets are strike NW-SE and ENE-WSW, indicating roughly an E-W compression.

METHODOLOGY

The information on the tectonic indicators (e.g. strike and dip of bedding, fractures, joints, fault, etc) were

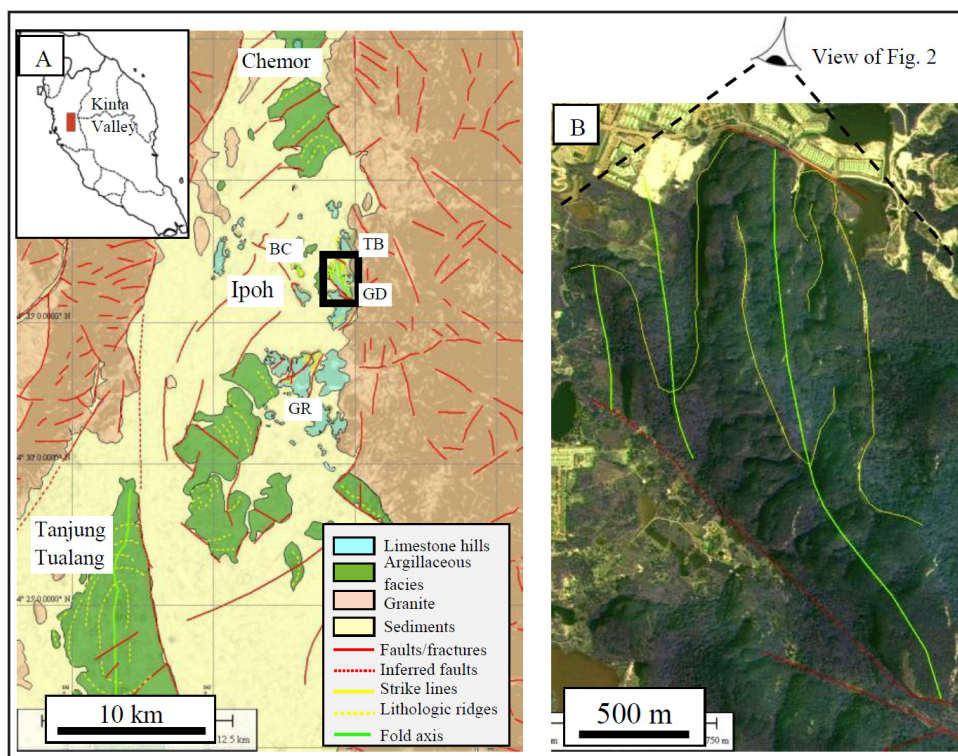


Figure 1: [A] Geological map of the Kinta Valley. Abbreviations: BC, Bercham; GD, Gunung Datok; GR, Gunung Rapat; TB, Tambun. Black box is the location where the limestone is tightly folded at regional-scale in Gunung Datok. [B] Satellite image (SPOT-5) of Gunung Datok where the limestone is tightly folded (black box in Figure 1A).



Figure 2: Aerial photograph of the limestone hills: Gunung Datok, Tambun, Ipoh. Narrow valleys are formed between the steeply dipping limestone beds. The limestone overlies the granite to the east.

collected from satellite image (mega-scale), outcrop and hand specimen (meso-scale). These data were divided into groups according to their characteristics and checked for cross-cutting relationships in order to reconstruct the tectonic evolution of the area. Relative chronology criteria are essential to decipher such a tectonic history.

With a mega-scale analysis, a tele-interpreted textural map (Figure 1B) was constructed by draping satellite imagery (SPOT-5, resolution 2.5 m) onto a digital elevation model (SRTM, resolution 90 m). Meaningful geomorphic features resulting from fractures/faults, bedding traces, folds and contrasting lithologies, were later systematically checked in the field. A meso-scale analysis included site visiting and hand-specimen study. Outcrops were chosen on the basis of accessibility and presence of fractures. The selected sites included Tambun, Bercham, Gunung Datok and Gunung Rapat, where different geological data and oriented hand specimens were collected (Figure 1). Dominant strike and dip measurements of fractures and bedding as well as

crosscutting relationships and fracture-filling materials, were recorded. Results from observations were captured in a geodatabase as a GIS layer and measurements were processed using the “Stereonet” software (Cardozo & Allmendinger, 2013). All data were plotted on a lower hemisphere, equal-area projection, and were used to compute the palaeo-stress field for each deformation event and the stress field.

The purpose of this analysis was to observe the trends and orientations of fractures which are difficult to measure in the field. The collected hand specimens were marked top or bottom surface and north direction in situ, so that the specimens can be restored into its field orientation in laboratory later. The specimens were cut in a way to obtain a 3D view of fractures and improve the measurement accuracy of fracture orientation. The cutting of the hand specimens was perpendicular to bedding because the maximum or minimum principal stresses are generally horizontal and parallel to it, which causes fractures to be inclined relative to the layers.

ANALYSIS AND RESULTS: DEFORMATION IN THE PALEOZOIC LIMESTONE

We observed both brittle and ductile deformation in the Palaeozoic limestone of Kinta Valley. In terms of brittle structures, four fracture sets have been revealed in the limestone i.e., (1) early set of conjugate fractures, (2) E-W conjugate fractures, (3) thrust faults and (4) N-S striking normal faults. All the deformations are described as follows:

Early set of conjugate fractures

Conjugate fracture sets that occur in two adjacent beds were observed on polished outcrops such as in the limestone cave of Tambun. The conjugate fracture sets developed

within beds of contrasting (competent and incompetent) rheologies (Figure 3A) and are highly crystallized. The fractures were found occasionally filled with white-coloured calcite and sometimes display offsets (Figure 3B). All fractures show steep dipping ($>65^\circ$) layer and strike N-S after unfolding. The fractures may have initiated as high angle in the competent beds and propagated into incompetent bed with a lower angle. These fracture sets could not be observed at the regional scale, suggesting that it was an early penetrative deformation at the scale of outcrop. It may have developed due to overburden within the basin, and may not be necessarily of tectonic origin. The conjugate fracture set that fall into this group is labeled as D1 throughout this paper.

E-W conjugate fractures

This fracture set occurs in both the gentle dipping limestone of Bercham and the vertical dipping limestone in Tambun. The conjugate strike-slip fault set (Figure 4) in Bercham show slickensides, which comprise sinistral (E-W striking) and dextral (NE-SW striking) movement with nearly vertical dip and horizontal pitch.

An E-W conjugate fracture set is also found in the limestone of Tambun, on the east flank of the valley, at both outcrop-scale (Figure 5) and hand-specimen scale (Figure 6). The fracture set of Tambun is slightly different to the strike-slip fault set of Bercham (Figure 5) after untilting, which probably affected by late deformation. Generally the overall structural style is showing E-W compression in the gently-dipping beds and in the restored vertical strata suggesting that the conjugate set was formed prior to folding, but within the same compressional direction. This conjugate fracture set is referred to hereafter as D2.

Thrust faults

Imbricated thrust faults are observed in satellite images and outcrops of the Tambun area (Figure 7), where they form

triangular-shaped pieces (TP). Apparent strikes of the faults are in a N-S direction. The faulted wedges propagate towards the granite in the east. The apparent dip of the thrust faults formed in the Tambun is around 30° . The thrust fault on the granite contact could be reactivated as normal fault later.

In Bercham, the thrust faults (Figure 8) appear to have propagated along the bedding planes as indicated by striations on the strata surface. The thrust faults postdate the E-W conjugate fracture set discussed above as they displace them. The transport direction is E-W but the sense of motion may be top to the East or top to the West depending on location. This thrust system, referred to as D3, indicates a compression which is again co-axial with the previous directions. Therefore a continuum of deformations can be envisaged.

Late ductile deformation

'Slump' structures are common in the limestone of the Banjaran Hotsprings in Tambun, and have been interpreted as representing syn-depositional gravity sliding of the cohesive carbonate sediment on a slope (Pierson *et al.*, 2009). However the centimetric to metric structures observed in the vicinity of the contact with the granite are different and seem to indicate a type of ductile behavior, also metamorphosed shale (hornfels) with tight microfolds are formed at the contact.

When the granite intrusion formed during Late Triassic to Early Jurassic (Bignell & Snelling, 1977; Darbyshire, 1988; Krahenbuhl, 1991) and came in contact with limestone, it was still at a high temperature and resulted in metamorphism of the limestone. This is attested by the ductile deformation of previously formed veins which cut the limestone beds as when they were already indurated. As shown in the Figure 9, the relatively thin, dark-coloured layers present in the pure limestone underline a top to the left simple shear. Interestingly, where ductile deformation

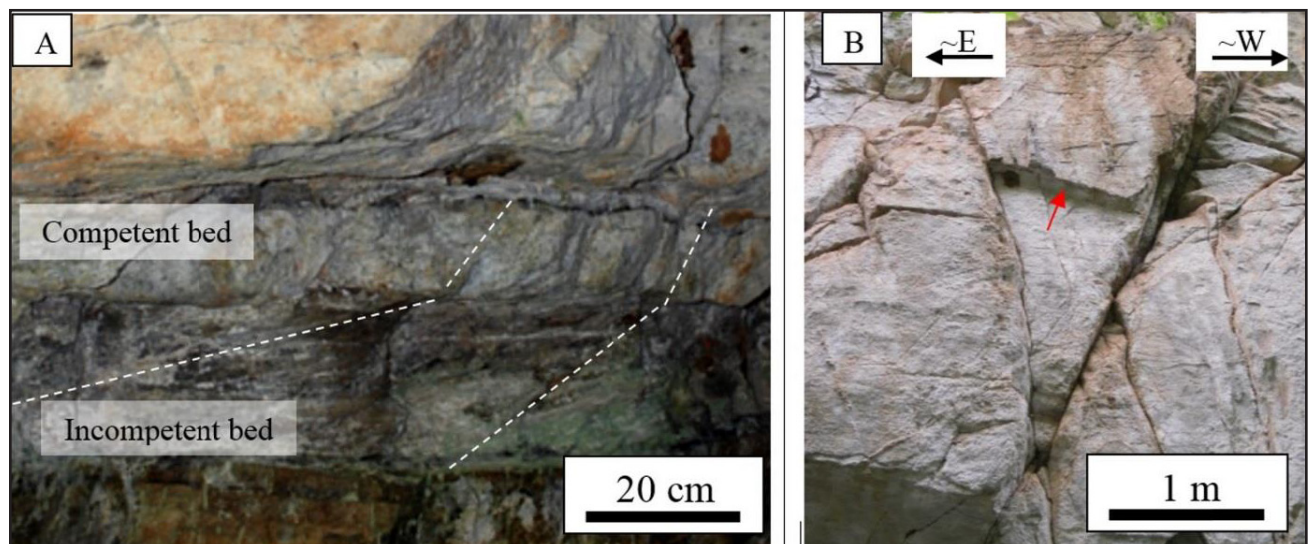


Figure 3: Conjugate fractures found in the limestone of Tambun. [A] Varying fault dip angle with lithology in the limestone cave of Banjaran Hotspring. Fractures initiated from the competent bed at top and propagated to the lower incompetent bed (white dash lines). Note that the bed orientation has been rotated and the bedding was originally vertical. [B] Fracture offset which probably developed within limited bed in the limestone of Lost World (arrow), and truncated by the later high-angle conjugate fracture located at both ends.

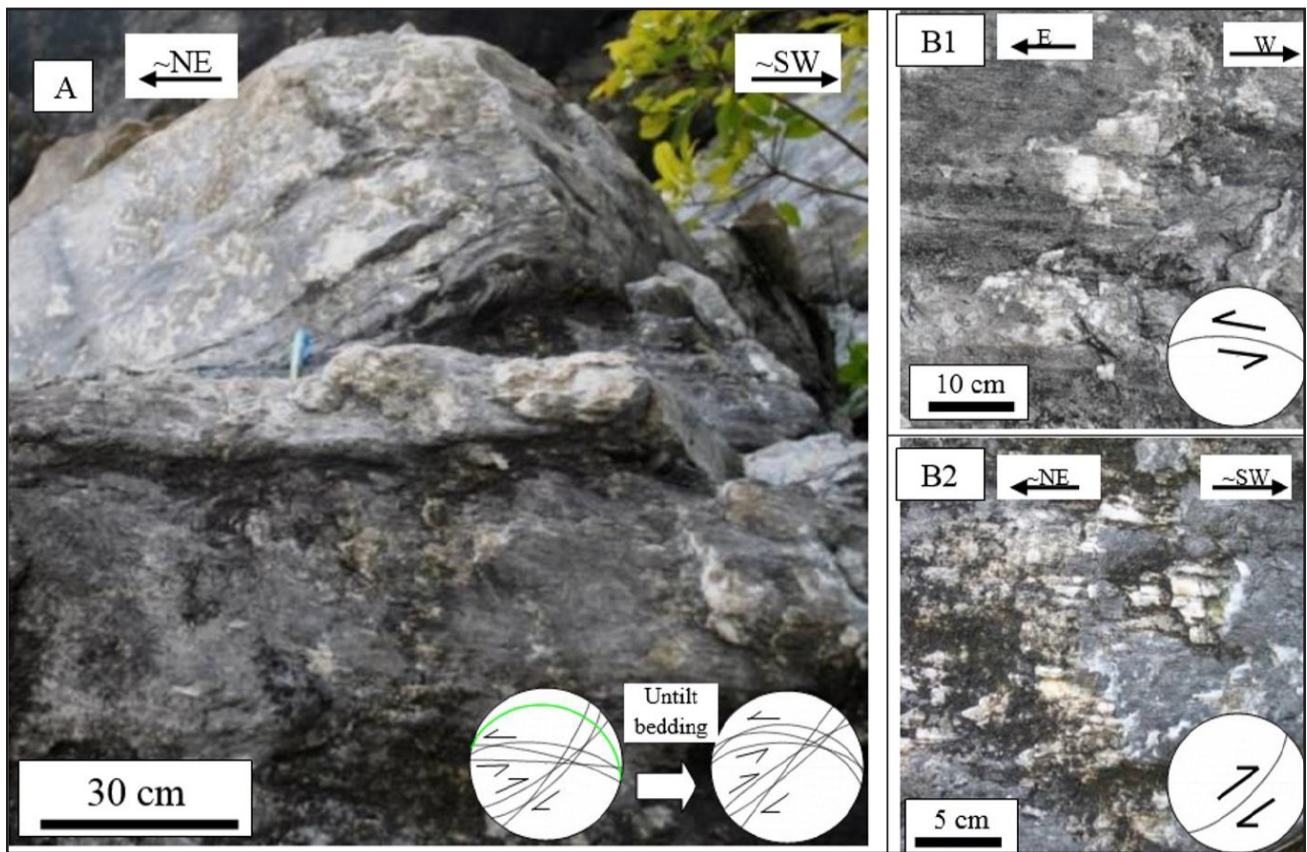


Figure 4: [A] Conjugate strike-slip faults formed in the limestone of Bercham. We clearly recognized slickenside, and deduce a ENE-WSW compression. [B1 and B2] Close-ups and stereonets of the fault planes showing sinistral [B1] and dextral [B2] movement respectively.

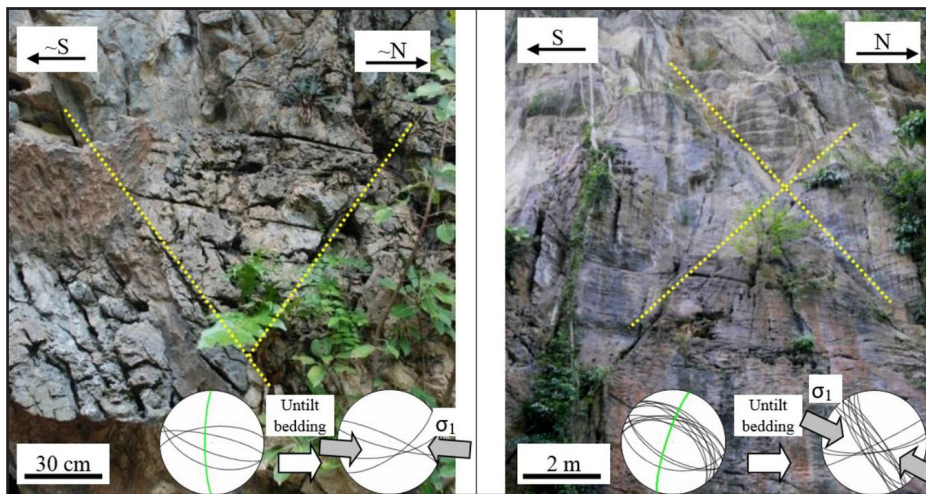


Figure 5: Conjugate fractures observed on the vertical limestone bed of Tambun. It is compatible with the strike-slip fault set in the Bercham after untilting bedding. Green line on stereonet represents bedding; black lines are conjugate fractures; grey arrows pairs represent the maximum principal stress direction (σ_1).

takes place, it overprints the previous brittle structures, which remain only as relicts.

N-S Normal Faults

Conjugate normal faults (Figure 10) striking N-S with high dipping angle, occur in almost all the limestone hills. This fracture set is probably a late deformation, because it often propagates through the whole outcrop and cross-cut other fractures. The narrow valley/lineaments found in the limestone hills generally underline these normal faults. The average altitude of the blocks at both sides of the lineament

is different, indicating block faulting or normal fault, (e.g. NW of Gunung Rapat, Figure 11). These extension faults are labeled as D4. Because strikes for D3 and D4 are co-linear (N-S), these faults might reactivate former thrusts.

SYNTHESIS AND DISCUSSION
Chronology of the major fracture sets

A fracture set is formed under same or similar stress conditions. Each fracture set is defined as a deformational stage. Four fracture sets and their associated deformation stages have been identified and described in the Paleozoic

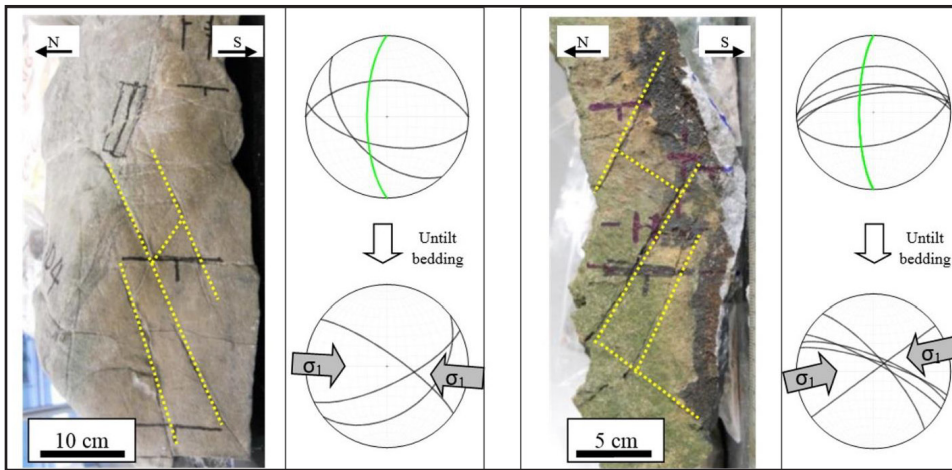


Figure 6: Conjugate fracture set formed on two oriented hand specimens. Note the similarity to the D2 fracture set at the outcrop-scale in Figure 5.

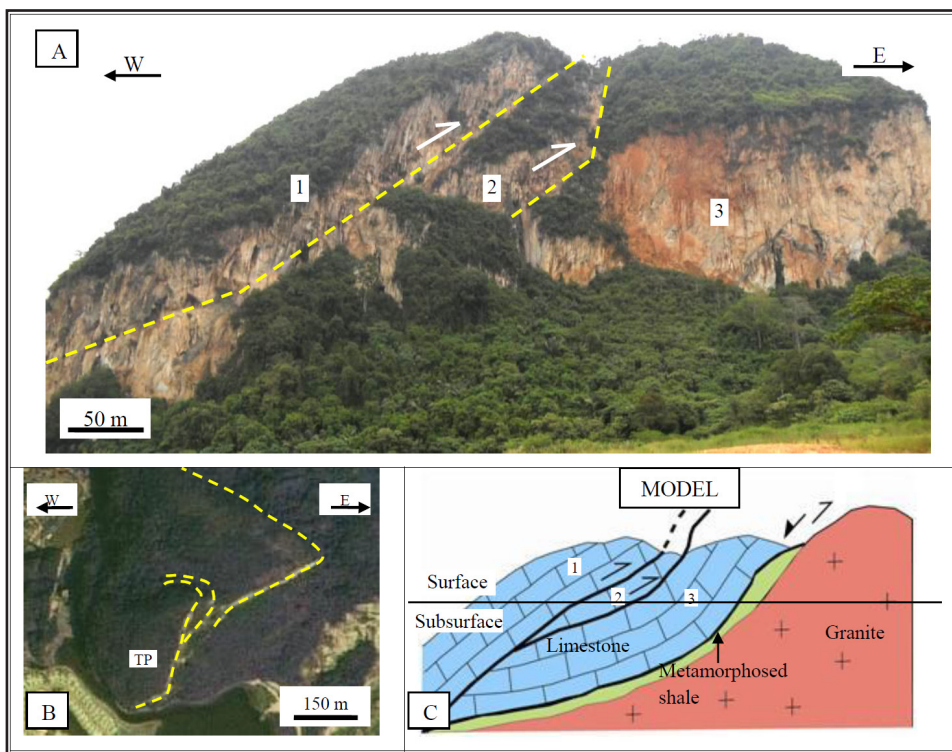


Figure 7: [A] Imbricate thrust faults in Tambun marked by yellow dash lines in the limestone outcrop, [B] Satellite image shows the triangular pieces (TP) representing thrust imbrications, and [C] Model illustrating the possible orientation of the thrust faults on the surface and subsurface. The thrust faults probably propagated in a sequence from 1 to 3. Thrust fault could be reactivated as normal fault later.

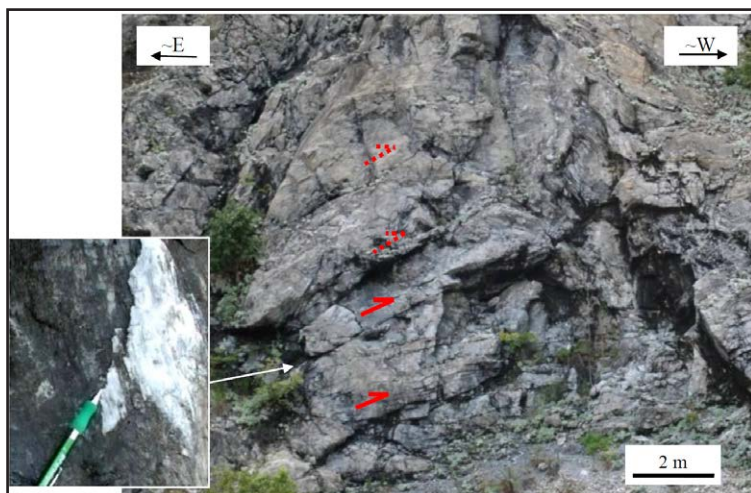


Figure 8: Thrust faults in the limestone of Bercham. The small insert shows well-preserved slickensides on the bedding planes and underlines D3 reverse slipping surfaces. The red arrows show the direction of the movement of the blocks, solid arrow for the confirmed movement, dashed arrows represent the inferred movement.

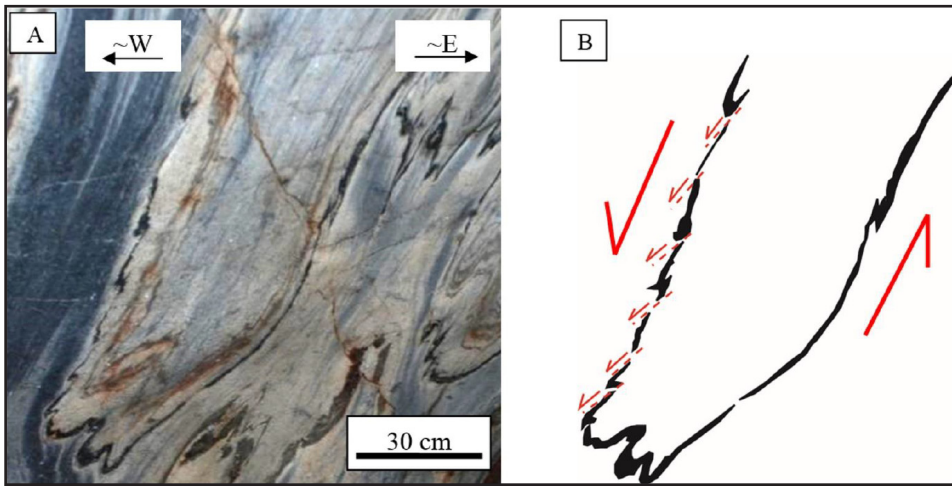


Figure 9: [A] Vertical section of slump fold-like structures in the meditation cave of Banjaran Hotsprings, Tambun, indicating ductile deformation. [B] The sketch of the limestone bed in [A] showing small normal faults on the bed boundary, showing the ductile behavior of this layer with left simple shear.

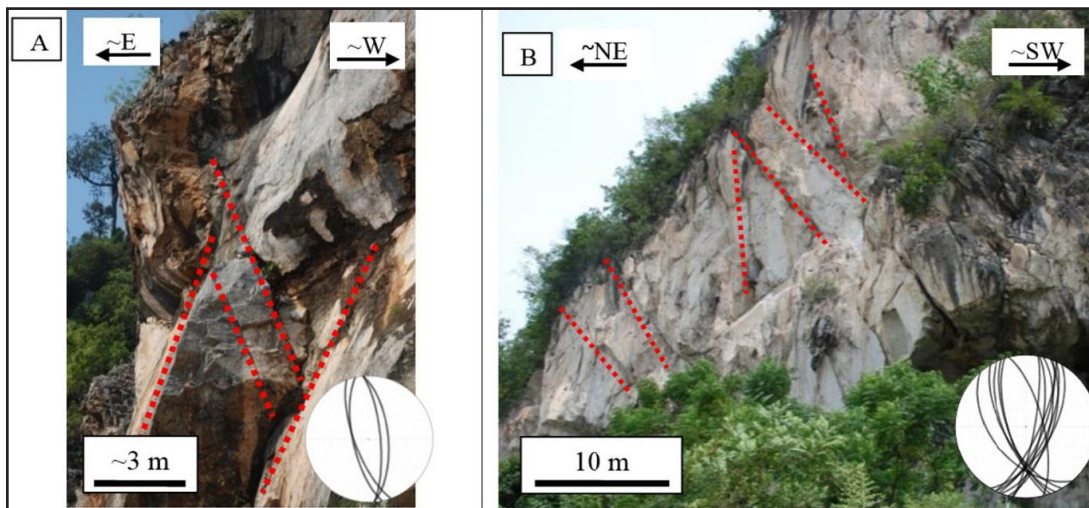


Figure 10: Conjugate normal faults in the limestone of Kinta Valley. The stereonet shows the orientation of the fractures. The outcrops are in [A] Bercham and in [B] Simpang Pulai.

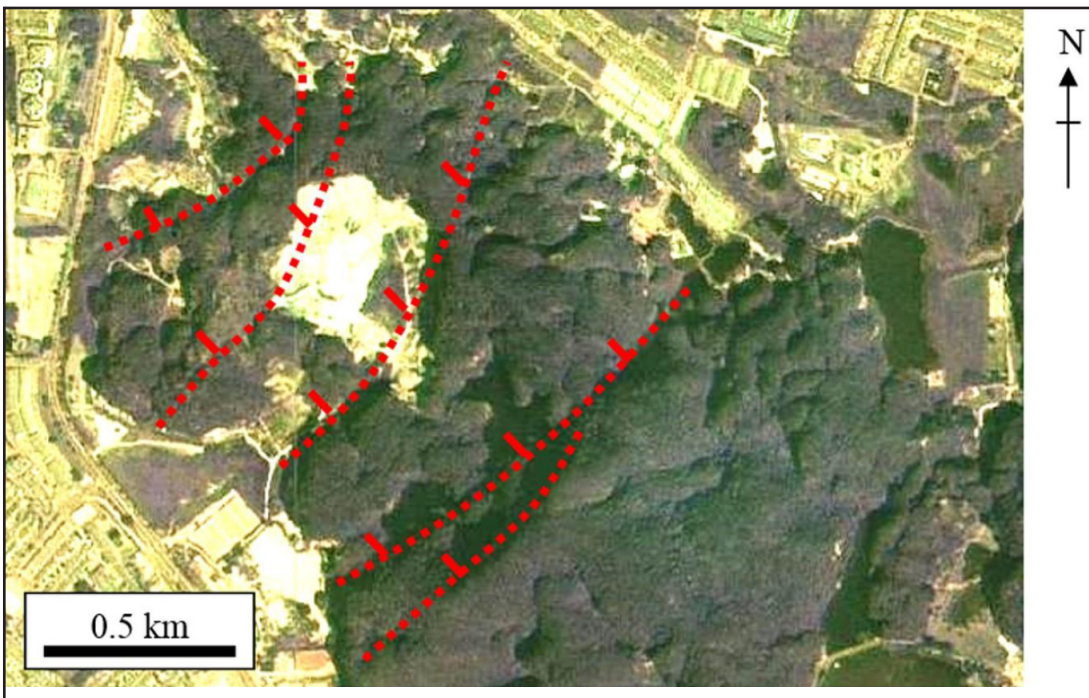


Figure 11: Topographic steps, underlined by narrow valleys formed by D4 fractures in the limestone hills observed in the Gunung Rapat area.

limestone of the Kinta Valley. The cross-cutting relationships were used to determine their relative ages.

During the Late Paleozoic, carbonate sediments were deposited and started to compact and consolidate (Ingham & Bradford, 1960; Suntharalingam, 1968). D1 fracture set occurred within relatively thin beds (a few centimeters) and is believed to have developed in situ during the last phase of the basin infill, right after the deposition stage of the carbonate sediments. As such, it may result from sagging rather than tectonics.

Both D2 and D3 fracture sets were observed in the limestone of the Bercham area, a few kilometers away from Tambun in the eastern edge of the valley. The slickensides of the D2 conjugate strike-slip faults are observable on the cliff face of the hills. The D3 thrust faults were mainly developed along the bedding planes on the outcrops and on the large limestone bodies. The D2 strike-slip faults about the D3 thrust faults, and sometimes displaced the cliff face or strike-slip fault plane (Figure 12), thus indicating that D2 occurred prior to D3.

D4 fracture set commonly propagates through the whole outcrop and cross-cut the previously-formed features at outcrop-scale and regional-scale, indicates late deformation. Long D4 fractures are traceable at map scale, e.g. NW of the Gunung Rapat, cut through the whole hill (Figure 11).

Structural history of the Paleozoic limestone

The structural history of the Paleozoic limestone of the Kinta Valley is summarized in the Table 1. Carbonate sediments continued to be deposited until the Middle Permian (Suntharalingam, 1968), subsequently hardened, and broke into small brittle conjugate fractures due to overburden. This basin development process was active probably until

the collision between the Sibumasu and Indochina blocks, during the Triassic (Metcalf, 2013).

The emplacement of granites by the Early Jurassic (Krahenbuhl, 1991) was probably at the same period as regional compression regime, which led to the formation of the D2 conjugate strike-slip faults or even folding of the limestone beds. Then, soon after D2, the D3 compression occurred. D3 generated a series of thrusts within the horizontal carbonate strata, which propagated toward the east approaching the granite contact. When the thrust sheets abutted the rising batholiths, the limestone became severely folded and became vertical in attitude. The limestone behaved in a ductile manner approximately 100 m next to the contact with the hot granite, as illustrated by localized flow structures and ductile shear. The ductile structures indicate normal movement, suggesting a gravitational collapse of the limestone parallel to the granite contact or drag effect of the rising batholith. The process would be similar to “roof-pondant” formation, but with high temperature (HT) conditions.

The extensional event D4 could be correlated with the development of the Tertiary basement-involved horst and grabens of the Strait of Malacca (Liew, 1995), the Mergui basins and onshore Tertiary basins of the Peninsular Malaysia, based on similar structural styles. Therefore the age of the D4 is probably between the Eocene to Middle Miocene (Liew, 1995).

CONCLUSIONS

The different fracture sets in the Paleozoic limestone of the Kinta Valley are presented in a sequential pattern and used to trace its tectonic evolution. The regional deformation began with E-W extension which occurred after of the deposition of the carbonate sediment in the basin (D1).

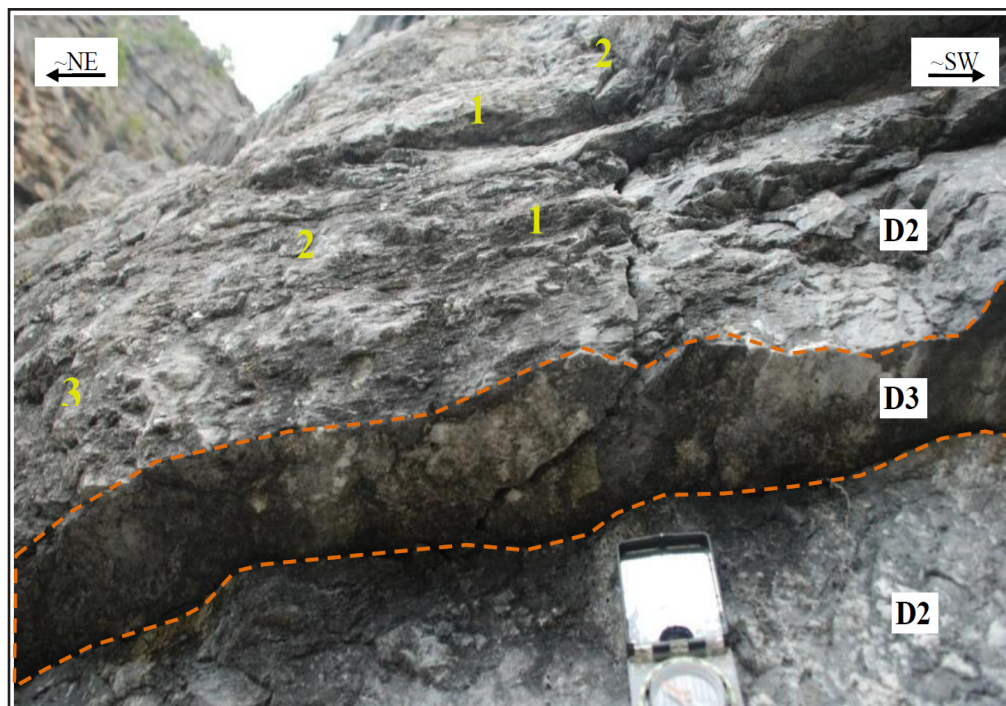


Figure 12: Vertical strike-slip fault (D2) formed at the cliff face, has been cut and displaced by gently dipping reverse fault/thrust fault (D3) which faced downward (orange-coloured polygon). The movement direction and sense of the faults was determined from the slickensides. Slickensides of the right-lateral strike-slip faults (D2) composed of components such as 1, fault roche moutonnée, 2, accretion spalls and 3, bruised stoss slopes. The width of the compass is 6.5cm.

Table 1: Summary of the structural deformation sequences in the Paleozoic limestone of the Kinta Valley. * dd = ductile deformation.

Age		Deform. stage	Model of deformation	Corresponded fracture sets
Quaternary		D4		
Neogene				
Paleogene				
Cretaceous	Late	D3		
	Early			
Jurassic	Late			
	Middle			
	Early			
Triassic	Late	D1		
	Middle			
	Early			
Permian				

E-W extension was followed by E-W compression which produced the conjugate strike-slip faults (D2) and thrust faults (D3), probably at the same time as granite emplacement in the Early Jurassic. The E-W compression events of D2 and D3, are believed to have caused the shortening in the limestone and resulted in the formation of tight folds and vertical bedding found at the edge of the valley. When the shortening occurred, the limestone was in direct contact with the hot intrusion, where the mobility increased because of partial melting. This resulted in shearing, and the ductile deformation. E-W extension took place in this region after D2 and D3. This late deformation phase created ~N-S striking normal faults.

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