

The geology of Kudat Peninsula, Sabah: New insights from field geology and subsurface interpretation

NABILAH MOHAMED ZAINUDDIN*, SITI NUR FATHIYAH JAMALUDIN, CHOONG CHEE MENG,
MOHD SUHAILI ISMAIL

Department of Geosciences, Faculty of Science & Information Technology, Universiti Teknologi PETRONAS, Malaysia

* Corresponding author email address: nabilahzainuddin21@gmail.com

Abstract: Northern Borneo is a geologically complex region influenced by the rifting and opening of the South China Sea during Oligocene to Middle Miocene. Kudat Peninsula, which lies in the northern tip of north Borneo expose part of this complex geology. Detail geological study of an area with a comprehensive and thorough understanding of the tectonic history avails in conceiving the geological evolution. Geological and geophysical study was conducted in Kudat Peninsula and offshore of the Kudat Peninsula to evaluate the structural framework and tectonic history of the peninsula. Four formations underlying Kudat Peninsula are Ophiolite Basement, which is overlain by younger deposits, Crocker Formation, Kudat Formation and a chaotic deposit known as *mélange*. Kudat Peninsula is underlain mainly by the Kudat Formation which comprises three members, Tajau Member, Sikuati Member and Gomantong Member, made up of interbedded sandstone and mudstone. Kudat Formation is believed to be sitting on top of the basement rock or ophiolite rock. We propose that the Kudat Formation and the basement layer extended into the offshore region of NW Sabah and the *mélange* unit found in the north of the peninsula is originated from the older formations such as the Kudat Formation and the ophiolitic basement that had been faulted, deformed and uplifted to the surface through faulting.

Keywords: Kudat Peninsula, seismic interpretation, offshore of Kudat Peninsula, Kudat Formation, *mélange*

Abstrak: Borneo Utara adalah sebuah kawasan yang mempunyai geologi yang kompleks disebabkan oleh pemuaian dan pembukaan Laut China Selatan semasa Oligosen ke Pertengahan Miosen. Semenanjung Kudat yang terletak pada bahagian hujung Borneo Utara adalah sebahagian daripada kawasan kompleks ini. Kajian geologi yang terperinci berkaitan kawasan kajian disertai dengan pemahaman yang komprehensif dan menyeluruh mengenai sejarah tektonik akan membantu dalam mengkaji evolusi geologi kawasan tersebut. Kajian geologi dan geofizik telah dijalankan di Semenanjung Kudat dan kawasan pesisirnya untuk menilai kerangka struktur dan sejarah tektonik semenanjung ini. Empat formasi utama yang membentuk Semenanjung Kudat adalah batuan dasar Ofiolit, ditindih oleh lapisan yang lebih mudah seperti Formasi Crocker, Formasi Kudat, dan unit campuran yang dikenali sebagai *mélange*. Sebahagian besar kawasan Semenanjung Kudat terdiri daripada Formasi Kudat yang mempunyai tiga ahli, Ahli Tajau, Ahli Sikuati dan Ahli Gomantong. Ketiga-tiga ahli ini terdiri daripada selang lapis batu pasir dan batu lumpur. Formasi Kudat dipercayai terbentuk di atas batuan dasar Ofiolit. Kami mencadangkan bahawa Formasi Kudat dan batuan dasar terbentuk hingga ke pesisir barat laut Sabah. Unit *mélange* yang terdapat di kawasan utara semenanjung ini berasal daripada formasi batuan yang lebih tua seperti Formasi Kudat dan batuan dasar ofiolit yang telah tersesar, terancang dan dibawa ke permukaan melalui sesar.

INTRODUCTION

Kudat Peninsula, part of the northern Sabah is a structurally complex province believed to be influenced by the rifting and opening of the South China Sea and Sulu Sea. The opening of the South China Sea (SCS) had initially undergone extensional phase. Two episodes of extension occurred during the period of Cenozoic (Cullen *et al.*, 2010). The early episode took place in Paleocene to Eocene (Cullen *et al.*, 2010) had spread widely and was recognized in a large area including Dangerous Ground (Thies *et al.*, 2005), Luconia (Mat-Zin & Swarbrick, 1997) and onshore Kalimantan (Satyana *et al.*, 1999). The later episode of extension during Late Eocene to Early Miocene had resulted in a high amount of crustal thinning. Forces produced from the collision and subduction of the proto-

South China Sea beneath Borneo plate had created a NW-SE and N-S compression on northern Sabah. Several episodes of deformation impacted northern Sabah forming faults, folds, and fold-thrust belt shaping the basin present today. The reactivation of these structures coincides with the second extensional phase during Late Eocene to Middle Miocene and the opening of South Sulu Sea during Middle Miocene (Tongkul, 1993).

The regional tectonic compressions had intensely deformed and imbricated the rock formations present in north Sabah including Kudat Peninsula (Tongkul, 2006). It is also believed that these events had eventually formed a chaotic unit consisting of ophiolitic basement, Crocker Formation and Kudat Formation, forming a *mélange* zone (Tongkul, 1990) commonly found in this region. Continuous

deformation and poor age control of the sediments in the peninsula had made it difficult to determine the exact geological events sequences and the timing of structuring. This paper will be discussing on the stratigraphy and structural style of the Kudat Peninsula and its offshore in the northwest region of the peninsula. This paper provides new insight on the geology of the Kudat Peninsula and its offshore, which would be useful in improving the structural history of the peninsula.

Geology setting of Kudat Peninsula

The remnant of the oceanic crust of the Ophiolite Basement, known as Chert-Spilitic Formation existed in NW Sabah during Cretaceous-Palaeocene. Subsequently, a deepwater turbidite sediments started to deposit in the same basin during Palaeocene to Middle Miocene. These deepwater turbidite sediments are represented by the Trusmadi Formation and Crocker Formation (Tjia, 1988). The collision of Palawan, Reed Bank and Dangerous Ground blocks with NW Borneo basin in Early Miocene had ceased subduction forming the Sabah Orogeny (Hutchinson, 1996), where it marks the end of deposition for the deepwater sediments and sedimentation continues in the shallow marine setting (van Hattum *et al.*, 2013). The compressional event had controlled the sediments distribution and shaped the sedimentary basins in Northern Sabah (Tongkul, 1993). According to Tongkul (1990), the continuous compression during Middle Eocene to Middle Miocene had formed the Kudat Formation. The opening of the South China Sea during Oligocene-Middle Miocene (Tongkul, 2006) had intensely deformed Northern Sabah, and these tectonic events had generated a NW-SE to N-S compressions (Tongkul, 1993), which resulted in the formation of major structures such as the fold-thrust belt zone of the accretionary-prism made up of Crocker-Trusmadi Formation (Tjia, 2000).

Another major tectonic event occurred during the Late Oligocene to Middle Miocene, leading to the formation of the imbricated mixture of the bottommost layer, ophiolite, Crocker and Kudat Formation forming a *mélange* unit (Tongkul, 1990). Kudat Peninsula is dominantly made up of Kudat Formation, a deep to shallow water sediment and this formation is divided into three (3) members referred to as Tajau, Sikuati, and Gomantong Members (Liechti *et al.*, 1960) or Lower, Middle and Upper Unit respectively (Tongkul, 2006; 2008). This research focuses on the stratigraphy and structural style of Kudat Formation and the *mélange* unit.

METHODOLOGY

The technical approach for this study includes field observation, sample collection, age dating, and subsurface interpretation of onshore and offshore of the Kudat Peninsula. Detail outcrops description on the lithology and structural measurements of beddings, faults, and folds found in Kudat Peninsula involving 82 outcrops were observed and recorded. Structural analysis utilizes the

positive lineaments measurement to determine the main bedding trends of each member in the Kudat Formation. Rock samples collected from a few selected outcrops were used for lithological description. Mudstone samples were collected and sent for age dating analysis (Figure 1). Complimenting these data are the seismic lines acquired in the onshore and offshore of Kudat Peninsula for the detail subsurface interpretation. Onshore acquisition had produced seismic data with higher noise to signal ratio, thus, an improvement was done to these seismic data by applying structural smoothing attribute to increase the continuity of the reflector (Abdul Latiff *et al.*, 2015). This attribute works by removing the noises and enhancing the structures in the seismic image. Furthermore, horizons and faults were manually picked as the auto-picking mode is usually used for high-quality data with continuous reflectors. The results and discussion shared in this paper are based on the onshore seismic lines, herein mentioned as K8 and K9 as well as offshore seismic line, herein mentioned as TL6. The classification of the geological units is based on the distinct characteristics of the seismic reflectors, lithological correlation with the exposed onshore rock formations and the information gathered from literature study.

RESULTS AND DISCUSSION

General geology of Kudat Peninsula, northwest Sabah

Based on field observation and interpretation, the Kudat Peninsula comprises of four formations, the Ophiolitic Basement, Crocker Formation and Kudat Formation, and the *mélange* unit. Kudat Peninsula is dominantly made up of Kudat Formation, a relatively deep to shallow water sediments (Rahim *et al.*, 2017; Lunt & Madon, 2017). Figure 1 shows the geological map of the Kudat Peninsula. The Gomantong, Sikuati and Tajau Members of Kudat Formation are made up of interbedded sandstone and mudstone. Gomantong Member is referred to as the Upper Unit of Kudat Formation by Tongkul (2006), possibly describing this unit as the youngest member. It consists of interbedded medium to fine-grained sandstone and mudstone, predominantly sandstone layer as shown in Figure 2. The sandstone bed is characterized by sedimentary structures such as parallel lamination, ripple marks, convolute structure, and water structure (Figure 3). Sikuati Member is made up of interbedded fine-grained sandstone and mudstone with abundance of sedimentary structures such as parallel lamination, cross lamination and wavy lamination as shown in Figure 3. The thick sandstone bed interbeds with thin mudstone layer had formed the northern Kudat terrane, known as Tajau Member and has Early to Middle Eocene calcareous nannofossils (Rahim *et al.*, 2017).

The *mélange* unit is found in a few localities mostly in the northern part of the peninsula. This *mélange* appears within a strip zone, bounded by major faults situated in

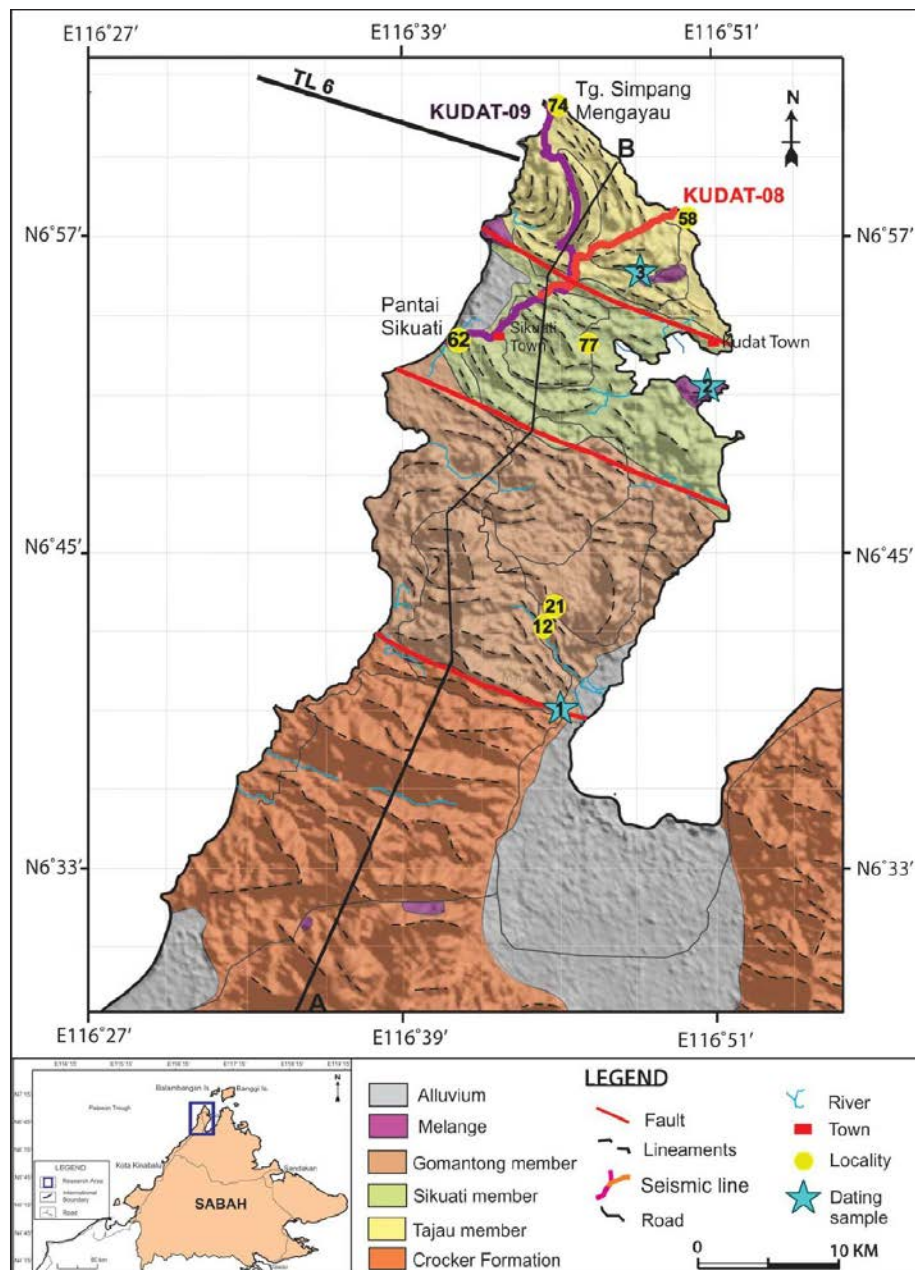


Figure 1: The Kudat Peninsula is dominantly made up of Kudat Formation, geologically classified into three (3) members of Gomantong, Sikuati, and Tajau Members and partly consist of Crocker Formation in the south. Field localities are labeled as the numbered circle and the geological cross-section of Kudat Peninsula is constructed from A to B.

between Tajau Member and Sikuati Member. It is made up of an intensely deformed mixture of the ophiolitic basement rock (Clennell, 1991) and presence in the form of knockers and lens-shaped phacoid structures (Chang *et al.*, 2019). Blocks of rocks that were identified in the mélangé are serpentinite, chert, and red mudstone. A knocker is defined as a complex outcrop showing random bedding orientation where each side have different reading, resulted in difficulties to obtain the accurate measurement and it is usually associated with a mélangé. The knocker found on the peninsula is a boulder of chaotic unit comprising of

red chert, green chert and red mudstone, originated from the basement rock that had been uplifted to the surface. This unit is highly deformed characterized by folds and refolded folds as shown in Figure 4. This mélangé strip is found in a faulted zone of strike-slip fault, indicated by the slickenside surface of serpentinite showing dextral sense of movement. Presence of *Cyclicargolithus floridanus* (NN6) and other associated nannofossils in the mudstone of the mélangé unit is dated Middle Miocene in age (Table 1). The paleoecology of these nannofossils is a shallow marine environment (Kallanxhi *et al.*, 2016).

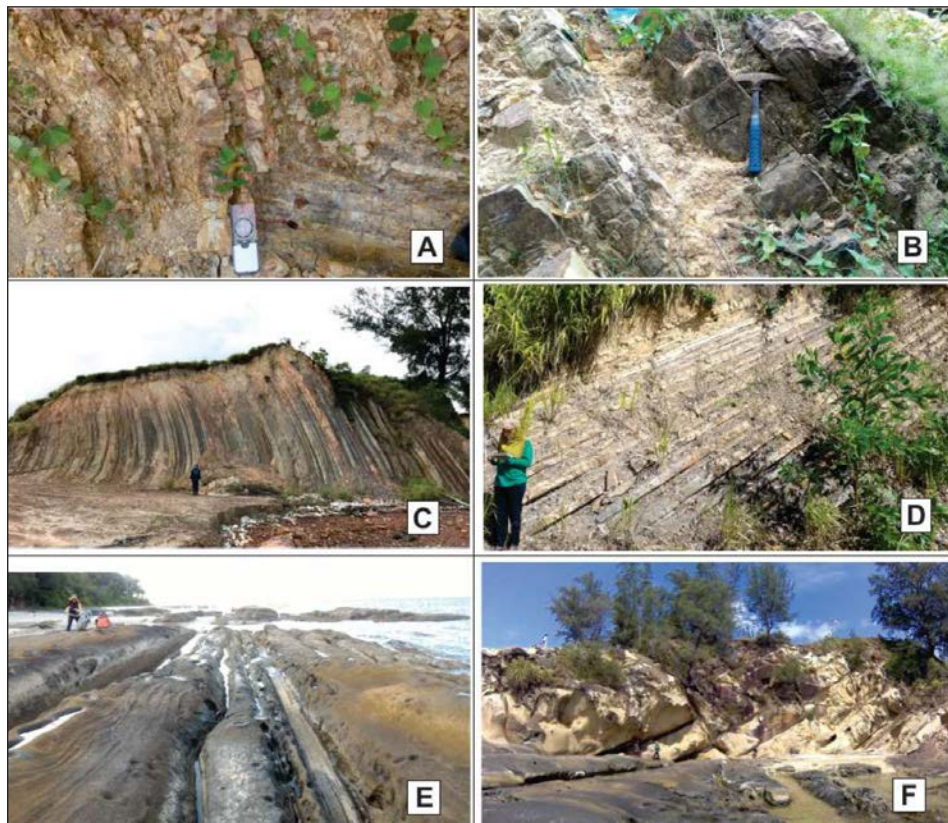


Figure 2: Interbedded sandstone and mudstone of Gomantong, Sikuati and Tajau Members. All outcrop numbering mentioned in this paper is based on the map in Figure 1. A) and B) Locality 12 and 21 have thick beds of sandstone interbed with thin mudstone layer and the outcrop in locality 12 shows a highly folded beds cross-cut by a normal fault. C) Locality 62 is made up of massive sandstone and mudstone beds with wavy boundary while D) Locality 77 has sharp straight boundary. These sandstone beds are filled with sedimentary structures such as parallel lamination, cross-lamination, and wavy lamination. C) Locality 62 is a freshly cut outcrop exposed in Pantai Sikuati. The strata are slightly folded on the north side of the outcrop showing the presence of a fold limb. E) and F) Locality 58 and 74 are exposed at the shoreface in Kg. Raja Laut and Tanjung Simpang Mengayau respectively. Thick sandstone layer with thin mudstone interbed.

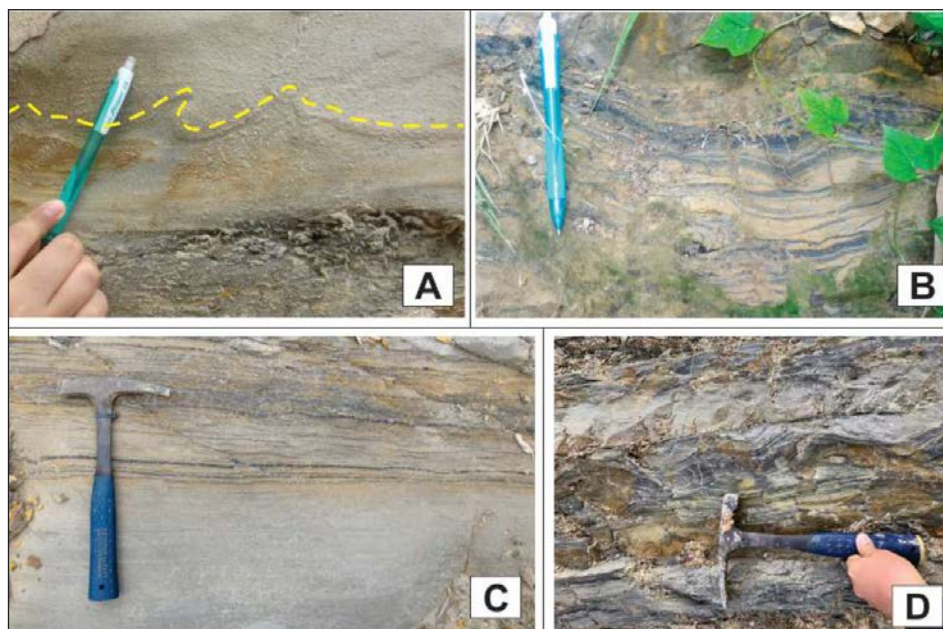


Figure 3: Sedimentary structures observed in sandstone of Gomantong and Sikuati Members. A) Flame structures in the thick sandstone layer in Locality 11; B) Parallel, wavy and cross lamination occurred in the sandstone layers observed in Locality 21; C) Parallel and cross lamination; D) Parallel and wavy lamination structures in sandstone beds in Sikuati Member.

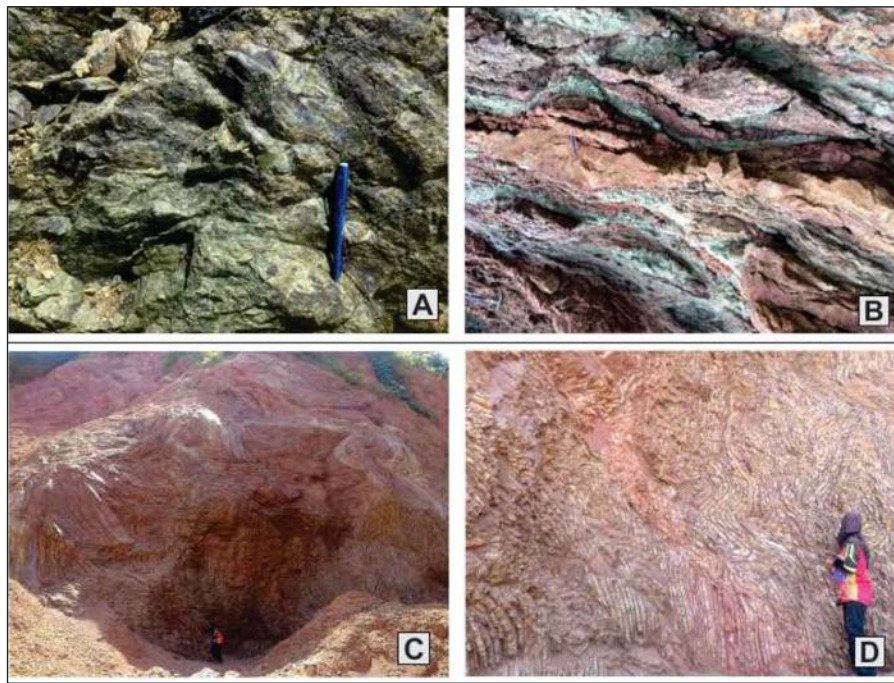


Figure 4: A) Serpentine in a strike-slip faults zone showing dextral sense of movement.; B) Phacoid structures of mudstone in the mélange unit; C) & D) Boulder of mélange comprises of red chert and red mudstone known as 'knocker'.

Table 1: Nannofossils occurrences in the members of the Kudat Formation in Kudat Peninsula (report from Geostrat Services).

| Sample No. | Lithology | Location | Preservation | Nannofossil/ Nanno Zone | | | | | | | | Age |
|------------|--------------|-------------|--------------|--|---------------------------|----------------------------|------------------------------------|--------------------------|--------------------------|----------------|--|-----|
| | | | | <div> <div>NN20/21</div> <div>NN15</div> <div>NN12</div> <div>NN6</div> </div> | | | | | | | | |
| | | | | <i>Reticulofenestra minuta</i> | <i>Sphenolithus abies</i> | <i>Ceratolithus acutus</i> | <i>Cyclicargolithus floridanus</i> | <i>Ceratolithus</i> spp. | <i>Sphenolithus</i> spp. | | | |
| 1 | Mudstone | Gomantong-1 | Poor | 1 | 1 | 1 | 1 | 1 | 2 | Middle Miocene | | |
| 2 | Red mudstone | Sikuati-1 | Poor | 1 | | | | | | Middle Miocene | | |
| 3 | Mudstone | Tajau-1 | Barren | | | | | | | Indeterminate | | |

The structural style of Kudat Peninsula

Structural analysis reveals that Kudat Formation has intensively folded strata in each member, having similar bedding trends of NE-SW to NNE-SSW and NW-SE (Figure 5). Examples of the strike and dip reading of the beddings are 294/30, 202/64, 318/32, 50/40, and 54/66. These bedding trends were induced by the N-S and NW-SE main compression (σ_1). Regional tectonic events had compressed these beds resulted in folded bed of sandstone

and mudstone. Based on the axial plane analysis of the main folding in Sikuati and Tajau, the fold in Tajau Member is plunging to ENE (N74°E) while Sikuati Member having fold plunging to East (N88°E). The E-W fold trend in the Kudat Peninsula are controlled by the N-S compression. Figure 5 shows the stereonet analysis of the main bedding and folding trends of the members.

Field data were interpolated along with the DEM to build a regional cross-section. Figure 6 shows the result of

the cross-section from point A to B going perpendicular to the main structures from south to north of the peninsula. The major rock formations are bounded by the reactivated faults. Within the major faults, several normal faults occurred forming repeated rollover anticlines. Other types of folds are also recognized, such as steeply folded anticline in Crocker Formation, synclinal fold plunging ESE in Sikuati Member and anticlinal fold plunging East in Tajau Member. The Gomantong Member shows the presence of an anticline and syncline folds which later were displaced by younger thrust faults. The *mélange* zones are found exposed in between Tajau and Sikuati Member and within the Crocker Formation. These *mélange* rocks was originated from the older basement rock that had been imbricated and deformed forming a mixture of rocks embedded in sheared mud matrix. The rocks identified in the *mélange* have similar characteristics to the Ophiolite Basement. Repeated occurrence of this unit in the younger formations indicates that the basement rock formed closed to these formations, where possibly

Kudat Formation is lying on top of the basement rock as shown in Figure 6.

Seismic interpretation of K8, K9 and TL6 in onshore and offshore of Kudat Peninsula

The onshore subsurface interpretation of seismic line K8 and K9 cut across the Kudat Formation and the *mélange* unit. Lithological boundaries between each unit were guided by field observation. Discrete characteristics displayed in the seismic reflectors had identified the presence of two (2) geological units referred to as Unit A and Unit B. Unit A is interpreted as the oldest unit underlying Unit B. It appears at depth ranging from 1800 m to more than 4000 m and the thickness of this unit varies from the south to the north. It is characterized by a low to medium amplitude of chaotic and discontinuous pattern reflectors. The reflectors are highly distorted and disturbed throughout this unit. Chaotic seismic pattern usually defines a carbonate or basement rock (Franke *et al.*, 2008). Kudat Peninsula is known for the widely distributed basement rock made up

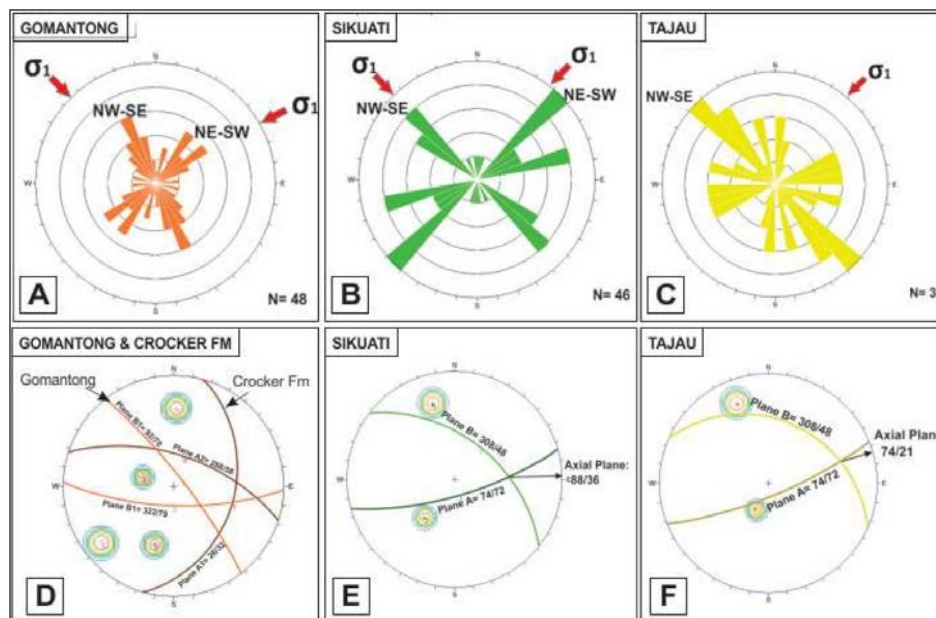


Figure 5: Structural analysis of Kudat Formation. The bedding analysis of A) Gomantong, B) Sikuati and C) Tajau showing the main strike direction of NW-SE and NE-SW. The NW-SE strike trend was induced by the NE-SW compression while the NE-SW strike trend was controlled by the NW-SE compression. D)-F) Interpretation of the fold axis of the folding in Crocker Formation, Gomantong, Sikuati and Tajau Members. These folds are plunging to the east-southeast.

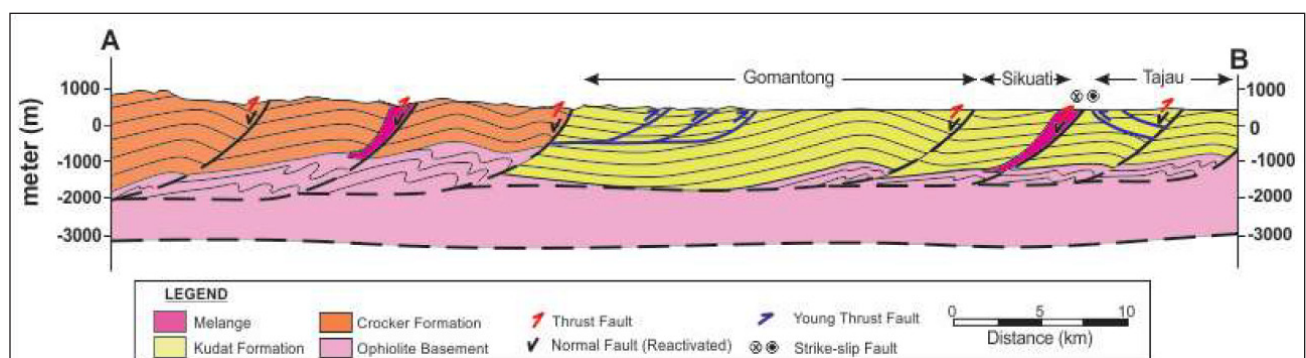


Figure 6: Cross-section from South (A) to North (B) of Kudat Peninsula, cutting across Crocker Formation, *mélange* zone and the Kudat Formation.

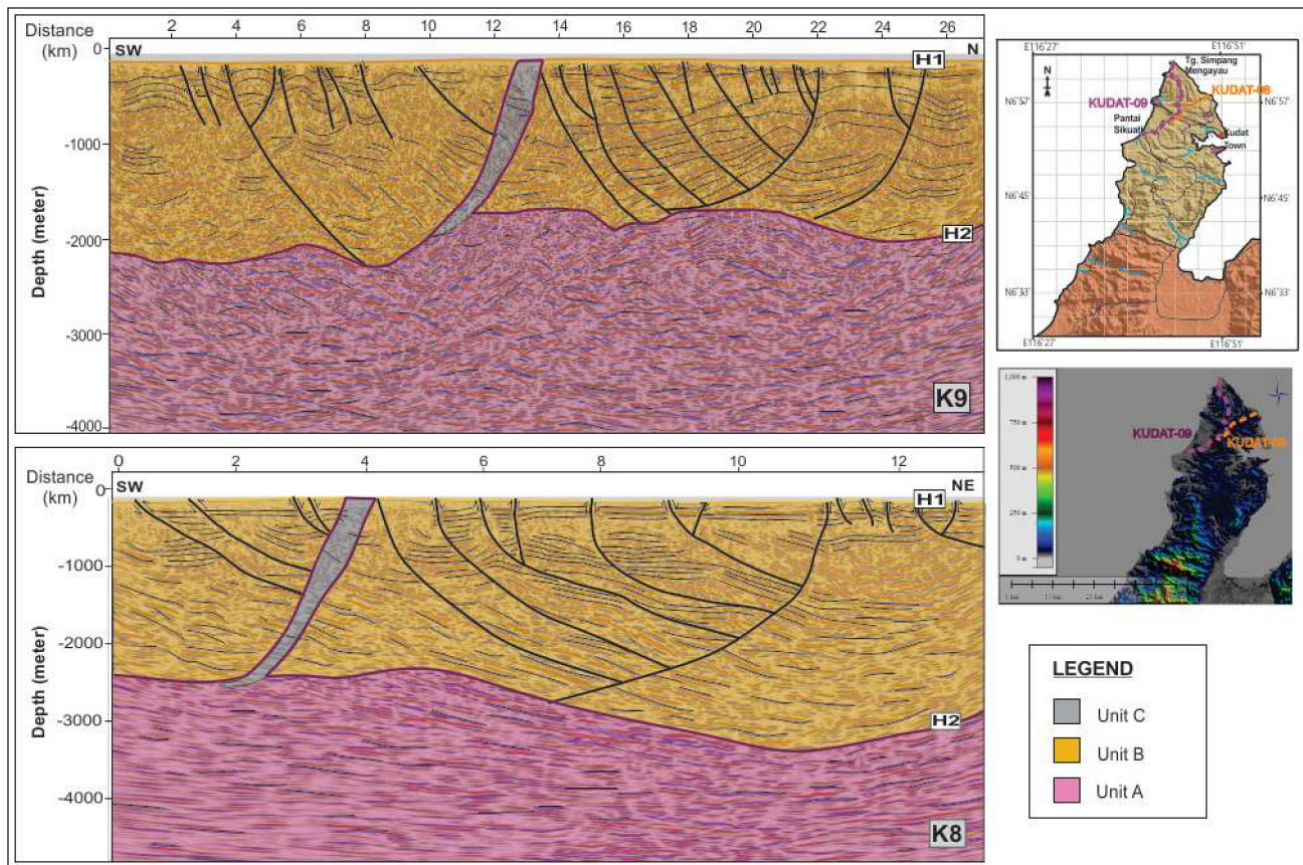


Figure 7: Seismic interpretation of onshore seismic line K9 and K8 located in the north of Kudat Peninsula. Two (2) horizons were interpreted in this area herein mention as H1 and H2.

of ophiolite sequence comprising of serpentinite, basalt, and hemipelagic sediments. The Ophiolite Basement is dated as Late Cretaceous to Late Eocene (Basir & Sanudin, 1988; Basir, 1990; Stephens, 1956) based on the radiolaria and microfossils yield from the chert, red shales, and shales from Kudat Peninsula, Bengkoka Peninsula and Taritipan River (Tongkul, 1994).

Based on the seismic image, Unit B which unconformably overlying Unit A is interpreted to be the younger unit. The seismic reflectors observed appears to have medium to high amplitude of sub-continuous to continuous reflectors (Figure 8). Previous and recent age dating of the mudstone sample from the Kudat Formation had suggested that Unit B was formed during Early Eocene to Middle Miocene, equivalent to the age of Kudat Formation. It consists of interbedded sandstone and mudstone, deposited in deep to shallow marine environment. It is exposed on the surface of the peninsula and extended into the depth of 1800 m - 2200 m beneath the surface. The reflectors are folded and highly faulted similar to the beds exposed on the surface. Folded reflectors observed in the northern section of K9 indicates the presence of folds in the formation.

Unit C occurred within the Kudat Formation in a thinly strip zone. Unit C intruded the Kudat Formation from the Ophiolite Basement. It is interpreted as the mélangé unit. The mélangé migrated along the fault plane to a higher

elevation position. This unit is exposed on the surface of Kudat Peninsula (Figure 6) as a chaotic mixture of serpentinite, chert and mudstone blocks.

The geological units interpreted in TL6, offshore of Kudat Peninsula is described as the remnant of the collapsed circular basin (Figure 8). The seismic reflectors in TL6 show the same characteristics with the reflectors of onshore Kudat Peninsula, particularly the bottom unit (Unit A), which is referred to as the ophiolitic basement rock. A half circular-basin features in Tajau Member can be clearly seen from the Digital Elevation Map (DEM), which could possibly be a collapsed circular basin (Figure 1). The sediments of Kudat Formation are believed to be deposited in a larger area that extended into the recent offshore region. Sedimentation took place in a circular basin in northern Kudat Peninsula prior to the faulting of Kudat Formation. However, the sediments in the offshore region had possibly collapsed due to normal faulting. The sedimentary deposits lying on top of Unit A and Unit B are defined as the younger units. However, there is no well data to clarify the lithology of the offshore region.

CONCLUSIONS

Kudat Peninsula is underlain by the Ophiolitic Basement, Crocker Formation, Kudat Formation, and mélangé unit. The members of Kudat Formation have distinguished lithology and structural style. Exposed Middle Miocene mélangé unit

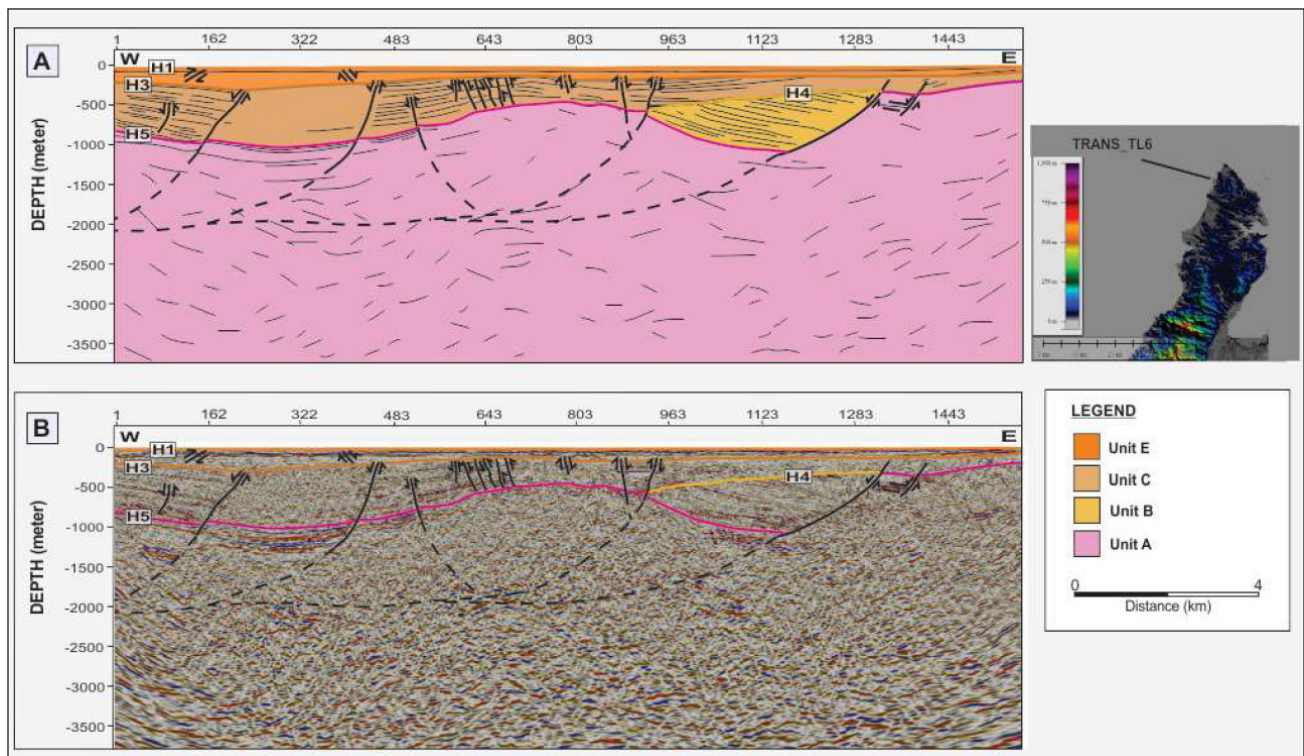


Figure 8: Seismic interpretation of offshore seismic line TL6 in the offshore west to Kudat Peninsula. The deformed Unit B is overlying the basement rock, and the younger units, C and E are sitting on top of Unit A and B. The seismic characteristics of Unit B is interpreted based on the reflectors in the yellow box.

found in the northern and southern part of Kudat Peninsula is made up of a mixture of older rocks such as serpentinite, chert, and red mudstone which were moved by the thrust faults and uplifted to the surface, in the form of a chaotic deposits. Regional tectonic events have greatly impacted and influenced the structural style of the northern Sabah as shown by the main bedding trends of Kudat Formation which is in the direction of NE-SW to NW-SE, coincide with the regional trends of South China Sea and South Sulu Sea. These trends were ceased by the NW-SE and N-S compressions and are believed to be related with the compression induced from the rifting of the South China Sea. Furthermore, the compression force exerted on the sediments in Kudat Peninsula had resulted in intensively folded and faulted strata interpreted to be associated with the reactivated faults. These faults are the structure responsible for the occurrence of the mélangé in the peninsula.

Comparison of the geological cross-section of Kudat Peninsula with onshore and offshore seismic interpretation give a new insight on the geology of Kudat Peninsula, showing that Kudat Formation is sitting on top of the ophiolitic basement and the mélangé unit found in Kudat Peninsula is originated from this basement rocks. Moreover, the offshore seismic interpretation suggested the Kudat Formation was deposited in a circular basin and extended approximately 10 km further offshore northwest to the Kudat Peninsula. However, major faulting which occurred parallel to the western shoreline had displaced part of this circular

basin. A thorough interpretation and analysis of seismic data and detail field study had given significant discoveries and a new insight on the geology of the Kudat Peninsula.

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