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A contemporary review of sedimentological and stratigraphic framework of the Late Paleogene deep marine sedimentary successions of West Sabah, North-West Borneo

Muhammad Jamil[1,2,*], Abdul Hadi Abd Rahman[1], Numair Ahmed Siddiqui[1], Noor Azahar Ibrahim[1], Nisar Ahmed[1]

[1] Department of Geosciences, Universiti Teknologi PETRONAS (UTP), 32610 Seri Iskandar, Perak D.R., Malaysia
[2] Department of Earth Sciences, COMSATS University Islamabad (CUI), 22060 Abbottabad, KPK, Pakistan
*Corresponding author email address: jamil287@gmail.com

Abstract: A timely and updated review of the Late Paleogene deep marine sedimentary successions is vital for a better understanding of the historical advances in sedimentology and stratigraphic evolution of West Sabah. The main objective of the study is to discuss the facies characteristics and depositional environment of the Late Paleogene rock formations. In addition, the stratigraphic aspects of the Paleogene interval will also be discussed. The Oligocene Temburong Formation exposed in several localities of West Sabah had been field researched with varying depositional processes and facies analysis. Moreover, the distribution of submarine fan, the observed variety of deep marine sediments associated with various sedimentary processes and the source of sediments of the co-eval West Crocker Formation were also investigated with contorted layers of mass transport deposits (MTD) reported first time in the formation. The upper and lower stratigraphic contacts of Late Paleogene formations, the age of individual rock formations and use of the term "Crocker Formation" in the literature are discussed with numerous unconformities and their stratigraphic positions in the Paleogene interval have been incorporated to understand the historical development of the Paleogene stratigraphy of the West Sabah. Owing to degrading tropical climate of the area, there are limitations and constraints on field-based research where the older outcrops are altered with housing development and dense vegetative cover. This review outlined the scientific developments and highlighted the ambiguities associated with stratigraphic placement of the Temburong and Crocker formations that still needed to be resolved to get an upgraded depiction of the Late Paleogene sediments of West Sabah.

Keywords: West Sabah, Late Paleogene, sedimentology, stratigraphic framework, Crocker Formation, Temburong Formation

INTRODUCTION

Sabah is situated in northern part of Borneo and is bounded by Sulu Sea in the East and South China Sea in the West (Figure 1A). The present study focuses on the sedimentary successions and stratigraphic framework of the West Sabah (Figure 1B) The Paleogene sediments of West Sabah are the oldest sedimentary rocks which lie stratigraphically above the Cretaceous basement. To date, more work had been done for the younger Neogene rocks, and research is less focused on the older Paleogene successions. The quest for new exploration opportunity in offshore Sabah has enhanced the chance to find out more petroleum plays particularly in the older Paleogene sedimentary sequence. Therefore, a better understanding of deep marine Paleogene successions is needed for future hydrocarbon exploration. Although, the available literature related to these Paleogene sediments discussed various aspects of sedimentology and stratigraphic framework, yet the review of published data is essential in order to discover the pathways for bridging the research gaps. In addition, the study will reveal uncertainties and ambiguities present in the literature and advance our understanding for future geoscientific research. The present review emphasizes on sedimentological and stratigraphic data to highlight the research questions and future academic pathways to resolve the geology of Late Paleogene sediments of West Sabah.

The Paleogene sedimentary successions exposed in West Sabah are divided into Early and Late Paleogene stratigraphic units. Early Paleogene units are the Trusmadi and East Crocker formations while the West Crocker and Temburong formations are of Late Paleogene age (Figure 2). Trusmadi and East Crocker formations represent the eastward continuation of Crocker-Rajang Group that was metamorphosed, folded and uplifted (Tongkul, 1995; William *et al*., 2003). Early Paleogene successions were deposited, and later weathered and re-sedimented to form the younger sedimentary successions including the West Crocker and Temburong formations of Oligocene to Early Miocene age (Tongkul, 1995; Crevello, 2002).

An integrated sedimentological and stratigraphic understanding of these Late Paleogene deposits is still deficient. The West Crocker Formation had been well studied due to exposed outcrops and competent lithology of massive sand units while the Temburong Formation is

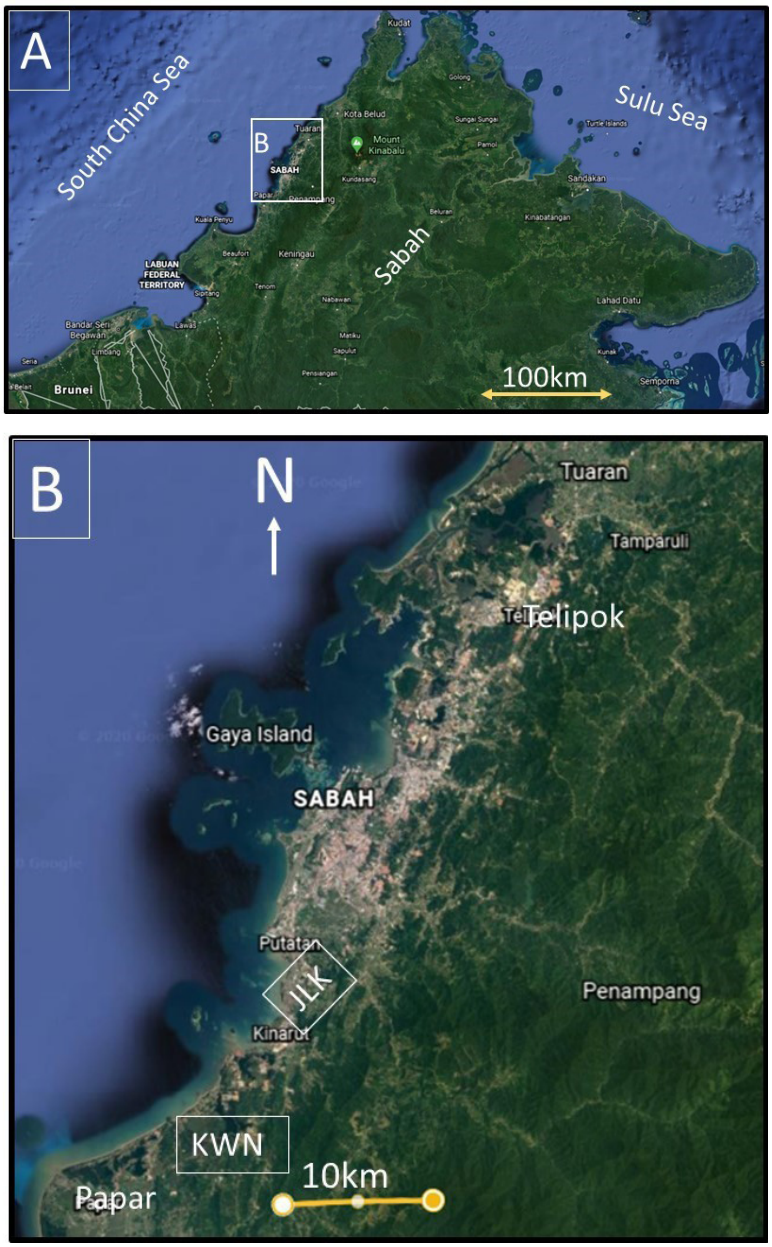

Figure 1: Regional map of Sabah (A) where South China Sea is present on the West of Sabah and Sulu Sea marks the eastern boundary. The location map of the study area is marked in white box (with B). Telipok is sited in NW Sabah while Jalan Pengalat Lok Kawi (JLK) and Kawang (KWN) is situated near Papar in SW Sabah (B). The study area includes the siliciclastic outcrops of Late Paleogene sedimentary sequences.

less studied owing to incompetent lithologies like shales, mudstones and siltstones which are more readily weathered and eroded. Furthermore, these argillaceous lithologies are readily covered with vegetation which consequently hinders detailed field studies. However, new infrastructure developments including the Pan Borneo Highway (also termed as Trans-Borneo Highway) construction work resulted in many new sections for a better understanding of the Late Paleogene strata.

FOCUS AND AREA OF THE STUDY

The available data and interpreted geology to date are noticeably marked by numerous uncertainties, confusions and assumptions. The major uncertainties include: 1) The detailed characteristics of the facies, facies associations and depositional model of the West Crocker and Temburong formations exposed in West Sabah have not been clearly defined and differentiated; 2) The proposed stratigraphic framework has been described by numerous and sometimes conflicting terms like Deep Regional Unconformity (DRU), Top Crocker Unconformity (TCU), Late Eocene Unconformity (LEU), Base Miocene Unconformity (BMU) and Early Miocene Unconformity (EMU) (Figure 2). The nomenclature of various unconformities and their ages within Paleogene strata mentioned in the literature is perplexing and multifaceted (Jamil *et al*., 2019; Lunt, 2019). The present study aims to review the sedimentological and stratigraphic framework of Late Paleogene sedimentary successions of West Sabah.

SEDIMENTOLOGY AND DEPOSITIONAL SETTINGS

There exists a great variety of the sedimentary processes prevalent in the marine depositional settings which are largely attributed for the vertical and lateral heterogeneities in the sedimentary successions (Siddiqui *et al*., 2016; 2020) These heterogeneities impose a great challenge in order to understand the submarine fan environment and depositional settings. Nevertheless, these divergences contribute to a variety of sedimentary processes and depositional environments interpreted for each type of sedimentary unit. The sedimentary features and related processes which are associated with the Late Paleogene sediments are discussed in this review.

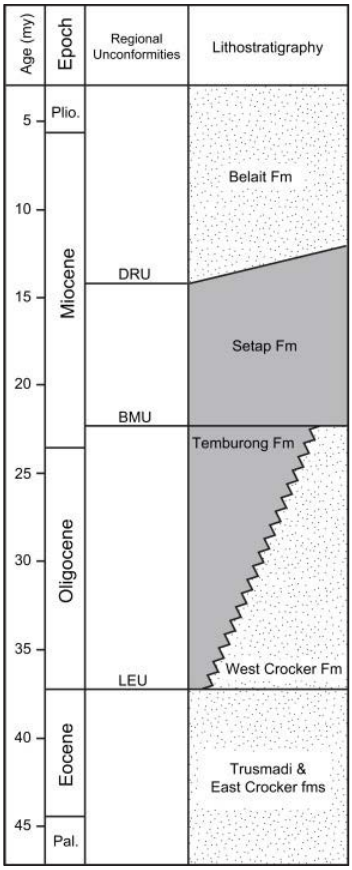

Figure 2: Generalized stratigraphy of West Sabah (Jackson *et al*., 2009). Trusmadi and East Crocker formations represent the Early Paleogene deposition whereas West Crocker and Temburong formations are of Oligocene to Early Miocene age. The Late Eocene Unconformity (LEU) separates the Early and Late Paleogene stratigraphic units. The upper contact of Paleogene formations is marked with Base Miocene Unconformity (BMU).

Temburong Formation

The flysch sediments of siltstone and shale were first assigned the name of Temburong Formation by Wilson (1964). The Temburong Formation is mainly composed of argillaceous units with calcareous shale in common (Hutchison, 1996). This formation is believed to be the representative of deep marine low energy environment. (Wilson, 1964; Bakar *et al*., 2017).

Sedimentary facies

Madon (1997) reported the argillaceous Temburong Formation having thin sandstone units interbedded with shale and siltstones in Labuan, Sabah. The Temburong Formation in Tenom area and Klias Peninsula, SW Sabah is principally containing fine-grained turbidites (Td and Te Bouma Sequence), which are representative of basin plain facies and was interpreted as the distal part of a deep marine fan (Asis *et al*., 2015; 2018). Abdullah *et al*. (2017) described the Temburong Formation as deep marine shale and sandstone units located in Sipitang-Tenom area of West Sabah. Leong *et al*. (2018a) described fine grained Temburong facies as Tc-Te Bouma divisions which are suggestive of the distal lobe deposition of deep marine outer fan while at some localities the formation has only Te facies which represent the basin plain settings (Table 1). However, Jackson & Johnson (2009) interpreted that the

Table 1: Sedimentary facies and depositional environment of Temburong Formation as discussed by various authors.

Reference	Locations	Lithofacies/Biofacies	Depositional environment	Age
Abdullah *et al*., 2017	Sipitang-Tenom, West Sabah	shale and sandstone	deep marine environment	Eocene to Early Miocene
Asis *et al*., 2015	Tenom, SW Sabah	fine-grained turbidites Td-Te Bouma sequence, planktonic foraminifera.	basin plain and distal part of submarine fan	Late Oligocene to late Early Miocene
Bakar *et al*., 2017	Labuan, Sabah	siltstone and calcareous pelagic shale units, benthic foraminifera.	deep marine bathyal to abyssal	Late Oligocene to late Early Miocene
Jackson & Johnson, 2009	Labuan, Sabah	debrites and turbidites, Ta to Te Bouma divisions.	lower slope to proximal basin floor	Early Miocene
Jasin & Firdous, 2019	Kampung Bebuluh, Labuan, Sabah	nereites, medium to thin bedded turbidites.	distal and proximal lobes of submarine fan system	
Leong *et al*., 2018a	Weston to Sipitang, SW Sabah	Tc-Te facies and Te facies only	distal lobe, outer fan of deep marine environment, and basin plain facies.	Upper Oligocene to Lower Miocene
Madon, 1997	Layang-Layangan, Labuan	sandstone mudstone interbeds	unstable slope and deep water	

Temburong Formation in Labuan was deposited in lower slope to proximal basin floor environment containing debrites and turbidites (Ta to Te Bouma facies).

Depositional environment

Madon (1997) interpreted the heterolithic clastic units of Temburong Formation exposed in Labuan as deposits of unstable slope and deep marine settings. Recent studies by Bakar *et al*. (2017) on Temburong shales exposed in Labuan area signify that the formation was deposited in deep marine bathyal to abyssal environment. Jasin & Firdaus (2019) currently distinguished that the Temburong Formation exposed in Labuan and Klias areas of West Sabah represents only distal part of submarine fan as it is mudstone dominant (Table 1).

West Crocker Formation

The tertiary sediments of Crocker Range were first named as "Crocker Formation" by Collenette (1957) who defined the formation comprising mainly of sandstone, with alternating siltstone, mudstone and shale. The Crocker sediments encompass graded units, spheroidal concretions poorly sorted and steeply dipping clastic units, having significant thickness of sediments reaches up to 6000 metres (Crevello, 2002; Hall & Nicols, 2002).

Submarine fan distribution

Sedimentology of the West Crocker Formation was discussed by Zakaria *et al.* (2013a; 2013b) and Mohamed *et al.* (2016) from outcrop sections North of Kota Kinabalu city to Tuaran, NW Sabah and some locations in SW Sabah. They classified the formation into sand dominated, sand and mud mixed, and mud-dominated lithologies which were deposited in all components of submarine fan corresponding to inner, middle and outer fan environments. However, Leong *et al*. (2018a) discussed the sedimentary facies of the West Crocker Formation as representing only the middle and outer fan facies in Weston-Sipitang areas of SW Sabah. Bakar *et al*. (2008a) described the formation as thin beds of sandstone, siltstone and shale which denote the levee-interchannel of deep marine environment (Table 2).

Types of deep marine sediments

Bakar *et al*. (2008b) construed that the West Crocker Formation in Inanam, Kota Kinabalu is mainly muddy and massive debrites in channel and slump facies. Zakaria *et al.* (2013a), Jackson *et al*. (2009) and Shafie & Madon (2008) stated a variety of deep marine Paleogene deposits including turbidites, debrites, co-genetic turbidite debrite (CGTD) and linked debrite facies in the West Crocker Formation which had been developed in a non-channelized and unconfined distal part of submarine fan. Abdullah *et al*. (2017) explained the West Crocker Formation having slump deposits in the Sipitang area of SW Sabah. The outcrops from NW Sabah also contain high-density turbidites, debrites, and slump facies of channelized and non-channelized lobes (Zakaria *et al*., 2013b). These slump deposits are also present in the West Crocker Formation near Telipok, NW Sabah (Figure 3). Mass Transport Deposits (MTD) with small scale sediment deformation termed "contorted layers" (Shanmugam, 2016; Shanmugam *et al*., 1995) are also present in Kawang outcrop near Papar in SW Sabah (Figure 4).

Sedimentary facies and processes

Tjia (2015) worked on outcrop sections exposed in Kaung village near Mount Kinabalu and assigned bathyal to abyssal depths for Crocker sandstone of Eocene to Early Miocene age. However, William *et al*. (2003) and Lambiase

Figure 3: Slump folding of mass transport deposits (MTD) in deep marine sedimentary successions present in the West Crocker Formation near Telipok, NW Sabah. The argillaceous strata stratigraphically present above and below the slump fold shows no sign of deformation which indicates the depositional nature of folding. The fine-grained sand and shale units are representing the distal part of the Crocker submarine fan.

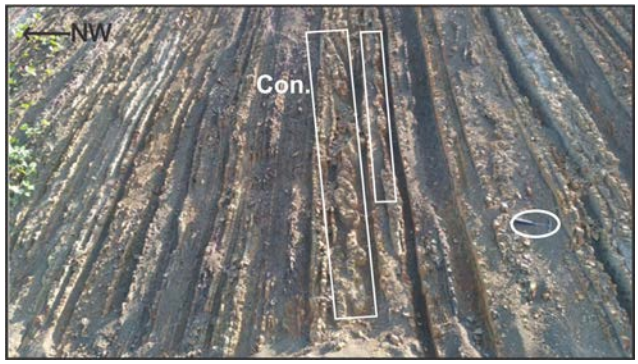

Figure 4: Deep marine mass transport deposits (MTD) are present in the West Crocker Formation in Kampung Kawang section, SW Sabah. As illustrated by contorted layers (labelled as Con. in figure) with a hammer of 28cm in length (white circle) for scale. The vertical thin units of fine sand and silt surrounding the contorted layers don't have any deformation

Table 2: Sedimentary structures, lithofacies, depositional settings and provenance of West Crocker Formation as reported by several authors.

Reference	Methodology & locations	Sedimentary facies	Sedimentary structures &Texture	Architecture elements	Depositional environment/type of flow	Provenance/age
Bakar *et al.*, 2008a	ichnofacies, Kota Kinabalu	heterolithic beds of shale with few interbeds of thin bedded sandstone and siltstone	horizontal grazing traces, several crawling and fecal casting.	leeve-interchannel	zoophycos and nereites ichnofossil groups present in the sediments represent deep marine environment (benthic)	
Bakar *et al.*, 2008b	field studies around Kingfisher Sulaman outcrop, Kota Kinabalu, and Inanam	muddy and massive debrites, poorly sorted, structureless and amalgamated.	load-cast, mud-clasts, flame structures, plant fragments, intraformational rip-up clasts.	large blocks of massive debrites floating in muddy matrix (slump) and fining and thinning upward trend (channel)	submarine debris flow, deep ocean currents.	sediments were deposited in tectonically active areas, deformation, uplift and erosion of Rajang fold and thrust belt during Oligocene-Early Miocene were related to opening of South China Sea resulting in deposition of West Crocker Formation.
Jackson *et al.*, 2009	Kingfisher, Taman Viewpoint, Low Kawi, NW Sabah.	mud poor massive sandstone turbidites which gradationally changes into debrite as moving upward succession termed as linked debrite.	water escape sheets, flute marks, current ripple lamination, climbing ripple, planar-parallel lamination, clastic injections.	linked debrites are commonly developed in non-channelized part of fan system while they are less in proximal channel levee and distal plain facies	single flow event having two phases: fully turbulent flow phase creating turbidites and weakly turbulent to laminar-debris flow developing debrites, high density turbidites.	West Crocker Formation of Oligocene to Early Miocene
Lambiase *et al.*, 2008	Bukit Melinsung, Jalan Sulaman, Maju around Kota Kinabalu.	three sedimentary facies: thick sandstones, interbedded sandstone with shale and shale facies.	thick sandstones: coarse sandstone having load structures, massive base with parallel lamination, convolute bedding, amalgamated units. flute casts, climbing ripples, shale: fine to silty sand, ripple cross lamination, immature texture, poorly sorted, angular to subangular	progradational lobes due to thickening and coarsening upward succession	High density turbidity currents, Ta, Tb, Td: Ta and Td, Ta and Tc, Ta and Te or just Ta, West Crocker Fm. mostly deposited in deep water depositional system having depth more than 1000m, rare trace fossils are cruziana and nereites.	mostly subarkose with some sublitharenite sandstone. Provenance of first-cycle product of an eroded orogenic belt. samples contain more feldspar and lithics. Age of entire formation could be variable. Eocene to Oligocene age based on foraminiferal and palynological studies.

Table 2: Sedimentary structures, lithofacies, depositional settings and provenance of West Crocker Formation as reported by several authors (continued).

Leong *et al.*, 2018a	Weston-Sipitang areas, SW of Sabah. facies analysis and facies association studies for renewed stratigraphy		cross lamination, parallel lamination.	middle fan: channel facies (Ta), channel-levee (Td). channel (Ta)-Lobe (Tb). lobe-lobe migration (Tb-Tc) outer fan: distal lobe and migration lobe (Tc with cross lamination)	Ta to Te. high density turbidite, deep marine environment, rare trace fossils and no microfossils found in the study area.	Early Miocene aged Crocker Formation
Mohamed *et al.*, 2016	Tuaran area, North Kota Kinabalu, NW Sabah.	sand dominated facies, mixed sand and mud facies and mudstone facies.	flute casts, ripple cross lamination, convolute lamination, parallel lamination, false bedding.	Inner fan: channel- levee complex, middle fan: channel- lobes, outer fan: distal lobe	low density turbidity currents, high density turbidity currents, debrite facies, deep-water sequence.	Oligocene to Early Miocene age of West Crocker Fm.
Roy *et al.*, 2015	NW Sabah	thick massive sandstone facies, amalgamated sandstone, fine grained poorly sorted sandstone, medium to coarse grained.	flute casts, convolute lamination, ripple lamination, rare cross stratification, floating mud-clasts, escape or dish structures, sand injections.		laminar to weakly turbulent flows (massive sand, structureless and fine grained), high density turbidity currents (fluid escape structures), debris facies (mud-clasts), linked turbidite-debrites (sand injections) and slump facies.	
Shafie & Madoon, 2008	Inanam, Sepangar, Kota Kinabalu, NW Sabah,	amalgamation, poorly sorted, massive sands.	scour, dewatering and soft sediment structures (convolute laminae), load structures, floating mud-clasts, rip-up clasts, clast injections.		mostly high density turbidite (thick bedded), debrite-turbidite couplet, muddy debrite facies. deep water depositional system.	Oligocene-Miocene
Tjia, 2015	Kota Kinabalu, and Kaung village, Mount Kinabalu		sole marks, groove casts, flute casts, load casts, spiral grove casts, drag casts, chevron casts.		bathyal abyssal depth of deposition, trace fossils including nereites zoophycos.	Eocene to Early Miocene age of Crocker formation,
Tongkul, 2015	Kawang, South of Kota Kinabalu, West Sabah	mudstones with thin sandstone interbeds			slope instabilities, debrites, deep water succession.	Oligocene West Crocker

Table 2: Sedimentary structures, lithofacies, depositional settings and provenance of West Crocker Formation as reported by several authors (continued).

van Hattum *et al.*, 2013	provenance, heavy mineral analysis of onshore samples of western Sabah		the first-cycle Crocker sandstones with muddy matrix have immature texture are less rounded, poorly sorted.			most of Crocker sediments were sourced from recycled orogen, based on nannofossils, the Crocker Formation was assigned the age of Late Oligocene.
William *et al.*, 2003	Jalan Sulaiman and Bukit Melinsung outcrops, Kota Kinbalu western Sabah	coarse to very coarse sand, amalgamated thick sandstone units, massive (rapid deposition), interbedded sandstone and shale.	load structure and rare tool marks, flute marks, parallel lamination, ripple cross lamination, climbing ripples, texturally immature, poorly sorted, mostly angular to subangular grains.	sand sheets (constant bed thickness) and small lobes unconfined (thickening and coarsening upward), no evidence of channeling.	high density turbidites, Mostly Ta, Tb and Td, Ta and Td, Ta and Tc, Ta and Te or just Ta Te. Slope apron depositional settings, common trace fossils nereites and paleophycos cruziana ichnofacies	sourced from nearby Rajang Group sediments, in response to initial phase of uplift that form Deep Regional Unconformity (DRU), compositions of sandstone are subarkose and sublitharenite and litharenites, first cycle product of orogenic belt.
Zakaria, 2013a	Kota Kinabalu SW Sabah, Taman View, Lok Kawi, Inanam.	sand dominated, thick bedded, massive, amalgamated, fine to coarse grained, medium to thick bedded sandstone, dominated by channelized and non-channelized lobes of basin floor depositional settings.	dewatering structures (Ta), flute marks, parallel lamination (Tb), current ripple lamination, tool marks, convolute lamination, climbing current ripples (Tc), ripple cross lamination, sand and mud injections, poorly sorted.	inner fan: channel- levee complex (thinning and fining upward succession), middle fan: channelized lobes (coarsening upward and overlain by fining upward succession), non-channelized lobes (coarsening upward), outer fan: distal lobes (mudstone facies)	high (thick bedded and amalgamated) to low density (very fine to medium grained thin bedded) turbidites, co-genetic turbidite- debrite (mudstone facies), debris flow or MTD (ungraded, massive chaotic beds, muddy debrites), Ta only, Ta, Tb, and Tc, Tc and Td.	structureless sandstone deposited in tectonically active and structurally controlled basin, paleocurrent data shows direction SW (proximal) to NE (distal) trend.
Zakaria *et al.*, 2013b	13 locations around Kota Kinabalu, NW Sabah.	sand rich sedimentary units, massive and amalgamated facies, overlain by fining upward laminated mudstone, thin sandstone units.	parallel laminations, fluid escape structures, clastic injections, rare convolute laminations.	channelized lobes, non-channelized lobes, distal lobes.	mostly high-density turbidity currents, debris flow deposits, slump deposits.	Oligocene age

et al. (2008) proposed that the outcrops of the West Crocker Formation around Kota Kinabalu city contain dominantly high-density turbidites (partial Bouma divisions) developed in bathyal depths only. Recent studies by Leong *et al.* (2018a) described both higher flow regime (Ta-Tc Bouma facies) and lower flow regime (Tc/d-Te Bouma divisions) in the West Crocker Formation (Table 2).

Bakar *et al*. (2008a) worked on trace fossils present in the West Crocker Formation that are majorly argillaceous shale interbedded with siltstone and sand representing the levee-inter-channel environment of deposition. The field studies on the West Crocker outcrops around Kota Kinabalu city contain massive debrite and slump facies (Bakar *et al*., 2008b). The outcrops sections in NW Sabah studied by Shafie & Madon (2008), Jackson *et al*. (2009) and Roy *et al*. (2015) described linked debrites, proximal channel and distal plain facies revealing both high-density flow and low-density flow processes in the formation. Lambiase *et al.* (2008) stated individual partial Bouma sequences in the West Crocker Formation (Table 2).

In SW Sabah, only middle to outer fan facies are present in the West Crocker fan system (Leong *et al*., 2018a); while the formation in the NW Sabah inner, middle and outer fan facies were interpreted (Mohamed *et al*., 2016). The debrites and slope instabilities in Kawang, Sabah were reported by Tongkul (2015) for the West Crocker Formation. Thick bedded, amalgamated, debrites, slump units are stated by Zakaria *et al*. (2013a) which are also representatives of inner, middle and outer fans (Table 2).

Provenance

William *et al*. (2003) discussed the provenance of West Crocker sediments was essentially the earlier deposited Rajang Group which was uplifted and eroded and re-deposited as the Late Paleogene sediments. Composition of the West Crocker sediments suggested that they are first cycle product of orogenic belt and are immature, poorly sorted angular to subangular grains which are symbolic for short distance transport of sediments. Lambiase *et al*. (2008) suggested that the West Crocker sediments are mainly subarkose and some are sub-litharenite having more content of lithic fragments and feldspar. Hall *et al.* (2008) found abundant plutonic quartz and K-feldspar and lithics in composition which are texturally angular to subangular, poorly sorted, and muddy matrix clasts in the Crocker Formation. A little abrasion of heavy minerals and unabraded abundant zircons and tourmalines demonstrating that the Crocker sediments are first-cycle sandstone and had relatively closed source rock and henceforth unlikely to be related with distant sediment source material.

van Hattum *et al*. (2006) found composition of the Crocker sandstones encompass more plutonic quartz, less metamorphic quartz and rare volcanic quartz which are compositionally immature. Major heavy minerals include euhedral and subhedral zircon and tourmaline which specified the provenance of Crocker sediments was fresh granitic source and ophiolitic basement of Borneo not from India-Asia collision or Indochina. Bakar *et al*. (2008b) suggested that the West Crocker sediments were deposited in tectonically active area where deformation uplift and erosion of the Rajang Group resulted in deposition of the West Crocker Formation.

Hall *et al*. (2008) also proposed that local sources were responsible for deposition of the Crocker fan from Eocene to Early Miocene and no evidence exists regarding the provenance of sediments from distant sources and therefore, there is no contribution from collision of India -Asia in deposition of the Crocker submarine fan system. Later, van Hattum *et al*. (2013) stated that the content of heavy minerals has abundant zircon and tourmaline which are chemically stable whereas volcanic materials are rarely present in the Crocker sediments. The provenance of the Crocker sands by QFL ternary plots and immature texture of siliciclastic materials suggest that the Crocker sands have recycled orogen provenance (Table 2).

STRATIGRAPHIC FRAMEWORK

The stratigraphy of Late Paleogene formations has been studied for many decades and numerous scientific developments are starting to enhance the understanding of the stratigraphy of West Sabah area. In the present work, the focus of the review is to discuss the uncertainties related to stratigraphic positions of the West Crocker and Temburong formations and the related unconformities which are present in the literature.

Unconformities

Rajang Unconformity (RU)

Hall & Breitfeld (2017) assigned the term Rajang Unconformity (RU) for the stratigraphic unconformable contact between Sapulut and Trusmadi formations. The age of this unconformity ranges between 45 to 40 million year ago which is close to Middle to Late Eocene times. This is the oldest defined unconformity within Paleogene sediments of West Sabah.

Although the Trusmadi Formation is older than the Crocker Formation yet the stratigraphic contact between Trusmadi and Crocker formations is often not marked with unconformity (Hall, 2013; Hall & Breitfeld, 2017). Hence, there exists a conformable contact between Trusmadi and Crocker sediments.

Late Eocene Unconformity (LEU)

The contact between East Crocker and (West) Crocker is marked by an unconformity (Leong, 1999). However, there is a debate regarding the stratigraphic position of the unconformity. The unconformable surface separating the East and West Crocker may range from Middle Eocene (Leong, 1999) to Late Eocene (Jackson *et al*., 2009). The term Late Eocene Unconformity (LEU) is used to mark the contact

between East Crocker and West Crocker formations. The estimated geological time for this stratigraphic unconformity is about 34 million years ago (Jackson *et al*., 2009). The LEU is younger and marks the lower contact or base of the West Crocker Formation.

Top Crocker Unconformity (TCU) or Base Miocene Unconformity (BMU)

Top Crocker Unconformity (TCU) often refers to the upper contact of the Temburong and West Crocker / Crocker formations. This unconformity was assigned the age of Early Miocene (Hall & Brietfeld, 2017). Prior to this, Jackson *et al*. (2009) proposed the term Base Miocene Unconformity (BMU) for upper contact of the West Crocker and Temburong formations which is stratigraphically equivalent to Top Crocker Unconformity (TCU) (Lunt, 2019).

Deep Regional Unconformity (DRU)

The initial literature marked the Deep Regional Unconformity (DRU) as the upper contact of West Crocker Formation (Levell, 1987; Hutchison, 2005). However, recent scientific work stated that the DRU only marks the upper contact of Setap Shale (Jackson *et al*., 2009; Hall, 2013; van Hattum *et al*., 2013). Hence the DRU is relatively younger than it was previously thought. The unconformity separates the deep marine sediments from the younger shallow marine to fluvial strata. The DRU is often placed above the Setap Shale and is usually assigned the age of Middle Miocene (Hall & Breitfeld, 2017).

Stratigraphic contacts of West Crocker/ Temburong formations

Early Paleogene Trusmadi Formation is separated from Late Paleogene West Crocker Formation by LEU while the upper contact of Late Paleogene is marked by BMU (Jackson *et al*., 2009). Hutchison (2005) stated that the West Crocker Formation is bounded DRU at the top of the formation. Hall (2013) placed the DRU at the top of Setap Shale while upper contact of Crocker Formation is marked by TCU. Both Crocker and Temburong formations were truncated by TCU as proposed by van Hattum *et al.* (2013). However, Jackson *et al*. (2009) marked the lower contact of the West Crocker Formation with LEU and the BMU designated as the upper contact of the West Crocker Formation (Figure 5).

Temburong Formation was deposited from Early Oligocene to Early Miocene (Hutchison, 2000; Lambiase *et al.*, 2008). However, Asis *et al*. (2015) designated the

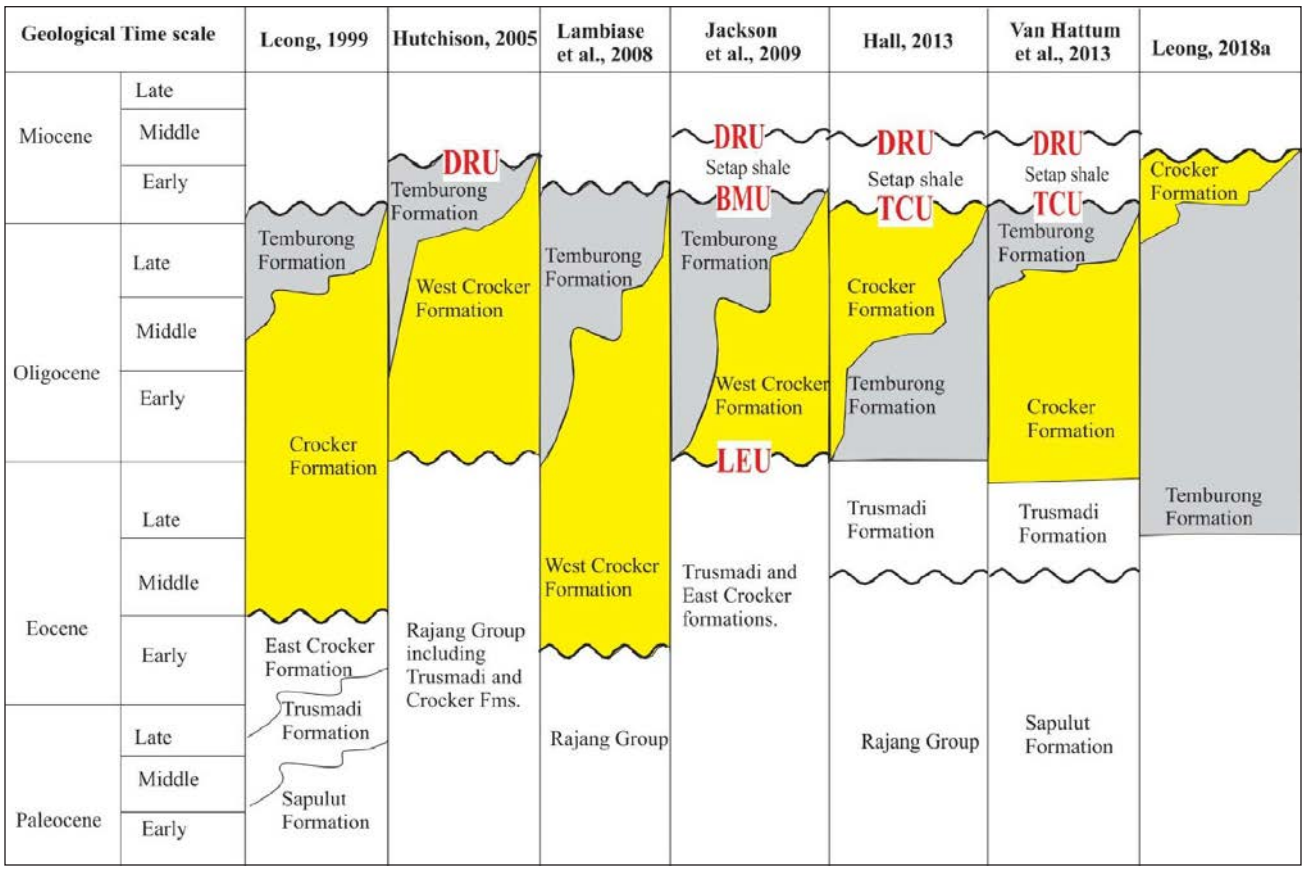

Figure 5: Brief summary of Paleogene stratigraphy of West Sabah as proposed by the referenced authors. The stratigraphic positions of West Crocker Formation and Temburong Formation are still under discussion with various unconformities reported like Deep Regional Unconformity (DRU), Late Eocene Unconformity (LEU), Base Miocene Unconformity (BMU), and Top Crocker Unconformity (TCU).

age of Temburong shales from Late Oligocene and extends up to late Early Miocene. Recent studies by Leong *et al*. (2018a) recommended the age of Temburong Formation start from Late Eocene which is older than formerly stated. More work by Leong *et al*. (2018b) suggested that the stratigraphic position of the Temburong Formation lies below the Crocker Formation which was previously thought to be above the Crocker sediments.

Age of West Crocker Formation

Lambiase *et al.* (2008) extended the base of the West Crocker Formation from Middle to Late Eocene (Figure 5) while it was previously thought to be deposited from Early Oligocene times (Hutchison *et al*., 2000). Cullen *et al*. (2012) calculated the age of fine- to medium-grained West Crocker sandstones from paleomagnetic data and assigned a Late Eocene age for the formation in the Kota Kinabalu area. The age of the West Crocker is significantly varied as designated by several authors who had worked in the various localities of West Sabah (see Figure 5).

Subdivisions of Crocker sediments

It is pertinent to mention here that the term "Crocker Formation" is used in literature for both East Crocker and West Crocker formations. Some of the scientific work like Hall (2013) and van Hattum *et al*. (2013) had not differentiated between the East and West Crocker formations. Many authors (Leong, 1999; Hall *et al*., 2013; van Hattum *et al*., 2013; Siddiqui *et al*., 2019; and Leong *et al*., 2018a) use the term Crocker Formation as stratigraphic position of the West Crocker Formation whereas a few authors use the term Crocker for the East Crocker Formation (Hutchison, 2005 and Jackson *et al*., 2009) (Figure 5).

DISCUSSION

Sedimentological characteristics

Sedimentology of the Late Paleogene rocks has been deliberated by various authors in several study areas of West Sabah. These locations also include discussion on sedimentary features and with respect to deep marine fan system. However, the present work collectively illustrates the data at a single podium to highlight the findings and to get a stratigraphic imprint of the West Sabah area. This review serves as a foundation to interrelate the findings of these studies to point out the research gaps for the future work.

The Temburong Formation exhibits the distal lobe and basin plain facies interpreted as the distal part of submarine fan, owing to the presence of fine-grained sand and shale units (Asis *et al*., 2015; Abdullah *et al*., 2017; Leong *et al*., 2018a) while few locations of the formation only has muddy unit representing exclusively the basin plain facies (Leong *et al*., 2018a). However, some locations also suggest the formation located within a slope (Madon, 1997) and proximal basin floor environment (Jackson & Johnson, 2009). Depositional settings of the Temburong Formation therefore significantly vary from unstable slope (Madon, 1997) to the most distal part of submarine fan (Jasin & Firdaus, 2019).

The West Crocker Formation represents the entire elements of a submarine fan system (Zakaria *et al*., 2013a; Mohamed *et al*., 2016) whereas some authors discussed only middle to outer fan facies had been observed in the formation (Leong *et al*., 2018a; Bakar *et al*., 2008a). Various types of mass transport deposits (MTD) including blocks and slabs, slump, slides and finer grained matrix having blocks of irregular sandstone and mudstones floating in it, are also formed the component of the West Crocker Formation (Bakar *et al*., 2008b; Shafie & Madon, 2008; Zakaria *et al*., 2013a; Tongkul, 2015; Abdullah *et al*., 2017). The present study also reveals the presence of contorted layers (a type of mass transport deposit) in the West Crocker Formation.

The provenance of Late Paleogene sediments is believed to be resulted from uplifting and erosion of Early Paleogene successions. Poorly sorted, angular to subangular and compositionally immature siliciclastic sediments are suggestive of first cycle sediments from nearby source material (William *et al*., 2003; Lambiase *et al*., 2008; Hall *et al*., 2008). Abundant plutonic quartz, and potassium feldspar, euhedral to subhedral zircon and tourmaline are indicative of plutonic or acidic source material for Late Paleogene sediments (van Hattum *et al*., 2006; Hall *et al*., 2008). Hence, provenance study of the sediments provided a clear picture of the sediment origin but the facies distributions, types of deep marine sediments and architectural elements of deep marine Paleogene successions of West Sabah are still not completely resolved and not fully understood.

Stratigraphic context

The stratigraphy of Late Paleogene sediments is intricate due to the diverse nomenclature used to discuss the stratigraphic surfaces and unconformities. These stratigraphic divisions are often equivocal due to the scientific terms used by numerous authors for understanding the age and stratigraphic position of the Paleogene formations. The current review is encompassing the stratigraphic vocabulary to highlight the multifaceted stratigraphic terms in the literature related to Paleogene sediments of the West Sabah.

Stratigraphy of Late Paleogene is marked by age-related unconformities like LEU and BMU as proposed by Jackson *et al*. (2009), which were later revised with contacts of the rock formations like TCU. The age of Late Paleogene is not precisely specified, and it varies from Middle Eocene (Lambiase *et al*., 2008) to Early Oligocene (Hutchison, 2005; Jackson *et al*., 2009; Hall, 2013). Furthermore, the upper contact of Late Paleogene is varied from base Miocene or Early Miocene (Jackson *et al*., 2009) to late Early Miocene (Leong *et al*., 2018a).

Since the accurate and precise age of Late Paleogene sediments is still undefined, hence the age-based unconformity terms are less likely to be popular for

describing the stratigraphic positions of unconformities. Moreover, the stratigraphic positions and relative ages of the West Crocker and Temburong formations are still vaguely defined. For example, some authors had positioned West Crocker as older (Lambiase *et al*., 2008; van Hattum *et al*., 2013) in the stratigraphic column, while others argued that the Temburong Formation is older than the West Crocker Formation (Leong *et al*., 2018a). It is therefore critical to work on the stratigraphic unconformities and relative ages of rock formations in order to refine the stratigraphy of Late Paleogene of West Sabah.

LIMITATIONS AND CONSTRAINTS

Field-based sedimentological research is vastly dependant on the quality of outcrop sections exposed in an area which are representative of stratigraphic intervals in a sedimentary basin. Onshore West Sabah area is highly influenced by demanding tropical climate and the resulting dense vegetation (Figure 6) affecting the outcrop coverage. Even a massive sandy unit can certainly be vulnerable to weathering especially in form of frequent rainfalls. Some of the representative outcrop sections which were hitherto presented in the literature are currently less significant for detailed fieldwork due to both physical and chemical weathering effects.

In addition, some of the stratigraphic units of Paleogene formations of West Sabah are mainly shales and siltstones which can be eroded within a very short span of time and highly susceptible to the weathering and climatic effect. Detailed facies and sedimentary features of these incompetent lithologies are frequently diffused and faded away making observation of sedimentary structures and features challenging.

Although Google Earth and Google Maps data are quite helpful in finding the outcrops in West Sabah and map resolution and street view of various features are quite impressive yet some of the locations on the maps are currently no longer feasible for detailed fieldwork. Infrastructure and housing development have frequently altered or removed the topography and field outcrops of the area. It is quite likely that previously mapped outcrop is now completely converted into a housing estate. Hence, it is hardly possible to conduct sedimentary investigations of all previously studied outcrops.

RECOMMENDATIONS FOR FUTURE WORK

This review serves as a foundation for bridging the research gaps and establishing the missing information for a more comprehensive stratigraphic view of the depositional settings of West Sabah. The following research items can be concerted to develop a thoughtful representation of Late Paleogene sedimentary successions of West Sabah:

1. Several outcrops of Late Paleogene sediments had been discussed in literature describing the detailed sedimentary features of stratigraphic formations. Nevertheless, the variation of sedimentological review from South-West Sabah, around Kota Kinabalu city to North-West Sabah should be incorporated to determine the broader configuration of depositional environments and basin settings.
2. Recent literature suggested that a great variety of deep marine sediments are present in Late Paleogene sediments especially in the West Crocker Formation which were previously considered as turbidites only. The current review highlighted the demand to differentiate various types of deep marine deposition which will help us to further refine the constituents of Paleogene submarine fan.
3. New outcrop exposures in West Sabah due to infrastructure development especially the Pan-Borneo Highway has revealed more details for Paleogene sedimentary successions for new scientific investigations (Figure 7).
4. Stratigraphic positions of Temburong and West Crocker formations are still under review to confirm the relative

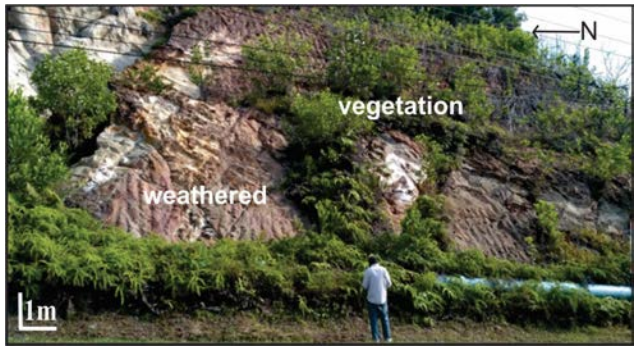

Figure 6: The adverse influence of weathering and vegetation due to tropical climate of Sabah which affects the massive sand units of West Crocker Formation exposed near Jalan Pengalat Lok Kawi, SW Sabah. The brownish stain within the massive sand units is indicative of weathered lithology.

Figure 7: Pan Borneo Highway and other infrastructure developments has positively exposed new outcrops in the West Sabah region. The shown outcrop is located near Kawang village, SW Sabah in which very fine sedimentary units can easily be observed along with mass transport deposits including contorted layers (Con.) and slump events. Also, it can be imagined that the erosion and destruction of argillaceous and incompetent lithology will take place only after few years of tropical climate with dense vegetation.

ages of the formations. This aspect needs to be further investigated and discussed to improve understanding of stratigraphic surfaces and unconformities which are present in the Late Paleogene sedimentary successions.

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