

# Onshore to offshore correlation of northern Borneo; a regional perspective

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**Abstract:** This review combines a wide range of onshore and offshore data from Oligocene to Pliocene sediments of northern Borneo to address the following topics: (i) the stratigraphic conditions before and after the Top Crocker Unconformity [TCU], (ii) Early Miocene palaeogeography, (iii) events during later Early to mid Middle Miocene times, including the Deep Regional Unconformity [DRU], and (iv) the waning of the Sabah Orogeny in Early Pliocene times. Emphasis is placed on dating the key events, in order to consistently identify the stratigraphic and tectonic changes observed in the different data sets.

The data shows a period of uplift and deformation in the north, perhaps focussed in southern Palawan, during the Oligocene then its sudden cessation at the TCU, with strong contrast in both facies and deformation style of Late Oligocene outcrops on the Kudat Peninsula compared to the Early Miocene sediments drilled offshore. This termination of tectonic deformation coincides with published estimates for the onset of ridge-jump and sea-floor spreading in the South China Sea northwest of Sabah. Following this unconformity the deposition of sediments during the Early Miocene appears to have consisted of a fluvio-deltaic high in the south (from central Borneo) and a broad deep marine basin in the north, from west of the Kudat Peninsula to at least the western part of the Sulu Sea. For the subsequent DRU, its timing and character appears to coincide with large scale sedimentary changes in eastern Sabah and this suggests a pause in regional compression during the early part of the long lasting Sabah Orogeny.

The stratigraphic description of these events has important implications in plate tectonic reconstructions for northern Borneo and the South China Sea. The role of subduction on the eastern side of Sabah may be a key component of revised tectonic models and further evaluation of the area from the Dent Peninsula south to the Indonesian border is recommended.

**Keywords:** Sabah, stratigraphy, outcrop, offshore, history, tectonics

## INTRODUCTION

This paper describes onshore and offshore data relating to selected periods of geological change through the Oligocene and Miocene of northwest Borneo. A very wide range of data is available to the authors who have focussed on correlating sedimentary facies at equivalent geological ages, and therefore the dating of sediments is a key part of this review. The field mapping of unconformities and the accompanying facies contrast is used to evaluate the magnitude of change, and also identifying important periods of stasis.

Geographically widespread data is available in sediments as old as those surrounding the Oligo-Miocene Top Crocker Unconformity and as young as the mid-Pliocene, although post Miocene sediments are rarely sampled in exploration wells offshore and have been widely eroded (or never deposited) onshore. This review describes data in roughly chronological order, dealing with widely known unconformable events, before a very preliminary comparison to the current competing tectonic models, known as the plate “extrusion” hypothesis of Tapponnier *et al.* (1982, and later revisions) and the “slab-pull” tectonic model (Hamilton, 1979; Rangin & Silver, 1991; and others).

## Onshore work

Twentieth century fieldwork was generally done by experienced field geologists backed-up with substantial

laboratory facilities. Companies such as Shell carried out onshore mapping projects and also supported the Geological Survey of Malaysia (now Minerals and Geoscience Department) with analyses. For example the 1957 “*Geology of the Crocker Range and Adjoining Areas*” by Bowen & Wright of Shell was a very large and detailed study, including extensive and still usable palaeontological and petrographical analyses. There has been a decline in mapping and in the past two decades onshore work has been undertaken mostly by students with some modern analyses, but lacking the depth of support and experience available to older surveys.

## Offshore work

The oil industry has the long-standing problem that its dominant geological samples are drill-cuttings, and economic considerations now discourage the taking of cores or sidewall cores in exploration wells. As a result of loss of experience in specialist consulting companies (Lunt, 2013), while geological science has advanced, the data available to oil industry explorers has declined over the past few decades, and determining age, correlating sections, determining environment of deposition is not much better now than it was in the 1980’s.

This stasis in geological research is one of the reasons behind the decision to undertake this review and to deliberately use a broad range of data rather than focus and rely on any single discipline.

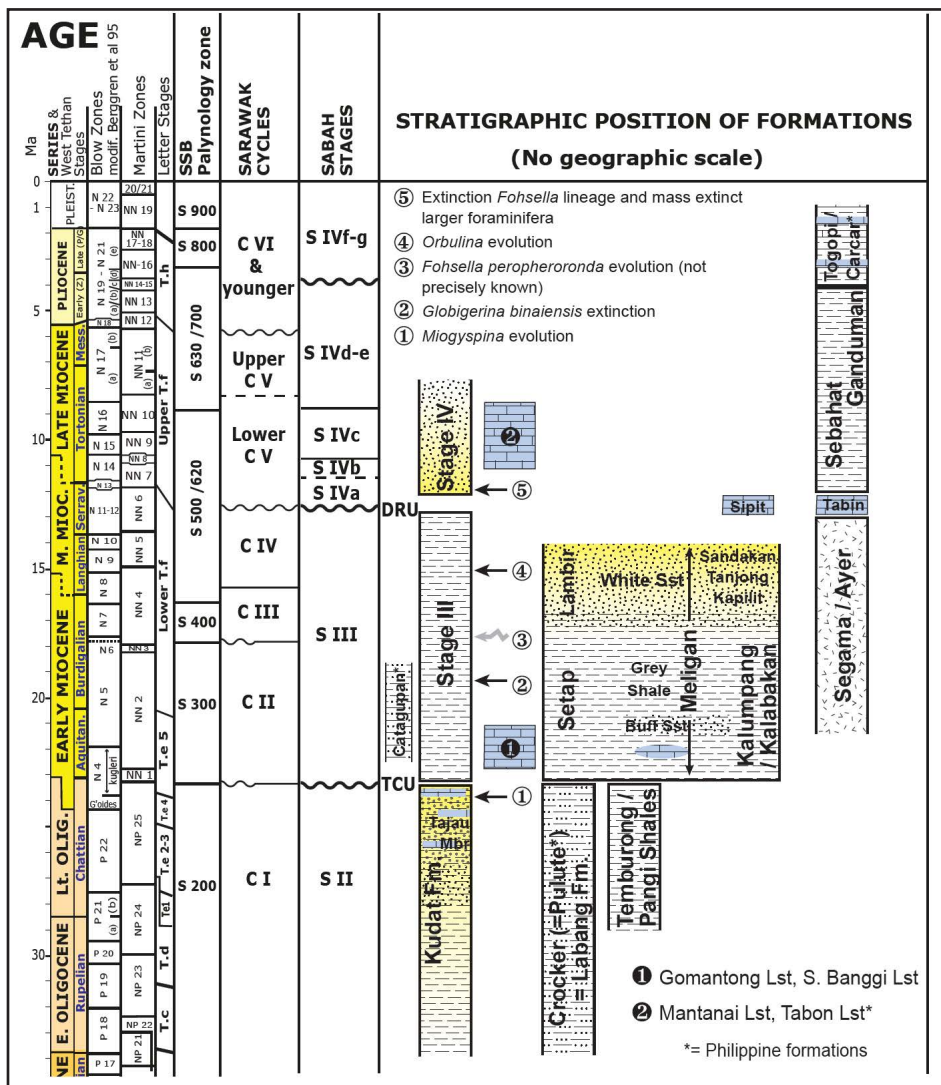
**TOP CROCKER UNCONFORMITY [TCU]**  
**Historical observations of the TCU**

As long ago as 1951 Reinhard & Wenk reported: “*This maximum movement took place between Te4 and Te5. This is the most important Tertiary orogeny of North Borneo*” (their emphasis, p.21 of their report). They had mapped angular divergence between formations with Letter Stage Te1-4 and Te5 microfossils (Figure 1) in the area around Labuk Bay, at Tangkulap in S. Milian and in S. Pinanga (Figure 2). The definition of the Te4 to Te5 boundary has not changed since 1951 and is still the reliable evolution datum of *Miogypsina* near the base of the Miocene, approximately 24 Ma (van Gorsel *et al.*, 2014).

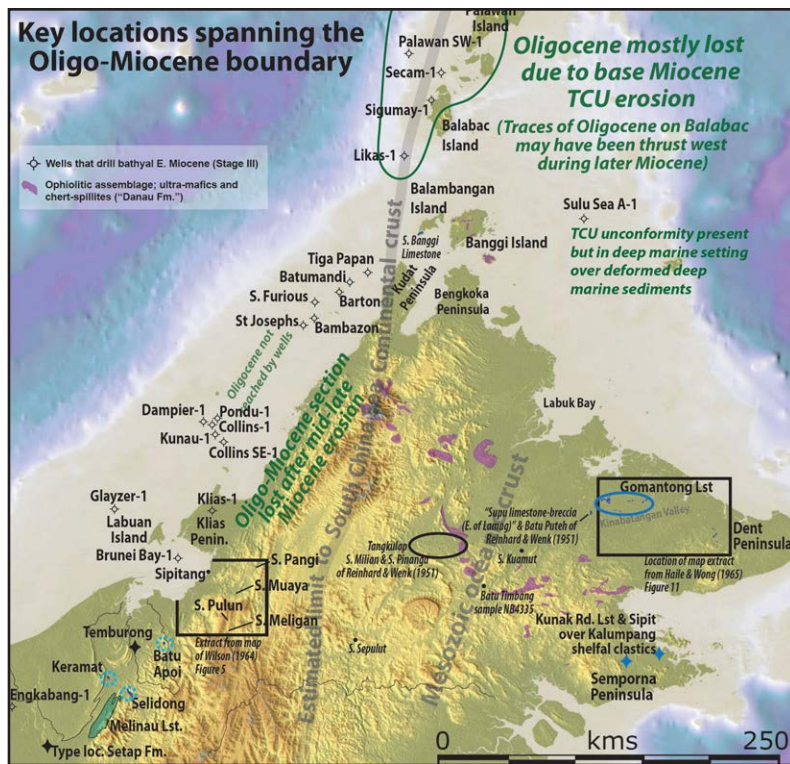
The detailed work of Bowen & Wright (1957) also reported that in west Sabah “*There is indirect evidence for unconformity within the Te succession, the lower shaley Te1-4 [latest Oligocene] being generally steeply dipping while the higher sandstone succession is generally more gently folded. ... Steeply dipping Te1-4 limestones (S. Pangi) probably predate the unconformity [and] the flat Te5 [early Miocene] limestones of S. Pulun*” (locations on Figure 2). The pre-unconformity Pangl Shales were later re-named the

Temburong Formation by Brondijk (1962), and the defining character of the Oligocene Temburong was that it was much more folded than the unconformably overlying Setap Shale that was as old as Te5. This unconformity was given the name “Top Crocker Unconformity” by Hall *et al.* (2008) although a senior name is Base Meligan Unconformity (see below). There is also frequent reference in oil company reports (e.g. Hageman *et al.*, 1987) to a “Base Miocene Unconformity” but this is an undefined term, used more in Sarawak than Sabah, although probably the same as the TCU.

On modern time scales the Te4 to Te5 boundary is dated as close to a number of events that have been used to define the Oligo-Miocene boundary. Figure 1 summarises the stratigraphic scheme and the various datums and boundaries around the Oligo-Miocene boundary. Planktonic foraminiferal datums and numerical ages used here are calibrated to Wade *et al.* (2011), nannofossils to Ogg & Ogg (2006). Historically the *Globigerinoides* datum and the Te4 to Te5 boundary have been used in SE Asia as proxies for base Miocene, in open marine and shallow marine facies respectively (e.g. multiple Robertson Research and Core-laboratory consulting reports).



**Figure 1:** Simplified summary of the stratigraphic units discussed.



**Figure 2:** Map showing locations relating to the top Crocker Unconformity. The location of the Wilson 1964 map in Figure 4 is marked as a rectangle, as is the extract from Haile & Wong (1965) in Figure 10. The location Batu Timbang is where Collette photographed deep bathyal to abyssal *Paleodictyon* in a mudstone with traces of transported Te1-4 (Late Oligocene) larger foraminifera.

### The regional extent of the TCU

The most well-known fieldwork on the TCU is in western Sabah, on Labuan Island, the Klias Peninsula, and the Temburong River in eastern Brunei (Figure 2) where it was described by Brondijk (1962). This coastal area faces the extinct spreading centre of the South China Sea, which was the site of active drift after the "ridge jump" of sea-floor spreading expanded from an area north of Palawan to include this zone orthogonal to Sabah and Brunei. The age of onset of this orthogonal plate spreading was about 25 Ma (Barckhausen *et al.*, 2014 - between anomalies 6b and 7, so some time between about 23.5 and 25 Ma) or 23.6 Ma (Li *et al.*, 2014). This coincidence of ages, for the single largest change in plate-movement and the single largest stratigraphic event in outcrops, during an approximately eight to ten million year period, implies a plate tectonic cause for the TCU. However, the onset of plate drift seems to have terminated deformation in NW Borneo rather than have started it. The age dating therefore indicates that the onset of drift terminated the stress that had previously been deforming northwest Sabah and southern Palawan.

In north-central Sabah, the TCU is also recognised as occurring after a major deformation and uplift event. Haile & Wong (1965) and McMonagle *et al.* (2011) describe the Gomantong Limestone (Figures 1 & 11) as being about 300 m thick and biohermal, occurring as outliers at about eight separate outcrops scattered within an area about 30 km east to west and 10 km north to south (cf. Figure 11). It unconformably overlies the very deep marine Labang Formation which contains the environmental index fossils *Bathysiphon*, *Cyclammia*, *Glomospira*, *Pullenia*, *Sphaeroidina*, *Laticarinina*, *Uvigerina*, *Gyroidina* and others

(Collette, 1965; Haile & Wong, 1965), as well as the bathyal to abyssal trace fossil *Paleodictyon* in sediments of the same age but at a location about 100 km southwest of Gomantong (Figure 2, illustrated in Collette, op.cit, Plate XV). At Gomantong, Haile & Wong (1965) noted the gently, westerly dipping limestone was bounded in the east by steeply dipping mudstones and calcarenite sandstones of the Labang Formation and they interpreted, but did not directly observe, an angular unconformity between the Te5 limestones and the Te1-4 Labang clastics.

McMonagle *et al.* (2011) used nannofossils, strontium dating and transported larger foraminifera to date the top of the Labang Formation around Gomantong as mid Oligocene (30.8 – 27.6 Ma, Te1, with nannofossils suggesting some samples as young as within NP25; slightly younger than 27.2 Ma), and the absence of any Te2-3 or Te4 latest Oligocene below the Gomantong Limestone. Multiple samples from the Gomantong Limestone were all Te5 in age (topmost sample arguably basal Tf on negative evidence), and strontium dating on a single sample dated as 20.97 Ma (McMonagle *et al.*, 2011). The absence of Te4 in the lowest limestone samples suggests the onset of reefal facies deposition was within lowest Te5.

Other sections crossing the Oligo-Miocene boundary are rare but about 200 km north of Gomantong there is the Sulu Sea A-1 well (Beddoes, 1976). This well drilled to an intermediate depth of 7000 ft, and set casing, and it was at about this depth that the proxy for base Middle Miocene, the evolution datum of *Orbulina*, was recorded. Drilling on through the Early Miocene, the very distinct form *Globigerina binaiensis* appeared at 7470 feet, indicating penetration of sediments deposited within older Early

Miocene (extinction datum at 19.4 Ma). Benthic faunas through this section are dominated by bathyal taxa.

At 8100 feet the well reached what both the early 1970s and modern seismic image shown as “acoustic basement”. At this depth the Sulu Sea A-1 well had originally been expected to reach igneous or metamorphic basement, but instead drilled into mudstones with elevated pore-pressures that forced termination of drilling at 8586 feet. The mudstones in the “acoustic basement” contained *Paragloborotalia* cf. *opima* (*opima* s.s. extinct at 27.5 Ma) and, around the seismic boundary - between 8000' and 8210' - there was the basal occurrence of *Florschuetzia semilobata* and the dominance of *F. trilobata* in the pollen record below, which approximates the top of the Oligocene (cf. van Gorsel *et al.*, 2014). The lack of seismic reflectors in “acoustic basement” (which continues over at least three thousand square kilometres around this site, see map in Beddoes, 1976) and elevated pore pressures are consistent with a formation that has been strongly folded and uplifted (Sulu Sea A-1 data also in CCOP document XII/46, and unpublished well reports).

All this data shows that a unique geological change, unlike anything that had occurred for at least five million years before or after, happened close to the Oligo-Miocene boundary over an area at least 300 km west to east and 200 km north to south (most of the area shown in Figure 2). Before the unconformity there was compression as well as deformation of widespread deep marine deposits (the Crocker and Labang formations), locally with considerable uplift; sufficient to allow reef growth.

### The Kudat problem in NW Borneo

Records on the TCU can be found in the northwest of the study area, in the Kudat Peninsula, the northern end of the Western Cordillera, and wells just offshore (Figure 2). Unfortunately the outcrops are of Late Oligocene age and the wells offshore reach early Early Miocene but not Oligocene sediments (with the possible exception of the 1954 Klias-1, but on which little data is available). However, these sediments, from either side of the age of the TCU, strongly contrast in both facies and degree of deformation, and this contrast fits the model established in the other areas.

The type Kudat Formation is Late Oligocene in age (Te1-4 foraminifera with some characteristic Eocene reworking, Liechti, 1960, the characteristic presence of reworking will be discussed later). Some reports (van Hattum *et al.*, 2013) have claimed a basal Miocene age for the Kudat Formation based on Clement & Keij (1958), but this old report does not claim a Miocene age, as defined on modern time scales. Clement & Keij (1958) have 26 of their samples containing Te 1-4 larger foraminifera faunas, eight with *Miogypsinoidea* (Te4) and only two other samples had the Te5 defining *Miogypsina*. Only three samples contained scarce planktonic foraminifera including the genus “*Globigerinoides*”, which on modern time scales is recognised to have evolved at the base of N4, near base Miocene (Figure 1). However in 1958 the taxon “*Globigerinoides*” included members of what would now be placed in *Catapsydrax* [ranges entire Oligocene and most

of the Early Miocene] and *Globigerinatheca* [ranges Middle and Late Eocene], and on pages 31 and 32 of Clement & Keij (1958) they clearly included in their “*Globigerinoides*” these two species with much longer, and older ranges. The stratigraphic nomenclature in the 1950's and 1960's mapping reports correlated the observed Letter Stage Te1-4 to an old concept of “Early Miocene” (see page XIV of Stephens, 1956, on Kudat), whereas now the same marker fossils and the Te1-4 Letter Stages are unequivocally placed in the Late Oligocene (Figure 1).

Since the mapping of Stephens (1956), the traverses of Clement & Keij (1958), mapping by Wilson (1961) and the synthesis of Liechti (1960), the later Oligocene sediments in the far north, around the Kudat Peninsula have been noted by all these workers to differ from the Crocker / Labang “flysch” formations found over the rest of west Sabah. The Kudat Formation sediments are usually sand-rich, making this formation locally hard to date, especially in the coarsely sandy upper part of the Kudat (the Tajau Sandstone Member, in the uppermost part of which, or on which, the Te5 limestone samples were recorded) which was interpreted as proximal debris flows and storm beds by van Hattum *et al.* (2013). The Kudat Formation is considered by all these authors to be a strongly regressive unit, when no regression was seen in the widespread Crocker Formation. This upper part also includes frequent thin, carbonaceous-rich beds, also the sands are often cross-bedded and there are calcareous cements, nodules and calcarenite sands with larger foraminifera (Stephens, 1956; Clement & Keij, 1958; Liechti, 1960). While modern sedimentological work is limited their overall character makes them distinct from the Crocker “flysch”, which lacks calcareous material and has rhythmically bedded, typically thin sands, with exclusively non-calcareous arenaceous microfauna. As noted above, near the upper part of the Kudat Formation, and also immediately overlying it, there are shallow marine limestones that are not found to the south (South Banggi Formation, Wilson, 1961).

The confusion regarding the identity of the Kudat Formation, was compounded when wells were drilled offshore through the major Deep Regional Unconformity [discussed below] and into deep marine, clay-dominated, beds (called Stage III by Sabah Shell; van Hoorn, 1977) which some oil company geologists thought were equivalent to the onshore Kudat Formation. These Stage III clastics in the wells were even named “Kudat Formation” by several operators (e.g. BP in their 1982 Batumandi and Tigapapan wells) but were positively dated as Early Miocene in these wells, using planktonic foraminifera and nannofossils. In multiple wells the so-called “Kudat” is always much younger than the type Kudat Formation, with most including sections younger than the extinction datum of *Globigerina binaiensis* (<19.4 Ma). Several wells drilled to sections older than the *G. binaiensis* extinction datum (Tigapapan-1, Dampier-1 and others) and are therefore as old as about the top of Letter Stage Te5. Bambazon-2 reportedly reached the basal Miocene *G. kugleri* (see Figure 1, most of Zone N4) which is basal Miocene, within Te5. Dampier-1 and

Collins-1 have species of the genus *Fohsella* in the highest Stage III mudstone, indicating an age as young as about 14-13 Ma (lower Middle Miocene). There is none of the regressive character of the type Kudat Formation and for this and other reasons given below it is very unlikely that these deep marine claystones are a diachronous extension of the onshore Kudat Formation.

Onshore the type Kudat Formation has very poor faunas in the mudstones. Analyses by Carigali-BP (in Frank, 1981) found no significant plankton (either foraminifera or nannofossils) in the mudstones, and only rare benthic *Haplophragmoides* / *Trochammina*, *Valvulina*, *Bathysiphon* and *Cyclammina* deep water arenaceous forms in the lower, muddier, part. The older work by Clement & Keij (1958) also found these bathyal arenaceous faunas and an absence of calcareous smaller foraminifera in the lower beds. Sand interbeds (increasing up-section) were the defining character of the Kudat Formation, as well as transported beds of larger foraminifera in calcarenite sands, along with reworked fragments of radiolarian chert, spilite pillow lavas and other old rock fragments. Analyses of the larger foraminifera by the specialist van der Vlerk for Clement & Keij found Te1-4 faunas with rare instances of Te5 in the uppermost part (upper Tajau Sandstone Member). The Te5 species were the transitional *Miogypsina* aff. *?Miogypsina primitiva* (see p. 30 of Clement & Keij for discussion). Adams (1980) also observed this dominance of Te 1-4 markers, including the Oligocene marker *Heterostegina* s.s., also locally with Late Eocene Tb reworking. He also recorded a sample with Te5 *Miogypsina* (from the same location where it was recorded by Clement & Keij, but independently also noted the single specimen to have "primitive-looking lateral chambers") suggesting the unconformity that is proposed to be the upper boundary to the Kudat Fm. is within lowest Te5 rather than exactly on the Te4-5 biostratigraphic datum.

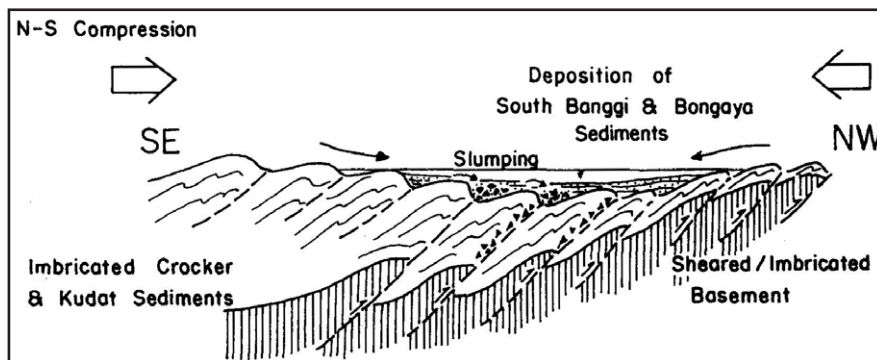
Offshore in wells, in the so-called "Kudat Fm.", planktonic and smaller benthic microfossils are common in the dominant claystone facies, transported larger foraminifera extremely rare, stratigraphically reworked foraminifera and interbedded limestone stringers are not present, and sands are very rare. This so-called "Kudat Fm." or Stage III beds were drilled as thick as 371 m in Batumandi-1 and these drilled sections contain almost no bedded sands at the decimetre scale of wireline log resolution.

In about 20 wells drilling Stage III or so-called "Kudat Fm." offshore, only the Collins-1, South Furious-5, and far to the south the Brunei Bay-1, have bedded sands thick enough to be resolved on wireline logs. Another important difference is that the offshore Stage III drilling has dipmeter logs recording low angle structural dips (typically 20 degrees or less) from the WNW to ESE compression of the mid Miocene Sabah Orogeny (see annotation on Figure 4). This contrasts with field-mapped structural dips and dipping reverse faults in the Kudat Peninsula which are often steep and dominantly down to the south or south-southwest, as also reflected by the topographic structural lineation following the strike produced by N-S compression (Figure 3, also Tongkul, 1994; 2006).

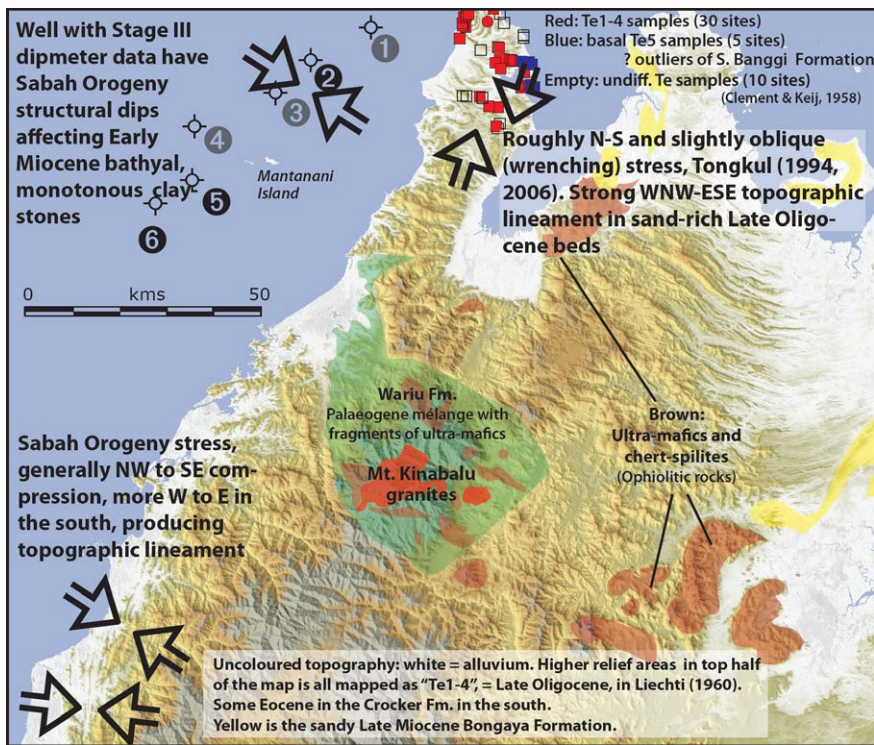
Palaeocurrent analysis by Tongkul (1994, his Figure 4), van Hattum (2005) and van Hattum *et al.* (2006) indicates the Kudat Fm. clastics were sourced from the north, the opposite direction to the flow in the Crocker Formation. Liechti (1960), Wilson (1961), and more recently van Hattum (2005), van Hattum *et al.* (2006), Hall *et al.* (2008) and Suggate & Hall (2013) have noted the sands in the Kudat Formation have a different petrology and heavy mineral provenance to the sands of the Crocker Formation.

The onshore type Kudat Formation and the Stage III beds differ in almost every aspect ranging from age, to lithofacies, environment of deposition and the presence / absence of stratigraphically reworked material, and particularly the absence of strong north to south compression in all the younger beds offshore. This offshore, Early to base Middle Miocene, deep marine sedimentary unit, is therefore concluded to have been incorrectly attributed to the Kudat Formation. It is concluded that the TCU is the event that separates these two stratigraphic packages, and that they are equivalent to the Early Miocene Setap Shale Formation that unconformably overlying the Oligocene Temburong Formation in the south (Brondijk, 1962).

Tongkul (1994; 2006) divided the deformation history around the Kudat Peninsula into four phases: an older, probably Eocene deformation of the Chert-Spilite oceanic basement into tight folds, then two parts to the deformation of the overlying Crocker and Kudat formations. He recognised uplift in the north in early or mid Oligocene times that triggered deposition of the Kudat Formation under new conditions that made it petrographically and



**Figure 3:** Section across northern Sabah and into the Kudat Peninsula (Tongkul, 1994) at the time of the deposition of the Te5 (basal Miocene) South Banggi Formation. The imbricated Te1-4, *?basal* Te5, Kudat sediments in the northwest includes common marine sands, interpreted as shallow marine by Stephens (1956) and Liechti (1960), and some limestone facies not found in the deep marine, flysch, Crocker Formation to the south.



**Figure 4:** Deformation of Late Oligocene and Early Miocene beds. (1), (3) and (4) wells with no reliable structural dip data in monotonous claystones. (2) Batumandi-1 has 371m of Stage III, Zone NN4-?NN3 Early Miocene bathyal claystones with structural dips typically 10 degrees down due east. (5) Bambazon-2 has 48m of Stage III bathyal claystone, basal Miocene *Globorotalia kugleri* zone, dips 25° down to WNW. (6) St Josephs-9st has 49m bathyal claystone dated as end of the Early Miocene, N8 to N9 boundary, dips 35° to SE. At the top of the map are the palaeontology results from Clement & Keij (1958) with their samples of Te1-4 age in red (30 locations) plus 5 sites in 2 clusters near Kudat of transitional Te5 markers, see text for discussion.

sedimentologically distinct from the Crocker Formation. This was followed by latest Oligocene compression to produce tight folds and thrusting, with fault planes dipping to the south. The TCU event does not crop out and Tongkul was unaware of the contrasting Stage III sediments offshore. However he did note the small outcrops of basal Miocene (Te5) South Banggi Formation limestone on Balambangan Island just north of Kudat (Figure 2), has an angular disconformity to the more severely deformed Kudat beds nearby. The South Banggi Formation is therefore considered a product of transgression over the TCU like the Gomantong Limestone in central Sabah. All these strata were more gently deformed by Tongkul's fourth deformation period in about mid Miocene times, which is related to the Sabah Orogeny described below.

**The TCU in southwest Sabah**

South of the Kudat Peninsula the Late Oligocene part of the deep marine Crocker Formation lacks the varied lithofacies of the Kudat Formation, with its increasing sand content and calcareous nature up section (Liechti, 1960), but in southwest Sabah a mud-rich facies of the Crocker, named the Temburong Formation contains slumped olistoliths as well as stratigraphically reworked microfossils and lithic-clastics, features which have been noted since the work of Bowen & Wright (1957). The degree of reworking diminished to the south and also stopped at the event of the TCU.

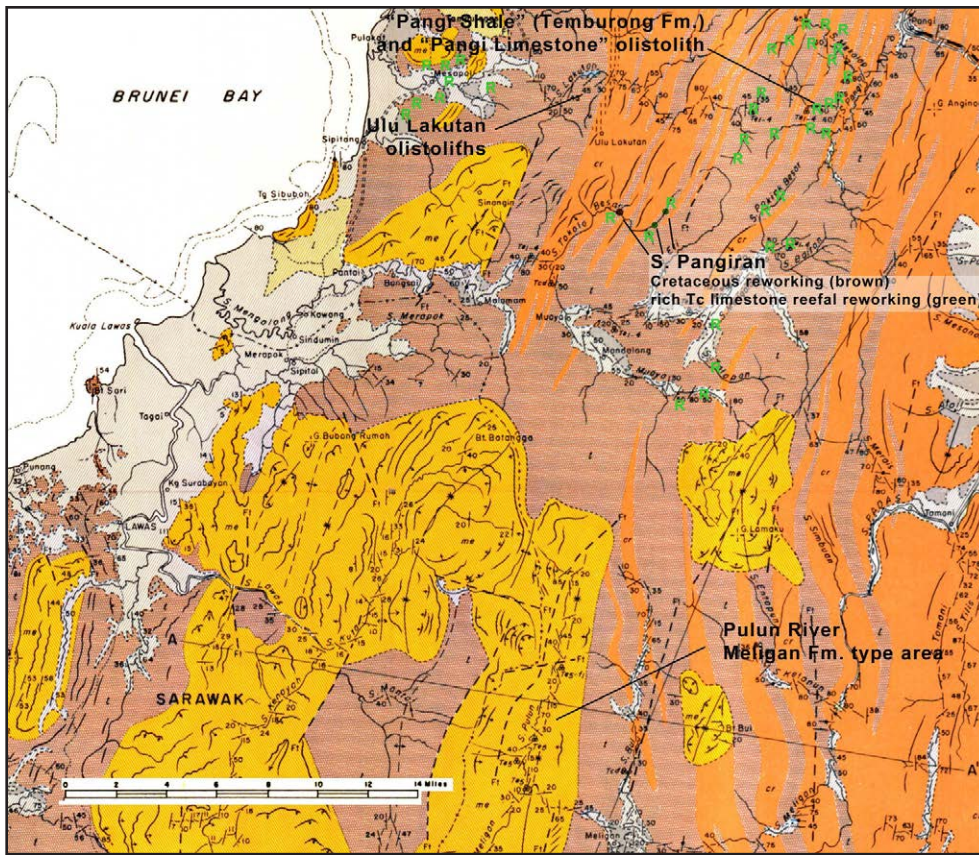
The area outlined in the SW on Figure 5, enlarged as Figure 5 was studied by Wilson (1964) who found several large, stratigraphically *in-situ* olistoliths within massive Temburong shale in the Melikut River about 2 miles from its confluence with the Pangli River [called the Pangli

Limestone], also at three places within a mile of each other in Ulu Lakutan, and the Batu Apoi Limestone. These all contain Te2 to Te4 index fossils in Late Oligocene Temburong beds. An important character of the Temburong / Crocker beds in the more northern area around Pangli was the presence of common stratigraphically reworked Cretaceous, Paleocene, Eocene and even a few Early Oligocene microfossils (Bowen & Wright, 1957; their data shown on Figure 5, samples with stratigraphic reworking noted as "R" in green). A section over about 2½ kilometres of the Sungai Pengiran have Late Oligocene mudstones [Te1-4 age] containing rich Early Oligocene Nummulitic limestone reworking. Also in this river three locations have Late Cretaceous Globotruncanid faunas reworked - a significant feature considering the lack of known Late Cretaceous sedimentary outcrops anywhere in northwest Borneo outcrops or wells.

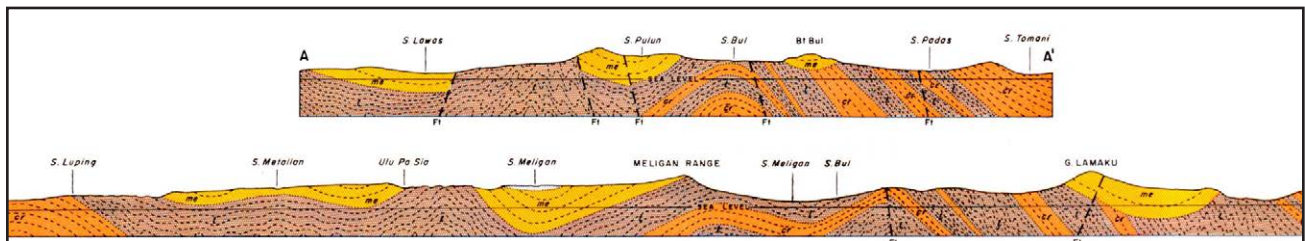
The abundance of stratigraphic reworking (as opposed to clasts simply transported or slumped downslope) in the northern Pangli district contrasts with other densely sampled Te1-4 locations to the south below the Meligan Formation, where Late Oligocene deep marine facies lack stratigraphically reworked fossils or lithoclasts. Bowen & Wright noted that this reworking rapidly diminished south of Sungai Muaya and deduced that the source of the reworked material could not have come far, as clasts were often large and angular, and that they thought could not have come through the southern route (as generally indicated by palaeocurrents in the more sandy Crocker Fm.) because the stratigraphic reworking was so scarce in that area.

**Effects of the TCU in south Palawan**

Three deep wells offshore south Palawan (Figure 2) drilled the Crocker equivalent "Pulute Formation"; the



**Figure 5:** The Pangi District. Map from Wilson, 1964, with sites from Bowen & Wright superimposed: “R” in green where there are late Oligocene beds with reworking. Brown dots are sites with Cretaceous reworking, two of which have abundant E. Oligocene limestone reworking. Cross sections A-A’ and the un-labeled perpendicular section marked are shown on the following figure.



**Figure 6:** The cross-section of Wilson, 1964, showing the base Meligan Unconformity. Location A-A’ is marked on Figure 5. The lower section is the line perpendicular (N-S) crossing A-A’ marked but un-labeled. At this scale it is not clear if the base Meligan unconformity is at the base of the formation as a whole (=TCU) or a second event near the base of the topographically prominent White Sandstone Member.

Likas-1 (1979), Secam-1 (1979) and Sigumay-1 (1980). The first and last of these have summaries in Hinz *et al.* (1986). Sigumay-1 was drilled on the coast of Balabac Island (off the south of Palawan), and Secam-1 drilled just a short distance offshore to the northwest, and both penetrated an upper unit that was correlated to the Early Miocene Catagupan Member outcropping on Balabac Island (Basco, 1964).

This outcropping and drilled Early Miocene formation consists of mudstones and lesser sands containing basal (Te5) Miocene index fossils “*Globigerinoides ?primordius*” and *Globoquadrina dehiscens*, *Miogypsina* and *Eulepidina*, along with coal fragments and molluscs not noted in the underlying formations. On Balabac Island these Miocene beds are underlain by a Late Oligocene unit that is similar to the sandy Kudat Formation but not the Crocker / Temburong flysch. They are calcareous mudstones and sandstones with calcarenite limestone interbeds (Basco, 1964). These are dated by a rich assemblage of *Eulepidina* and early forms

of *Lepidocyclina* (*Nephrolepidina*), with *Spiroclypeus* s.l. in its upper part, indicating Late Oligocene Letter stages Te2-4. As with many other locations in western Sabah, Eocene larger foraminifera are noted to be reworked into the Late Oligocene.

In the wells offshore the Late Oligocene is missing, due to erosion by the TCU, and the Early Miocene directly overlies Eocene “Pulute” flysch, dated on planktonic foraminifera. The Likas-1 well to the south and close to the border with Malaysia, drilled through Paleocene to Eocene flysch, above which is a major compound unconformity overlain by the later Miocene and shallow marine Tabon Limestone.

### Summary of the TCU

The sum of all these observations shows that the Late Oligocene around western and central Sabah and the southwestern Sulu Sea was a time of compression, with uplift

in the north. This uplift was probably most severe around what is now southern Palawan, where some offshore well locations have had the entire Oligocene section removed. The end of this compression coincided with the onset of sea-floor spreading in the SW arm of the South China Sea (Barckhausen *et al.*, 2014 and Li *et al.*, 2014). This does not fit the model that has Proto-South China Sea oceanic crust subducting under NW Borneo as the driving force for plate movement in the modern South China Sea. This slab-pull model would require the onset of drift on the Oligo-Miocene boundary to be associated with accelerated compression around the new subduction zone, and the onset or acceleration of accretionary wedge deformation, and also for such deformation to be aligned along a NNE to SSW striking zone, not the north to south directed, north to south diminishing, and W-E striking, compression seen in the Oligocene sediments.

### EVENTS OF THE LATEST EARLY TO MID MIDDLE MIOCENE

As noted in the previous section, the senior term Base Meligan Unconformity is abandoned in favour of the term Top Crocker Unconformity (Hall *et al.*, 2008), for the event on the Oligo-Miocene boundary, as examination of outcrop data from the Meligan area suggests two separate unconformities might be present below the White Sand Member that is the most obvious and most widely mapped part of the Meligan Formation.

The type Meligan Formation was well sampled and studied by Bowen & Wright (1957), summarised in Liechti (1960), and mapped again by Wilson in 1964. Little modern work has been done in this remote location.

The deposition of this formation began after the TCU including the local marker of the Te5 Pulun Limestone, and then about 1000 m of Buff Sandstone Member, followed by 2000 m of mudstone called the Grey Shale (these two being lateral equivalents to the Setap Shale, see Figures 1 and 7). On top of the Grey Shale Member is about 2000 m of the White Sandstone Member. The sands throughout the Meligan Formation are quartzose (lacking lithic clasts or reworked fossils), fine to medium grained, and coarse grained in the White Sandstone Member where the sands are “cross-bedded and ripple marked” and contain “abundant plant remains”.

There is ambiguity regarding the Meligan Formation and the stratigraphic position of unconformities, unlike the clear Setap to Temburong [TCU] contrast to the west. Bowen & Wright (1957) thought they could see conglomeratic sandstones at the base of the Meligan succession and an angular bedding change. However in 1964 Wilson was less certain about the angularity contrast in the field traverses but Plate XXX of Wilson, and the cross section reproduced here (Figure 6), showed the white sandstone of the Meligan Formation resting unconformably on folded Temburong Formation. Wilson (1964, p. 91) noted that this unconformity was easily recognised on air-photographs.

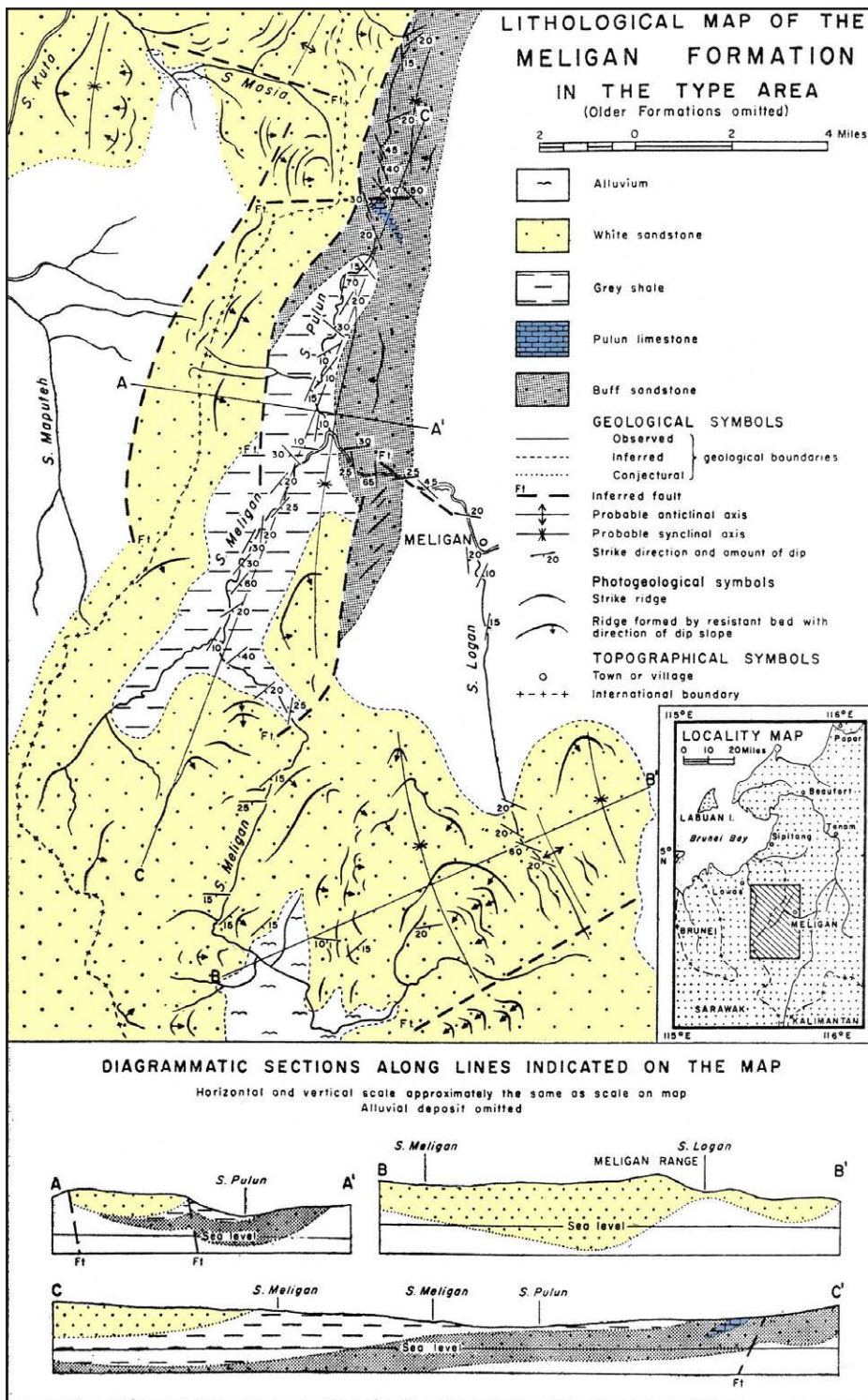
An unconformity therefore seems to be present, but its precise stratigraphic position on the ground is not clear, and it

has been assumed to the TCU defined to the west and dated as below the Te5 Pulun Limestone. However the TCU may not be the only unconformity, and a second event may be present below the White Sandstone Member in the middle to upper part of the Meligan Formation. The local mapping and cross-section of the type section (Figure 7) seems to suggest a second unconformity between the ridges of the hard White Sandstone and underlying muddier members.

The Ulu Pulun section in the type Meligan Formation area was summarised in Bowen & Wright (1957, redrawn as Figure 8 here). It is significant that the Te5 Pulun limestone [containing both *Miogyopsina* and *Eulepidina*] is underlain by deep marine (bathyal) mudstones that have no Miocene markers, but all mudstone samples above the limestone and within the Buff Sandstone are bathyal deposits and have Miocene planktonic taxa such as *Globigerinoides* and “*Globorotalia fohsi barisanensis*” (now *Fohsella peripheroronda*). Even though it is rare, the presence of any planktonic foraminiferal species with a rudimentary angular to keeled periphery would indicate an age younger than roughly 17½ Ma, within N6 (cf. Bolli & Saunders, 1985). In spite of the sand content there is no significant difference in environment of deposition between the Temburong and lower Meligan samples, just an increase in transported material that probably includes an olistolith or calcarenite debris flow of the Pulun limestone itself (cf. Liechti, 1960). However there is considerable shift in environment of deposition and lithofacies between the upper Buff Sandstone and the overlying White Sandstone, with an inner neritic to estuarine facies, and this is indicative of uplift or rapidly accelerated sediment fill, and therefore possibly a major sequence boundary.

The age of the White Sandstone Member is not clear. It contains few fossils even in the claystone beds, but when fauna is present it is mostly *Ammobaculites*, *Hormosina* and *Trochammina* species indicative of a brackish environment (Wilson, 1964). In the Ulu Basio syncline, on the eastern side of the Meligan outcrops there are bedded coals at Bukit Rimau, with interbedded clastic sediments containing the same brackish water fauna (Liechti, 1960). From the age data in the underlying clays, the White Sandstone is no older than later Early Miocene age, in which case it might directly correlate to the Lambir Formation in the area around Miri that is the first major sand over the Setap Shales (Liechti, 1960). It is also a similar age and facies to the sandy Tanjong / Kapilit Formations about 80 km to the east in Sabah (Collenette, 1965, location on Figure 9). These quartzose fluvio-deltaic units have multiple mudstone samples in the Pinangah River with Early Miocene planktonic faunas (*Globigerinoides*, *Globoquadrina altispira*, *Paragloborotalia mayeri*, but no *Orbulina*) and interbedded limestones at Batu Sinobang with larger foraminifera including the Early Miocene *Miogyopsinoides* and *Austrorillina* (Collenette, 1965). The Tanjong and Meligan Formations are significant as both regress into delta-top facies (with coals, including the now abandoned coal mine at Silimponon in SE Sabah), which were the first widespread shallow marine sediments in





**Figure 7:** Map of the Type location of the Meligan Formation (Wilson, 1964). Note that on this sketch (bottom left, and supported by the form of the mapped outcrops) there is angularity between the White Sandstone or upper Meligan and the Buff Sandstone or lower Meligan; an intra-Meligan unconformity supported by regional data and suggesting that the “Base Meligan Unconformity” of these early workers might be a compound unconformity, from two phases of tectonic movement.

northern Borneo. This northwards progradation of clastics seems to have been accelerated by an intra Early Miocene uplift in central Borneo.

This uplift was recognised on seismic geometries and facies in well samples from offshore Sarawak wells. The palaeogeography / sedimentation maps of Hageman (1987, published in Hutchison, 2005) show that at about the time of their Cycle II to III boundary (shortly before the evolution of *Globigerinoides bisphericus*, or older than about 16½ to 17

Ma on modern scales) the sediment source for the Sarawak basins moved from its long-standing location in the SW to being in the SE (central Borneo). Older parts of the Meligan Formation (Buff Sand and Grey Shale Members) and the Kalabakan Formation below the Tanjong Fm. pre-date this and are widespread deep marine sediments (Collenette, 1965). The progradation of the Meligan White Sand and Tanjong formations seems to coincide with the uplift of central Borneo recognised by the Sarawak workers. This

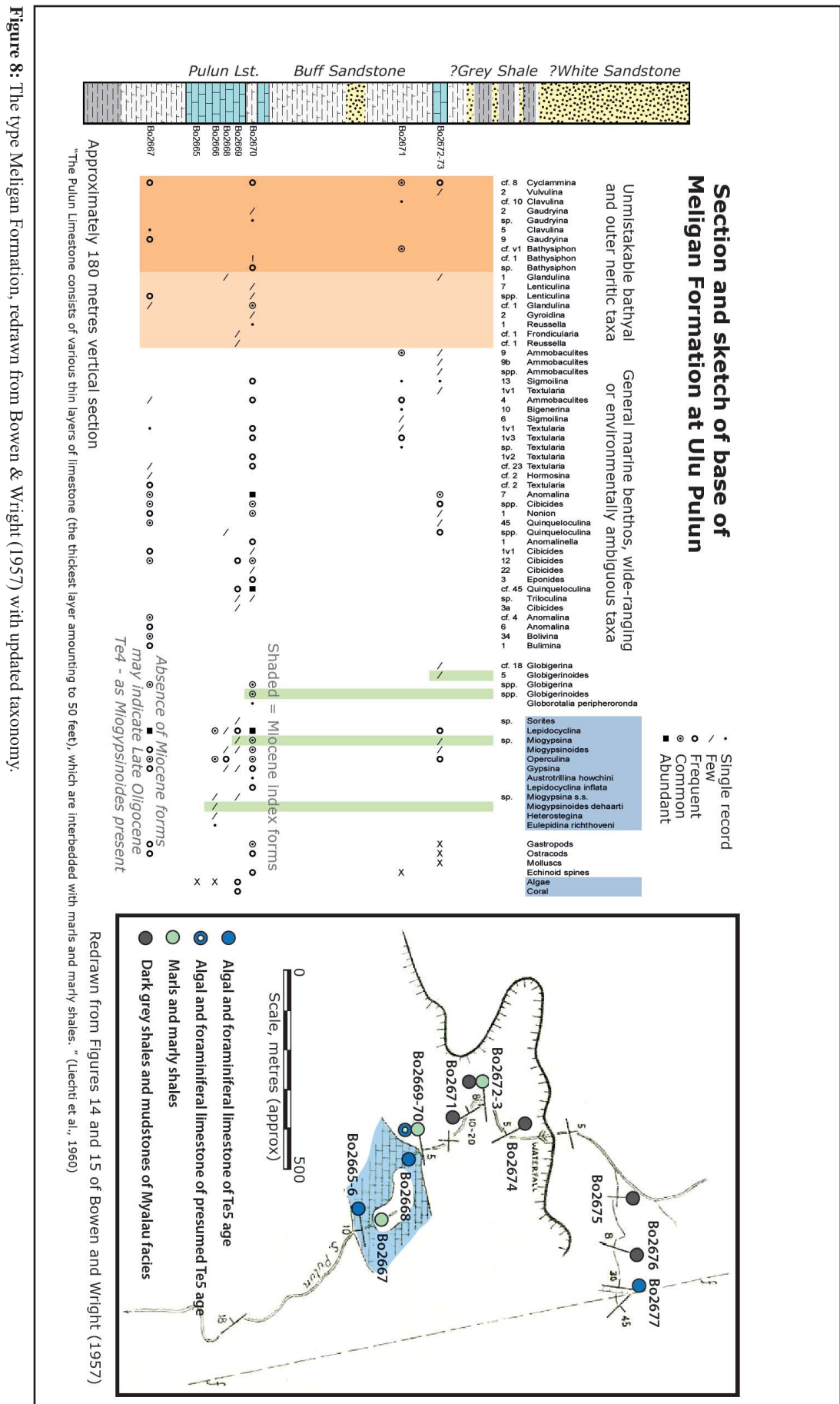
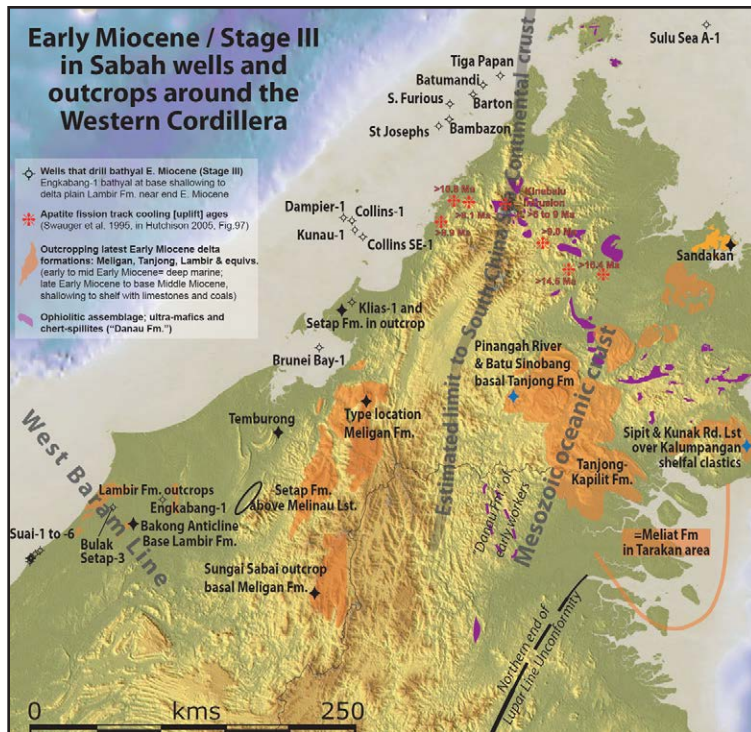


Figure 8: The type Meligan Formation, redrawn from Bowen & Wright (1957) with updated taxonomy.



**Figure 9:** Fluvio-deltaic sands moved into northern Borneo during the latest Early and early Middle Miocene, as a result of uplift in central Borneo. Between the Collins wells and Sulu Sea A-1 are clay dominated deep marine sediments of early Early Miocene to base Middle Miocene age that suggest a broad palaeo-slope from the south where shallow marine to delta plain facies are observed in Early Miocene deposits. Sandakan was a delta front to at least middle neritic marine location within early Middle Miocene times. A postulated N-S accretionary prism interpreted in the area from the type location of the Meligan Formation through NW Sabah and the length of Palawan (e.g. Balaguru & Hall, 2009) is not consistent with the observed facies of this age outcropping and seen in wells.

new sediment supply therefore shed coarse siliciclastics northwestwards into what is now the offshore Sarawak area, and northwards into the depocenter of central Sabah, and eventually (basal Middle Miocene) even as far north as the Sandakan Formation near the town of that name (Lee, 1967; Ujie, 1970).

This uplift in Central Borneo in mid to later Early Miocene times is significant in palaeogeographic reconstructions because the progradation of a fluvio-deltaic apron stretching from the Lambir Formation in the west, including the widespread Meligan Formation and Tanjong / Kapilit Formations in the east, correlates to the Stage III deep marine, sand-poor claystone deposition in offshore NW Sabah wells, as well as the Sulu A-1 in the west Sulu Sea (a broad swath in the area north of the equally wide Meligan and Tanjong outcrops). These sections cover at least the time from before the evolution of *Globigerina binaiensis* (19.4 Ma) to after the evolution of *Fohsella peripheroronda* (after 17½ Ma). Therefore for a period of about 4 to 5 Ma there must have been a wide, south to north descending, palaeo-slope from near coastal settings down to fully bathyal environments. This is contrary to the slab-pull tectonic model that requires a Proto-South China Sea oceanic plate subducting under Sabah at this time. The reconstruction of Balaguru & Hall (2009, Figure 4) shows this alternative interpretation, which does not fit the clay-dominated, distal, deep marine facies observed in the offshore Kudat Stage III and Sulu Sea A-1 wells, and the extensive delta plain deposits at Meligan to Tajong, Kapilit, Meliat and eventually Sandakan (Figure 9).

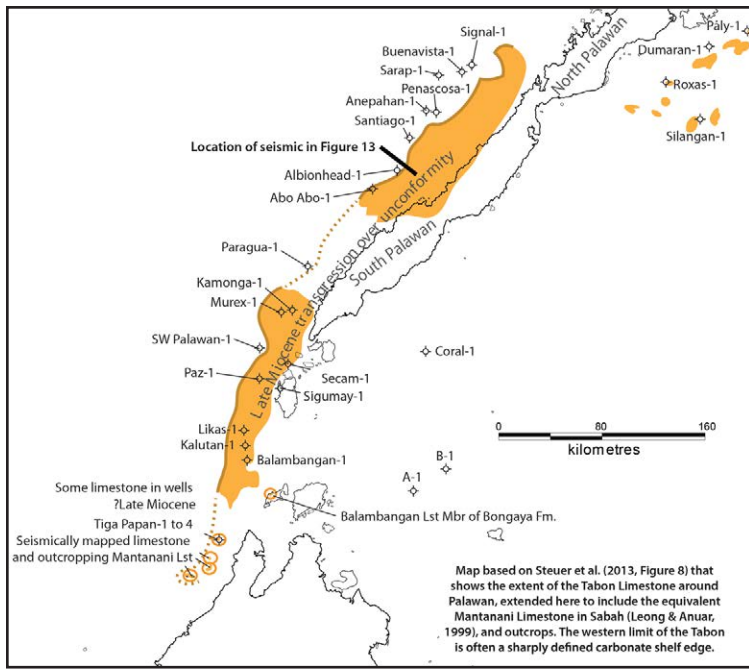
### ONSET OF THE SABAH OROGENY

In the later Early to base Middle Miocene times there was renewed uplift under west Sabah and Palawan Island;

the start of a process that was named the Sabah Orogeny (Hutchison, 1996). Although there had been hinterland uplift in central Borneo (described above), the first uplift along the elongate Western Cordillera to Palawan Island trend of the Sabah Orogeny is argued to have been in latest Early Miocene times. Note that this is at about the same time as the Sarawak Cycle III to IV boundary and the rapid rifting extension of the Bunguran Trough in west Sarawak at c. 16 Ma (Lunt & Madon, 2017).

Fission track data (Swauger *et al.*, 1995, unpublished but detailed in Hutchison, 2005) in NW Sabah shows significant uplift and the associated cooling that re-sets fission track ages, had begun before basal Middle Miocene times. The two oldest cooling ages being 14.5 and 16.4 Ma both  $\pm 1.9$  Ma, in Oligocene sandstones (red symbols on Figure 9).

The effects of the uplift of Palawan is observed in wells offshore in the west. These include Albionhead-1, Murex-1, Kamonga-1, Paragua-1, Likas-1 and SW Palawan-1 (Figure 10) which have the first appearance of reworking of distinct Cretaceous and Palaeogene microfossils beginning in latest Early Miocene times (Hinz *et al.*, 1986), indicating exposure of buried strata (although this does imply very fast exhumation of older beds, or a slightly older onset of uplift). The last named well also drilled into a tectonically induced mélangé or olistostrome facies sampled by a core within Zone N8 (*Globigerinoides sicanus* and *Praeorbulina* markers). A similar core of “pebbly mudstone debris flow” in a bathyal setting, was deposited close to the evolution datum of *Orbulina* (base N9, c 15.1 Ma) in Tiga Papan-3 (location 1 in Figure 4). Van Hoorn (1977) noted chaotic dipmeter data in the latest Early to base Middle Miocene South Furious wells during Stage III (location 3 in Figure 4) which he interpreted as a “contorted unit of slumps and



**Figure 10:** Map of the latest Middle and early Late Miocene limestones that transgressed over the Deep Regional Unconformity. The location of the seismic line in Figure 14 is shown, and there are similar seismic lines over the Tabon carbonate shelf edge in Steuer *et al.* (2013).

mudflows”. These olistotrome or mass transport deposits [MTDs] are seen on modern seismic offshore Palawan, and dated by correlation to the mentioned wells. This was a new phase of sedimentation as now MTD units can be recognised on seismic before these. The basal and middle Early Miocene deposits are typically low-energy clastics with a planar, well-bedded, seismic character.

Barckhausen & Roeser (2004) and Barckhausen *et al.* (2014) suggested that spreading in the South China Sea ended at about 20.5 Ma, while others see evidence for plate drift as late as 16 or even 15 Ma (Briaies *et al.*, 1993; Huchon *et al.*, 2001; Li *et al.*, 2014 - see Table 1 of the latter reference for a compilation of estimates of ages by various workers). The outcrop and well geology, discussed above, indicates that from about 24 or 25 Ma to about 17 or 16 Ma there was stratigraphic stasis in the location where a trench and wedge should have been actively forming (the onshore west Sabah to Palawan zone), but it was only after about 16 Ma that there were signs of uplift along this trend. This uplift, the earliest onset of the Sabah Orogeny, therefore cannot be related to any plate drift in the South China Sea.

### THE EVENT OF THE DEEP REGIONAL UNCONFORMITY

Since it was described and dated by Levell (1987, following van Hoorn, 1977; unpublished) it has been assumed that the Deep Regional Unconformity [DRU] was an outstanding event in the geological history of Sabah and southern Palawan. Levell, and many others after him (e.g. Hutchison, 2004; Hall, 2013), thought the DRU was, by the nature of its outstanding magnitude, the unconformity associated with the end of sea-floor spreading in the South China Sea. This report suggests a modified view; that uplift had begun in latest Early Miocene times and was paused by the DRU event, but the uplift (the Sabah Orogeny)

then resumed to continue forming the Western Cordillera mountains of Sabah and the island of Palawan. The pause left a distinct seismic discontinuity, but the Sabah Orogeny was a longer compressive phase lasting throughout the Middle and Late Miocene (Levell, 1987). This means there is a need to find a cause for the whole Sabah Orogeny, and a separate explanation for the DRU interruption. The following account will look at the events around the time of the DRU, based on well and outcrop data.

On Levell’s seismic data the DRU covered an area of 3000 sq. kms, and he concluded that “it is regarded as the major break in basin history”... “The angular unconformity has been dated by 19 exploration or appraisal wells and is closely constrained to occur within the *Globorotalia peripheroacuta* zone, i.e. early Middle Miocene”. The *G. peripheroacuta* zone was established by Blow (1969) and later became renamed N10 in his 1979 scheme, and is the short interval from the evolution datum [FAD] of *F. peripheroacuta* to FAD *F. fohsi*, and the “*G. fohsi* Zone”, or 14.23 to 13.34 Ma on modern time scales.

Van Hoorn (1977) documented wells that drilled through the DRU in Sabah and described the now famous, major facies contrast between shallow marine to littoral beds in Stage IV above the DRU and deep marine clastics of varying Early to base Middle Miocene ages below. Wells such as Dampier-1 contained the *Fohsella fohsi* and *F. peripheroronda* markers below the unconformity but lower coastal plain facies with rare *Paragloborotalia mayeri* and *Globigerinoides subquadratus* markers above [extinct at 10.5 & 11.5 Ma respectively]. Collins-1 and Ponde-1 had *F. peripheroacuta* below the event and several other wells had *F. peripheroronda* below the event. In the west (above a seismically diminished DRU) the more distal Glayzer-1 has the *Fohsella lobata / robusta* forms recorded for several hundred feet above the DRU, in a middle neritic facies. On

modern time scales this dates the DRU horizon as older than 11.7 Ma and younger than 13.34 Ma, with the record from Dampier-1 indicating the event to be slightly younger than the age summarised in Levell (1987). The relationship of this distal horizon to the time of onset and offset of tectonic events in the focus zone of the unconformity are of course not addressed by this “peak” age date.

The extinction of the genus *Fohsella* at the top of Zone N11/12 was also at almost the same time as the mass-extinction of larger foraminifera that is Top Lower Tf Letter Stage (van Gorsel *et al.*, 2014; Lunt & Allan, 2004; Figure 1 here). The importance of stressing these clear biostratigraphic markers is that both the Deep Regional Unconformity and the age of other regional events are well constrained, and old reports can be used reliably to identify facies changes of this age over a wide area.

A further demonstration of the dating of the Sabah DRU as within Zone N11/12, within the equivalent NN6 nannofossil zone and close to the top of Lower Tf, is in the area from Mantanani Island and the Tiga Papan wells (Figure 10). In this area a thin limestone transgressed onto the unconformity surface and now crops out on the island where it is called the Mantanani Limestone. This limestone is described in outcrop by Idris & Kok (1990) as an epi-reefal carbonate mixed with minor sandy clastics. Idris and Kok noted that the Mantanani Limestone was a unique carbonate in a clastic-dominated area, thus justifying a distinct formation name. It is at least a hundred meters thick. Apart from coral, coralline algae and molluscs these authors give a brief summary of foraminifera, including the presence of *Orbulina* (evolved 15.1 Ma). The larger foraminifera were examined by the specialist Geoffrey Adams (1981, unpublished) who concluded the limestone was deposited after the end of the Lower Tf mass extinction of larger foraminifera. A Carigali-BP report (1984) compiled data from the nearby Tiga Papan wells which drilled this same limestone and sandy carbonates [called by them the “Tiga Papan Unit” but stated to be synonymous and seismically correlatable with the Mantanani Limestone]. The sedimentology of this Tiga-Papan unit was described by Mohammad Yamin Ali (1992; 1995) as a ‘storm-dominated shoals’ deposited on palaeotopographic highs in a mixed clastic-carbonate shelf environment. Nannofossils date the sediments overlying the limestone as at “not younger than NN10”, but more importantly, just below the limestone in two of the Tiga Papan wells is the highest *Sphenolithus heteromorphus*, indicating the Upper Tf carbonate was deposited over sediments of NN4 or NN5 age. Therefore the unconformity is dated as between 12 and about 14 Ma. In this location seismic suggests there was only minor erosion of pre-unconformity sediments.

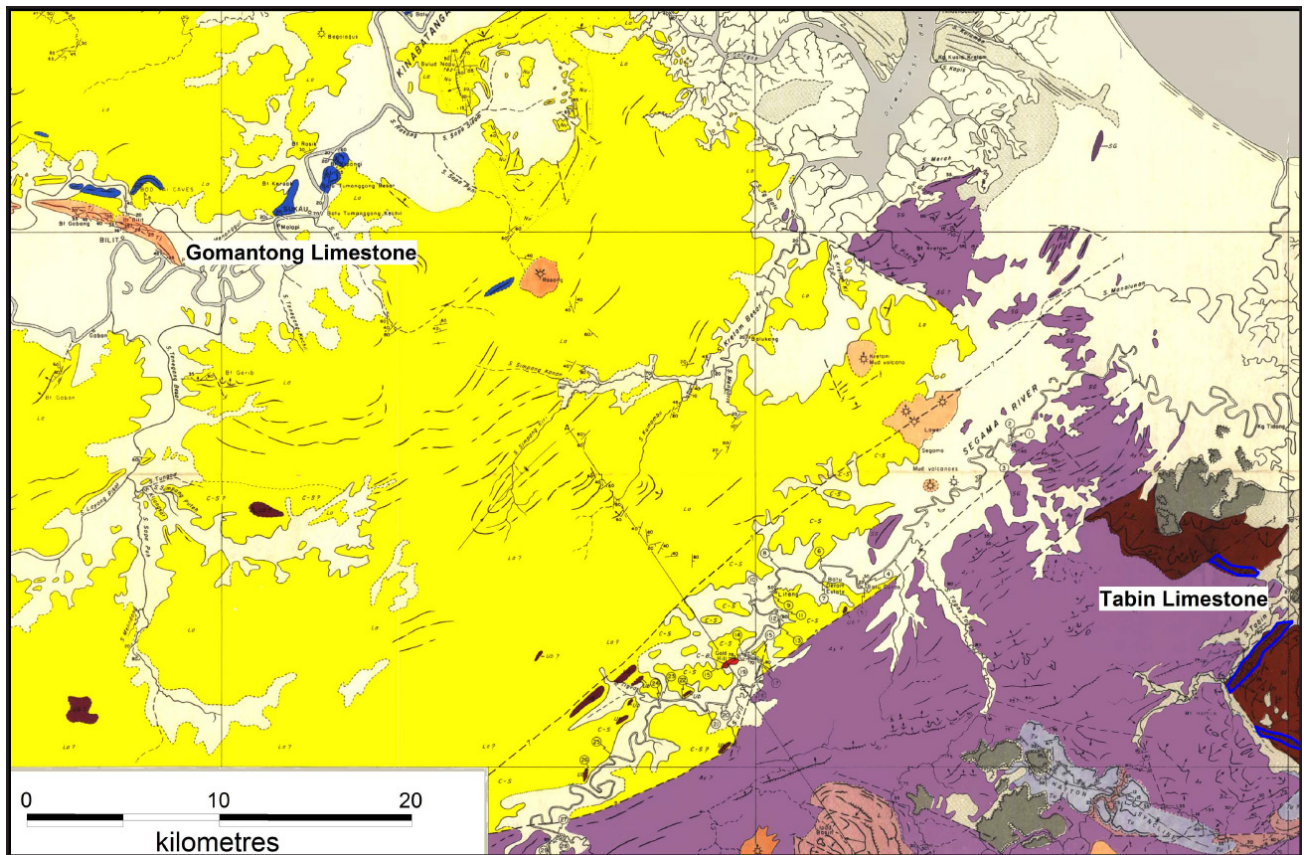
In Palawan the equivalent of the Mantanani Limestone is the Tabon Limestone. This was studied by Steuer *et al.* (2013; Figure 10 here). In multiple wells the Tabon Limestone followed on from an important unconformity. None of the Tabon Limestones samples have the distinct Lower Tf, pre- 12½ Ma mass-extinction event larger

foraminifera. These workers concluded that the overthrust unit “did not form in the Palawan area prior to c. 18 Ma.” They also noted that renewed compression and uplift then deformed the Tabon Limestone. As Steuer *et al.* note, the Tabon Limestone is an important geological marker as it is the first major limestone in Palawan since the Oligocene Nido Formation.

In east Sabah there is another geological event of outstanding magnitude dated as after the evolution of *Orbulina* and *Fohsella fohsi* (sensu lato, as in old reports) or just after about 14 to 14¼ Ma, and before the top of Lower Tf at about 12½ Ma. This was rapid and deep subsidence of reefal limestones such as the outcropping Tabin Limestone, on the Dent Peninsula (Figure 11), and the Sipit or Kunuk Road Limestones on the Semporna Peninsula (Figure 2). Claystone beds deposited above these limestones contain microfaunas with a high planktonic to benthic ratio and presence of *Orbulina*, *Paragloborotalia mayeri*, *Fohsella robusta* and *Bolivinita quadrilaterata* (Lower Claystone of Sebahat Fm., p 75-76 Haile & Wong, 1965) indicate an age no younger than 13.1 Ma and at least an outer neritic environment of deposition, for a location just west of, and above, the Tabin Limestone. There is very little time gap between the end of deposition of the reef and an influx of deep marine clastics into the off reef lows and even covering the crests. There must have been a strong transgression over, or rapid subsidence of, the early Middle Miocene reefal limestones on the Dent Peninsula.

Two wells drilled offshore the Dent Peninsula reached the Tabin Limestone, the 1973 Sebahat-1 and 2008 Segama-1 (locations on Figure 12). Unfortunately neither of these wells had biostratigraphic analysis of the coralline carbonate, but both had fully bathyal clastics deposited over the reef crests (the Sentry Bank and Sentry Bank Reef wells drilled 15 and 17 km away have *Fohsella peripheronda* within an equivalent reefal build-up indicating an age for these limestones as no older than about 17½ Ma). Segama-1 was on a high relief pinnacle and a time gap is obvious on seismic, and also in the biostratigraphic age of the sealing clastics (Zone NN9, near basal Late Miocene covers the reef crest). The Gem Reef-1 was drilled on the side of the same reef a few kilometres away and reached total depth just short of the reef flank with *Fohsella robusta* (N11/12) in the deepest claystone samples. The Sebahat-1 well also has *Fohsella* planktonic faunas and bathyal *Cyclammima* benthic faunas above the seismically lower relief coralline carbonate it reached at TD. At both Segama-1 and Sebahat-1 the reef tops are now some 2.3 and 3.6 kms below sea level, showing continued subsidence over the past 12 Ma. Other un-drilled reefs have been seen in this area on seismic (Murray & Lunt, 2012; CCOP, 2008) with reef tops commonly 3 kms, and sometimes as much as 5.5 km below modern sea-level. The coralline Tabin Limestone outcrops were covered by at least 2.3 kms of Sebahat Fm. marine clastics (Haile & Wong, 1965) before Pliocene folding and uplift of the Dent Peninsula.

In the Semporna Peninsula the Kalumpang Formation is a bedded clastic unit showing shallowing and coarsening



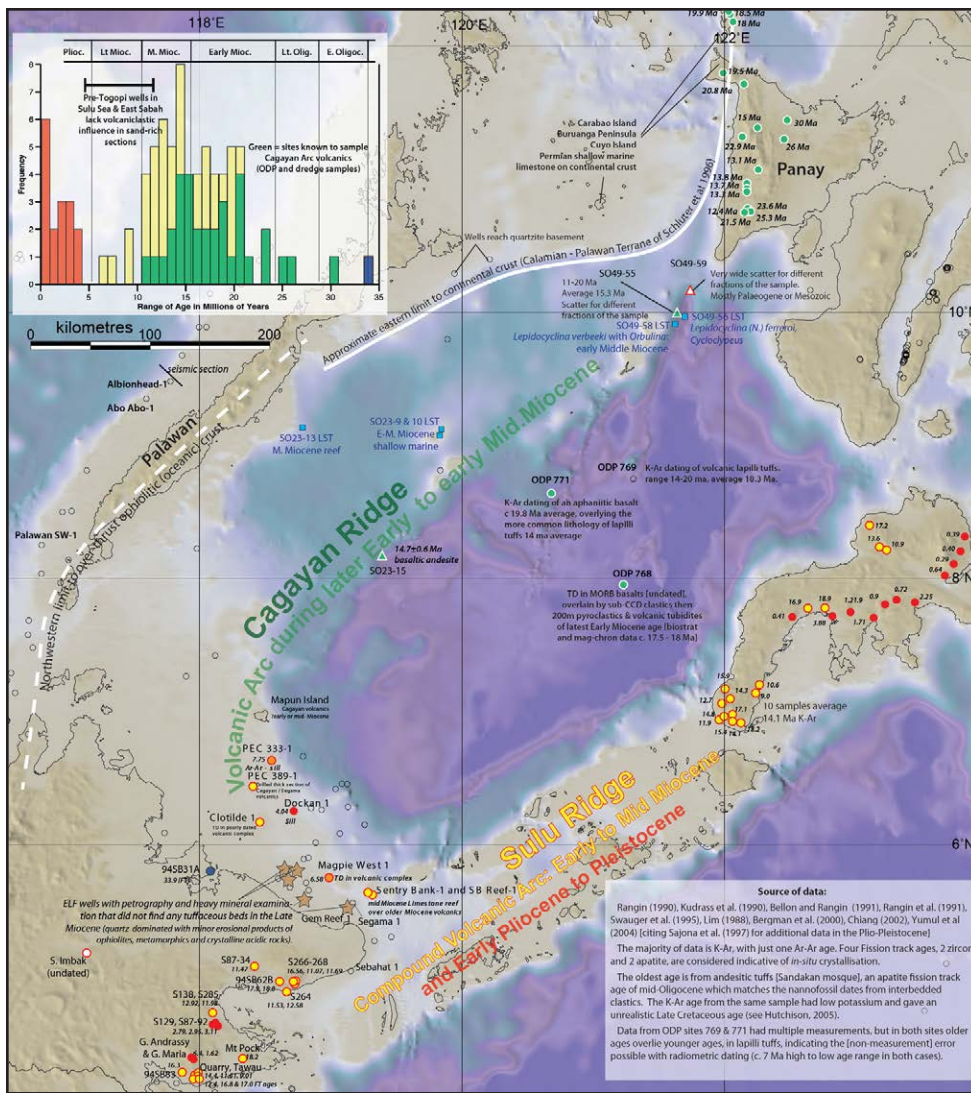
**Figure 11:** Map of the Kinabatangan valley, north central Sabah (Haile & Wong, 1965; location shown on Figure 2) showing locations of the cluster of Te5, basal Miocene [roughly 20-23 Ma], age Gomantong Limestone and the top Lower Tf, early Middle Miocene [roughly 12½-15 Ma] age Tabin limestone. Until the Pliocene Togogi Limestone these are the only significant carbonates seen in northeast Sabah. Yellow is the widespread deep marine Labang Fm., purple is the Ayer Formation slump mélange of the Segama Group, and dark brown is the Late Miocene Sebahat Formation (siliciclastics). The location of the Sipit limestone and Kunak Rd. Limestone, age equivalents to the Tabin.

upwards, but without the thick and coarse grained quartz sands and coals of the age-equivalent Kapilit and Tanjong Formations to the west. Marine foraminifera are more common than in those western formations, and the age of the unit covers most of the Early Miocene to basal Middle Miocene, but no younger (Tables 4 & 5 in Lim, 1981). At four locations [Kunak Road, Kalumpang area, hills near Sipit River in north Semporna] there are platform to reefal limestones on top of the clastics. These are Lower Tf and Middle Miocene in age [*Katacycloclypeus annulatus*, *Miogypsina* and *Orbulina*] and were deposited at close to sea-level. About 5 km from the Kunak Road Limestone is the type location of the Balung Formation (Lim, 1981), a locally richly carbonaceous claystone dated as lower and middle S600 palynology zone by Shell (reported in Lim, 1981; a later Middle and early Late Miocene age). Table 7 of Lim (1981) also shows foraminiferal faunas from 26 different samples, and apart from 4 that have very few fossils, all are deep marine, typical bathyal assemblages (*Cyclammina cancellata*, *Ammodiscus*, *Eggerella*, *Glomospira* and many others). Twenty kilometres to the south of this outcrop the Tawau Offshore 1 and 2 wells drilled several hundred metres to perhaps a kilometre of poorly fossiliferous mudstones with *Cyclammina*, *Ammodiscus* and *Haplophragmoides*/

*Trochammina* bathyal faunas passing up into slightly more calcareous deep marine faunas with the Late Miocene index foraminifera *Neogloboquadrina acostaensis*.

It is a reasonable deduction that over a wide area of East Sabah, early to mid Middle Miocene sediments were gradually filling an old depocentre, shallowing the sedimentary baseline to near sea-level. The Tungku Tuffite Member that underlies the Tabin Limestone is defined on an abundance of bedded carbonaceous material and plant remains, the abundant plant material proving newly emerged terrestrial locations somewhere nearby (in an area that was once remote, over Mesozoic oceanic crust with prolonged deposition of bathyal sediments). The single episode of reefs of similar age appears to be the product of an early transgressive systems tract, but rapid subsidence over several hundred square kilometres led to complete drowning. Seismic data offshore shows a slightly more complex story, with some folding associated with the transition, continuing into basal Sabahat times, but overall the mid-Middle Miocene event in east Sabah is one of major drowning followed by rapid, new sedimentation into the newly deepened marine basin.

In association with these mid Middle Miocene stratigraphic events in eastern Sabah, there was also a



**Figure 12:** Distribution of igneous rocks, by age. Note that the Late Miocene was generally a period with little volcanic activity and then, approximate at the age of the base Togopi / Base Carcar unconformity at 4 Ma there seems to have been a renewal of igneous activity in the Sulu Arc.

change in igneous activity. Before the mid-Middle Miocene event quartz clastics were being brought in from central Borneo, but local volcanic sources in Dent and Semporna contributed large volumes of often coarse volcanoclastic material, which was the distinguishing feature of the pre mid-Middle Miocene Segama Group, from the post mid-Middle Miocene Sebahat Formation (Haile & Wong, 1965). Both radiometric ages of igneous crystallisation (Rangin *et al.*, 1990; Kudrass *et al.*, 1990; Bellon & Rangin, 1991; Rangin & Silver, 1991; Swauger *et al.*, 1995; Lim, 1988; Bergman *et al.*, 2000; Chiang, 2002; Yumul *et al.*, 2004; Sajona *et al.*, 1997; see Figure 12) and the feldspar or volcanic lithic components in Sebahat clastics diminish rapidly after about 12 Ma (unpublished heavy minerals analysis of Gem Reef-1, Manalunan-1, Benrinnes-1). It is likely the Sulu Arc faded in activity at this time.

The Meligan, Tanjong and Sandakan Formations described earlier are all delta-top facies (including coals) of later Early through early Middle Miocene age, and these formations have a high thermal maturity from burial (Jordan & Ford, 1990, unpublished, and Clennell, 1991), suggesting that two to three kilometres of sedimentary overburden

have been removed from a wide area (from around the later folded structures known as the “Circular Basins” of central Sabah, as far as Sandakan on the north coast). In order to create accommodation space for such overburden to have been deposited these delta-top sediments must first have been subject to substantial subsidence. The mid Middle Miocene event, which was the termination of Tabin Limestone to the east and also top Cycle IV subsidence in Sarawak to the west (Lunt & Madon, 2017) is the most likely candidate for this, as it has the required magnitude. It was also followed by rapid sedimentation of the Sebahat and Ganduman formations as candidate overburden units, before a period of young Neogene uplift and erosion.

**THE BASE TOGOPI / CARCAR EVENT**

A major unconformity is observed all around the Sulu Sea, and is dated as having peaked in the Early Pliocene (at roughly 4 Ma). It is assumed here to be a single event, but as few wells take samples in this very shallow section, age dating and regional correlation are limited. Seismic often shows strong angularity at the event, usually transgression over a truncation surface (see Figures 13 &

14), and lithologically it is usually a shift from clastic dominated facies below to mixed clastics and carbonates above. It appears to be the most pronounced and widespread stratigraphic feature since the early to mid Middle Miocene “DRU” some 8 or 9 Ma earlier. This Pliocene event, which is at the base of the Togopi Formation in Sandakan, and the Carcar Limestone in Palawan, seems to have been the termination of the Sabah Orogeny in those areas. However, in west Sabah the “Horizon II” unconformity of Levell (1987) has the same intra Early Pliocene age, and after Horizon II Levell identified a late Pliocene-Pleistocene uplift in the offshore northwest part of Sabah, and a resulting unconformity called Horizon I, so it seems the Sabah Orogeny continued in some places after the mid Pliocene.

In the offshore Sandakan area, in the few wells where samples were recovered and analysed, the Togopi Formation above the unconformity has long-ranging shallow marine foraminiferal assemblages, and most wells pre-date modern nannofossil analysis. However in Rhino-1 (drilled 2004) there are modern biostratigraphic analyses, and the unconformity occurs well above the top Miocene marker (top NN11, extinction of *Discoaster quinqueramus*), and below

the top Early Pliocene (the NN15 and older, the *Sphenolithus abies* datum is recorded above the unconformity). In this well the overlying Togopi Formation contains transgressive marine sediments, contrasting with the paralic or non-marine fluvio-deltaic sediments below. The environmental contrast between marine Togopi and deltaic Ganduman formations increases to the south and west of this well.

On the Dent Peninsula the outcropping Ganduman Formation sediments below the event are paralic, rich in lignites and very poor in marine fossils of any type. The Togopi Formation above is rich in shallow marine corals, molluscs and foraminifera. Limestones contains the later Miocene to Recent *Alveolinella quoyi*, the very latest Miocene to Recent and distinct form *Calcarina spengerli* (Haile & Wong, 1965), and McMonagle *et al.* (2011) dated a Togopi limestone location using strontium isotopes as 1.7 Ma.

Many of the structures drilled on the Malaysian side of the Sandakan Basin were formed by oblique compression that terminated at the Ganduman to Togopi unconformity, with some features such as those near Pad-1 (Figure 13) showing structural growth over a prolonged period through

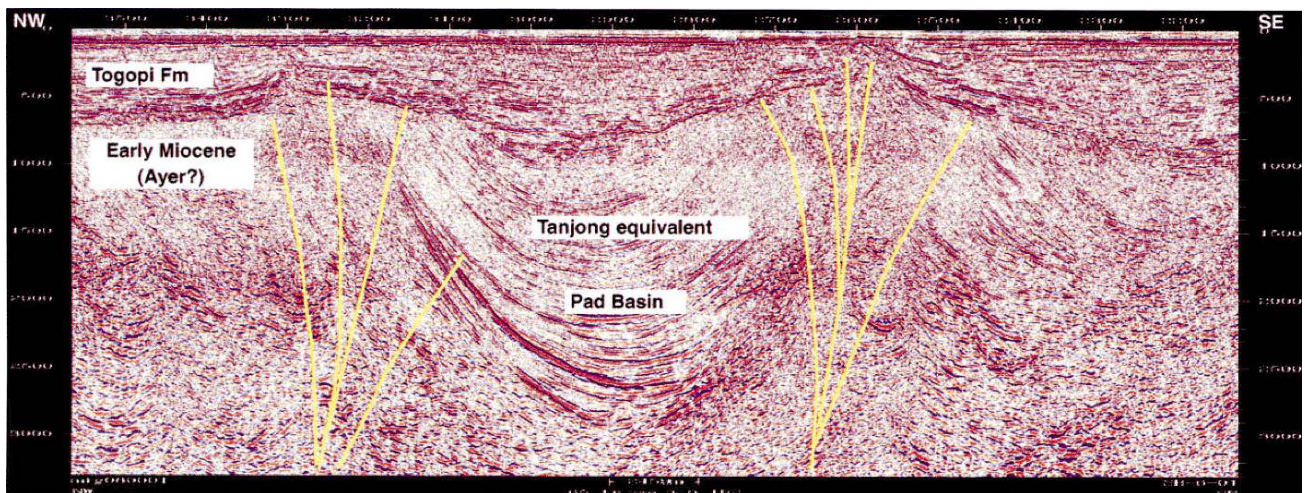


Figure 13: NW-SE seismic section across the Pad Basin showing the synclinal feature (From Leong & Anuar, 1999).

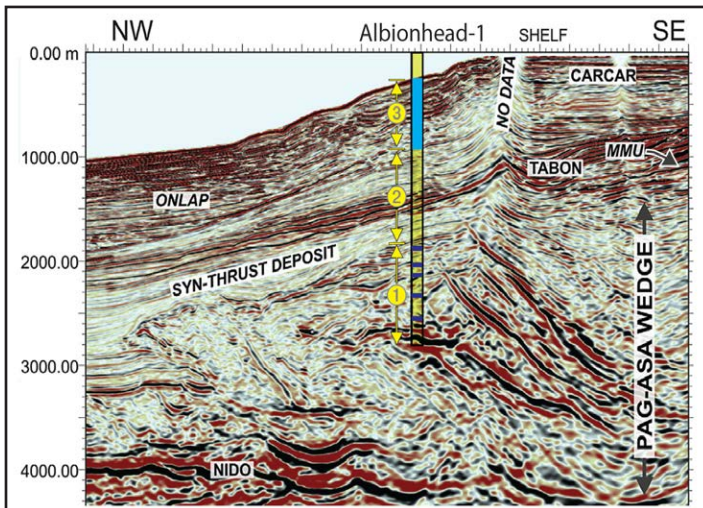


Figure 14: The Carcar Limestone transgressing over thrust and angular older Miocene beds offshore Palawan, from Aurelio *et al.* (2014), with deeper water Carcar equivalents onlapping the same horizon NW of the shelf edge. This depth-scaled line passes within a few kilometres of the Albionhead-1 well in which there are three main sedimentary units (well reports and Park & Peterson, 1979). (1) is an interval of thrust early Middle Miocene clastics with transported limestone / argillaceous limestone beds. This section is locally sandy, and stratigraphic reworking is consistently present. Section (2) is less severely thrust and consists of claystones with minor thin sands of later Middle to Late Miocene age. The section marked (3) is limestone rich, at the base with deep marine benthic foraminifera, common planktonic foraminifera. The Pleistocene marker *Globorotalia truncatulinoides* was found in the upper part of the carbonate, where there are also transported shallow marine bioclasts such as coral and mollusc fragments.



the latest Miocene and into basal Togopi Formation beds. Overall the onset of the deposition of the Togopi Formation was a subsidence of the basement, and also the end of a phase of deformation.

On and around Palawan, a poorly dated, but approximately Early Pliocene unconformity is seen on seismic as a clearly angular event. This is recognised in the area around the Coral-1, Sulu Sea A-1 and B-1 wells, through offshore SW Palawan, and in many wells off the west coast of north Palawan. In all these areas the change, through time, over the transgressive unconformity is to a much more calcareous section, called the Carcar Formation.

In Coral-1 (Hinz *et al.*, 1986; Beddoes, 1976) the distinct marker species *Globigerinoides obliquus extremus* is noted in the section above the unconformity indicating an age, for the post-event sedimentation, between latest Miocene and basal Late Pliocene. The section below the unconformity is slightly deeper marine with diverse planktonic foraminifera including *Orbulina* and *Sphaeroidinellopsis* species, but no *Globorotalia tumida*, suggesting the pre-unconformity sediments are Late Miocene [or slightly older] in age. In this area the tectonic change preceding the unconformity included some uplift and erosion, seen on seismic to have been focussed in the SW, but seismic geometries, and the growth of the Coral-1 Carcar age pinnacle reef, suggests there was simultaneous basement subsidence to the north-east or east of this wells.

In southern Palawan wells such as P296-1, Penascosa-1, Paragua-1, Paz-1, Murex-1, Kamonga-1 and SW Palawan-1 (Hinz *et al.*, 1986) all drilled through a section of Carcar Limestone above later Miocene or basal Pliocene clastics. Inboard of Paragua-1 seismic data shows that there is angularity and erosional truncation at the base of this limestone. Dating this event is difficult as the shallow marine limestones usually lack age diagnostic planktonic foraminifera, and the underlying mudstone is also sparsely fossiliferous. Many well reports record only rare marker species so it is almost certain that “first downhole occurrences” are not true extinction datums. In Paragua-1 there are some *Globorotalia tumida* specimens in several samples of the mudstone below the Carcar Limestone, dating the basal unconformity as younger than its evolution at base Pliocene. In the original biostratigraphy report for Paragua-1 (also observed at Kamonga-1 & Paz-1) the unconformity was dated as within the Late Pliocene because the distinct marker *Dentoglobigerina altispira* (extinct in basal Late Pliocene 3.46 Ma) were not seen until some 400 feet below the unconformity. However the *D. altispira* markers occur as “rare” and only in a small number of samples, so the highest record is unlikely to be the extinction datum, and a pre-mid Pliocene age is probably for the entire section to the base of the Carcar Limestone.

In the Albionhead-1 and Paragua-1 reports the “extinction” of *Neogloboquadrina acostaensis acostaensis* is used to define top Pliocene, but according to Bolli & Saunders (1985; and other sources) this is not an age marker as the species is extant. In Albionhead-1 *Gt. truncatulinoidea*

is found as high as about 200 feet into the lowest Carcar Formation, dating its onset as intra Pliocene. In Cadlao-1, as soon as the angular event of base Carcar Formation limestone was drilled, Early Pliocene fauna and flora appeared in the cuttings (*Globorotalia margaritae*, *Sphenolithus abies* and others) also indicating the unconformity is within the Early Pliocene.

From this sparse sample coverage over a distinct seismic unconformity it seems that across the region there was possibly just one intra Early Pliocene unconformity, leading to a carbonate rich, generally transgressive, sequence. The event was the end of a compressive phase that had been active through the middle and later Miocene. Off west Palawan it also appears to have been the end of a phase of sub-aerial erosion over highs, and sub-marine slumping on slopes.

## CONCLUSIONS AND REGIONAL IMPLICATIONS

Many generations of field and well data has been reviewed and correlated to a consistent modern time scale, to which South China Sea spreading ages can also be linked. The review is a history of large-scale facies units in the context of the known major unconformities. The relative ages of which are shown in Figures 1 and 15. This age dating, which is defended in the text, is a critical part of this review.

The Late Oligocene was a time of compression from north to south, with most uplift and deformation in the northwest Sabah, Kudat to south Palawan area, and with effects diminishing to the south. An area around south Palawan and Balabac islands was uplifted and eroded, and the Kudat Peninsula saw deposition of regressive sediments. The data shows that this compression terminated at the time of the onset of plate drift in the SCS (Barckhausen *et al.*, 2014; and others). This is contrary to the “slab-pull” subduction model of a proto South China Sea plate under Sabah during the Early Miocene, under which conditions it would be expected that the *onset* of compression and deformation would be linked to the *start* of plate drift.

Sediments deposited during the Early Miocene across Sabah appear to be widespread claystones until changes at roughly 17 Ma, with uplift in central Borneo accelerating sediment supply from the south. For the first time shallowing-upward deltaic units prograded over the long-standing deep water basin of northern Sarawak and Sabah, resulting in the fluvio-deltaic facies of the Lambir, Meligan White Sandstone, Tanjong, and Kapilit formations, with the mixed sandy to marine clay unit of the Sandakan Formation in the far north. Depending on the magnetic anomaly interpretation dating the end of spreading in the South China Sea (at 20.5 Ma, or as young as 16-15 Ma: Barckhausen & Roeser, 2004; Barckhausen *et al.*, 2014; Briaies *et al.*, 1993; Li *et al.*, 2014) this system of south derived quartzose sediments either wholly or partially post-dates the proposed plate subduction in the west to central Sabah area, yet there appears to have been prograding deposition independent of any subduction trough or accretionary wedge topography.

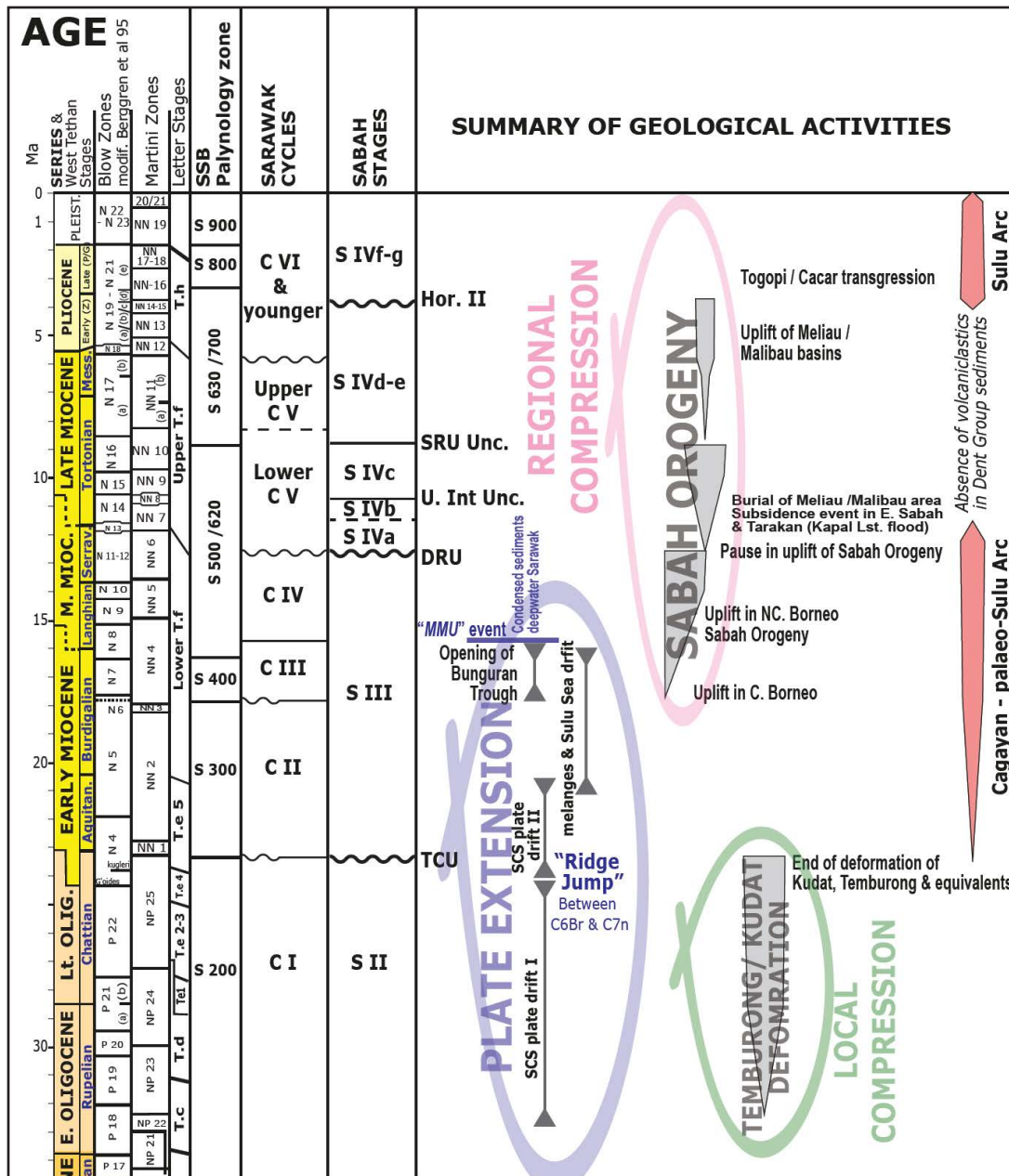


Figure 15: A stratigraphic summary for events around Sabah and Sarawak.

The main topographic trend at that time seems to have been a north to south downwards slope, from fluvial to bathyal, suggesting that there was no such underlying plate subduction topography.

The Sabah Orogeny does not appear to be a subduction related accretionary wedge as its first appearance post-dated the termination of the plate drift, and its peak activity was through the entire Middle and Late Miocene, long after any plate drift in the SCS. ODP work (Rangin & Silver, 1991) and a compilation of radiometric dating of igneous rocks indicates that during the onset of the Sabah Orogeny there was sea-floor spreading in the Sulu Sea, and the Sulu Arc was replacing the Cagayan Arc as the active volcanic trend (Figure 11). The existing data on the Cagayan Arc also indicates it is wholly or at least mostly younger than plate drift in the SCS and is therefore unlikely to be an

island arc related to any drift in the SCS. Also, as shown on Figure 12, the northern continuation of the Cagayan Arc, in the Antique Ranges on west Panay Island, are immediately adjacent to a continental terrain identified by Schlüter *et al.* (1996) that has wells drilling into quartzite (Durkee, 1993) and several locations with Permian fusuline limestone (Aurelio & Peña, 2010). In less than a twenty kilometer gap between Miocene volcanic arc and Permian limestone there is no space for a palaeo-subduction complex. It is more likely that subduction was in the east, and Hall (2013) has already proposed subduction roll-back of the Sulu Arc splitting away from the Cagayan Arc. Extensional mélanges were deposited onshore east Sabah as part of this new rifting (Clennell, 1991; Leong, 1974). Studies that date the extensional mélanges as older than this (Balaguru *et al.*, 2003; Balaguru & Nichols, 2004) have been investigated,

and the few samples with an older age found to be a long way outside the well-dated type location of the mélanges and they are not polymict mélanges like the type formation. The analyses of Leong specifically on the matrix of the mélanges over a wide area has *Fohsella peripheronda* and *Globigerina binaiensis* indicating a depositional age from before 19.4 Ma to after about 17½ Ma.

The cause of the Sabah Orogeny is still not known, but the DRU event is explained as a pause in this compressive phase, leaving a distinct seismic surface that can correlated with the time of major subsidence in the east. This eastern subsidence left reefal facies rapidly overlain by very deep marine clastics, and is also the candidate for the onset of new and thick sedimentation over the Tanjong, Kapilit and Sandakan delta-plain sediments as all these record high levels of burial thermal maturity. Moderately thick Stage IV sediments began to be deposited over the DRU surface itself not long after the end of erosion, as the focus of the Sabah Orogeny uplift shifted slightly east to the present Western Cordillera to Palawan trend. The relationship of widespread subsidence across Sabah to apparently accelerated clastic sedimentation is not understood, but it might be linked to the emergence of new, perhaps narrow, uplifted zones.

This mid Middle Miocene event is close to the age of the Cycle IV to V subsidence in Sarawak (Lunt & Madon, 2017). It is also approximately the age of a sharp decline in activity of the Sulu volcanic arc (Figure 12), which may be linked to locally increased subsidence along that trend. It is assumed that subduction towards the northwest under the Sulu Arc had ceased, and this change in geological stress caused a temporary interruption to the long-lasting Sabah Orogeny.

In modern times Palawan Island and the Western Cordillera is an aseismic zone and it is thought that the Sabah Orogeny strongly faded in Early Pliocene times. Data from around the Sulu Sea, from Palawan to north Sabah, shows a major transgressive surface at the end of the compressive phase, and the replacement of regressive, erosional clastics with rapidly transgressive carbonates and clastics. These include the Carcar Limestone of Palawan and the Togopi Limestone of northeast Sabah.

While this history of events gives no support to, and in places contradicts, the slab-pull model of subduction under Sabah, it does not necessarily support the only current alternative, the “extrusion” hypothesis of Tapponnier *et al.* (1982; and later revisions). There is no time specific event in the extrusion model that can be tested against stratigraphic data.

The Early Miocene rifting of the Sulu Sea and splitting of the Sulu volcanic arc away from the fading Cagayan Arc indicates that subduction on the north-eastern side of Borneo may be an important part of a new tectonic model (Hall’s 2013 “roll-back” model). This might have released extensional stress in the SCS and caused the end of the second phase of drift there, as measured at 20.5 Ma (following Barckhausen *et al.*, 2014).

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