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An erosional unconformity at the top of the Nyalau Formation near Bintulu, Central Sarawak (Malaysia): Its regional context and significance

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Abstract: This article documents an erosional unconformity at the top of the Nyalau Formation (Oligocene-Early Miocene) exposed in a road-cut northeast of Bintulu in central Sarawak. The outcrop succession essentially comprises a lower unit of thickly-bedded sandstones representing wave-dominated shoreface facies overlain by fluvio-tidal channel deposits that were deposited following a base-level lowering. This gently tilting sand-rich unit is cut by an irregular concave-up erosional surface, overlain by mudstones and thinly interbedded heterolithics that show large-scale internal stratification indicative of multiple scour-and-fill structures, progradation and/or lateral accretion. The erosional surface separating the two units not only marks a significant shift in sedimentary facies but the fact that it cuts into deformed and tilted strata (Upper Nyalau) suggests that it is an erosional unconformity caused by a tectonic deformational event. Based on regional structural synthesis and stratigraphic evidences, the unconformity probably represents the eroded top of the Nyalau Formation, overlain by a relatively undeformed succession tentatively correlated with the Early-Middle Miocene post-Nyalau formations in the Mukah-Balingian region.

Keywords: Nyalau Formation, Sarawak Cycles, unconformity, erosional surface, facies

INTRODUCTION

Due to the sparsity of outcrops that are few and far between in this humid tropical climate, we often do not have enough information to place them in a regional context, as correlating between isolated outcrops poses a challenge. Nevertheless, some outcrops deserve to be documented before they disappear into oblivion. Along the old Bintulu-Miri Road and the relatively new Pan-Borneo Highway many interesting exposures of the Nyalau Formation (Oligocene-Early Miocene) have been studied by students and academics over the years. One particular outcrop, which is the subject of this article, is located on the Bintulu-Miri Road, between Tg. Kidurong and the Similajau Industrial Park (Figure 1A, Outcrop no. 7; longitude 113.212502°, latitude 3.325615°). This road cut exposes sandstones of the Nyalau Formation overlain by a mudstone-filled channel-like feature. The contact between the sandstone and mudstone is an irregular, concave-upward surface which is interpreted as representing a major regional unconformity. This article describes the outcrop and the nature of the unconformity in the context of the regional geology of central Sarawak, both onshore and offshore. In examining the possible origins of the unconformity, a synthesis of the structural and stratigraphic framework of the study area and its regional significance are discussed.

GEOLOGICAL SETTING

Central Sarawak between Tatau and Miri is tectono-stratigraphically part of the Miri Zone (Haile, 1974; Hennig-Breitfeld *et al*., 2019), which is the onshore portion of the Late Eocene-Quaternary Sarawak Basin that extends offshore beneath the Sarawak shelf and deep-water areas (Figure 1B). The Sarawak Basin unconformably overlies folded and eroded Upper Cretaceous to Mid-Eocene Rajang Group turbidites and debrites which make up the Sibu Zone (Haile, 1974; Bakar *et al.*, 2007; Galin *et al*., 2017). The Miri Zone essentially comprises post-orogenic fluvio-deltaic to marine sedimentary strata of Oligocene-Miocene age (Haile, 1974; Bakar *et al*., 2007; Hennig-Breitfeld *et al*., 2019; Breitfeld *et al*., 2020). These shallow water deposits were laid down unconformably upon uplifted and eroded deep-water sediments of the Rajang Group during the Sarawak Orogeny in the Middle to Late Eocene (Hutchison, 1996). Recent works on the Rajang Group rocks in this area include Bakar *et al*. (2007) and Galih *et al*. (2019), among others. Along with the Crocker Formation in Sabah which may be as young as Early Miocene in age, the Rajang Group forms the backbone of Borneo, stretching from Sibu to Kota Kinabalu in Sabah (Figure 1B).

In the Tatau area, southwest of Bintulu, the basal sediments of the Miri Zone are represented by the Tatau

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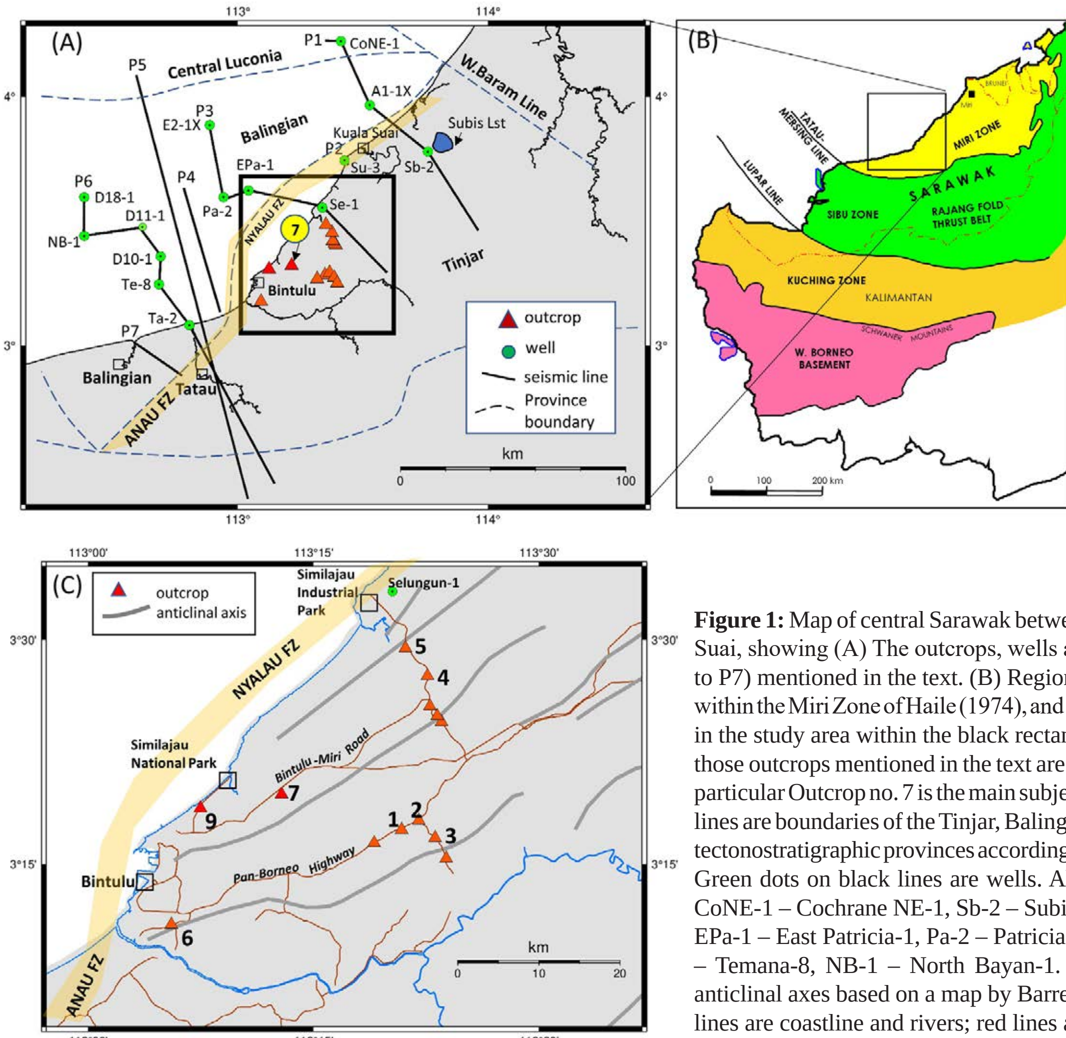

Figure 1: Map of central Sarawak between Balingian and Kuala Suai, showing (A) The outcrops, wells and seismic profiles (P1 to P7) mentioned in the text. (B) Regional setting of study area within the Miri Zone of Haile (1974), and (C) Location of outcrops in the study area within the black rectangular area in (A). Only those outcrops mentioned in the text are labelled (nos. 1 to 9). In particular Outcrop no. 7 is the main subject of this article. Dashed lines are boundaries of the Tinjar, Balingian and Central Luconia tectonostratigraphic provinces according to Shell (Madon, 1999). Green dots on black lines are wells. Abbreviated well names: CoNE-1 – Cochrane NE-1, Sb-2 – Subis-2, Se-1 – Selungun-1, EPa-1 – East Patricia-1, Pa-2 – Patricia-2, Ta-2 – Tatau-2, Te-8 – Temana-8, NB-1 – North Bayan-1. Also shown are major anticlinal axes based on a map by Barrett & Kuek (1986). Blue lines are coastline and rivers; red lines are major roads.

Formation which consists of fluvial sediments (Rangsi Conglomerate) that rest with angular unconformity upon folded and steeply dipping Belaga Formation of the Rajang Group (Hutchison, 2005; Madon *et al*., 2013; Hennig-Breitfeld *et al*., 2019, Breitfeld *et al*., 2020). The Tatau Formation is conformably overlain by the Nyalau Formation, which has been mapped over much of central Sarawak spanning across an area of over 150 km northeastwards from Tatau to the Subis area in northern Sarawak (Figures 1A, 1B). In the study area between Bintulu and the Similajau Industrial Park, shallow marine deposits are exposed along the Bintulu-Miri Road and the Pan-Borneo Highway (Figure 1C).

The Nyalau Formation, of Late Oligocene to Early Miocene age (Liechti *et al*., 1960), consists of lower coastal plain to shallow marine sediments and is correlated to Cycles I and II in Shell's offshore stratigraphic scheme (Ho, 1978). Recent detailed studies by Breitfeld *et al.* (2020) have confirmed the Late Oligocene-Early Miocene age assigned by early workers (Kirk, 1957; Liechti *et al*., 1960; Wolfenden, 1960) and re-introduced the original subdivision of the Nyalau Formation into the Biban Sandstone Member (=Cycle I) overlain by the "Upper Nyalau Member" (Cycle II). Since Cycle I and Cycle II units are important hydrocarbon-bearing reservoir intervals in the offshore Balingian Province to the north (Figure 1A), the Nyalau Formation provides direct outcrop analogues for exploration and development studies. Examples of oil and gas fields in Cycles I and II reservoirs are D18, D35, Temana and Patricia (Almond *et al*., 1990; Hasegawa *et al.*, 2005; Meor Hakif *et al*., 2017). The sedimentology of the Nyalau Formation was described by previous authors as comprising fluvial, nearshore and shallow marine deposits (e.g., Meor Hakif *et al*., 2013; Shoukat *et al*., 2019). Provenance studies suggest that these paralic to shallow marine sediments were derived from two main sources: (1) the Malay Peninsula via an east-flowing Sunda river system during the Oligocene to Early Miocene and (2) the uplifted Rajang fold-thrust belt in the Kuching and Sibu zones and the Schwaner Mountains of West Borneo via the proto-Rajang system during Early-

Middle Miocene (Hennig-Breitfeld *et al*., 2019; Breitfeld *et al*., 2020). Based on these studies, Breitfeld *et al*. (2020) suggested that a change in the sediment delivery system from a westerly to southerly source coincided with the change in paleoshoreline orientation from NW-SE to NE-SW which was documented by previous workers (Hageman, 1987; Hutchison, 2005). The switch in provenance source areas is thought to be related to the Nyalau Unconformity at *ca*. 17 Ma (Breitfeld *et al*., 2020). Said (2020) studied some exploration wells onshore and on the shelf and found that the Nyalau-equivalent Cycles I and II sediments were sourced predominantly from West Borneo.

STRATIGRAPHIC FRAMEWORK

Figure 2 summarises the stratigraphy of the study area in central Sarawak in the context of the Sarawak Basin. The stratigraphic chart is based on earlier compilations with updates from various sources, including Barrett & Kuek (1986), Boodoo *et al*. (1989), Madon (1999), Madon & Abolins (1999), Madon & Redzuan (1999), Jong *et al*. (2016) and Lunt & Madon (2017). Wheeler-style diagrams along regional profiles AA’, BB’ (Figure 2A) and AC (Figure 2B) schematically show the stratigraphic relationships across the basin. Each profile represents the stratigraphy in different parts of the basin. Profile AA’ (Figure 2A) is from Central Luconia to Balingian, in a “dip” direction from NW to SE, and Profile BB’ is from East Balingian westward to Tatau Province in a “strike” direction (parallel to coastline). Profile AC is from Central Luconia to the onshore region from Mukah northeastwards to Subis region. The Wheeler diagrams are especially useful in visualizing gaps in the stratigraphic record (shown as white spaces) and their spatial and temporal relationships.

The stratigraphy of the Sarawak Basin is essentially subdivided into Cycles I to VIII which are interpreted to overlie folded Rajang Group as the pre-Cycle I “basement”. Offshore continuation of the Rajang Group beneath Cycle I is evident in seismic data from various parts of the basin (e.g., Ismail, 1996; Iyer *et al*., 2013; 2019). In addition, a number of wells on the SW Sarawak Shelf were reported to have penetrated the Rajang Group (Rice-Oxley, 1992). Oil discovery at well Nuang-1 in offshore Tatau province was in metasediments believed to be the Rajang Group equivalent in a tilted half-graben fault block (Jabbar *et al*., 2015).

In many places the Cycle boundaries are marked by erosional unconformities which represent hiatuses of varying time span that were caused by erosion and/or non-deposition. As discussed by Lunt & Madon (2017), the Cycle boundaries and their correlative unconformities are thought to be related to tectonic deformation events that may be of regional significance. For instance, the Base Cycle II Unconformity (~24 Ma) is thought to coincide with a ridge-jump from E-W to NE-SW oriented sea-floor spreading in the South China Sea (Lunt & Madon, 2017). Recent onshore works suggest that a major event at ~23 Ma also coincided with a major provenance change in the Nyalau Formation (Cycles I and II), from predominantly fluvial channel deposition in the Biban Sandstone (Lower Nyalau) to tidal deltaic deposition in the Upper Nyalau (Hennig-Breitfeld *et al*., 2019; Breitfeld *et al*., 2020).

The Base Cycle II Unconformity occurs locally in the offshore (Lunt & Madon, 2017; Figure 2A) and seems to be more prominent in offshore West Balingian and further west into offshore SW Luconia and Tatau provinces. It may have been present in the offshore East Balingian and, possibly, less prominently in the adjacent onshore areas. The region west of the Balingian Province is known to be an extensional terrane characterized by normal faults and associated half-grabens that were formed during the initial rifting of Sarawak Basin during the Late Eocene-Oligocene (Madon & Redzuan, 1999; Jabbar *et al*., 2015). Hence, the Base Cycle II may be considered as the end-of-synrift or “break-up” unconformity.

Similarly, the Base Cycle III Unconformity to the west of Balingian Province (Figure 2A) probably represents the end of a second phase of extension during Early Miocene times. This extensional phase is likely to have been responsible for the pervasive NNE-SSW extensional faulting that occurred during the later part of Cycle III times, as shown in the structural maps of Central Luconia by many authors (e.g., Kosa, 2015; Ting *et al*., 2021). This crustal extension phase resulted in the formation of intrabasinal highs that acted as the substrate upon which carbonate reefs started to grow in late Cycle III times and continued into Cycle V (Figure 2A). Onshore, the Base Cycle III was interpreted as the Nyalau Unconformity (~17 Ma) by Hennig-Breitfeld *et al*. (2019) and Breitfeld *et al*. (2020). Base Cycle IV is the only other visible unconformity in the onshore region, marked by the Begrih Conglomerate on top of the Balingian Formation (Hennig-Breitfeld *et al*., 2019; Breitfeld *et al*., 2020).

As shown in Figure 2, other Cycle boundaries offshore are also marked by erosional unconformities, including Base Cycle V, Base Cycle VI and Base Cycle VIII. With increasing intensity of deformation towards the basin margin, the unconformities became more pronounced landward due to uplift and erosion, as they cut deeper into progressively older units down to Cycle I and even into the underlying Rajang Group. As a result, the stratigraphy of central Sarawak in both onshore and adjacent offshore is characterized by a large regional hiatus, the “Central Sarawak Hiatus”, from which much of the basin succession is missing due to either erosion or non-deposition (Figure 2). Due to multiple phases of deformation, the onshore Tinjar Province between Tatau and Subis (the study area shown in Figure 1) are underlain by the equivalents of only Cycles I and II, which are mapped as Nyalau Formation. In addition, the Subis Limestone (see Figure 1) have been well dated to be the time equivalent of the Upper Nyalau or Cycle II (Adams, 1963; Mihaljević *et al*., 2014; Saw *et al*., 2019; Breitfeld *et al*., 2020).

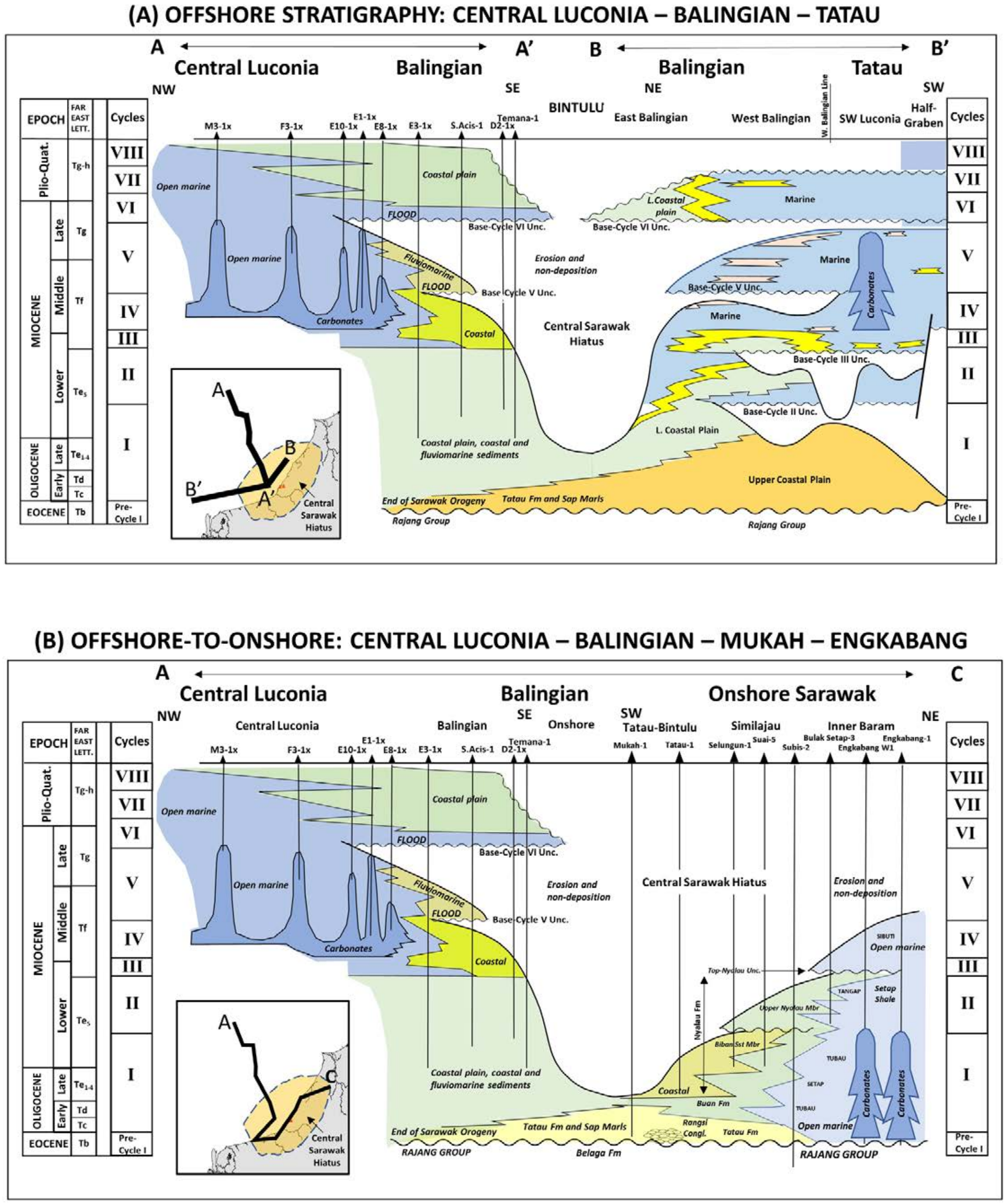

Figure 2: Stratigraphic summary of the Sarawak shelf and onshore central Sarawak. (A) General stratigraphic profile from Central Luconia to offshore Balingian to Tatau provinces showing the major stratigraphic relationships and unconformities. (B) Profile from Central Luconia to Balingian Province to onshore Tatau and Tinjar provinces showing the correlation between the offshore Cycles, onshore formations and major unconformities. Note that in the central offshore Sarawak (Balingian) the progressively "deeper" erosion (stratigraphically) from sea to land caused Cycle VI to rest directly on Cycle I in some parts of the nearshore and coastal areas. Also, the prominent erosion or non-deposition in the near offshore (Balingian) and onshore in the Bintulu-Suai-Subis area, as reported also by Lunt & Madon (2017, their figure 16), resulted in the prominent missing section, referred to herein as the "Central Sarawak Hiatus". Inset maps show the approximate profile locations. Beige shaded area in the inset maps represents the approximate extent of "Central Sarawak Hiatus". Compiled and modified from various sources, mainly Barrett & Kuek (1986), Madon & Redzuan (1999), Morrison & Wong (2004), Jong *et al*. (2016) and Lunt & Madon (2017). Horizontally not to scale.

It should be emphasized that the Central Sarawak Hiatus is due to a combination of non-deposition as well as erosion of pre-existing formations during successive tectonic/uplift events. It therefore represents a compound unconformity formed of several unconformities merged at the basin margin. Most unconformities would have been completely removed by younger subsequent events. Depending on the palaeotopography and basin geometry, it is still possible that vestiges of those unconformities may be preserved in places, especially on the basin margins. It may be difficult, however, to ascertain which of those unconformities have been eroded. This article describes one occurrence of such an unconformity and its possible interpretation.

OUTCROP NO. 7

The outcrop of interest, which we call Outcrop no. 7, is located about 25 km to the northeast of Bintulu (Figure 1). The main exposure is in a 100 m-long road cut on the east side of the Bintulu-Miri Road (Figures 3A, 3B). A smaller version of the outcrop can be seen on the opposite side of the road (Figures 3C, 3D). At the main outcrop (Figure 3A), there is a spectacular example of what appears to be a mudstone-filled channel-like feature with irregular, erosive basal surface cutting down into moderately tilted thickly-bedded sandstones. The channel-like feature has a characteristically sharp, locally spoon-shaped erosive base, with a mud-dominated sediment fill. An angular discordance between the bedding above and below the surface is observed as a truncation of the sandy beds by the erosive base of the channel-like feature. Internally, the mudstones above the erosive base have well-developed sigmoidal surfaces lined by thin cm-scale sandy and silty layers. When viewed from a distance, these surfaces appear to downlap onto the erosional surface (Figure 3A). Figures 4A and 4B show close-up views of these features.

The sandstones underlying the erosional surface are equally remarkable, not just because of the sheer thickness of some individual beds (over 2 m) but for the presence of large convoluted internal laminations that look like giant load casts or ball-and-pillow structures with associated intraformational soft-sediment deformation (Figure 4C). These loading features are 3–4 m high and are separated by vertical zones of deformation which seem like upward-moving mud-laden fluidized pipes between the downloading sand-rich load balls, akin to load-and-flame structures commonly seen at the base of massive turbidite sandstones. These features are probably gravity-induced soft-sediment deformation associated with rapid sedimentation and subsequent overpressuring, leading to the development of water-escape features.

A schematic log of the outcrop succession is shown in Figure 5. The overall succession begins with a coarsening-upward unit of heterolithic sand-mud facies overlain by a thick (~6 m) bed of fine-grained hummocky cross-stratified sandstones with the giant load cast features at the top. The erosional surface has at least 15 m of relief, from the lowest point to the top of the road cut. However, since the bedding of the underlying strata is inclined at angle of *ca.* 30° the actual relief (paleo-relief) on the erosional surface could be greater. Based on the log, it is quite apparent that the incision by the erosional surface into the underlying strata is at least 40 m. This suggests that that erosion represents a significant event, probably of a regional scale.

The log in Figure 5 is comparable with that of "Coastal Road Outcrop J" from Meor Hakif *et al*. (2013) which is reproduced in Figure 6. The hummocky cross-stratified sandstone beds in the lower part of the outcrop are interpreted as storm-generated deposits in a wave-dominated lower shoreface facies succession (WDS). The WDS facies succession is overlain by an approximately 10 m-thick interval of large-scale trough cross-bedded sandstones. This is in turn overlain by mudstones with an irregular and erosional basal contact. The sandstones and mudstones overlying the WDS is interpreted by Meor Hakif *et al.* (2013) as a fluvio-tidal channel (FTC) facies succession composed of several sand-filled, tide-dominated channel deposits. The rapid change in facies from thick-bedded hummocky cross-stratified sandstone erosively overlain by cross-bedded sandstones indicates a significant basinward shift in facies from WDS to FTC. Meor Hakif *et al*. (2013) identified a subaerial unconformity between the WDS and FTC, marking the start of a regressive cycle resulting from the basinward shift in facies due to lowering of base level. The FTC facies succession is interpreted as an incised valley fill deposited during the following transgressive cycle. However, while in the interpretation in Meor Hakif *et al.* (2013) the irregular erosive surface separating the FTC sandstone and overlying FTC mudstone units was not considered as a significant erosional surface, this study presents evidence that the erosional surface represents a major regional unconformity.

INTERPRETATION OF THE EROSIONAL SURFACE

During several visits to the outcrop, a common interpretation by geologists was that the erosional surface between the lower sandy and upper muddy parts of the FTC facies succession represents the base of a mud-filled channel (Figure 6). A closer look suggests, however, that the erosional surface is not sea-level related and that its tectonic significance has been overlooked. The internal stratification of the mudstone unit seems to suggest deposition by lateral accretion or down-current (northeasterly directed) foreset bedding. In fact, as shown in Figure 6, there are at least 3 successive erosional scours laterally stacked against one another to make up the erosional surface, indicating progradational or lateral accretion of the sediment filling the erosional scour.

A more obvious interpretation would be that there was a sudden drop in base level to erode part of the shoreface

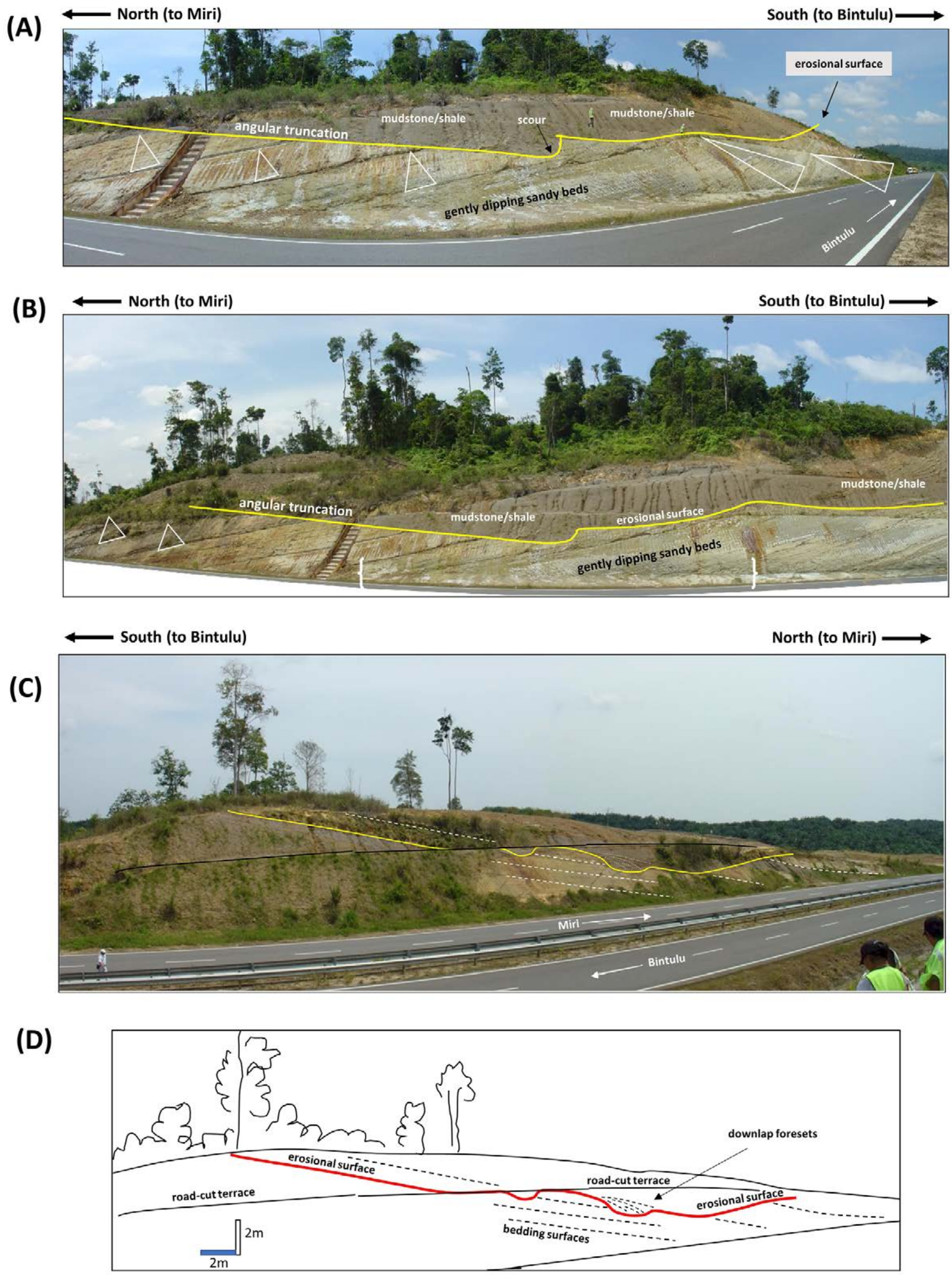

Figure 3: Field photographs of Outcrop no. 7 (see Figure 1 for location). (A) Panoramic view of the outcrop on the eastern side of Bintulu-Miri Road, looking approximately towards the southeast. The outcrop shows a large mudstone-filled channel-like feature, with a very sharp, scoop-shaped erosional base, cutting into thick-bedded sandstone sequence. White open triangles pointing upward represent fining-upward sandstone units. (B) The same outcrop in A, viewed towards the east, showing the prominent erosional surface. (C) Outcrop of the erosional surface at the same location but on the opposite (western) side of the road looking approximately towards the northwest. The irregular surface, shown by the thick yellow line, cuts into a sandstone-dominated unit and is filled by mudstone. (D) Line drawing of the outcrop in C, showing the unconformity marked in red bold line.

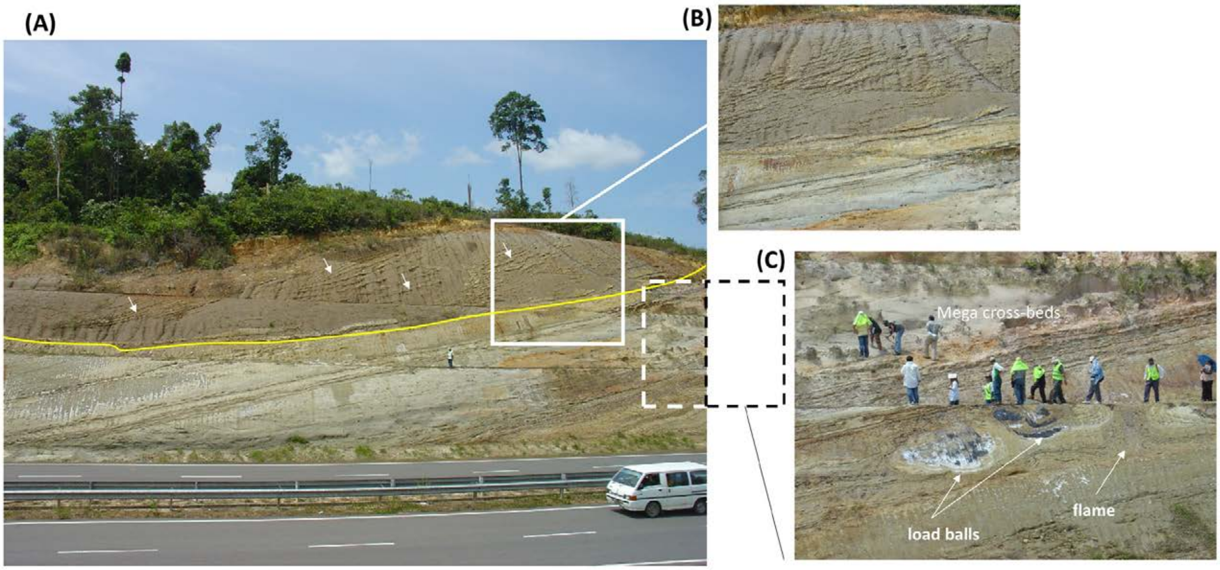

Figure 4: Closer views of Outcrop no. 7. (A) Concave-up erosional surface (yellow line) overlain by mudstone with inclined or sigmoidal bedding surfaces marked by thin sandstone/siltstone layers (white arrows). (B) Close-up of the white rectangle in A showing the internal stratification of the post-erosional mudstone, which could represent lateral accretion or down-current foreset bedding. (C) Photograph of rectangular area marked by dashed lines in A, partly off the field of view, in which thick bedded sandstones beneath the erosional surface show convoluted internal laminations that look like load casts or ball-and-pillow structures, with giant load balls and associated flame structures in between.

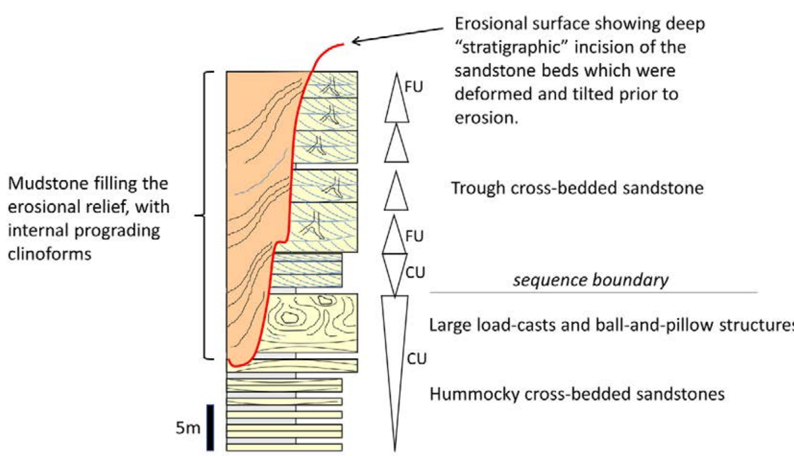

Figure 5: Schematic vertical sedimentary log of Outcrop no. 7 showing the stratigraphic relationships between a lower unit of sandstone beds and overlying mudstones separated by an erosive surface, which could be interpreted as a channel base or an angular tectonic unconformity. As the sandy beds are tilted relative to the horizontal, the erosive surface actually cuts down deep into the stratigraphy and thus is most likely to be post-depositional. CU - coarsening upward, FU - fining upward.

sands (e.g., "forced regression") due to tectonic movements (uplift of the hinterland), followed by rapid transgression and deepening of the environment (rising base level). The forced regression may have resulted in deep incision of the shelf, creating the concave up, spoon-shaped erosional surfaces. The structural evidence, however, suggests that this surface is not merely an unconformity created by a shifting shoreline or a change in sediment supply, but could be tectonic in origin and probably of regional significance.

The strongest evidence for the erosional surface being a regional unconformity is that it is post-deformational; the erosion occurred after the deformation and tilting of the sandy strata (WDS and lower FTC). The angular stratal relationships between mudstone fill above and sandy strata below the erosional surface indicate that the erosion did not occur just by the lowering of sea level, but was preceded by a tilting and uplift event. If the tilted strata are restored to the horizontal, we could see that there was a deep post-

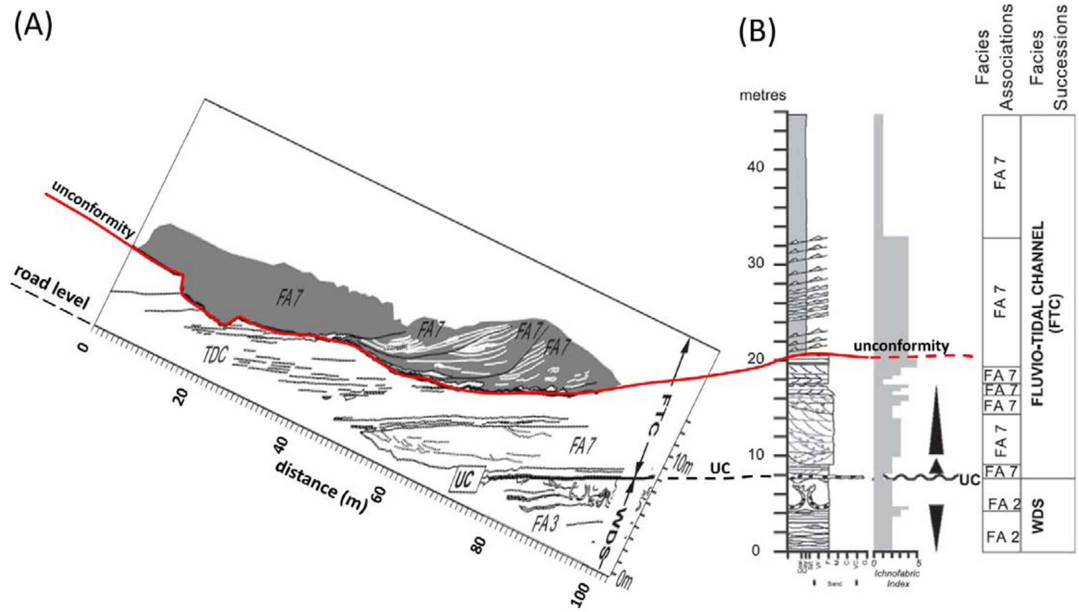

Figure 6: Field sketch and sedimentary log of Outcrop no. 7 from Meor Hakif *et al*. (2013, their "Coastal Road Outcrop J"). (A) Field sketch of the outcrop with interpretation of the facies sequences. Internal features in the mudstone suggest that the erosional surface is almost parallel to paleo-depositional surface and was produced after the underlying beds had been deformed and tilted. The outcrop sketch in A is rotated about a horizontal axis so that the tilted sandstone beds are horizontal and show the deep incision of the erosive surface into the pre-existing tilted strata. The angular discordance between the sandy beds and the mudstone above the erosional surface indicates that erosion was post-deformational, i.e., after the tilting of the sandstones. This suggests that it is a tectonic unconformity (marked red), as opposed to the minor unconformity (UC) or sequence boundary.

deformational stratigraphic incision into the underlying uplifted Nyalau Formation.

Below we examine further the evidences for the nature and origin of this unconformity based on a synthesis of the surrounding geology.

STRUCTURAL SYNTHESIS OF CENTRAL SARAWAK

Onshore structures

Most of the earlier studies on the Nyalau Formation had been restricted to the area around Bintulu town, near the Bintulu Airport, and to the southwest towards Tatau (e.g., Meor Hakif *et al*., 2013). More recent work has covered a much greater area to the northeast of Bintulu all the way to Subis (Hennig-Breitfeld *et al*., 2019; Breitfeld *et al*., 2020). The Nyalau Formation in this part of Tinjar Province is essentially lower coastal plain/delta plain coal-bearing deposits, comprising mixed wave- and tide-influenced coastal depositional systems (Meor Hakif *et al.*, 2013, 2017). The facies show increasing marine influence towards the northeast, consistent with the prevailing palaeogeographic model that shows a NW-SE oriented Oligocene-Early Miocene palaeo-coastline facing the sea to the east (Hutchison, 2005; Madon, 2013; Lunt & Madon, 2017; Hennig-Breitfeld *et al*., 2019; Lunt, 2019; Breitfeld *et al*., 2020).

Therefore, in contrast with outcrops to the west of Batang Kemena, where coal-bearing facies are common (Meor Hakif *et al.*, 2013, 2017), outcrops to the northeast indicate more open, shallow marine facies. Figure 8 shows some examples of the sedimentary facies observed in these outcrops. Exposures of the Nyalau Formation along the Pan Borneo Highway from Bintulu towards Similajau Industrial Park include tidally-influenced, thinly bedded sandstone-mudstone facies with ripple marks and abundant trace fossils (e.g., *Ophiomorpha*, *Planolites*, *Palaeophycus*, *Thallasinoides*), storm-wave generated sandstone facies with hummocky cross-stratification with gutter casts (traces include *Ophiomorpha nodosa*), a thick unit of offshore dark-grey mudstones with sideritic concretions, and occasionally metre-thick calcareous beds with shell fragments.

A major Late Miocene uplift event in the eastern Balingian (offshore) and adjacent Tinjar (onshore) provinces had created a pronounced tectonic unconformity over much of onshore and near offshore central Sarawak (Figure 2). This event was followed by a major transgression with the ensuing rejuvenation of clastic sediment supply from the uplifted hinterland. A change in sediment provenance from a westerly source (Malay Peninsula) to southeasterly source (Borneo) coincident with the *ca.*17 Ma unconformity at the top of the Nyalau Formation was described by Hennig-Breitfeld *et al*. (2019) and Breitfeld *et al*. (2020). As a result, the Nyalau Formation now exposed in Tinjar Province is characterized by an undulating topography due to the numerous NE-trending anticlines and synclines (Figure 7A) (Liechti *et al*., 1960; Hutchison, 2005). Some of the

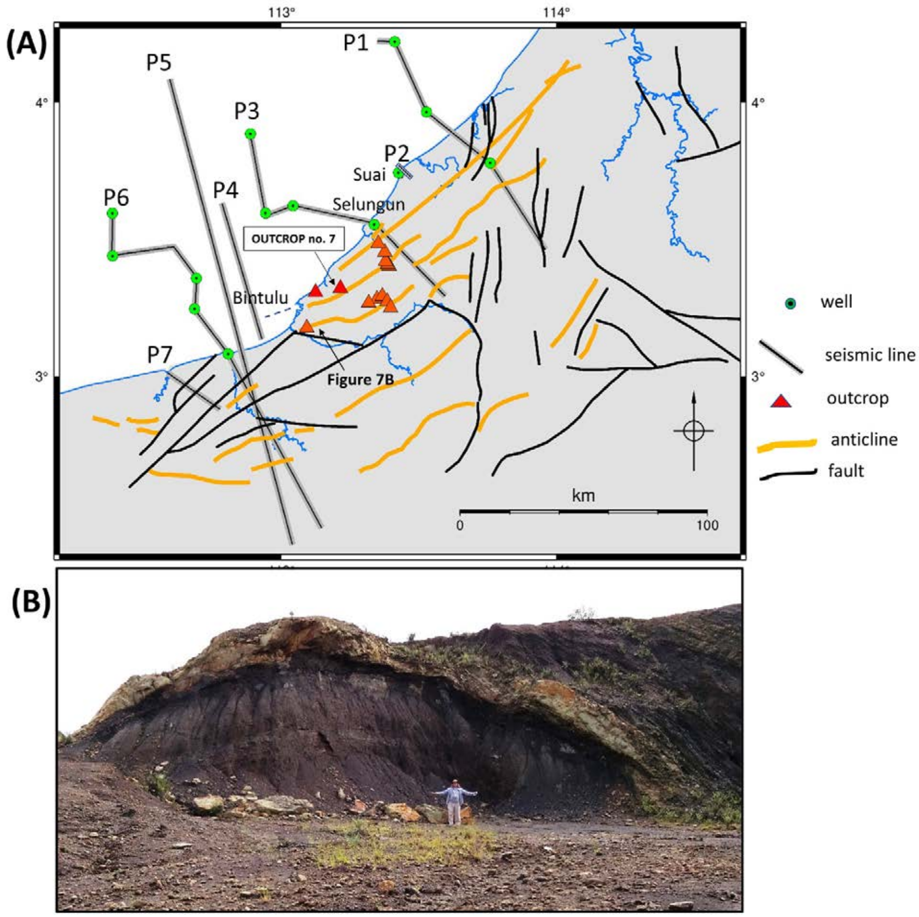

Figure 7: (A) Simplified structural map of central Sarawak with major anticlines and faults based on a map by Barrett & Kuek (1986). Location of geological cross-sections and wells are the same as in Figure 1, shown as reference for Figures 9 and 10. Red triangles are outcrop localities mentioned in the text. (B) Field photograph of shale-cored anticline near Bintulu town (Outcrop no. 6 in Figure 1C) at the western end of the Bala anticline.

anticlinal trends can be traced for a distance of up to 120 km, e.g., the one from Bintulu to Bulak Setap (Figure 7A). Another anticline, the Bala anticline, is partially exposed near Bintulu town to reveal a shale-rich core (Figure 7B).

In the onshore areas, the top of the Nyalau Formation was reported to be marked by an erosional surface (Wolfenden, 1960), but this is rarely preserved, as the region had been subjected to multiple episodes of uplift and erosion even up to Late Pliocene times (e.g., Kessler & Jong, 2015a, b; 2016a, b), causing much of the Nyalau Formation and younger strata to be eroded. Since onshore evidence is scarce, we can instead look in the offshore areas to understand the nature of this unconformity that cuts into the Nyalau Formation and its equivalents, Cycles I and II.

Onshore-to-offshore correlation

In the adjacent offshore area, Cycles I and II are generally correlated with the Nyalau Formation. This seems to be a widely held assumption by most workers (e.g., Mohd Idrus & Redzuan, 1999). Recent summaries of the onshore-to-offshore correlation essentially re-affirmed this correlation (Hennig-Breitfeld *et al*., 2019; Breitfeld *et al.*, 2020). The key points of these studies are that Cycle I is correlated with the lower part of the Nyalau Formation (Biban Sandstone Member; 37-22.5 Ma) and Cycle II with the Upper Nyalau Member (22.5-17 Ma). The authors noted, however, that no unconformity could be detected between Cycle I and Cycle II onshore. It is interesting that in their map of onshore central Sarawak, Barrett & Kuek (1986) essentially assigned the Nyalau Formation southwest of Batang Kemena to Cycle I and northeast of it as Cycle II, which is consistent with the recent studies. Breitfeld *et al.* (2020) further proposed that Cycle III (18-15 Ma) is probably equivalent to the Balingian Formation or the “Kakus unit” that overlies both the Biban Sandstone and the Upper Nyalau Member in central Sarawak. Ramkumar *et al.* (2018) dated a tephra layer of late Middle Miocene age (*ca.* 11.4-11.8 Ma) in the Liang Formation in the Mukah region, which suggests that it could be equivalent to Cycle IV (15.5 to 11.5 Ma) along with the Begrih Formation. Breitfeld *et al.*

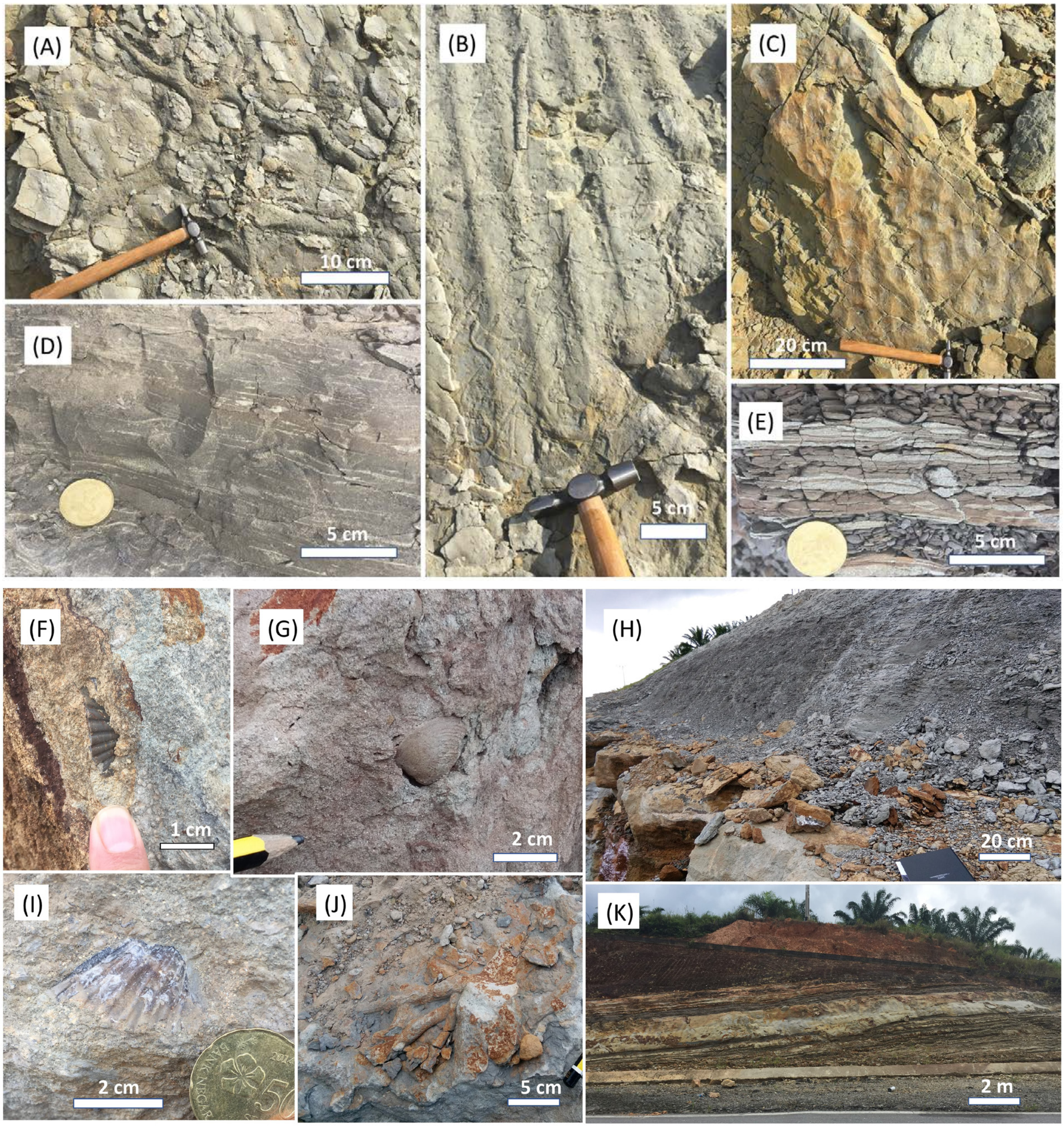

Figure 8: Field photographs of sedimentary features in the outcrops along the Pan-Borneo Highway and the Bintulu-Miri Road (locations in Figure 1C). Photographs A to E are from Locality 1, F to J from Locality 5 and photograph K from Locality 3. (A) Horizontal branching *Thallasinoides* burrows. (B, C) Ripple marks on bedding surfaces. (D) Lenticular bedding in mudstone. (E) Heterolithic sandstone-mudstone facies. (F, G, I) Fragments of bivalves in calcite-cemented sandstone (hardground?) horizon in thick mudstone interval (H). (J) Branching horizontal burrow (*Planolites*?). (K) Hummocky cross-stratified sandstone bed with gutter cast at the centre of the photograph.

(2020) suggested that Cycle V (*ca*. 11.5 to 5 Ma) could be correlated with the Tukau and Liang formations in the Miri area, which are of Late Miocene-Pliocene age (Sandal, 1996; Wannier *et al.*, 2011).

It is well-known from offshore studies by the oil industry (as summarized by Madon & Abolins, 1999), that Cycles I and II were subjected to deformation throughout the Sarawak Basin, which resulted in both extensional and compressional structures beneath a regional unconformity. In the offshore areas, both Cycles I and II are capped by an erosional unconformity, particularly in the western part of the Sarawak shelf (Lunt & Madon, 2017) (Figure 2B).

Post-Oligocene sedimentation in Sarawak Basin was also punctuated by at least three main tectonic pulses: Early Miocene (culminating in Base Cycle III Unconformity), Middle Miocene (Base Cycle V Unconformity) and Late Miocene (Base Cycle VI Unconformity). It is difficult to ascertain how these unconformities relate to onshore geology since much of the sedimentary record is missing at the Central Sarawak Hiatus (Figure 2).

The stratigraphic and structural relationships between the Oligocene units offshore (Cycles I to II) with the onshore formations can be seen more clearly from seismic profiles that cross the coastal plains and the near offshore in central Sarawak (black lines P1 to P7 in Figure 7A). These profiles are based mainly on the work of Shell and Oxy geologists in the late 1980s (Barrett & Kuek, 1986; Boodoo *et al.*, 1989) while some are from Ismail &Tucker (1999). In Line P1 (Figure 9A), the Nyalau Flexure Zone (NFZ) is an important structural feature that forms the northern limb of a northward-verging thrust anticline straddling the coastline at Subis. Well data and seismic interpretation in this area (Barret & Kuek, 1986) indicate that deformed Cycles I to V intervals are truncated by the Base Cycle VI Unconformity offshore. Base Cycle VI is roughly equivalent to Base-Pliocene Unconformity (Lunt & Madon, 2017). Cycle VI onlaps onto this unconformity, but due to a later episode uplift and erosion (probably intra-Pliocene), the Base Cycle VI Unconformity is unlikely to be exposed or preserved on land.

The NFZ continues southwestwards parallel to the coastline into the Suai area, where the core of the Suai anticline is made up of folded and upthrust Cycle I/II rocks, which are truncated by the Base Cycle VI Unconformity (Line P2, Figure 9B). The latter is in turn overlain by flat-lying Cycle VI sediments (Figure 9B). Therefore, the Base Cycle VI Unconformity marks the culmination of the deformation and thrusting of Nyalau and younger formation that may have been present but eroded. This same unconformity is seen offshore to the northwest where it truncates Cycle V strata at Cochrane-1 and A1-1X, indicating that it represents a late Cycle V deformation event. Cycle III, which may be conformable or partly disconformable with the underlying Cycles II in the offshore area, crops out in the Subis area and were generally mapped as Nyalau Formation but may now be part of the Kakus unit (Breitfeld *et al*., 2020) (Figure 9A). Hence, based on the offshore-onshore correlation, we can confidently establish that Cycle I and Cycle II are equivalent to the Nyalau Formation in the study area. Cycle III may be correlated with the Kakus unit or Balingian Formation, which is unconformable upon the Nyalau Formation (Breitfeld *et al.*, 2020).

Southwestwards from Suai, the coastline bends towards the headland at Similajau Industrial Park to cut across the NE-SW structural trend of Tinjar Province. We can see in Figure 7A that the four headlands between Suai and Bintulu are formed by the more indurated cores of the anticlines where they intersect the coastline. The well Selungun-1 was drilled in 1956 on a steep northward-dipping monocline part of the NFZ with its anticlinal core exposed landward. The well penetrated highly deformed Cycle I strata, which are on-trend with Suai along the NFZ. In the nearshore area Cycle I and Cycle II strata are shown in the cross-section to be overlain unconformably by Cycle VI sediments (Line P3, Figure 9C). Cycle I continues landward as Nyalau Formation which has been deformed into anticlines and synclines that impart the characteristic rolling topography (Figure 9C). Driving up and down the hills along the transverse link road between the Pan-Borneo Highway and Similajau Industrial Park one could observe the structural dip changing from one anticlinal limb to another.

As the coastline cuts across the Tinjar fold belt diagonally between Suai and Bintulu (Figure 7A), the NE-SW trending anticlinal structures can be correlated with the offshore structures in several seismic profiles. Figure 10A is an interpreted N-S seismic line (P4 in Figure 7A) from Ismail &Tucker (1999) located west of Bintulu. The profile shows the crests of compressional anticlinal structures eroded and overlain unconformably by flat-lying Cycle V and Cycle VI sediments. These structures were interpreted by Ismail &Tucker (1999) as positive flower structures caused by wrench fault activity of the NFZ (which lie within ~10 km from the coastline) during Late Miocene times and are truncated successively by the Base Cycle V and Base Cycle VI unconformities. The anticline on which Outcrop no. 7 is located may be traced westwards (dashed line in Figure 7A) from south of Bintulu town into the offshore Balingian sub-basin just south of Temana in Figure 10A. We can see that the anticlinal crests are truncated by flat lying strata starting with Cycle V upwards. This suggests that the deformation event that caused the folding occurred sometime between Cycle IV and Cycle V times (Middle to Late Miocene). It is important to note also from this profile that Cycle II is truncated by the Base Cycle III Unconformity, indicating a earlier deformation/uplift event in the Early Miocene.

In Figure 10B a N-S section across the NFZ (Line P5 from Othman *et al*., 2001) shows outcropping Cycles I and II (Nyalau Formation) south of the Tatau Horst, whilst Cycles V and VI which onlap onto the structure from the north are absent on land. Similarly, older units down to Cycle II are eroded on the crests, and are overlain unconformably by relatively undeformed Cycles V and VI strata. The boundary between Cycle V and VI is a major unconformity – Base Cycle VI Unconformity (Figures 9A, 9C, 10C), whereas the Base Cycle V Unconformity is pronounced only locally on the crests of anticlinal structures (Figure 10A). In Figures 9 and 10, we observe that Cycle V and Cycle VI tend to be eroded away in the onshore towards the northeast but are preserved offshore.

The NFZ is partially exposed in the Similajau area where small-scale strike-slip and thrust faults can be seen at outcrop (Figure 11). On a large scale, fold orientations

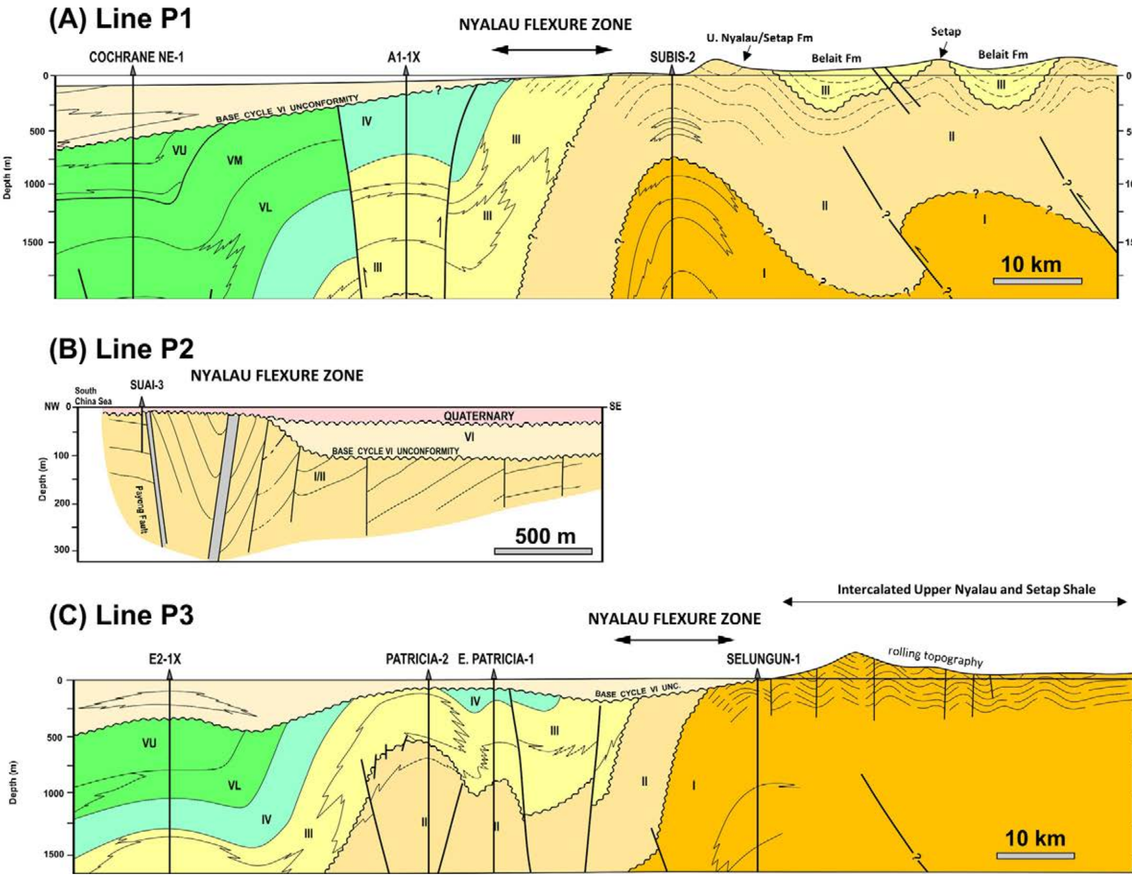

Figure 9: NW-SE geoseismic profiles across the onshore Tinjar Province (right) to offshore Balingian Province (left), showing the stratigraphic relationships of the Sarawak Cycles based on seismic interpretation and onshore formations. (A) Line P1 across the Subis area. (B) Short Line P2 at the Suai coast. (C) Line P3 through the Similajau Industrial Part where well Selungun-1 is located. Note the main structural elements, in particular the Nyalau Flexure Zone. The Nyalau Formation is correlated roughly with the offshore Cycles I and II, overlain by Cycle III. The latter is thin or absent in most places but preserved in synclinal areas in the interior regions, where it is mapped as the Belait Formation (Liechti *et al*., 1960, as shown in A). The Setap Shale is considered the fine-grained equivalent of the Nyalau and tends to interdigitate with it. Lines P1 and P3 have the same scale; Line P2 has 20 times the horizontal scale of Line P1. All cross-sections were redrawn and modified from Boodoo *et al*. (1989).

on either side of the NFZ (onshore and offshore) suggests that its main displacement was by left-lateral shear, as was documented by earlier workers (e.g., Madon & Abolins, 1999). Fault patterns in the Temana field also indicate NE-SW oriented left-lateral shear (Hasegawa *et al*., 2005). Southwest of Tg. Kidurong, the NFZ bends southwesterly towards Tatau to merge with the NE-SW trending Anau Fault, marking the northwestern edge of the Tatau "Horst" (Line P6, Figure 10C). At the well-known outcrop along the Tatau-Bintulu road at the southern edge of the Tatau Horst, the 37 Ma Rajang Unconformity clearly separates folded Belaga Formation from overlying Rangsi Conglomerate (Ismail, 2000; Hutchison, 2005; Madon *et al*., 2013; Hennig-Breitfeld *et al*., 2019; Breitfeld *et al.*, 2020). An interpreted land seismic profile from Ismail (2000) (Line P7, location in Figure 7A) shows an eroded Tatau Horst onlapped and overlain by a TS4 unit (equivalent to Cycle V) which he interpreted as the Rangsi Conglomerate and correlated it with the Balingian Formation of Late Miocene age. This interpretation which was reproduced by Hutchison (2005) is inconsistent with the cross-sections in Figure 10B and Figure 10C wherein Cycle V and VI are absent from the Tatau Horst. Subsequent works have confirmed that the Rangsi Conglomerate is Early Oligocene in age (Wong, 2011; Hennig-Breitfeld *et al*., 2019; Breitfeld *et al.*, 2020).

The Anau-Nyalau Fault Zone, as the combined structure is called, appears to be a strongly asymmetric thrust anticline with a seaward-dipping monoclinal limb formed of Cycles I-V overlain unconformably by Cycle VI sediments (Figure 10C). Between Tatau and Bintulu, the Anau-Nyalau Fault Zone is mostly covered by Quaternary sediments but seismic data show that beneath the coastal plains north of the Tatau Horst Cycle VI sediments overlie deformed Cycles I and II strata. A major phase of uplift (probably of Tf3 age) led to the erosion of pre-Cycle VI sediments southeast of Temana, as has been reported by Madon & Abolins (1999). Cycle VI seems to represent the last phase of sedimentation that followed a widespread, laterally extensive Base-Pliocene

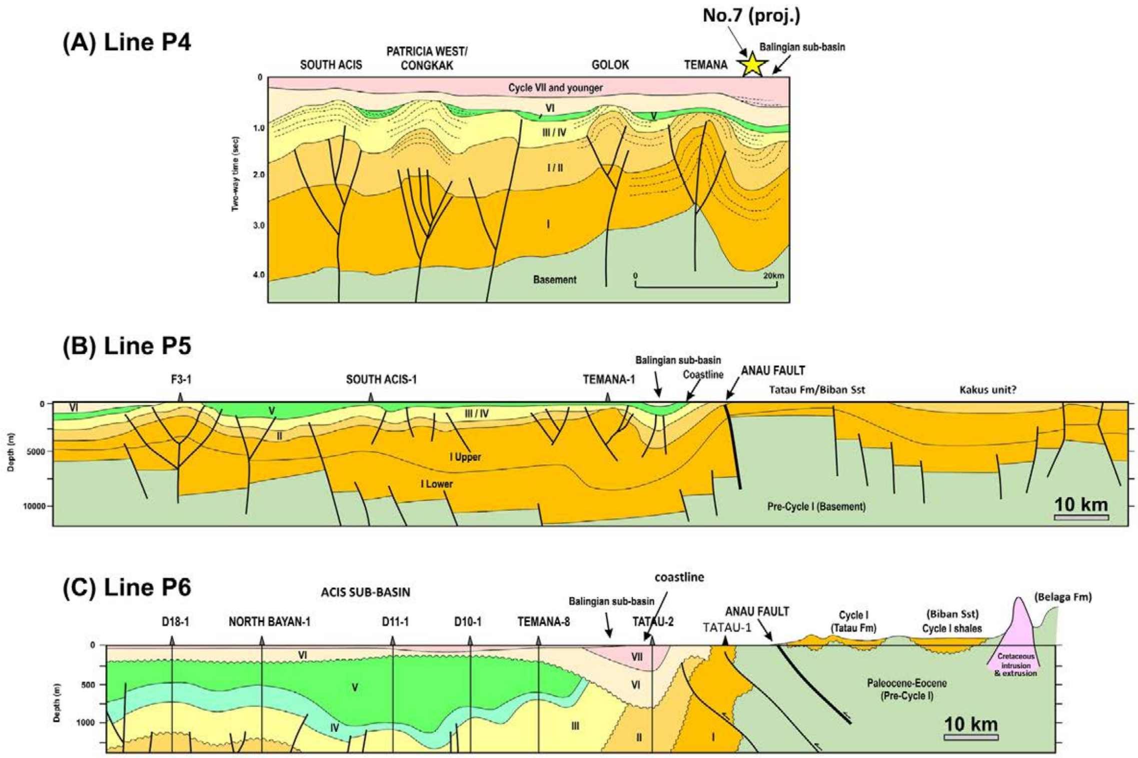

Figure 10: Geoseismic profiles across the coastal plain and near offshore, central Sarawak. (A) Line P4, which is Line F from Ismail & Tucker (1999), shows the eroded crests of transpressional flower structures formed by a Late Miocene deformation event, probably late Cycle V times, based on the preservation of deformed T4S (equivalent to Cycle V) sediments in the synclinal areas. Yellow star indicates the approximate lateral position along strike from Outcrop no. 7. (B) Line P5 is a profile from Othman *et al.* (2001) at the same horizontal scale showing the main structural style across offshore Balingian towards the hinterland in central Sarawak. Cycles I-III are shown schematically to crop out onshore as the Tatau Formation, Biban Sandstone and possibly also the Kakus unit. (C) Line P6 shows the Balingian sub-basin north of the coastline where Tatau-2 well is located. The sub-basin appears to be a flexural depression formed as a result of the northward-verging thrust front along the Anau-Nyalau Flexure Zone. Cross-section modified from Boodoo *et al.* (1989).

transgressive surface (Base Cycle VI, or Base TS5 of Ismail &Tucker, 1999) covering much of the peneplaned and deformed pre-Cycle VI strata. In Figure 10C, Late Pliocene deformation caused an increase in subsidence in the Balingian sub-basin above the Base Cycle VI Unconformity, which is probably related to an Intra-Pliocene Unconformity identified in NW Sarawak at the base of the Liang Formation in the Miri area (Kessler & Jong, 2017) and probably also in adjacent Brunei (Sandal, 1996).

NATURE OF THE UNCONFORMITY

There are several possible interpretations for the unconformity at Outcrop no. 7 and the overlying post-Nyalau sediments, which are equivalent to Cycle III or younger. Figure 12 shows the distribution of known post-Nyalau outcrops in the study area. As mentioned above, Cycle III is very thin offshore and rarely preserved, while almost absent onshore. The Kakus unit which lies unconformably upon the Upper Nyalau Member in central Sarawak is a possible Cycle III equivalent (Breitfeld *et al.*, 2020). The Miocene formations considered to be equivalent to Cycle IV and V include Lambir, Belait, Miri in the NE (Miri and Brunei areas) and Balingian, Begrih and Liang in the SW (Mukah-Balingian area). Other than possibly Tukau, which could be Cycle V as well, Cycle VI is also practically absent. The Liang Formation in the Miri and Brunei regions is generally considered to be of Late Miocene-Pliocene age (e.g., Sandal, 1996; Wannier *et al.*, 2011; Kessler & Jong, 2017) and may be equivalent to Cycle VI.

A possible correlative of Outcrop no. 7 is located 10 km away, along the coastal road to the Similajau National Park (Outcrop no. 9, longitude 113.1245164° E, 3.314829556° N, Figure 12). Outcrop no. 9 (Figure 13) exposes a slightly tilted sand-rich unit of thick-bedded, trough or tabular cross-bedded fine-grained sandstone, showing low to moderate bioturbation, with interbedded coal seams and dispersed carbonaceous debris and clasts. The irregular, angular unconformity surface cuts down into the sandy unit and is overlain by subhorizontal beds of relatively soft mudstones and minor sandstones with coal layers. The sandy unit below is clearly part of the Upper Nyalau Member in which sedimentary features indicate high-energy estuarine

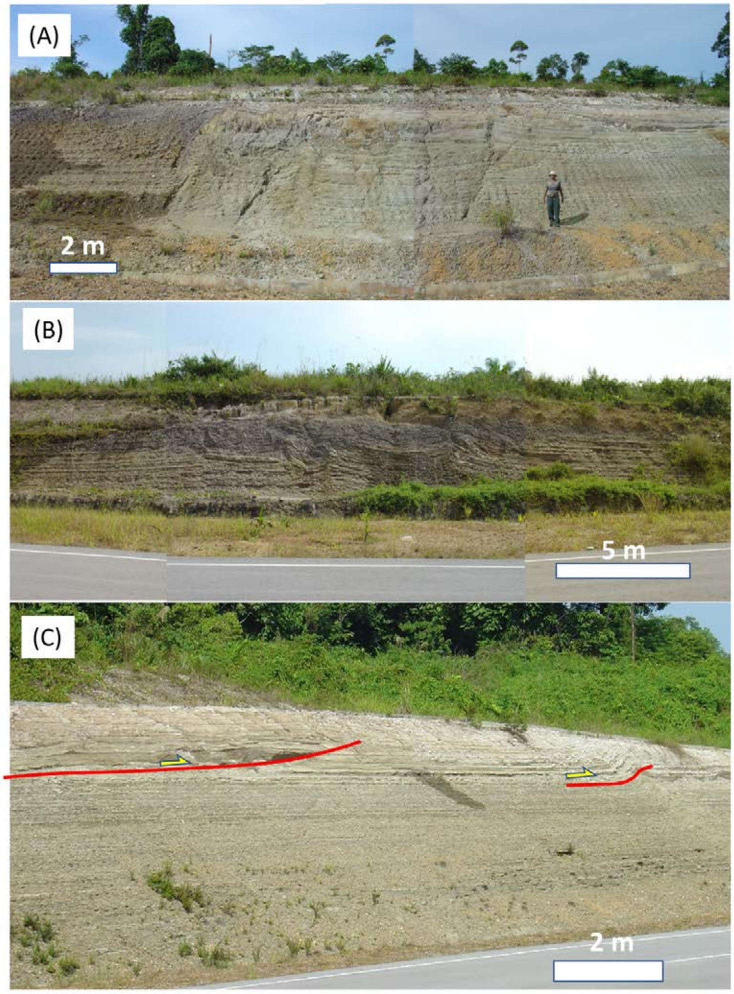

Figure 11: Some examples of small-scale deformation observed in the vicinity of the Nyalau Flexure Zone at the Similajau Industrial Park. All examples are from the same locality (location in Figure 1). (A) Steep, branching faults in sandstones, likely to be strike-slip or wrench faults. (B) Small compressive deformation zone due to wrench faults. (C) Small-scale thrust faults (marked by red line) in sandstones.

channel-fill facies. Similar facies were observed in other outcrops in the Bintulu area (Meor Hakif *et al.*, 2013). The lithology and sedimentary features of the sediments above the unconformity are similar to the Liang Formation in the Mukah area described by previous authors (Liechti *et al*., 1960; Murtaza *et al*., 2018; Hennig-Breitfeld *et al*., 2019; Breitfeld *et al*., 2020). The post-Nyalau sediments at Outcrop no. 7 may be correlated with those at Outcrop no. 9 even though the sedimentary facies may be different due to lateral facies change. As mentioned, based on Ramkumar *et al*. (2018), the Liang Formation in Mukah-Balingian region is of late Middle Miocene age, equivalent to Cycle IV.

In the geoseismic profiles shown in Figures 9 and 10, Cycles IV, V and VI are generally limited to the coastal areas where they onlap onto older uplifted units along the Anau-Nyalau Fault Zone but do not extend inland. Since Cycles V and VI equivalents on land mostly occur in NE Sarawak and Brunei, it is unlikely that post-Nyalau sediments at Outcrop no. 9 are correlatives of those formations. A correlation with the so-called "Brunei Liang" (Late Miocene-Pliocene) is therefore considered highly unlikely. However, a Cycle IV or even Cycle III age for the sediments above the Nyalau in the Suai-Bintulu area is consistent with the increasing age of outcropping strata from NE to SW (Figure 2B).

An important observation made by Liechti *et al*. (1960) was that the post-Nyalau formations occur along the coastal belt from the Mukah-Balingian area to the Suai coast and further NE into the Miri/Brunei region but rarely extend further than 45 km inland. These main occurrences appear to be at the margins of the Balingian sub-basin, a Late Miocene depocentre bounded to the west and south by the West Balingian Line and the Anau-Nyalau Fault Zone, respectively. The depocentre is also clearly identified by a prominent gravity anomaly low (Figure 12). It is likely that these isolated pockets of post-Nyalau sediments were preserved at the faulted margins of the basin that were

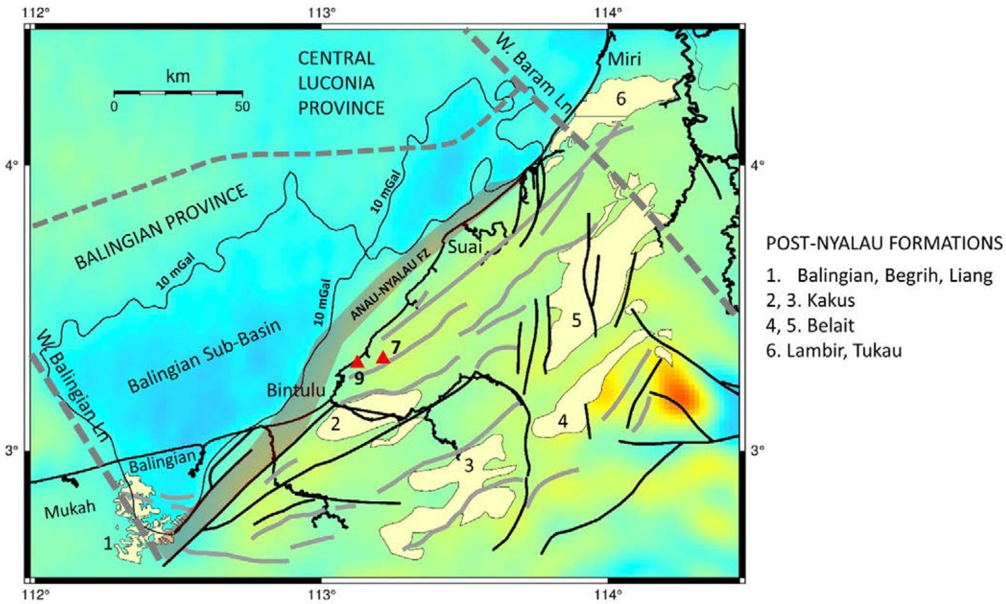

Figure 12: Map of study area in central Sarawak showing the distribution of post-Nyalau formations that may be correlated with the post-Nyalau mudstones at Outcrop no. 7 and possibly also Outcrop no. 9. Both outcrops are probably correlatives of the late Middle Miocene formations (Balingian, Begrih and Liang) in the Mukah-Balingian region (labelled area 1) that are exposed at the highly faulted margins of the Balingian sub-basin, marked by the West Balingian Line and the Anau-Nyalau Fault Zone. Background map is free-air gravity anomaly from Sandwell *et al.* (2014) grid version 30.1; warm colours represent high anomaly; cool colours represent low anomaly. The outline of the Balingian sub-basin is roughly indicated by the 10 mGal gravity anomaly contour. The post-Nyalau formations (equivalent to Cycles III, IV and V) onlap onto the basin margins and are exposed at the surface due to later uplift. Another possible correlation is the Kakus unit (labelled area 2) which is unconformable upon the Biban Sandstone (Lower Nyalau) (Breitfeld *et al*., 2020). Correlation with the more remote and generally sandy Belait, Lambir and Tukau formations is considered unlikely.

subjected to deformation and uplift during Late Miocene tectonic activity.

Alternatively, the mudstone above the unconformity could be equivalent to the Kakus unit which is described as being unconformable upon the Upper Nyalau Member and therefore probably equivalent to Cycle III (Breitfeld *et al*., 2020). Based on onshore well and outcrop information clearly cuts into progressively older stratigraphy from NE to SW parallel to the coastline (Figure 2B). Differential uplift in the southwest and tilting towards the northeast had resulted in Cycle III (Kakus unit) generally missing except in the Bala Anticline and Segan Syncline area, south of Bintulu, suggesting an important structural control on its preservation (Figure 12). In the Tatau area, SW of Bintulu, Cycle II (Upper Nyalau) has been eroded such that Cycle III (possibly Balingian Formation) rests directly on tilted Cycle I (Biban Sandstone) (Hennig-Breitfeld *et al.*, 2019; Breitfeld *et al*., 2020).

CONCLUSIONS

Based on the above synthesis, the unconformity at Outcrop no. 7 represents an eroded surface at the top of the Upper Nyalau Member (Cycle II), and may be interpreted as the ~17 Ma unconformity identified by Hennig-Breitfeld *et al.* (2019) as the "Top-Nyalau Unconformity". In the absence of actual dates, the post-unconformity sediments at Outcrop no. 7 may be correlated with any of the three post-Nyalau formations in the Mukah-Balingian region (Balingian, Begrih, Liang). On the basis of lithology and facies, it is not possible to determine which of those formations the post-Nyalau mudstones at Outcrop no. 7 likely belong to. The Begrih is a relatively coarse sediment with gravel conglomerates (see e.g., Murtaza *et al.*, 2018; Hennig-Breitfeld *et al.*, 2019), which is unlike the post-Nyalau sediments observed at Outcrop no.7. Massive mudstones seem more prevalent in the Balingian or Liang formations. Hence, the post-Nyalau strata at Outcrop no. 9 may be tentatively correlated with the Liang Formation (late Middle-Miocene). Another possible correlation is with the Kakus unit, which Breitfeld *et al*. (2020) inferred to occur unconformably above the Upper Nyalau Member. It is recommended that future work should include dating the sediments and unconformities using biostratigraphic and other means.

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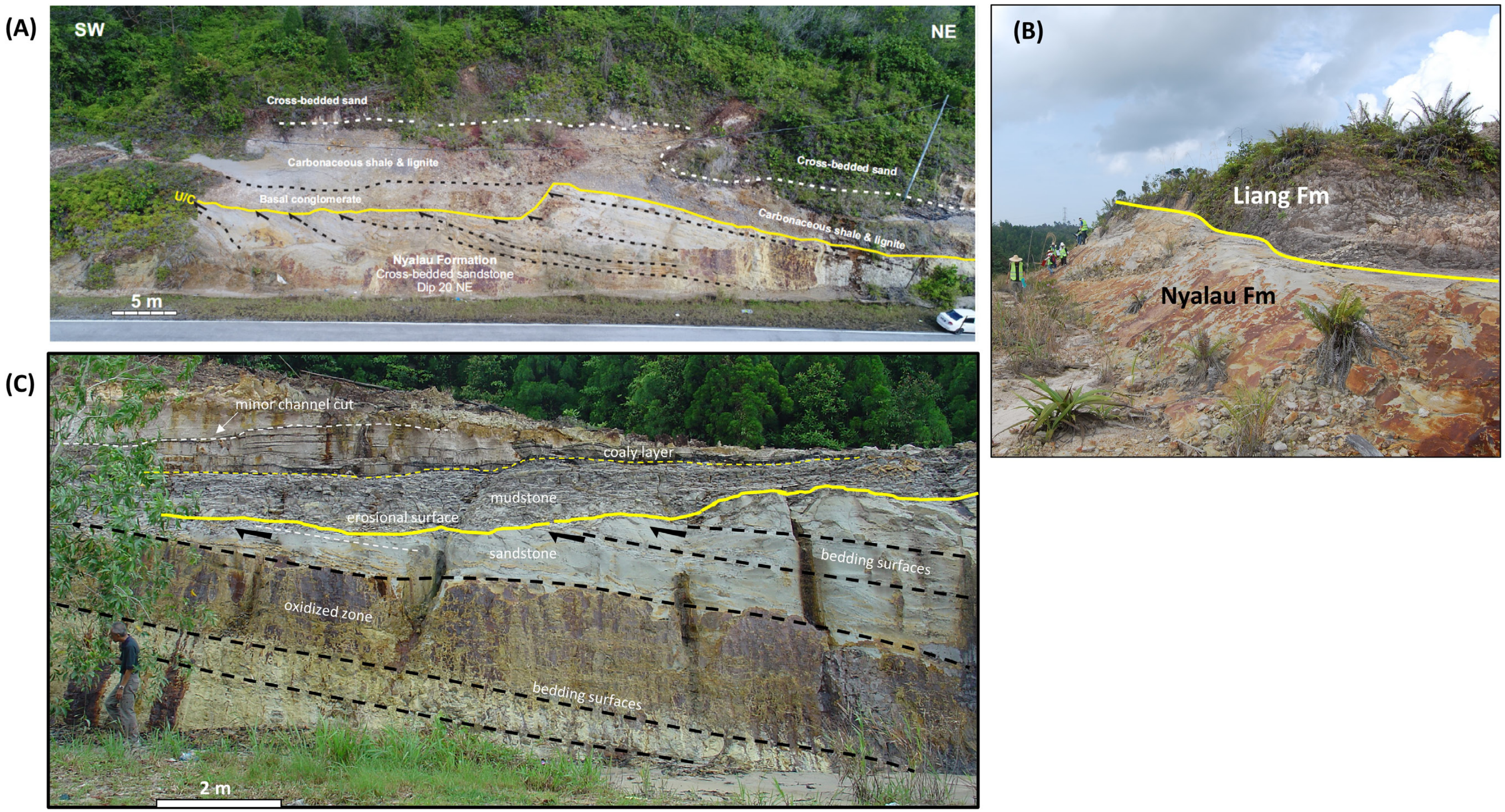

Figure 13: Field photographs of Outcrop no. 9, which is located near the coast, about 10 km from Outcrop no. 7. See Figure 12 for location. (A) Sketch of Outcrop no 9. showing gently tilted Upper Nyalau strata comprising cross-bedded fine-grained sandstones and minor mudstones and coaly beds, overlain unconformably by flat-lying mudstones and sandstones with coaly layers, tentatively assigned to the Liang Formation. (B) Oblique view of the outcrop and the unconformity between the Nyalau and ?Liang formations. (C) Closer view of a part of Outcrop no. 9, to the left of the photograph in A. Sandstone beds of the Upper Nyalau Member, including a bedding-parallel weathered/oxidized zone, are truncated by the unconformity (yellow line), above which is a flat-lying sequence of mudstone, coal/lignite and sandstone. Note a minor channelised sandstone in the upper left of the photograph.

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AUTHOR CONTRIBUTIONS

MM - paper conceptualization, field data interpretation, drafting maps, writing original draft and editing (lead); MHAH - field data interpretation, writing (supporting), JJ - regional analysis, writing and editing (supporting), figure redrafting.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare in connection with this article.

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