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Penecontemporaneous deformation in the Nyalau Formation (Oligo-Miocene), Central Sarawak

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Abstract: In the Nyalau Formation (Late Oligocene to Early Miocene in age) exposed near Tg. Similajau and Bintulu areas, structural features indicate that penecotemporaneous deformation is common. These features include (1) "disharmonic" thrusts and associated folding within shaly intervals, (2) detached normal and reverse faults within mud-dominated intervals, (3) subtle stratal termination and onlap patterns associated with faulting, folding and (probably subaquaeous) erosion of the sedimentary layers, (4) slump and load structures within lower shoreface to offshore-transition successions. These characteristics may be a common feature in deforming foreland basins, and indicate the importance of tectonic over eustatic controls on sedimentation and sequence development in the Tertiary NW Borneo basins.

INTRODUCTION

Foreland basins are commonly subjected to penecontemporaneous deformation (i.e. deformation occurring during or soon after sedimentation) arising from the prevailing tectonic stress associated with plate convergence. As a result, stratigraphic development of foreland basins is often punctuated by deformation events that disrupt the otherwise continuous subsidence and sedimentation. Such events are visible as regional or sub-regional unconformities that are seen particularly in the hinterland area, where erosion occurs in response to isostatic uplift of the deforming fold-thrust belt. These tectonic effects were recognized in the Neogene succession in offshore NW Sabah as major unconformities or sequence boundaries produced by basement-involved compressional/wrench tectonics (Levell, 1987).

Besides regional unconformities and hiatuses, compressional basin successions may preserve the more subtle tectonic imprints on sedimentation in the basinward position, which is less directly affected by sea-level fluctuations, i.e. subtidal as opposed to shoreline/coastal environments. In this paper, we describe some evidence for penecontemporaneous deformation in the Oligo-Miocene Nyalau Formation, central Sarawak (Figure 1), which signify the close interplay between sedimentation and tectonics in this formerly active deforming foreland basin.

REGIONAL SETTING AND STRUCTURAL STYLES

That the Sarawak Basin (i.e. post-Rajang Group "flysch" succession) evolved as a foreland basin has been illustrated by James (1984) and Koopman (1996). Our knowledge of the region suggests that the onshore Sarawak area has had a similar geological history to that of the NW Sabah region, involving plate convergence and the initiation of a peripheral foreland basin above the subducting proto-South China Sea lithosphere (Madon, 1999; Madon *et al*., 2007). The continuing compressional deformation since Oligocene times has clearly influenced the sedimentation and structural styles in the Sarawak Basin. In the inboard regions of the basin (Balingian and Tinjar provinces) the structures indicate compressional deformation of the Oligo-Miocene post-Rajang Group succession, which includes the shallow marine to coastal sediments of the Nyalau, Setap, Sibuti, Tukau, Miri and Belait, which may be termed collectively post-orogenic "molasse" deposits. Structural styles are dominated by compressional structures, including wrench-related folds and faults (M. Idrus and Redzuan, 1999).

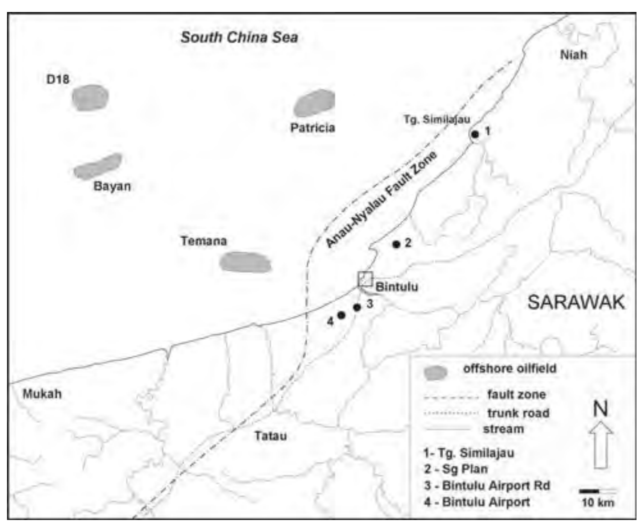

Figure 1: Location of outcrops described in this paper.

THE NYALAU FORMATION OF CENTRAL SARAWAK

The Nyalau Formation in central Sarawak is dominated by shallow marine, coastal and intertidal facies. Sedimentological studies have been carried out by previous workers, mainly in the Bintulu area (e.g. Abdul Hadi, 2001; Shushan *et al*., 2006). The common facies types include hummocky cross-stratified sandstones and heterolithic sandstone-mudstone facies of varying sand-mud proportions, displaying the full spectrum of flaser, wavy to lenticular bedding fabrics. Some parts of the Nyalau Formation are coal-bearing and are of interest to petroleum geochemists (e.g. Wan Hasiah, 1999). The heterolithic facies have features indicative of strong tidal influence, such as mud drapes and flaser structures, tide-generated herringbone cross-stratification and sigmoidal foreset laminae. Figure 2b is an example of tide-generated cross-bedding in sandstone at the base of the Tg Similajau outcrop. The results of on-going sedimentological studies will be reported elsewhere.

DEFORMATION STRUCTURES

In this paper, penecontemporaneous deformation structures from two outcrop localities are described. They are (1) within the grounds of the new Bintulu Airport, about 21 km from Bintulu town, and (2) along the new Bintulu-Miri coastal road, near Tanjong (Tg) Similajau (Figure 1).

"Disharmonic", layer-bound deformation

A commonly observed feature in the Nyalau formation is the occurrence of deformation zones that appear to be "disharmonic", i.e. the deformation is restricted to a certain interval in the succession, mainly in the shaly or mud-dominated interval. The adjacent strata above and below the deformed zone are undeformed. Ordinarily, this type of structure would be regarded as disharmonic, if it is assumed that the entire section, including the layers above and below the deformed layer, is subjected to the same deformation event. However, a closer inspection of some of these thrust faults show that they terminate at a certain horizon that is often represented by a marked lithological change (e.g. shale-sand contact) and/or an erosional surface. This suggests that such layer-bound deformation structures were formed soon after the deformed layer had been deposited, but before burial by the overlying sediment. Also, the upper bounding surface seems to record a period of non-deposition and/or erosion after the deformation event. These structures vary in scale: at the Bintulu Airport outcrop, a major low-angle thrust fault (apparent dip c. 20°) is about 50 m long, but at the Tg Similajau outcrop, the faulted sedimentary layer is about a metre or so thick.

Figure 2b shows a panoramic view of the outcrop facing the Bintulu Airport terminal and carpark, viewed approximately eastwards. It shows the typical structural style of the Nyalau formation – overall, gently to moderately dipping strata with occasionally very steep dips that indicate a tight fold axis or fault zone nearby. The thick vegetation overgrowth on the outcrops has obscured the structural relationships. However, a low-angle thrust fault is inferred to occur based on the abrupt change in bedding attitudes and actual exposure of the fault, particularly at site A23. In Figure 3a, at site A23, the thrust fault is observed to terminate within a shaly interval, which evidently had accommodated the strain caused by slip on that thrust fault. Complex deformation of this partly ductile shale interval was able to take up the strain, partly by faulting and partly by folding, as shown in Figure 3b. The presence of a relatively thick ductile shale layer in the succession may have prevented the thrust to propagate upwards by "absorbing" the deformation.

A small-scale thrust system

At the Tg Similajau outcrop, a very low-angle thrust is observed within a thinly bedded heterolithic sand-mud interval (Figure 4a), which had resulted in the thickening of the layer due to repetition of the stratigraphy. Without examining the outcrop closer, the presence of the thrust and other related structures would have been missed, as the layers above and below do not show any displacement or deformation.

Shown in Fig, 4b, a sequence of events could be inferred from the stratal patterns and relationships in this outcrop.

1. deposition of Bed 1.
2. deposition of Bed 2, followed by compressional faults 2a, 2b, 2c and 2d.
3. deposition of Bed 3 (probably preceded by a phase of erosion).
4. normal fault 3a cuts Bed 3 downwards, soling out at the pre-existing fault 2a.
5. deposition of Bed 4.

The Tg Similajau outcrop shown in Figures 4a and 4b is a fine example of a small-scale thrust system developed soon after the sedimentary layers were laid down, presumably after the sediments have attained a certain degree of cohesion at relatively shallow burial depths. The deformation front appears to have propagated southeastwards (to the right of picture), judging from the increase in the fault-dip angles towards the right. The low-angle thrusts are easier to fail and slip, causing the layer to thicken slightly where displacement and stratigraphic repetition have occurred, whereas the higher-angle faults to the right have negligible displacements on them.

Normal faults

Although the deposition of the Nyalau sediments took place under a compressional stress regime (e.g. James, 1984), there are instances where normal faults occur in close association with reverse and/or thrust faults. The Tg Similajau outcrop indicates that tectonic stresses change directions through time, in this example, from compressive to tensional. An interesting example is observed at the Tg Similajau locality, where the normal faults were evidently formed after the thrust system had been buried by the overlying layer (Figure 4c). The very sharp, albeit subtly erosive, contact between the thrust-deformed layer and the overlying less sandy layer (Figures 4a and 4b) suggests that there had been a phase of erosion or non-deposition after the thrusting event. The overlying layer was subsequently affected by high-angle normal faults, which are also non-penetrative and limited only to that layer. In Figure 4b, the normal fault cuts downward and soles out along the pre-existing thrust plane, perhaps taking advantage of the clay smear that may have resulted from the earlier deformation. The resulting bend in the fault has produced a fault-bend fold or "rollover" structure in the hangingwall of the normal fault.

Detachment surfaces

A frequent feature of the penecontemporaneous deformation structures is that faults that cut through the deformed layer tend to sole out along a detachment (or *decollement*) surface at or near the base of the deforming layer (e.g. Figure 4). Such behaviour is observed in both reverse and normal faults. The presence of detachment surfaces enabled the strain to be accomodated totally by the deforming layers. Figure 5 shows another example from the same deformed layer at Tg Similajau, of a normal fault that distinctly soles out along a detachment surface above a basal sandstone layer. Based on this example, it appears that detachment surfaces do not necessarily require thick shale beds to exist. The presence of ductile shale interbeds has been shown to exert a strong influence on the formation, evolution and geometry of thrust faults in foldbelts (e.g. Gestain *et al*., 2004). In the Bintulu outcrop (Figure 3c), shale interbeds may also act as a ductile deformation zone into which thrust faults propagate and terminate.

Stratal terminations and onlap

A manifestation of penecontemporaneous deformation in the Nyalau Formation is the occurrence of subtle erosive, stratal terminations or truncations which, evidently, have resulted from post-kinematic erosion of part of the deformed layer. Both outcrop localities in Bintulu and Similajau show evidence of such erosive events associated with the penecontemporaneous deformation. At the Bintulu outcrop (sites A22 and A24) onlap (Figure 6) and truncational patterns (Figures 7a and 7b) are observed. Both are clearly related to penecontemporaneous deformation, i.e. folding of the rock layers, probably related to thrust or reverse faulting. In Figure 7b, a series of low-angle thrusts are seen to terminate below the erosional bounding surface that marks the base of the post-kinematic layer.

In Figure 2a, at the Tg Similajau outcrop, there is a concave-up erosive surface which may also be a tectonically induced feature related to the deformation of the Sarawak foreland. The sedimentary environments indicated by the lithologies and sedimentary structures in these sediments suggest that the erosional surfaces were probably subaqueous, for there is no evidence for subaerial exposure.

Slump, and associated load structures

The term "slump structures" is generally used to refer to all types of penecontemporaneous deformation structures formed due to movement and displacement of semi-consolidated sediment layers, mainly under the influence of gravity (Reineck and Singh, 1986). Slump structures were also observed in outcrops along the main Bintulu-Tatau road towards the new Bintulu Airport, south of Kemena River. Although the structures are not common and limited to certain levels only, the slumped interval itself may reach a thickness of about 100 cm. Ball-and-pillow structures also occur at the Sg Plan new village outcrop in north Bintulu. These broken up, pillow-shaped sand bodies range from 10 cm to 60 cm in width. They occur in association with shallow marine, coastal facies successions.

The limited occurrence of these structures and their association with shallow marine, lower shoreface and marginal marine coal-bearing facies, suggest that a sloping depositional surface and rapid deposition are not the only determining factors forming them. Their close association with the other, tectonically induced structures, described above suggests that they may be related to some intermittent tectonic activities. Tate (1976) described similar structures from some Tertiary successions in Brunei, and attributed them to earthquake events.

IMPLICATIONS OF THE PENECONTEMPORANEOUS DEFORMATION

The occurrence of penecontemporaneous deformation structures in the Nyalau formation has important implications. In particular, it signifies the strong influence tectonics may have on the sedimentation in foreland basins. The effects of tectonics may surpass those of eustatic sea-level fluctuations such that they may enhance base-level changes (transgressions and regressions), which have direct impact on sequence development. Indiscriminate use of the so-called "global" eustatic curves (e.g. Haq *et al*., 1988; Gradstein *et al*., 1994) in sequence stratigraphic analysis by force-fitting those to local transgressions and regressions in these types of basins may lead to erroneous interpretation.

Another implication is the occurrence of normal faults in close association with thrusts indicates (local?) changes in stress regime during basin evolution. Such stress perturbations may result in reactivation of pre-existing faults. Though on a smaller scale (probably 4th or 5th order tectono-eustatic cycles), these structures exemplify the

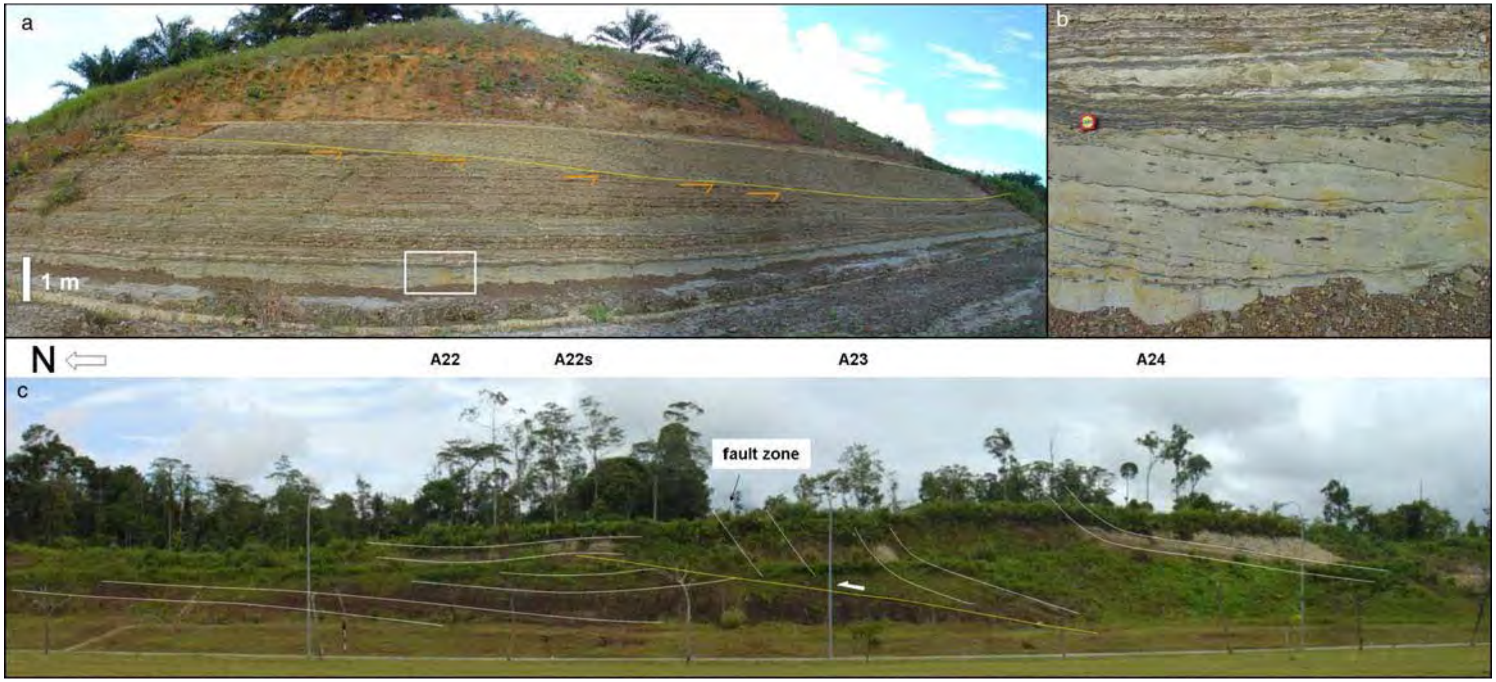

Figure 2: a- Outcrop of Nyalau Fm near Tg Similajau, showing a low-angle truncation surface. The origin of this surface is uncertain, but is either erosional scour or tectonically induced. b- Example of tidal-generated cross-bedded sandstone facies at the base of the Tg Similajau outcrop shown in Figure 2a. Field of view is about 1 m high. (c) Outcrop of Nyalau Fm at Bintulu Airport, showing the structural style affecting the shallow-marine sedimentary rocks, including a major low-angle thrust fault verging northwards, and associated deformation in the hangingwall, with steeply dipping beds. A poorly exposed fault zone exists between A22s and A23, which explains the marked difference in bedding attitudes between the two localities. The relationship of this fault zone with the thrust fault in uncertain. Length of outcrop is ca. 150 m.

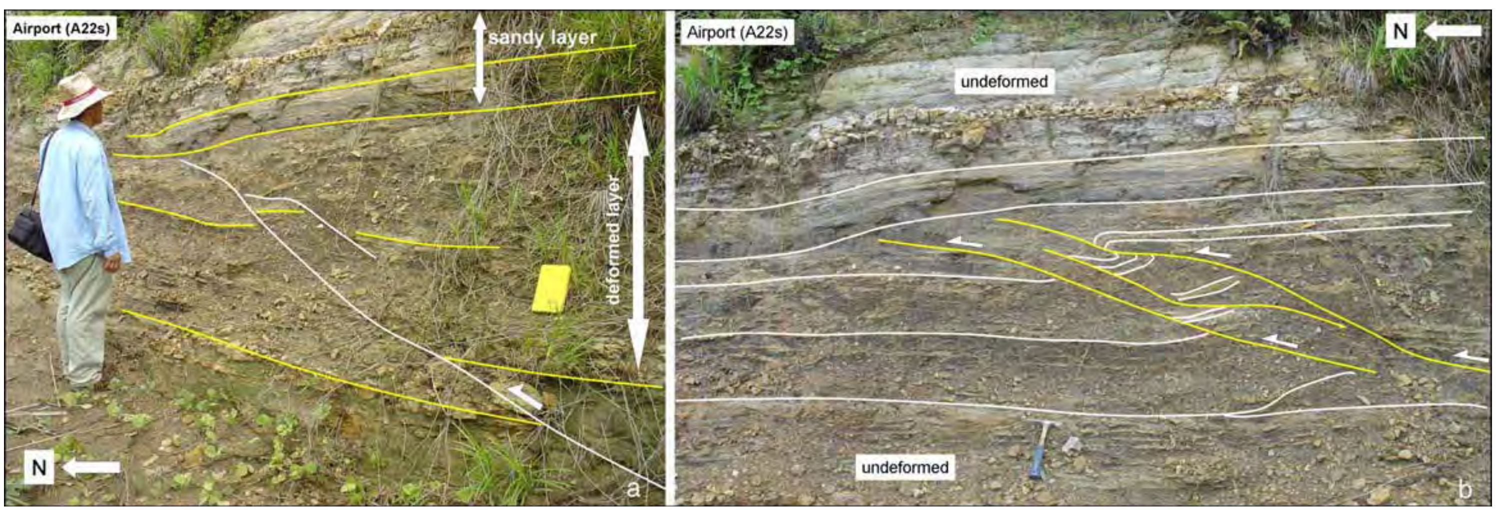

Figure 3: a- Closer view of the tip of the low-angle thrust in Figure 2c affecting a shaly interval. Note how the thrust terminates below the sandy layer. There is complex deformation associated with the thrusting. Geologist is 1.7 m tall. b- View of deformation zone in (a), showing the thrust faults within muddy layer. The thrusts terminate at the base of the sandy layer (HCS sandstone). Hammer is 30 cm long.

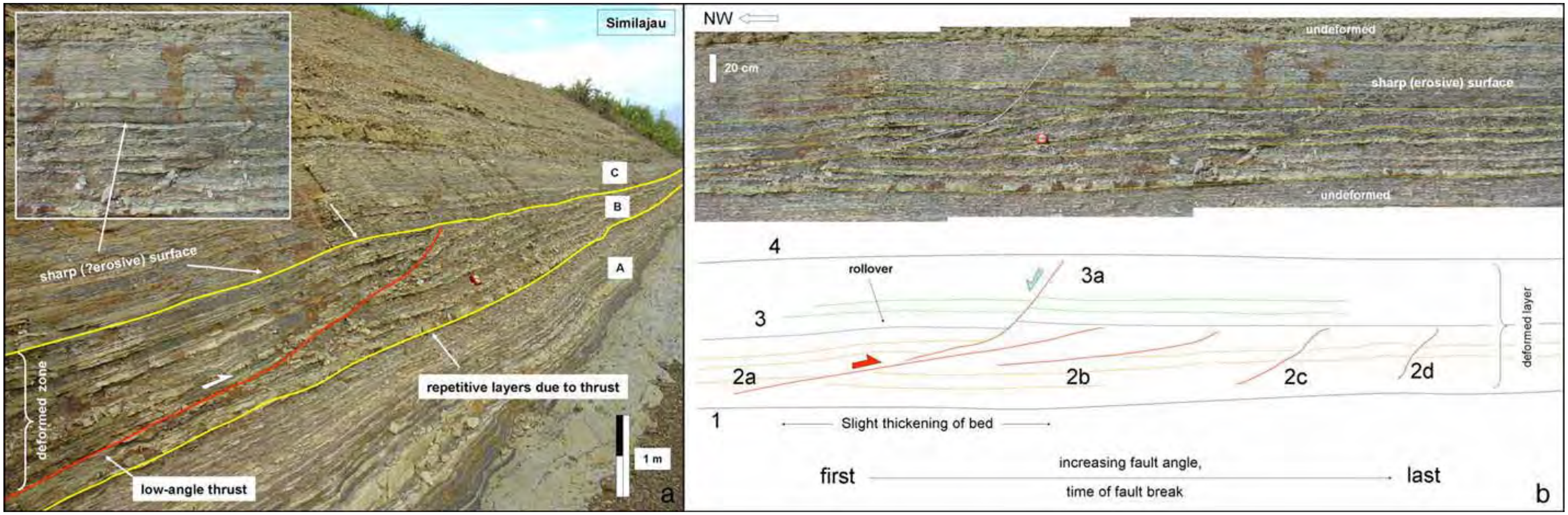

Figure 4: a- Outcrop of heterolithic sand-mud facies which appears to be of intertidal to shallow marine origin, near Tg Similajau. There is a layer about a metre thick containing several thrust faults and associated deformation. Viewed approx. towards SE. (inset: close-up of erosive surface between layer B and C). b- Frontal view of a small-scale thrust system in heterolithic sand-mud facies, showing a series of thrusts probably representing southeastward movement of the deformation front (see text for explanation). The thrust-deformed layer (2) was subsequently buried by layer 3, which were affected by a normal fault that partly reactivates the underlying thrust.

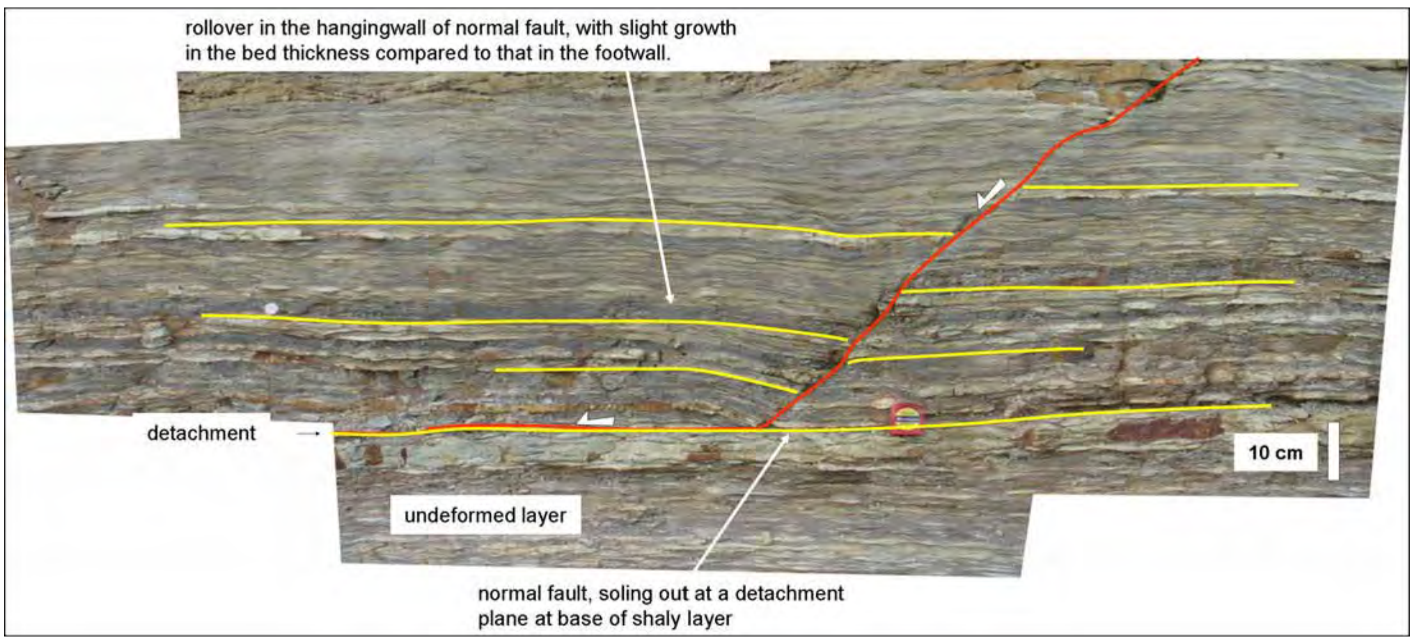

Figure 5: Example from Tg Similajau of normal fault that soles out on a detachment surface above a sandy layer. This example suggests that it does not take a thick shale bed to become a detachment zone to accommodate fault movement.

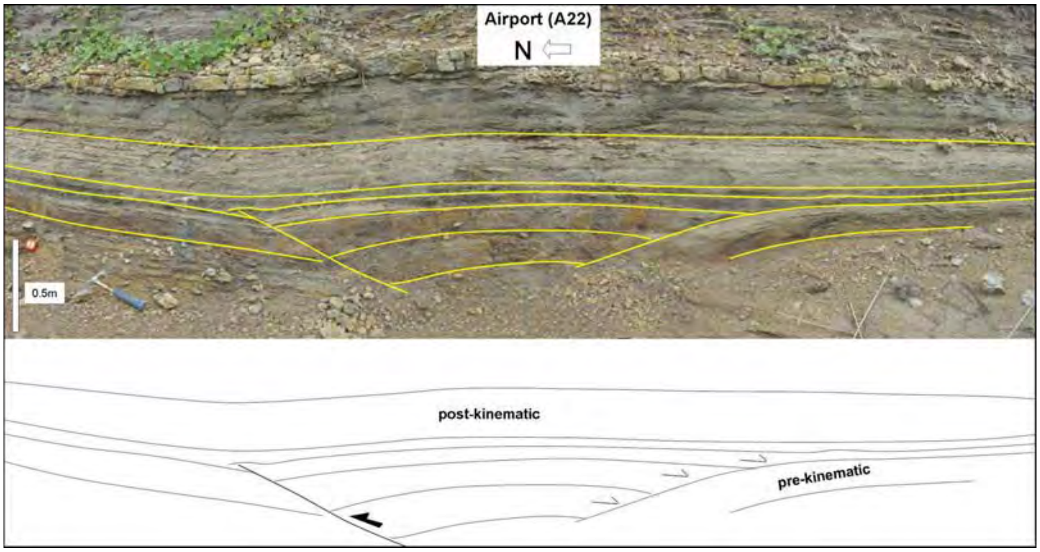

Figure 6: Example of stratal onlap pattern in syn-kinematic strata, Bintulu Airport outcrop, site A22. Onlap onto gentle fold to the right could be the result of structural growth associated with reverse fault (left) due to compressional stresses.

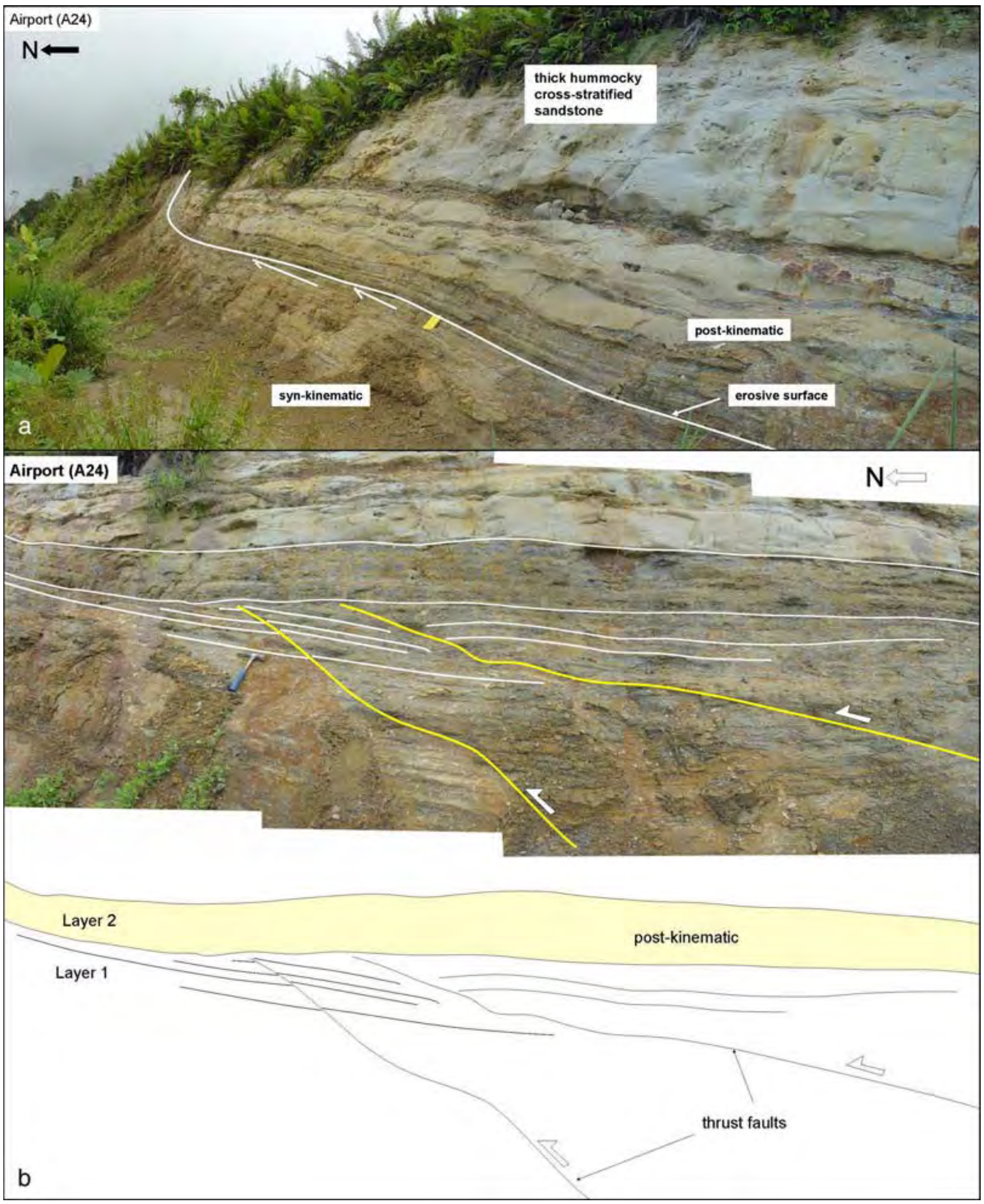

Figure 7: Oblique view of site A24, Bintulu Airport outcrop, showing a "razor-sharp" bounding surface below a thick section of hummocky cross-stratified sandstone. The subtle truncation of underlying shaly strata suggests penecontemporaneous structural deformation. Only by careful examination can one recognise the truncational character of the bounding surface (shown by arrows). Exposure is about 3 m high. (b) View of previous outcrop at a slightly higher angle. Beneath that erosional bounding surface, there are at least 2 main reverse/thrust faults affecting the strata. The truncation suggests that the thrust faults were formed by deformation before layer 2 was deposited. Hammer is 30 cm long.

importance tectonics have on stratal geometries and sequence development.

The outcrop localities described in this paper are probably related to the Anau-Nyalau Fault Zone, which is a major thrust fault zone that extends offshore (Figure 1). Further studies on similar outcrops in the vicinity would be useful in understanding the deformation history of this major fault zone, which may have some impact on the oil fields nearby, such as Temana and Patricia (Figure 1).

CONCLUSION

Several outcrops of the Nyalau Formation in the Bintulu and Tg Similajau areas show evidence of penecontemporaneous deformation associated with the prevailing compressional stresses in the deforming Northwest Borneo margin during Oligo-Miocene times. The deformation features include layer-bound thrust and normal faults, which often sole out to a detachment surface, and subtle stratal terminations caused by erosion of the structural culminations that result.

Similar deformational features may be common elsewhere in deforming foreland basins. Detailed field studies of these structures provide insights into the tectonic effects on sedimentation of these basins, and the relative role they play in controlling sequence development.

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