DESTRUCTIVE DIAGENESIS OBSERVED IN OUTCROP EXAMPLES OF NEOGENE SANDSTONE RESERVOIR AND CLAY CONTACT ZONES, MIRI, NORTHERN SARAWAK

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ABSTRACT

The occurrence of diagenetic siderite and iron oxide deposits has been recognized in offshore subsurface reservoirs of Baram Delta fields. Iron-rich intra-reservoir deposits are relatively common in coastal Sarawak, but good examples are rare. In this article, we present outcrop examples of the Miri area. In three selected locations, geometries and composition of diagenetically-derived iron precipitates can be explored, measured and analyzed. The destructive impact of siderite rims on net reservoir volume for STOIIP calculation, and their potential interaction with chemicals used for enhanced oil recovery (EOR) is also noted.

Keywords: *diagenesis, siderite, reservoir, Neogene, sandstone, clay*

INTRODUCTION

The occurrence of diagenetic siderite rims within Neogene sandstone reservoirs was recognized and probed by A.R. Abdul Hadi & T.R. Astin (1995) in cores of the Baram Field in offshore Sarawak. Authigenic siderite was found to form cemented zones in sandstone reservoirs bordering clay-dominated sequences, with a maximum thickness of 200 cm. The effect of the diagenesis led to deposition of siderite and caused a marked reduction of reservoir quality to 10 % porosity and 2 mD permeability, hence producing a very marginal reservoir for both oil and gas. The understanding of siderite deposition in sedimentary sequences is important mainly in the context of two investigative subjects:

(i) Volumetric calculations. It is important to discount siderite rims, and these may not be counted as net reservoir;
(ii) The strong presence of iron-rich deposits may interact with enhanced oil recovery agents affecting chemical EOR performance (e.g., Lee et al., 2018).

In April 2019, the authors led a short field campaign in the surroundings of Miri, northern Sarawak, with the objective to investigate siderite rims, and to locate suitable outcrops, where siderite deposits can be studied.

REGIONAL GEOLOGY AND STRATIGRAPHIC SETTING OF MIRI AREA

The greater Miri area is characterized by moderately folded siliciclastics of Neogene age: the Late Miocene Miri and Lambir formations, and the Pliocene Tukau Formation, as illustrated in Figure 1. The Lambir and Tukau formations form the subject of this article, which was investigated during our recent field excursion.

A simplified litho-stratigraphy scheme of the investigated area is shown in Figure 2 (Jong and Kessler, 2017):

- The Pliocene Tukau Formation unconformably overlies the Lambir/Miri formations and was formed by intertidal clastics, in particular tidal channel deposits, which appear strongly amalgamated, and are interbedded with silty parallel layers. Individual channel beds are often characterized by "side-stepping" and asymptotic foresets, in which laminae can consist of thin, gray claystone or of lignite (Kessler and Jong, 2015 & 2016).
- The Mid-Late Miocene Lambir and Miri formations form the crestal area of the Bukit Lambir and Miri Hills (Figure 1). These formations contain about equal amounts of claystone and sandstone, the latter mainly formed by (sometimes nested) tidal channels and beach bars. Most channels are "reworked" and strongly amalgamated (Kessler and Jong, 2015 & 2016).

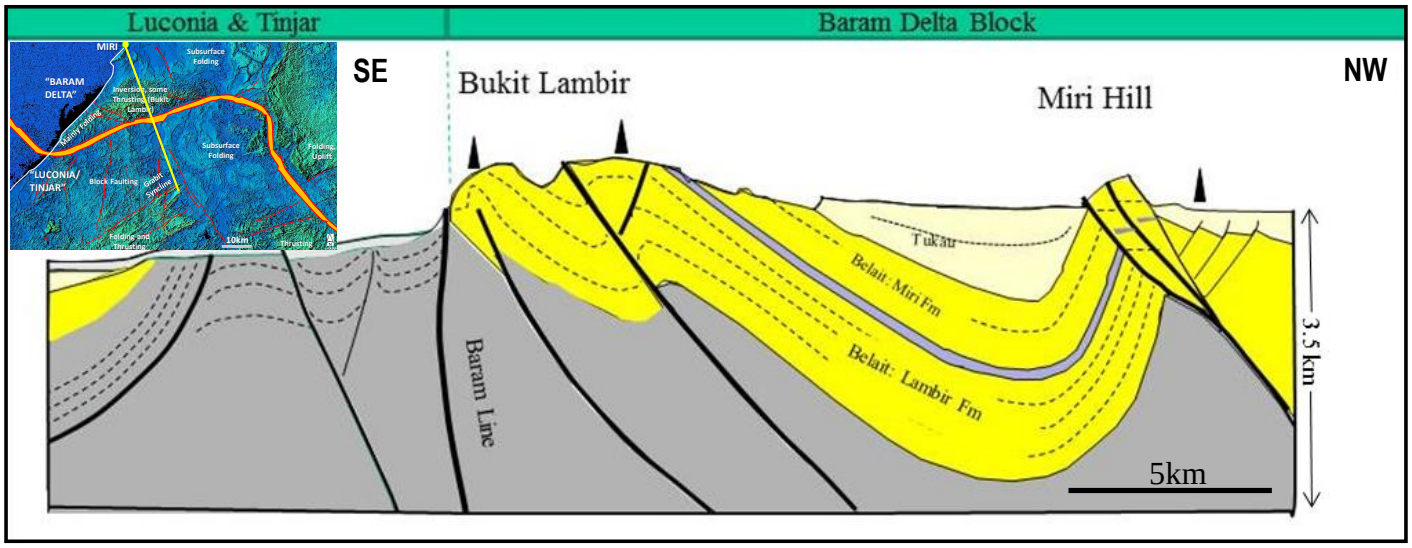


Figure 1: *Tectono-stratigraphic cross-section showing folded Neogene sediments, with inset map showing the line location in northern Sarawak. The black triangles indicate the approximate positions of old exploration wells. From Kessler and Jong (2016).*

DIAGENETIC PROCESSES LEADING TO SIDERITE DEPOSITS

Reservoir diagenesis observed in offshore Malaysian fields varies. In offshore Peninsular Malaysia (Malay and Penyu basins), we see in particular mobility of $Si0_2$ and recrystallisation (Ibrahim and Madon 1990; Tan 2009; Maga et al., 2015; Kessler and Jong, 2018). Along the NW Borneo margin however, such as the Baram Delta, diagenetic effects are less severe and are mainly characterized by dolomite and siderite cements (A.R. Abdul Hadi and T.R. Astin, 1995).

The Baram Delta basin offshore Miri is formed by sandstone and clay deposits, and very minor carbonate occurrences. Sandstone dominates the shallow (Miocene to Pleistocene) stratigraphy, whilst clay is abundant within the older (Oligocene to Mid Miocene) record (Kessler and Jong, 2015). In simplified terms, the following physical and chemical processes take place:

When clay compacts, it releases cation-rich fluids, again once the clay minerals recrystallize; they eject additional fluids (Figure 3). Iron is also released when pyrite within the clay matrix is oxidized leading to Fe^{++} irons, these being mobilized as Fe_2S0_4. Clay-derived and relatively acidic fluids percolate in the sedimentary deposits, pervade sandstone reservoirs and interact with the original, relatively alkaline reservoir fluids.

These contain Ca^{++} and Mg^{++} ions in the form of calcium and magnesium carbonate ($CaHCO_3$, $CaMgCO_3$). The reaction leads to a precipitation of siderite ($FeCO_3$) and dolomite ($MgCa(C0_3)_2$), leading to rim deposits at the sandstone/claystone interface.

In the studied outcomes, we observe siderite (mostly transformed to hematite) lacing sandstone to clay boundaries. In the outcrops, the iron deposits reach a maximum thickness of some 10 cm, forming an observed migration barrier for fluid mobility and reducing permeability. Interestingly, the layers are of laterally constant thickness suggesting that the observed sediments are derived from regional rather than punctual processes.

OUTCROPS FOR SIDERITE STUDIES

Although “iron rims” are pervasive and are seen on many sandstone-to-claystone boundaries, we would like to single out three outcrops, which are relatively easy to access and allow studies on the 100 m to 1 mm scales. A location map of studied outcrops is shown in Figure 4.

Sungai Rait (SR) Outcrop (approximate coordinates: 4.2655^{0}N/113.9539^{0}E)

The youngest Cycle VI sediments (Tukau Formation) of the Miri area are deposited in the –

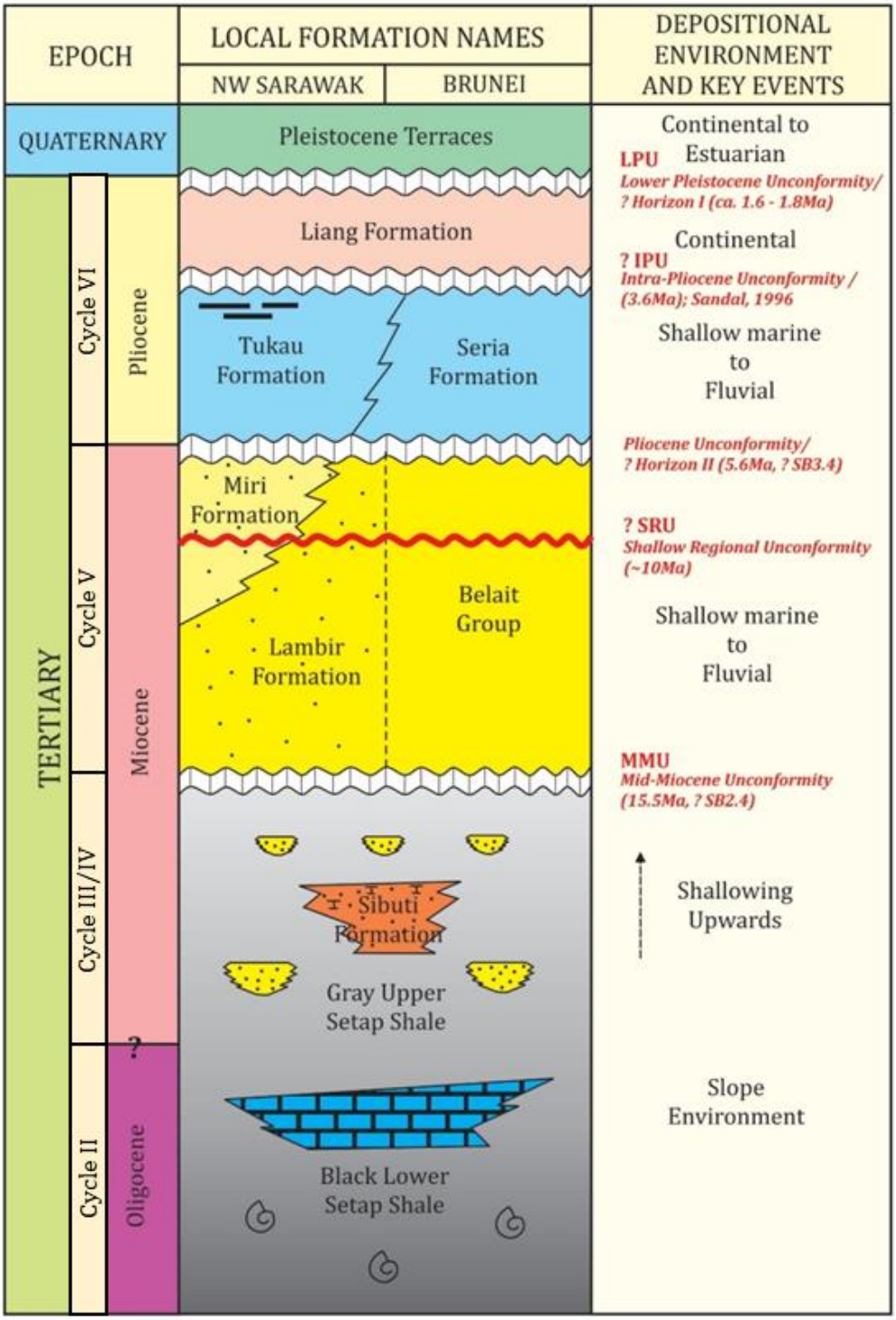


Figure 2: *Simplified litho-stratigraphy scheme of northern Sarawak with approximate equivalent offshore Cycle interval shown. The term Miri Formation is generally used in the greater Miri area and is age-equivalent to the upper section of the Lambir Formation, Sandal (1996) however, placed the formation partially age-equivalent to the lower Tukau Formation. Likewise, the mid Early Miocene Sibuti Formation is more locally confined with the Subis Limestone Member deposited in the lower part of the Gray Upper Setap Shale (Banda and Honza, 1997). Carbonates are also widespread in the Palaeogene section, and are seen in a number of outcrops and wells (e.g., Batu Niah, Engkabang-1; Jong et al., 2016). The observed unconformity events as annotated are established by Kessler and Jong (2017), and modified after Kessler and Jong (2015).*

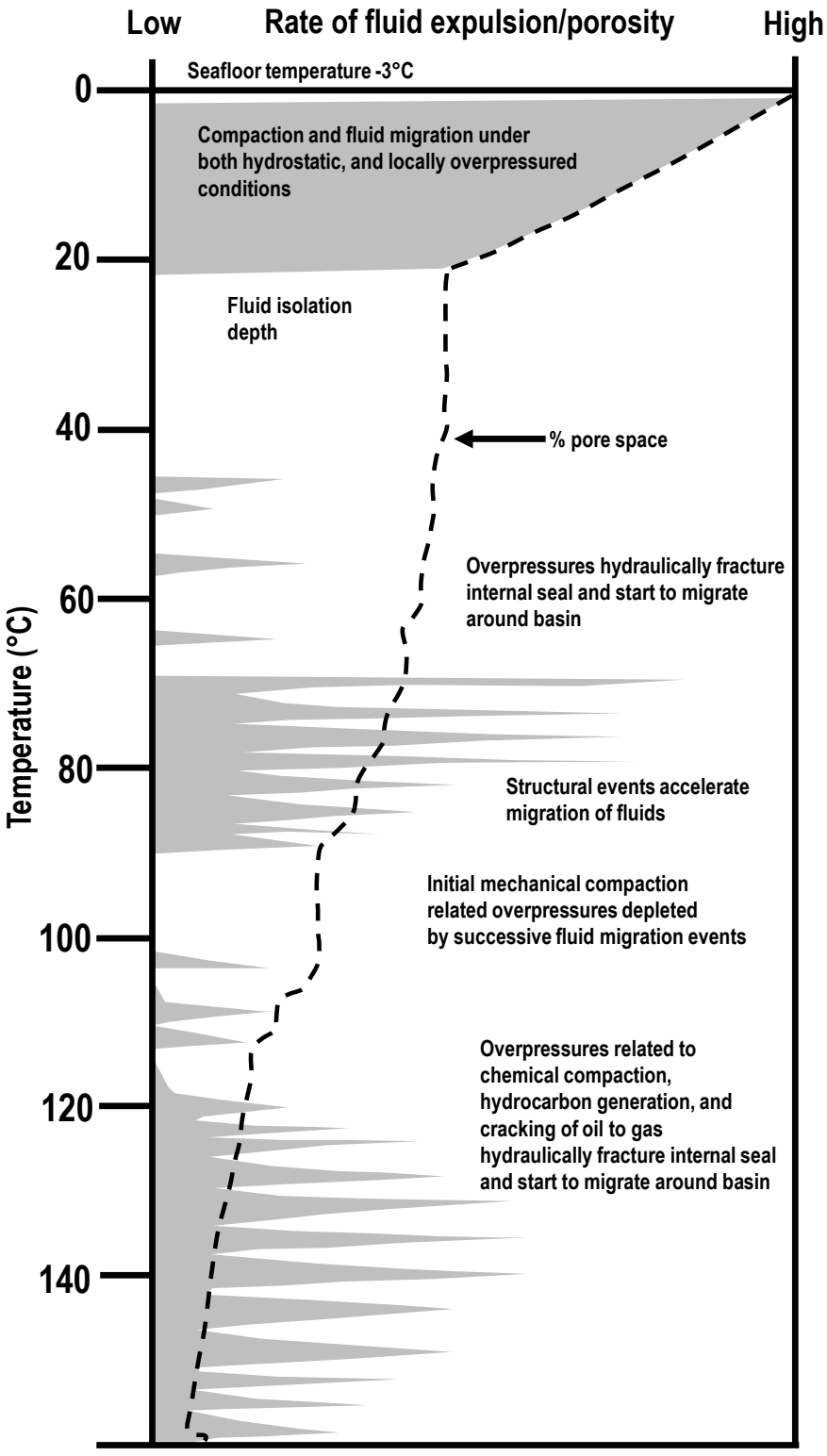
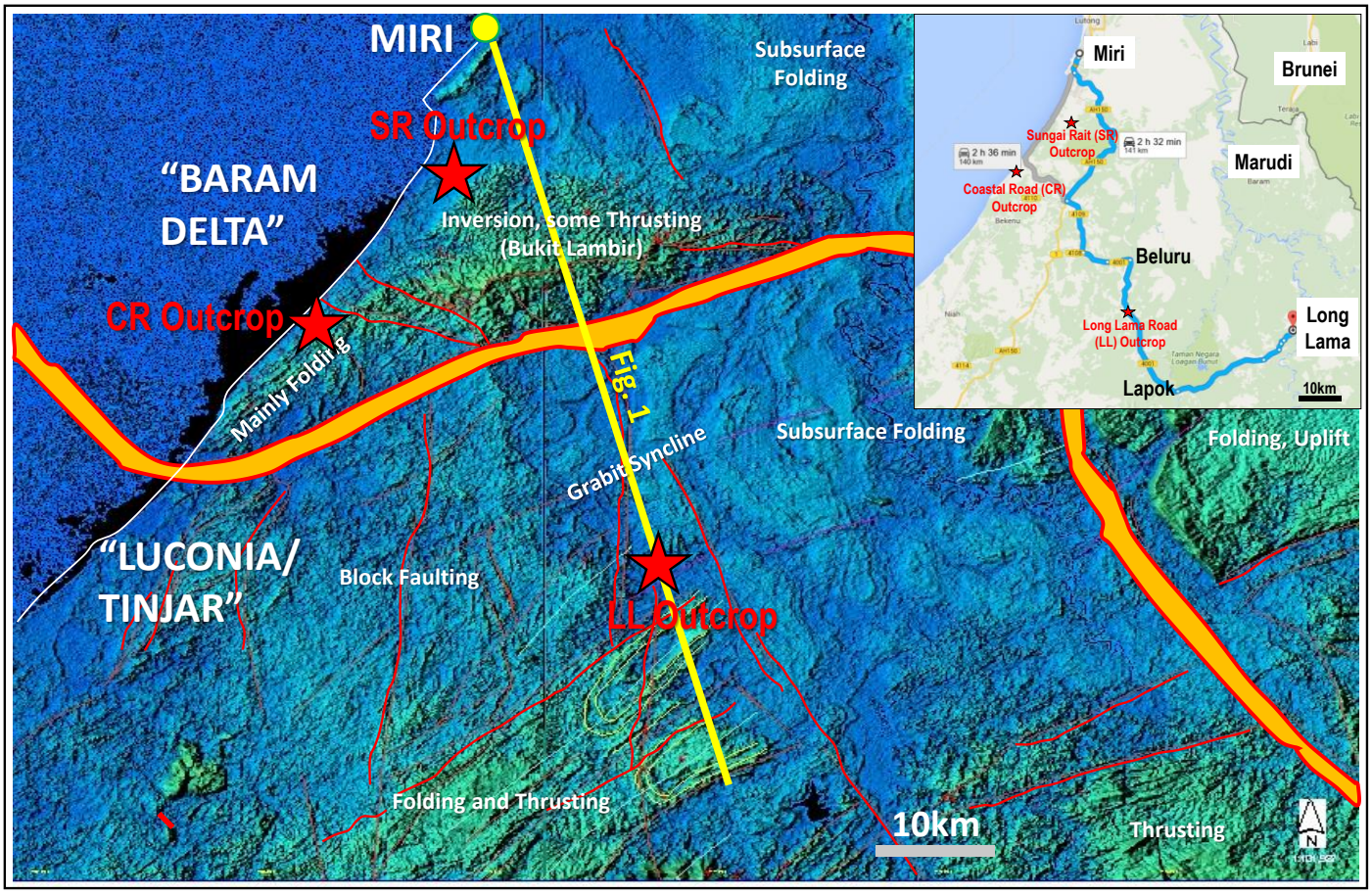


Figure 3: *Schematic illustration of fluid expulsion events in the Setap Shale, Miocene, Baram Delta, Sarawak (after Morley et al., 2014). Cation-rich fluids are expelled from clay, as the latter is being heated up during burial.*

Liku Sycline, and were penetrated by two freshwater wells during the 1990's, but there are no significant outcrops. The Sungai Rait outcrop is located in the shallowest outcropping stratum of the Cycle VI Tukau Formation, the outcrop shows a cliff formed by massive clay, which hosts several sandy channel complexes (Figures 5 and 6). The composite clay and channel sequence is capped by a sandy layer formed by amalgamated channelized sandstone beds. Overall, we observe braided intertidal-shallow marine sands in lenses and ribbons, in which (mainly) sandy channel fills incise a thin-bedded intertidal-deltaic sequence. The sequence corresponds to a gross reservoir unit with laterally strongly varying poro-perm and flow barriers.



Legends: Faults (red); Syncline Axis (pale blue); Baram Line (orange fill); approximate location of Figure 1 (yellow line)

Figure 4: *Approximate locations of the studied outcrops shown as red stars in context of a regional tectonic map, and see text for location coordinates (SR = Sungai Rait Outcrop. LL = Long Lama Road Outcrop near Kampung Liku, some 10 km from Beluru in the inset map. CR = Coastal Road Outcrop some 5 km from the Tusan Junction). The orange Baram Line constitutes an important facies boundary, with carbonate dominate in Luconia/ Tinjar and clastics in the Baram Delta Block.*



Figure 5: *Sungai Rait (SR) outcrop (Pliocene Tukau Formation, Cycle VI).*



Figure 6: *Sungai Rait (SR) outcrop. Dr. Jong pointing to a 7 cm thick veneer of massive iron-rich sediment (oxidized siderite, probably hematite).*

Long Lama Road (LL) Outcrop near Kampung Liku (coordinates: 3.8756⁰N/114.0880⁰E)

At the flank of the Miri to Long Lama road near Beluru, along the road from Miri to Long Lama, there is a profile of the Late Miocene Lambir Formation (Figures 7 and 8; Kessler and Jong, 2015), shown by a series of clay to sandstone interfaces where we can observe:

- Slumped coastal sediments within slope deposits;
- Diagenesis affecting sandstone beds at the Base Cycle V unconformity, as well as on several sandstone / claystone contacts within the Cycle V sequence (Figures 8 and 9).
- Angular Base Cycle VI unconformity. During our last visit, the precise location of the unconformity was overgrown. There is a marked change in dip between the marine beds of Cycle V, and flat-lying Cycle VI deposits formed by coal and non-marine sand. Unfortunately, the beautiful outcrop of 2012 is now almost entirely overgrown by creeper plants (Figure 10). Therefore, it may not be possible to carry out comprehensive studies, without clearing the underbrush cover, and a sample was subsequently retrieved for further analysis (Figure 11).



Figure 8: *Detail of the fresh outcrop in 2012, hematite band at the base of pink sandstone (righ hand sequence in Figure 7).*



Figure 7: *The fresh Long Lama Road (LL) Kampung Liku outcrop in 2012 (Kessler and Jong, 2015). The contact zones between sandy and clay packages display a pink-brown colour.*



Figure 9: *Long Lama Road (LL) Miocene Lambir Formation, Cycle V. Red-brown veneers of hematite are seen lining the boundary between a porous sandstone and prominent clay bed. It corresponds to the upper pink sandstone shown in Figure 7.*



Figure 10: *The overgrown Long Lama Road (LL) outcrop in 2019, photo taken during the recent fieldtrip.*



Figure 11: *A sample from Figure 9 outcrop area was retrieved for further analysis, with a five cents coin for scale.*

Coastal Road (CR) near Tusan Junction (coordinates: 4.1215^{0}N/113.8500^{0}E, *ca.* 33 m above sea level)

About 2 km from the Tusan Junction along the Coastal Road, this outcrop is located in the lower section of the Pliocene Tukau Formation, with beds that are steeply dipping (Figure 12). The unconformity contact to the underlying Lambir Formation is not exposed, and likely overprinted by a series of strike-slip faults running roughly parallel to the Coastal Road.

The sequence exposed in the outcrop consists of alternating intertidal (often bioturbated) sandstone and clay laminae. Fossils, other than massive crab burrows have not been preserved. In this particular outcrop we see iron oxides (derived from siderite) staining sand laminae individually (Figure 11), but a thicker hematite deposit is seen at the sand-to-claystone interface. In subsurface reservoirs, these iron oxide layer would have formed a permeability barrier for fluid mobility in addition to occluding the pore spaces.



Figure 12: *Coastal Road outcrop (CR) Pliocene Tukau Formation, Cycle VI. Iron oxides have impregnated well-sorted and layered sandstone. Inset figure shows the details of iron oxide layering in porous sandstone.*

CONCLUSIONS

The Miri area offers a number of good outcrops, in which geometries and composition of diagenetically-derived iron precipitates can be explored, measured and analyzed. In subsurface reservoirs, these iron oxide deposits occurring in porous layers would form a significant barrier for fluid mobility and also reduce the effective net reservoir volume for STOIIP calculation. In addition, the strong presence of iron-rich deposits may interact with enhanced oil recovery agents thus affecting chemical EOR performance.

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