Fabric variability within layered Fe-oxide deposits in Mid-Late Miocene sedimentary formations, NW Borneo: Impact on facies architectural interpretations

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Abstract— Iron (Fe) can accumulate in various forms in sedimentary environments that experience alternating moisture conditions, hydration and dehydration processes and redox processes. It has been pointed out that there is a major gap in the understanding of the composition of mixed solid-phase minerals, their size, morphology and arrangement in the matrix and possible interactions with pore solutions and the environment of deposition. Variations in the fabric within concretions in some Mid-Late Miocene beds in NW Borneo suggest that there were more changes in the energy levels and processes involved than what has been perceived from routine fabric analyses of the sedimentary rocks. The sedimentary rocks are essentially carbonaceous claystones containing varying amounts of highly restricted marginal-marine fauna. The fauna probably accumulated in brackish waters, and comprise in-situ buried turritellid snails, fish teeth and bone tissue, fragments of crabs, very few forams and possibly ostracod shells. Evidence exists to support the concept of reworked cobble or pebble-sized fossiliferous mudstone clasts picking up contemporaneous shell fragments in these restricted conditions. Iron oxide content is seen as (i) micrite-size primary components forming part of a muddy matrix and (ii) diagenetic coatings. Coatings occur in a non-rhythmical pattern after the formation of mudstones, and the reworking of the material and subsequent coatings by iron. Iron coated pebbles/cobbles may experience re-cementing into large sheets giving the appearance of red beds. These occur under some very special redox conditions. These iron-concretion rich horizons appear then to represent extreme (climatic, etc) facies developments that were restricted to coastal areas during Mid-Late Miocene. Present-day iron deposition processes might be a key to understanding past processes. This study forms the basis for an enhanced understanding on facies architectural interpretations.

Keywords: Lambir Formation, NW Borneo, Fe-concretions, facies architecture

INTRODUCTION

Iron can accumulate in various forms in sedimentary environments that experience alternating wet and dry periods, which not only favor redox processes, but also hydration and dehydration processes (Sherman & Kanehiro, 1954; Beckman, 1962; Amouric *et al*., 1986). In many cases, sand-size quartz grains that act as nucleus, are corroded and coated with Fe-oxides. In extreme cases, the entire quartz grain is replaced by Fe-oxides. It is known that the particle size and morphology of Fe-oxides is dependent on the precursor and conditions of transformation (Schwertmann *et al*., 1977; Lewis and Schwertmann, 1979). Schwertmann and Taylor (1989) discuss the environments favoring the formation of various Fe-oxides. For example, silicate anions usually coexist with Fe-oxides and retard or inhibit the transformation of this mineral to more crystalline products (Herbillon & Tran Vinh An, 1969; Schwertmann, 1985). Vempati *et al*. (1990) showed that the morphology of hematite synthesized from ferrihydrite is influenced by the presence of SiO_3^{2-}. Remobilization of Fe is easily possible through a reductive reaction. As the condition changes from that of reduction to oxidation, Fe may become immobilized.

Considering the redox reactions (Krauskopf, 1967), Fe-oxides can, under acid conditions, accept electrons from water molecules and as such become reduced (Equation 1) and mobilized, making the environment perhaps somewhat basic in comparison to the soil system.

$$Fe_2O_3 + 6H^+ + 2e^- \rightarrow 2Fe^{2+} + 3H_2O \quad \text{.................} \ 1$$

However, when the reduced Fe diffuses to the surface of the coating, oxidation reverses the reaction (Equation 2), and H+ is released to the environment making the precipitation zone acidic.

$$Fe^{2+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ + e^- \quad \text{.................} \ 2$$

These reactions may be influential in the weathering of mineral particles which are entrapped within the coating.

The Lambir Formation has been rigorously studied over the last 3 decades or so. Similarly, a lot of work has been done on Fe-concretions from around the world. Despite this, there seems to be a lack of information on the impact of fabric variability in Fe-concretions on facies architectural interpretations. This information will enhance our ability to correlate beds across the landscape and refine our understanding of the structural styles in such areas.

MATERIALS AND METHODS

The study area is located in NW Borneo and covers a coastal region of 60 km south of Miri. The Mid-Late Miocene sedimentary beds that contained Fe-concretions or other forms of Fe accumulation were logged. Representative rock and water samples were collected for mineralogical, petrographical and chemical analyses. The preliminary results of a portion of the ongoing study encompassing the entire Lambir Formation is presented here.

RESULTS AND DISCUSSION

Climate

The study area is under the influence of tropical climate (type Af) with a bimodal distribution of rainfall in a given year. The coastal area comes under heavy influence of longshore drifts that tends to retain material in solid or dissolved forms within coastal environments. Coastal waters have high energy and are the main contributors to erosion and receding of the coastline. Fluctuations in precipitation amounts influence the tides and thereby modify coastlines as well as topographic heights along the coastline. It is not uncommon to observe the construction of topo-highs within caves carved into fine grained sandstones. These topo-highs consist of fine to medium grained sand.

Concomitant with exceptionally high energy, the cave floors may be covered with pebbles and cobbles of concretions and sometimes rock fragments. Such features are common during extreme climatic conditions only.

Field Characteristics

The Lambir Formation in the study area is composed of fine to medium grained sandstone and mudstone of varying thickness. The sections studied are from the limb of a plunging anticline (with dips of 50^o–65^o) that stretches several kilometers in length. Concretions can be found either as part of concretionary strata that are parallel to beds (limited lateral extent), as horizontal surfaces on the floor of caves (limited lateral extent) or as loose material on the beach. It is not common to find such strata in any given outcrop or vertical section in the entire Lambir Formation.

Chemical Analyses of Natural Waters

The Fe in soils, sediments and rocks is leached out by percolating waters. Under current conditions, saline waters containing Fe had 8-9 mS/cm of salinity when measured over a three month interval. The pH of the water ranges from pH6.8 to pH7.0. The Fe will not remain in a dissolved state under these conditions. Physical deposition of Fe as thin laminae on fine sand is a common feature along the shorelines. In addition to this, Fe that is in suspension in saline waters can coat rock surfaces. There is very little evidence to suggest that Fe in suspension in saline waters (Figure 1) is able to cement cobbles of claystones. This is due to the fact that Fe-containing saline waters are not in contact with the pebbles or cobbles (found in topo-highs or in cave floors) as opposed to the influx of Fe-enriched percolating waters. Furthermore, In retrospect, leachates containing Fe that is derived from inland soils, sediments and rocks appear to be the cementing agent. Leachates can be correlated with the onset of precipitation events. However, presence of high amounts of Fe tends to be linked with very high precipitation amounts and possible fluctuations of groundwater in the inlands. Therefore, such features are manifestations of extreme climatic conditions.

Mesofacies analyses

Concretions

Concretions have a nucleus and concretionary layers that are made up of grey colored mudstone indicative of a low energy environment (Figures 2 and 3). Fragments of shells are present in the matrix of the nucleus (Figure 3). These fragments are of random orientation and do not exhibit any stains of Fe-oxyhydroxides. Furthermore, the shell fragments do not extend from the nucleus into the exterior concretionary layers. This indicates that the material in the nucleus had originally been subjected to a Fe-poor environment, not excluding the possibility of low redox potential enviroment. This also indicates that the mudstone is a pre-weathered material from a different facies of development compared to the surrounding concretionary layers. The dominance of grey color is indicative of the presence of phyllosilicates and possibly small quantities of quartz and the general absence of Fe-oxyhydroxides as observed in thin sections. The boundary between the nucleus and the concretionary layers is sharp (Figures 2 and 3). This indicates that the onset of concretionary development was sudden or rapid and that the crystallization process (of Fe) was fast enough to prevent infusion of Fe-oxyhydroxides into the matrix of the mudstone nuclei.

The concretionary layers have a matrix of mudstone as well that is usually indicative of a low energy environment. The alternating colors in the concretionary layers reflect varying composition in the oxyhydroxides of iron. This indicates that the microenvironmental conditions were subject to alternating redox potentials. The direct consequence of this is that the microenvironmental site has apparently been under the influence of the influx of differing types of dissolved Fe-oxyhydroxides. In addition to this, this suggests that the provenance has been subject to alternating O_2-rich and O_2-poor situations. Some concretions exhibit uniform thickness of the laminations with individual lamina being clearly distinguishable from one another. This suggests that the concretion has undergone reworking during the concretionary development. In addition to this, it is evident that the influx of Fe-oxyhydroxides is time-dependant and inconsistent in terms of quantity and quality. The possibility of Fe being resolubilized from the interior concretionary layers and moving to higher redox potential areas (as predicted by equation 2) is not excluded.

In higher magnifications, it is evident that fragments of shells have been embedded in the concretionary layers. The sedimentary rocks contain varying amounts of highly restricted marginal-marine fauna. The fauna probably accumulated in brackish waters, and comprise in-situ buried turritellid snails, fish teeth and bone tissue, fragments of crabs, very few forams and possibly ostracod shells. However, only some of these fragments are stained on the external surfaces by the Fe-oxyhydroxides. The

Figure 1: Pool of Fe-enriched saline water in the shores of the study area.

Figure 2: Concretionary layers (yellow colors being dominant) encompassing a Fe-depleted mudstone from another facies. Note the sharp boundary between both materials.

Figure 3: Concretion with poorly developed concretionary layers enclosing fossiliferous mud ball nuclei from another facies.

internal parts remain unstained. This indicates that during concretionary development, there was insufficient time for permineralization of the fragments.

Such samples indicate that the coastal region in the past had experienced similar energy environments but with differing influx of mineralogical components during the concretionary development. It is evident that the presence of Fe-oxyhydroxides can be linked to a specific and unique Eh-pH condition of the paleo-environment.

Concretionary Strata

It is not uncommon to find concretionary strata that are either yellow or red in color indicative of varying composition (Figure 4). In low P-T conditions, red colors in Fe-oxides are usually indicative of the dominance of hematite, whereas, yellow colors are dominated by goethite. Under saline conditions, other combinations are possible involving CO_3^{2-} ions. In general, the difference in color indicates fluctuation in moisture conditions in the sediments. In this respect, yellow colored platy concretions have been detected on grey shales (Figure 5). This provides and additional evidence that the facies under which the yellow colored platy concretions developed (oxidizing environment) is different from the facies involved in the development of the grey shales (reducing environment). In the location where this was detected, the platy concretions do not form a continuous layer but the fragments are parallel to the bedding. This suggests that the deposition of the platy concretions were syngenetic (Pettijohn, 2004). The formation of the platy concretions however, evidently occurred before being transported to the depositional site under very special conditions that are different from the main processes involved in the formation of the grey shales. The platy concretions are made up of mud suggesting that they are part of an older weathered laterized layer. Under such circumstances, it is difficult to envisage the onset of diagenetic processes after deposition in a relatively impermeable material within the concretions as well as in the surrounding rock. Field examination confirms this view at the scale of observation.

In retrospect, there is a widespread occurrence of wave-carved caves along the beach fronts. Most of these caves comprise concretions of various sizes that are currently being recemented together by Fe-enriched waters originating from inland. The surrounding areas have soils that have high contents of Fe. Percolating waters transport Fe-coated clay or pseudo-silt particles towards the beach front. During this process, these waters travel through swamp or peat areas

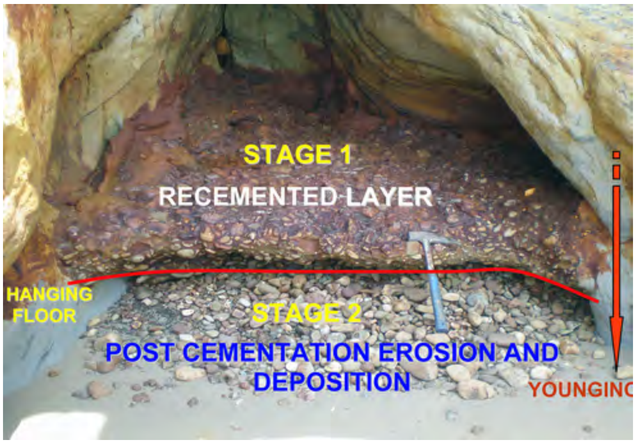

Figure 4: Recementation of laterized and Fe-poor cobbles (earlier phase) overlying layer of more recent mixture of similar material in a temporary cave. Picture provides clear evidence of an inversion of sequence of development.

Figure 5: Platy concretions lying parallel to bedding planes. Surrounding material is grey shale. Arrows point to the concretions lying in the plane of deposition.

Figure 6: Development of concretionary stratas in a fine-grained sandstone. This provides a clear evidence that of a time-lapse and change in facies until the concretions have cemented in place. Arrows point to the remnants of the concretionary stratas.

where the resident pH conditions (pH 1.5 – 2.5) favor the transformation of Fe^{3+} into Fe^{2+}. Chelation between organic matter originating from the swamps or peat and ferrous Fe may occur. Subsequent coatings of the chelated Fe-organic matter waters on the concretions of various sizes under oxidizing environment, enhance the transformation of ferrous iron to ferric iron with concomitant cementation.

As mentioned earlier, the pebbles and cobbles of either pre-weathered concretions or uncoated materials are deposited in caves as well as in topographic highs along the coast. The phenomenon occurs when the energy levels of the marine waters are very high. This feature is not widespread along the coastline and neither is it a common feature as it requires waters with very high energy for the deposition to occur.

An interesting feature was noticed in some caves where erosion of sand layers below the recently-formed concretionary layers occurred. Subsequent to this erosion, deposition of cobbles depleted in Fe occurred below the recently-formed concretionary layers. This phenomenon occurred over a period of 5 months in 2007-2008. The cave, in the current setting, would possibly give the erroneous impression that the first deposition was that of Fe-depleted material (conforming to a possible Fe-depleted environment) followed by a Fe-enriched material when, in fact, an inversion of the process was involved. Field observations confirm the observations that concretions can be recemented under special conditions even in the past (Figure 6). This process can be summarized as an inverted sequence of sedimentary development under very unique conditions. As such, younging of the strata occurs downwards. It is worthy to note that strata that resemble these inverted sequences in caves and topo-highs have been found in isolated parts of the Lambir Formation inland (Figure 7). Such strata have limited lateral extends, reinforcing the hypothesis that they were formed in a similar manner as the concretionary strata of recent times.

Armoured mudballs

It is not uncommon to find armored mudballs embedded in host rock or even on the beach (Figure 8). The latter can be subdivided into recent mudballs and older ones. Older ones can experience partial weathering on the outer layers.

Figure 7: Occurrence of Fe-concretionary strata with limited extends in inland areas of the Lambir Formation. Note that these strata are usually not traceable across the highways onto the opposite slope cuts.

Figure 8: Armoured mudballs with mixture of fossilized and recent shell fragments. Small arrows point to recent shells on the sand as well as on the mudball. Inset, cross section of the mudball (mid-section) showing fossils within the mudball and recent shells on the exterior.

The softened material can now act as an accretionary layer, picking up contemporaneous shells or fragments of shells in the inter-tidal zones as it rolls around under the influence of waves. However, a time-lapse in events is evident.

CONCLUSIONS

The study shows that the formation of Fe-concretions and other forms of layered Fe-deposits can occur along several pathways in coastal environments. Many of the concretions encountered belong to older phases of concretionary development. The presence of such layers is usually indicative of sudden and strong erosion processes and may not be linked to syn-depositional concretionary development processes. The formation of Fe-concretionary beds is linked to cave-settings or topographic highs along the beach front. These iron-concretion rich horizons appear then to represent extreme (climatic, etc) facies developments that were restricted to coastal areas during Mid-Late Miocene. The processes outlined in this study indicate that a time-lapse is involved in each phase. This suggests that the presence of concretionary strata is a definite indication of unconformities in the depositional history of the sequence characterized further by an extreme or unique depositional environment. Several processes such as cementation of Fe-concretions to form strata may undergo an inversion in sequence of development. Present-day iron deposition processes might be a key to understanding past processes. This study forms the basis for an enhanced understanding on facies architectural interpretations.

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