

Facies Characteristics and Static Reservoir Connectivity of Some Siliciclastic Tertiary Outcrop Successions in Bintulu and Miri, Sarawak, East Malaysia*

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Abstract

A significant percentage of the world's hydrocarbon reserves are found in shallow marine sandstone rocks. Understanding the outcrop geometry and static connectivity of these shallow marine sandstones in terms of reservoir model, is a challenging task. This research work focuses on outcrop analysis and characterization of six well-exposed marginal to shallow marine succession in Bintulu and Miri area, Sarawak, East Malaysia. The lateral extents of the studied outcrops are 200 to 500 m, consisting mostly of siliciclastic Tertiary sandstone with mud-rich interval deposits and some isolated sand bodies. The main objective of this study is to characterize the reservoir properties (grain size, petrography, poroperm, and static connectivity) of different sandstone facies to a construct 2-D intermediate-scale model from outcrop. Techniques involve field description in terms of facies distribution, measurements of dimensions of sand bodies and rock sample for grain-size analysis (Folk and Ward methods), and petrographic analysis (by point count method for porosity, sorting, grain-size and sand-mud percent) and poroperm (for porosity and permeability). These were used to quantify and examine seven different types of sandstone facies; i) hummocky cross-stratified sandstones (HCSS), thickness varies from 0.5 - 4 m, ii) herringbone cross-bedded (HBSC), thickness from 1 - 7 m, iii) trough cross-bedded sandstones (TCB), thickness from 0.5 - 2 m, iv) wavy- to flaser-bedded (W-FBS), thickness varies from 2–9 m, v) cross-bedded sandstone (CS), thickness from 0.5–3 m, vi) bioturbated sandstone (BS), thickness from 1 – 5 m, and vii) massive sandstone (MS), thickness from 1–5 m. These results show that sandstones of HCSS and HBSC are better sorted, with minimal mud content, and the depositional pattern indicates increasing vertical and lateral connectivity, even in bioturbated rich sand, as compared to other sandstone facies. On the other hand, sandstones of BS and CB are of poor

quality in terms of grain sorting and poroperm. Based on these results, a 2-D outcrop model is constructed providing additional insight into the significance of small-scale heterogeneity and static connectivity of shallow marine sandstone deposits.

Introduction

The characteristics of shallow marine sandstones from outcrop geometry and its vertical and lateral connectivity in terms of a subsurface reservoir model is a challenging task for a successful exploration and production. Therefore, outcrops have increasingly been studied to understand the reservoir heterogeneity, geometry, connectivity and sand body stacking patterns to understand the fluid flow behavior (Richard and Richard, 2007; Joseph, et al., 2000; Karl and Dalrymple, 2002; Matthew, et al., 2005, 2007, 2008; Brandsaeter, et al., 2005; Havard, et al., 2007). Intermediate-scale heterogeneity within an individual sand body also affects the reservoir properties and is generally associated with facies distribution, grain size and sorting and lithology variation (Richardson, et al., 1978; Lasseter, et al., 1986; Thomas, 1998; Tyler and Finley, 1991; Willis and White, 2000; Matthew, et al., 2007). This intermediate scale reservoir architecture are commonly difficult to characterize with the subsurface data because of the limited lateral extent of the outcrop model, which is commonly less than the typical well spacing in developed fields (Matthew, et al., 2007). To identify the scale dependent disputes, outcrop analogs of well-exposed shallow marine sandstone deposits of the Nyalau and Miri formations, Sarawak, East Malaysia, were evaluated in terms of its facies, reservoir properties and connectivity model. Detail 2D outcrop model of well-exposed rocks were constructed using field data and measurements. Therefore, we believe that these results of outcrop model are applicable to varieties of other well-exposed outcrops in these areas.

Study Area and Geological Background

The study area is near the towns of Bintulu and Miri, Sarawak, East Malaysia. It is bounded by latitude N03°20' 07.7" to N03°15' 51.3"; longitude E 113°10' 31.2" to E 113°05' 11.4" for the Nyalau Formation ([Figure 1A](#)) and latitude N 04°21' 52.2" to N 04°07' 30.2"; longitude E 113°58' 46.4" to E 113°49' 12.4" for the Miri Formation ([Figure 2A](#)). The oldest strata in the Bintulu area is the Biban Sandstone, member of the Nyalau Formation which is equivalent to cycle I and II of offshore hydrocarbon bearing formations of Late Oligocene - Middle Miocene age (Almond et al., 1990). The Nyalau Formation consists predominantly of soft to moderately hard, thinly to thickly cross-bedded sandstones alternating with mud and sandy with coal seams (Liechti et al., 1960; Wolfenden, 1960). All the sandstone-bearing stratigraphy units interfinger and gradually pinch out northeastward into mudstone-dominated, deep-water marine deposits of the Setap Formation ([Figure 1B](#)). The Nyalau Formation conformably overlies by Eocene deposits of the shallow marine Buan Formation in the southwest and south. Whereas,

the rock exposed around the Miri town, which belongs to the Middle to Late Miocene age, is the uplifted part of the subsurface, oil-bearing sedimentary strata of the offshore West Baram Delta and is exposed predominantly as an arenaceous succession (Liechti et al., 1960). The lower Miri unit consists of interbedded shales and sandstones, and passes downward into the underlying Setap Shale Formation, which inter-fingers with the Lambir Formation (SW) ([Figure 2B](#)). The upper Miri unit is rapidly recurrent and irregular sandstone-shale alternation, and more arenaceous laterally.

Methods and Materials

- Sedimentological field data and rock sample collection.
- Grain size analysis by using microscope and sieving method by using Folk and Ward methods.
- Petrographic analysis by making thin sections impregnated with blue epoxy for quantitative and qualitative analysis.
- Point count (300 points per slide) method for porosity measurement.
- Porosimeter PASCAL 240 was used to determine of pore size, porosity and permeability measurement.

Results and Discussion

1. Sedimentology and facies description. Detailed sedimentological observations and measurements were collected from different outcrops located in the Bintulu and Miri areas ([Figure 3](#) and [Figure 4](#)). Based on lithology, geometry, sedimentary structures and sandstone quality, the Nyalau and Miri formations are divided into seven different types of sandstone facies ([Figure 5](#)).
2. Grain Size Analysis. Grain size analysis was carried out by using the sieving method and observation under a binocular microscope. Representative samples were collected from each of the facies. The sieving results were plotted as histograms frequency percentage (for sorting, textural group, skewness, mode and mean values) curve to represent the grain size distribution in different facies of Nyalau and Miri formations ([Figure 6](#) and [Figure 7](#)).
3. Petrography. The petrographic analysis shows the seven different sandstone facies ([Figure 8](#) and [Figure 9](#)). Typically, the samples consist of moderately sorted to well-sorted and fine- to very fine-grained sands. The HCSS sample contains the scattered pore space having an intragranular $\phi = 29\%$ with interconnected pore spaces ([Figure 8A](#)). The HBCBS sample shows the grains which are tightly packed with some inter and intragranular $\phi = 19\%$ but permeability is low as compared to the HCSS sample ([Figure 8B](#)). The TCB sample shows fractured grains and having good intragranular $\phi = 28\%$ with interconnected pore

spaces ([Figure 8C](#)). The W-FBS sample shows that the quartz grains are scattered throughout the thin section and mostly are very fine-grained. The porosity is good but the connectivity is poor due to the coal fragments and some possible pseudometry ([Figure 8D](#)). The sample of BS shows compacted grains with an intragranular ϕ of less than 5% and the grains are in contact such that there is no connectivity, which leads to very low permeability compared to the other four sandstones ([Figure 9E and 9F](#)). Cross-bedded sandstone (CBS) is quartzarenite with fracture porosity having good connectivity ([Figure 9G](#)) and massive sandstone with good primary porosity and permeability with some inclusion of clay minerals ([Figure 9H](#)).

4. Poroperm. The porosimeter PASCAL 240 was used to determine of pore size and volume, in the range of 3.7 and 7,500 nm of radius, by means of mercury intrusion at high pressure. By measuring the quantity of mercury penetrated in the sample pores at equilibrium pressure, experimental data are obtained to calculate the pore volume distribution as a function of their radius for the calculation of porosity (ϕ) and permeability (k). The following results of poroperm from seven different sandstone facies of Nyalau and Miri formations are shown in [Table 1](#).

5. Scale of heterogeneities. Many publications discuss the geological factors that affect the reservoir quality evaluation (e.g. the SAIGUP projects, Manzocchi et al., 2008). [Figure 10](#) summarizes the findings of a selected data set, which are formularized and experimentally designed with statistical analysis, shows the main factor identified in this study for heterogeneity. From these findings, it is clear that several scales of heterogeneity are important for each type of sandstone reservoir. This shows that these factors in shallow-marine deposited sandstone are large and small-scale factors, which have some significance in subsurface reservoir quality evaluation.

6. 2D-Connectivity model. The analysis above documents a static connectivity model for different sandstone facies. Static connectivity was evaluated by using two outcrops from Bintulu (outcrop 1) and Miri (outcrop 1) (locations are marked in [Figure 1](#)). Static descriptive measures can be used to quantify characteristics of a reservoir model (Joseph and David, 2007). 2D outcrop models based on different lithology, shale, observed grain-size trends, petrographic properties and poroperm analysis are constructed here, which shows the heterogeneities in vertical and lateral extent ([Figure 11](#) and [Figure 12](#)). These 2D connectivity models cab be the analogue to subsurface reservoir quality evaluation.

Conclusion

Outcrop analogues give detailed information on sandstone facies geometry, architecture and facies connectivity that cannot easily be understood directly from the subsurface. Based on traditional field analysis, observed grain-size trends, petrographic

properties and poroperm analysis of Nyalau and Miri formations, 2D outcrop models are constructed providing additional insight into the significance of small-scale heterogeneity and static connectivity of shallow marine sandstone deposits. These results provide guidelines for good analogue to subsurface sandstone reservoir quality evaluation.

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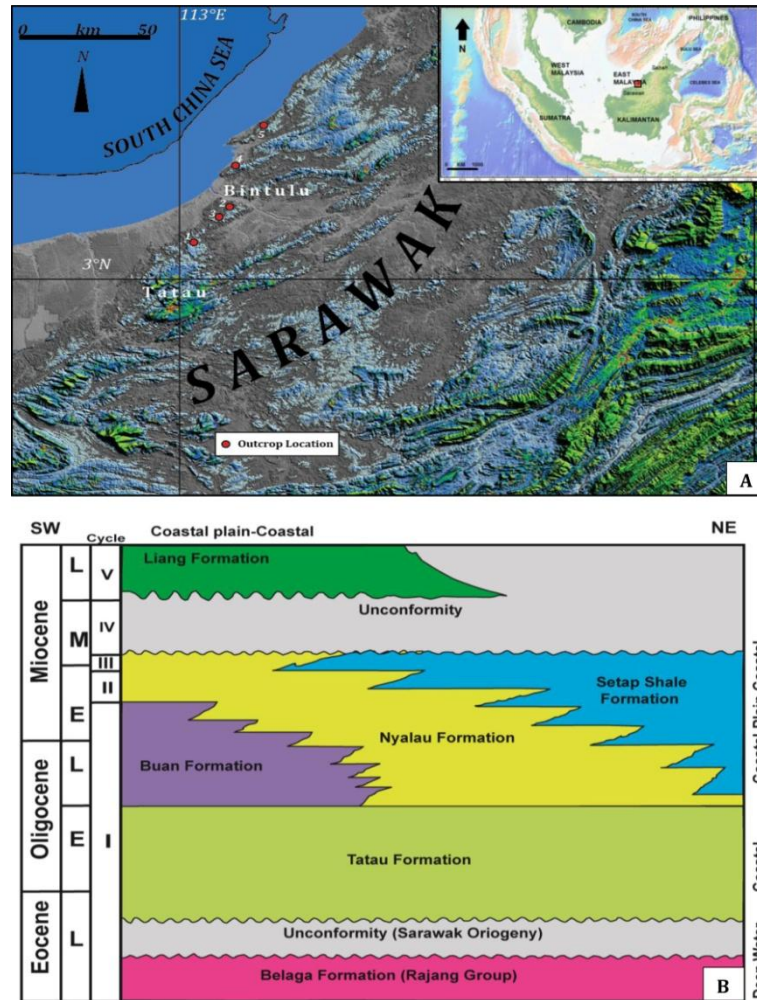


Figure 1. A) Showing the South-East Asia map and outcrop locations of Nyalau Formation near Bintulu town with geological and structural features, Sarawak, East Malaysia (Numair et al., 2014). B) Stratigraphic framework for the onshore northwest coast of Sarawak represent the cycle and age of Nyalau Formation (from Meor et al., 2013).

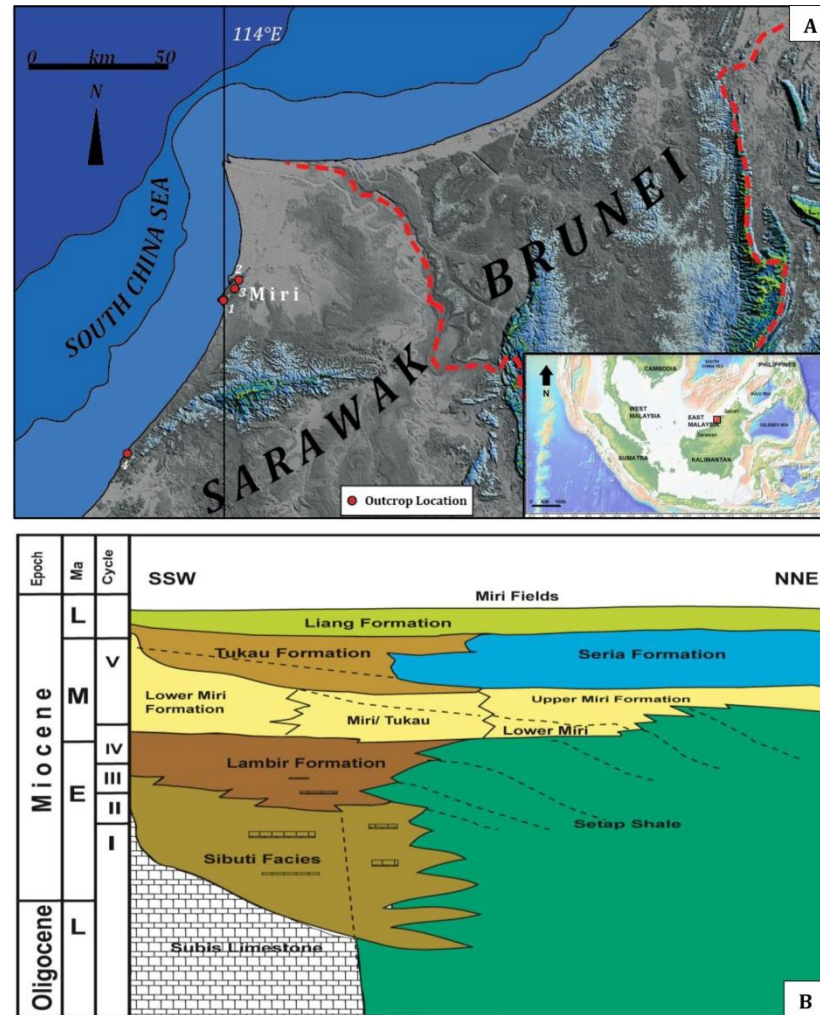


Figure 2. A) Showing the South-East Asia map outcrop locations of Miri Formation near Miri town, Sarawak, East Malaysia. B) Stratigraphic framework for the onshore northwest Sarawak represents the units of Miri Formation (modified from Mazlan, 1999).

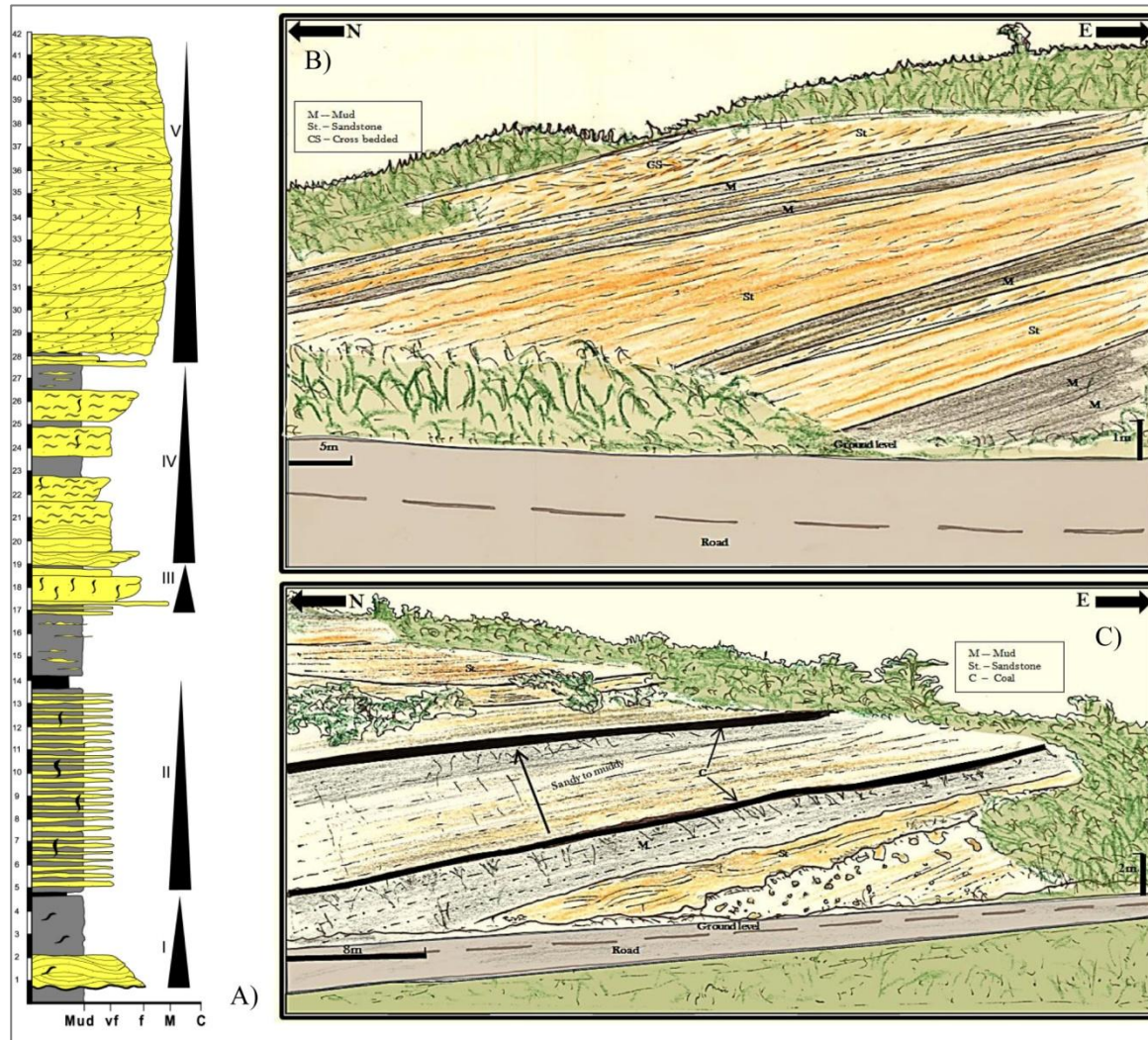


Figure 3. A) Stratigraphic log and diagrammatic sketch of Outcrop 1 (Sungai Mas Camp), B) upper section, and C) lower section of Outcrop 1.

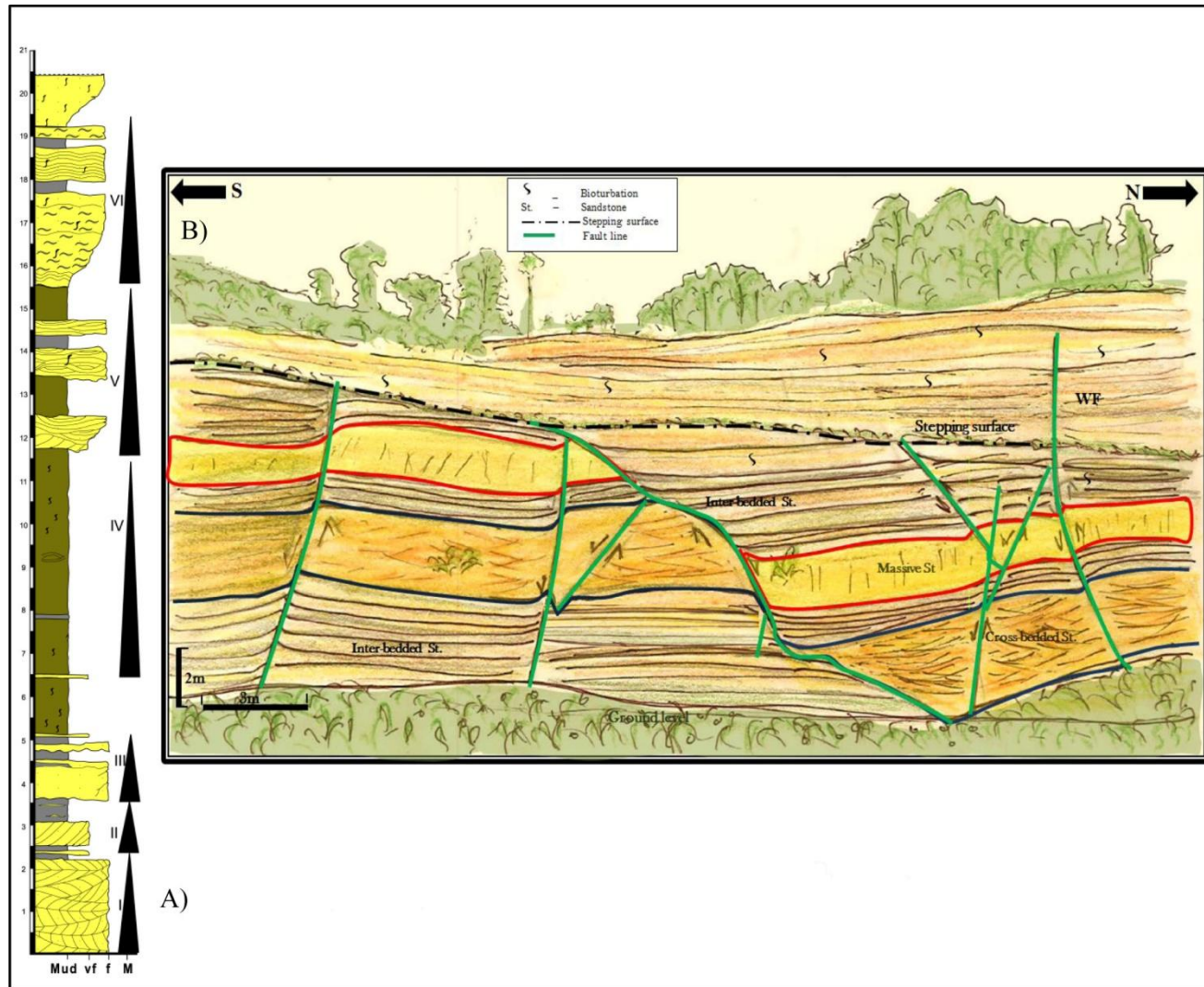


Figure 4. A) Stratigraphic log of Miri Outcrop 1, B) Outcrop sketch of Miri Formation, Airport Road Outcrop.

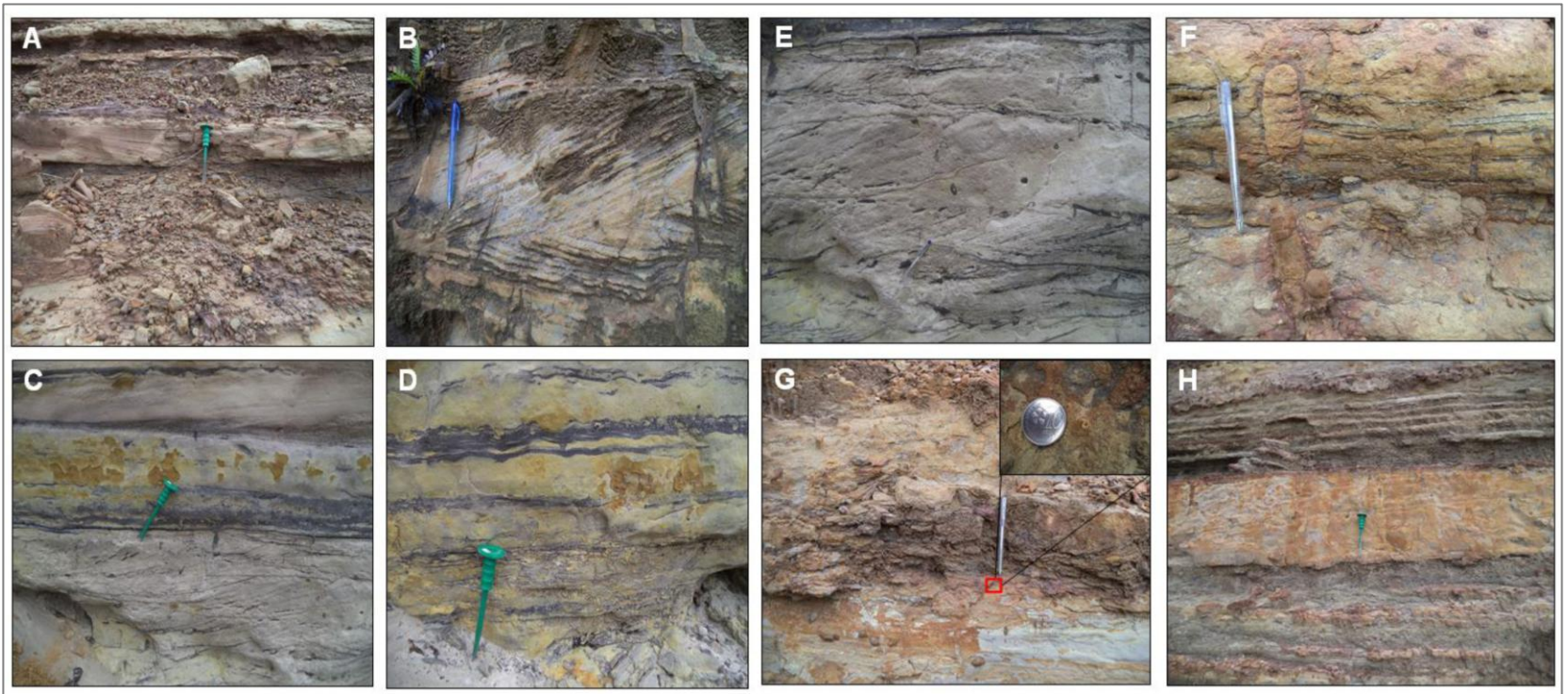


Figure 5. Major sandstone Facies of Nyalau and Miri formations, A) hummocky cross-stratified sandstone (HCSS), B) herringbone cross-bedded sandstone (HCBS), C) trough cross-bedded sandstone (TCB), D) wavy to flaser bedded sandstone (W-FBS), E) cross-bedded sandstone (CB), F) Bioturbated sandstone (BS), G) Coarse-grained bioturbated sandstone, with fossilized Mollusk Sea Shell in small picture and H) Massive sandstone (MS).

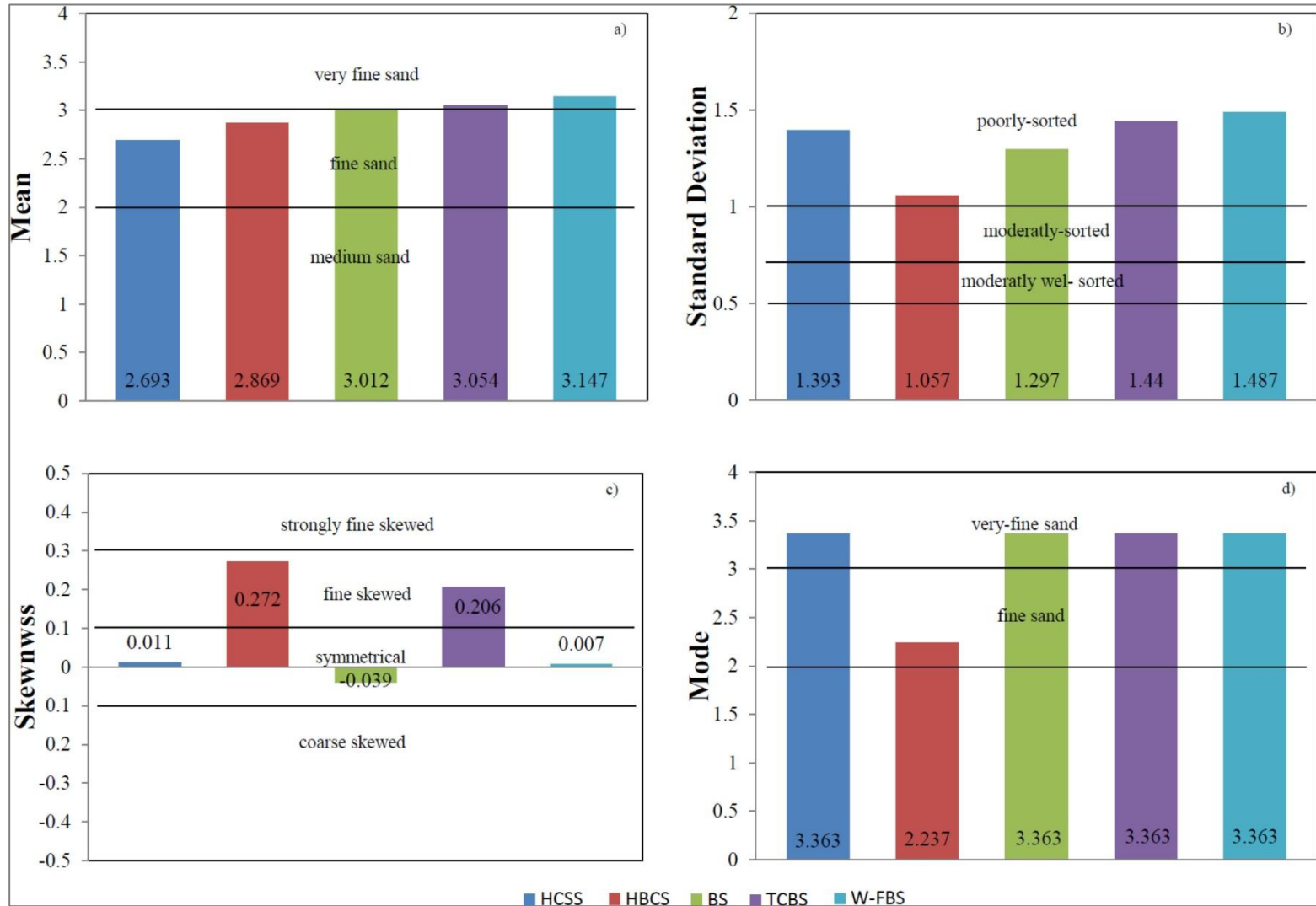


Figure 6. Comparative histograms of five different sandstone type; a) Mean, b) Standard deviation, c) Skewness and d) Mode.

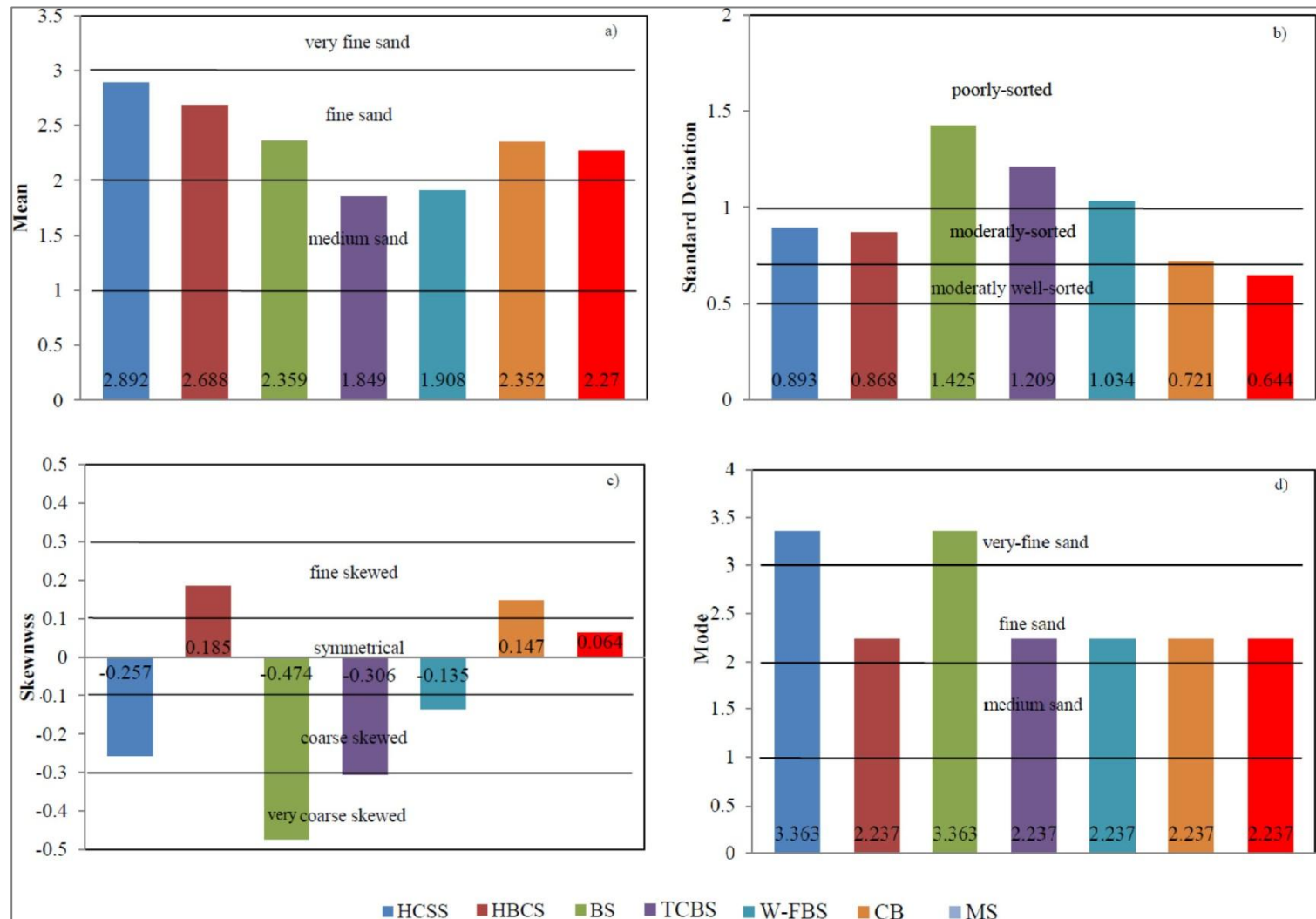


Figure 7. Comparative histograms of seven different sandstone types in Bintulu and Miri: a) Mean, b) Standard deviation, c) Skewness and d) Mode.

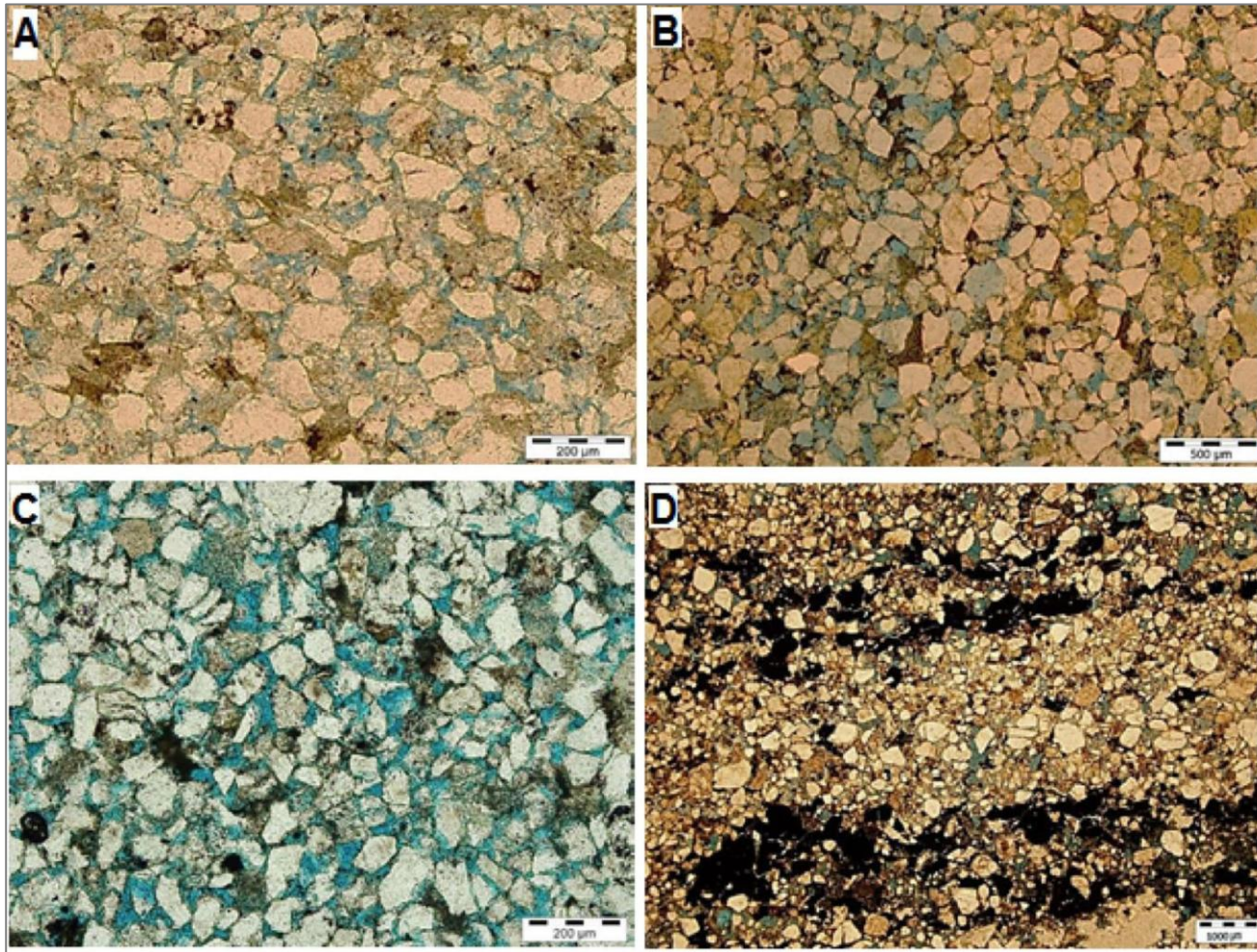


Figure 8. A) Framework grains of hummocky cross-stratified sandstone (HCSS), is quartzarenite with monocrystalline quartz having few inclusion and little undulosity with primary intergranular porosity of 29%. Some grains show intragranular porosity by compaction in between grains; B) Framework grains of Herringbone (*Presenter's notes continued on next slide*)

(Presenter's notes continued from previous slide)

cross-bedded sandstone (HBCBS), grains are tightly packed with some inter and intragranular $\phi = 19\%$ but permeability is low as compared to the HCSS sample. The sandstone is quartzarenite with monocrystalline quartz with clay $> 5\%$ and some carbonaceous material; C) Trough cross-bedded sandstone shows fractured grains and having good intragranular $\phi = 28\%$ with interconnected pore spaces. The sandstone is quartzarenite with matrix-supported grains. The grain is monocrystalline with 80.58% sand and 9.52% clay which reduces the permeability by infiltration; D) wavy-to-flaser bedded sandstone (W-FBS), having porosity 12% but the connectivity is poor due to the coal fragments and some possibly some pseudometry with high percentage of clay (37.40%).

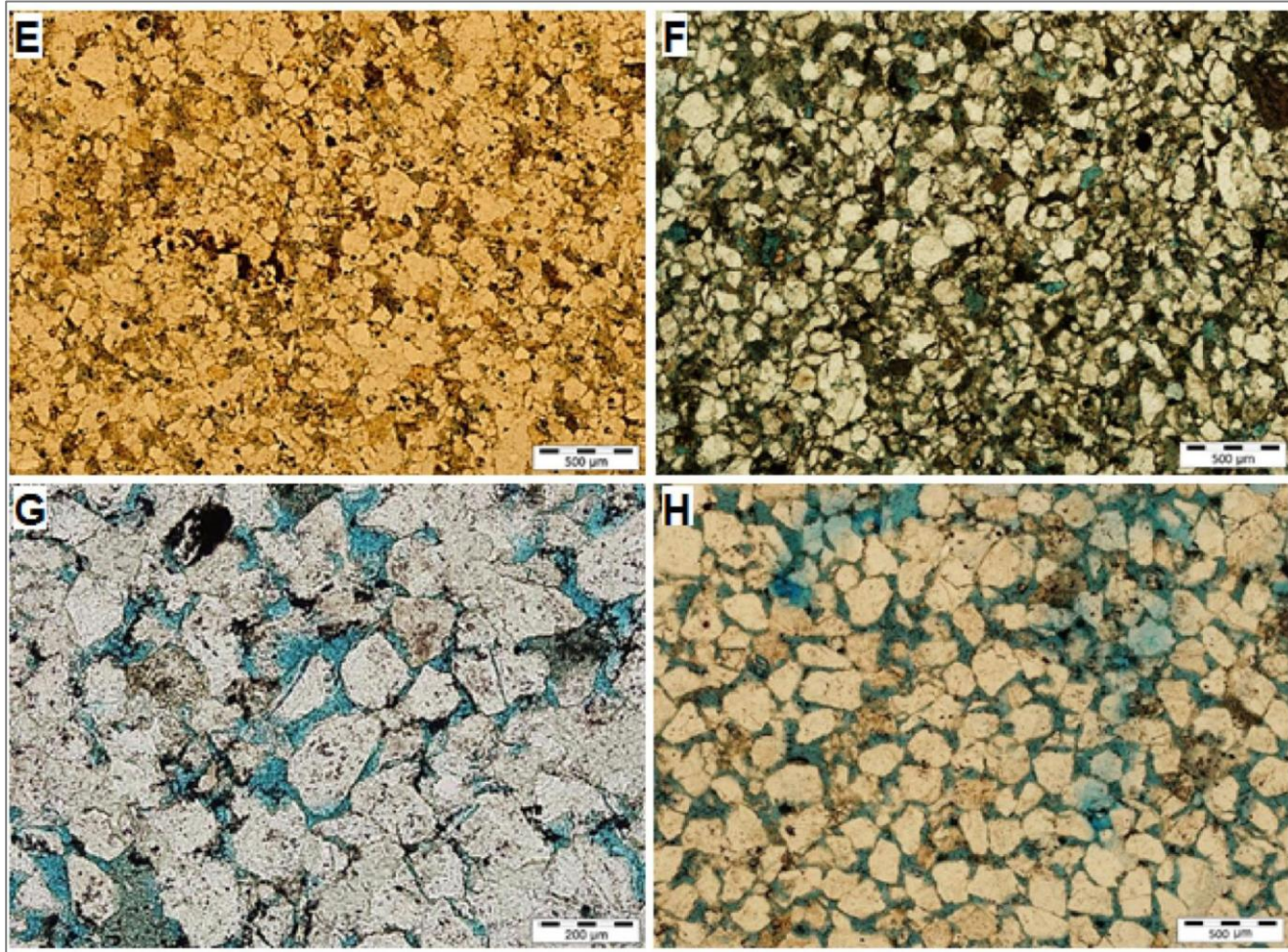


Figure 9. E) and F) Framework grain of Bioturbated sandstone (BS). The sandstone is quartzarenite and monocrystalline grains. The porosity is low due to intense bioturbation and clay minerals (mostly of chlorite and illite) with clay percentage of 17.20% (texturally immature); G) Cross bedded sandstone (CBS) is quartzarenite with fracture porosity having good connectivity; and H) massive sandstone with good primary porosity and permeability with some inclusion of clay minerals.

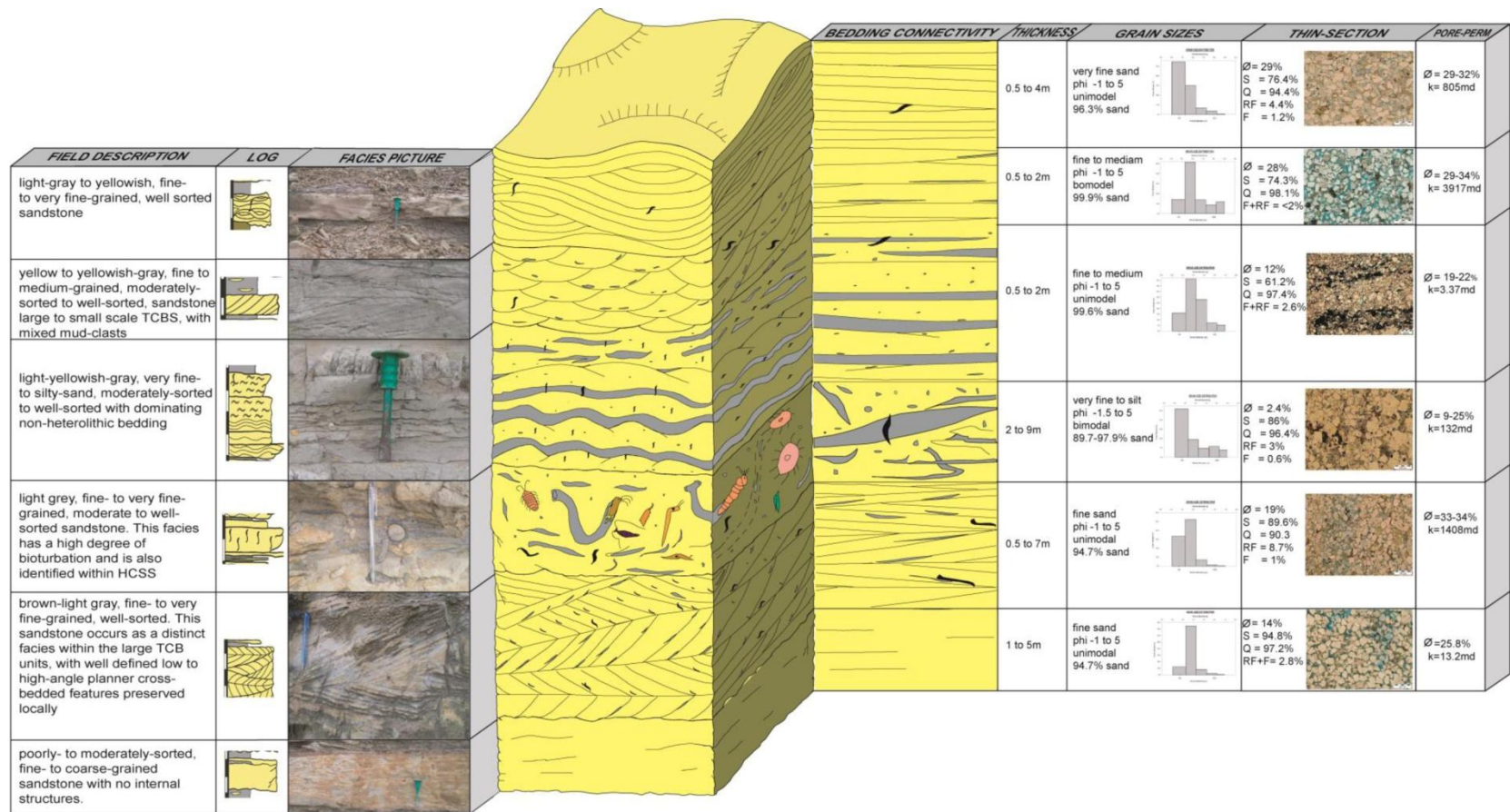


Figure 10. Summarizing the findings of a selected data set, which are formularized and experimentally designed with statistical analysis, showing the scale dependent variability and heterogeneity.

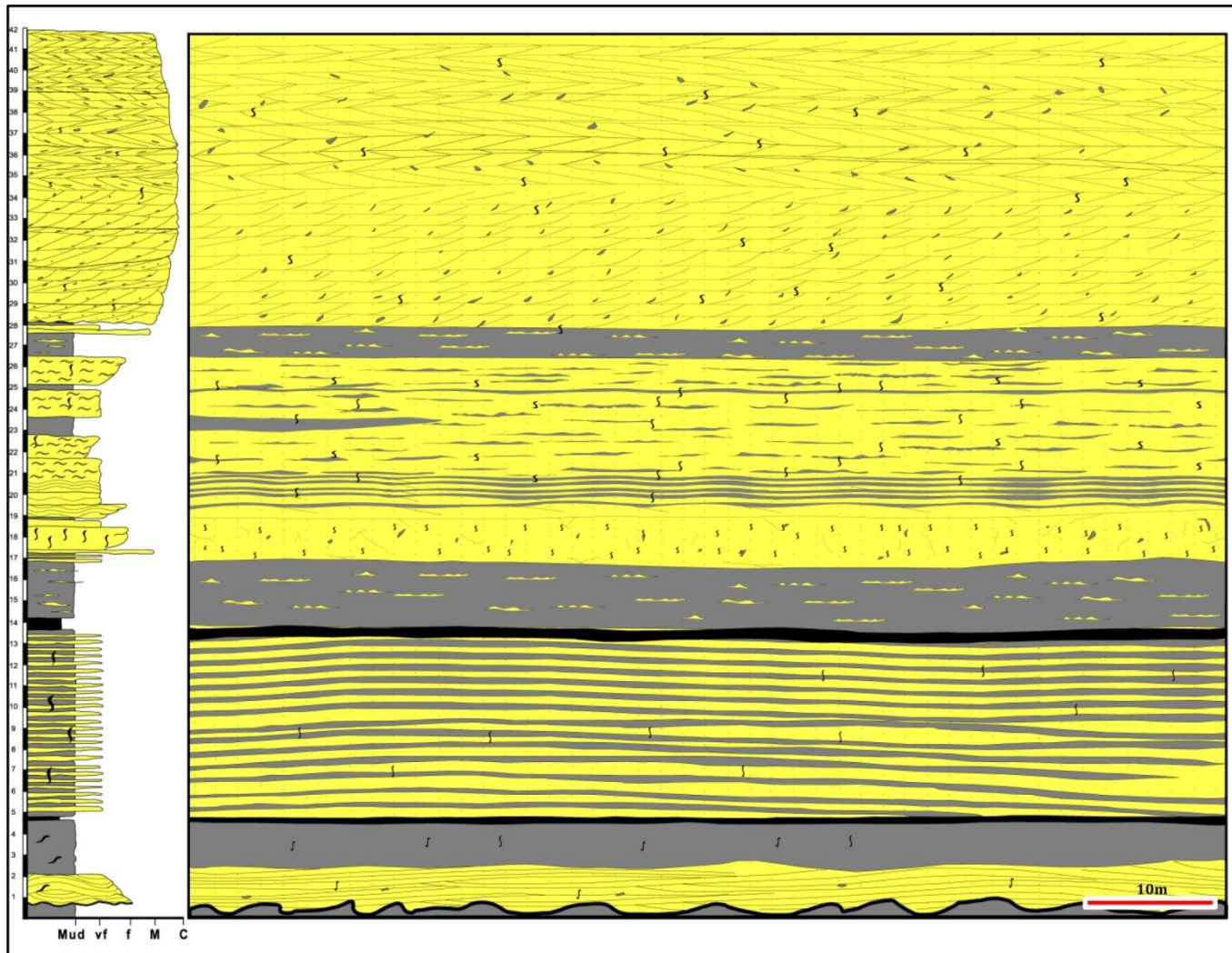


Figure 11. Outcrop 1 of Bintulu area Nyalau Formation; 2-D model and stratigraphy with vertical and lateral variation and connectivity between different sandstone facies.

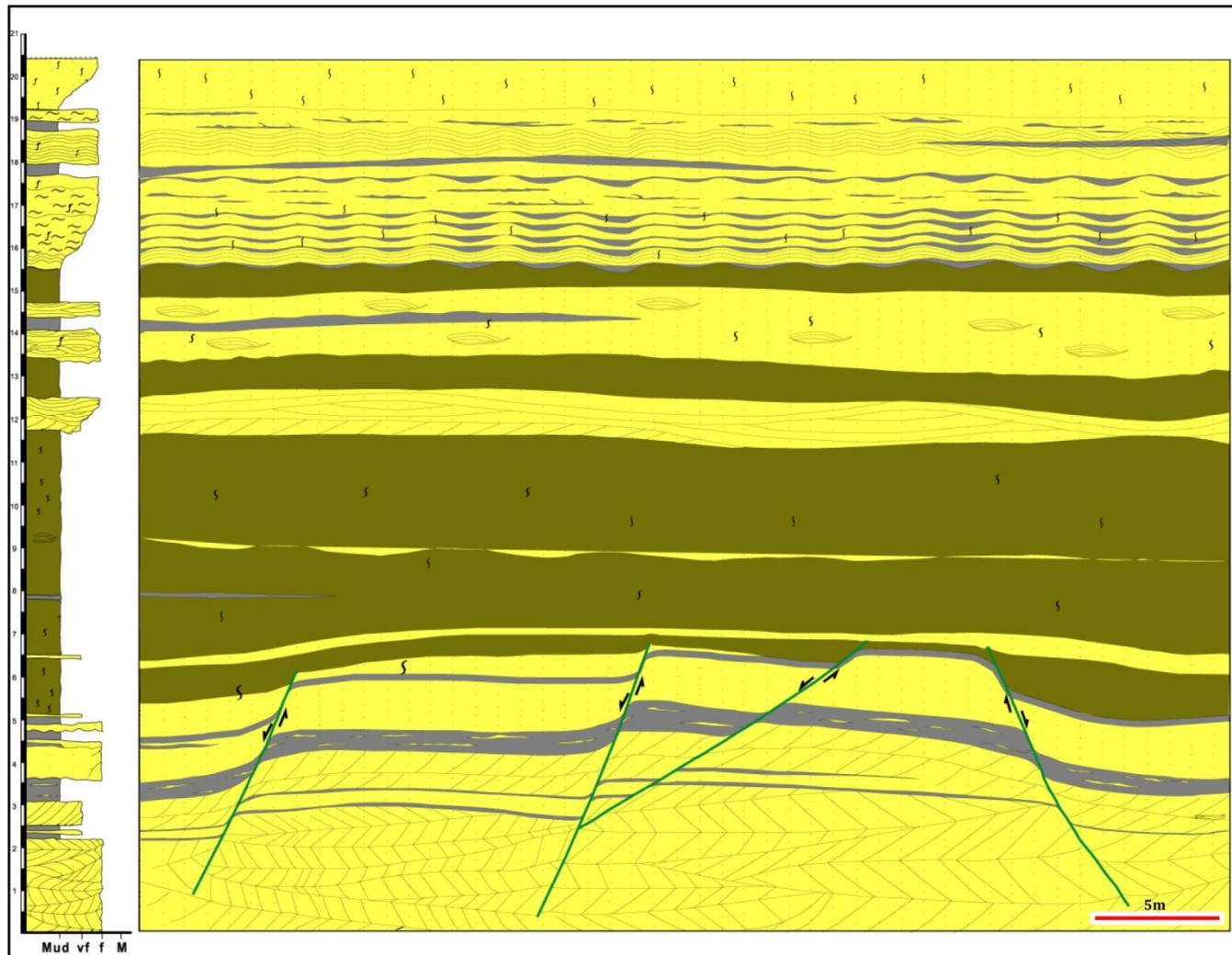


Figure 12. Outcrop 1 of Miri formation; 2-D model and stratigraphy with Vertical and lateral variation and connectivity between different sandstone facies.

Sample	Porosity (%)	Permeability (md)
Nyalau Formation		
Hummocky cross-stratified sandstones	32.07	669.58e-5 μm^2 = 6.78
Herringbone cross- bedded sandstones	33.31	175.13e-4 μm^2 = 17.5
Trough cross-bedded sandstone	29.2	495.75e-5 μm^2 = 5.01
Wavy- to flaser-bedded sandstone	19.40	224.03e-5 μm^2 = 2.27
Bioturbated sandstone	25.10	345.44e-5 μm^2 = 3.4
Miri Formation		
Hummocky cross-stratified sandstones	29.31	794.93e-3 μm^2 = 805
Herringbone cross- bedded sandstones	30.41	138.96e-2 μm^2 = 1408
Trough cross-bedded sandstone	34.41	386.61e-2 μm^2 = 3917
Wavy- to flaser-bedded sandstone	22.04	336.8e-5 μm^2 = 3.37
Bioturbated sandstone	9.74	130.78e-3 μm^2 = 132
Massive sandstone	25.80	130.86e-4 μm^2 = 13.2
Cross-bedded sandstone	34.35	217.01e-1 μm^2 = 21988

Table 1. Results of porosity-permeability by porosimeter of seven different sandstone facies, Nyalau Formation and Miri Formation.