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THE VARIOUS CONTROLS ON THE PLATFORM ARCHITECTURE OF CARBONATE BUILDUPS IN THE CENTRAL LUCONIA PROVINCE, OFFSHORE SARAWAK

Ari Yusliandi[1], Benjamin Sautter[2], Michael C. Poppelreiter[1]*

[1] *South East Asia Carbonate Research Laboratory (SEACARL), Department of Geosciences, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia*

[2] *Department of Geosciences, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia*

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Abstract

Cenozoic isolated carbonate buildups around the world have been studied by many authors. These buildups are commonly dominated by corals, coralline algae, and large benthic foraminifera. Their development is the result of the interaction of multiple factors including tectonics (subsidence and antecedent topography), eustasy, climate, siliciclastic influx, nutrition, and environmental condition, which control the relationship between carbonate production and accommodation space, and furthermore determine the internal sedimentary architecture and facies distribution within carbonate buildups. In this study, controlling factors that influence the platform architecture of buildups in Central Luconia will be discussed. Factors will be differentiated based on local influence on single buildup, or if they have a regional effect on the entire Central Luconia region. Based on the quantitative description of the predictive attributes, there are similarities and differences that indicate the controlling factors not only affect regionally but there also factors that work uniquely on single buildup.

***Keywords**: Miocene buildups; Central Luconia province; Controlling factors; Platform architecture.*

1. Introduction

During Late Oligocene to Miocene, the climate and oceanographic settings, like clear tropical water conditions [1], enhanced the coral growth extensively [2-4], causing the formation of isolated carbonate buildups. Southeast Asia contains a wide range of carbonate settings, from barrier reef to isolated carbonate buildups. The Central Luconia Province provides an ideal example of isolated carbonate buildups to understand the effects of interactions between sea-level changes, tectonic, oceanographic circulation, climate changes on the platform evolution in the Southeast Asia region. During the Middle to Late Miocene, the Central Luconia Province (see Chapter: Geological Setting) was a stable area, characterized by extensive isolated carbonate buildups. In the Late Miocene to Pliocene the platforms became gradually covered by northwest prograding siliciclastic sequences of the Baram delta in the southeast [2].

The Miocene isolated carbonate buildups in Central Luconia have been discussed in the past few decades with the focus on various topics [2, 5-16]. However, the understanding of controls affecting the carbonate development and platform architecture is still unclear. No previous studies have attempted to study the relationship between factors that controlled the carbonate growth and its evolutions in Central Luconia Province.

In this study, controlling factors that influence the platform architecture of buildups in Central Luconia will be discussed. Factors will be differentiated based on local influence on single platforms, or if they have a regional effect on the entire Central Luconia region. This is accomplished by a comprehensive analysis of seismic data integrated with sedimentological data from cored intervals. To predict how significant the individual controlling factors are, five predictive attributes are proposed in this study to distinguish between local factors and regional controls:

- Facies composition
- Stratigraphy architecture
- Thickness changes
- Karstification
- Geometry

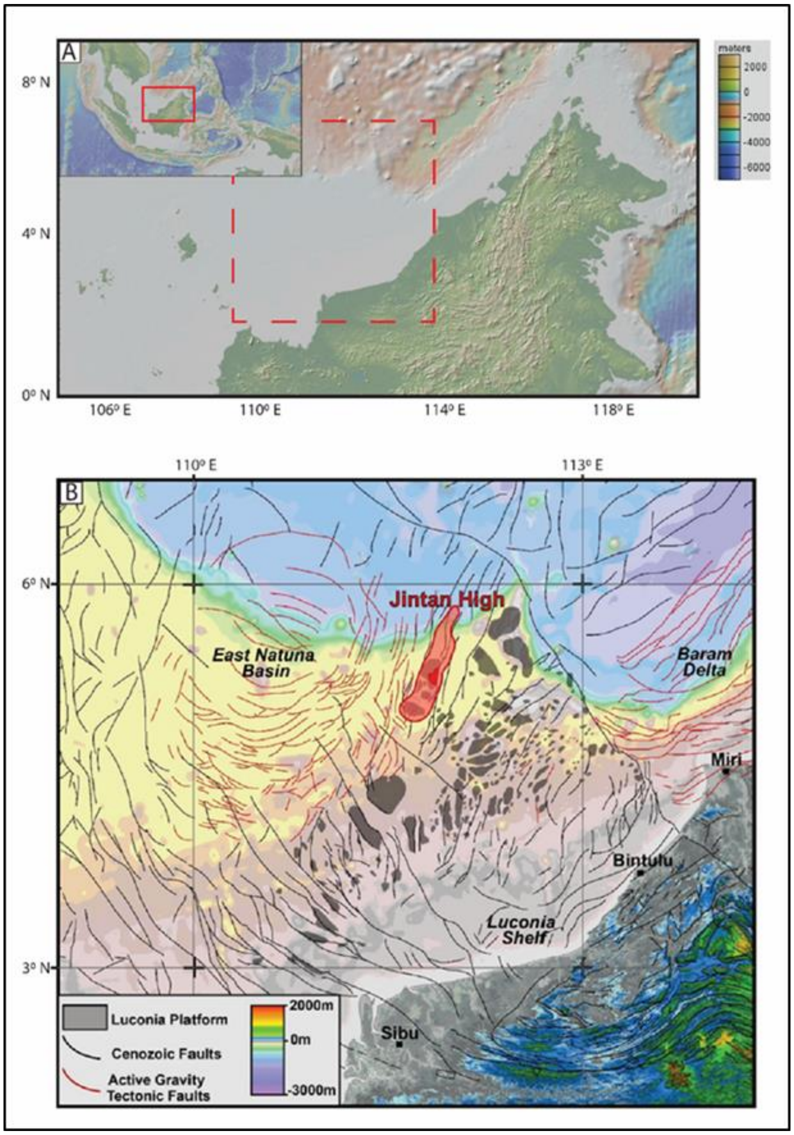

Figure 1 A). Geographical location of the Central Luconia Province, offshore Sarawak, Northwest Borneo, Southeast Asia (map also available at http://www.geomapapp.com). (B). Location of the Jintan High in a regional structural map in the Central Luconia Province. Black lines indicate the Cenozoic faults, and red lines represent the active gravity faults due to sediment load in the Baram and Rajang Delta (East Natuna Basin)

The study area is located in the northern part of the Central Luconia Province on the Jintan High (Fig. 1). Several former isolated carbonate buildups at the base of the Jintan High amalgamated and formed a Mega Platform. The Mega Platform is a 1200 m thick carbonate buildup and extends 30 km x 50 km in a roughly SW-NE orientation [7]. For a regional understanding, predictive attributes, as listed above, will not only be studied on the Mega Platform but will also be compared to other platforms of Central Luconia as calibration points. The comparison on a regional scale is necessary to identify similarities and differences in several locations, and thus to classify them as a local or regional factor. In total six buildups were selected as calibration points, including MY, FX, FY, BX, EX, and EY (Fig. 2). The selected buildups were chosen based on several factors, such as their relative position from paleo-coastline (siliciclastic influx) and relative position to the margin of the continental shelf related to the wind-wave energy.

2. Geological setting

Central Luconia is a province located offshore Sarawak, NW Borneo, surrounded by three deep depressions: The West Luconia Delta in the the west, the Baram Delta in the east separated by West Baram Line, and the North Luconia province on the northern side. In the south, the shortened Balingian province marks the transition between Central Luconia and onshore Sarawak [12, 17-19].

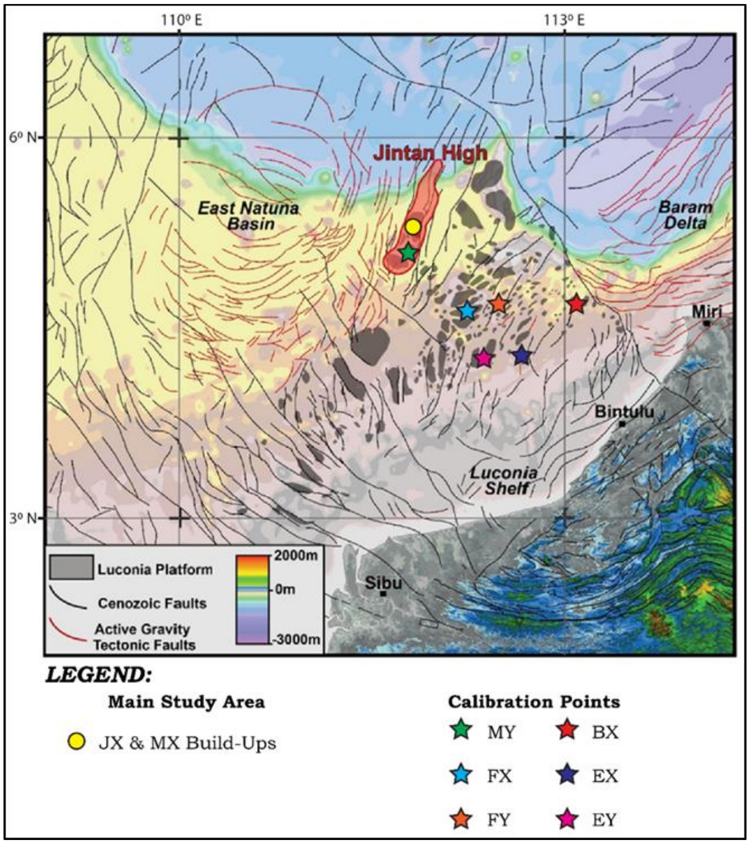

Figure 2 Location of the Mega Platform and other platforms that were used for comparison and a regional understanding of the Central Luconia Province

The Central Luconia Province consists of regional structural highs and troughs interpreted to represent horsts and grabens inherited from the South China Sea rifting. These basement highs are striking north-south to northeast-southwest [12]. The study area is located in the most northern part of Central Luconia (Fig. 1). The Mega Platform grew on one of these paleo-highs known as the Jintan High, that was formed due to normal faulting during the Late Oligocene to Early Miocene rifting of the South China Sea [7]. Faulted blocks in the northern part have south-southwest to north-northeast trends and are bounded by northeast-southwest trending normal faults (Fig. 1) [10].

Figure 3 shows a roughly NNE-SSW cross-section through the Mega Platform, including MY-s, MY, MZ, SX, JX, MX, and MX-E. The section shows that the growth of the buildups initiated on fault-bound structural highs. They are also influenced by syn-depositional faulting during their growth history. However, this study only focuses on the JX and MX buildups.

3. Datasets and methods

The datasets consist of 3D seismic data which cover the Jintan and M1 build-ups, almost 400 metres of core description from three wells: JX-a, JX-b, and MX-c. More than 650 thin sections and analyses of well log suites, including gamma ray, density, neutron, sonic and porosity readings (Figure 3). All cores have been carefully examined and correlated based on well log data, lithology, litho facies types and litho facies association (Fig. 4). Subaerial exposure features, such as karst, and flooding surfaces, marked by muddier facies like wacke- and packstones, were identified. To enhance the 2D correlation and the regional understanding, well log data was used in uncored wells and correlated to JX-c, MX-a, and MX-b (Fig. 4).

Seismic volume data in this study consists of two volumes: JX and MX. The JX seismic was acquired in 1992, while the MX volume seismic is part of the Terumbu Luconia 3D acquisition in 2015-2016. The workflow for seismic interpretation in this study includes well tie seismic through creation of synthetic seismogram, fault and horizon interpretation, seismic reflector pattern interpretation, and generate sub-environment interpretation. Thie interpretation was conducted using the softwares Paleoscan by Ellis™ and Petrel by Schlumberger™.

Isolated carbonate build-ups were interpreted on seismic data using the identification criteria of Burgess et al., (2013). Seismic stratigraphy analysis includes the identification of main unconformities and their associated seismic sequences [21]. Within each seismic sequence, the platform margins were mapped, and the seismic facies were identified. Seismic facies were mapped on the 3D seismic data at carbonate unit.

Seismic attributes were applied on the 3D seismic and horizon stacking from base to top of carbonate. Coherence attributes were applied to identify the major discontinuities (e.g. faults, platform margins, and karst features) [22-23]. Spectral decomposition was applied to enhance the visualization of sub-environments and karstification events through specific frequency.

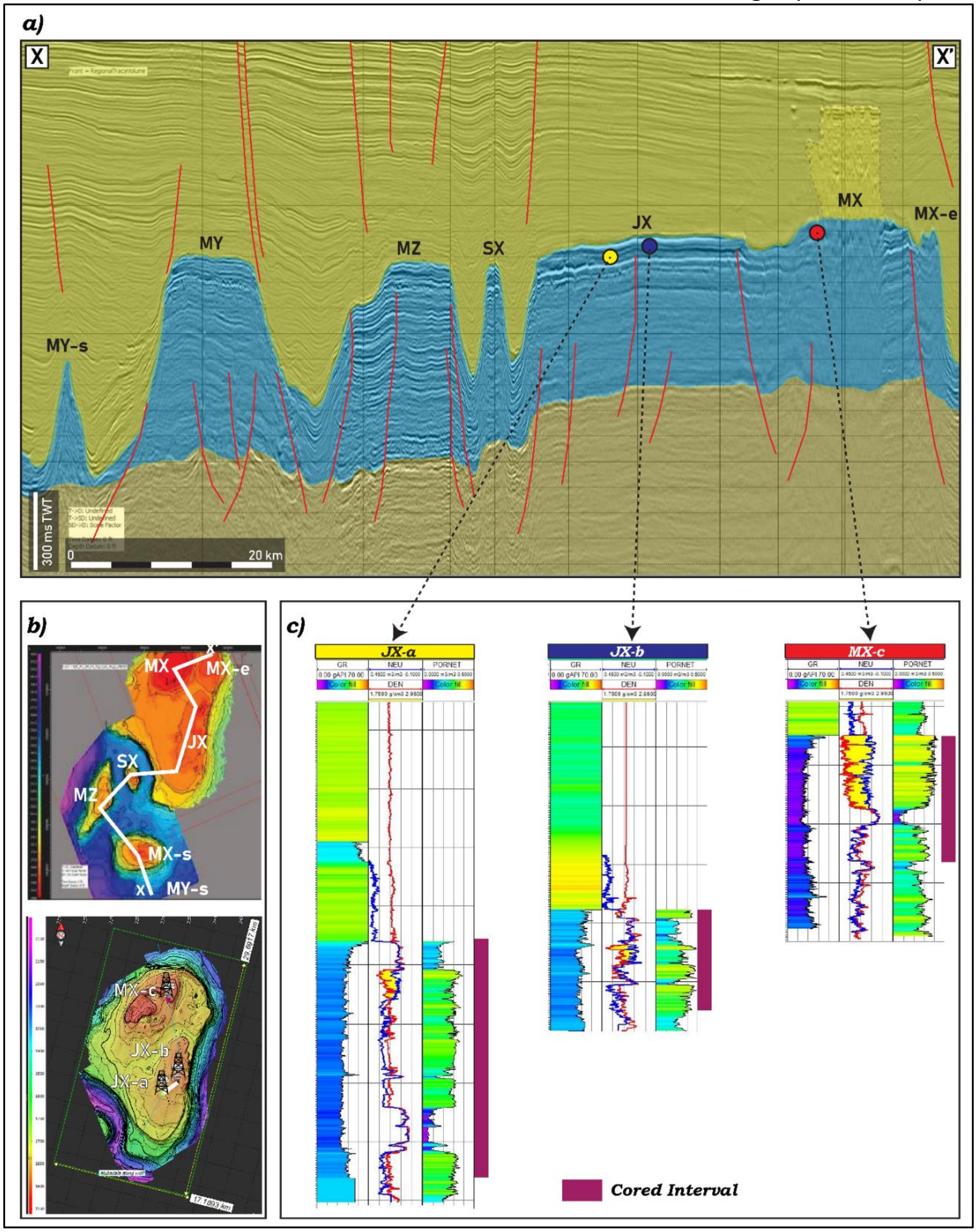

Figure 3 a). Regional cross section of the Mega Platform, b). Upper part: location map of the Mega Platform, lower part: top structure of JX and MX buildups, c). Well log and cored interval in studied wells: JX-a, JX-b, and MX-c.

4. Results and discussions

4.1. Sedimentological characteristics

A detailed sedimentological description and characterization are based on core descriptions and thin section analyses. The cored intervals of the studied buildups display distinctive cyclic depositional sequences. The facies stacking forms a cyclic depositional pattern consisting of repetitive transgressive and regressive sequences that represent the alternation of porous and tight carbonate layers, as shown in seismic, logs, and cores. These sequences are bound by flooding surfaces and horizons which experienced subaerial exposure. From cores observation, 3 (three) tight interval layers can be mapped across the entire study area (Fig. 3).

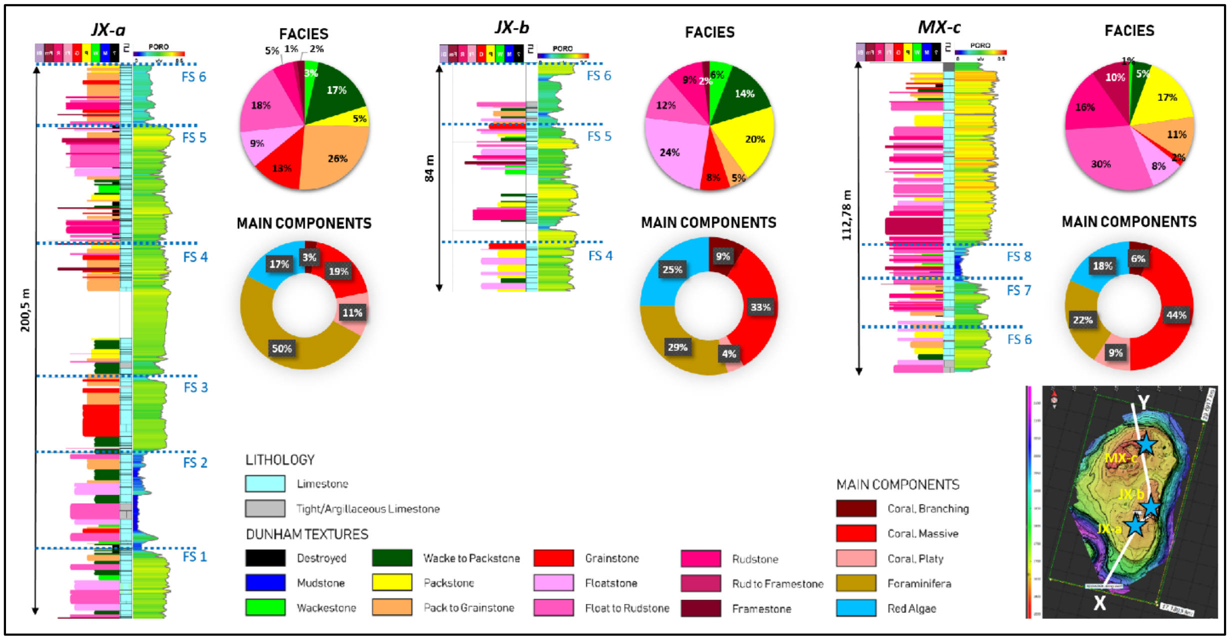

Figure 4. The facies types and facies associations of studied cored intervals from three wells

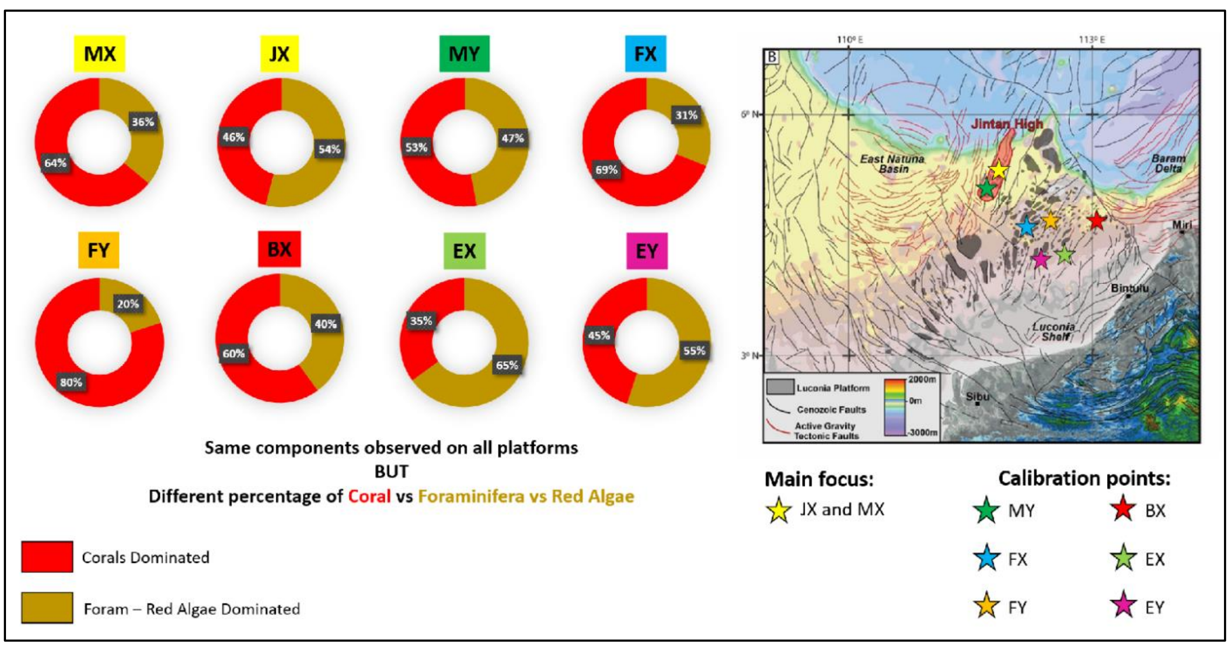

Figure 5. The regional facies composition comparison across selected buildups in Central Luconia Province

The main observed lithology is limestone with occasionally slightly tight-argillaceous limestone intervals, which commonly occur in low porosity intervals. Facies types and facies associations were described from core data. The main facies are floatstone to rudstone and wackestone to grainstone (Fig. 4). The platform is mainly composed of corals, foraminifera and red algae. MX-c is more coral dominated than JX-a and JX-b, which are dominated by foraminifera and red algae (Fig. 4). The different percentage of coral vs foraminifera – red algae is related to the position of each well, and thus the distance to the platform margin (wave energy). For a regional understanding, the facies composition is compared to six other platforms. A relatively comparable component composition was observed on all platforms with slightly different percentages of coral vs foraminifera-red algae (Fig. 5). It is assumed that the variation of these percentages depends on the platform location and, thus the overall wave energy.

4.2. Stratigraphic architecture

The stratigraphic framework of the Mega Platform was established on two scales (Table 1): stratigraphic sequence (small scale) and seismic unit (larger scale). Boundaries of stratigraphic sequences are marked by flooding surfaces (Fig. 4). This stratigraphic framework also correlates to reservoir zonation by Shell. A total of 20 stratigraphic sequences was observed from base carbonate to top carbonate (Table 1). The interval between tight layers in all platforms is approximately 100 m thick (Fig. 6). The tight layers are commonly associated with moldic and microporosity, while the porous layers are associated with karst and vuggy pores.

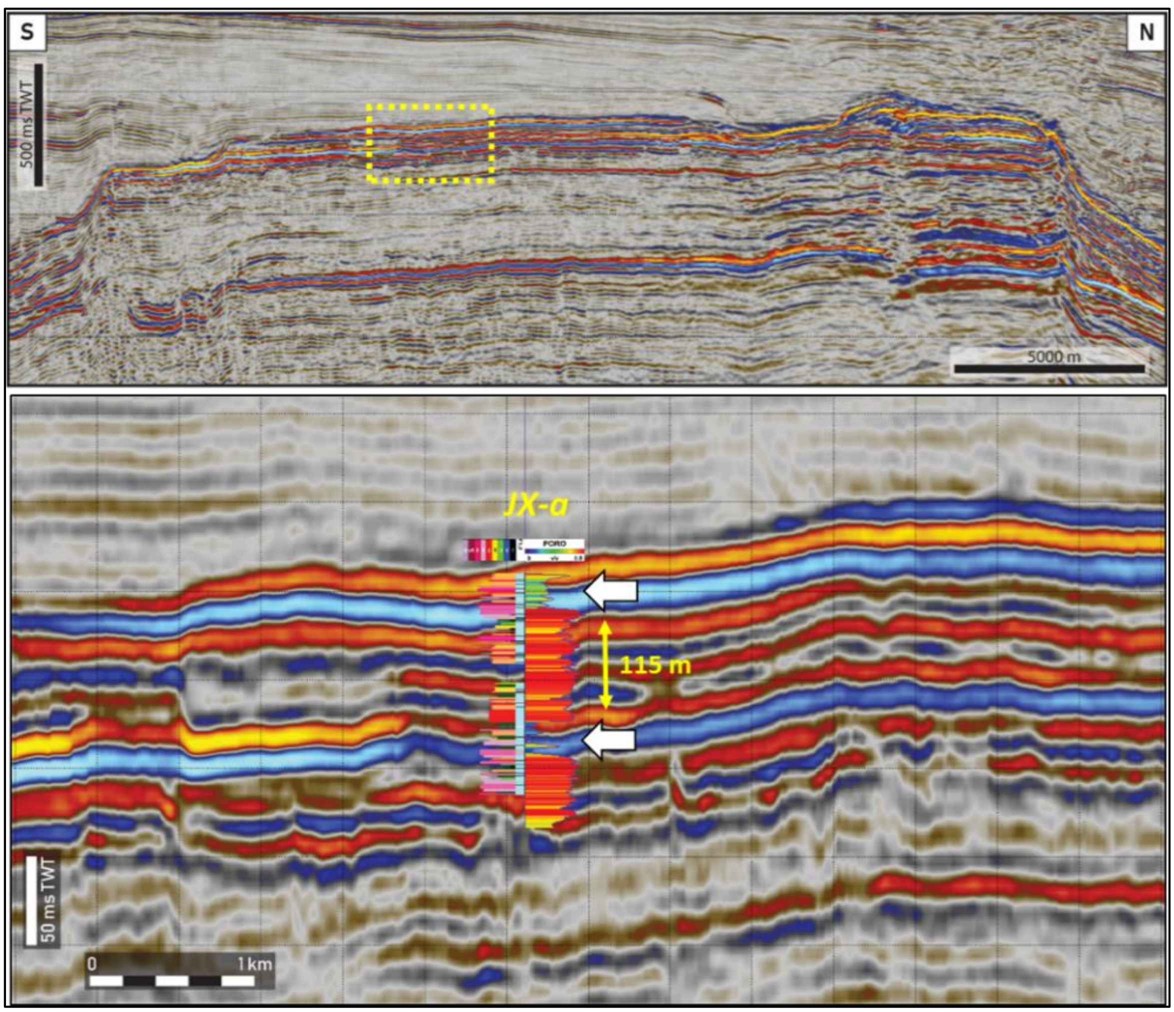

Figure 6. The interval between tight/low porosity layers is approximately about 100 m thick

Table 1. The stratigraphic frameworks have been established in this study

Time	Event	Seismic unit	Stratigraphic sequence	Shell's nomenclature
MIDDLE – LATE MIOCENE	*End of MX build-up*	SU 6	SS 20	I
			SS 19	II
	End of JX build-up		SS 18	III
		SU 5	SS 17	IV
			SS 16	V
			SS 15	VI
			SS 14	VII
			SS 13	VIII
	Major Backstep		SS 12	IX
		SU 4	SS 11	
			SS 10	
		SU 3	SS 09	
			SS 08	
			SS 07	
		SU 2	SS 06	
			SS 05	
			SS 04	
		SU 1	SS 03	
			SS 02	
	Base of Mega Platform		SS 01	

4.3. Seismic units

Seismic units are based on geomorphological aspects such as backstepping events. Six seismic units were observed in the study area, all associated with in- and decrease of flank deposits, which are interpreted as carbonate debris or talus deposit (Fig. 7).

Seismic Unit 1 (SU 1) consists of SS 01 (trough; blue reflectors in section) to SS 03 (trough). SS 01 represents the base of carbonate deposition on the Mega Platform. SU 1 (SS 01 to SS 03) corresponds to a low to moderate amplitude and represents small carbonate mounds and patches, which are interpreted as the first recognizable flooding event of the Middle Miocene Unconformity (Fig. 7). The thickness of SU 1 ranges from 145-155 ms TWT in the middle area to 170-200 ms TWT in the south-eastern part and northwest area. This thickness-trend follows the fault with north-northeast to south-southwest orientation (Fig. 8).

Seismic Unit 2 (SU 2) is underlain by SS 03 (a trough; blue reflectors in section), capped with SS 06 (a trough). SS 03 to SS 06 are cut by numerous steep normal faults that trend north-south and northeast-southwest (Fig. 7). The thickness of SU 2 ranges from 85 to 125 ms TWT (Fig. 8). The thickest part is located on the southern part of the Mega Platform due to an extensive normal fault that caused the progradation of sediment into the depression area. In the middle part of the platform, normal faults do not seem to be associated with changes in stratigraphic thickness. It is thus assumed that deformation occurred after the deposition of SS 06.

Seismic Unit 3 (SU 3) is underlain by SS 06 (a trough), capped with SS 09 (a trough). The reflectors of SS 06 to SS 09 are semi-continuous to continuous. The thickness of SU 3 ranges from 100 ms to 190 ms TWT. Seismic unit 3 overlies seismic unit 1-2's faulted area in the southern part (Fig. 7 and Fig. 8).

Seismic Unit 4 (SU 4) is underlain by SS 09 (a trough), capped with SS 11 (a trough). SS 11 is represented by a high amplitude response and indicates the flooding of the Mega Platform in the Late Miocene (Major Backstepping). This seismic unit is associated with a period of quiescence of tectonic activity. At the end of SU 4, the Mega Platform experienced a significant sea-level fall, which led to the karstification of the entire Mega Platform. This karstified event can be observed throughout the Mega Platform and is marked by a regional high impedance layer (Fig. 7). The thickness of the seismic unit ranges from 130 ms TWT up to 140 ms TWT (Fig. 8).

Seismic Unit 5 (SU 5) is underlain by SS 11 (a trough; high amplitude), capped with SS 17 (a trough). SS 17 represents the top of carbonate deposits in the JX build-up (Fig. 7). SU 5 is mostly marked by high amplitude parallel reflectors with some discontinuous pattern. The discontinuous pattern indicates the locally karstified horizons in JX and MX build-ups. The thickness of SU 5 ranges from 45 ms TWT to 80 ms TWT (Fig. 8).

Seismic Unit 6 (SU 6) is underlain by SS 17 (a trough), capped with SS 20 (a peak, red reflectors in section). SU 6 is interpreted as the last stage of the build-up in the studied area (MX build-up) (Fig. 7) with a total thickness of up to 87 ms TWT (Fig. 8).

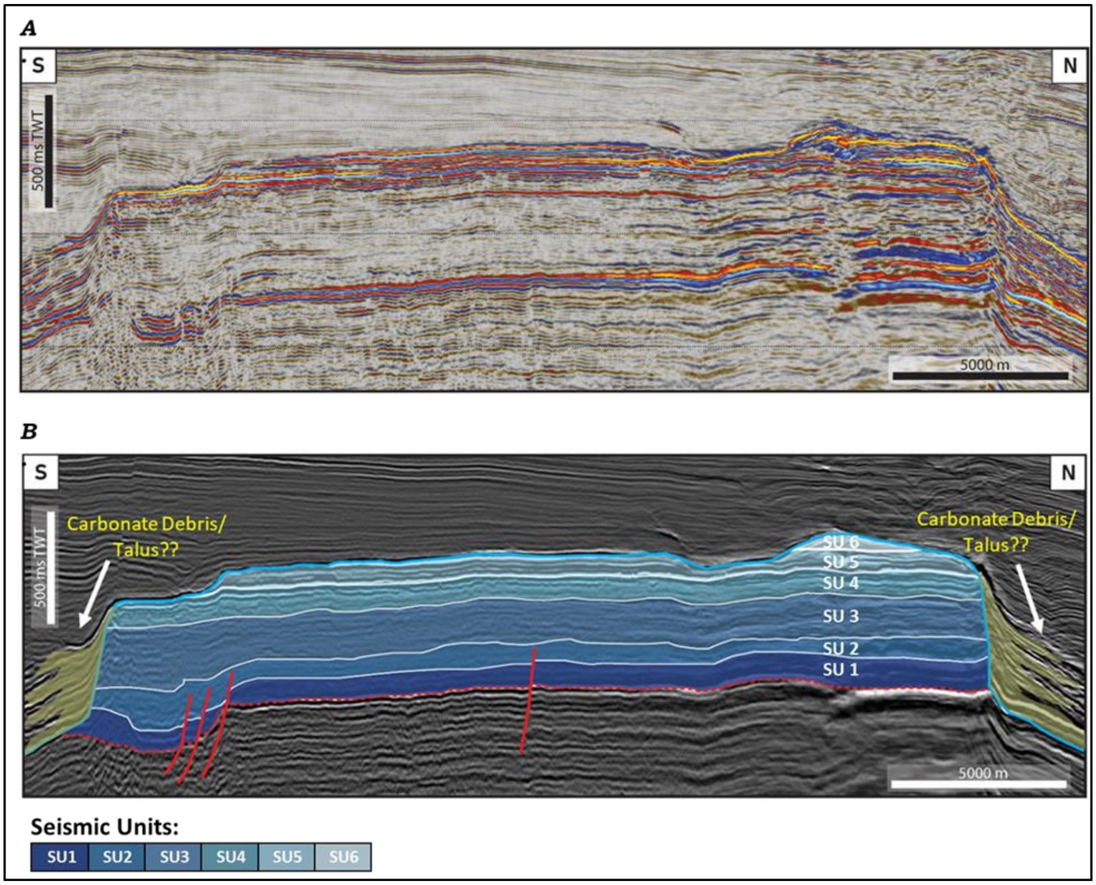

Figure 7 A). Uninterpreted seismic section of Mega Platform, B). Interpreted section, 6 (six) seismic units were observed with carbonate debris/talus deposits in the flanks area

The time thickness map from six seismic units reveals thickness variations in SU1 to SU 3. These thickness changes are likely controlled by syn-sedimentary active faults with north-northeast to south-southwest orientation. SU 4 represents the last unit of the platform with a relatively stable area and more or less constant thickness of the entire platform. In the upper part, minor faults striking northeast-southwest were observed (Fig. 8).

4.4. Karstification

Extensive karstification is present in the upper part of the platform (SU 4 and SU 5) (Fig. 9.A). Karst is in seismic is characterized by discontinuous to chaotic seismic facies (Fig 9.B). In four intervals, such indicators were observed: SS 10, SS 11, SS 12, and SS 14 (Fig. 9.B). In time slices, karstification is indicated by "dendritic patterns" as shown in Fig. 9. This pattern correlates with chalkified limestone with mouldic and abundant vuggy pores in core samples and thin sections. To enhance the visualisation of karstification in time slices, the spectral decomposition attributes were applied with specific frequency in every single interval (Fig. 9.C-F).

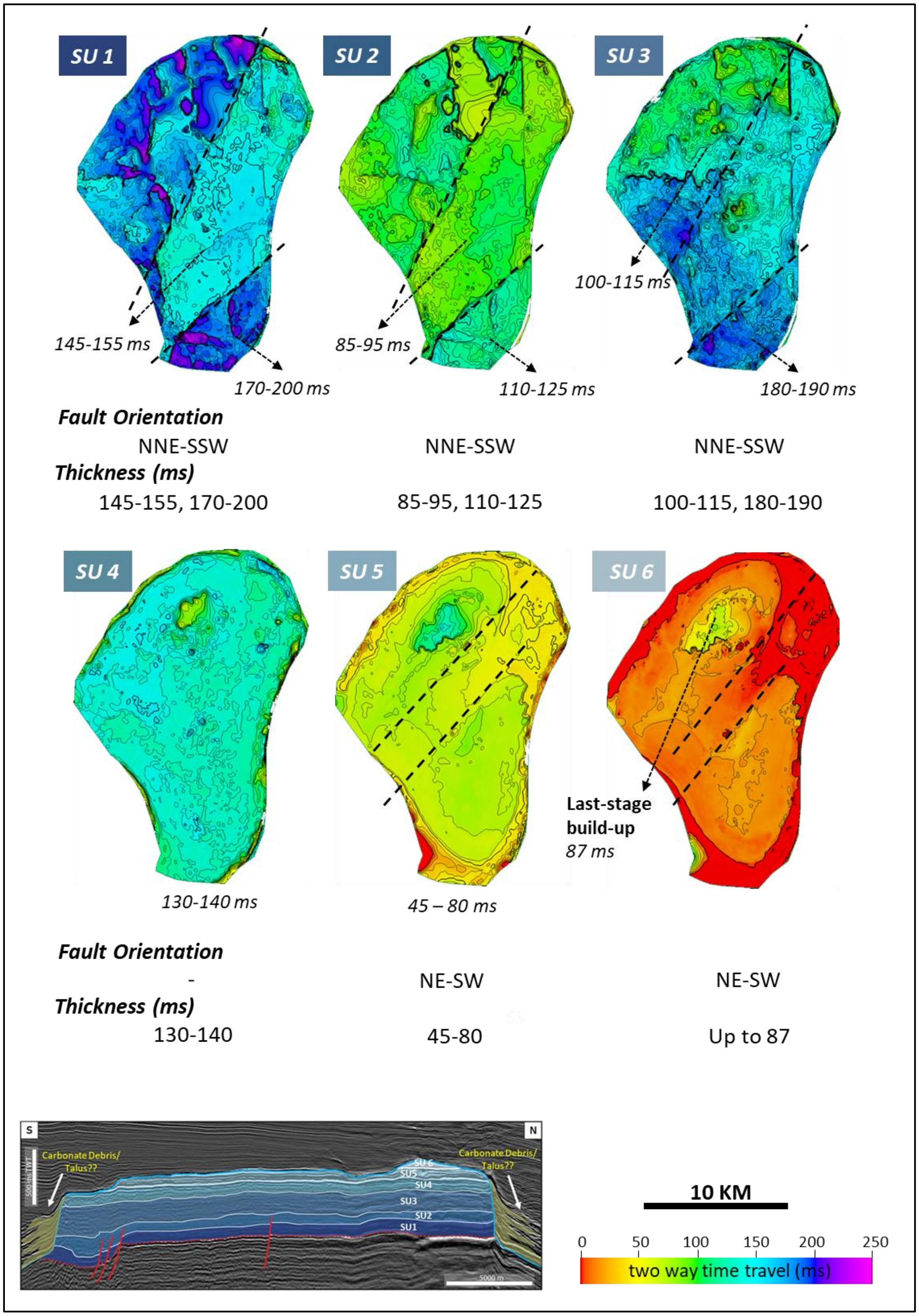

Figure 8. Time-thickness map of the study area

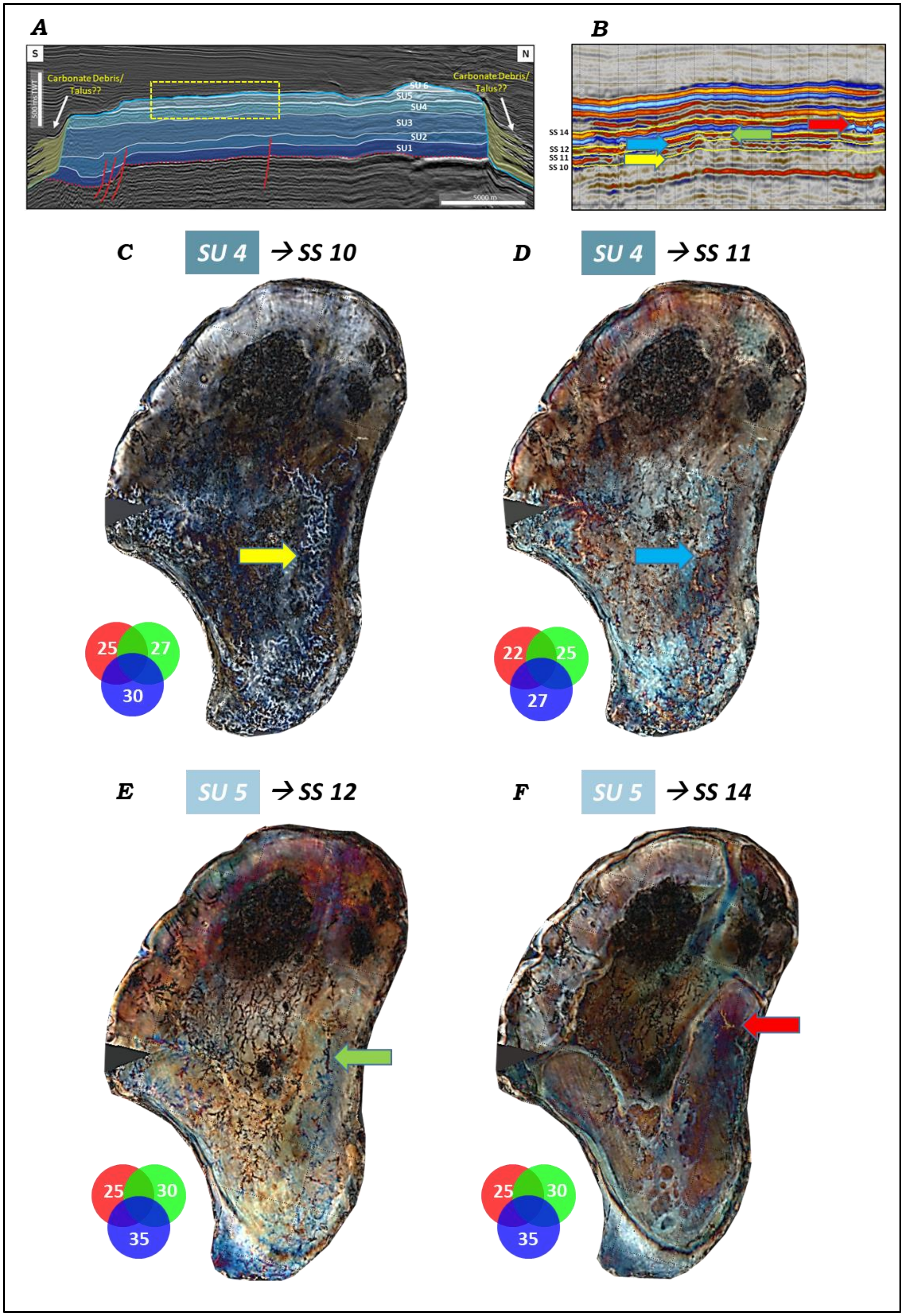

Figure 9. Karstification visualization using spectral decomposition attributes

Horizons with clear karstification were compared to likely time-equivalent intervals in other platforms. Whereas in the main study area four karst horizons were observed, six horizons were identified in the FX build-up, four in the FY build-up, none in the BX, EX and EY build-ups, and no data was available for the MY build-up (Fig. 10). Based on this observation, the most extensive karstification seems to have occurred in Cycle IV and less extensive in Cycle V. Conclusively, karstification seems to occur particularly in the middle and the northern part of the Central Luconia Province. Karstified layers seem to be present in predictable stratigraphic position below flooding surfaces, which are associated with low-impedance values and covered by high-impedance layers (flooding surfaces).

Karstified layers:

Build-Ups	*Layers*
JX and MX	4
MY	No Data
FX	6
FY	4
BX	0
EX	0
EY	0

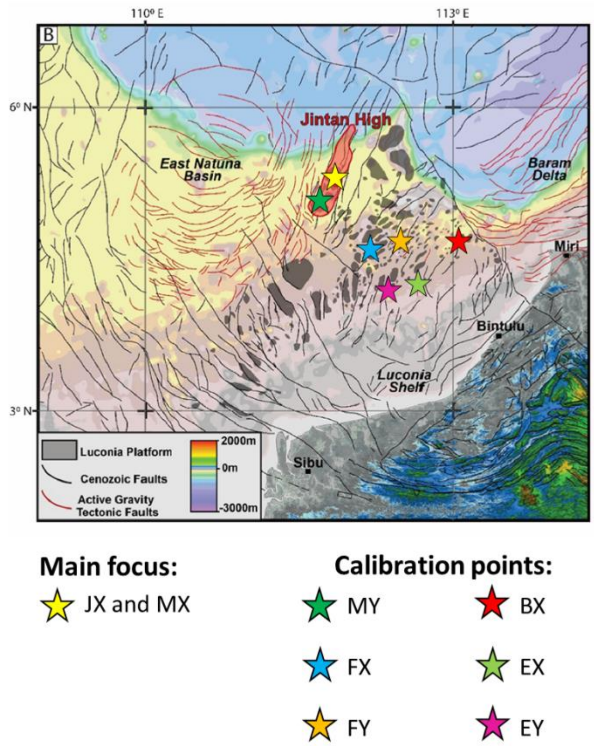

Figure 10. The regional comparison karstified layers seismic-scale in the Central Luconia Province

Table 2. The windward-leeward angle of studied platforms

Build-Ups	Windward	Leeward
JX and MX	60^0	40^0
MY	65^0	30^0
FX	60^0	20^0
FY	50^0	40^0
BX	50^0	30^0
EX	30^0	20^0
EY	15^0	10^0

Table 3. The tilting angle of studied platforms

Build-Ups	Tilting Angle	Orientation
JX and MX	3^0 to 5^0	SW
MY	No data	No data
FX	1^0 to 2^0	W
FY	0^0	-
BX	5^0 to 8^0	NE
EX	7^0 to 9^0	E
EY	0^0	-

5. Conclusion

Based on the five proposed predictive attributes, the platform architecture of carbonate buildups in Central Luconia is marked by numerous similarities and differences. The facies composition on northern and southern buildups shows similar components on all buildups with major components consisting of foraminifera, red algae, and a variety of corals. Although minor differences in each buildup are present, depending on the location relative to the current – wave energy.

The stratigraphical architecture shows similar trends in the distribution of tight-porous zones. These tight zones/layers are characterized by the presence of slightly argillaceous limestone related to flooding intervals. Seismically, the tight zones/layers appear as continuous high amplitude reflectors around 100 m thick. In contrast, the porous zones are related to the reefal facies characterized by chaotic-mounded facies.

The influence of basement tectonics is widespread but differ between northern and southern buildups. In the northern buildups, the lower carbonate mostly shows variations within the thicknesses of the unit due to normal faulting activity during the early growth history of these buildups. In contrast, the southern buildups illustrate no major change in stratal thickness, although there are several major offsets in the lower carbonate unit in southern buildups testifying of minor intermittent faulting during early growth stages.

The karstified layers seem to occur in a predictable position below the flooding surfaces, and mostly found in cycle IV and less in cycle V. Although the origin of karstification appears related to sea-level fluctuation, karst occurrences are limited exclusively the northern and middle part of the Central Luconia Province suggesting another poorly understood influence

The geometries between northern and southern buildups show similarities and differences. The windward angle of buildups always shows steeper than the leeward margin. The windward margins are the favorable site for the reef to grow and develop along the margin while the leeward margins are predominantly defined by coral debris. The orientation of buildups is closely replicating the substrate paleo-high morphology and also influenced by the wind-wave directions on each buildup.

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To whom correspondence should be addressed: Ari Yusliandi, South East Asia Carbonate Research Laboratory (SEACARL), Department of Geosciences, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia, E-mail ariyusliandi@gmail.com