Petroleum and Coal

Article **Open Access**

Seismic Multiatributes Characterisation of Karst Distribution Pattern in an Isolated Middle Miocene Carbonate Platform: FX Field, Central Luconia Province Malaysia

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Received October 20, 2020; Accepted December 22, 2020

Abstract

Characterization of isolated carbonate build-ups in seismic is important as it is a well-known target for hydrocarbon explorations. Seismic attributes analysis is commonly used in seismic interpretation for reservoir characterization. This study aims to discuss and suggest more accurate attributes to characterize the external and internal anatomy of isolated carbonate build-ups. Central Luconia province is located in offshore Sarawak, Malaysia and is characterized by its widely spread subsurface isolated carbonate build-ups. Few previously published studies showed that the build-up's anatomy is unlikely similar from each platform due to the influence of sea-level fluctuation, tectonics, topography, and windward directions which play a huge role to influence the morphology. FX field which is located in the central region of the province has been selected for this study. Spectral decomposition, Chaos, and RMS amplitude were applied on FX field seismic cube to enhance the interpretation of karst architecture. The results show that spectral decomposition is one of the most recommended attributes to highlight the reef rim and karst architecture, chaos attribute highlighted the reef rim and RMS amplitude enhance talus distribution surrounding the platform. Dendritic patterns interpreted karst are well observed using spectral decomposition attributes and geometries were compared with the National Mulu Caves aerial photograph for a better understanding analogy comparison with a potential modern analogue.

Keywords*: Karst; Anatomy; Isolated carbonate platform; Multi-attributes; Mulu caves analogue.*

1. Introduction

The reversion of the global cooling trend during the Middle Miocene Climate Optimum (MMCO)'s has provided warmer ocean water temperatures which are highly favourable for the growth of isolated carbonate build-ups (ICBs) (MMCO- [1-2]). In southeast Asia, extensive carbonate deposition has taken place during this era. Luconia Province in Borneo [3-4], offshore Madura in Indonesia [5], Malampaya area in the Philippines [6-7], the Zhujiang carbonate platform in the South China Sea [8] are some of the examples of ICBs deposited during this era in South East Asia [9].

Isolated carbonate build-ups (ICBs) were defined as carbonate platform strata deposited as a geomorphic feature with significant depositional relief relative to adjacent, time-equivalent, deeper-water strata, lacking any significant attachment to a continental landmass and including several depositional environments such as reefs, lagoons, tidal flats, and flanking slopes [10-11]. An ICBs platform contains a series of different depositional elements which may be several kilometres in length, and commonly contains strata with good reservoir properties. ICBs are well-known targets for hydrocarbon exploration in both frontier and mature basins and they are commonly containing significant accumulations of hydrocarbons [12].

The seismic data provide important structural and stratigraphic information in three dimensions. Seismic attributes are useful tools for detecting fractures or faults and geological lineaments that are below the seismic resolution (sub-seismic, normally less than 15 meters). Reservoir characterization by using seismic attributes has been commonplace for many years [13].

In this study, selected seismic attributes were used for evaluating the isolated carbonate build-ups anatomy and suggest the most suitable attributes for delineating external and internal isolated carbonates build-ups for reservoir architecture and karst geobodies.

2. Geological setting

The Central Luconia Province of offshore Sarawak (South China Sea) with more than 250 carbonate platforms of Oligocene to Recent age are a well-known area represents a natural laboratory to explore isolated platform systems due to many of these accumulations form proved hydrocarbon reservoirs, and thus have a wealth of data across a range of settings [14]. The only period carbonate growth encompassed the entire Central Luconia shelf is during the middle to late Miocene which is known as mid-Miocene unconformity (MMU; [15]) and recognized along the entire northwest Borneo shelf [16].

Central Luconia is a geological province of some 45;000 km^2. The province is characterized by multiple carbonate build-ups aggrading from a shared sub plantar middle Miocene substrate [4] (Figure 1). The carbonate sedimentation in Central Luconia is controlled by regional tectonic, climates, and eustatic sea-level changes [3,17-19]. Syndepositional faults not only control the growth of carbonates but also it is characteristic of N-S elongation [18].

Central Luconia is controlled by two major structured line faults of the West Baram in NE and Rajang line in SW (Figure 1). Seafloor spreading in South China Basin during Oligocene to middle Miocene compartmentalized the topography into horst and graben structures. These structural conditions were favourable sedimentation of carbonates at different times and different isolated platforms [17-19].

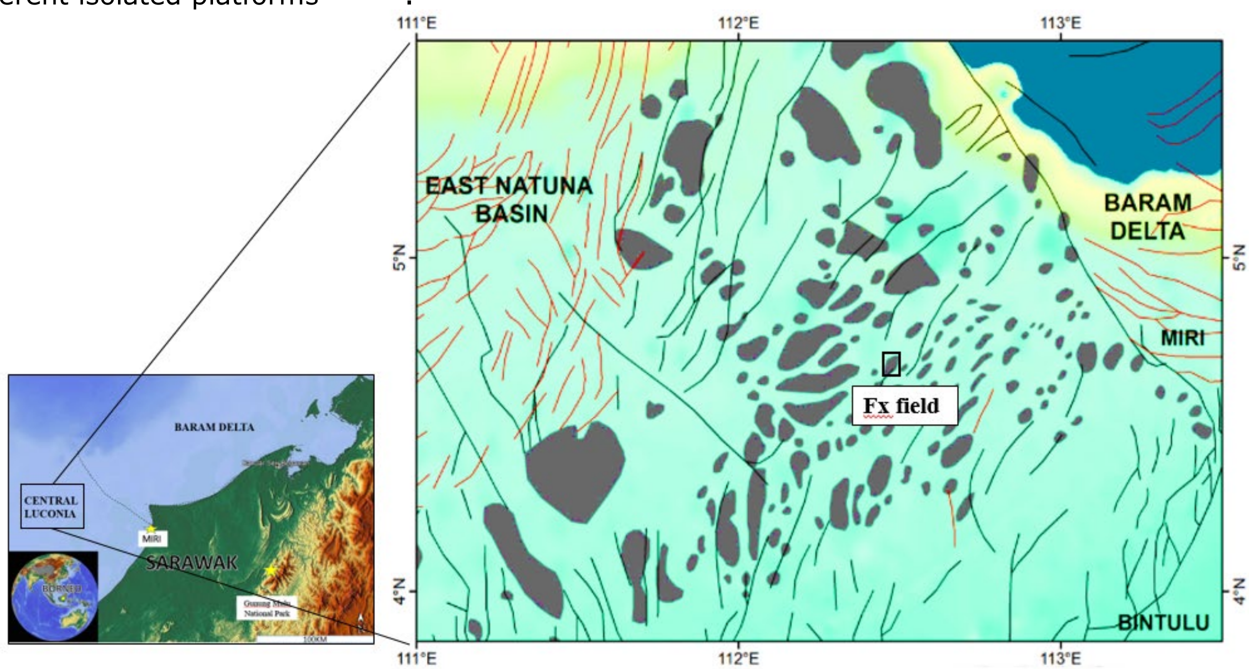


Figure 1. Location of FX field in Central Luconia province and Gunung Mulu National Park in Sarawak, Malaysia

The FX field with a distance of approximately 178 km from offshore Bintulu is located in the central region of Central Luconia province. A steeply dipping flanks were observed at the FX field's SE to NW side which coincides with the downwind direction of Miocene paleo winds [20]. Top and base carbonate maps were generated and presented closely spaced contour indicate a steep flank which can be interpreted as a windward margin (Figure 2).

The windward margin indicated by the gentle flank by the contour line can be observed at the SE to NW side. In contrast, the leeward margin is bulging and shows a steeper slope at NW to SE. The location of the margin was found to be prograde due to winnowed carbonate particles [20].

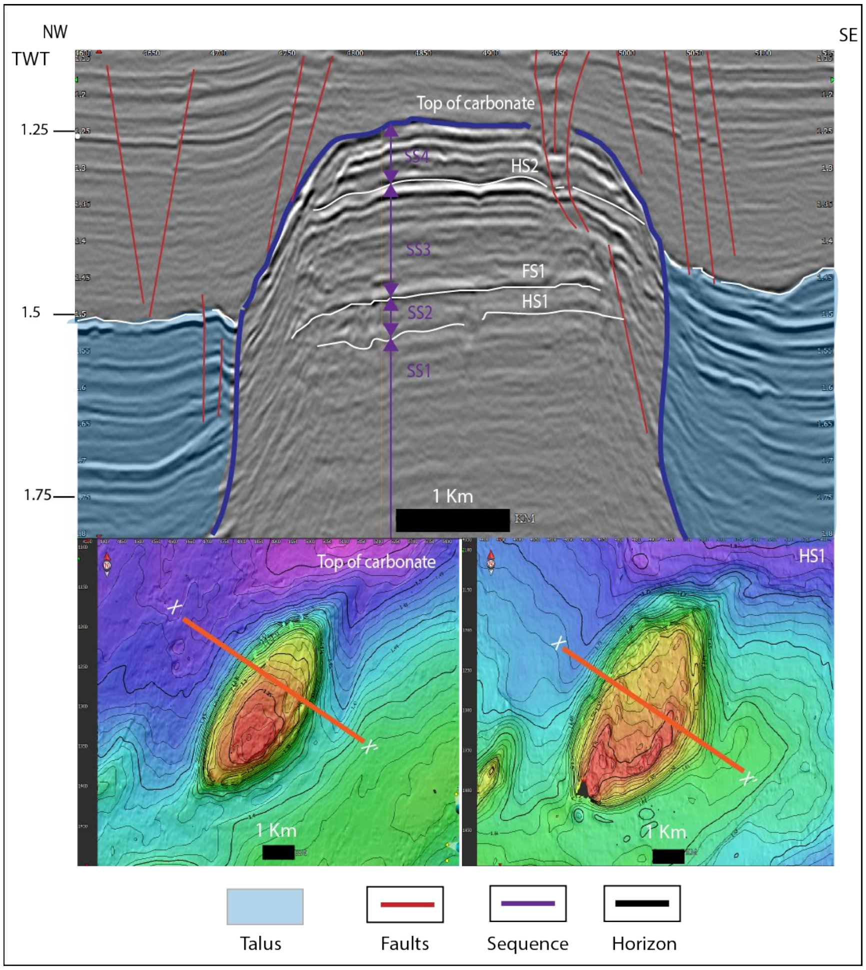


Figure 2 A. NW-SE seismic inline B. Structural map of the top of carbonate C. Structural map of base of carbonate build-up

Karst resulted from the freshwater leaching diagenetic process has been discovered at an early age [3]. A considerable fall in sea level causes the carbonate build-up to become emergent which leads to the leaching of skeletal grains and mid-sized crystal dissolution [3].

Karstified layers seem to occur in a predictable position below the flooding surfaces and are mostly found in cycle IV and less in cycle V [21]. The karst in Central Luconia is poorly understood and the distribution is limited to the northern and central region [21].

In this study, a modern analog for karst study has been used to having a better understanding of the karst geomorphology features. Gunung Mulu aged the same Cenozoic Era as Central Luconia and located only 300 KM away is the best karst modern analogue as it is the most intensively studied area of tropical karst in the world (Figure 1). Gunung Mulu is the second-highest mountain in Sarawak with approximately 295 kilometres of caves shows classic underground geomorphological features that reveal an evolutionary history of more than 1.5 million years. They include one of the world's finest examples of collapse in karst terrain and the Sarawak Chamber, the largest cave chamber known. The geology consists of a slightly metamorphosed sedimentary sequence of Palaeocene-Miocene age. The 2376m mountain is formed of the 4000-5000m thick Mulu Formation Palaeocene-Upper Eocene interbedded sandstone and shales.

3. Material and methodology

3.1. Material

The data used in this study is a high quality three-dimensional seismic cube of an FX platform from Central Luconia, offshore Sarawak, Malaysia acquired from 2015 to 2016. The sampling interval is 4 millisecond (ms) with 25m inline-crossline interval and the total recording time was 800 ms. Three seismic attributes were applied to the seismic cube to enhance the ICB anatomy and karst geobody. The software used in this study was PaleoScan™ 2020 software.

Three wireline wells were used in this study: FX-1, FX-2 and FX-3. Fx platform seismic was tied to the well to have seismic to well logs correlations.

3.2. Methodology

The seismic attributes play an important role in deriving critical information from the seismic data because they can increase seismic resolution [13]. Spectral decomposition (SD) is a common geophysical method for mapping by its spectral content. This technique was applied to highlight the stratigraphic features and extracting the reef architectural elements such as reef rim belt and dendritically karst patterns [22].

Spectral decomposition, Chaos, and RMS Amplitude attributes were applied on the FX's seismic cube using PaleoScan™ 2020 software (Figure 3). The chaos attribute measures how consistent the signal is regarding the local covariance matrix estimation of the gradient vector and is used to highlight inconsistent seismic structures such as salt bodies, faults or channels. The RMS Amplitude attribute represents the measure of reflectivity and allows the detection of amplitude variations mainly for channels and bright spots (to be correlated with the envelope attribute). It is computed within a time window. The spectral decomposition attributes allow to create seismic trace-based attributes in order to better highlight geological features (channels, faults…). The main purpose of this tool is to improve the seismic signal into different energies corresponding to each frequency in the volume to create a spectrogram. By analyzing the spectrogram, it is possible to select several remarkable frequencies corresponding to geological targets. In combination with Horizon Stack and RGB Blending in PaleoScan™ 2020 software, this tool can highly facilitate the target detection based on frequency imaging.

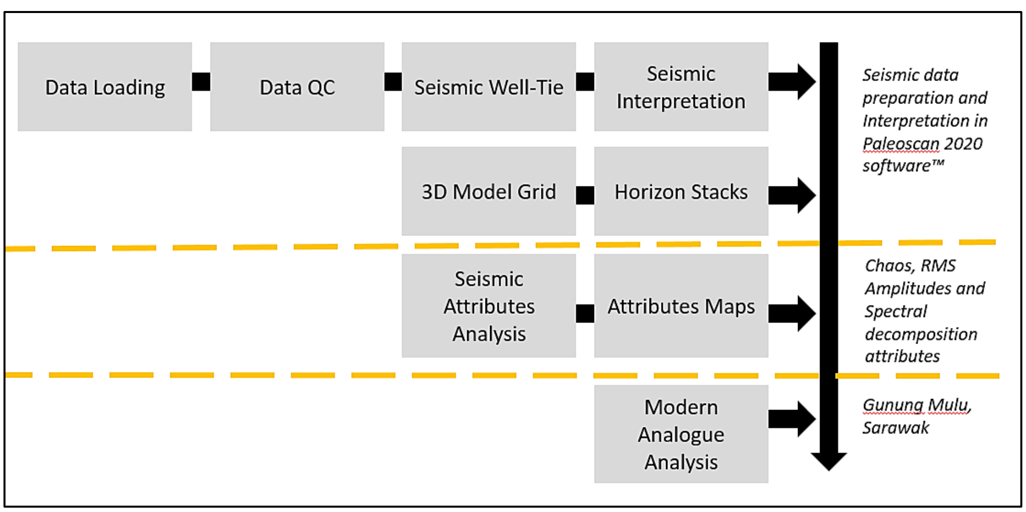


Figure 3. Methodology and workflow carry out for this ICB anatomy and karst characterisation using multi attributes

Four horizons based on maximum flooding surfaces were pick using the horizon stack module of PaleoScan™ 2020 as shown in Figure 2 labelled as HS1, FS1, HS2, and Top of carbonate. All three attributes were applied on the four horizon stacks in order to observe the changes of ICBs architecture and the presence of karst geobody vertically for four sequence stratigraphy of SS1, SS2, SS3, and SS4.

Open - source imagery data from Google Earth 2020 was used for comparative study. Non-hyperspectral image data has been used in many applications. The ease of obtaining free images from any region of the world has directed many investigations towards the interpretation using RGB format [23].

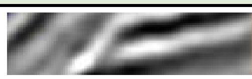
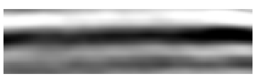
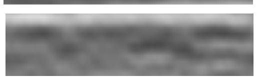
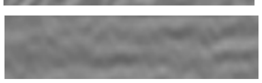
4. Results

4.1. Seismic geomorphology

From the FX carbonate platform, six seismic facies were identified based on the geometry, continuity, amplitude, and bounding relationship of the reflectors. Based on the observation of reflector's behaviour, a general possible depositional environment is assumed for each of the seismic facies. Figure 1 shows the interpreted seismic sections subdivided by the behaviour of reflectors labelled as A, B, C, D, E, F.

Table 1 shows all the six seismic facies represented by the high to low amplitude, high to low frequencies, semi-continuous to discontinuous reflectors surrounded with subparallel, mounded, and chaotic reflection configurations. The 3D view of the FX platform's top of carbonate shows prominent features of the steep talus. The ICB of the FX field was surrounded by a few normal faults as interpreted and highlighted in blue (Figure 4).

Table 1. Table enlists the six seismic unit interpreted from the nature of corresponding seismic reflectors subjected to FX build-up.

Unit	Seismic	Amplitude	Frequency	Continuity	Reflection Configurations
F		High	High	Semi-continuous	Sub-parallel to Mounded
E		High	High	Continuous	Parallel
D		Low to Medium	Medium	Semi-continuous to Discontinuous	Sub-parallel to Mounded
C		Low to Medium	Medium	Semi-continuous to Discontinuous	Chaotic to Sub-parallel
B		Low to Medium	Low	Semi-continuous to Discontinuous	Chaotic
A		Low	Low	Discontinuous	Chaotic to Sub-parallel

4.2. Multiattibutes

The multi attributes did enhance the seismic and delineate the reef rim, talus, and karst geobody of the FX field (Table 2). Chaos, RMS amplitude and Spectral decomposition attribute applied on the seismic to improve the seismic interpretation for ICB anatomy, and karst geobodies.

4.2.1. Chaos

Chaos attributes highlighted the reef margin, talus, and probably karst geobody seismic structure in the collapse zone of SS1 (Figure 5). The Chaos attribute's purpose is mainly to assist in highlighting seismic structures such as fault and channel. SS2 shows a clear ring structure in orange which is the reef rim margin of Fx field with a width of 1 km. SS1 did highlight a clear structure in the lagoonal area and collapse zone which could possibly be the karst features.

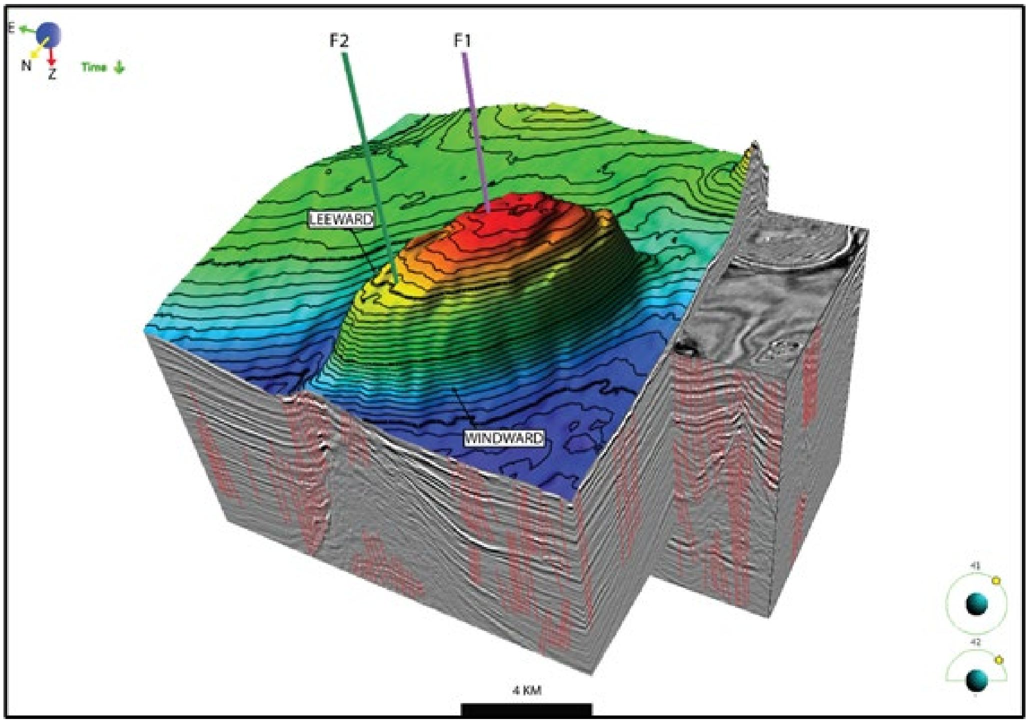


Figure 4. 3D seismic sculpted cube at the top of the carbonate

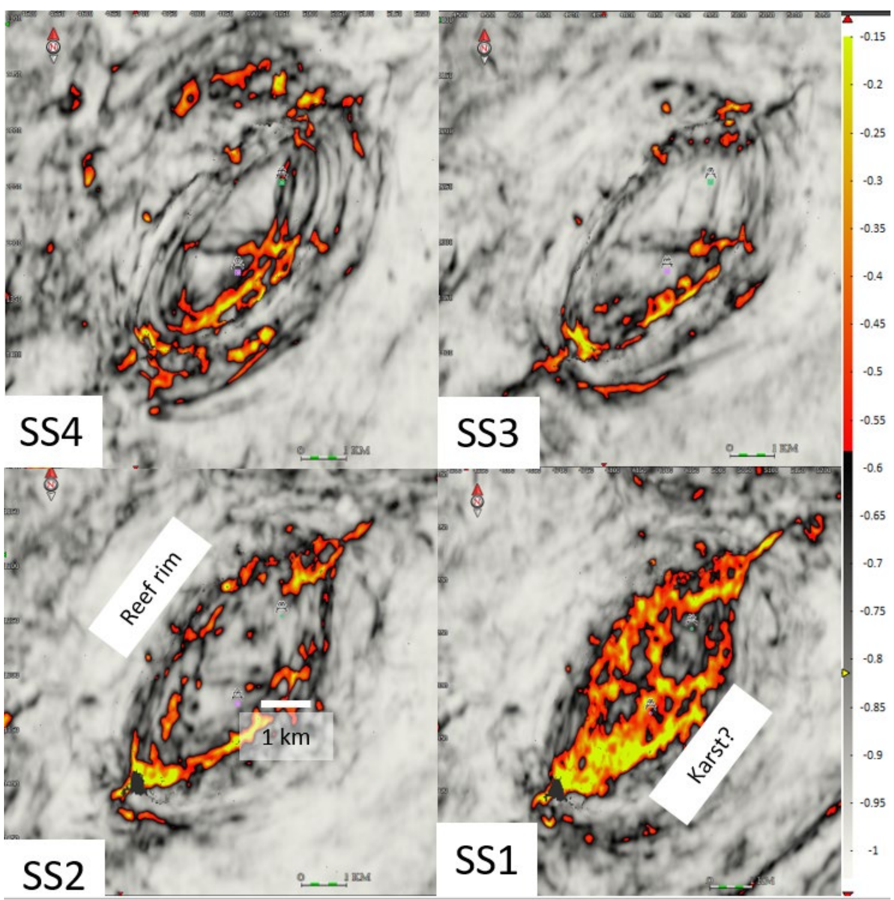


Figure 5. Chaos attributes on the four horizon stacks which highlighted reef margin in SS2 and possibly karst features in SS1

4.2.2.RMS amplitude

RMS Amplitude attribute highlighted talus features and some chaotic dendritic patterns. RMS amplitude purpose is to detect amplitude variations mainly for bright spots and channels. In the horizon stack of SS2, a bright orange talus with 1Km width is highlighted while in SS1 some dendritic patterns (highlighted in orange oval) with the possibility of karst pattern were observed (Figure 6).

4.2.3. Spectral decomposition

Spectral decomposition with Morlet style and frequency of 26Hz, 46Hz, and 66Hz were applied to the seismic. The results show a clear reef rim anatomy in SS4. Dendritic patterns could be observed clearly in SS2 with 1km to 2km length in SS1 highlighted in yellow (Figure 7).

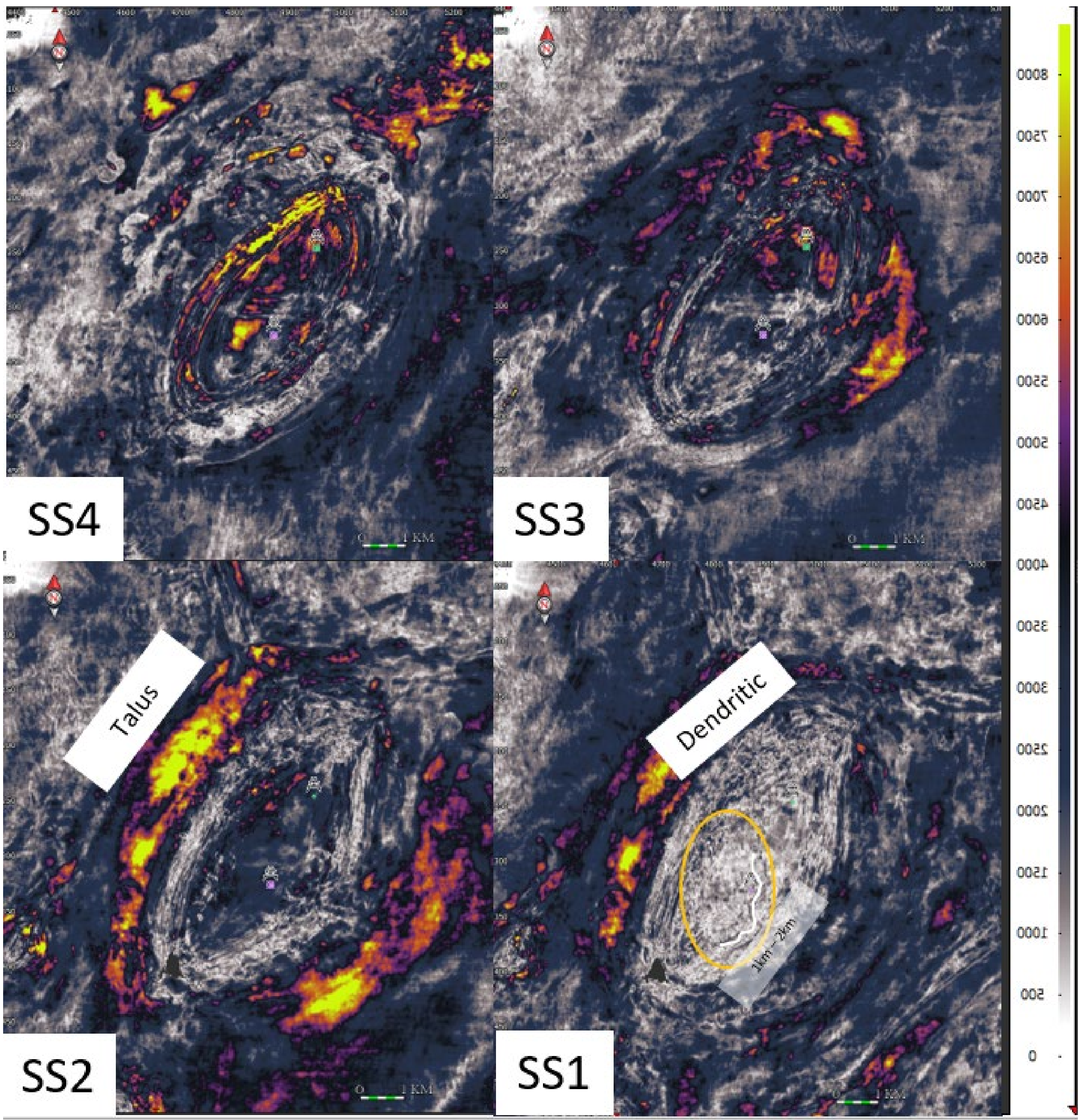


Figure 6. RMS Amplitude attributes on the four horizon stacks which highlighted talus in SS2 and dendritic possibly karst pattern in SS1 (highlighted in orange oval)

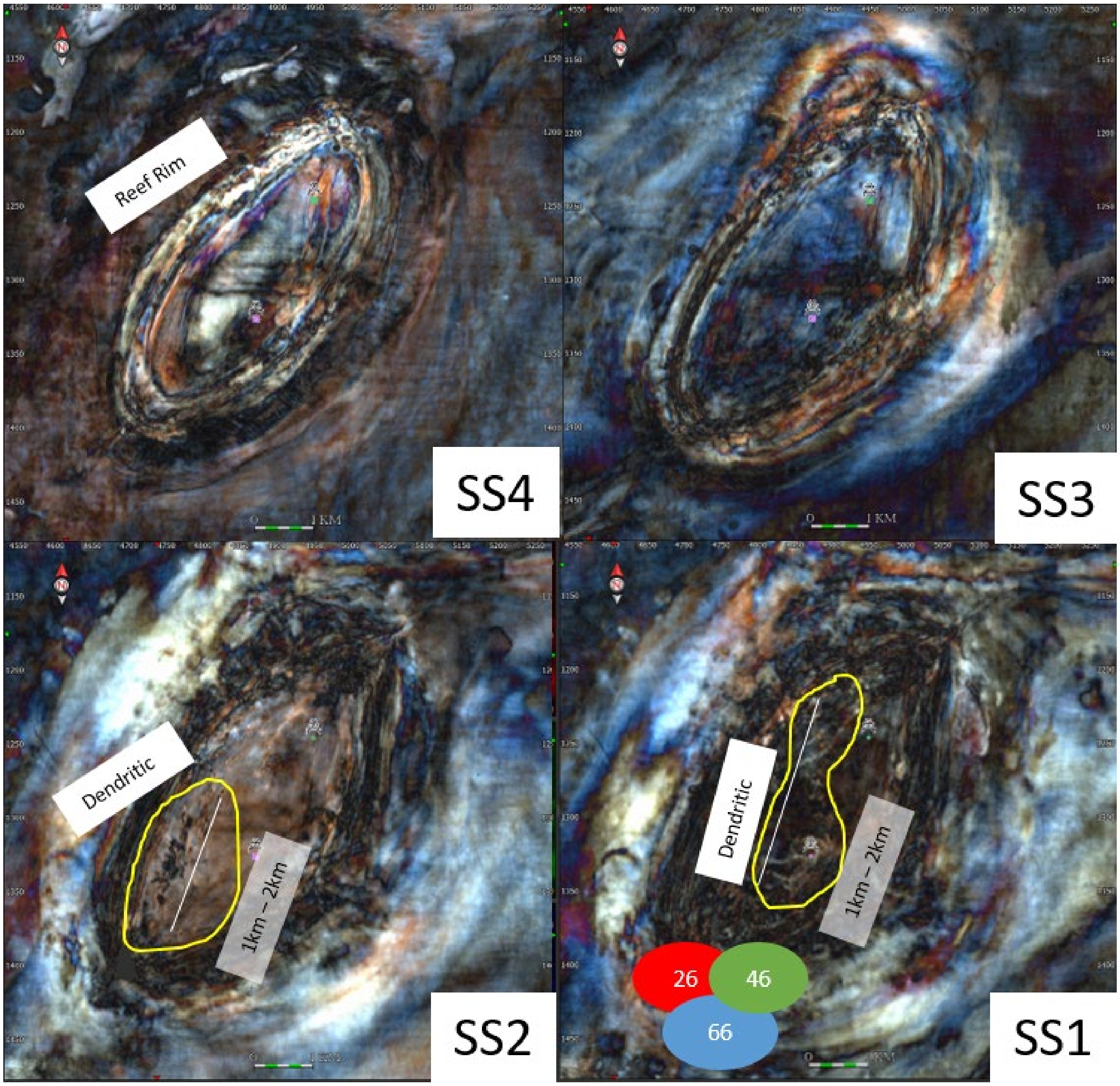


Figure 7. Spectral decomposition attributes with frequency of 26Hz, 46Hz and 66Hz with RGB colour blending highlighted talus in reef rim margin in SS1 and dendritic pattern in SS2 and SS1

Table 2. Result of the attributes analysis which delineate ICB anatomy and karst geobody.

	Reef Rim	Talus	Karst
Chaos	✓	×	✓
RMS Amplitude		✓	✓
Spectral Decomposition Style: CWT Morlet Frequency: 26Hz, 46Hz, 66Hz Colour Blending: RGB	✓	×	✓

5. Characterisation of paleo-Karst and modern analogue Karst cave

Karst in ICBs of Central Luconia province has been commonly discussed [24-28]. It is well known that drilling into a karst environment may generate a well management problem. Karstification in Central Luconia was first detected in the early days of exploration when the majority of the drilled well-encountered mud loses and other complications [25]. The secondary porosity created by the karst system tends to remove the water quicker depending on the pores because of the uncertainty of porosity for the karstified features and also due to the geometries and karst location. Prediction of karst remains challenging as the seismic image of karst surfaces is poor and was frequently mistakenly interpreted as noise [27]. Hence it is a strong business to characterize karst in ICBs earlier to prevent drilling problems.

Spectral decomposition attributes with Continuous Wavelet Transform (CWT) Morlet style at 34hz, 51hz, and 66hz shows better results of karst dendritic pattern in horizon SS1 (Figure 8).

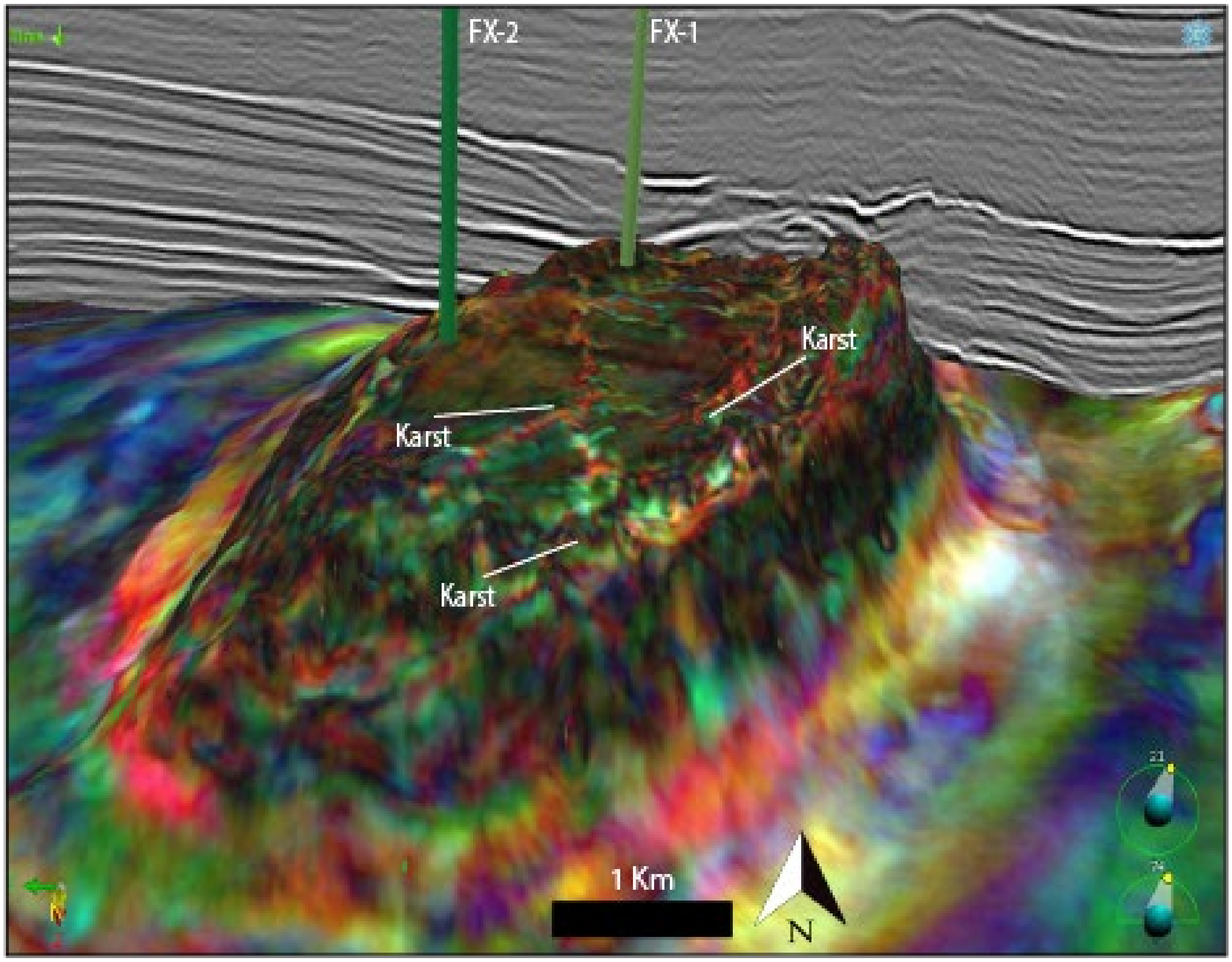


Figure 8. 3D Image of horizon SS1 shows a very prominent dendritic patterns after spectral decomposition attributes were applied

However, no wells have been drilled penetrated to the dendritic geobody pattern. Hence, Gunung Mulu National Park which located approximately 315KM from FX field and known as the most intensively studied area of tropical karst in the world has been chosen as a modern analogue to the FX field's karst [29].

Mulu caves consist of four major terrains which are the Western Ridges developed on the weak Belait and Setap Shale Formations; the Alluvial Plain and Terraces are underlain partly at least by limestone; the Limestone Hills and Mountains; and the Mulu Mountains developed from the indurated sandstones and shales of the Mulu Formation [30].

The aerial photographs which show some dendritic patterns appear strikingly (Figure 9). Both dendritic patterns in the FX field and Mulu cave show an almost similar pattern as highlighted in white (Figure 10). As believed that the present is key to the past, the dendritic patterns that commonly found on ICBs of Central Luconia province could be related to karst geomorphology.

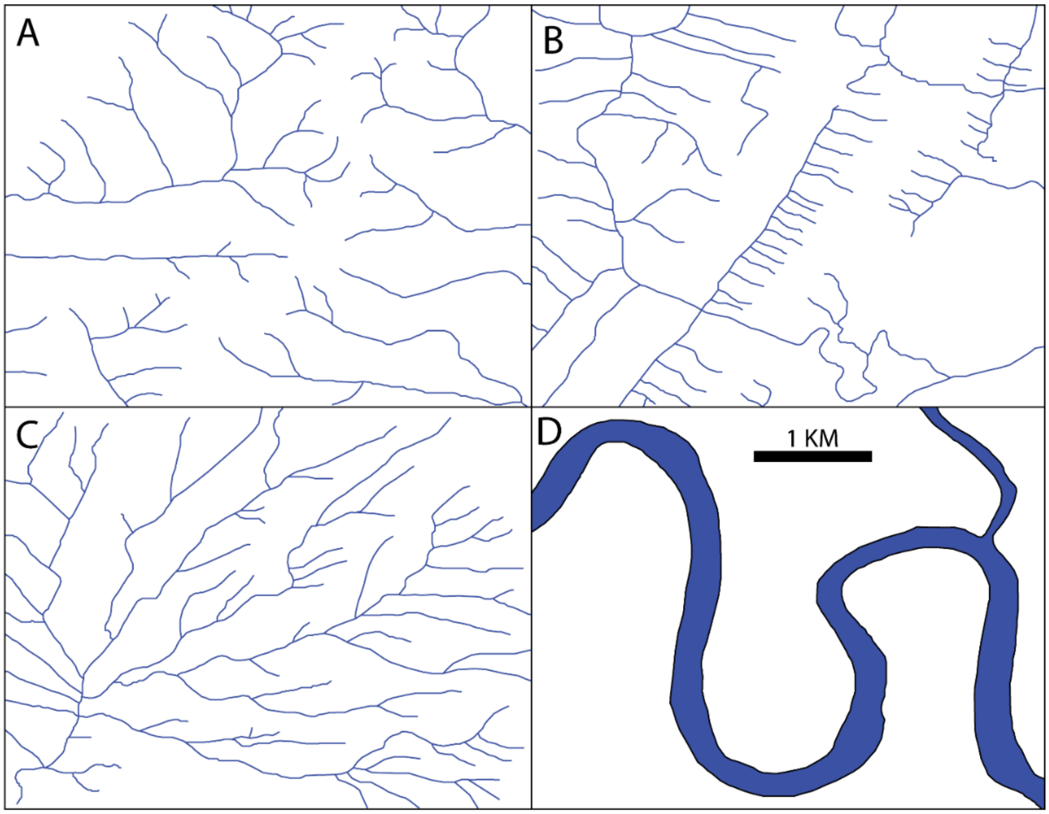


Figure 9. Typical drainage patterns visible on 1:25 000 vertical air photographs: A. Belait B. Setap Shales C. Mulu Mountains (Melinau Paku valley) D. BaramRiver E. Alluvial Plain (Melinau River). A, B, C, E are all at the same scale [30]

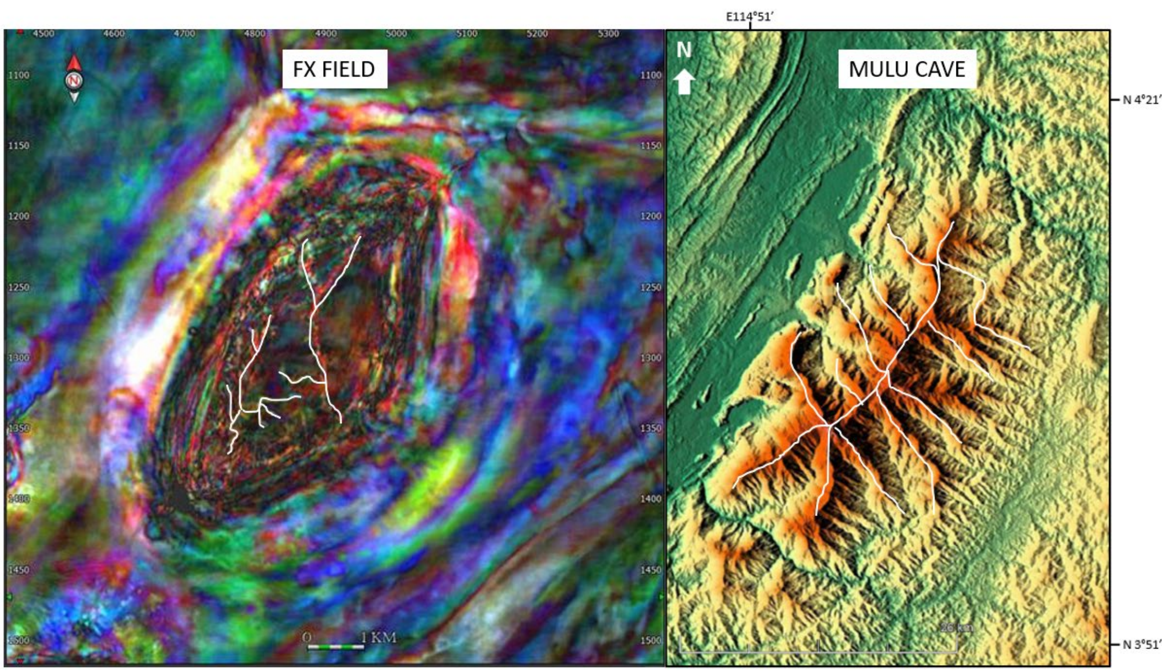


Figure 10. Comparative external karst distribution of a modern identical dendritic patterns on the ICB of the FX field in comparison with the modern analogue of Mulu caves aerial photograph.(source: Google Earth terrain map)

6. Discussion

Multiattributes analysis is one of the key methods to improve seismic interpretation for ICB anatomy and karst characterization. In this study, three amplitudes were run on four different sequences. The result shows that different attributes could highlight different anatomies and delineate the karst geobody of the ICB platform. The chaos attribute could highlight the reef rim and possible karst region, region. RMS amplitude improves seismic interpretation for talus while Spectral Decomposition delineates more prominent karst dendritic features using 34hz, 51hz, and 66hz frequencies and RGB blending for visualization of the karst distribution.

A comparative study between Mulu and FX platform showed that horizon SS1 and Mulu cave river drainage (expected to be similar in the subsurface of the cave) have similar external structure and orientation towards NE-SW. However, the frequency observed in SS1 horizon is lower and localized compared to Mulu cave, several paleo processes like dissolution may have affected the localized distribution of the paleokarst in FX. In both tectonic activity and faulting may have contributed to the distribution of actual karst geometry observed in the Mulu and FX carbonate field.

7. Conclusions

Seismic attributes could delineate the important features of an ICB anatomy such as reef rim, talus, and karst geobody. However, integrated multiscale analysis from core and well data is highly suggested to improve interpretation for better geological control. The Multiattribute analysis method is suggested to characterize ICB anatomy and karst geobody. Karst characterization is important to reduce the risk of mud loss drilling hazards.

Acknowledgement

Authors are thankful to Universiti Teknologi PETRONAS (UTP), Geoscience Department and the South East Asia Clastic & Carbonate Research Laboratory (SEACARL) for providing the facilities to support this research work. Thank You to PETRONAS MPM for permission to used proprietary data for this research. We extend our thanks to Elis for providing PaleoScan 2020™ software to conduct this research. This research work is funded by YUTP grant and SHELL endowment to Universiti Teknologi PETRONAS.

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