Evolution and controlling factors of Miocene Carbonate build-up in Central Luconia, SE Asia: Insights from integration of geological and seismic characterization

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Abstract- During the late Oligocene and Miocene period, the Central Luconia area was characterized by the development of shallow-water carbonates and reefs. The development of these carbonate build-ups were strongly influenced by the interplay between eustatic sea-level and basinal tectonics. Detailed analysis involving core, log and seismic-based reservoir characterisation is key to the construction of an accurate reservoir model. The Carbonate Platform addressed here is one of the seismically best imaged isolated carbonate platforms in central Luconia and illustrates platform evolution from origination, to growth and expansion, to eventual back-stepping and drowning. New insights into carbonate platform evolution have been gained from detailed seismic geometries and facies analysis and their relationships within a larger seismic-scale chronostratigraphic framework. Evidence from 3D seismic data indicates that the Carbonate platform displays a ‘horseshoe’ geometry open towards the eastwards. The shape of the platform and its progradational geometries indicate that relative sea level change effects dominated by structural subsidence had a greater control on platform evolution than environmental factors such as prevailing winds and oceanographic currents.

I. INTRODUCTION AND GEOLOGICAL SETTING

The Central Luconia Province is located in the South China Sea. It is bound by the extensional South China Basin to the north and the compressional Balingian Province to the south [1]. Seafloor spreading in the South China Basin during the Oligocene to middle Miocene affected the continental crust to the south, which resulted in the formation of a southwest-northeast–trending horst-graben system that which controlled the distribution of the subsequent reefal carbonate growth [1]. From Middle Miocene to Late Miocene, the Central Luconia province witnessed the development of shallow-water carbonates and reefs. The development of carbonate build-ups was strongly influenced by the interplay between eustatic sea-level, basinal tectonics and clastic sediment supply. The sediment supply caused areal decrease of some of the fields before finally been buried. Tectonic and eustatic processes combined cause relative changes in sea level, which control the space available for sediments to accumulate on the tops of build-ups. Tectonics played a role in creating horst and graben structures which served as basement for the onset of carbonate deposition and exerted an influence on the size and shape of the build-ups. The latter also dictated both type of the depositional facies and their distribution which governed the reservoir properties within a particular field.

Located offshore Borneo, the carbonate build-up addressed in this paper (denoted as Field “A”) is situated on the north-eastern part of a distinct structural high, known as the Bunga Pelaga High (BPH) (Fig.1). The BPH forms an integral part of the Central Luconia province and dips gently northwards towards the shelf edge. Carbonate build-ups situated on the BPH are aerially larger in size (>512x10^6 ft^2); whilst build-ups situated both specifically to the east and to a lesser extent the west of the BPH are usually smaller (<200x10^6 ft^2). Field A, a gas field, is a large carbonate build-up which straddles the BPH towards the north-east. It has a surface area of approximately 645x10^6 ft^2 and decreases at the gas-water contact (GWC) to 452x10^6 ft^2. The field has been penetrated by two wells, an exploration well (well-1) which was drilled in 1970 and an appraisal well (well-2) which was drilled in 2008. The Crestal, well-1 encountered 227ft of reservoir whereas well-2 was drilled 7200ft east of the exploration well and penetrated a shorter reservoir interval of 135ft. The average hydrocarbon column of the field was found to be 100ft. From the available well data it was evident that reservoir properties deteriorated towards well-2. In order to put in place a field development plan in such a large field it was essential to identify the facies, their spatial distribution and their overall reservoir properties.
II. AVAILABLE DATA

The data available included three-dimensional (3D) seismic reflectivity data, wireline log and core data. Recent advances in seismic acquisition, processing, and visualization techniques have provided the opportunity to image carbonate reservoir architecture with unprecedented resolution. In particular, the increase in 3-D seismic data acquisition and the improvements in processing techniques have contributed to these advances and have resulted in higher-resolution imaging of sedimentary bodies. The 3D seismic data in this study was acquired in 2006 over an area of 5x10^9 ft^2. Pre-stack time migration processing was applied to the dataset. The final processing bin size was 82ft x 41ft, with 3ms sampling rate. The frequency content of the data is up to 80Hz at the reservoir interval. The excellent resolution of the seismic enabled detail recognition and mapping of the various carbonate facies and geometries (e.g. patch reefs, clinoforms, margin reefs, Karst) observed in Field “A” (Fig.2). Data acquired from well-1 was limited to specific wireline logs, however in well-2 a full suite of logs (gamma ray, spectral gamma ray, resistivity, density, neutron and sonic) was acquired together with vertical seismic profile (VSP), 175ft length of core and a well test information. Both conventional and special core analytical techniques were carried out on the core. Routine core analysis (grain density, porosity and permeability measurements) was carried out on 161 horizontal and 32 vertical samples. Special core analysis was similarly carried out on nine samples specifically selected to cover the different facies that were identified. The measurements performed included electrical properties, capillary pressure, relative permeability and rock mechanical properties. Petrography and detail core description was also carried out.

III. DATA ANALYSIS AND OBSERVATIONS

Due to limited well penetrations it was critical to maximise the value of the available 3D seismic data in order to gain a better understanding of the reservoir facies distribution and their properties. Detail analysis of vertical seismic reflectivity sections were carried out both in crosslines, in-lines and time slices. Several seismic facies and geometries were observed including, small and large mounded features, inclined strata and those that were parallel and chaotic in nature. A total of five seismic horizons were mapped and tied to the wells. Various attributes were then extracted from the mapped horizons and a variance (semblance) volume was also generated (Fig.3). In depth each horizon and its attribute (e.g. amplitude) was subsequently draped onto a corresponding variance slice.

This enhanced visualisation and provided an appreciation of the spatial distribution and frequency of the various seismic facies and geometries with respect to the build-up evolution (Fig.4a).

Repeated exposure and the associated diagenetic changes of carbonate build-ups have a major impact on porosity evolution and reservoir quality [2]. Dendritic features, interpreted as Karst, were found to be very prominent throughout the field. Karst is a diagenetic facies, an overprint in sub-aerially exposed carbonate bodies produced and controlled by dissolution and migration of calcium carbonate in meteoric waters. The exploration well-1 encountered total losses while drilling which was believed to be the result of penetrating in to Karst (common in Central Luconia carbonates).

This is supported by attributes generated from the 3D seismic data which revealed the presence of an extensive network of dendritic-like features (Karst). Seismic variance attribute volume was used to highlight lateral seismic discontinuity, which is also the seismic response of a Karst feature. The process involved the extraction of 3D geobodies based on a specific clipping value of variance attribute. This technique involved extensive quality check to ensure noise and non-Karst signal were not interpreted as Karst geobodies. For example, the dendritic features (Karst) and the patch reefs (non-Karst) both possess lateral seismic discontinuity and could have easily been interpreted as...
potential Karst geobodies. Hence, the patch reefs (circular features on the semblance) needed to be excluded from the Karst geobody identification exercise (Fig.5).

Reservoir zonation was constructed in a hierarchical manner. The 'higher level' hierarchy was based on both seismic markers and electro-facies identified in wells. These reservoir zones correspond to 3rd and/or 4th order sequences and were further subdivided into reservoir sub-zones. The latter was discerned by repetition of cycles in well logs. ‘Tight’ and ‘porous’ cycles were identified based on porosity contrast and density-neutron separation. This is often referred to as porosity partitioning (Fig.6). These high frequency sequences are believed to represent changes in relative sea level, with the tight layers reflecting periods of flooding. A further subdivision of these shoaling upward cycles into distinct tight and porous units was performed in order to capture changes in reservoir properties. As such, each genetic flow unit contains a basal ‘tight’ subdivision and an upper porous zone. The stratigraphic markers defining the tops of each sequence were used to create intra-reservoir horizons. A high gamma ray peak was observed in well-2 which showed a dramatic increase of uranium as stylolites. This high gamma ray peak is less pronounced in well-1. The core acquired in well-2 was described and evaluated as part of this study. The main carbonate facies and environments interpreted from both the core and petrographical data illustrated two distinct major facies groups. The upper facies consists of intermittent beds of grain- and mud-dominated foraminiferal-algal packstone, limestone. This facies was probably deposited in moderate to low energy shallow open marine to deeper open marine, fore-reef to off-reef environment with tidal influences. The upper part of the lower facies consists of heavily burrowed grain-dominated coral boundstone grading to grain- and mud-dominated foraminiferal-algal grainstone to packstone of high to moderate energy lagoon to reefal environment. The deepest part consists of mud-dominated and grain-dominated limestone deposited in a low energy protected lagoon (close proximity of patch reef) environment of deposition (Fig.6).

Figure 4b. Seismic cross sections through field “A” displaying various seismic facies

Figure 4c. Seismic cross section illustrating various inclined geometries.

Figure 5. Karst geobodies extraction before and after edit/quality check
IV. FINDINGS

Evidence from 3D seismic data indicates that Field “A” displays a ‘horseshoe’ geometry trending towards an east-west direction (Fig.7). The shape of Field “A”/build-up and its fragmented nature indicate that relative effects of structural subsidence (relative sea-level) had a control on the evolution of the build-up. The most striking features of the build-up are the numerous Karst and dendritic like patterns which drain into the interior parts of the build-up (Fig.3,6a,5, and 7). These dendritic patterns range in size from a few 100ft to a 1000ft in some cases. They disintegrate and fragment the build-up to several keys. Location of the Karst and dendritic features is believed to have been influenced by the presence of pre-existing deep-seated faults. In the vicinity of well-1 layered seismic facies were observed and are interpreted to be back-reef to interior build-up facies (Fig.4b, section a-b and Fig.7). To the east of well-1 and towards well-2, a sediment wedge can be observed thickening eastwards towards the deeper lagoonal setting (Fig.4c and Fig.7). In this lagoonal setting, several mound-like structures were identified in seismic and were recognised by their unique chaotic signature (Fig.4b, section a-b and Fig.7). The larger reefal bodies are believed to have been able to establish themselves due to the larger available accommodation space. From various 3-D seismic attributes and vertical sections it was possible to observe numerous stratigraphic relationships (Figs. 4b & 4c, e.g. retrograding and prograding geometries). The carbonate build-up (Field “A”) is believed to have suffered several episodes of exposure more specifically of its western area which was subsequently followed by episodes of drowning especially of the eastern parts of the build-up resulting in an overall retreat of the build-up onto the BPH (Fig.8).

V. CONCLUSIONS

During the Early Miocene to Late Miocene times, offshore southeast Asia was characterised by the development of shallow-water carbonates and reefs strongly influenced by the interplay between sea-level and basinal tectonics. The build-up addressed here is one of the best seismically imaged isolated carbonate platforms on the BPH in central Luconia and illustrates platform evolution from origination, to growth and expansion, to eventual backstepping and drowning. Identification of the prime depositional controls (a combination of basement morphology and relative sea fluctuations) provided additional support to define depositional geometries. The west and southwestern parts of Field “A” are believed to have been emergent several times followed by episodic drowning of the eastern and northeastern parts of the build-up either due to sea level rise/or tilting of the platform towards the ENE or both, creating lagoonal conditions which deepened eastwards to the open sea. The final stages of build-up evolution are expressed by the shrinking of the build-up and its fragmentation and the development of isolated patch reefs to the east and northeast. Higher reservoir quality carbonates are expected to be found closer to well-1 in the interior build-up and shallower lagoonal areas, whereas relatively poorer quality reservoir is expected to be located in the deeper parts of the lagoon (east of well-2).

REFERENCES


Figure 6. Well-1 and Well-2 correlation panel. Well 2 core and thin section photographs of both the lower and upper intervals identified. The upper interval is characterised as being mud-dominated tight algal-bioclastic and the tight argillaceous limestone indicating the deeper open marine. This is also supported by the presence fauna including Lepidocyclina spp and Cycloclypeus spp. The lower interval consists of heavily burrowed grain-dominated coral boundstone grading to grain- and mud-dominated foraminiferal-algal grainstone to packstone of high to moderate energy lagoon to reefal environment.
Reef margin
Lagoon
Carbonate deposition is accelerated during highstand periods due to the fact that larger areas of the platform are submerged (CP>>AS). This enables the carbonate platform to build up (aggrade) and out (prograde).

During lowstand periods, carbonate is deposited during a gradual rise in SL (AS<<CP). The decrease in AS leads to the build out (progradation) of the platform and retreat of the lagoonal facies.

During TST periods, carbonate is deposited during a rapid rise in SL (CP<<AS). The rapid increase in SL results to the retreat of the platform (back step).

Carbonate deposition is accelerated during highstand periods due to the fact that larger areas of the platform are submerged (CP>>AS). This enables the carbonate platform to build up (aggrade) and out (prograde).

Similar to carbonate platforms in Central Luconia Field “A” carbonate development initiated on a horst block(s). Field “A” carbonate platform evolution was governed by the interplay between RSL and tectonics (subsidence & uplift).

Figure 7. Interpreted mapped horizon in depth overlain onto a semblance slice.

Figure 8: Schematic diagram illustrating Field “A” build-up evolution. CP = carbonate production, AS = accommodation space RSL = relative sea level, LST = lowstand system tract, TST = transgressive system tract, HST = highstand system tract