Abstract

It is commonly assumed that the Miocene carbonate platforms of Central Luconia, Sarawak developed and grew on a stable substratum. This paper documents evidence of syn-depositional tectonic movements in the ‘Mega Platform’ in the northern part of the Central Luconia Basin. Detailed 3D seismic interpretation techniques consisting of spectral decomposition, acoustic impedance opacity rendering, and structurally oriented semblance filtering were used to better constrain geological processes affecting, controlling and modifying the evolution and demise of the platform. Syn-depositional tectonic movements impacting stratigraphy architecture at a scale sufficient to fragment or break up a platform occurred during platform growth. Depending on the magnitude of the movements, carbonate platforms responded in different ways:

1. Platform fragmentation and permanent separation of part of the platform; this happened in the southern part of the mega-platform early on in its growth history. Two smaller platforms separated from the main one and continued growing as separate entities.

2. Step subsidence and infill of new accommodation space; part of a platform subsides but the surviving part generates sufficient sediment volume to fill in the new accommodation space through progradatation. A flat platform is eventually restored over the whole or part of the initial platform surface.

3. Step subsidence and contraction of a platform; part of a platform subsides but the surviving platform does not have the capacity to produce the sediment volume required to fill in the new accommodation space. The down-stepped part of the platform eventually drowns.

Faulting not only created topography as a template for the initiation of carbonate platform deposition but also as pedestals for the localization of backstepped platforms. Cessation of syn-depositional faulting may create tectonic quiescence period that instigated progradation as a result of deceleration of accommodation-space production.
Introduction

The Central Luconia province is located in the South China Sea. Structurally it is in an intermediate position between areas of extensive tectonic activity characterized by subsidence and faulting in the North and zones of pronounced Early to Mid Tertiary compressional tectonic in the south (Epting, 1980) (Fig. 1). He suggested that Central Luconia was a broad and stable platform characterized by the extensive development of Late Miocene carbonate build-ups that developed on horsts in response to sea level fluctuations.

Shallow water carbonates and reefs of the South China Sea that developed during the late Oligocene and early-middle Miocene time were strongly influenced by structural patterns provided by a complex plate tectonic history (Fulthorpe & Schlanger, 1989). Several authors have indicated the role of tectonics on the Central Luconia build-up development (e.g. Doust, 1981 & Coca, 2006). In Central Luconia Miocene carbonate build-ups formed in a tectonically more active setting than the present shelf (Doust, 1981). The development of carbonate build-ups was strongly influenced by the interplay between eustatic sea level fluctuations and basinal tectonics. Tectonic and eustatic processes combined caused relative changes in sea level, which controlled the space available for sediments to accumulate on the top 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 (Ting et al, 2010).

However, the detailed description of the role of tectonics on the development patterns and stratigraphic architecture is only documented in a few cases: e.g. the Tertiary Kutei Basin and the Tonasa Platform of South Sulawesi (Wilson et al, 2000), and the Miocene-Pliocene Segitiga platform of the East Natuna Sea, Indonesia (Bachtel et al, 2004). These platforms were not only located on basement highs related to earlier structures, but were also affected by syn-depositional faulting that influenced their vertical and lateral accretion and the geometry of the platform margin. Platform distribution was largely governed by faults and tilted blocks and the growth architecture of the platforms, was affected by syn-depositional faulting. Bachtel et al, 2004 concluded that eustatic sea level changes controlled the timing of sequence-boundary formation, but structural movements modified the internal sequence character and facies distribution. Carbonate sequence stratigraphic models emphasize the role of inherited physiography as an important control on platform development (Hunt & Fitchen, 1999).

The main objective of this paper is to investigate the effect of tectonics on the development of Miocene platforms of Central Luconia and their influence on facies distribution.

The study area, referred to as the Mega Platform is a 30-x 50-km-large and 1.2-km- thick carbonate platform located in the Northern part of the Luconia province (Fig. 2). There are six build-ups which make up the Mega Platform area referred to in this paper as Mega Platform Build-ups MPB1-6 (Fig. 2).
Data Set and Methodology

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 3D seismic data acquisition and the improvements in processing techniques have contributed to these advances and have resulted in improved resolution imaging of sedimentary bodies. The 3D seismic data in this study were acquired in 1993 over an area of 335.6 sq. km. The survey consists of 660 subsurface lines shot at 158/338-degree direction with average line spacing of 25 meters. An acquisition overprint can be seen in this direction. The data were acquired at 2 msec to 5.0 sec, with a 240-trace, 40-fold configuration. A Jason Constrained Sparse Spike Inversion (CSSI) was carried out in 2004. Apart from the gas chimney areas above northern build-up on MPB-2, the quality of the data is good. The excellent resolution of the seismic data enabled detailed recognition and mapping of the various carbonate facies and geometries (e.g. facies type, platform margin reefs, patch reefs, clinoforms, fault swarms and Karst) observed in the mega platform area.

In this study detailed 3D seismic interpretation techniques consisting of spectral decomposition, acoustic impedance opacity rendering, and structurally oriented semblance filtering were used to better constrain geological processes affecting, controlling and modifying the evolution and demise of the platform. A combination of old vintage two dimensional and high resolution three dimensional seismic surveys were used to better understand the platform growth and evolution.

MPB-2 was discovered in 1999. An appraisal well MPB-2b was drilled to test the northern part of MPB-2. This was followed by well MPB-2a which tested the southern flank of the field. All of the appraisal wells have full suites of logs (gamma ray, spectral gamma ray, resistivity, density, neutron and sonic) which were acquired together with 741ft of core from MPB-2b (84 ft) and MPB-2a (657 ft). During the development stage, an additional 172ft of core was acquired to evaluate the northeast flank. Petrography and detailed core description were also carried out. In addition to the well, core data acquired from several build ups in the mega-platform provide ground truth to the relationship between seismic observation to facies and depositional environment.

Structural setting of the study area

The Luconia province developed in response to complex tectonics related to the opening of the South China Sea at about 45 Ma with the phase of rifting following the initial collision of Indian plate (King, R.C. et al, 2010). This movement initiated a series syn-rift, half graben, sub-basins bounded by NE-trending normal faults and N-trending dextral normal faults, sub-perpendicular to the direction of rifting motion. The carbonate reefs started to grow during Early to Late Miocene on the uplifted half graben footwalls. Early Miocene dextral strike slip movement resulted in the development of an elongated through comprising en echelon NNE trending half graben (Teasdale, J.P. et al, 2002) (Fig. 3).

The interpretation and analysis of observed lineaments near to the base carbonate horizon shows kinematics of conjugate Riedel systems that are made up of synthetic R-shears and antithetic R’-shears (Fig. 4). The individual Riedel shears may organize into broadly distributed intraformational conjugate systems. Reverse secondary faults formed perpendicular to the maximum horizontal stress. Maximum horizontal stress direction is WNW-ESE.
Fig. 3: The study area the Megaplatform is bounded by a zone of oblique extension to the west. (a) Structure map of the basement sequence underlaying the carbonates (marked by red color horizon). This sequence consists of continental to shallow marine sediment. (c) Seismic cross-section A-A' shows a wide extension zone that bounded the half-graben structures.

Fig. 4: Seismic semblance extraction map of a horizon near to base of carbonate. Several sets of lineaments are interpreted and confirmed using the geometry and kinematics of Riedel system. (b) Interpreted faults model. The NE SW oriented major basement lineaments initially developed as normal faults. During the rifting, the faults reactivated in an oblique slip fashion by potential transtensional tectonic episodes.
Sequence and seismic facies

In this study the Mega Platform is divided into a southern, central and northern part. The southern part of the mega-platform is characterised by the presence of isolated build-ups which include MPB 3-6 situated on highly faulted substrata (Fig.5).

In addition, a seismic line across the central MPB-2 clearly shows the presence of four distinct seismic sequences. These seismic sequences can also be correlated in the wells (Fig.6).
Fig. 6b: Correlation panel showing hierarchical reservoir zonation from seismic markers and repetition of cycles in well logs of MPB-2. The pink column represents the cored interval.

Sequence I (Base Carb- H12)

This sequence is 2400 ft in thickness and is characterised by a transparent seismic package which is stratigraphically underlain by numerous tilted basement fault blocks. Some of the basement faults intersect sequence 1. This seismic sequence was not penetrated by any of the wells. Several units within this package display thickening and thinning of the stratigraphy indicating the influence of syn-depositional tectonics (Fig. 7a). Aggradational seismic packages can be seen on horst blocks whilst between horst blocks thinner progradational geometries are present. Faster subsidence the southern block was most likely made up for by a faster carbonate growth in that part of the platform, resulting in a thicker carbonate section and figure 7b shows this part is more highly faulted (Fig. 7b).
Sequence II (H12-H9)

In MPB-2 and on vertical seismic profiles the second seismic sequence, which is about 600 ft in thickness, displays inclined geometries and is also characterised in places by chaotic seismic signature. Chaotic seismic facies can be seen in the southwestern part of the MPB-2 whilst towards the northeast more distinct inclined geometries can be observed (Fig. 8a &ii). The clinoforms can also be depicted from seismic amplitude extractions. Platform segmentation is observed and marked by abrupt amplitude changes that may imply a facies change. Towards the southern edge of the MPB-2 a small intra-platform basin bounded by faults can be observed (Fig 8b). The northern part of the platform (platform margin) is characterised by the presence of a chaotic seismic signature possibly indicating a collapse zone (Fig. 8 a&b).
Fig 8a: Cross line E-E' shows a transition from layered seismic facies in the NE to chaotic seismic facies in the SW.

Fig 8b: Seismic amplitude extraction at horizons H12-H10. Red lines indicate seismic acquisition overprint (left). Overlay of basement faults (dotted black lines) shows the control of these faults on facies distribution.
Sequence III (H9-H6)

This sequence has an average thickness of 250 ft. In MPB-2 two distinct seismic facies can be observed from the seismic. These distinct seismic facies are depicted from vertical seismic profiles and seismic attribute maps. The central part of MPB-2 is characterised by the presence of asymmetrical large horseshoe or V-shaped pattern (Fig.9a), indicating platform segmentation.

![Fig9a: Seismic amplitude extraction at horizon H9. An overlay of basement faults (dotted lines) shows the control of these faults on facies distribution. Platform segmentation and breakup gave an asymmetrical horseshoe shape to the platform.](image)

At the basal part of this sequence, the south-western part of the horseshoe platform is represented by a hard kick (blue negative loop). An abrupt lateral change in seismic amplitude is observed towards the eastern part (Fig.9a & b-ii). A core from well MPB-2a, which is located in a deeper marine setting at this particular interval, contains deeper marine, lagoonal facies at the base, including platy coral floatstone-wackestone, argillaceous foram rhodolite bioclast packestone lithofacies (Fig 10).

![Fig9b-i: Seismic inline D-D' (flattened at H9) shows the seismic character of this sequence; inclined and layered geometry.](image)
At shallower levels, this sequence is characterised by more chaotic seismic facies in the west and a more layered seismic facies to the east (Fig 9a & b). Furthermore, seismic amplitude extractions overlain by semblance maps of the eastern part of MPB-2 exhibits isolated circular to semi-circular geometries. A south-north seismic section of the eastern part of MPB-2 shows transition from inclined geometry at the base of this sequence to more layered and sheet like geometry can be seen prograding from both southern and northern bank (Fig 9b-i).

The cored interval of the shallower level, H8, consists of a grain-dominated lithofacies of bedded, well-orted, very coarse to medium size, bioclastic grainstone and packstone with rhodolites and coral-rich intervals. The fossil content is diagnostic normal marine, deeper water, off reef sand apron in a lagoon. MPB-2J and MPB-2g, both located in the northeast, show a
tighter porosity and shallowing-upward trends from well logs while MPB-2a, located near the broad channel, displays a uniform porosity log throughout the interval (Fig. 6b). Towards the top, the biotic constituents in H7 contain slightly restricted inner platform assemblage of forams, mollusks, red algae, and corals. The lithofacies consists primarily of well-sorted, fine to medium-grained coral/bioclastic grainstone, locally with coarse-grained, bioclastic grainstone intervals. This interval is interpreted as a leeward prograding sand and talus apron. In summary, the core records a transition from a deeper setting to a shallow back-reef or lagoonal deposit.

Fig 10: i) Core photo of MPB-2a at H9: deeper platy coral floastone in tight wackestone. II) Core photo of MPB-2a at H8: Thick uniform (66 ft) of well sorted bioclast grainstone. III) Core photo of MPB-2a at H7.

Sequence IV (H6-TOC)

This sequence marks a turning point in the history of the platform, with the onset of platform and reef rim contraction. Semblance maps overlain by amplitudes maps indicate that the southwest flank experienced contraction, indicated by inward displacement of the reef rim. In addition the seismic amplitude map shows a series of distinct NS and NWSE trending low amplitude anomalies located in the centre of the horseshoe build-up (MPB-2) (Fig 11a). A flattened seismic line through these anomalies indicates the presence of a series of ridges bounded by faults (Fig 11b).
Well MPB-2a was drilled into one of these highs. Core (Fig 11d) and porosity data (Fig 6b) show that this sequence has a porous basal part consisting of bioclastic grainstones capped by a low porosity argillaceous foraminiferal rhodolitic wackestone. The contact between the two facies is sharp and signifies a sudden deepening event. SW-NE Porosity log correlation superimposed onto seismic reflectivity data shows that this low porosity unit is not continuous across the entire MPB-2 build-up and is restricted to the southern and southwestern parts of the horseshoe platform (Fig.11d). This observation is supported by the porosity data and the seismic data which show a softening in amplitude character towards the north (MPB-2j & g).

Fig11b: Flattened seismic section at H6 shows the ridges (denoted by green line) with dimming on top and hard amplitude at edge of the ridges.

Fig11d: Detailed seismic opacity rendering shows that the top of MPB-2a and MPB-2b area have the higher amplitude packages, which are softening in amplitude character towards the north (MPB-2j & g).

Fig11c: Core photo of top of shallowing upwards sequence Z5: mottled bioclast packstone. III) Core photo of Z4 sequence dominated by stylolites and larger Lepidocyclina foraminifera.
Platform Evolution

Detailed observations made from seismic vertical sections and attribute maps on the various sequences, coupled with responses from wire line logs and cored intervals enabled a better understanding of the MPB-2 platform evolution and control of structural movements, as described below.

Initiation and structural control separation of carbonate platform

This sequence is characterized by the presence of numerous faults with increasing structural complexity towards the southwest. The structurally complex southwest part of the Mega Platform (MPB-3, MPB-4, MPB-5) is characterised by the presence of smaller pinnacle-like build ups that evolved as isolated entities (Fig.5).

Step subsidence and infill of new accommodation space

Platform coalescence and expansion: Sequence I (Base Carb- H12)
In MPB-2, carbonate deposition is believed to have nucleated on numerous fault blocks (Fig.7a). Prolific marine conditions are believed to have dominated and enhanced carbonate production which led to the development of aggradational and progradational carbonate packages (Fig.7a). These carbonate packages later coalesced to form a major carbonate bank. The thinning and thickening of packages across faults is evidence of the interplay between tectonics and sedimentation. This sequence is capped by a marine flooding surface which is marked by a continuous hard kick seismic loop (Fig.7a).

Initial platform fragmentation: Sequence II (H12-H9)
Figure 12a shows seismic amplitude maps, generated from 3D seismic data show distinct amplitude character with an abrupt lateral change. The southwestern part of MPB-2 is characterized by low amplitude values, whilst the northeast has high amplitude values as observed in the first map. The second amplitude map (H10-H9) shows a similar character with the low amplitude values covering a larger area. The amplitude maps were then overlain by structural lineaments that had been identified in sequence 1 and below. It can be observed that the abrupt changes in amplitude coincide with structural lineaments. A thickness map between H12-H10 was generated which indicated a relatively thicker sediment package in the southwestern part of MPB-2. It is interpreted that the reactivation of some of the major basement faults may have caused localized subsidence in the southwestern part of the MPB-2, thus leading to a relatively deeper marine setting as compared to the more stable northwestern part. Unlike the northwest where more layered and inclined seismic facies can be observed, the southwest is characterized by chaotic seismic facies which are observed from both the vertical and amplitude maps. These chaotic facies may represent patch reefs (Fig.12a & Fig.8b).

Late platform fragmentation: Sequence III (H9-H7)
Sequence III experienced continuous platform fragmentation especially in the southwestern part of MPB-2. This fragmentation can be attributed to instability of the underlying horst blocks coupled with episodes of relatively rapid sea level rises. Figure 13a-c shows three seismic semblance maps which were overlain by amplitude maps. Geometrically, figure 13a clearly shows the southern and central part of MPB-2 as a horseshoe. The figure also shows that build-up fragmentation varied considerably with the southwestern part experiencing the most segmentation. This fragmentation episode led to the development of several keys and a north-south trending channel which splits the horseshoe buildup into two parts. This fragmentation process can be attributed to several factors including frequent episodes of fault reactivation, subsidence and sea level fluctuations. Overlaying the basement faults on figure 13a indicates that the location of this channel may have been influenced by deeper underlying faults. Isolated circular to semi-circular geometries can be seen occupying the space created by this channel. In contrast, fringing reefs can be observed in the the northeastern part of the horseshoe build-up which shows very little fragmentation. It is interpreted that periods of tectonic quiescent enabled favourable conditions for carbonate growth to dominate and as such the southeastern part of the horseshoe build-up was able to re-establish itself (Fig.13b). The pre-existing channel was infilled by excess carbonate sedimentation (Fig.13b). The onset of platform and reef rim contraction can clearly be seen in the southwestern part of the platform (Fig.13c). This contraction can be attributed to rapid sea-level rise coupled with the resumption of tectonic activity.

Step subsidence and contraction of a platform

Drowning of carbonate platform: Sequence IV (H6-TOC)

Figure 14a shows that the southwestern part of the horseshoe geometry witnessed further contraction. This is indicated by inward displacement of the reef rim and, locally, the formation of an inward, subparallel concentric reef rim, characteristic of back stepping. The central part of MPB-2 was reduced in area to approximately 4.82x10^8 ft^2; recording a loss of about 30% of
the initial horseshoe platform area. The southwestern part of the platform records a wider displacement of the reef rim that may be attributed to more fragmented and tilted pre-existing basement. The reef rims are clearly defined at the eastern edge of the platform, (Fig. 14a). Away from the platform margin are series of low seismic amplitude ridges that consist of back-reef to lagoonal facies. These ridges are more developed in the southwest; overlaying the basement faults on figure 14 may suggest a tectonic reactivation. Subsequently, a rapid rise of relative sea level drowned the southwest part and the platform margin back-stepped to the northeast, presumably topographically higher (Fig. 14b). The deeply submerged southwestern part was capped by a tight rhodolitic wackestone with larger foraminifera while, towards the northeast, the carbonate platform continued to grow before being terminally drowned and buried.

Fig 12: a) Seismic amplitude extraction at H12-H10 (top left) and H10-H9 (top right). The horizon and sequence are illustrated on Figure 8a. b) The schematic drawings depict the interpretation of facies distribution. c) Thickness map of H12-H10
Fig13a-c Seismic semblance maps which were overlain by amplitude maps extraction at H9-H8, H8-H7 and H7-H6. Refer to Figure 9B for horizons and sequences.
Seismic semblance maps which were overlain by amplitude maps extraction at H6-H5, H8-H7 and H7-H6. Refer to Figure 11b for horizons and sequences.
Conclusions

This study demonstrates that tectonic movements have taken place throughout the growth history of the Mega Platform. These tectonic movements resulted in active faulting: Riedel faults in a strike slip tectonic setting. Faulting not only created the topography that allowed the initiation of carbonate platform deposition but also episodically fragmented the platform, creating new topography on and from which the platforms evolved vertically and laterally in response to relative sea level changes during tectonically quieter periods. Several parts of the platform, however, separated by early faulting from the initial platform, evolved as isolated entities, to the north and to the south of the main platform body. The main platform, fragmented by faulting several times during its growth, was regularly restored as a single platform through progradation and lateral infill of newly created accommodation space. The platform eventually experienced a final phase of syn-depositional tectonics that broke up the main platform in three sub-entities, separated by a wide channel, orientated along the axis of the main faults, i.e. NNE-SSW to the east and WNW-ESE to the west. The platform did not recover from this late fragmentation. In the final phase of growth of the megaplatform, each sub-entity experienced back-stepping of the margin resulting in a contraction in size of the platforms until the ultimate demise of the last platform in the northeast. This study, conducted on the Mega Platform highlights processes that have likely taken place in other platforms of Central Luconia.

References


