Depositional history and origin of porosity in a Miocene carbonate platform of Central Luconia, offshore Sarawak

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Abstract: Recently acquired 3-D seismic reflection data, wireline logs and selected core samples were used to reconstruct the growth history of the platform as well as the sequence of diagenetic events and origin of porosity. Platform growth started by coalescence of isolated patch reefs. Growth history includes phase of progradation, backstepping and collapse of the platform flanks. The most pronounced seismic reflectors in the platform correspond to flooding events (transgressive systems tracts), occasionally preceded by lowstands. Platform growth was terminated by gradual submergence (drowning) indicated by smooth, concentric seismic reflections forming a convex mound. Syndepositional low-offset normal faults controlled the geometry of the platform and triggered large landslides that can be seismically traced about 5,000 ft (1.5 km) in the basin. Three different processes have significantly contributed to porosity in the carbonate rocks: selective leaching during exposure, dolomitization and leaching during deep burial, probably related to warm fluids rising from depth. Quantitatively, the last group is the most important. As most of the carbonate porosity formed by carbonate dissolution under deep burial, the slide masses and related turbidites may contain highly porous rocks in the basins between platforms. These bodies can be separated by the platforms where their upslope ends are enveloped in clay-rich hemipelagic sediment. In other places, the porous slides and turbidites may establish connections between neighbouring platforms.

Keywords: carbonate platform, 3-D seismics, Miocene, growth history, diagenesis.

INTRODUCTION

Tertiary carbonates in Southeast Asia are extensive, diverse, and often form hydrocarbon reservoirs in the subsurface (Epting, 1989; Grötsch & Mercandier, 1999; Wilson and Moss, 1999; Wilson, 2000; Kusumastuti *et al.*, 2002; Wilson, 2002). The Luconia province, offshore Sarawak (Malaysia), is one of these Miocene subsurface carbonate deposits that form productive hydrocarbon reservoirs (Fig. 1). Over an area of 240 by 240 km more than 200 Miocene carbonate platforms have been mapped, ranging in size from a few to more than 200 km². While carbonate deposition is still ongoing at the northern part of the province in the Luconia shoals, most platforms have been buried by prograding deltaic siliciclastics (Epting, 1980; Aigner et al., 1989; Epting, 1989).

Miocene carbonate platforms in the Luconia province typically include several stages or cycles of development. However, previous studies differed considerably on the evolution and demise of the Luconia carbonate build-ups, as well the diagenetic processes (Epting, 1989; Vahrenkamp, 1998; Bracco Gartner, 2000).

This study relied on recently acquired 3-D seismic reflection data, wireline logs and core samples for a reconstruction of the depositional history as well as the sequence of diagenetic events and origin of porosity in a Miocene carbonate in Central Luconia Province.

CENTRAL LUCONIA CARBONATE PROVINCE

Structurally, Central Luconia is located in an intermediate position between areas of subsidence and faulting in the north and zones of pronounced Early to Mid Tertiary compressional tectonics in the south (e.g. in the Balangian area; Epting, 1980; Hutchison, 1989). The area was characterized by fairly continuous subsidence with moderate faulting during the Oligocene to Lower Miocene. The most important subsidence commenced in Middle Miocene along a network of NNE-SSW trending normal faults inducing the formation of horsts and grabens (Epting, 1980; Doust, 1981). These faults are basement controlled, and they have affected the sedimentation and the carbonate pattern.

Carbonate deposition in the Luconia Province started during the Early Miocene (Cycle III), but was most prolific during the Middle to late Miocene (Cycles IV and V; Epting, 1989). At the end of Cycle V the prograding Baram and Rajang-Lupar deltas extended offshore burying several of the Central Luconia carbonate platforms (Doust, 1981; Hutchison, 1989).

DATASET AND METHODOLOGY

Data in the form of 3-D seismic reflection cube, wireline logs, core samples and thin sections were made available by PETRONAS (Petroliam Nasional Berhad) and Sarawak Shell Berhad. The 3-D survey contains 493 inlines and 1558 crosslines covering an area of approximately 200 km². Frequencies range from a maximum of 60 Hz in the shale to a maximum of 35 Hz in the carbonate platform.

Seismic data were loaded in Geoframe 3.7 for interactive 3-D interpretation. Using Charisma Volume attribute application a variance cube was generated in the time domain, with a sample size of 16 bit, with orthogonal neighbourhood definition and with a window of 11 samples. Variance is a seismic attribute that converts a volume of continuity (normal reflections) into a volume of discontinuity highlighting faults and other boundaries.

Synthetic seismograms were generated to tie seismics to wells. Both wavelet generation and wavelet extraction routines of the Charisma synthetic package (Geoframe, Schlumberger) were applied. In the wavelet generation routine a positive Ricker wavelet and applied frequencies ranging from 15 to 40 Hz were chosen, characteristic for the carbonate platform. The wavelet generation routine allows the modeler to determine all the parameters a priori. The wavelet extraction routine, on the other hand, estimates the wavelet from seismic based on reflectivity curve and reference seismic trace along a borehole and takes into account not only a single frequency value, but a range of them directly detected by an original seismic section and the filtering applied to it.



Figure 1. Location map of the carbonate platforms of the Luconia Province, offshore Sarawak (Malaysia). Modified after Epting, 1989.

RESULTS

Depositional history

The architecture and the growth history for the studied platform were based on four lines of observations:

- *Platform stratigraphy.* Those platform reflections were mapped and named, labelled from bottom to top "horizon 1" to "horizon 2" that were particularly prominent and coincided with distinct changes at the outer boundaries of the platform. An extra marker labelled "shale/ carbonate" is not a stratigraphic horizon but shows the carbonate to shale boundary (Fig. 2A).
- Basin stratigraphy. Independently of the platform stratigraphy, a stratigraphy in the surrounding shale was established by tracing continuous reflections, labelled from top to bottom "shale" to "shale 6" (Fig. 2B).
- *Correlation*. Correlation of the shale and the inner platform stratigraphy was attempted. The correlation, at the later stages of growth, becomes ambiguous (Fig. 2C).
- *Ties between seismics and wells*. Seismics were tied to wells via synthetics (Fig. 3).

Platform growth is dominated by rapid vertical aggradation combined with backstepping of the margins. Backstepping is particular obvious at horizon 2 and 3 (Fig. 4). Backstepping indicates partial drowning and deep flooding of the platform and often leads to increased deposition of terrigenous fines on the platform. Thus, the mapped horizons were interpreted as flooding events (transgressive systems tracts) when slightly argillaceous, deep-water material is deposited on top of clean carbonates.

Two main stages of progradation were observed (Fig. 4). The first one is between horizon 1 and horizon 2 when isolated reef patches first rose above the surrounding sea floor and then prograded and coalesced in a larger platform. Between horizon 2 and 3 the platform prograded again but this phase of progradation is characterized by steep and high slopes that repeatedly collapsed in large landslides possibly triggered by faults. Slide masses can be traced seismically for approximately 5,000 ft (1.5 km) in the basin and they form zones of wavy reflections that wedge out both in upslope and downslope directions. High-amplitude reflections extending basinward from the slide are interpreted as layers of carbonate sand and rubble associated with the slide masses (Fig. 5). In time slices, the slide deposits are characterized by checkered, patchy patterns in otherwise smooth reflections (Fig. 6A).



Figure 2. The growth history of the studied platform is based on: (A) mapping the stratigraphy in the platform. Those platform reflections were mapped and named that were particularly prominent (horizon 1–4) and coincided with distinct changes at the platform horizon. Marker "shale/carbonate" is not a stratigraphic horizon but represents the shale to carbonate boundary. (B) Independently from the platform stratigraphy we also established a stratigraphy in the surrounding shale by tracing continuous reflections (horizon shale to shale 6). (C) Finally the shale stratigraphy was correlated with the platform stratigraphy.



Figure 3. Synthetics for one of the three vertical wells: (A) Using wavelet generation routine. Note good match in reflection character but persistent shift of reflection positions. The shift in phase corresponds to 95°. (B) Synthetics using wavelet extraction routine. Shift in phase is reduced between 20° and 30°.

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Figure 4. Model of the platform growth history (A) compared with a seismic section (B). Two main phases of progradation were identified: the first one occurred at level of horizon 1 when isolated carbonate patches prograded and coalesced to one larger platform. During the second phase of progradation slopes were high and steep and collapsed into large landslides (dashed lines and stringers). Triggered by faults (grey bands). The growth history is characterized by alternation offlooding associated with backstepping (horizon 2) and exposure events associated with lowstand tracts (striped bands). In the final stages of the growth the platform changed from a flattopped to a mound-shaped, indicating submergence and drowning.

They lie basinward of the slide scar, tend to widen in the transport direction and end in indistinct lobes. Slide scars appear as crescent-shaped embayments, in time slices (Fig. 6B), and as steep concave segments of the slope, in vertical sections. However, they show a planar morphology when they coincide with fault planes (Fig. 5).

Faulting not only appears to be the main triggering mechanism for the slope failure, but it also influences the geometry of the platform. The western and eastern flanks were controlled by lowoffset faults that were active during the platform growth and the narrow northern and southern flanks occupy the space between fault zones (Fig. 7). In the final stage of growth (above horizon 4) the platform changed from a flat-topped to a moundshaped geometry.

Porosity and diagenesis

Past studies on the Luconia platforms have argued for a strong link between growth history and porosity (Epting, 1980; Vahrenkamp, 1998). Most porosity was attributed to three factors: (i) primary depositional texture, (ii) selective leaching during exposure periods and (iii) early dolomitization in the shallow subsurface (Epting, 1980; Vahrenkamp, 1998).

Core slabs and thin sections of the 2 wells show that primary and early secondary porosity are certainly present but rarely constitute the dominant portion of pore space. In the studied samples, most porosity postdates pressure solution and is related to late leaching under deep burial conditions (Fig.



Figure 5. In vertical section the slide deposits (dashed line) appears as zone of discontinuous, wavy reflections. In the western flank the slide mass extends about 5,000 ft (1.5 km) basinwards from the platform margins. Slide scar appears as an exceptionally steep segment of the slope.

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Figure 6. Variance analysis time slices to illustrate landslides (A) and slide scars (B) on both flanks of the platform. Major slides are indicated by coloured arrows pointing from the slide scars (B) to the slide masses (A).

8). From the analyzed thin sections we established a general sequence of diagenetic events. The most important steps in this sequence are:

- Fibrous marine cement in minor amounts in plus evidence for lithification of muddy sediment (Fig. 9A and B).
- Leaching of skeletal aragonite (and some magnesian calcite) from between lithified mud (Fig. 9A and B).
- 3) Mechanical compaction (fracturing, grain rearrangement).
- Precipitation of traces of calcite druse in secondary pores created by leaching of skeletal aragonite (Fig. 9A and B).
- Partial dolomitization (timing as yet not well constrained; Fig. 9C and D).
- Abundant limpid blocky calcite cement in primary pores, secondary pores of skeletal aragonite and compaction fractures (Fig. 9E and F).
- 7) Pressure solution producing stylolites and sutured boundaries of interlocking calcite crystals; stylolites are nearly always parallel to bedding, thus they are mainly caused by overburden rather than tectonic stress.
- 8) Pervasive leaching, preferentially near stylolites. This dissolution event is generally not grain selective, probably because it affected a rock where all aragonite and most magnesian calcite had already stabilized to calcite or had been converted to dolomite. The leaching clearly postdates much of the pressure solution. It produces vugs and solution channels (in thin sections tens to hundreds of micron in diameter



Figure 7. Variance time slice showing plan view of fault sets. Deformation affects the entire area but it seems to be more pervasive around and in the studied platform. Faulting is interpreted to be the triggering mechanism for the slope failure and also to influence the characteristic N-S elongation of the platform.

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Figure 8. Contributor of different pore types to total visible porosity, based on point counts of thin sections. Lateleaching porosity can be identified in both limestone and dolomites. In limestone, all primary and early secondary porosity is classified as "pore surrounded by blocky calcite". Pores with corroded blocky calcite are interpreted as early pores that were widened by late leaching and are listed as a transitional category. In dolomites, all porosity predating late leaching is of intercrystalline type. The chalky porosity in dolomites is also pronounced by late leaching. It was counted separately and the point-count value divided by 2, assuming that the chalky areas have a microporosity of 50%. Encircled numbers: total visible porosity.

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Figure 9. (A) Diagenetic history of limestone in large thin section. Microphoto (crossed nicols and gypsum plate) of skeletal grainstone dissected by dissolution channel (pink) created during late leaching. The rock below the dissolution channel consists mainly of the remnants of a coral with large septal walls (now whitish mosaic of blocky calcite) and dark muddy sediment fill of the original openings of the coral skeleton. (B) Drawing of A showing the various diagenetic products in different symbols and colours. White: skeletal wackstone filling openings between coral skeleton. Yellow: blocky calcite cement (and few sediment particles) filling moldic pores created by early leaching of aragonitic coral. Ruled: embedding sediment of coral, a skeletal grainstone and packstone with ghosts of fibrous marine cement. Green: dissolution channel. The recorded diagenetic events include: (i) early fibrous cement in grainstone and lithification of muddy sediment in coral (event 1 of Table 1); (ii) leaching of aragonitic coral (event 2 of Table 1); (iii) rearrangement of the already lithified muddy internal sediment by mechanical compaction (event 3 of Table 1); (iv) filling of moldic pores by thin calcite druse and blocky calcite cement (event 4 of Table 1) and (v) late leaching creating the dissolution channel with bare walls (event 8 of Table 1). (C) Diagenetic patterns and pore types in dolomite. Microphoto showing crystalline dolomite with ghosts of depositional particles appearing dark (micritic). Porosity in blue. (D) Drawing of C showing distribution of pore types. Yellow intercrystalline porosity bounded by euhedral dolomite crystals and interpreted as a result of the dolomitization process. Blue: pores with bare walls that are larger than the intercrystalline pores, extended into the micritic areas and often follow hairline cracks. This porosity is attributed to late leaching (event 8 of Table 1). (E) Diagenetic patterns and pore types in peloidal grainstone. The microphoto shows peloids and skeletal grains, blocky calcite cement (light coloured) and residual pore space (blue). (F) Drawing of the distribution of pore types. Yellow: primary porosity in pores lined by blocky calcite cement with euhedral terminations (event 6 of Table 1). Blue: pores with bare walls that extend into micrite areas or replace micritic grains (late leaching, event 8 of Table 1).

and several centimeters long) that represent modified compaction fractures. It also creates a chalky rock matrix that gets partly washed out during core cutting and thus appears as large secondary vugs (Fig. 9A-F).

9) Calcite, clay minerals and a unidentified isotropic mineral (probably fluorite) grow occasionally as cm-size monocrystals in all pores and as replacement of the rock matrix.

Diagenetic steps 1-3 took place in the depositional environment or during short exposure phases of the platform. They are therefore early diagenetic and pre-burial.

-	Diagenetic events	Environments
1	Fibrous cement	marine
2	Leaching of skeletal aragonite	fresh water?
3	Mechanical compaction	burial
4	Precipitation of trace of calcite druse in secondary pores	burial
5	Partial dolomitization	burial
6	Blocky calcite cement in primary pores	burial
7	Pressure solution	burial
8	Pervasive leaching	hydrothermal
9	Calcite and fluorite	hydrothermal

Table 1. Sequence of diagenetic events.



Figure 10. Late leaching porosity (purple) along a stylolite in deep-water deposits. Stylolite with insoluble residue of clay and organic matter (dark) dissects limestone with indistinct grainstone texture. The sample is taken from breccia with limestone clasts and marly matrix at the transition from the buildup to the overlying shale. Crossed nicols, gypsum plate.

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Step 4 (dolomitization) probably occurred during shallow burial. Steps 5–9 took place under deep burial conditions, largely in the realm of pervasive pressure solution, i.e. under several hundred meters of overburden. Table 1 shows the sequence of diagenetic events established in this study and the related depositional environments.

DISCUSSION

Drowning and subaerial exposure

Previous studies based on 2-D seismic lines, core slabs and thin sections proposed contrasting interpretations of the demise and evolution of carbonate platforms in the Luconia Province (Epting, 1980, 1989; Vahrenkamp, 1998). Epting (1980, 1989) suggests that the carbonate platforms ware drowned by relative sea-level rise that exceeded the rate of carbonate production. Vahrenkamp (1998) on the other hand suggested that sea level lowering and subaerial exposure terminated the platform growth.

No evidence was found for a subaerial exposure event associated with the demise of the studied platform. In time slices, the uppermost platform reflections are smooth and concentric, indicating a mound-like geometry of the platform during the final stages of growth. It is suggested that the transition from flat-topped platform to mound reflects the gradual drowning of the build-up and its submergences below the zone of wave action. It is possible that the drowning was caused by rapid sea level rise combined with the environmental change related to the incoming siliciclastics (Fulthorpe and Schlanger, 1989).

Pronounced subaerial exposure events have been described for earlier stages of the platform growth based on evidence from cores and thin sections (Epting, 1989; Vahrenkamp, 1998). The seismic expression of exposure is not evident, except for the interval at horizon 2 that shows a lowstand systems tract prior to the flooding event that marks horizon 2 itself.

Late-leaching porosity

The distribution of this late-leaching porosity is influenced by depositional patterns. Late leaching seems to be most prominent at the boundaries of aquitards such as stylolites and argillaceous interval that diverted the rising fluids in bedding parallel directions. Fractures and faults can provide the main conduits for the vertical movement.

The fraction of late-leaching porosity in the total visible porosity was estimated from a number of thin sections. Late-leaching porosity is closely associated with stylolites and concomitant fractures 148

(Fig. 10) and postdates nearly all blocky calcite cement (Fig. 9). Only minute traces of euhedral calcite crystals are occasionally observed on the otherwise bare pore walls. In contrast, primary pores and pores generated by early leaching are lined with a thick druse or large isolated crystals of blocky cements (Fig. 9E). Most of the blocky cement was interpreted as a burial feature because it postdates intensive compaction fracturing.

Estimates of late-leaching porosity in dolomitic rocks are also fraught with some uncertainty, mainly because dolomitization is rarely complete. The most common rocks are calcite dolomites consisting of a mosaic of largely euhedral dolomite crystals with variable amounts of calcite in between. Most porosity is of intercrystalline type and it is often difficult to determine how much of the intercrystalline pore space was created during dolomitization and how much is the result of selective late leaching of calcite from between a framework of dolomite crystals. However, the presence of late leaching can be demonstrated also for the dolomitic rocks where solution-widened fractures and stylolites as well as pores are often much larger than the crystals of the dolomitic mosaic (Fig. 9C and D).

A genetic model for extensive leaching of carbonates under burial, termed mixing corrosion, has recently been advocated for the Tertiary limestones of the Bombay High (Esteban and Taberner, 2002; Minero *et al.*, 2000). According to this model, porosity is created when resident pore



Figure 11. (A) Time slice in the variance cube showing the studied platform and the other main platform in the area covered by the 3-D survey. White arrows show slumps of platform material extending several kilometers across the lower slope and the basin floor. (B) Vertical seismic line covering the shortest distance between the two platforms. Carbonate tongues from both platforms reached at least the half way point between them. This creates the potential for teleconnection and aquifer communication.

fluids mix with warmer hydrothermal fluids rising from depth. Typical resultant features are leached stylolites and fractures, as well as secondary porosity minerals such as siderite, dickite (hightemperature kaolinite) fluorite and barite.

Off platform reservoirs and flow conduits

The results indicate two different scenarios for off platform reservoirs: (i) the possibility of reservoir bodies that are detached from the platforms or poorly connected with them and, (ii) teleconnections among neighbouring platforms such that pressure changes are partially passed on from one platform to another.

The depositional architecture of the flanks of the two main platforms shows slumps of platform material extending several kilometers across the lower slope and basin floor (Fig. 11). Modern analogues and theory of sediment gravity flows indicate that in transport direction these slumps are likely to pass into debris-flow deposits and turbidites, i.e. breccias and carbonate sands. These deposits are below seismic resolution but may easily extend 20,000–25,000 ft (6–8 km) across the basin floor to the base of the next platform slope (Hine *et al.*, 1992, 1994). Thus, the debris tongues of adjacent platforms are likely to interfinger and occasionally even touch each other on the intervening basin floor (Fig. 11).

The diagenetic history of the studied platform shows that much secondary porosity was created by dissolution during deep burial. This late secondary porosity is particularly common adjacent to stylolites and clay horizons of low permeability. If the burial dissolution process is driven by hydrothermal circulation and deep-seated hydrocarbon expulsion related to fault tectonics as proposed herein, then it may be expected that the process is not limited to the carbonate platforms but affects the slopes and intervening basins too. Thus, the carbonate slumps, debris-flows and turbidites on the lower slopes and basin floors may well contain significant secondary porosity. This geologic set-up leads to at least two different scenarios concerning the connection between the slide deposits and the main platforms. Where these bodies extend halfway up the platform flank they may contain charged reservoirs with updip stratigraphic closure. Those debris bodies that extend across the flat basin floor may occasionally connect via faults or stratigraphic contact with the debris apron of an adjacent platform and thus create a teleconnection of platforms.

A second scenario for teleconnections is possible conduits in the lower deposits of Cycle IV. At that time, platforms were more extensive and rose only 165-250 ft (50-80 m) above the surrounding sea floor. If the platform tops were at sea level, the surrounding sea floors were probably still in the photic zone. If terrigenous influx was low, the sediment accumulating between the platforms may have been rich in carbonate and thus prone to late leaching in the same fashion as the carbonate gravity-flow deposits.

The possibility of detached reservoirs on the flanks and in the basins that are not connected with the main platform hinges on the presence of seals separating flanks and platform. Based on observations in the two wells and our understanding of the regional sedimentation such separation is possible with the most likely seal being argillaceous limestones or marls. In the Miocene, clear water in the Luconia province was restricted to a thin surface laver. The main water body carried ample terrigenous fines such that during all major flooding events (e.g. horizon 3 and horizon 2) argillaceous limestones were deposited on the platform top. As a consequence, the flanks always collected some clay together with carbonate debris from the top. At times of low carbonate input, this terrigenous background became an important fraction of the flank sediment. The breccias in well 3, interpreted as debris flows at the toe-of-slope (Bracco Gartner, 2000), are sandwiched in argillaceous limestones and marls. Major slide masses almost certainly slid over clay-rich sediment at the toe-of-slope. They were probably also covered by clay-rich sediment after the event. It is quite conceivable that in certain areas the two argillaceous units made contact thus sealing the slide mass on its upslope end (Figs. 12 and 13A).

An alternative seal could be tightly cemented hardgrounds. These might have formed on the platform flanks when they had become too steep for sedimentation by debris flows and turbidity currents. Flows would bypass these steep slopes, sweep them clean, and expose them to cementation by sea water. The slide scars formed during landslides on the west flank as well as the scar on the opposite flank certainly were steep enough to become bypass slopes. However, we have not found clear evidence for cemented hardgrounds in the two analyzed wells.

Figure 13B shows a second scenario for generation of small detached reservoirs in the form of isolated mini-platforms during the early part of Cycle IV of Epting (1989). The relief at this time, as previously indicated, was very subdued such that in areas of low clay input the entire basin floor may have accumulated carbonate sediment, thus producing a carbonate layer on the basin floor. In areas with higher clay input, carbonate production may have been restricted to the isolated, favourable patches in the basin, giving rise to scattered miniVALENTINA ZAMPETTI, WOLFGANG SCHLAGER, JAN-HENK VAN KONIJNENBURG AND ARNOUT-JAN EVERTS

platforms that may have risen few tens of meters above the basin floor and were subsequently buried by argillaceous deeper-water deposits. The variance cube provides some support for the existence of mini-platforms between horizons 1 and 2.

CONCLUSIONS

The growth trend and the origin of porosity of a Miocene carbonate platform in the Central Luconia province was reconstructed using highresolution 3-D seismic reflection data, wireline logs, core slabs and thin sections.

The build-up trend of the carbonate platform is characterized by an upward growth with flat top coupled with backstepping of the margin. Two main phases of progradation were identified. The younger progradation phase is characterized by steep and high segments of the slope that collapsed in large landslides triggered by faults. Syndepositional normal faults partly control not only the growth of the platform but also its characteristic N-S elongation. In the final stage of the growth the platform is characterized by smooth, concentric reflectors forming a convex mound onlapped by sub-horizontal basinal shale reflectors that strongly indicate gradual drowning.

Porosity in the studied platform is very heterogeneous in origin. Primary and early secondary porosity are present but rarely constitute the dominant portion of pore space. Most porosity postdates pressure solution and is related to dissolution under deep burial conditions.

The flanks and basin floors around the studied platform in Central Luconia probably contain significant volumes of carbonate rocks transported from the platform by sliding, debris flows and turbidity currents in the wake of large-scale slope failure during the late stages of growth or related to short-lived growth of small reef patches during sea-level lowstands in the early growth phase when platform-basin relief was low. All these carbonate deposits are likely to contain significant secondary porosity created by carbonate dissolution under



Figure 12. Conceptual model of porosity creation by mixing corrosion under deep burial conditions. Warm fluids rise along the faults and spread horizontally along argillaceous aquitards. Mixing of these warm fluids with cooler residents fluids creates carbonate-unsaturated fluids that partly dissolve the carbonate horst rock, creating significant secondary porosity. In the platforms this secondary porosity is widespread. In the basins, between platforms, it is probably restricted to carbonate packages sandwiched between clay-rich sediment. However, the porous layers may extend across the entire basin floor, thus forming "teleconnections" among neighbouring platforms. Two types of porous carbonate packages are illustrated: (A) slides, debris flows and turbidites created by slope failure and (B) an interval of very low depositional relief at the early stages of the platform growth when mini-platforms were common and the areas in between them were also covered by carbonate sediment with terrigenous influx was low.

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deep burial. Together with numerous minor faults, these carbonate bodies may form teleconnections among platform reservoirs. In other locations, the deep-water carbonates may form reservoirs in their own right that are detached from the platforms where the upslope terminations of the deeper-water carbonate bodies are encased in clay-rich hemipelagic sediment.

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Figure 13. Scenarios for detached reservoirs on the platform flanks and in the basins. In both scenarios it is assumed that the porosity is generated by dissolution under deep burial. (A) Slide mass that has moved over argillaceous sediments at the toe of the slope and is covered by similar argillaceous material at the top after gravity sliding had ceased. A stratigraphic trap may form if the slide mass wedges out between argillaceous substrate and cover in an upslope direction. (B) During early stages of the platform growth (e.g. horizon 2) platform rose only 165–250 ft (50–80 m) above the basin floor. These carbonate layers were subsequently covered and surrounded by argillaceous basin sediments.

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REFERENCES

- AIGNER, T., DOYLE, M., LAWRENCE, D., EPTING, M. AND VAN VLIET, A., 1989. Quantitative modeling of carbonate platforms: some examples. *In:* P.D. Crevello, J.L. Wilson, J.F. Sarg, and J.F. Read (Eds.), *Controls in carbonate platform and basin development*. SEPM Special Publication, 27–37.
- BRACCO GARTNER, G.L., 2000. High resolution impedance model of outcrops and their application in seismic interpretation. Dissertation thesis, Vrije Universiteit, Amsterdam, 105– 123p.
- DOUST, H., 1981. Geology and exploration history of offshore central Sarawak. In: M.T. Halbouty (Ed.), Energy resources of the Pacific region. AAPG Studies in Geology, Tulsa, OK, United States, American Association of Petroleum Geologists, 117–132.
- EPTING, M., 1980. Sedimentology of Miocene carbonate buildups, central Luconia, offshore Sarawak. *Bull. Geol. Soc. Malaysia*, 12, 17–30.
- EPTING, M., 1989. The Miocene carbonate buildups of central Luconia, offshore Sarawak. In: A.W. Bally (Ed.), Atlas of seismic stratigraphy: AAPG Studies in Geology, 168–173.
- ESTEBAN, M. AND TABERNER, C., 2002. Reconstructing Fluid Flow Evolution from Compressional to Extensional Regimes. Late Corrosive Fluids: A Key Factor for Porosity Formation and Enlargement. *In:* Proceedings of AAPG Hedberg Conference, 623.
- FULTHORPE, C.S. AND SCHLANGER, S.O., 1989. Paleo-ocenagraphic and tectonic settings of early miocene reefs and associated carbonates of offshore Southeast Asia. AAPG Bulletin, 73, 729–756.
- GRÖTSCH, J. AND MERCADIER, C., 1999. Integrated 3-D reservoir modeling based on 3-D seismic: the Tertiary Malampaya and Canago Buildups, offshore Palawan, Philippines. *AAPG Bulletin*, 83, 1703–1728.
- HINE, A.C., LOCKER, S.D. AND TEDESCO, L., HALLOCK, P., BELKNAP, D.F., GONZALES, J.L., NEUMANN, A.C. AND SNYDER, S.W., 1992. Megabreccia shedding from modern, low-relief carbonate platforms- Nicaraguan Rise. *Geol. Soc. of America Bulletin*, 104, 928–943.
- HINE, A.C., HARRIS, M.W., LOCKER, S.D., HALLOCK, P., PEEBLES, M., TEDESCO, L., MULLINS, H.T., SNYDER, S.W., BELKNAP, D.F., GONZALES, J.L., NEUMANN, A.C., AND MARTINEZ, J., 1994. Sedimentary infilling of an open seaway: Bawihka Channel, Nicaraguan Rise. *Journal of Sedimentary Research*, B64, 2–25.
- HUTCHISON, C.S., 1989. *Geological Evolution of South East Asia*. Monographs on Geology and Geophysics, Oxford, Oxford University Press.
- KUSUMASTUTI, A., VAN RENSBERGEN, P. AND WARREN, J.K., 2002. Seismic sequence analysis and reservoir potential of drowned Miocene carbonate platforms in the Madura Strait, East Java, Indonesia: AAPG Bulletin, 86, 213–232.
- MINERO, C.J., ESTEBAN, M. AND SARMIENTO, R., 2000. Burial Porosity Reservoirs in Bassein Formation, Bombay Basin, offshore India. AAPG Bulletin 84, 1465–1466.
- VAHRENKAMP, V.C., 1998. Sr-isotope stratigraphy of Miocene carbonates, Luconia Province, Sarawak, Malaysia; implications for platform growth and demise and regional reservoir behavior. *In:* Anonymous (Ed.), *AAPG* 1998 annual meeting: Annual Meeting Expanded Abstracts — American Association of Petroleum Geologists, Tulsa, OK, United States, American

Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists.

- WILSON, M.E.J. AND MOSS, S.J., 1999. Cenozoic palaeogeographic evolution of Sulawesi and Borneo. Palaeogeography, Palaeoclimatology, Palaeoecology, 145, 303– 337.
- WILSON, M.E.J., 2000. Evolution and controls on isolated Cenozoic carbonate platforms in SE Asia. *AAPG Bulletin*, *84*, 1515.
- WILSON, M.E.J., 2002. Cenozoic carbonates in Southeast Asia: implications for equatorial carbonate development. Sedimentary Geology, 147, 295–428.

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