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Central Luconia Carbonate Build-Ups: A Review and Future Outlook

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ABSTRACT

It is known that carbonate reservoirs account for about half of the world's oil and gas reserves but not many have been put to production. In Central Luconia, Offshore Sarawak, Malaysia for example, there are about 200-250 known carbonate buildups that can account for between 40-70% of the country's total gas reserves. Most of these carbonate reservoirs have significantly high CO_2 composition with widespread karst features. Previous attempts to delineate the karsts and establish structural relationships to their geometry and distribution have not been exhaustive. Also, geo-sequestration techniques to capture and store the CO_2 are not cost effective as a result of extensive surface infrastructure that will be required to connect the widely spaced reservoirs/fields. Geologic, petrophysical, geochemical, geophysical, core analyses and other studies have been carried out but future investments in these prolific fields are yet to be seen. This article reviews the main impediments and challenges to Central Luconia Carbonate field development and proposes a future outlook that can guarantee renewed interests for more productivity.

Keywords: *Karst, CO_2, geo-sequestration, Gas-Water-Contact (GWC), Water Breakthrough (WBT), Full Wave Inversion (FWI)*

1. INTRODUCTION

Malaysia is widely known to have high CO_2 gas fields in the world and these fields have remained under developed [1]. 15 offshore gas fields with High CO_2 content i.e. 13.2 Tcf of natural gas for 27.32 Tcf of CO_2 have been identified [2]. Central Luconia is an important geological province located offshore Sarawak, NW Borneo [4] (Fig.1) and is home to most carbonates in Malaysia contributing about 40-70% of its total gas reserves [5, 6]. It is renowned for extensive and multiple carbonate build-ups that are prolific hydrocarbon reservoirs [7, 8] and these carbonate buildups have high porosity some even in excess of 30% [9, 10]. A carbonate buildup is a body of locally formed yet laterally restricted carbonate sediment with topographic relief [11]. Luconia buildups particularly have individual complexities and are more regionally variable [12] but their commercial prospectivity remains a major concern [6].

One of the most common issues in Malaysia offshore is the problem of shallow velocity variations as a result of gas accumulations [13] and imaging of the carbonate rocks is always challenging due to their heterogeneity and the existence of karst features [14]. Also, while trying to unlock deeper potentials in the Sarawak basin, poor seismic due to low frequency at the deeper sections and shallow gas cloud were part of the impediments to testing for hydrocarbon prospectivity [15].

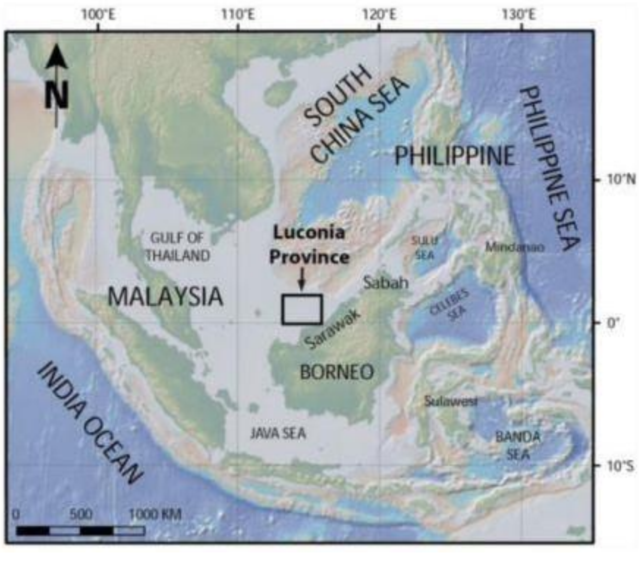

Fig.1: Location map of Luconia province and Sarawak [18]

Similarly, micro porosity, prevalent throughout the Miocene carbonates, often overprints wire line logs and affects the reservoir fluid flow properties including ultimate recovery of hydrocarbons [4]. The dominant lithology of the carbonate rocks are mainly limestone and dolomite [16] and many of these over 200-250 known build-ups [11, 17] (Fig.2) contain about 65 Tcf recoverable gas with minor oil reserves [12].

2. BACKGROUND

It is known that carbonate reservoirs account for about half of oil and gas reserves in the world [19], yet, not all have been put to production as a result of their heterogeneous nature. The understanding of these reservoir heterogeneities is very important in predicting GWC movements and for improved well, reservoir and facilities management particularly to aid in taking preventive steps at mitigating against early Water-Break-Through (WBT) thereby maximizing the ultimate recovery [20]. The key heterogeneous units cause either baffles to fluid (gas/water) flow or are high permeability units. In the Alpha field for example, after about 30 years history of production, some of the wells have experienced high WBT due to uneven GWC rise with faster rise in the southern part than north of the field [21]. Same scenario is observed in the Delta field where after 20 years' production history, all the wells were already producing water due to the uneven rise of the Gas-Water-Contact (GWC) [22].

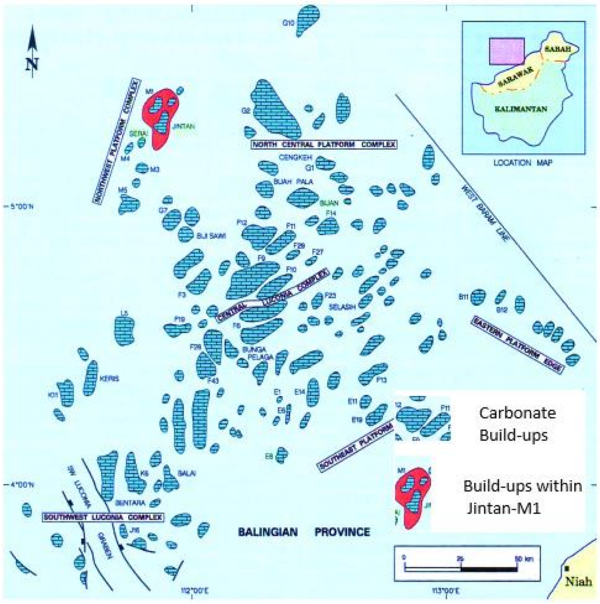

Fig.2: Map showing the extensive build-ups of carbonates in Central Luconia [23]

The origin and occurrence of CO_2 in SE Asia carbonate fields has been a subject of interest to researchers and it is difficult to predict due to diverse petroleum systems [24] and a number of perceived sources ranging from basinal (volcanic emanations, reservoir processes involving mineral transformations, hydrolysis and metamorphism) including poorly understood physio-chemical phenomena (like differential solubility of gas components and phase segregation) to secondary processes e.g. migration style, mineralogy, pressure anomalies and solubility [25].

Tectonic setting, basement fault density, reservoir temperature and pressure are thought to be the key elements controlling the CO_2 abundance in SE Asia yet, there are no structural controls to support this assertion. Though more data will be required to understand some of the physio-chemical processes but it is commonly observed that increase in CO_2 deeper in the reservoir should be commensurate with increase in CO_2 with temperature and pressure but this is not the case in Sarawak Basin [25].

Also, velocity varies rapidly due to the structural complexities of the carbonate build-ups, therefore, accurate velocity information is crucial in reducing the structural uncertainties which will then aid geologic interpretation and reservoir characterization [13]. Evidence from analyses of carbonate core samples from Central Luconia shows non-linear response of high porosity, because carbonate formations have several facies and different diagenetic parameters influence the reservoir quality [26]. The carbonate minerals also undergo a much greater degree of diagenesis than siliciclastic deposits [27]. Similarly, information from pressure data indicates that vertical reservoir connectivity is impaired by lateral barriers to flow. This is however not supported by a structural interpretation [10].

3. GEOLOGY OF THE AREA

The relatively mature Malay, Sarawak and Sabah basins are among the most prolific in SE Asia with extensive exploration and production since oil was first discovered in Miri, Sarawak in 1882 even though most of the production have been from the offshore fields [6]. The resulting discovery of seven giant fields and some twenty smaller accumulations by Sarawak Berhard in the shelf area of Luconia made the area an important gas province [28]. In Central Luconia, core analyses show dominant diagenetic parameters of micritization, cementation, fractures, compaction and dissolution [4] and revealed two types of low porosity layers, though tight [29], one is formed during flooding events and composed of fine grained argillaceous material with large lateral extent and continuity but acts as baffle to fluid flow delaying water rise for several years [21], while the other is discontinuous, patchy and unevenly distributed related to exposure events, composed of cemented, brittle limestone, often acting as minor, local barriers to flow but also serves as conduits for water when they are associated with karsts and fractures [22]. Karst are found in carbonate terrains that have diagenetically altered producing joints, caves and collapse structures [30].

These karsts are formed during high frequency sea level fluctuations in the Miocene caused by rapid sub aerial exposure and re-submergence of the carbonate platforms. These karsts can accelerate early water breakthrough in the wells and may also constitute drilling hazard/losses due to their high permeability [6]. Increase in karst permeability also resulted in increase in water production [31] since karst networks are associated with faults and fractures with high permeability [14]. It has also been discovered that gas chimneys having karst leaching are caused by CO_2, H_2S and methane degradation of oil and the collapse structure of karst is due to carbonic acid dissolution leading to CO_2 generation [32].

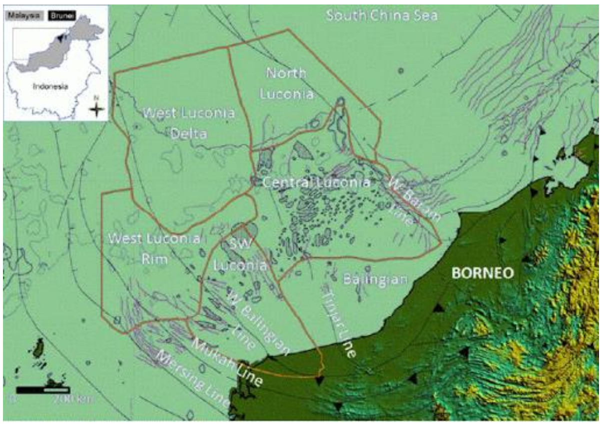

Fig.3: Map showing the characteristic geologic features in Central Luconia [16]

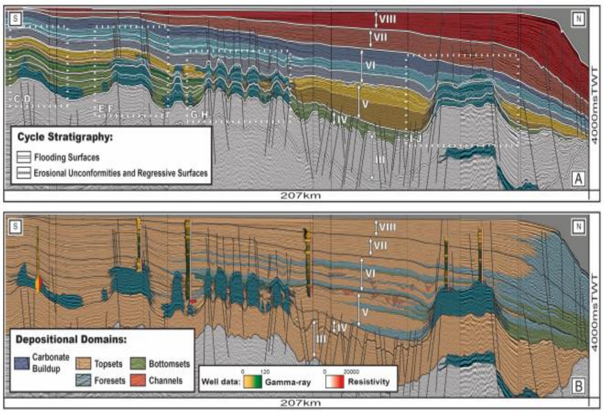

Fig.4: Regional seismic sections across Central Luconia across carbonate build-ups showing syndepositional faulting along the depositional cycles [12]

The main characteristic geologic feature of the Central Luconia province are reefs and carbonate build-ups of the Miocene to recent age [17] (Fig.3). The well-defined carbonate build-ups have been affected by syn-depositional faulting during their growth as revealed by the seismic sections [18] but Stratigraphically, Central Luconia fields can be grouped as carbonate build-ups embedded in shales and siliciclastic [33, 34] (Fig.4). This carbonate deposition started in the early Miocene (CycleIII) (Fig.5) but more prolific during the middle to late Miocene (Cycle IV/V) [4]. Below the carbonates of Cycle IV and V, though not detailed, is a thick succession of carbonates and siliclastics of Cycle III [11]. The Sarawak units in particular are sub divided according to shell nomenclature with cycles I/II as oldest while cycles VI/VIII classified as youngest [6]. It is pertinent to note that these cycles are widely but inconsistently used often leading to ambiguity and confusion [35]. However, Cycle V is known for its hydrocarbon potential and pool of gas-prone carbonate build-ups [36].

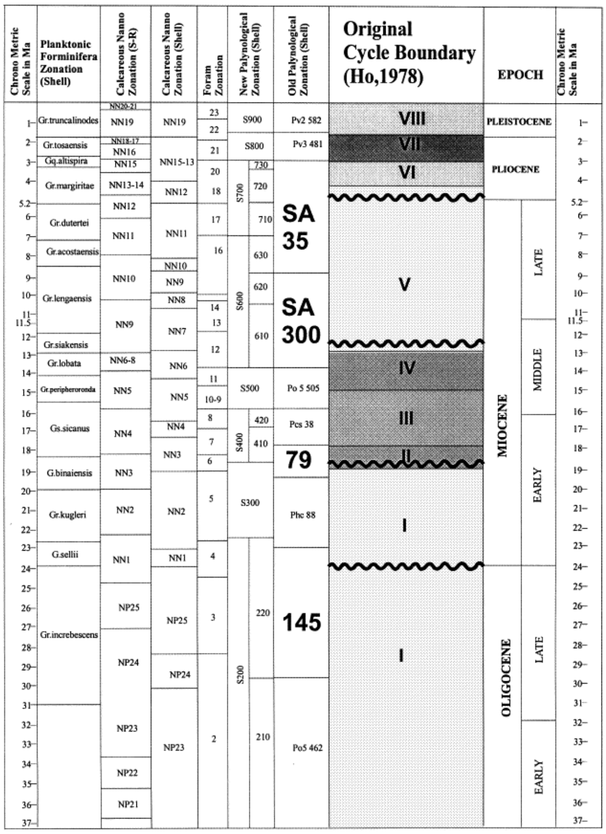

Fig.5: Map showing the Sarawak Geologic Cycles [37]

4. TECTONIC SETTING

The Sarawak basin was initiated as a foreland basin as a result of the collision of rifted South China Continental Fragment called Luconia with Sarawak (Fig.6) Luconia is actually known as the tectonic province of the Sarawak basin [17]. Regional tectonics and eustatic sea level changes are the two main controls for carbonate sedimentation in Central Luconia. Tectonics caused the creation of horst and graben structures upon which carbonate deposition started that resulted in modifying the sizes and shapes of the build-ups [38].

The tectonic evolution and structural style of the South China Sea is therefore very important in the formation of the Sarawak Basin. Sea-floor spreading in the South China Sea during the Middle Oligocene to Early Miocene typified by the symmetrical pattern of roughly east-west trending magnetic anomaly [39, 40] caused rifting and formation of rift basins during the Late Cretaceous to Eocene. The sea-floor spreading of the Oligocene resulted in the drifting of several micro-continental blocks southwards colliding with the northern Borneo margin [41]. This rifting caused the separation of the Luconia and Dangerous Grounds micro-plates from the major Eurasian Plate (Maddon et al. 1999a) initiating a series of syn-rift, half-graben sub basins. Noteworthy is that in the NE Dangerous Grounds, a prominent reflector in seismic data is linked to the top of a widespread Oligocene to early

Miocene carbonate platform [42]. During Paleogene, oceanic part of the South China Sea was subducted resulting in the formation of a large accretion complex along the north-western margin of Borneo. Tectonic activities during the Miocene uplifted the accretion complex through the under thrusting of thinned continental crust in northern Borneo [39, 43, 44]. This development caused the deposition of thick succession of sediments into basins offshore to the west, north and east of Borneo, and into a Neogene basin that is now exposed in extensive areas of eastern and southern Sarawak [45, 46].
Though it is thought that the Miocene carbonate of Central Luconia developed on a stable platform, but there is evidence of syn-depositional tectonic movements impacting on the stratigraphy architecture during the platform growth [47]. It was also observed that the entire platform had drowned in the past due to tectonic uplift and tilting [48], but lots of uncertainties still exist to support this claim even though syn-depositional tectonics could have been a factor [47]. Seismic data indicated that the rifted crusted topography was marked by a regional Early Miocene Unconformity (EMU) thought to represent major hiatus or erosion and condensed section of sediments. [49]. A number of other basins, offshore Sarawak e.g. Balinga province also have technically complex structures [50] that are generally challenging to image. There is particularly a spectacular reservoir architecture revealed by seismic in the Central Luconia province and the recognition of the architectural growth, faults and karsts is key to exploiting the hydrocarbon reservoirs of the mega platform [51].

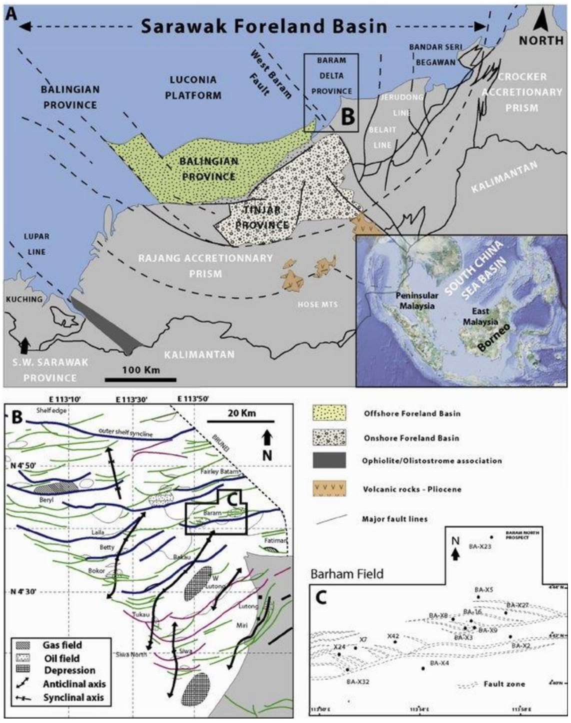

Fig.6: Map showing the tectonic evolution of Sarawak/Luconia [28]

5. PREVIOUS WORK

In Central Luconia, difference in acoustic properties due to lithologic and facies variations has enabled characterization of carbonates through seismic attributes analyses and various attributes can be applied to widespread problems [52] but the seismic data required must be of high quality with high signal to noise ratio.
Imaging has been a problem from the data available in Central Luconia especially in Sarawak basin. The quality of data in Malaysian basins are usually distorted by wipe-outs caused by shallow gas or gas leakage from a deep reservoir, for example in Baram field, there is the problem of poor imaging due to this challenge, same in Malay and other adjacent basins [6]. This is so because the reservoirs are complex and compartmentalized leading to a complex evolution and interaction in the seismic signature of the Miocene isolated platform succession and the adjacent siliciclastic [11]. Though, new carbonate plays in Sarawak have been discovered due to some improvement in data quality, yet, there are still lots of challenges from the imaging point of view especially the structural styles [6].
[6] have also attempted to use multifaceted approach to solve this imaging problem in Malay basin for example deploying converted sheer waves and using Common Focus Point (CFP) techniques including the Q-model/Q-migration concept but it was concluded that further research is necessary as optimal solution to this problem is yet to be seen.
Reservoir fluid analyses carried out in one of the characteristic fields in central Luconia, Alpha field, which is part of the chained carbonate gas fields build-ups, located along the Bunga Pelaga high about 250km offshore, Sarawak [38] indicated that the field has high CO_2 content up to about 70% [2]. The Alpha field is one of the mature isolated carbonate platforms covered with seismic data in central Luconia [38] but [6] in their paper reported wide range of geophysical challenges all of which can be attributed to imaging problem. Some of these challenges are imaging below seismic resolution (thin sands), below gas clouds and carbonates, basement internal architecture, velocity analyses, relative anisotropy and multiples. This Alpha field is a very important example of fields affected by karstification which is widespread in Central Luconia. For instance, the first exploration well (Alpha-1) encountered total losses while drilling as it was thought to have been drilled into karsts. These Karsts have become a big problem in well management, development strategies and even hydrocarbon-in-place as they provided substantial secondary porosity. Therefore, the detailed interpretation of the Karsts is very crucial for field development to avoid drilling complications and to maximize hydrocarbon recovery [38].
Technology has been deployed to separating the high content CO_2 from production wells. Examples include chemical absorption, physical absorption, cryogenic distillation, membrane system and others. The membrane system is thought to be the most effective, however, its

performance breaks down over time and only about 45% CO_2 gas content has so far been developed [1]. Simulator experiments can be performed much more easily and rapidly than actual experiments [53] but have been used for different sometimes conflicting purposes in Central Luconia gas fields, for instance, a compositional 3D model has been applied where CO_2 was treated as a separate component within a reservoir and tracked throughout the production and injection processes [2]. In other studies, time lapse seismic changes in a number of these fields were due to aquifer infiltration into the gas columns as these aquifers are the major drive mechanism for the fields in Central Luconia [19] but there are also time shifts caused by compaction of the reservoir due to production even though pressure naturally should decrease with production. Also, mass balance estimate of remaining volumes and simultaneous multi volume inversion have been applied in the M4 field for example to assess the residual gas saturation and remaining volumes but other production related mechanisms could also explain some of the observations as demonstrated by [19].

The best workflows using Petrel, Landmark and Shell software packages for example have been applied to generate seismic attribute volumes for karst interpretation [14, 38] including using analogues to produce subsurface model yet the only method to input and incorporate the karst geobodies into the static model is by first converting to point data before upscaling [38] which is susceptible to errors and misinterpretation of the karsts. The karst and fractures significantly increase permeability along exposure surfaces and where pervasive, karsts may act as vertical conduits forming potential drilling hazards [54]. Nonetheless, apart from being potential geohazards, these karsts are also possible voids for hydrocarbon accumulation [14]. Hence, different attempts have been made to delineate the karst geometry, but it still remains an unresolved problem in central Luconia due to their heterogeneous nature [6]. A combination of seismic attributes and techniques including spectral decomposition, opacity rendering etc. have been used to delineate the karsts [6], yet their location and geometry are unresolved even though they are seen on seismic as dendritic having discontinuous pattern in seismic reflectivity [31]. These dendritic features interpreted as karst are very prominent throughout the Alpha field for example [38]. It has been observed that several transgressive, aggradational and progradational cycles are masked by these karst features [51], yet, the biggest challenge in Karst interpretation is the separation of the karst which in this case would be the signal from the background noise laterally or vertically [38]. Furthermore, there is the problem of Porosity overprint as observed on the seismic amplitudes ([19]. Similarly, the dynamic behaviour of different reservoir geobodies such as reef margins, faults and karsts have been modelled using 4D time lapse and surveillance data sets giving insights on water influx and sweep which was then projected to carbonate fields with less data [55]. However, a detailed shallow velocity model is necessary for the geologic interpretation of deeper section of the carbonate reefs [13]. In the same vein, Full Wave Inversion (FWI) has been applied to model the shallow water field of a central Luconia basin to obtain an improved shallow velocity model. This is because standard reflection based velocity model cannot effectively image the velocity variations. However, for a successful FWI, it has to be applied alongside broadband data processing where a dedicated reprocessing of the seismic data should first be carried out. In Balinga province offshore Sarawak for example (D18 field), 3D seismic was carried out to investigate the extent of faulting at reservoir level in order to understand and improve on the structural imaging [50]. It has therefore been established that proper imaging of 3D seismic would be helpful in reducing some of the uncertainties associated with untested carbonates in Central Luconia [5], though fracture networks in carbonate rocks have previously also been examined but only on outcrops [56].

6. CHALLENGES

Structural complexities among fractures and faults such as fault intersections strongly control fluid flow such as magma, hydrocarbons and ground water, but not much work has been done to quantify and visualize this relationship [57, 58] even though there are evidences that paleo fluid flow exist in areas of high structural complexity [56]. Therefore, understanding the faulting system in relation to carbonate growth would be useful going forward to revisit the mature hydrocarbon reservoirs in Central Luconia [18].The structurally complex Central Luconia carbonate build ups has often been subject of conflicting interpretations [12] in their paper, noted that the seismic images of these build-ups show complex, feathery structures in various forms intercalating with surrounding siliciclastic deposits but these have suffered a lot of limitations from interpretation on one hand and the software used on the other. Also, the feathery edges are not easily interpreted, so is the lithologic boundary between the carbonate and siliciclastic sediments which ultimately leads to wrong estimation of the reservoir-rock volume.

The floor of the carbonate build ups has often been simplified creating artificial basal carbonate layer (regional base) with the carbonate build-ups themselves rounded up with a regional top into a single map especially because many of the seismic modeling software packages are layer based requiring vertical separation between surfaces [12]. This single map is easily identified as a simple 4-way closure but in reality, most of the carbonate build-ups are characterized by more complex marginal morphologies with numerous overlaps of carbonate and siliciclastic lithologies. In the Baram field for example, a field-wide dip oriented seismic section shows a traceable, regional, and mature horizontal to slightly convex upward layers [59] but [12] concluded that these imaginary closing contours and/or spill points are in fact interpretation artefacts as it is established that some geological artefacts are known to limit quantitative analysis and stratigraphic interpretations [11]. Interpreting the carbonate bodies,

preclastics below the carbonates, understanding hydrocarbon response in carbonates and the high CO_2/H_2S contamination are some of the major challenges today [6]. In fact, the so called 'gas clouds' or 'gas chimneys' have posed serious interpretation problems that conventional approach has not been able to resolve satisfactorily [60]. The carbonate fields in Central Luconia have been subjected to karstification and analyses of the seismic data shows some level of uncertainty on the size, geometry and occurrence of the karsts as well as its effect on Gas Initially in Place (GIIP) and water breakthrough [31, 51]. These karsts arise from the dissolution and migration of calcium carbonate in meteoric waters [14, 38] and the dissolution process causes the enlargement of inter particle pore space, thereby increasing porosity ([61]. Although it is easier to interpret faults and channels on time slices, but karst terrains have complex patterns indicating strong structural control on their geometries [30].
If reservoir gas is highly contaminated with CO_2, its economic value decreases. In the Sarawak basin, over 13 Tcf hydrocarbon gas is locked in high CO_2 fields and effective EOR and CO_2 field development is necessary to overcome these challenges but the requirement of CO_2 for EOR purposes is across various fields scattered around and the high CO_2 fields to serve as source for CO_2 EOR are located far away. Also, due to high processing costs, efforts to commercialize high CO_2 content natural gas have been disappointing. Added to the challenge is the geochemical CO_2-water-rock interaction in the reservoir which inevitably causes the mineral dissolution of calcite altering its mineralogy and texture. The uncertainties are further deepened by the conclusion from [25] that reservoir related attributes do not have any correlation with CO_2 levels in Sarawak basin and even if they did, the distribution of the data points are sparse and not diagnostic. Yet, a thorough understanding of the CO_2 distribution, the geologic controls as well as its possible sources are critical for successful hydrocarbon gas exploration.
The CO_2 within the reservoirs has a high flow rate and in a number of cases, the amount of CO_2 to be produced is actually more than the requirement of EOR, yet, during production, hydrocarbon must take higher priority because of demand. Therefore, an innovative approach must be adopted in order to be able to produce the hydrocarbon gas without sequestrating the CO_2. One of the plausible ways to reduce the volatility of the CO_2 and hence, decrease its flow rate as experimented in several literature is to pressurize the CO_2 below 31.1 °C and 7.4 MPa and the CO_2 will be liquid which then makes the hydrocarbon gas to be carefully produced through detailed well planning. Also, improved structural imaging below the carbonate build-ups may as well reveal possible sources and pathways of the CO_2 into the reservoirs and mitigation strategies can be adopted.

7. SUMMARY

The origin of the CO_2 especially its occurrence in natural gases has proven difficult to predict and almost all approaches are either based on circumstantial evidence of basinal sources or through some statistical analyses of reservoir attributes [25] but little data exists to support these hypotheses, hence, a more detailed study is necessary especially through improved seismic imaging to find out the prevailing factors contributing to the high CO_2 content in Central Luconia gas fields. Gas isotope data which may give further insights into this challenge are rare and when available, poorly distributed [25].
As prevailing as structural control seems for the origin of high content CO_2 in the reservoirs, not much has been done or achieved to establish this relationship. Therefore, an important issue that must be addressed going forward is to know what geological factors control the hydrocarbon bearing potential of a carbonate build up and to what degree it is filled [23]. Though it was suggested that the presence of a 4-way dip closure in the pre-carbonate sequence under a prospective build up increases the chances that they may be hydrocarbon bearing but it has been proven that most hydrocarbon bearing carbonate reservoirs in central Luconia are under filled [12] Carbonate build-ups in central Luconia are prone to faulting along the crests and flanks [23], hence should the faults leak, through a structurally high spill point for example, the accumulated hydrocarbon column thickness will be reduced as there will be a possible escape and this will definitely affect the ultimate recovery but there is considerable level of uncertainty around the estimation of recoverable hydrocarbon and production from the reservoir owing for example to the effect of microporosity especially impact on morphology of pores and connectivity of the pore network [4, 62]. Micro pores have a strong softening effect on carbonate rocks, lowering the sonic velocity [61] but with high resolution imaging, the pore networks and their relationship with the reservoir fluid composition can be determined.
Also, during production from the reservoir, there is need for water management as it breaks into the producing wells but this is heavily dependent on the reservoir properties which are controlled by depositional features and diagenetic overprints [4, 22]. The heterogeneous reservoirs in the carbonate fields of central Luconia, e.g. Alpha field, are typified by high permeability platform margins and upper slope deposits in the flanks interpreted as conduits speeding up the GWC rise but seismic mapping indicate shedding of more carbonate sediments whose properties remain uncertain [21]. An improved imaging will hence give more insights in to this since reservoir heterogeneities with effect on production and recovery are associated with faults, fractures, karsts, argillaceous layers, and facies [63].

8. FUTURE OUTLOOK

The prospect for renewed exploration and production activities in Central Luconia can be brighter by resolving the imaging challenges with a more dedicated and integrated approach to structural interpretation including top notch processing/reprocessing so as to understand the nature, extent and geometry of the karsts and their effects as well as to establish the prevailing structural elements that control the high CO_2 content in the fields, their sources and distribution including impact on hydrocarbon gas production.

In particular, we have identified key strategies that could substantially change the narratives about the prospectivity of the Central Luconia Carbonate build-ups:

1. Developing detailed structural imaging and interpretation beneath the carbonate build ups and gas clouds to understand the structural styles, faults/fracture orientation, their evolution/distribution and densities in relation to the reservoir fluid entrapment.
2. Creating a different approach to delineate the widespread karsts and karstification establishing the nature of their occurrence, geometry, evolution and distribution in order to predict future field development in Central Luconia.
3. Evaluating the structural controls on CO_2 source, flow rate, distribution, emplacement and saturation in the reservoir including their interaction with hydrocarbon gas after depressurizing for a more realistic ultimate recovery.

9. CONCLUSION

The challenges that have impacted the development of Central Luconia Carbonate build-ups have been highlighted. The widespread Karstification can be resolved through a more focused structural imaging and prediction is possible to differentiate between possible production-aiding karsts and those that can constitute drilling hazards to guide drilling work programs and future field development. We believe faults and fracture associations, interaction and intersections could be mapped and designated as sweet spots for drilling and the high CO_2 in the fields can be depressurized to reduce the flow rates in the wells thereby enabling smarter ways of producing the hydrocarbon gas without CO_2 geo-sequestration.

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