Diagenetic Evolution of "Buried-Hill" Carbonate Reservoir Analogs in Outcropping Permian Carbonates, Saraburi Province, Thailand

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Abstract

In order to better understand controlling factors on karstification in central Thailand, field and laboratory studies are conducted on two geographically-separate karstified Permian carbonate outcrops. Using field observations, along with detailed petrographic and stable isotopic determinations, the aim is develop better relevant local analogs for the fluid and structural evolution system that created the economic porosity in producing "buried-hill" carbonate reservoirs in subsurface of Thailand.

Both studied outcrops are in inactive quarries in Saraburi province, and the two regions show somewhat different effective porosity distributions in the karst, both of which are controlled by the permeability contrasts present at the time the karst was forming. One set of permeability contrasts is related to compactional bedding orientation, with bedding-parallel stylolites controlling karstification. This creates sub-horizontal vugs oriented parallel to bedding. The other set of controls is a combination of inclined bedding and conjugate fractures. This is related to permeability contrasts created by fracture and fault-damage zones that were created during thrusting and uplift. Many of the documented karst features preserve textural evidence of recent meteoric karst formation and these are features with preservation potent and so their remnants are recognizable in ancient counterparts. These "pointer" textures include a range of characteristic speleothems and soils; terra rossas, collapse breccias, stalactites, stalagmites and a variety of flowstones.

The integration of outcrop observations, petrography and isotope study reveals a diagenetic history that, in addition to its modern telogenetic overprint, includes textural and isotopic evidence of the effects of earlier burial-related hydrothermal fluids. This subsurface diagenesis included one or more episodes of mesogenetic vug formation, but these features are now mostly filled with burial cements. Therefore, most open-cavities in the study outcrops formed in the modern telogenetic environment, ultimate driven by uplift tied to the Himalayan Orogeny.

Plotting of δ18O/16O and δ13C/12C shows two distinct plot field trends, that can also be recognized in a studies of drill cuttings in subsurface counterparts.

The isotope plot field trends are: 1) a burial trend typified by increasingly negative oxygen values, related to the increasing temperatures of ongoing burial and 2) a meteoric-mixing trend related to negative carbon residing in soil gases passing into in meteoric waters, which then precipitate speleothem calcite in the uplifted rock and fissures. The burial trend relates to fracture development, stylolite formation, hydrothermal flushing and thrust-related calcite veins and cements. The meteoric-mixing trend relates to collapse breccias and speleothem formation in the modern karst zone.

Keywords: Mass Transport Complex

1. Introduction

Current "buried hill" Permian carbonate reservoirs in Thailand are developed in two main fields, which are Nang Nuan and Phu Horm fields. These fields contain evidence of the complexity of their tectonic evolution interacting with karst process to create the buried hill structures. Permian carbonate reservoirs in Nang Nuan field and Phu Horm field were produced in hypogenically overprinted karstified carbonates, flushed by hydrothermal alteration and hydrothermal leaching of the carbonate hosts, associated with fracturing and dolomitizing respectively (Racey, A., 2011). The later paleo-high structures of these reservoirs allow further karstification (that both fields were formed by as yet still poorly understood combinations of meteoric and hydrothermal processes). Therefore, this outcrop study of karst processes and the effects on limestone textures, poroperm evolution and chemical properties will lead to a better understanding and karst development and poroperm-modifying processes in karstified carbonate reservoirs in Thailand.

2. Locations

Two outcrops were selected for study via detailed fieldwork in Saraburi Province, central Thailand (Figure 1). Both exposures are Permian carbonate platform successions (Dawson and Racey, 1993) and exhibiting distinct control factors of karst development. One outcrop is a quarry in the east of Saraburi Province that was used to slab cut large facing stones and the other is inactive aggregate/cement quarry in the northwest of Saraburi Province. They are called Quarry-1 and Quarry-2 respectively located respectively at 14°53'54.55"N/101°21'51.95"E and 14°40'15.25"N/100°49'26.99"E.

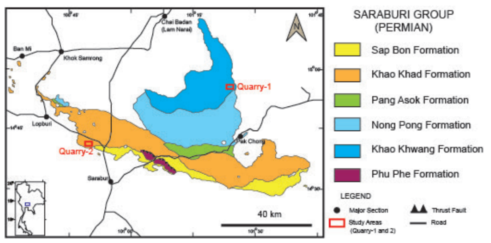

Figure 1 Locations of study area.

3. Objectives

Objectives of the research are to determine the main diagenetic controls and their order of development, especially in terms of outcomes that influence directional porosity and permeability in a karstified carbonate reservoir, The approach is to integrate then interpret data collected from the outcrop down to microscopic scale. This will improve our predictive understanding of controlling factors in diagenetic history of karst development in the study area and use it to better understand the current and future development options in buried-hill karstified carbonate reservoir in Thailand.

4. Methodology

Research methodology can be separated into 2 parts; 1) field study and 2) laboratory study.

Field study

Geological information was collected by a combination of outcrop sketches, photos, measurement of bedding/fracture orientations and sampling of representative rocks for laboratory analysis. Additional focus was given to vug/cave orientation and karstified features present such as soil-fills in vug/cave (terra rossa), speleothems and karstified breccias.

Laboratory study

In the laboratory the field data including orientation data was collected and interpreted, and petrographic, isotopic and XRD analysis were done. All the collected field data measurements, consisting of bedding, stylolite and fracture orientations were plotted on Rose diagrams in order to define the major trends relating to karstification. Fifteen rock samples were chosen for petro-

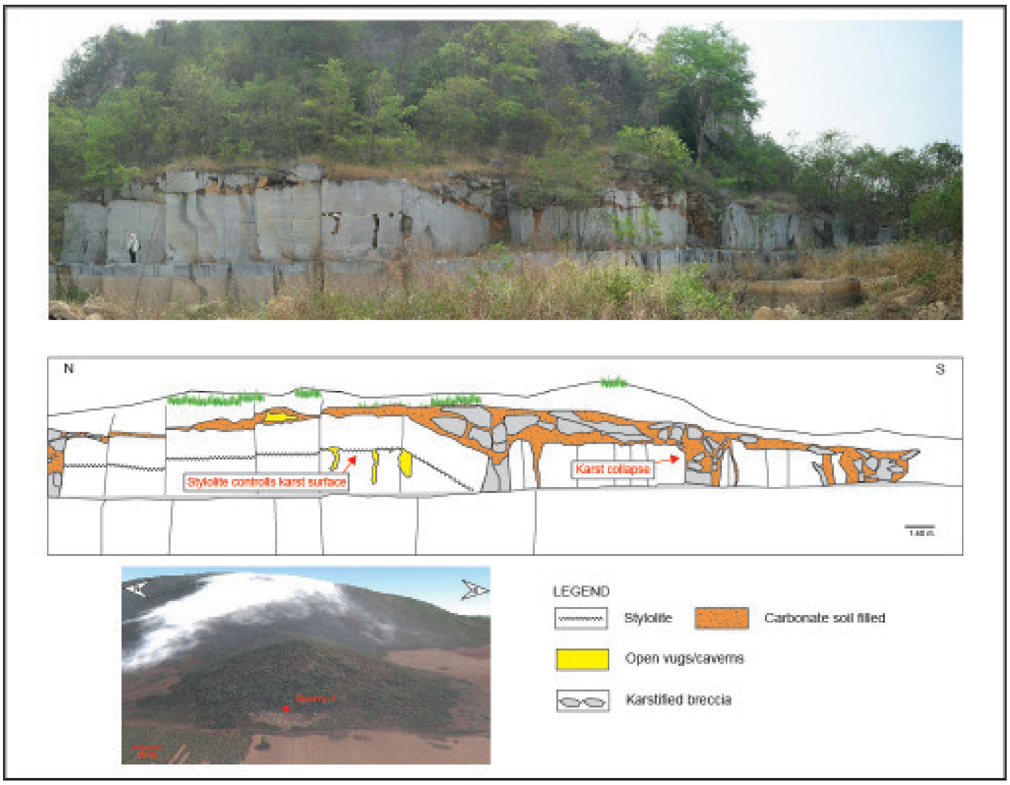

Figure 2 Simplified karstified outcrop in Quarry-1.

graphic study by thin sections. This aids in definition of diagenetic timing and porosity modification of the rocks. Some thin sections-controlled samples were also submitted for XRD analysis to confirm the presence of minerals seen in thin section. Furthermore, using slabbed faces, 155 samples were run for stable isotope analysis ($\delta^{13}C$ and $\delta^{18}O$) in order to better understand fluid types that have circulated at some time through the rock during burial to rock deformation and uplift and karstification. Finally all the results of the laboratory study were integrated with field observations to upgrade our understanding of diagenetic history, porosity evolution and structural evolution in karstified carbonates.

5. Macro-meso scale karstification

- Macroscale controls on cavern development

Quarry-1 is an inactive slab quarry. It extends 40 meters from North to South with beds showing N50E strike and approximately 30° SE dip direction. Bedding parallel stylolites are the major factor controlling the karst formation exposed in the quarry (Figure 2).

Quarry-2 is an inactive aggregate/cement quarry. It extends about 100 meters from East to West and the quarry

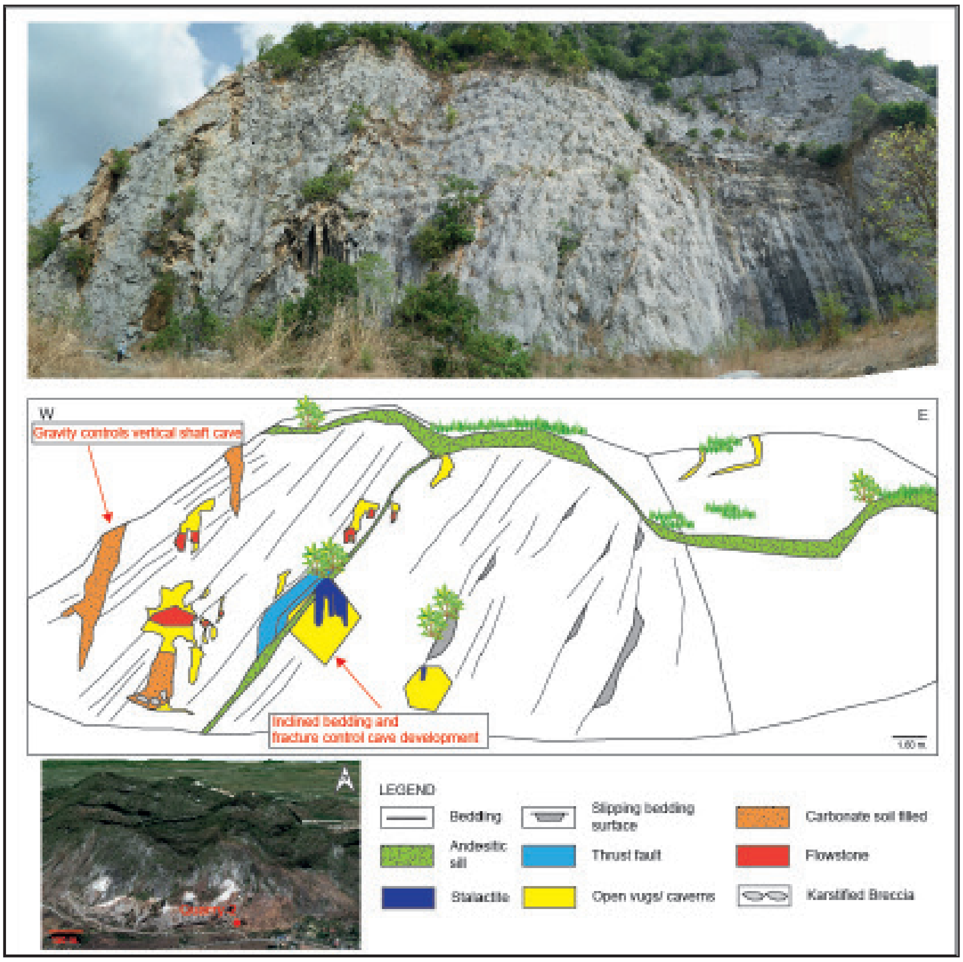

Figure 3 Simplified karstified outcrop in Quarry-1.

wall is over 10 meters high. Bedding in this quarry is steeply inclined compared to the near horizontal bedding in quarry-1. Bedding direction is W80E strike with an average 55° SSW dip angle. Inclined bedding and fractures are the main controls on karst development in Quarry-2 (Figure 3).

- Beddings and stylolites

Quarry-1

Bedding was indicated by irregular surfaces enriched in corals and bivalves, which are interpreted as representing the paleo-sea floor. Bedding trends are consistently low-angle to sub-horizontal. Moreover, I found that major stylolite trends correspond to these bedding attitude defining an outcrop with mostly bedding-parallel stylolites with NE strike and average 30° SE dip direction.

Quarry-2

Bedding in quarry-2 is more steeply inclined than Quarry -1 and has a consistent bedding trend across the quarry exposure, showing a ESE strike trend, and a dip direction to SSW, with dip angles ranging from 45°to 65°. Two main directions of stylolites were measured in quarry 2, they are; 1) nearly NW-SE trend with an average S60E strike (parallel to bedding) and 2) locally NE-SW trend with N60E strike (inclined to bedding). However, these trends of stylolite did not tend to enhance cavern development.

- Fractures

There are two main fracture trends developed in Quarry-1, which are WNW-ESE trends and NNE-SSW. A variety of fractures were observed in this area and were consistently filled with calcite.

In quarry-2, there are two main trends of fracture measured. These fracture trends are oriented in WNW-ESE (bedding-parallel fractures) and NE-SW (bedding-inclined fractures) with averages of S58E and N45E, respectively. They are conjugate fracture sets related to the imposed compression and shear regimes. Most of fractures are filled by calcite but there are some that have not been filled.

- Karst features

Examples of karst features in the quarries include vugs/caverns, and karst collapse breccias can be described as follows;

Vugs/caverns

The two types of vugs/caverns defined in quarry-1 are; 1) vugs/caverns with soil fill and 2) open vugs/caverns without soil fill.

The soil-filled vugs/caverns tend to be located nearer the current landsurface. Most soil-filled vugs/caverns are laterally elongated parallel to stylolites and bedding surfaces, nearer to the landsurface. They tend to be more aligned along fractures and block collapse in the deeper parts away from the landsurface.

Open vugs/caverns without soil fill define 2 trends: sub-horizontal open vug/caverns and vertical to near-vertical open vugs/caverns. The horizontal open vugs/caverns relate to permeability barriers created by sub-horizontal stylolite trends and parallel the bedding surfaces. Vertical open vugs/caverns are associated with fractures and gravity driven water infiltration (Figure 2).

In quarry-2, the two trends of vugs/ caverns development are; 1) NNW-SSE trend associated with bedding-parallel fractures and inclined bedding and, 2) NE-SW trend related to bedding-inclined fractures. Vugs/ caverns in quarry-2 are classified into the same types as quarry-1, namely; 1) vugs/caverns with soil fill and 2) open vugs/caverns without soil fill.

Soil filled vugs/ caverns are connected to the landsurface via open conjugated fractures and inclined bedding. Moreover, the strong vertical orientations of the majority of the soil filled vugs/caverns reflects the strong gravitational control to leaching in the vadose infiltration and percolation zones.

The rhombohedral cavern shape is a response to permeability contrasts created by the intersection of conjugate fractures and inclined bedding. The vertically-oriented speleothems in the interior of the caverns and are linked to roof fracture intersections acting as drip-seep feeds and gravity.

Likewise in quarry-1, in terms of macro-scale porosity, connected porosity is seen in soil filling vugs/ caverns and isolated (broader scale) porosity typifies open vugs/ caverns. There are many hydrological factors involved in vugs/caverns development and they will discussed later, after the presentation of the isotope analyses.

Karst collapse breccia

Karstified breccias are associated with karst collapse, one creates the other. The breccias are also related to soil-filled carbonates and variably etched rock surfaces. Breccia textures tied to karst, range from mosaic to fitted mosaic to crackle breccias depending on whether one can rejoin the clasts from their present orientations. Many of the larger breccia clasts in quarry-1 have not moved far from the source position and so are defined as fitted mosaic breccias.

In quarry-2, collapse breccia is found as association with terra rossa. It show non-symmetrical pattern orientation of breccia clasts identified as karstified breccia. Breccia clasts are comprised of limestone host and stalactite. The calcite cementation in between grain of breccia clasts was also observed.

- Faults

A minor thrust fault oriented sub-parallel to bedding with a N90E/ 70°SE direction intersects the quarry wall and creates a permeability contrast that influences cavern developement and calcite veining. Close to the thrust, there is a higher intensity conjugate fractures compared to areas further from the thrust zone.

6. Micro scale karstification

- Porosity modification

Matrix porosity

Because of the high levels of calcite cement permeating matrix and grains, there are is no remnant matrix porosity in any sample. In the subsurface, these rocks are tight. The intragranular and intergranular primary porosity was cemented during early marine cementation and on into burial. Wherever there was fluid access many of these cements were further overprinted and influenced by hydrothermal waters, Some of these hydrothermal water created hypogenic porosity, in places indicated by barite linings (Figure 4A, 4B), but ongoing mesogeneitc cementation filled these voids as well, so the dominant rock character, prior to uplift, was strata that had been completely cemented and so, unless, faulted were impervious.

Fracture porosity

In general, fractures have been cemented by calcite. However, there is some minor fracture porosity as remnants of an episode of hydrothermal flushing created zones of weakness enlarge during uplift (Figure 4A). This caused dissolution/ recrystallization of early calcite fills in fracture and created isolated micro vug porosity.

Hydrothermal porosity

During burial, hydrothermal fluid associated with thrusting created minor isolate vugs (Figure 4C). However, these isolated vug porosities were cemented by calcite due to subsequent episodes of hydrothermal crossflow.

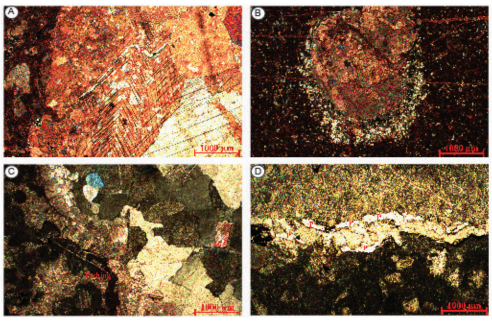

Figure 4 Representative micro-scale features related to porosity modification.

Karstified porosity

Karstification is related to sub aerial exposure and variangly connected porosities are developed across the micro to macro scale. Dissolution is ongoing as seen in the granular calcrete where isolated vugs are forming in this carbonate soil. Calcite-filled stylolite textures are being dissolved by meteoric water creating new vuggy porosity (Figure 4D). This microscale process is part of the same meteoric-driven dissolution of limestone driving collapse and creating caves, variably filled with karst breccias. The various modern karst-related soils and cements can fill these voids with aligned calcite cements composed of aligned and bladed crystal that make speleothem cements.

- Stable isotope analysis

Selected texture-based calcite samples were analyzed to determine their $\delta^{18}O/^{16}O$ and $\delta^{13}C/^{12}C$ values. During burial, an increasingly negative oxygen isotope value is related to rock-fluid driven re-equilibration and fractionation in a subsurface environment subject to increasing fluid temperatures (Hoef, 2009). Carbon isotope values are less dependant on temperature and tend to vary according to the source of CO_2. The source of CO_2, which supples the bicarbonate to the calcite cement,- may be from oxidizing of carbon due to soil weathering, biogenic activity or hydrocarbon maturation and fractionation.

Crossplots of $\delta^{18}O/^{16}O$ and $\delta^{13}C/^{12}C$ are shown in the Figure 5, where two trends stand out. One is the burial trend which matches the isotope burial trend as defined by previous studies of the Saraburi Limestone; Ampaiwan (2011), Thanudamrong (2011) and Kuenphan (2012). The other trend is a mixing trend tied to calcite precipitated in recent speleothems.

Trends in the two quarries are divisible into two groups, namely: 1) Group or Zone I, which is interpreted as cements and re-equilibrated matrices that preserve the signatures of somewhat cooler (shallower, possibly earlier) stages of burial and; 2) Group or Zone II, which is interpreted as mostly derived from vein cements with few values coming from thermally re-equilibrated matrices. Group II preserves the isotope signatures of hotter (deeper, possibly later) stages of burial.

Clearly, the limestones in Quarry-1 have a more thermally-evolved diagenetic history than the limestones sampled in Quarry-2, perhaps because matrix porosity was lost completely during shallower (but still thermally elevated) burial at Quarry-2. In contrast the limestones in quarry-1 continued to experience ongoing burial evolution and requilibration. It is likely that the rocks in the region of Quarry 1 continued to be fractured and subject to increasingly hotter fluid crossflows, long after the fracture-related permeability-forming processes had ceased to be active in the region of Quarry 2. Differences in hydrothermal activity, related perhaps to different intensities in arc volcanism is one possibility to explain the difference in burial histories.

Recent speleothem samples give slightly variable but consistent negative carbon values across both quarries and define end members of a mixing trend. That is, two plotzones can be recognized (mostly using the variation in carbon values) are called zone III and zone IV (Figure 13). Zone III is a zone of soil samples from karst collapse breccias, wthese soils contain as mixture of

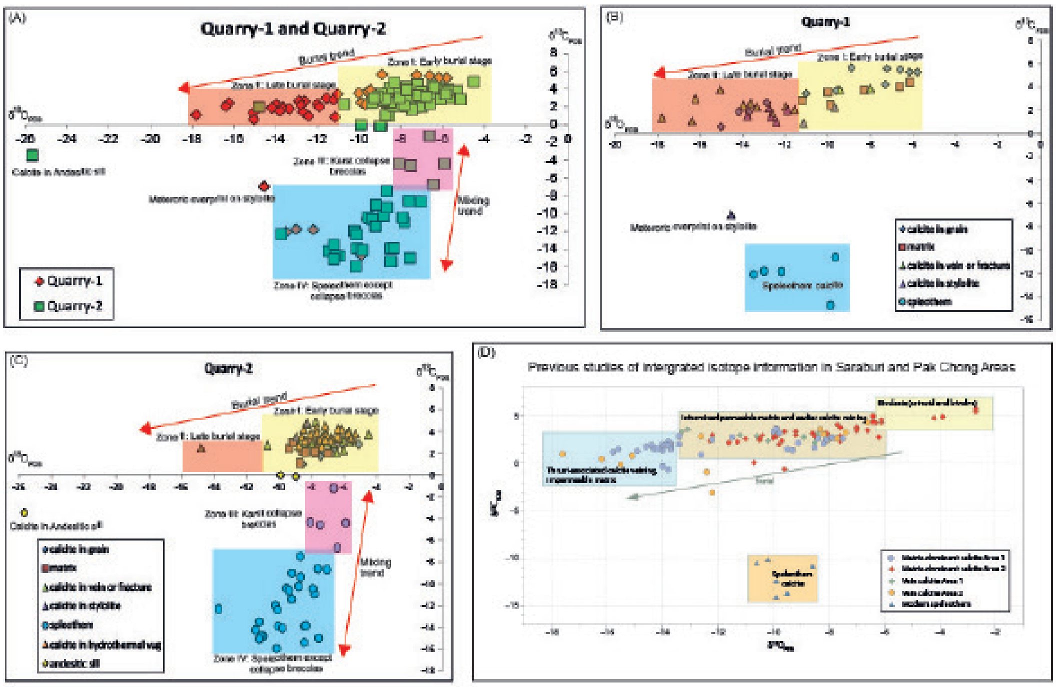

Figure 5 Isotope plot in quarry-1 and quarry-2 (A, B, and C) and comparison with the previous studies by Ampaiwan (2011), Thanudamrong (2011) and Kuenphan (2012) establishing the regional isotope trend (D).

Permian limestone clasts and microclasts. Zone IV is zone of carbonate soil and speleothems without any collapse breccias (no etched and rilled Permian clasts) and includes samples of terra rossa, stalactites and flowstones. Zone III plotfield contains elevated (less negative) carbon isotope values than zone IV. This difference corresponds to the proportion of carbon in the pore waters derived purely from modern meteoric waters in the soil matrix speleothems versus precipitative waters with chemistries influenced in part by the dissolution of Permian clasts. Hence, Zone II and Zone IV plotfield define a mixing trend.

7. Interpretation

- Controls on karst development

Quarry-1 and 2 are characterized as meteoric-influenced karstified limestone systems where most of the current exposures are in the vadose zone (above water table). Uplift, karstification and formation of speleothems in Permian carbonates of the area was ultimately driven by the Himalayan orogeny.

In Quarry-1, lateral caverns were developed along and parallel to a near-horizontal stylolite trend. This trend parallels to bedding in NE-SW direction. Thus, the main control of cavern in Quarry-1 is bedding parallel-stylolites. However, gravity and WNW-ESE joint trends also influence cavern development in a vertical direction. Karst collapses tend to follow fracture/joint trends and if they reach the landsurface can create the zones that can fill with carbonate soil.

In Quarry-2, inclined bedding and conjugate fracture sets are the main control on cavern development. Additionally, caves have formed along the porosity created by slipped bedding surfaces and fractures especially in areas within or close to the damage zone created by the thrust fault that crops out in the quarry wall. Thus exposed thrusts can be a significant factor in enhancing cavern zone development as they can create exhumed intervals of enhanced factoring that facilitate meteoric dissolution in an otherwise massive limestone. Vertical cavern filled or partially filled by carbonate soils were created by gravitational infiltration of meteoric waters.

Stage	Early → Late	Porosity: Decrease	Porosity: Increase	$\delta^{18}O$ and $\delta^{13}C$ Signature
Eogenesis				
1.Deposition of grainstone with early marine cement		⇦		Positive carbon isotope and increasing negative oxygen isotope
Mesogenesis				
2.Calcite precipitate in cavity of bioclasts		⇦		
3.Development of stylolite and fracture due to compaction		⇦		
4.Multi episodes of hydrothermal alteration creating etching vugs with filled by carbonate cement, recrystallized calcite and isolated vug in fracture		⇦	⇨	
5.Progressive fracture development and stylolite relating to compressional stress and thrusting with calcite cement		⇦		
Telogenesis				Wide range (-1 to -16) of negative carbon isotope and negative oxygen isotope
6.Dissolution of limestone along fractures and stylolite associated with terra rossa forming			⇨	
7.Granular calcretes precipitating in the vuggy/ cavern porosity		⇦		
8.Dissolution of granular calcretes			⇨	
9.Karst collapses		⇦		

Table 1 Diagenetic evolution summary

- Age and Diagenetic history

Fusulinids were used to help identify age of the outcrops in the two study area. This determination was verified by Assist. Prof. Thasinee Chaleonthitirat, paleontological specialist in the fusulinids of Thailand. Neoschwagerian, Verbeekina, Sumatrina, and Preudodoliolina were found in Quarry-1 indicating a middle Middle Permian age. Chalaroschwagerina was found in Quarry-2 indicating a Lower Permian age. The age is Permian in both quarry, corresponding to the regional distribution of limestone formation in Saraburi group (Figure 1).

Even though there are slightly differences in the age of both quarries, their diagenetic histories are somewhat similar with hydrothermal influences related to burial overprinted by uplift-related effects of recent meteoric karstification. Table 1 summarises the diagenetic history in both quarries and integrates evidence from the macro to microscale in order to define what drives porosity modification.

Porosities created by the distal effects if the Himalayan orogeny uplifted the studied carbonates as a subaerially fed karstified systems became active, especially in the upper parts of the exposed limestone. This telogenetic stage created vuggy/ cavern porosity in both quarries driven by meteoric water crossflows. Dissolution of the limestone allowed ongoing water entry, joining up along the expanding fractures and joints that further enhanced the porosity. As dissolution continued, vertical shafts with the karstified limestone were created during to karst collapse. This allow new broader pathways for carbonate soil to fill to earlier vuggy and cavernous porosity and so reduce permeability.

8. Implication

- Structural model

In the subsurface, providing there was thick mudstone overburden the porosity patterns seen in both quarries could create a buried-hill structure, dominated by meteoric karstified carbonate rock signatures that could be recognized beneath a subaerial unconformity. It would preserve remnant textures in the form of weathering products from the limestone host rock. They would include speleothem, soil and karst features. If isotope analyses were run on cuttings collected across the unconformity they should show a distinctive plot field. Seismically defined zones, where thrust faults intersected the surface, may indicate zones of fracture/meteoric enhanced karstification, due to an increase in the intensity of open fractures.

Figure 6 is a model of meteoric-influenced karstification based on observations in both quarries and shows idealized sets of cavern orientation controls. Quarry-1 shows cavern porosity created by dissolution of calcite along permeability contrasts created by bedding parallel stylolites with no fracture related intersecting jointing to create a plumbing pathway. In contrast, in quarry-2, the fractures are connected to the cavern porosity. This creates connecter pathway for hydrocarbon flows.

Furthermore, if these quarries are to be burial hill analogs the model would require deposition of an organic rich

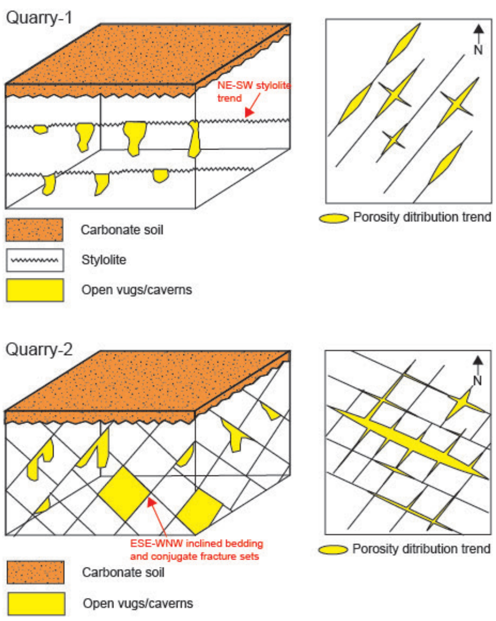

Figure 6 Model of meteoric karstified carbonate reservoir in study areas.

shale post karstification. This is needed create both a source rock and top seal to the buried hill structure, as in Renqui Field in China.

- Implication to petroleum exploration and development of a "buried-hill" play in Thailand

The developed "buried-hill" karstified carbonate reservoirs in Thailand field (Nang Nuan and Phu Horm fields) are related to hydrothermal alteration (Recey, A., 2011) and resulting from karstification and enhancing reservoir quality within different tectonic settings, both create a burial hill structure. However, petrographic and isotope studies in both study areas reveal that there were many episodes of hot fluid flushing that mostly occluded porosity and permeability. Early hydrothermal fluids active in the earlier burial stages created hydrothermal vugs that were completely cemented by calcite. Only minor isolated micro vugs in fractures were preserved from later hydrothermal fluid cements and so production from both fields is patchy and difficult to predict. The effect of hydrothermal activity in both areas was mostly negative in terms of reservoir quality.

Timing of karst formation in uplifted outcrops with post-uplift meteoric crossflows enhancing porosity is different in both areas is developed by meteoric water crossflow is different within known karst fields in Thailand. Nevertheless, meteoric effects must have occurred in both Phu Horm field and Nang Nuan fields. Production in both is from a zone immediately below an unconformity. Clearly, both unconformities must have been subaerial features at some stage in the basin history and so there must have been a stage of meteoric flushing. Thus, the identification of karst zone in outcrops helps to define the nature of the karstified reservoir in Phu Horm and Nang Nuan field.

In conclusion, outcrops showing unconformities with weathered surface covered by terra rossa, karstified collapse breccia and open cavities all point to the location of a burial karst zone in a buried hill play. Understanding the porosity distribution associated with karst nearsurface features is currently import in effectively producing the remaining oil in Renqui field (giant oil field in China), which is now largely depleted. These karst-derived fractures control the remaining pathways for pressure communication in the reservoir of Renqui field.

9. Conclusions

1. It is obvious seen that karst development in quarry-1 is controlled by bedding parallel stylolites. In contrast, quarry-2 karst was developed along inclined bed intersections with conjugate fracture sets. The proximity of fractures to thrust fault has enhanced cavern development in quarry-2.

2. There are two main stages in the diagenetic history of the studied carbonates related to vug development; 1) episodes influenced by hydrothermal fluids in the mesogenetic realm and 2) meteoric dissolution episodes in the telogenetic realm in response to nearby subaerial exposure. However, most mesogenetic vugs are filled by hydrothermal calcite cements and only minor showing isolated micro vuggy porosity remains from episodes of vug creation in the mesogenetic realm.

3. Isotope study defines a burial trend and a mixing trend. The burial trend shows increasingly negative oxygen isotope values. It is sampled by a number of features that include early vein fracture cements, early hydrothermal flushing events and some stylolites developed in early the burial stage. This is followed by hotter (more negative) ongoing vein fracture fill, stylolites and later hydrothermal fluid alteration overprints and is indicated by more negative oxygen isotope value. The mixing trend shows a broad range of negative carbon isotope values that become less negative in the karstified breccia collapse intervals. This indicates mixing of purely meteoric waters with waters influences by dissolution of nearby Permian limestone clasts that define in the collapse breccia zones

4. Buried hill reservoirs in Thailand fields (Nang Nuan and Phu Horm) are karstified carbonate rocks, which have been hydrothermally leached to create vuggy and cavernous porosity perhaps under deep burial condition, but the nature of their geological columns with fluvial sediment atop the unconformity shows they must also have experienced an episode of meteoric diagenesis. Furthermore, good permeability in both reservoirs is associated with fracture distribution near faults. Karstification under an unconformity surface due to sub aerial exposure improve reservoir quality when it connected the fractures (in both fields). This can be linked to both studied outcrops it showed that porosity linking of meteoric karstified cavities occurred. Identifying carbonate soil and speleothem remnants is the key to defining karstified reservoir zones.

Recommendations

According to results of isotope studies of the studied outcrops, separate subsurface burial trends and meteoric karstified trends were established. This may be an isotope tool that can be applied to cuttings collected across likely karst zone intersections in the subsurface (in order toseparate systems created by burial versus meteoric processes.

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