Textural and Isotopic Characteristics of Tectonic Hydrothermal Breccias in Fractured Carbonates in Northeast Thailand, a Contrast with the Features of Meteoric Karst Breccias

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Abstract

Fractured and cemented Permian carbonates in a quarry in Chumpae region, Khon Kaen district, Northeast Thailand, reveal two fault-related hydrothermal breccia zones with distinctive features that can be used to differentiate fault-related hydrothermal breccias from meteoric karst breccias. Mesoscopically (core-observation relevant scale), hydrothermal breccias possess a set of distinctive features that include: calcite-encased sharp angular edge boundaries, rotated fitted clasts, offsetting calcite-filled fractures and calcites following (folded) bedding planes, with distinct low spectral gamma values; whereas, meteoric karst breccias edges tend to show rounded solution-enlarged boundaries, calcitic speleothems or soils passively penetrating the host rock along planes of pre-existing weakness (solution-enlarged joints and fractures or sub-cropping fault intersections with the land surface). Isotopic data, from the matrix and calcite vein cements in the hydrothermal breccias, exhibit two main burial diagenetic trends, namely; 1) A regional burial trend that is the same as the regional isotopic burial trend seen in Ratburi limestone across central and northern Thailand with increasingly negative values of oxygen and mostly positive, but decreasing values of carbon with time; and 2) Another trend or plot field shows aligned values of both oxygen and carbon that are all negative, defining a burial-related mixing of the rock matrix with a cementing fluid derived from an organic-influenced fluid source. This fluid is considered as related to pressurised fluid crossflows and entry into hydrofractured rock. This distinctive fluid/faulting event is diagenetically later than diagenetic fluids of Indosinian burial; it may relate to the stresses driving the rotation of the Khorat Plateau during the Himalayan Orogeny.

Keywords: Tectonic hydrothermal breccias, Meteoric karst breccias.

1. Introduction

In northeast Thailand, fractured carbonate reservoirs are of increasing interest to the oil industry. However, there are still many uncertainties and controversies in terms of defining the origin of these reservoirs, especially; is it a deep burial or meteoric karst? Nang Nuan field is an example of this problem (Heward et al., 2000). This thesis therefore was undertaken in order to: 1) Define the characteristics of cavern-fill breccias formed in zones of tectonic deformation in Permian carbonate in NE Thailand; 2) Use these characteristics to define the features that allow us to differentiate tectonic hydrothermal fracture systems from meteoric karst breccias (often joint controlled); and 3) Better understand breccia geometries and trends in terms of structural context and isotopic signal.

2. Data and Methods

A quarry map was constructed showing bedding, breccia occurrences, fracture orientations, fault and fold orientations; positions of samples and spectral gamma ray traverses (Figure 1).

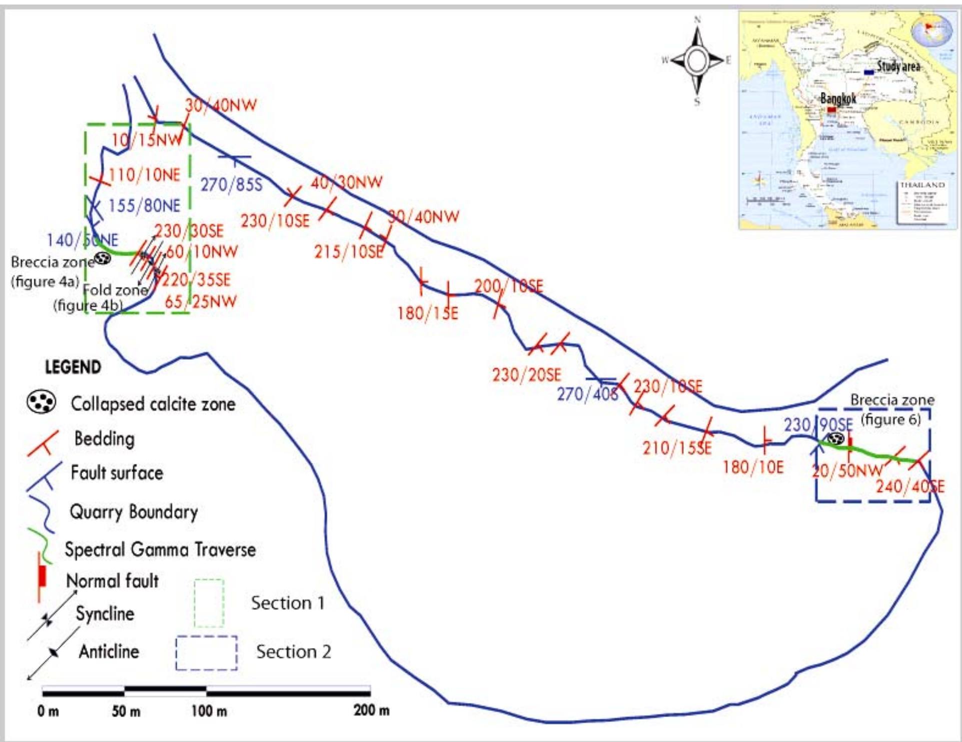

Figure 1. The structural framework map of the quarry. Positions of the samples taken are illustrated in the Figures 2a, 2b (section 1) and Figure 3 (section 2).

3. Results

3.1. Mesoscopic observations

3.1.1. Section 1

This section is characterized by a triangluar breccia zone, some 16m long and 9m high (Figure 2a). The dominant rock type is grey to dark grey in color and fine to very fine grain (crystal) size, around 0.1 to 0.5cm. Macroscopically, the rock is rich in matrix and classified as a matrix-supported wackestone.

At the mesoscopic scale, calcite veins disturb the bedding by invading along sub-horizontal bedding plans or as crosscutting, near orthogonal features that cross cut bedding to create sharp-angular edge features. In the folded part of section 1, the calcite vein is injected along folded bedding planes (Figure 2b).

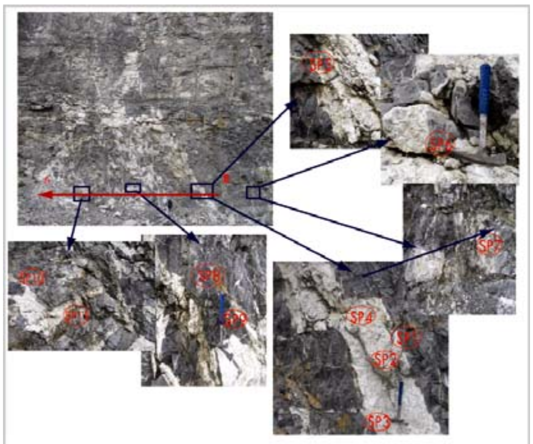

Figure 2a. An overview of section 1and sample positions as well. These samples are almost all in the hydrothermal breccia zone. The red line AB is the position of the gamma ray traverse (see more the figure 1).

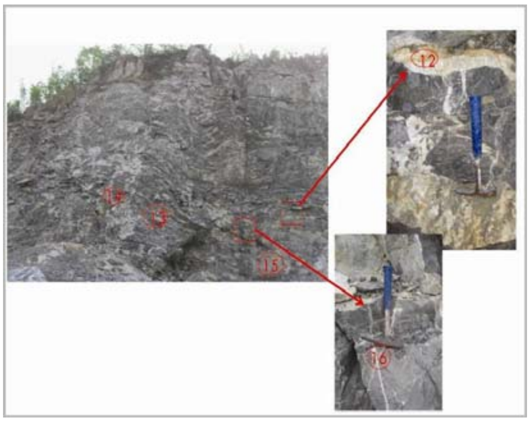

Figure 2b. Sample positions as in section 1. They are outside the breccia zone, near the adjacent fold zone. (See more the figure 1).

3.1.2. Section 2

Section 2 is the other breccia body exposed in the quarry, it is around 18m long and 4m high (Figures 1, 3). There are two main lithofacies hosting the breccia body 1) Matrix-supported wackstone that is grey to dark and fine to very fine grain (crystal) size, near identical to the lithology hosting the breccia in section 1. But in section 2 the matrix supported wackestone is interlayered with 2) Light grey coarsely-crystalline (0.3 to 1cm) grain-supported crinoidal rudstone.

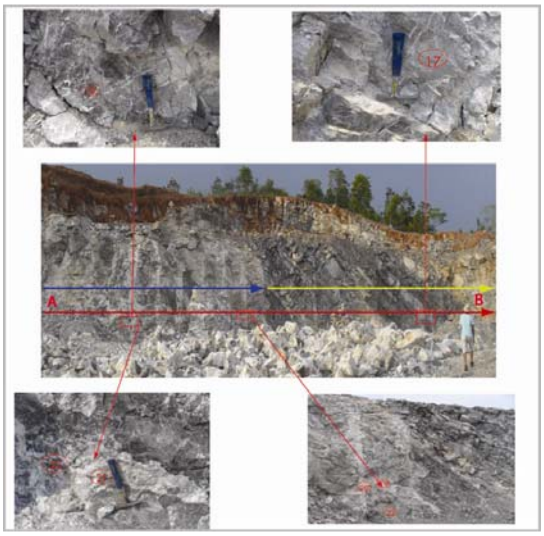

Figure 3. An overview of section 2 and sample positions as well. The red line AB is gamma ray traverse with two parts: calcite rich breccia zone (blue line) and different facies (yellow line) (see more figure 1 for the location).

As at the section 1 site, breccias in section 2 are associated with a combination of bed-parallel and crosscutting veins, creating sharp angular edge features. A modern karst surface, with its own soil-hosted breccias and speleothem features, overlies the hydrothermal breccia body in section 2.

3.2. Spectral gamma ray

In section 1 the spectral gamma ray transect was run to document variation of the gamma values as the transect passes through the breccia zone. The main breccia body shows a layered GR signal, created by matrix and calcite mixing: gamma values tend to be very low in calcite veins and masses (red arrows), and higher in the wackstone blocks in the breccia and across the adjacent strata (blue arrows) (Figure 4).

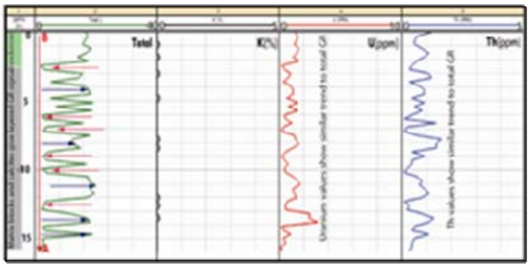

Figure 4. The variation of spectral gamma ray through breccia zone with very low values in calcite-filled fractures.

In section 2, GR signal in main breccia zone encompasses two lithotypes: the first is a calcite-rich breccia zone with very low GR; the other is made up of matrix intermixing with calcite to give a layered GR signal. Another interval in the section 2 transect shows runs across bedded lithofacies, with gamma values: higher in the wackstone facies and lower in the crinoidal rudstones (red box on Figure 5).

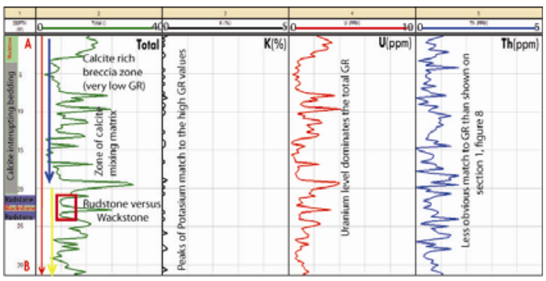

Figure 5. Gamma ray signal in section 2 for both breccia zone and different facies interval.

3.3. Fracturing

In section 1, the major orientations of the calcite-filled fractures are; 1) N110-120E as strike with dips $40-50^{0}$ to the NE and, 2) N250-265E as strike with dips $55-65^{0}$ to the SE. The maximum horizontal stress (S_{hmax}) directions are mainly NE-SW. This set of fracture orientation in section 1 are consistent with stress fields created by the collision between India and Eurasia and are interpreted as a consequence of NE-SW compression (Chuviroj, 1997).

Whereas, in section 2, the major orientations of the fractures are; 1) N230-260E as strike with dips of $50-60^{0}$ to the SE and, 2) N330-345E as strike with dips of $60-70^{0}$ to the SW. The S_{hmax} here is considered as NW-SE.

3.4. XRD and Petrography

The XRD results show that calcite is the dominant mineral in both vein and matrix for both wackstone and crinoidal rudstone.

Thin sections data also help to better define the nature of rock facies and textures seen at the mesoscopic scale in the quarries and to establish the nature and timing of the calcite vein fill. The study of the thin sections sets up an interpretation framework for texture-specific isotope determinations (Figure 6 and 7).

3.5. Stable isotope determinations and fluid evolution.

3.5.1. Following the shallow burial regional trend line of Ratburi limestone.

Matrix samples, indicated by red and pink squares for wackstone and rudstone, respectively, in sections 1 and 2 were mostly from blocks in the breccia zone and show that carbon isotopic values are mostly positive (0.1 to 1.6 PDB) across a range of increasingly negative oxygen values (from -7.9 to -12.1 PDB) (Figure 8). These points are bounded by the blue outline, which matches well with the burial related isotopic values in the Ratburi limestone, shown as green triangles, determined by Bair (1993) and refined by Ampaiwan (2011) and Thanudamrong (2011) (Figures 8 and 9).

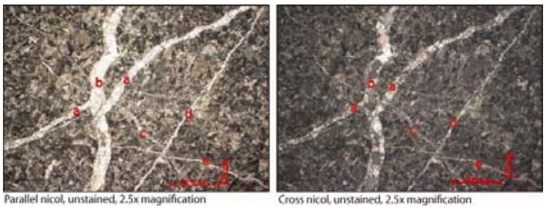

Figure 6. SP6: showing high density of fine calcite veins cutting the matrix.

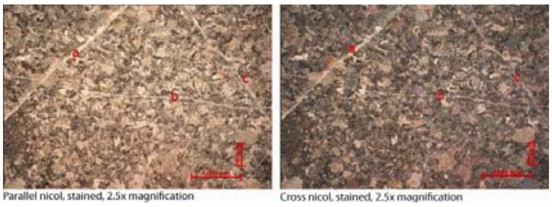

Figure 7. SP10 showing the less calcite cutting the matrix, creating a relative smaller mixing of isotope values of calcite and matrix.

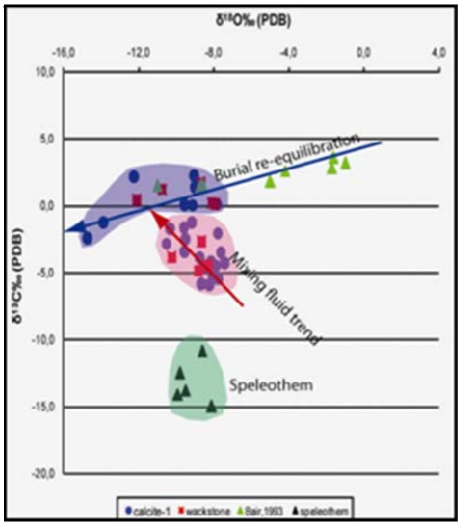

Figure 8. Cross-plot shows isotopic values of calcite and matrix in section 1.

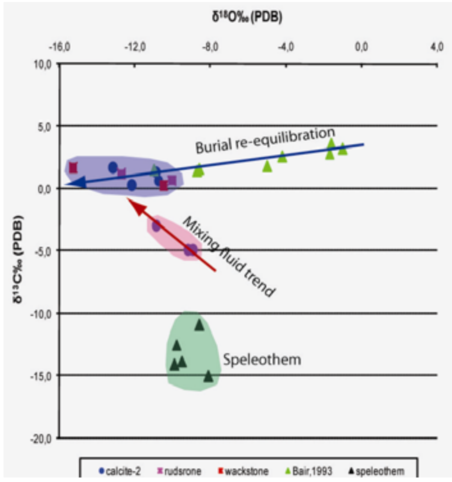

Figure 9. Cross-plot shows isotopic values of calcite and matrix in section 2.

The increasingly negative linear trend values of oxygen is interpreted as indicating recrystallization and re-equilibration of matrix calcite under increasing temperatures and are most likely indicative of increasing burial depth. Although the matrix values in the quarry show a similar trend to the regional trend of Permian Ratburi limestone (dark blue line), the blue outline of the quarry matrix values lie at the higher temperature portion of the trend line which once started in carbonates formed in Permian marine seawater. The lack of any lower temperature values in the quarry samples implies pervasive ongoing recrystallization and fractionation of the rock matrix, which ultimately resulted in complete loss of matrix permeability.

This trend of increasingly negative oxygen values is not related to the effects of metoric water. The plot field of modern speleothem calcites in central Thailand, collected by Ampaiwan (2011) and Thanudamrong (2011) is indicated by the black triangles in Figures 8 and 9.

3.5.2. Re-crystallization of matrix-calcite versus vein calcite in later diagenesis

The negative values of $\delta^{13}C$ that typify the pink plot field suggest a trend line can be overlain on these values, especially in section 1, where the sampling density was much higher.

The isotope value field outlined in the pink is characterized by more negative carbon and less negative set of oxygen's compared to the burial trend (outlined in blue). This negative carbon indicates an organic-rich carbon source (Fischer, 2006). The significance of this carbon source can be interpreted in two ways as follows:

Firstly, the depleted values of carbon indicate a high level of catagenic CO_2 in the fluids sourcing the calcite in veins. That is the CO_2 phases were generated during the burial evolution of organic matter in a source kitchen; this CO_2 would then be from an enriched carbon source from organic matter degradation at depth. Through time, the increasingly depleted values of oxygen (trend shown by red arrow) indicate that during ongoing burial, the temperatures increased. As a result, after an initial burst the supply of catagenic CO_2 decreases and it mixes with re-equilibrated fluids that contain increasing amounts of carbonate from the host rock, so creating more and more positive values in the carbon signatures in calcites in the breccias.

Alternatively, the carbon value trend line could be interpreted with a time arrow pointing in the opposite direction. In this case the carbon values become increasingly negative with time, while the oxygen values become more positive. This scenario indicates cooler burial temperatures in the oxygen, as the carbon becomes more negative. Such a scenario may be a response to uplift as the fluid in the fractures in the deep phreatic realm increasingly under the influence of cooler water with its higher oxygen values.

The conclusions as the two fluid sources will be more obvious if we have a similar set of isotopic determinations in a number of other quarries in the region and also in calcite veins in cores from fractured Permian carbonates in the subsurface. This could then be used to establish more regional flow trends and so perhaps decide on which scenario is more likely.

4. Discussions

4.1. Local and regional.

Based on the isotope analysis above, we can identify two main trends in isotopic values in Permian limestone in the Chum Phae region.

The first one is similar to the regional burial trend of Permian carbonates, determined by Baird, 1993.

Another trend is totally different from the normal trend. The limestone in the studied quarry lies within a regional strike slip (sinistral?) fault. It is not a thrust fault related to the Indosinian deformtion (Utomo and Susanto, 2010). In addition, calcite veins in the quarry, related to this regional strike-slip fault, show a different origin and source for the calcite filling. There may be two main sources of vein calcites; the first one is related to enriched carbon source from organic matter degradation and the other one could be related to deeply circulating meteoric waters. Therefore, fluid flow system capture in the isotopic signatures of the veins in the limestone may be related to the Cenozoic Himalayan orogeny.

4.2. Features of tectonic hydrothermal breccias

At the mesoscopic scale, there are some recognizable features in studied breccia zones, including; sharp boundaries, angular edges and rotated clasts (matrix) (b on Figure 10), with strong structural control as the breccias largely confined to fault zones and parasitic fold cores in the immediate vicinity. It implies that the formation of the breccia was most affected by structural and tectonic factors, instead of dissolution at the water table; many rocks hosting the breccias have been cracked by extensional regimes. At the time the calcite-precipitating fluids entered the rock, some were sufficiently pressurized to open along bedding-parallel fractures that maintain their bed parallel nature even in folds (as in Figures 10, 11), or calcite can fully fill the space created by the extensional regimes, so creating offset calcite filled fractures ("jig-saw calcite" is indicated by red arrows in Figure 10; black arrows in Figure 11).

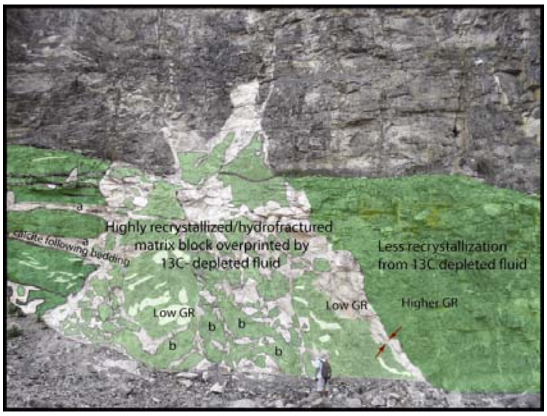

Figure 10. Outcrop with features of tectonic hydrothermal breccias such as sharp boundary clasts (b), offsetting fracture (red arrow), and calcite following (folded) bedding (a).

In terms of spectral gamma ray (SGR) signatures, the SGR values are very low through the calcite-rich breccia bodies; whereas adjacent matrix typically has higher API values. But to reliably identify a breccia zone in the well, rather than misinterpret it as a cleaner carbonate interval, would need an image log, such as FMI.

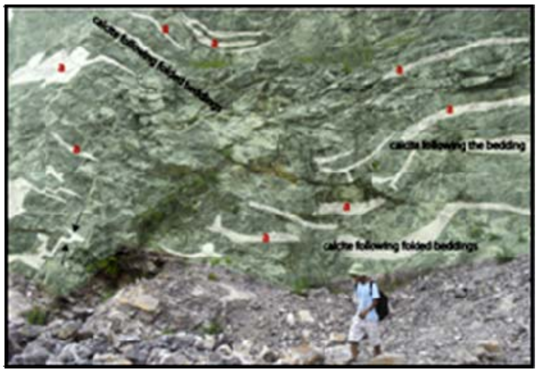

Figure 11. Hydrothermal breccias with calcite following folded bedding (a), section 1, indicating a distinctive late diagenetic syndeformation distribution.

At the microscopic scale, isotope data from the studied hydrothermal breccias indicate two main trend lines: the first follows the regional burial trend and the other one is totally different implying the influence of a second chemical distinct fluid. Whether or not such distinct fluid signatures are present varies according to the rock's burial evolution.

4.3. Hydrothermal breccias versus meteoric breccias

Mesoscopically, the two types of breccias can be differentiated, even in the subsurface, thanks to their special features (Table 1). For instance, hydrothermal breccias have sharp angular edges (b) or offsetting calcite-filled fractures, (red arrows) implying the effects of fracturing in response to tectonic and structural factors (Figure 10, and Figure 12 (blue line interval)). Another point is that the calcite veins in hydrothermal fractures following the bedding planes across sharp speleothem-free contacts (a, Figures 10, 11).

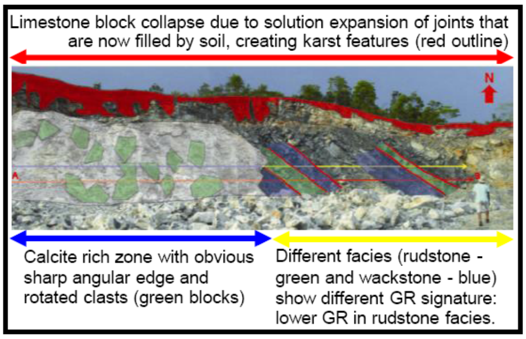

Figure 12. Section 2 is defined as a calcite-rich breccia zone with sharp boundary and rotated clasts. Another feature is karst and speleothem signatures. GR for different facies is also done in this section.

Whereas, in meteoric karst breccias, there is little or no coarse calcite mosaic spar growing from both sides of a vein-filing fracture, no kink bands in thin section, rather there are: crosscutting dissolution and curved dissolution embayment surfaces, along with gravitationally-driven speleothem features such as stalactites, stalagmites and flowstones.

Meteoric karst breccia features such as rounded clasts and speleothems precipitating from water crossflows and curved dissolution edges to caverns are visible in the modern karst carapace that forms the uppermost layer in the quarry (Figure 13). There the calcite penetrated the host rock, creating speleothem features (purple color). It also has a distinct isotopic signature. Other meteoric-defined karst features obvious in the upper part of the quarry wall, include; limestone block collapse and solution expansion of joints (black lines) that are now filled by soil (light red outline) creating karst features, as seen in the Figure 14.

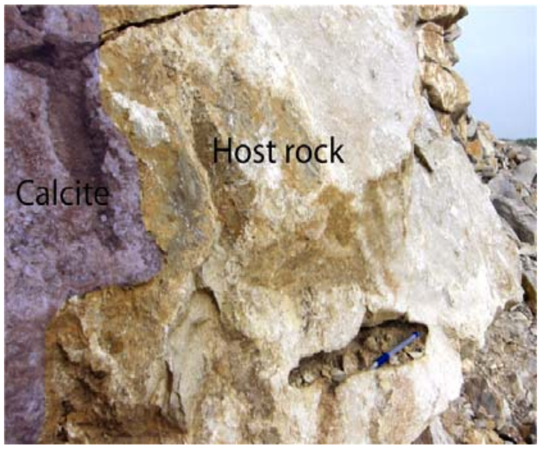

Figure 13. Calcite speleothem mantle solution enlarged fractures and joints. (Photo is taken from Thanudamrong, 2011, Saraburi limestone).

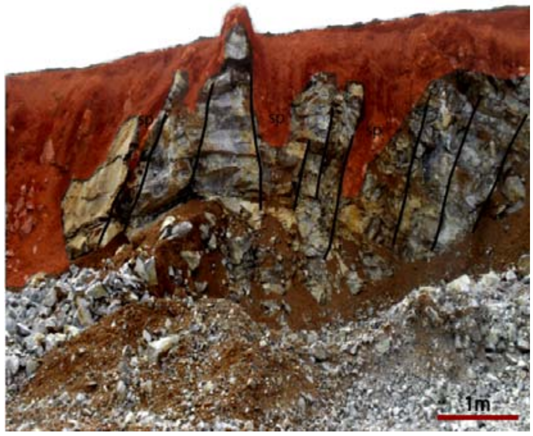

Figure 14. Karst features, in section 2, with soil filling the limestone (green outline) due to joints affected (black lines).

4.4. Implication in terms of reservoir quality in breccia zones (for fractured reservoirs in Thailand)

In northeast Thailand, gas-bearing fractured carbonate reservoirs are considered viable drilling targets. However, there are still problems and controversies related to type and origin of fluids driving the fracture system: meteoric or burial origin. This problem has been raised in the article by Heward, 2000, discussing the origin of karst reservoirs in Nang Nuan oil field.

Although they noted the possibility of a deep burial origin of these reservoirs, they did not come to a conclusion, noting that neither interpretation could be rejected based on current evidence. They did not run stable isotopes on core samples, yet published core photos in their paper suggest sequential isotope analysis could be undertaken on veins present in core. Nor was a detailed isotope burial trend well understood (only the very general curve from southern Thailand of Bair (1993) existed at the time of their study).

The present study defines a separate fluid signature plot field in calcites influenced by the Himalayan orogeny. We know from the work presented in this report that isotopic signatures can be used to help solve the problem of calcite timing associated with multiple fluid events. This type of analysis should be run on calcite-veined cores from Nang Nuan field.

5. Conclusion

Hydrothermal breccias have distinctive characteristics at the mesoscopic and microscopic scales (thin section, isotopic analysis and spectral gamma ray measurement). Mesoscopically, hydrothermal breccias can be recognized based on features such as; sharp angular edge boundary, rotated fitted clast and offsetting calcite-filled fractures. Calcites veins can follow, instead of penetrating, the bedding plane, do not showing the signal of dissolution features such as speleothem coats on dissolution surfaces. Isotopic data from the study area show two main trend lines: one follows the regional shallow burial trend of Ratburi limestone; whereas the other trend implies a fluid with oxygen and carbon plot fields different from the burial trend fluids and indicative of an organic-influenced fluid source.

Breccia zones can be identified based on spectral gamma ray measurements, as they show very low values of SGR, but differentiating a calcite-dominated breccia zone from a cleaner limestone in a wireline data suite requires the collection of an image log.

Hydrothermal and meteoric karst breccias have distinctive characteristics at both the mesoscopic and microscopic scales of observations (Table 1).

In terms of structure and tectonic context, based on outcrop observation, fracture measurements and detailed isotopic analysis of calcite vein fills, the Permian Saraburi limestone in the quarry were affected by two different tectonic regimes; a younger, possibly Cenozoic, strike-slip system with uplift related to extensional (transpressional) movements controlling breccia distribution and an older Indosinian thrust-fault system driving regional and earlier deep burial of the Saraburi limestone.

Table 1. Comparisons between hydrothermal and meteoric karst breccias)

ISSUES	TYPES OF BRECCIAS	
	Meteoric karst breccias (based on study conclusions and references	**Tectonic hydrothermal breccias (based on study conclusions)**
Mechanism	Typically a combination of features related to gravitational collapse (Eliassen, 2005) and to dissolution effects: - Suffusion: downward migration of cover deposits through dissolutional conduits accompanied with ductile settling - Sagging: ductile flexure caused by differential corrosional lowering of interstratal karstification of the soluble bedrock (Gutierrez, 2007)	Structural and tectonic effects: strike slip movement or extensional regimes cracking the host rock and then calcite filled.
Mesoscopic	- Rounded and sorted boundary clasts, speleothem features, soil and calcite penetrating host rock. - Some solution-enlarged fractures are filled with internal sediments, indicating fractures formed in near-surface environments in which physical compaction were not great (Fu, 2006) - Surficial karst breccias typically have a micritic or argillaceous matrix (Katz, 2006)	- Sharp boundary edge clasts, offsetting calcite-filled fractures (jig-saw calcite), implying cracked host rock and calcites filling later. Such features are readily developed on all sides of the breccia body. - Calcites following the (folded) bedding planes, implying no dissolution, no water-table related penetration of calcite into host rock.
Isotopic signatures	High depleted values of carbon and oxygen, especially with speleothem samples, indicating soil waters in meteoric calcite and characeristic fluid origin	Medium negative values of carbon and calcite, totally different regional trend line, implying a differential origin of fluid and calcite, hydrothermal calcite.
Reservoir quality	Creation of near surface open porosity, good permeability and thus can be come good reservoirs	Almost calcite-filled fractures, very low or no porosity and permeability, typically useful in terms of studying original fracture systems and "future" exploration strategies for zones where similar open fractures still exist in the subsurface.
Thin section	- The leaching of grains and morphology of cement crystals grains, implying the precipitation in the meteoric phreatic zone rather than during burial (Fu, 2006) - Iron-stained pisolite with geopetals filled by sparry meteoric cements. Speleothem deposit (Katz, 2006)	- Coarse aligned calcite growing symmetrically from vein wall - Crossing micro vein network in matrix - Offset micro veins by late veining - No signatures of meteoric cement or speleothem deposits
There are some similar meso-scale terms applied to both breccias such as mosaic breccias, chaotic breccias with the difference related to interaction between rotated clasts and calcite cement. It should be noted when using these terms; what is the relationship between timing of breakage/fracturing and calcite emplacement?		

6. Acknowledgements

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