CHARACTERIZATION OF POROPERM DEVELOPMENT IN A PALEOZOIC CARBONATE RESERVOIR ANALOG, NORTHERN VIETNAM

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Abstract

In offshore northern Vietnam, a number of vertical wells have been drilled to test "buried-hill" plays in fractured Devonian carbonates, sealed by shale. So far, there has been little success, with either dry holes, or wells showing low subeconomic rates of return when tested. So the question that needs to be answered for this play type is: why did they fail and how can we target more successfully in this play type? A detailed geological characterization of fractured Devonian carbonates was undertaken in a quarry outcrop (20058'40''N latitude and 106041'43''E longitude) in the Thuy Nguyen district of Northern Vietnam. This work integrates the results of detailed mapping and interpretation of lithologies and fracture orientations, along with detailed petrographic and isotopic analyses and leads to the following conclusions. (1) Significant levels of poroperm in fractured Devonian carbonates in the region are mostly confined to NE-SW fracture sets created and enlarged in the telogenetic realm; fracture trend relates to uplift in a stress field created by movement of the Red River Fault. (2) Equivalents to this style of diagenesis likely occur in subsurface as potential fractured Devo-nian reservoirs in the nearby offshore. (3) Successfully exploring and developing such reservoirs will require directional (not vertical) wells and a better rock-based understanding of the controls, orientations, timings of major fracture events (requires outcrop and core-calibrated FMI interpretation). (4) Poroperm predictions in subsurface counterparts require an improved understanding of fluid evolution and the relative timing of the various diagenetic events that can occlude or enhance porosity and permeability in both matrix and fractures (requires detailed petrographic study tied to texture-aware isotope sampling of cuttings or core).

Keywords: Stable isotope, poroperm, enhance, diagenetic processes

1. Introduction

For many years, fractured carbonate reservoirs have been considered a viable reservoir type and explored for as a potential hydrocarbon target in offshore, northern Vietnam. However, the geological characterization of this fractured carbonate reservoir is so far little studied and poorly documented. Until now, many wells testing this play type in Northern Vietnam have been failures or show low rates of return in testing, even though they were drilled in high structures ("buried hills" with inferred storage in fractures and possible leached matrix). So, the question that needs to be answered for this play is: why did they fail and how can we target more successfully in this play type? To answer this, a geologically-viable carbonate reservoir analog needs to be developed, as the first step in better understanding and gaining an insight into the complicated poroperm development typical of fractured carbonate plays. We need to understand the controls and timing of fracture characteristics, fluid evolution and the relative timing of the various diagenetic processes that occlude or enhance porosity and permeability. Developing such a reservoir analog in outcrop, at a play-relevant scale, is the goal of this current study.

2. Methodology

The studied outcrop is in an abandoned quarry ($20^0$58'40''N latitude and $106^0$41'43''E longitude), in Minh Tan commune, Thuy Nguyen district, Hai Phong city (Figure 1). This quarry is located in the western of Bac Bo Gulf and in the Trang Kenh Formation (D_2gv-D_3tk), which also includes the various islands of Ha Long Bay, and consists of limestone containing abundant corals, stromatoporoids and some brachiopods (Thanh, T.D., et al., 2011). The Trang Kenh formation is dark grey Devonian limestone in the coastal zone known as "Duyên Hải". The outcrop in the studied quarryis quite fresh

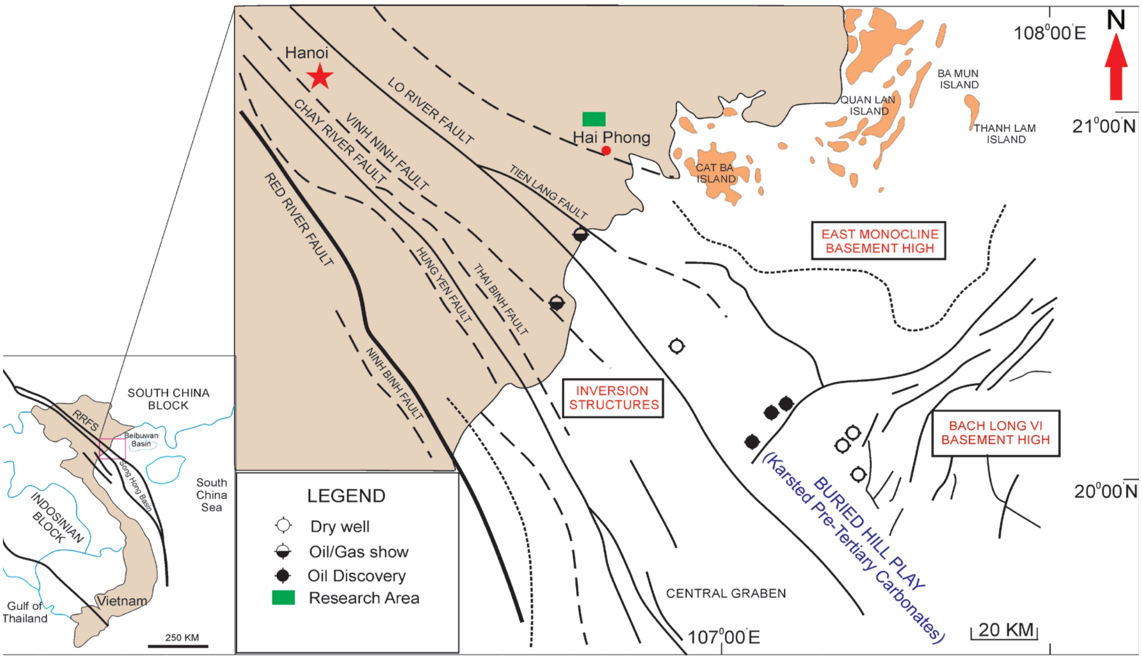

Figure 1. Location map of the research area, also shows the position of onshore and offshore wells drilled to test "buried hill" plays (After Michael B.W. Fyhn, 2007; Nielsen, L.H., 1999; Cuong T.X 2013; Hoang N.V, 2014).

and of sufficient quality for quality thin section, XRD and isotope analysis

Both open fracture and calcite vein orientations exposed in the quarry were measured, along with bedding dip directions and dip angles. Based on detailed study of the various units exposed in the quarry, 19 representative samples were collected (Figure 2B). These samples were slabbed in the lab and photographed. Once textures were identified, a subset of texture-aware samples was selected for isotope, thin-section and XRD analysis.

3. Field component

Observations and measurements made in the field, as well as in the laboratory, are now presented. Interpretation of this material is given in the next part of this report, as are the implications of this work. on the combination of field textures and thin section analysis). Both black limestone and grey limestone are recognized in field and show a strong reaction with 10% HCl. Speleothems, carbonate soils in caves, open vugs and caverns are obvious as crosscutting exposures in the quarry walls (Figure 2B). In the field, early marine cement linings to voids and yellow to buff-brown rock types were mapped, this was latter shown in thin section and XRD results to be dolostones and dolomitic limestones.

A total of 193 fracture sets were measured, including calcite veins (mineralized fractures that are calcite filled) and open fractures. The open fractures cut through bedding are not dependent on the lithology and are typically 0.5-1m or more long. Open fractures in the quarry have more than two trends: a major WNW-ESE trend, and two minor trends NNE-SSE and NE-SW. The calcite orientations can be divided into two trends; with a major trend NNW-SSE, and a minor trend NE-SW. Both open fracture and calcite vein strikes are displayed in the Figure 2D. Bedding thicknesses vary from 30-60cm, with dips from 40^0 -60^0.

3.2. Petrography and XRD

Petrography and XRD were done to better identify the mineral variety and textures mapped in the field. Thirteen samples were selected from slabbed rock samples for thin section analysis and half of each thin section sample was stained with Alizarin red-s and potassium ferricyanide to better that relate

3.1. Field work

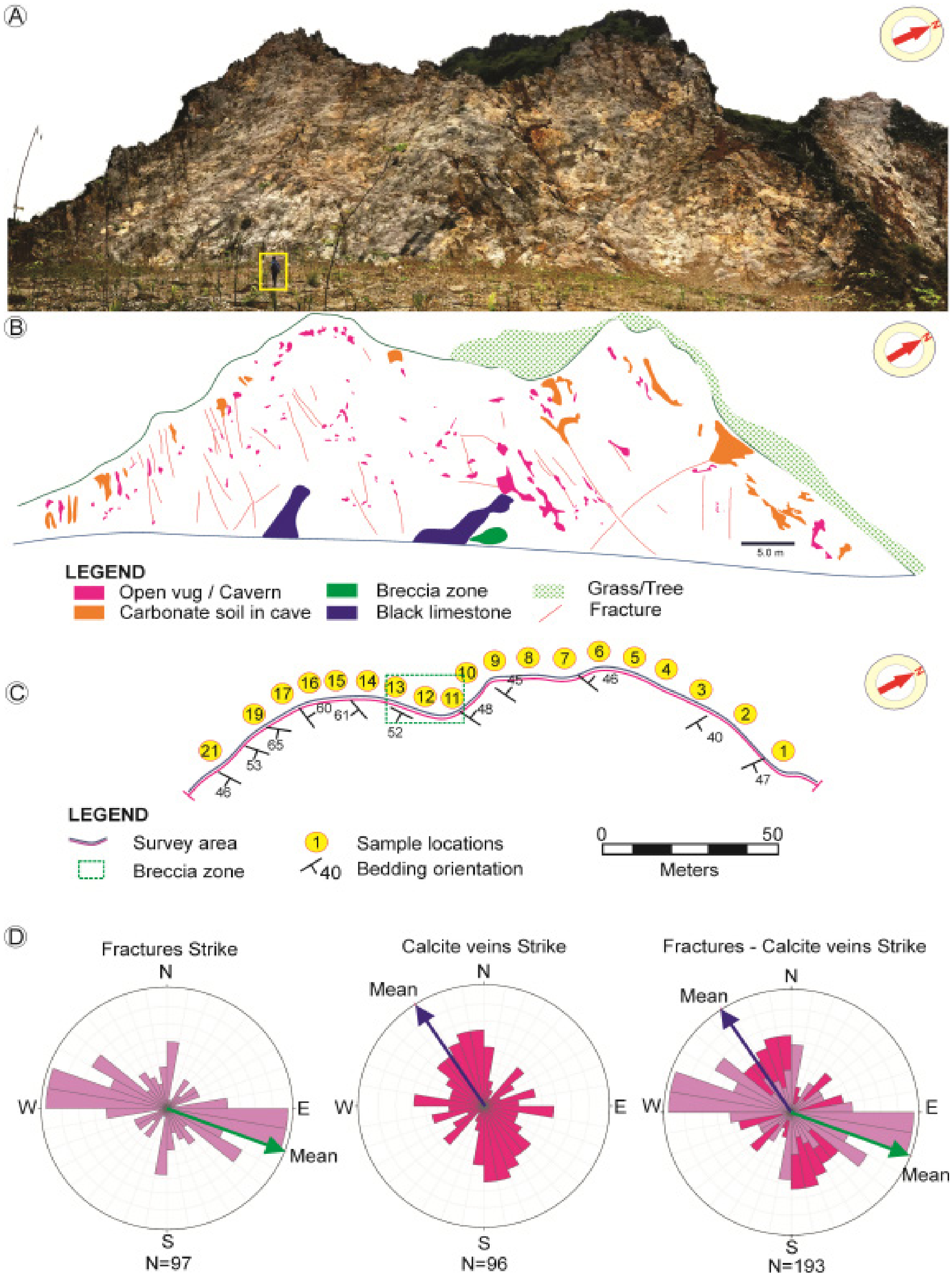

Figure 2. Outcrop overview: A. Quarry face, B. Sketch of features identified in quarry face, C. Plan view of mapped research area, showing dips measured at detailed observation sites, D. Strike of calcite veins and fracture orientations measured in field.

textures to isotope signature determinations. In addition, major mineral components, as inferred in stained sections, were tested by XRD analysis using powder samples. XRD samples were collected with a dental drill from slabbed rock faces in positions that mirrored the position of the thin section collection point on the other face of the slabbed rock sample.

XRD results confirm the staining in the thin sections, namely, the dominant minerals are dolomite or calcite with sub-dominant calcite and sub-dominant dolomite respectively.

Early marine cement textures such as morphology, distribution patterns or crystals sizes are visible both in the field and in thin section.

In the figure 3A (yellow arrow), illustrates typical isopachous rim cements that infilled open pore space and likely relate back to the marine phreatic (eogenetic) environment.

Circum-radial crystals grew into a former void and likely formed in warm shallow marine waters. These aligned calcite crystal rims show sweeping extinction, which defines radiaxial calcite, and prior to replacement by calcite were likely composed of acicular aragonite rinds, which are a typical marine cement in modern and ancient oceans (Moore, 2009). In the middle zones (turquoise arrow, Figure 3B), of now cement-filled pores, blocky calcite with pink to red stained color indicates later and hotter burial cement phases (as proved by their isotope signature – see later). The blue-stained blocky calcite crystals relate to higher iron content and likely formed in the more reducing waters of burial realm (mesogenetic; Ahr, 2008).

Early medium-grained (10-100µm) dolomite occurs as planar-e (euhedral), planar-s (subhedral) or nonplanar forms that lack stain in thin sections. The pervasive occurrence of the dolomite crystals in the dolostones, the sutured contacts between many dolomite crystals, and the complete lack of any remaining polyhedral porosity, indicate over-dolomitization. Final dolomite crystal growth occurred in the relatively warm parts of the mesogenetic realm (Figure 4, Moore, 2009). Early stage, pervasive dolomitization of ancient basinal limestone is typically interpreted to be the result of magnesian-fluid reflux (Land, 1982; Warren, 2000). The nonplanar dolomite crystals suggest higher temperatures and higher super saturation levels.

Black limestone was observed as m-thick bedded units in the field and samples were collected to better define the nature of this darker colored material and its textures. In thin section, the result shows the lithology is unstained (calcite) with local black or darker zones that could be due to deposition in a marine environment that was enriched in algae and organic material (Figure 5). XRD confirms the most abundant mineral is calcite.

Breccia zones with large calcite crystals infilling the interspace between the breccia clasts was sampled and slabbed for thin section, XRD and isotope analysis. Clasts show a variable packstone to grainstone matrix with bryozoans and oolites clearly visible in thin section. Breccia zones can be developed as tectonic features (transect bedding) or as karst collapse features under meteoric mixing conditions (tend to be strata bound but can transect bedding). Either type of breccia can have significant roles in improving fractured dissolution and so become a significant carbonate reservoir. The origin of this breccia may be related to its stable isotope signature (see later). Binding algae, especially Renalcis nubiformis (middle-upper Devonian),

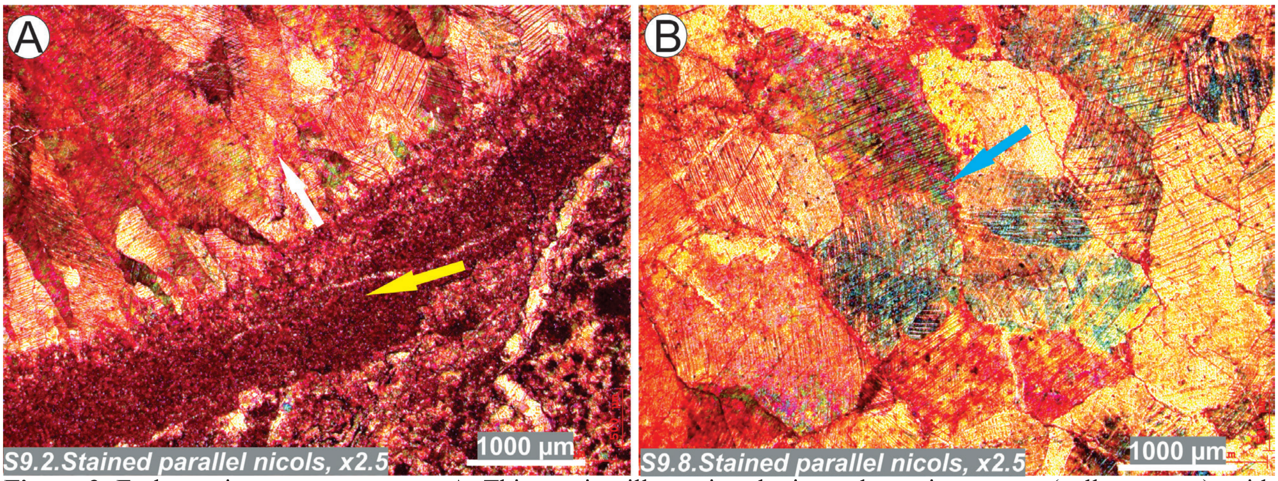

Figure 3. Early marine cement textures, A. Thin section illustrating the isopachous rim cement (yellow arrow), with elongate bladed calcite crystals (white arrow), B. Blocky, variably blue-stained, calcite crystal mosaics filling the interiors of most voids (turquoise arrow).

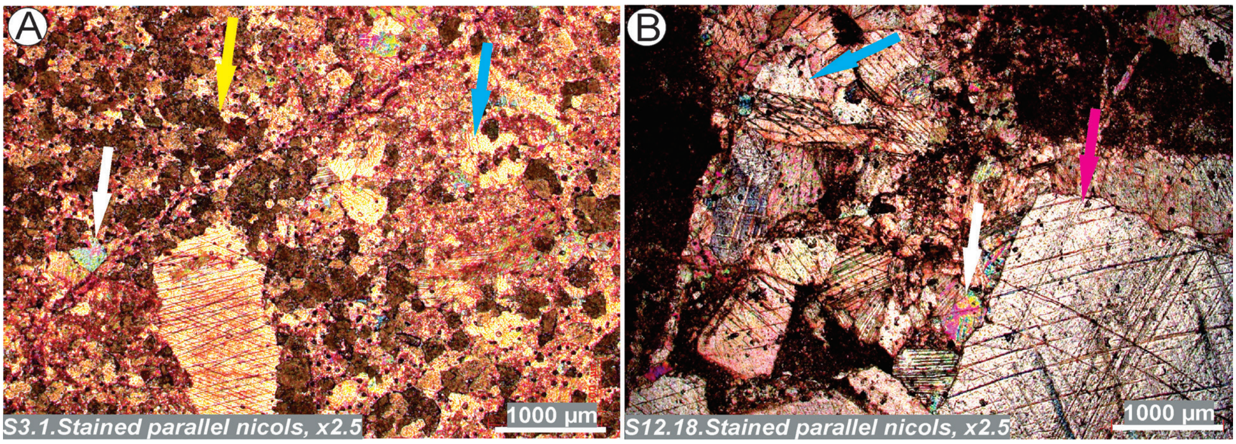

Figure 4. Early to late burial dolomite: A. Planar-e to planar-s (yellow arrow), ferroan calcite (white arrow), B. Later dolomite (turquoise arrow) and saddle dolomite (purple arrow) show an unstained crystal curvature, compared with pink-stain calcite crystals and matrix.

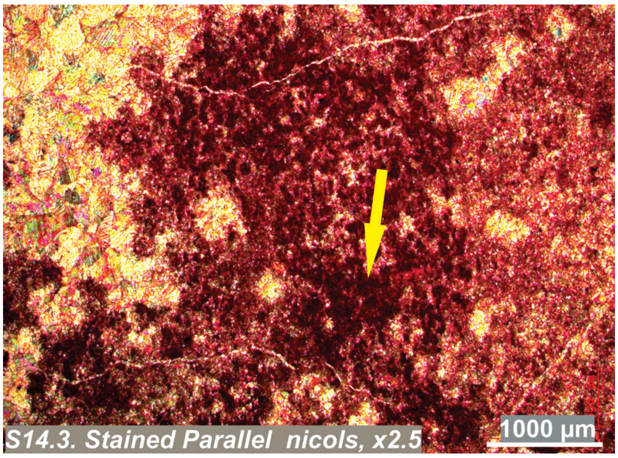

Figure 5. Stained thin section result. Black color likely relates to an enriched algal or organic content (yellow arrow).

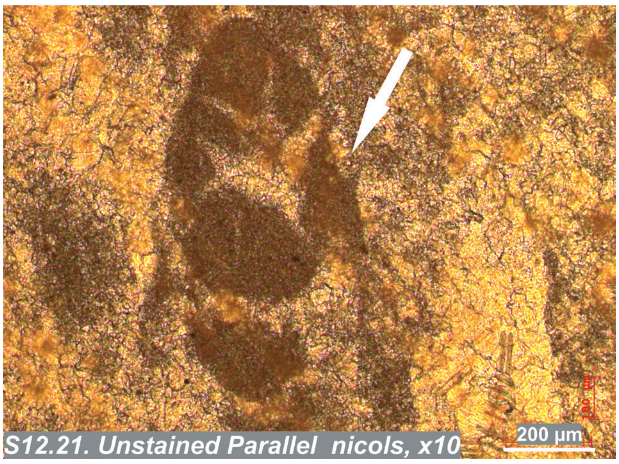

Figure 6. Thin section showing the age-specific algae Renalcis nubiformis - middle-upper Devonian (white arrow) in breccia zone.

are present in some clasts and are illustrated in figure 6. The age-specific nature of this fossil supports the assignment of this quarry outcrop to the Trang Kenh Formation.

Speleothems in crosscutting cavities and fissures are abundant in the quarry face (Figure 2) and indicate dissolution of soluble carbonate rock via meteoric water percolating from overlying soil or bedrock surface. Figure 7 indicates the porous, but typically isolated or focused nature of the vuggy porosity at the slabbed rock sample and thin section scale.

The effects of mechanical and burial compaction are clearly visible in thin section. Figure 8A indicate the stress-induced deformation in calcite veins formed in later stage of mesogenesis. Carbonates in the quarry display a wide variety of pressure solution phenomenon, which indicate a combination of burial diagenesis and deformation. Stylolites are the typical evidence of ongoing burial stress induced dissolution of rock matrix material and most tend parallel to bedding in the quarry. Worldwide, stylolites are among the most prominent deformation patterns in carbonate sedimentary rocks. Stylolites document localized pressure solution, which ultimately leads to porosity shutdown in most ancient carbonates residing in the mesogenetic realm (Moore, 2009). In the studied samples, diagenetic cementation by calcium carbonate was accompanied by widespread aggradingrecrystallization and leaching of calcium carbonate

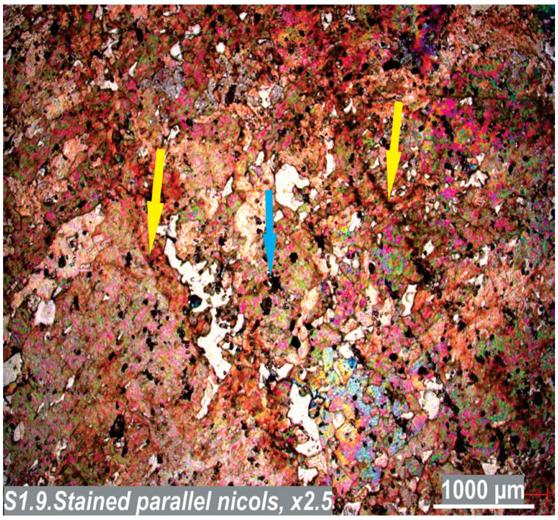

Figure 7. Thin section indicates the enclosed laminated layers (yellow arrows) showing a typical poikilotopic set of aligned calcite crystals that compose many of the speleothem textures. Also shows zones of crosscutting vuggy or dissolution porosity (turquoise arrow).

(Figure 8 B; Ebner et al., 2010). In figure 9B, later stylolites occur as a serrated surfaces that cut across but are mostly parallel to the calcite vein edge. Vugs and fractures tend to be more obvious in the dolostone units (Figure 8C, 8D) and document the dissolution and compaction processes, which can have significant roles in improving fractured reservoir quality.

All textures and mineral phases in the research area were recognized based on the combination field observation, thin section and XRD results. These textures, as documented in this study, are related to varying intensities of the overprints of eogenesis, mesogenesis and telogenesis. These features are always present in textures preserved in uplifted sets of ancient carbonate (Moore, 2009). But how do these documented textures correlate to the measured isotope signatures (fluid and temperature indicators)? Isotopic values, in conjunction with a knowledge of the textures sampled, can better define inter-relationships between fluid evolution, burial diagenesis and tectonic development.

3.3. Isotopes

Eight major categories were defined based on the textures and lithologies seen in a combination of outcrop, thin section and XRD as described in the previous section, namely: 1) early marine cement, 2) dolomite, 3) partly dolomite, 4) grey limestone, 5) black limestone, 6) calcite vein, 7) calcite in breccia zone and 8) speleothem. Fifty isotope samples were collected from slabbed rock sample faces contain these eight categories in order to capture the fluid history of the various textures and lithologies. The resulting bivariate isotope plot listing the relevant $\delta^{18}O$ and $\delta^{13}C$ values is presented as figure 9.

Group 1 retains on the basic trend of somewhat decreasing (but positive) $\delta^{13}C$ values from 3-0‰ (only one carbon value in this trend is negative, i.e., less than 0‰), combined with increasingly negative oxygen values ranging from -4 to -10‰. This covariant C-O trend is widely accepted as indicating ongoing burial re-equilibration and recrystallization tied to increasing temperature and burial depths (Moore, 2009; Warren et al., 2014). The following components make up the Group 1 trend:

Early marine cement: negative oxygen values vary from -3.86 to -8.54‰, with increasingly negative oxygen values from samples collected in the isopachous rim cement (Figure 3A). It indicates that not only did bladed aligned calcite crystals replace the original marine aragonite splays, but that the rock-fluid re-equilibration of the replacement calcite was ongoing in the mesogenetic realm, under increasingly hotter conditions. In contrast, this ongoing dissolution-replacement of the calcite did not greatly fractionate the carbon values, although they do tend to become slightly more negative ranging downtrend from +1.82 to –0.29‰.

These carbon values, imply carbon values in the various mesogenetic calcite precipitates are more closely aligned their original genetic environment ($\delta^{13}C$ of sea water is near 0‰) compared to the greater thermal fractionation captured by the evolution of the oxygen values in the same calcites (Nelson, 1996).

Dolomite and partly dolomite: were separated based on the XRD and thin section observations with dominant dolomite and sub-dominant dolomite respectively. The oxygen isotope signatures largely overlap the early marine cement plot field, but with lighter (more positive) δ13C values from +0.92 to +2.73‰. Dolomite can be formed early, even in the same eogenetic setting as the early marine cements as a metastable Ca-rich precursor hase, often associated with CO^2-rich waters. Early dolomite is metastable an often evolves and expands in extent when flushed by later eogenetic and mesogenetic waters (Warren, 2000). The diagenetic evolution of dolomite, even to the extent that many intervals are now over dolomitised and extensively recrystallized into nonplanar forms, is seen in the thin section results. In terms of the isotope signature, later burial stage dolomite tends to have more negative $\delta^{18}O$ oxygen isotope values, indicating the precipitation from fluids at somewhat higher temperature than those of the initial platform dolomites (Mishari Al-Awadi, 2009). Late-stage dolomitisation typically is not extensive unless overprinted on earlier metastable crystals because pore fluids and ions are progressively lost with continued compaction and insufficient new magnesium is available (Land, 1982). This explains why, in this research, separating clearly between the earlier and later dolomite texturesis difficult (other than by the isotope covariant trends).

Black limestone and grey limestone: Both have the same $\delta^{18}O$ oxygen isotope range from -8.3 to -9.4‰, which is the most negative set of oxygen isotope values along the group 1 burial trend. It may that the pure matrix of this group, with the most depleted oxygen content, may have been the last in the group 1 rock types to have lost all its matrix porosity (i.e., fluid crossflows and thermal re-equilibration continued deeper in this set of darker colored lithologies). The black limestone has light, slightly more positive $\delta^{13}C$ values than the grey limestone, from + 1.37 to +1.55‰ compared with +0.81 to -0.54‰. As seen in thin section, the black limestone contains abundant algal or organic material and is unstained by alizarin red-s and potassium ferricyanide. This organic-rich set of lithologies could have continued to release its fluids via organic maturation well after the other lithologies in possibly allowed thermal equilibration of the calcite system into somewhat warmer and deeper diagenetic realms, before the dark-colored limestones also underwent a burial-induced complete-shutdown of the poroperm system.

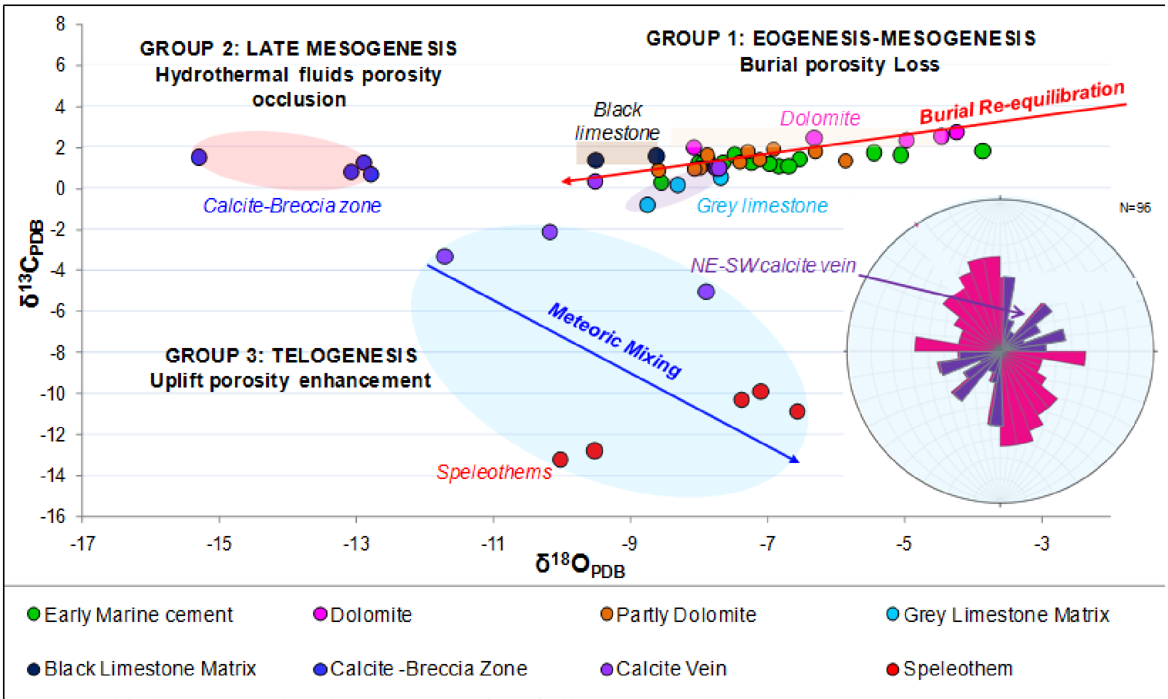

Figure 9. Stable isotope results, shows a cross plot of all sample results.

Group 2 (blue points, Figure 9) the plot field is made up of $\delta^{13}C$ values in the range 0 to +2‰ with strongly depleted $\delta^{13}C$ values from -13 to -16‰. These are the most negative (hottest) oxygen values in all the collected samples. All the Group 2 samples came from calcite-vein filled in inter-spaces between the matrix clasts of the breccia zone. The highly negative oxygen values suggest the possibility of hydrothermal fluids flowing though the breccia zone. The brittle-response tectonics created entry permeability, via brittle fracture to fluids from or in a hot deep part of the mesogenetic realm. This event took place well after matrix poroperm was lost, as evidenced by the complete separation in oxygen value clusters between Groups 1 and 2.

Oxygen values in the mesogenetic realm are not related to assign timing, only to relative burial temperature. So these hydrothermal fluids could to major strike-slip fault movements and active hydrothermal circulation tied to the effects of Himalayan Orogeny (Figure 1). Whatever its timing, this hot fluid did not drive significant fractionation in the $\delta^{13}C$ values.

Group 3 (Figure 9) shows moderately to strongly depleted $\delta^{13}C$ values ranging from -2 to -14‰ and a narrower range of $\delta^{18}O$ values from -8 to -10‰. This group includes some c alcite veins and a set of speleothems that are the precipitates of modern meteoric waters.

Speleothems: Five points were drilled from three speleothem samples S1, S10, S13. Speleothems have more negative $\delta^{13}C$ values and less negative $\delta^{18}O$ values compared to the calcite vein samples in this group. CO_2-enriched surface waters and soil gases enriched in biogenic outputs explain the more negative $\delta^{13}C$ values of the speleothems. Speleothem calcites tend to precipitate where percolating meteoric water escape as drips or flows into a cavity and so degasses driving the drop-out of calcite from the solution.

Calcite vein: The calcite vein signatures (three points) in Group 3 plot (Figure 9) between the speleothem value cluster and the typical value dissolution of uplifted Devonian carbonate (with Group 1 values) and a portion of the bicarbonate in the groundwater was recently circulating in the atmosphere (meteoric waters – as exemplified by the speleothem values). All three points in these calcites were taken from minor NE-SW calcite veins, not major NNW-SSE trending vein sets. Meteoric mixing signatures are significant as they establish an identifiable telogenetic plot cluster, which the field work shows is tied to the generation of fissure and open uplift-related secondary porosity in an otherwise tight carbonate host.

4. Discussion

There are three diagenetic process sets and textural associations present in all ancient sedimentary carbonates, namely eogenetic, mesogenetic, telogenetic. Each of the three drives diagenetic processes that can change the intensity of cementation, dolomitization, compaction, replacement, recrystallization and solution. Textures and isotopic signatures of all three process sets are present in the studied outcrop and are documented by the detailed integration of thin section, XRD and isotope analyses that form the quantitative base to this research report (as documented in previous sections).

4.1. Poroperm evolution significantly enhanced in telogenesis.

After initial deposition, diagenetic processes will modify primary porosity and secondary porosity may develop (Moore, 2009). Porosity in the carbonates of study area evolved via dissolution, cementation and dolomitization, first driven by both subaerial and subaqueous processes in eogenetic realm (Figure 4, 5, 6). The isotope signature shows these early marine cements and early dolomites re-equilibrated once they entered the mesogenetic realm (Group 1 -burial trend.Walls and Burrowes (1985) conclude that marine cementation, dominantly indicated by radiaxial calcite, is the single most important diagenetic process affecting porosity levels in Middle and Upper Devonian reefs of western Canada. The prevalence of radiaxial calcite in the current study area implies these Devonian carbonates also experienced significant eogenetic porosity loss.

Typically, entry into the burial realm

drives mechanical and chemical compaction (stylolitization) that further decreases porosity connectivity and ultimate leads to very low permeability in the matrix (Moore, 2009). In general, diagenesis in the mesogenetic zone is marked by slow porosity modification and is dominated by compaction and compaction-related processes. While rates are slow, the time interval over which diagenetic processes are operating can be enormous, and hence porosity modification (generally destruction) may well go to completion (Heydari, 2000; Moore, 2001). Based on thin section analysis done in study area, later dolomite and ferroan calcite (Figure 4) indicate the effects of deeper burial with hotter mesogenetic fluids. The replacement of earlier carbonate by saddle or sutured dolomite and/or calcite recrystallization during deep burial diagenesis further reduces porosity. Zones of such porosity destruction is indicated by a depletion both $\delta^{18}O$ and $\delta^{13}C$ isotope signature values (Figure 9). Ultimately, no eogenetic or early mesogenetic porosity and permeability remains in the deeper parts of the mesogenetic realm as seen in the thin section analysis (Figure 3 – Figure 6).

When the telogenesis occurs, the carbonate reservoir is exhumed to shallower depth and ultimately to exposure under subaerial condition. Telogenesis is tied to crossflows of meteoric vadose and phreatic diagenetic waters. Soil weathering and carbonate mineral stabilization involving dissolution of limestone and sediments and subsequent precipitation of calcite cements in the vadose and shallow phreatic zones will generally result in cements and limestone with moderately negative $\delta^{13}C$ compositions (Allan et al., 1982). The isotope signature of the meteoric mixing trend is present in the study are, and recognized by more negative $\delta^{13}C$ values (more exposure to carbon from soil gas weathering) and less negative $\delta^{18}O$ values (Figure 9; uplift is tied temperature decrease).

Dissolution, in both the vadose and phreatic zones, is the dominant active process in the telogenetic realm (Loucks, 1999). Water moves through the vadose zone in two contrasting

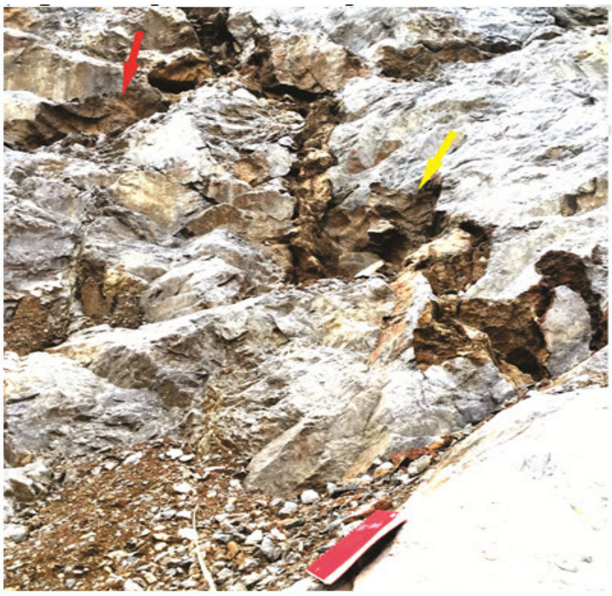

Figure 10. Solution-enlarged fractures (vuggy fracture) (yellow arrow), and channels (red arrow)

trickles through a network of small pores and fractures and (2) vadose flow, where water rapidly moves through the vadose zone via solution channels, sinkholes, joints, and large fractures directly to the water table (Figure 10; Loucks, 1999; Wright, 1991). Speleothems, formed as meteoric waters pass through vadose zone, have a significant influence on secondary porosity.

Speleothems associated with newly developed vuggy and fissure porosity have been observed at both the field and thin section scale (Figure 7). These figure illustrates a variety of pore sizes ranging from tiny vugs to caverns, as well as solution enhanced joints and fissures seen in outcrop. At all scales, telogenesis helps create effective porosity in an otherwise tight carbonate.

Modern karst is seen to be widespread in and near the studied area. Therefore, in buried counterparts telogenetic porosity development will normally be associated with important regional unconformities (palaeokarst horizons) cutting through ancient limestone successions. Such palaeokarst levels can lead to significantly enhanced porosity and the development of major hydrocarbon reservoirs in the carbonate units below the unconformity (Loucks, 1999; Wright, 1991). Many palaeokarst terrains are host to significant hydrocarbon reservoirs across the world, in fields such as the Permian Yates Field, West Texas, USA, the Ordovician Ellenburger Fields of West Texas, USA or the Triassic Rospo Mare Field, Italy. However, soil fills combined with pervasive meteoric and mixing zone calcites can be deposited form the same meteoric waters that initially drive dissolution. If precipitation is ongoing and pervasive, this can significantly occlude most solution porosity residing in meteoric vugs or caverns. Loucks (1999) goes on to suggest that meteoric karst cavernous porosity cannot exist under deep burial conditions (>4000m) because the intrinsic strength of the rock is ultimately exceeded by lithostatic load.

Most fractured carbonate reservoirs in offshore Vietnam have been explored above 4000 mTVDss. High volumes of mud losses have been observed in the carbonate basement section because of karstified caves and highly altered zones (Cuong, 2013). Therefore, paleokarst recognition and evaluation are very important to consider when designing vertical or horizontal wells, both in exploration and in development stages.

The studied carbonate formation has been uplifted and affected by major NW-SE faults of Red River Fault System (RRFS), the tectonically induced uplift has created the extensive cavernous porosity and karst brecciation system that typifies the current land surface. Fractures in carbonate sequence can act as conduits to increase the porosity and permeability. NW-SW open fractures in dolostone have been proven in outcrop and thin section results. Newly induced tectonic fractures can play a major role in fluid flow in deep burial, even if paleokarst horizons are occluded by mesogenetic cements.

Fractured zones, solution-enlarged open fractures and channels are widespread in outcrop (Figure 10). These fractures were enlarged by dissolution (vuggy fracture) and now play a significant role in poroperm enhancement, as well as defining directional conduits. Dissolution and further fracture porosity enhancement can also occur in the subsurface when rocks and water are out of chemical equilibrium (Ahr, 2008).

The meteoric diagenetic environment is one of the most important diagenetic settings relative to the development and evolution of carbonate porosity in Northern Vietnam. It typically drives porosity reduction in eogenesis and mesogenesis (via cementation dolomitization, replacement, recrystallization and compaction) and considerable secondary porosity enhancement in telogenesis (brought by about uplift activity, fracture generation and dissolution).

4.2. Which fracture orientations relate to the meteoric access?

Open fracture orientations in the study area are strongly affected by Red River fault system (Figure 1). Given that the Indo-Eurasian plate collision continues up to the present time, strike-slip dislocations within the RRFS require comprehensive examination. Both major NNW-SSE calcite vein and major WNW-ESE open fractures orientations in study area correspondto strike-slip displacement of RRFS. The minor NE-SW calcite vein and fractures trending could be generated by compression during strike-slip. As discussed above, the meteoric water will enhance the poroperm evolution in carbonate reservoirs. Based on isotope signatures, the samples plotting the meteoric mixing trend are NW-SW trending calcite veins (Figure 9, 11).

This observation is useful evidence for future drilling orientations designed to maximize open fracture intersections, as NE-SW trending fractures are related to the modern meteoric environment. These open fractures are enhanced by dissolution and so may play significant role for hydrocarbon exploration in subsurface equivalents. Most nearby offshore wells testing the “buried hill” carbonate play have been drilled as vertical wells either on the crest of structures, or following zones of the major fault (fracture) damage, but none have focused on fissure trends related to preferential directions of telogenetic enhancement.

This could be a reason for the many unsuccessful or low flow rate wells in offshore carbonate plays Vietnam. These wells were not designed to maximize penetrations of the better

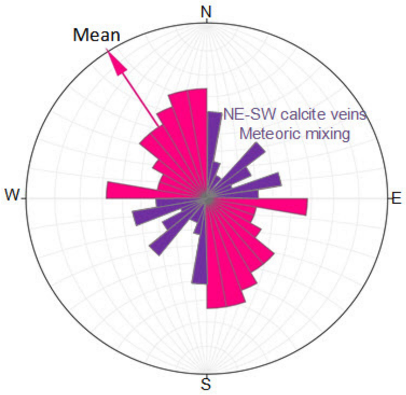

Figure 11. Calcite vein strikes follow the major RRFS trends.

open-fracture orientations. Therefore, a future "buried-hill" well should be designed to test-multiple intersections with NE-SW trending fractures, rather than drilling another test of the so-far unsuccessful assumption that hydrocarbons in buried hills reside in a leached and porous cap structure. The current study shows there is likely little potential for widespread matrix storage in a buried hill play hosted in Devonian carbonates.

Successful exploration for this type of "buried-hill" target requires directional drilling and the ongoing integration of core, log, seismic, borehole image data in order to define and predict the poroperm distribution in such subsurface reservoir. An integrated approach using the seismic attributes to detect the major faults zone, FMI to determine the fracture orientation in the play area, and an isotope analysis of cuttings to evaluate whether a meteoric mixing zone has been intersected, may define future drilling successes, rather than failures, in this as yet under-explored region of northern Vietnam.

5. Conclusion

Field study integrated with petrographic and stable isotope determinations clearly defines fracture and calcite vein sets that correspond to the background structural elements of RRFS and their diagenetic evolution. NE-SW calcite vein signatures are related to meteoric mixing fluids. his oriented subset of telogenetic processes has significantly enhanced poroperm values in open Tfractures in what is an otherwise tight carbonate matrix system.

Across the units exposed in the studied quarry, the diagenetic history of three sets of diagenetic processes (eogenetic, mesogenetic and telogenetic) has driven both poroperm reduction and enhancement. Textures and isotope signatures related to all three sets of processes remain in the outcrop, but only the most recent telogenetic overprint has created affected porosity and permeability. Poroperm has been destroyed by mesogenetic cementation, dolomitization, replacement, recrystallization and compaction. However, porosity and permeability are enhanced in zones of telogenesis. Secondary poroperm features, such as vugs, solution-enlarged fractures (vuggy fractures), channels, and cavernous porosity is generated via major dissolution activity drive by a combination or uplift and meteoric mixing.

In buried counterparts, palaeokarst process are predicted to have made a significant improvement to subsurface reservoir quality but these improved zone are strongly directional and tied to open fracture trends. There is little improvement in reservoir matrix quality away from zones of meteoric fissures and fractures.
This outcrop study is the first step to understand Paleozoic fractured carbonate reservoir plays in subsurface, offshore Vietnam. Combining the cores, logs, seismic attributes, FMI, cutting, thin section will help develop insightful understanding leading to future drilling success.

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