Poroperm Evolution through Different Deformation Stages: Stable Isotopes Define Fluid Evolution in Permian and Older Carbonates in Thailand*

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Abstract

Stable isotopic studies, focused on calcite cement, vein-fill calcite, various bioclasts and early burial diagenetic cement rims and replacements, can be used to define the burial evolution of ancient carbonates in outcrop in central Thailand and the resulting curve applied to better understand the timing and positions of subsurface poro-perm evolution. To establish a burial evolution base-curve for carbon and oxygen isotope covariant isotope curve, texture-aware sampling was undertaken across a mapped suite of variably deformed and thrusted Lower and Middle Permian carbonates of the Saraburi Group, as well as older (mostly Ordovician) carbonates in western Thailand. Samples were collected in a number of quarries in the thrust succession in the Saraburi-Lopburi area, from cuttings in the Phu Horm gas field and within the shear zone of the Three Pagoda Fault Damage Zone of the Western Highlands of Thailand.

Across Thailand, the integration of isotope data with its structural setting establishes a clear separation in burial-fluid events in carbonate matrices, related to two time-separate tectonic episodes in a world-class suture belt. Its stable-isotope fluid chemistry defines platform burial and porosity loss, followed by the Permo-Triassic closure of the Paleotethys with thrust fault veining, and its subsequent reactivation and porosity creation during the Tertiary collision of India and Asia. This combination of outcrop and subsurface derived isotope covariant plots demonstrates the utility of isotope studies in defining the diagenetic and poro-perm history of ancient structurally-overprinted carbonates. Once a base-line burial curve is established, subsequent work can be done solely using drill cuttings. This offers a new paradigm to the oil industry where drill cuttings can be used to define proximity to zones of tectonic deformation, cementation and porosity creation.
Selected Reference

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Fractured Carbonate Basement Studies Group
Petroleum Geoscience, Department of Geology
The reality of carbonate pores in a fractured reservoir
Controls on hydraulic flow units in a tight-matrix fractured-carbonate reservoir

Fault geometries favorable to generate pathways for corrosive fluids and leaching hot spots

Fault Tip-Line Area

Fault Interaction Area

Fault Intersection Area
Stable isotope values in carbonate cements evolve over time

Evolution of carbonates in time

- Primary deposition
- Syndepositional cements
- Marine rims isopach meteoric
- Recrystallisation Stylolitisation
- Saddle dolomite, catagenic leaching
- Later burial cements
- Hydrothermal cements
- Tertiary (uplift) cements
- Karst fill, soil & speleothems
- Replacement (all, dolomitisation)
- Dehydration (e.g. gypsum, carnallite)
- Cementation (carbonate and evap.)
- Faulting (extension and compression)
- Dissolution (all phases; early & late)
- Dissolution (all phases)
- De-dolomitisation
- Karstification (all)
- Localised faulting/flow
- Dedolomitisation

Permian (late burial)
Holocene (eogenesis)

Warren, 2016
Fluids evolve in fractured carbonate basement plays in Thailand

- Carbonate textures (cement and matrix) are continually reset during burial and uplift.
- Process is driven by various fluid crossflows.
- Shuts-down when permeability is lost, starts again if rock is subsequently fractured or dissolved.
Passive margin burial, then tectonic events, drive different fluid crossflows.

(a) Early - Middle Permian
B) Late Permian (Indosinian I)
(c) Late Triassic - Early Jurassic (Indosinian II & III)
(d) Cenozoic - includes effect of Himalayan orogeny

IZ: Inthanon Zone
SZ: Sukhothai Zone
KZ: Klaeng Zone
SKCZ: Sa Kao-Chanthaburi Zone

Indochina Block
Nan Back-arc Basin
Sukhothai Arc System
Sibumasu Block
Palaeo-Tethyan oceanic rocks

MyF: Mae Yuam Fault
CRTL: Chiang Rai Tectonic Line
NSZ: Nan Suture Zone
MPFN: Mae Ping Fault (Northern strand)
MPFS: Mae Ping Fault (Southern strand)
TPFZ: Three Pagodas Fault Zone
SKS: Sa Kaeo “Suture”
KMF: Khlong Marui Fault
KYF Khao Yai Fault

Eogenesis and early mesogenesis
Mesogenesis in passive margin burial
Late mesogenesis collision driven fracturing
Uplift, water ingress in fractures (telogenesis)

Neo-Tethys opening
Neo-Tethys (Meso-Tethys)
Neo-Tethys island arc
Sukhothai island arc
Sibumasu
Sibumasu Arc
Jinghong-Nan-Sra Kaeo Back-arc Basin
Pha Som Complex in Nan Uplift
Phetchabun Foldbelt
Accretionary Prism in Nan Uplift
Western Indochina Granitoids
Volcanic Belt
S-type Granitoids
I-type Granitoids
Sibumasu Arc

Lop Buri Continental Rift
Volcanics at 55-9 Ma
Himalayan Belt
Lithosphere
Asthenosphere
Paleocene event in Thailand
The “miracle” of porosity and permeability illustrated

- Thrust Mesogenesis: Veins mostly proximal to, & aligned with, thrust zones. Fluid flow is focused in thrusts and related fractures.
- Indosinian compression
- Pre-deformation burial, rock-fluid re-equilibration, increasing loss of matrix $\phi$
- Mesogenesis
- Early mesogenesis
- Burial away from intense deformation
- Eogenetic (best preserved in deep water carbonates)
- Uplift and telogenesis (post Paleocene, mostly Quaternary)

$\delta^{13}C_{PDB}$ value ≈ -11-12% defines loss of all matrix permeability in burial of Permian carbonate in central Thailand

(Warren et al., 2014)
Outcrop dominated by relatively undeformed Permian open platform cements (mesogenetic), with later fluid signatures showing Quaternary karst overprint (telogenetic)
Outcrop with fluid-cement signatures indicative of depositional and early mesogenetic textures.
Outcrop with fluid-cement signatures dominated by Indosinian thrust faulting
The “miracle” illustrated

Veins mostly proximal to, & aligned with, thrust zone. Fluid flow in thrust and related fractures

δ¹⁸O value ≈ -11-12‰ defines loss of all matrix permeability in burial of Permian of central Thailand

Pre-deformation burial, rock-fluid re-equilibration, increasing loss of matrix φ

Indosinian compression

Thrust Mesogenesis

Mesogenesis

Burial away from intense deformation

Early mesogenesis

Eogenesis (best preserved in deep water carbonates)

Uplift and telogenesis

(Warren et al., 2014)
Learnings from the Permian carbonates of central Thailand

- Most matrix and mesogenetic cement-fluid trends tied to increasing burial temperature

- Matrix permeability shutdown in burial indicated by $\delta^{18}O_{PDB}$ values around -10 to -11‰.

- Hotter fluid trend in veins is tied to subsequent Indosinian thrust faults

- Later meteoric trend related to uplift, exposure and karstification
“Get your facts first. Then you can distort them as you please.”

–Mark Twain, American Author
Application of the Saraburi isotope burial curve

1. Definition of diagenetic events associated with poroperm development in Phu Horm field

2. Improved fluid definition in the 3 Pagoda fault-damage zone in the Salak Phra area in Ordovician limestone matrix.
Is there useful isotope information in drill cuttings?
**Sinpahuorm field, Thailand**

- Produces gas from the Permian reservoir carbonate (buried-hill) in Pha Nok Khao Formation, Saraburi Group.

- Reservoir is in fractured, dolomitized and hydrothermally altered carbonate hosts.

- Matrix porosity (plug-measured) averages 2% for limestone and 5% for more massive dolomite intervals.

- Region is located well away from main Indosinian suture belt.
Faulted and thrusted “buried hill” play
Late-stage separate-vug porosity dominates the reservoir section

- Skel-moldic or pin-point porosity
- Post-fracture & post-stylolite leaching
- Multiple generations of clear spar cement
Fractured carbonate basement reservoir, Phu Horm field, Thailand

**Diagram:**
- Low porosity, high permeability (typifies fractures)
- Low porosity, low permeability
- Higher porosity, low permeability (more dolomite)
Cutting classification template in Phu Horm field

- **Calcite with rhombohedral shape, white and perfect cleavage**
- **Dolomite with dark grey to black color, hard, strong reaction with HCl, XRD results show as dolomite**
- **Cloudy limestone, white to light grey, soft, reacts with HCl**
- **Massive limestone, light to medium brown color, strong reaction with HCl**
- **Crystalline limestone with medium to dark grey color, reacts with HCl**
- **Recrystallised calcite, prismatic shape, clear color and dark color from rock inclusions (dolomitic?)**
Phu Horm field all wells

2 trends

$\delta^{13}C_{PDB}$

Well A, B and C
Trends are visible in clear calcite alone.
Phu Horm clear-calcite trend is not seen in Saraburi plotfield (does this indicate Paleocene fluids?)

δ¹³C PDB

δ¹⁸O PDB

δ¹⁸O value ≈ -11-12‰ defines loss of all matrix permeability in burial of Permian of central Thailand

(Warren et al., 2014)
Learnings

• Cuttings can define diagenetic style when interpreted in the context of the regional isotope burial curve.

• The isotope signature that is hydrocarbon-associated is clearest when calcite spar cuttings are used for isotope work (collection can be done by technician with geologist as QC).

• Fracture analysis using image logs or oriented core is required to confirm timing of the hydrocarbon-associated porosity phase (study integrating Phu Horm FMI is currently underway).
Some applications of the Saraburi isotope burial curve

1. Definition of diagenetic events associated with poroperm development in Phu Horm field

2. Improved fluid definition in the 3 Pagoda fault-damage zone in the Salak Phra, Kanchanaburi area (Ordovician limestone host)
More mineralogically evolved matrix and veins than in the Saraburi region

- Veins can show multiple episodes of overprint
- Polycyclic fluid flow signatures are typical
Hotter fluids in calcite cements in the 3 Pagodas fault damage zone.

Temperature limit of sampled oxygen values ($\approx -15\%$) in the Saraburi region.

Hotter signatures in vein calcites (cluster 3 is $> -15\%$) from the 3 Pagodas damage zone.

Shaded polygons outline the various plot fields as defined in the Saraburi region.
Stereo plot of poles to veins, shows two dominant vein sets:

- NE-SW trending vertical to sub-vertical veins
- NW-SE trending lower angle veins
Are we seeing evidence of hot basement Palaeocene fluids?

Cluster 3 signatures tie to veins that are vertical and interpreted as younger (perhaps created/reactivated by Himalayan event?).
Learnings

• There is no distinctive “Paleocene event” fluid signature in fractured carbonates of Thailand (can be hotter or cooler depending on local geothermal gradient at the time the fracture-related vein calcites precipitated)

• Understanding of poroperm evolution can only occur when vein isotope values are understood within a petrological and structural framework
Poroperm implications

- Permeability creation hosted in Permian carbonates, some of which is still open in the subsurface, most likely occurs in zones of faulting or fault renewal driven by stresses created by the Paleocene (Himalayan) event.

- There is no “one-size-fits-all” isotope approach! Refined understanding of rock-fluid evolution only comes when isotope values are placed in a petrographic and structural framework.
Now what?

Further integrated studies using combinations of outcrop, well data (FMI and cuttings) and stable isotope values are now underway to better understand poroperm evolution.

Current projects involve the new fractured-basement discovery in the Suphanburi Basin, western Thailand, as well as other fracture-timing and poroperm studies in Vietnam and Indonesia.