Structural Controlled Hydrothermal Dolomite Reservoirs in the Precambrian Dengying Formation of the Central Sichuan Basin, Southwestern China*

Feng Mingyou[1,2], Liu Xiaohong[1,2], Qiang Zitong[1], Tao Yanzhong[1], and Xia Qingsong[1]

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Abstract

The Sichuan basin (southwestern China) is a foreland basin and contains Paleozoic and Mesozoic sediments that include carbonate, siliciclastic, and evaporite sediments. The Dengying Formation presently lies 8,200-19,685ft (2,500-6,000 m) below the surface in the study area in the central part of the Sichuan Basin. The study area (G-M area) is located in the central Sichuan basin, at the border of the Anju and Anyue country. This area is part of the central of Sichuan sedimentary basin, which lies between the Longquan and the Huaying Mountains in the southwestern of China. Upper Edicarian Dengying Formation dolomites form part of the southeastern of the paleo-rifting of Leshan - Longnvsi in central Sichuan basin, the southwestern most of China.

The Dengying Formation is a depositional sequence at the third-order level and thickness is about 1400 m. Regional transgressive cycles separate the Dengying Formation from the Dengying first Member, second division beneath and the overlying Dengying third and fourth division. The Dengying first and second division in the study area comprises an upward - darken succession about 1000 m thick, main formed by grey micritic algal dolomite. The Dengying third member is about 0 to 40m main formed by grey mud and interbeded with dolomitic-mudstone reflecting deposition in relative deep-water environments, respectively. The Dengying fourth division in the study area comprises an upward-shallowing succession about 0 to 336 m thick.

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Structural Controlled Hydrothermal Dolomite Reservoirs

- ***Specificity*** **of distribution**

reservoir is tectonically controlled By basement-root faults

- ***Effective*** **Reservoir Rock**

other dolomite reservoirs influenced by diagenetic heterogeneity

- ***High*** **hydrocarbon potential**

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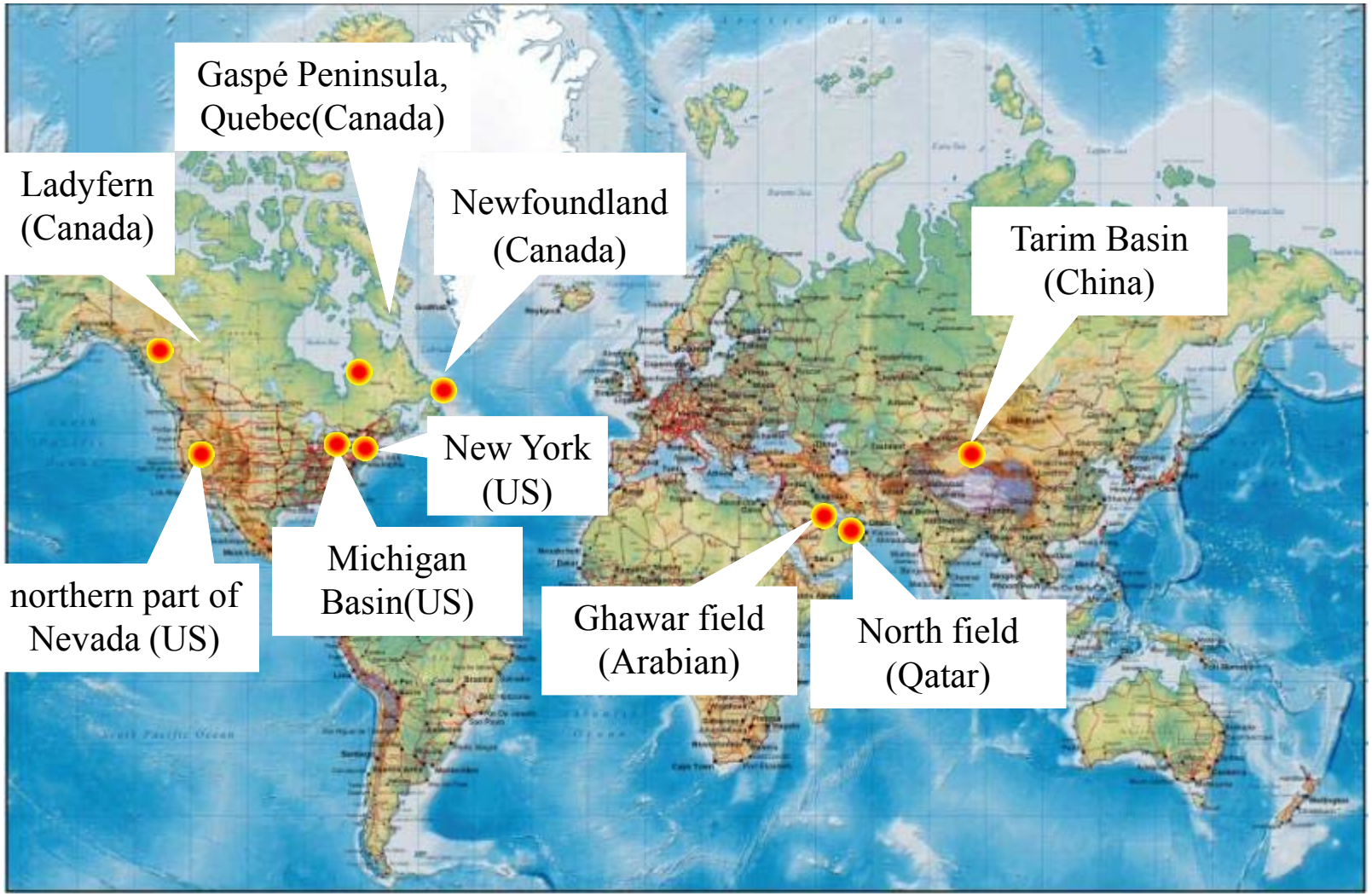
HTD Reservoirs in various basins:

there exist numerous similarities among reservoir conditions



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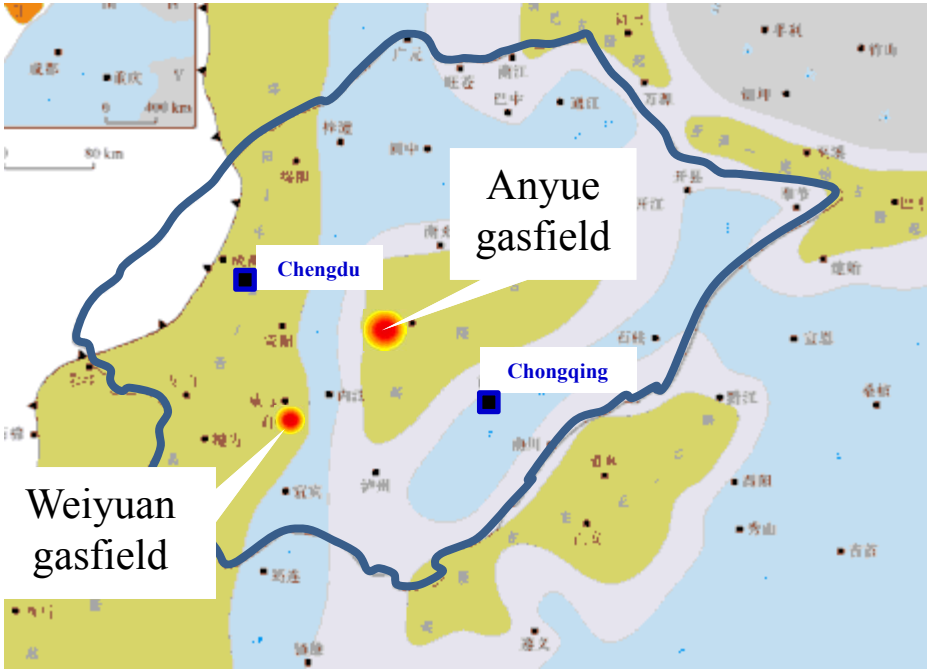
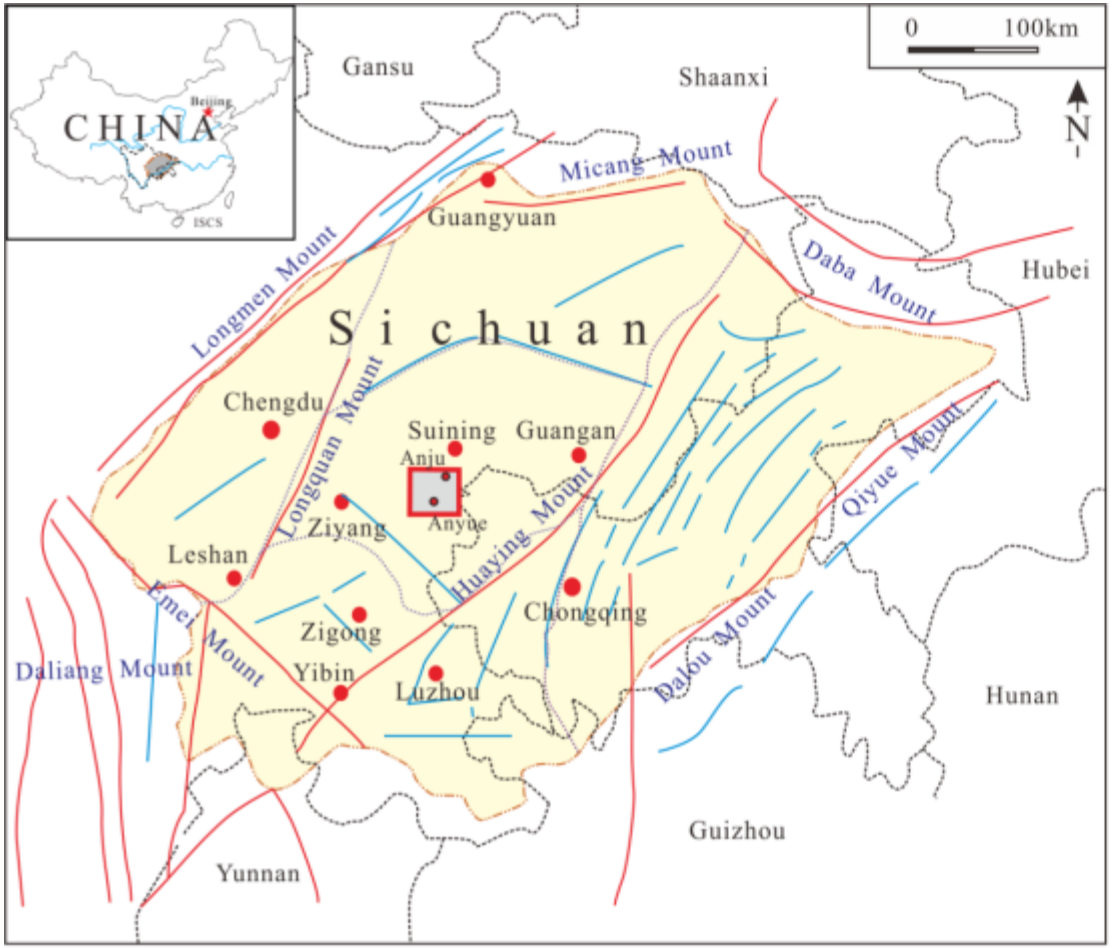
Location of Sichuan Basin, southwestern China

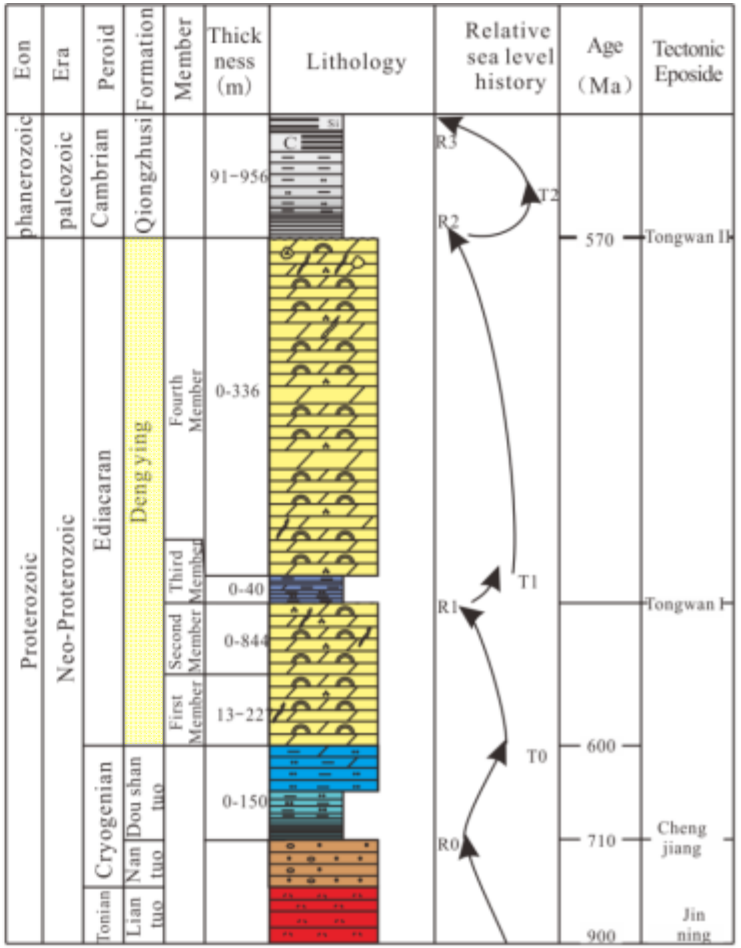
Exploration history in deep dolomite reservoir of Sichuan Basin

- In 1949 and 1964, No great breakthrough in Sichuan Basin
- 1964 to 1977, **Weiyuan** gasfield (Precambrian Dengying Formation); **structural gas reservoir**;
- 2011 to 2014， **Anyue Gasfield**(G-M area) (Eozoic &Cambrian) developed reserves more than a hundred billion cubic meter; **Karst related reservoir**



Geological Background

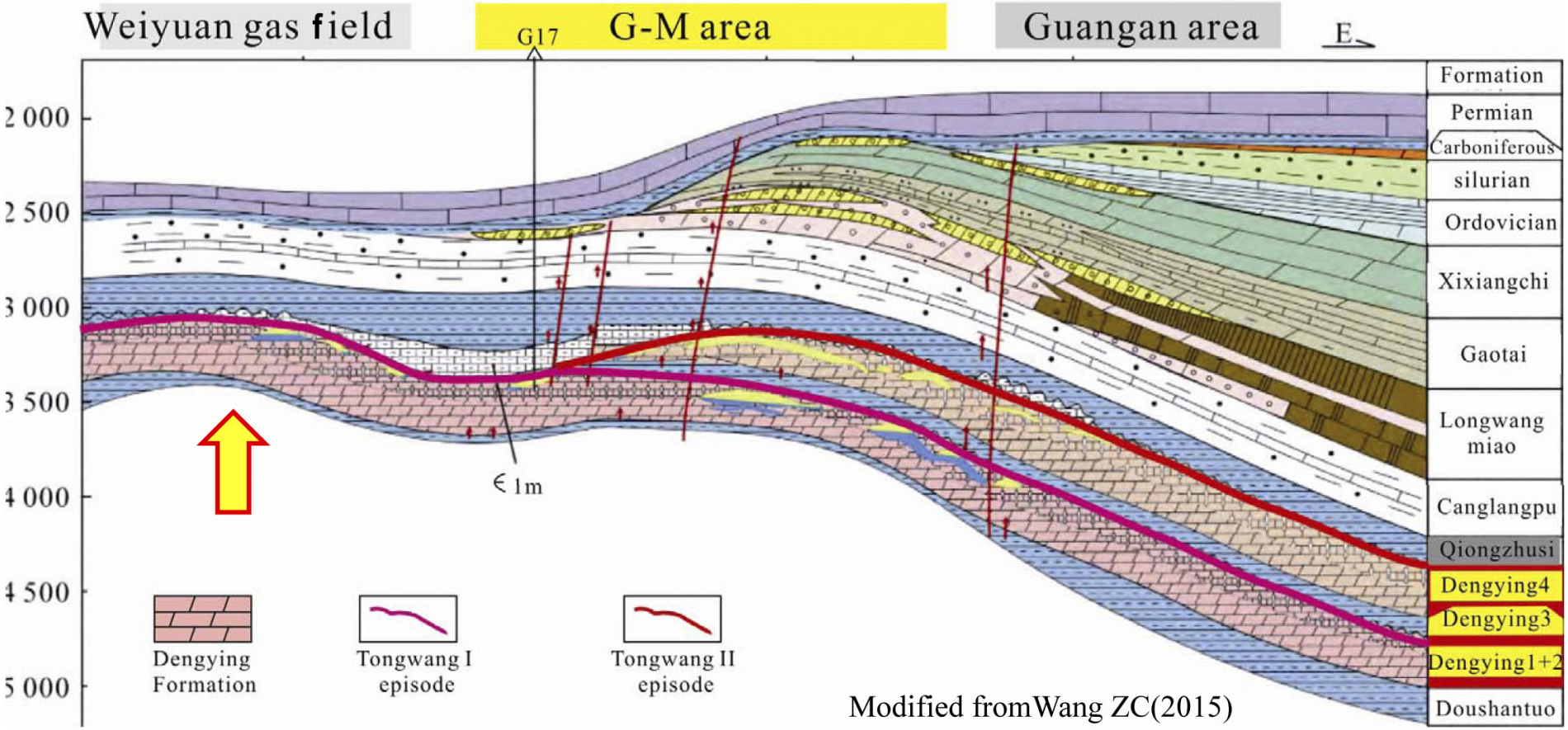




Region boundary
Large fault
Plate boundary
Basin boundary
Study area
County
R0 Regressive
T0 Transsgressive

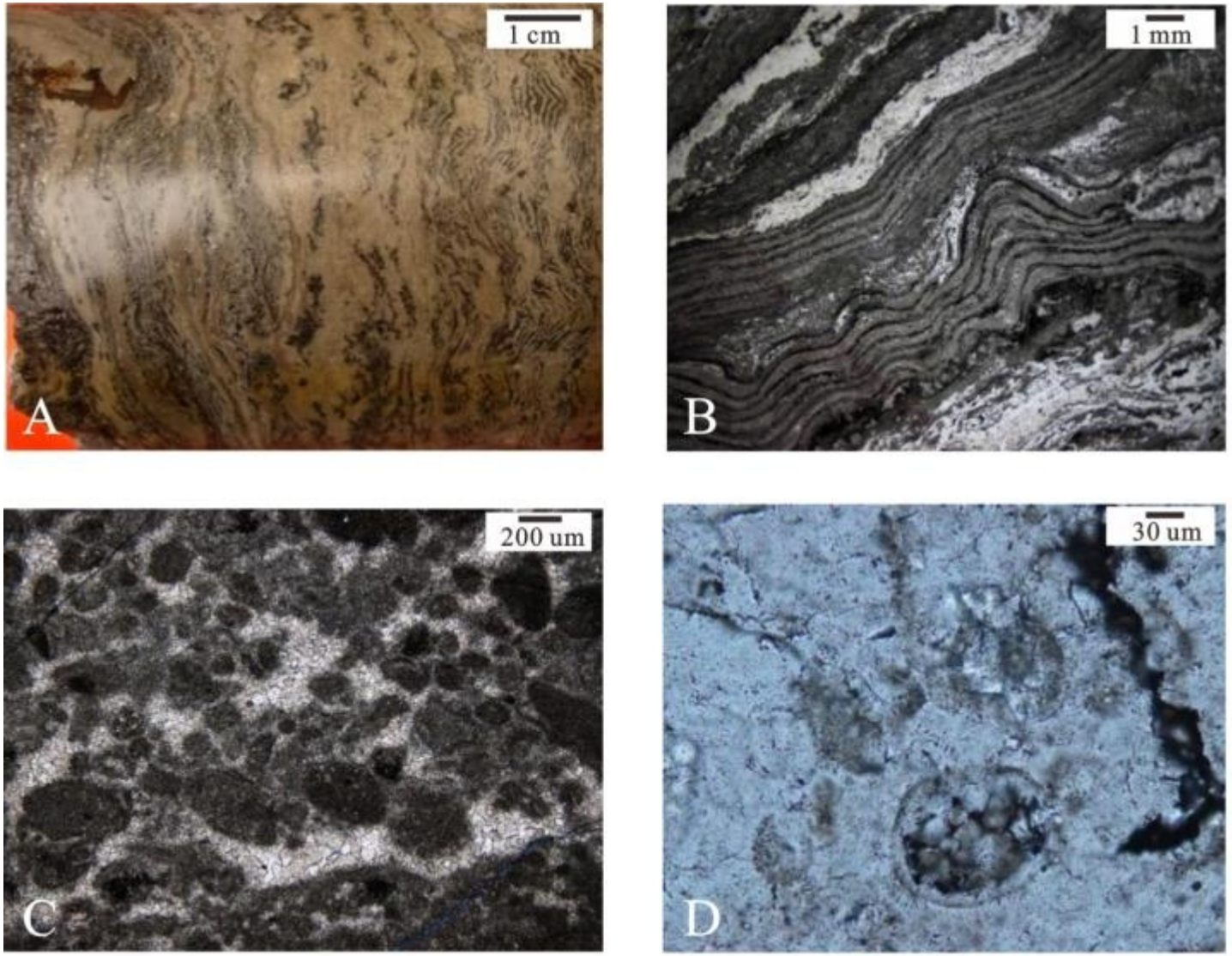
Dolostone
Algal dolostone
Ice-congglonmates
diabase
Shale and mudstone
Mud-Siltstone
pores and fractures
Dissovoled breccia and vugs

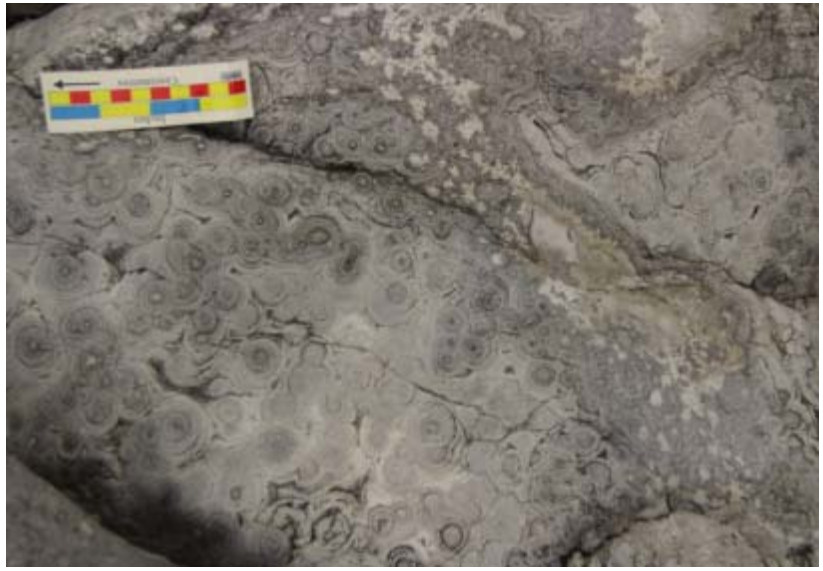
Geological Background



Precambrian Dengying Formation in G-M area After the late Precambrian rifting of the **Tongwan I** episode orogeny and **Tongwan II** episode orogeny, central of Sichuan basin was located on a paleo-rift miniature over the Leshan-Longnvsi, The Lower Cambrian Qiongzhusi black mud and shale (15–750 m thick) rests unconformably on the top of Dengying stratum and is overlain by the Cambrian–Ordovician carbonates and siliciclastics.

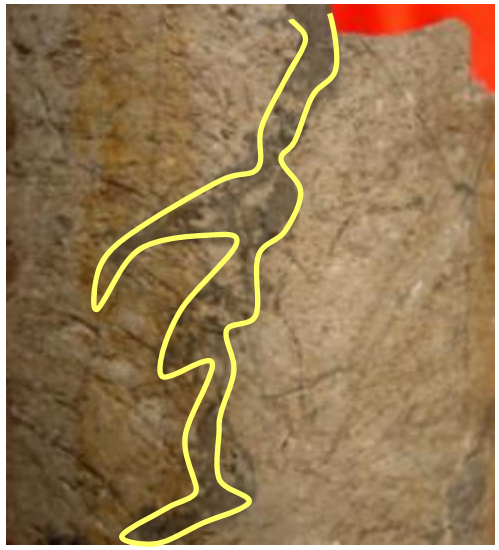
The Dengying Formation is composed of the algal/ cyanobacteria dolomite and micro-dolomite, which has common botryoidal lace, vugs, breccias, and fractures partially filled with saddle dolomite





Algal dolomites which has botryoidal lace and laminar structures

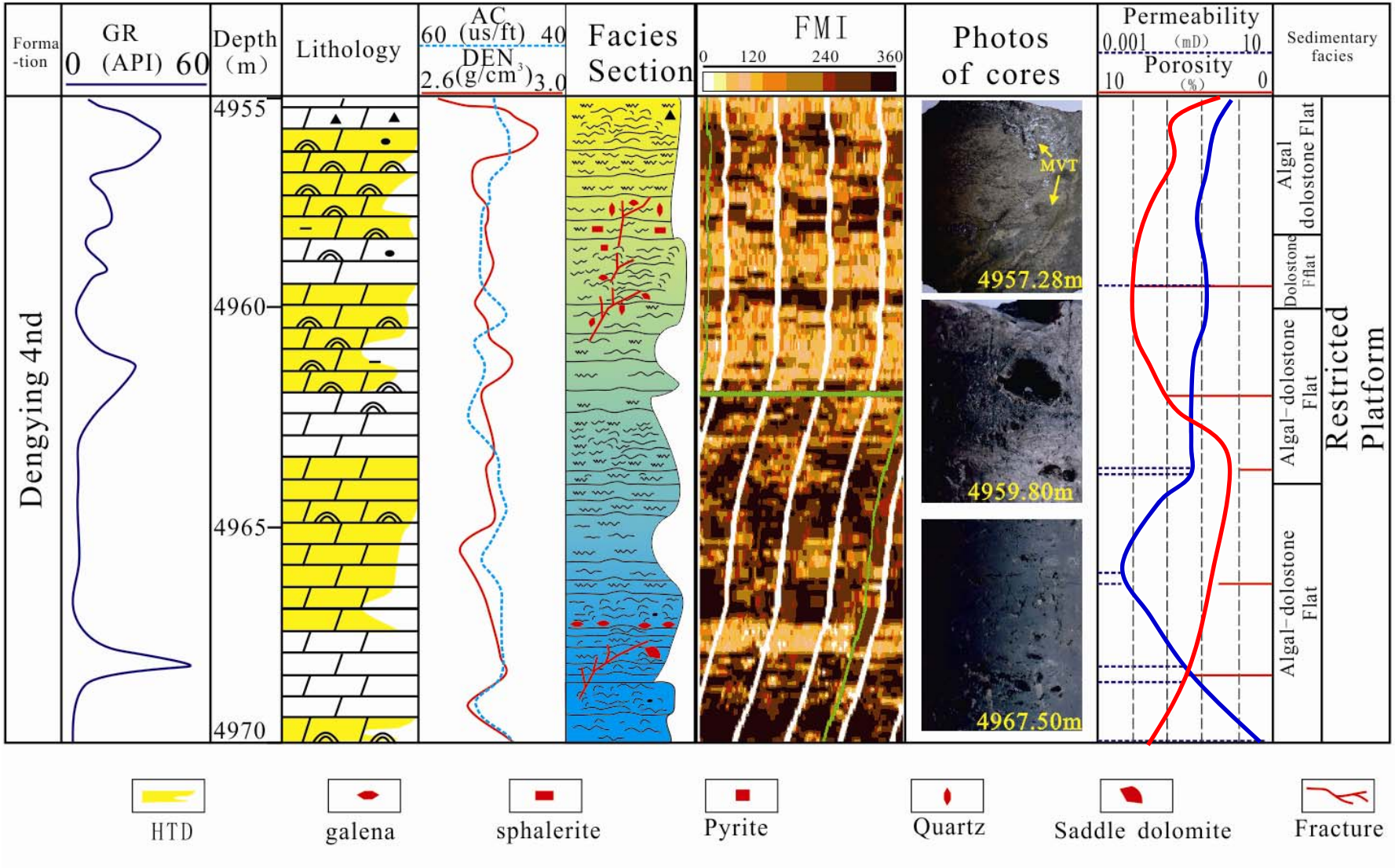
stromatolite algal dolomite



karst fissure

dissolution caves

Except karst related reservoirs, have any other types about dolomite reservoir in Precambrian Dengying?



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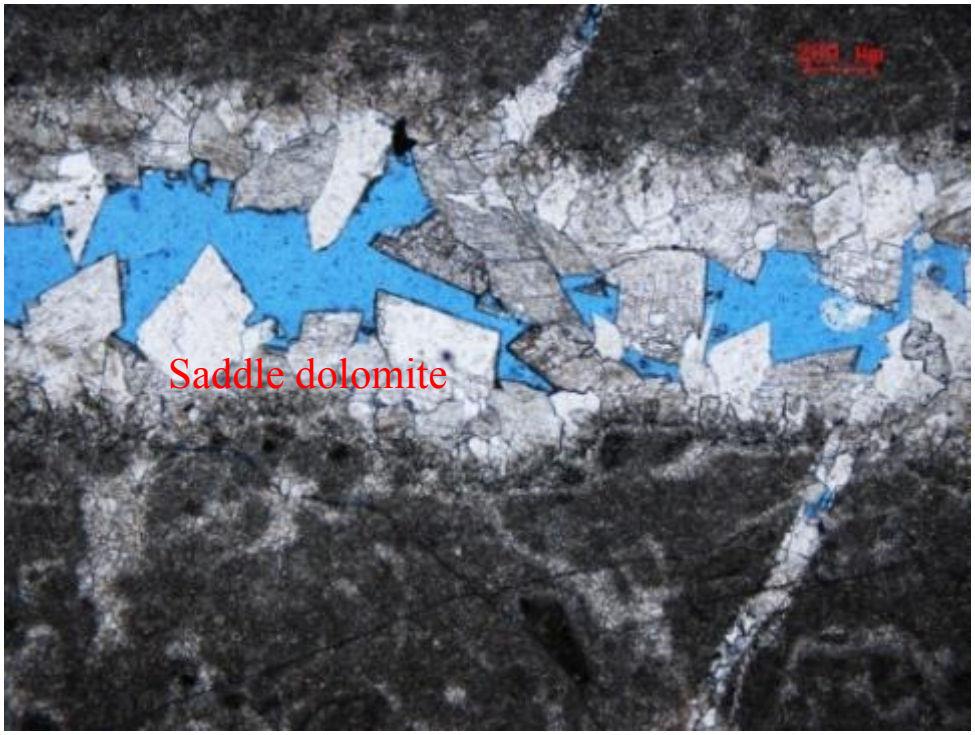
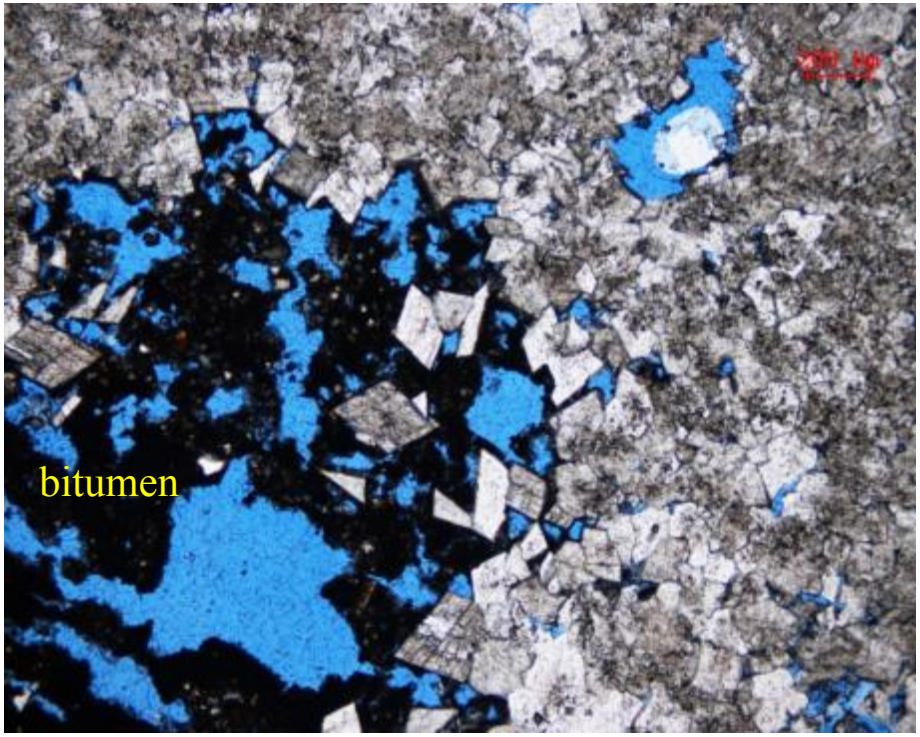
Except karst related reservoirs, have any other types about dolomite reservoir in Precambrian Dengying?





Coarse-saddle dolomites which are develop vugs and fractures in G-M area are porous and permeable, but these reservoirs mostly are ignored

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The evidences of HTD dolomite in the Dengying Formation, Central Sichuan Basin

- Petrography
- Fluid Inclusion
- Trace Elements
- Oxygen and Carbon isotopes
- Sr isotopes
- REE Data
- Seismic Data
- Regional tectonic features

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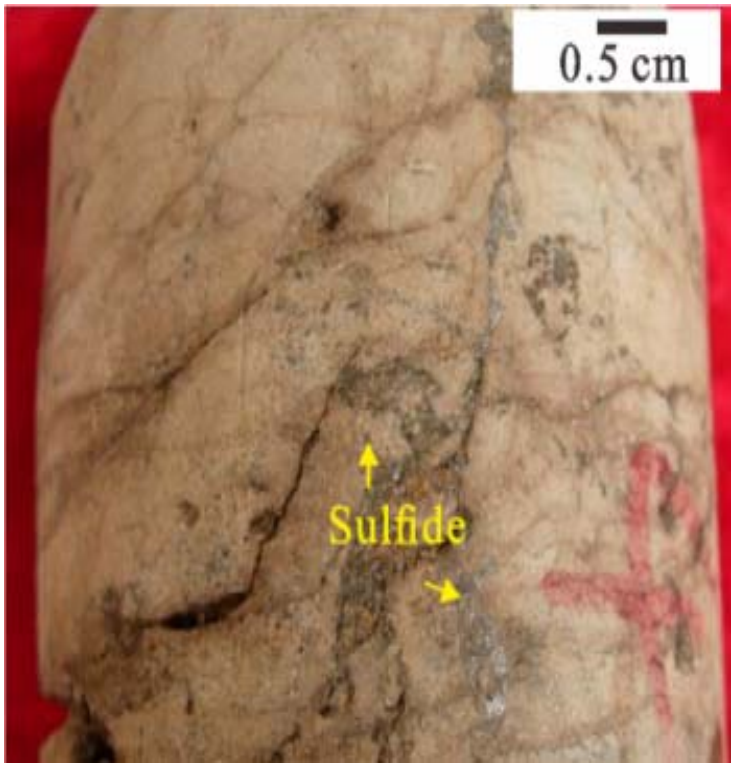
Low-temperature sedimentary hydrothermal minerals and related accessory minerals are developed of Dengying Formation in G-M area

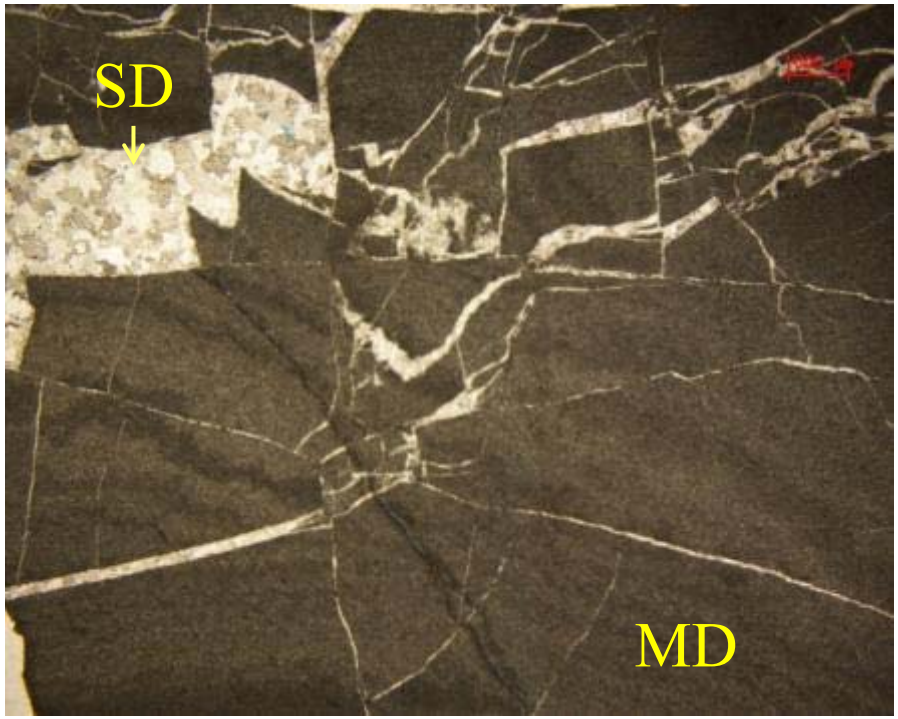


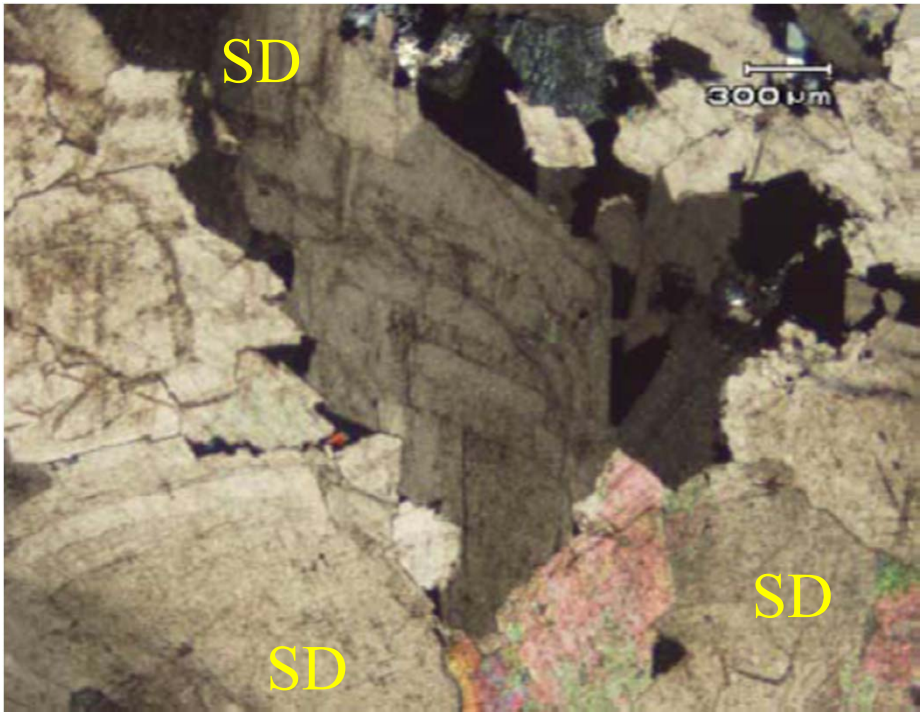
Zebra structure, tectonic breccia by hydrofracturing and sulfide are developed in fractures and vugs

Low-temperature sedimentary hydrothermal minerals and related accessory minerals are developed of Dengying Formation in G-M area

Sphalerite, galena, Pyrite and other minerals are found in fractures and vugs

Low-temperature sedimentary hydrothermal minerals and related accessory minerals are developed of Dengying Formation in G-M area





- Saddle dolomites are infilled in the tension-shear fractures;
- The dolomites show undulated extinction under Orthogonal polarized, hints that in the process of crystal growth from high temperature and high pressure which resulted in cleavage plane bending

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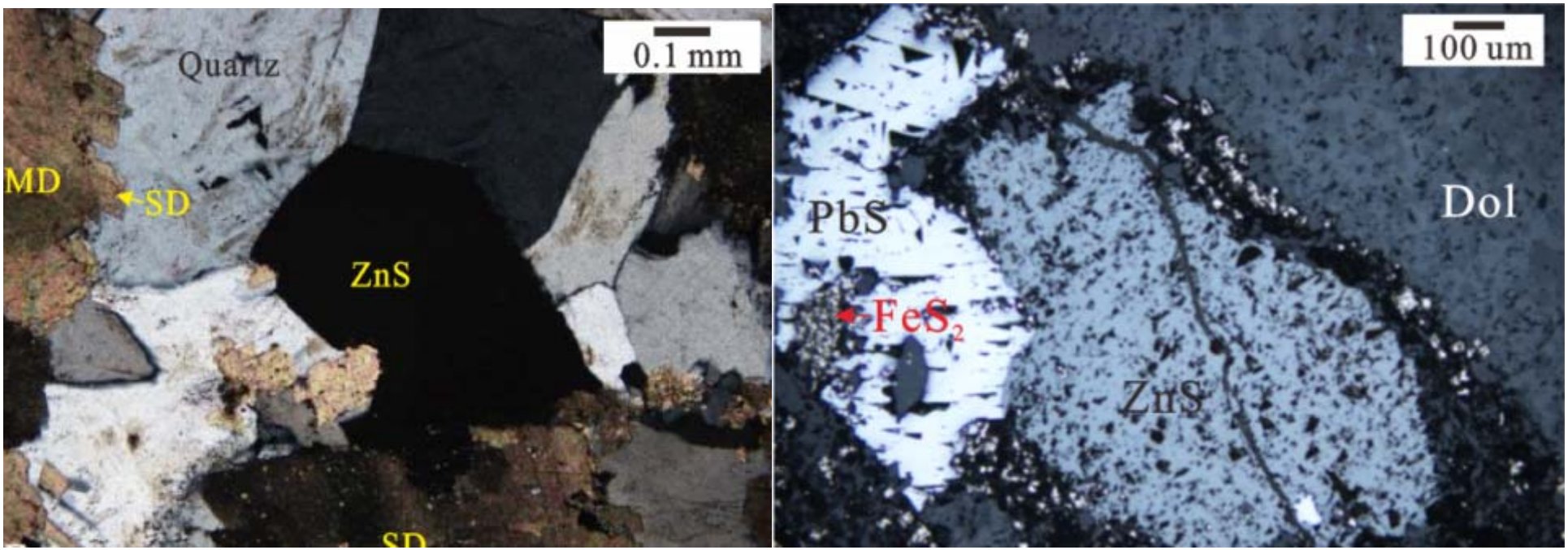
Low-temperature sedimentary hydrothermal minerals and related accessory minerals are developed of Dengying Formation in G-M area



The authigenetic minerals ' paragenetic sequence of MVT minerals is:

1.Micrit dolomite(Matrix)- Saddle dolomite (SD)-Quartz-Sphalerite (ZnS)

2.Micrit dolomite(Matrix)-Saddle dolomite (SD)-Galena(Gn)-Pyrite(FeS_2) – Sphalerite (ZnS)

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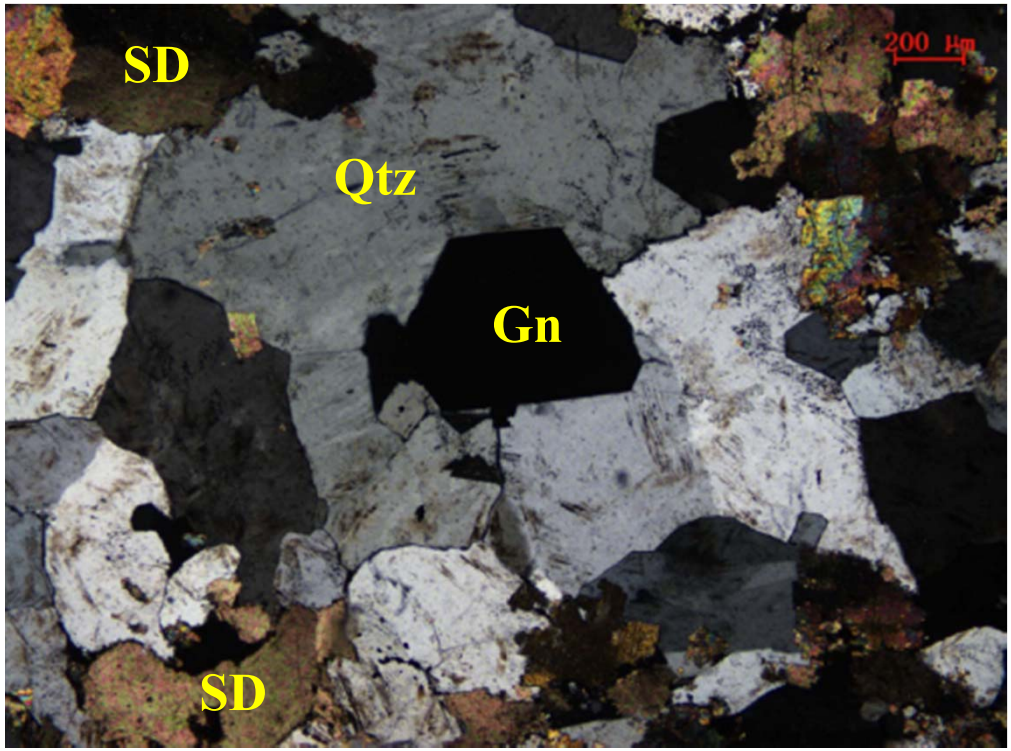
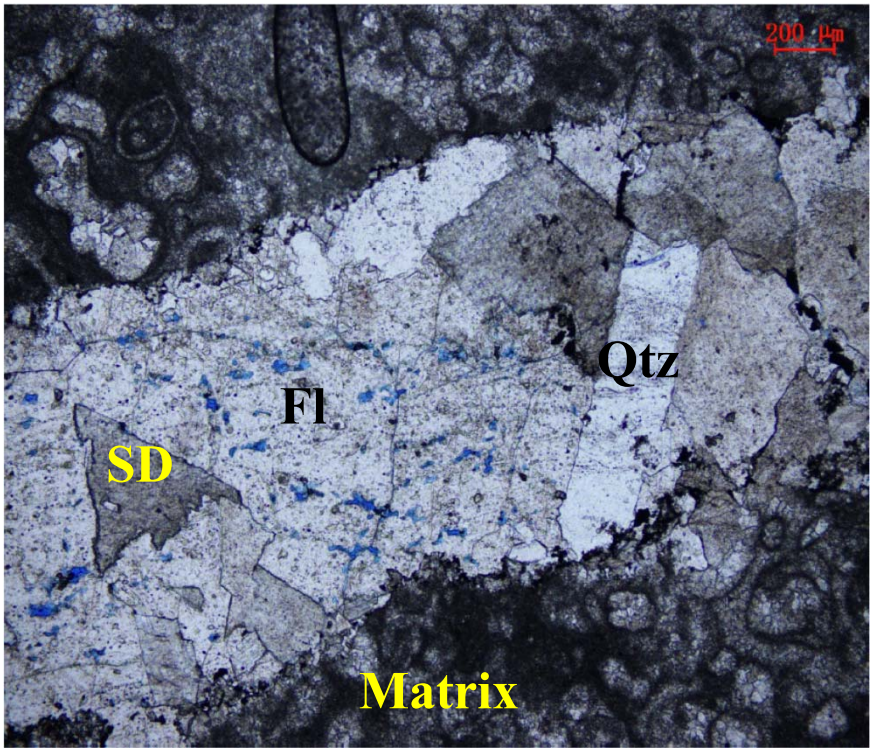
The MVT mineralization of Dengying Formation in G-M area , Sichuan Basin, Southwestern China





The authigenetic minerals ' paragenetic sequence of MVT minerals is:

3.Micrit dolomite(Matrix)- Saddle dolomite (SD)-Quartz-Galena(Gn)

4.Micrit dolomite(Matrix)-Saddle dolomite (SD)-Flourite(Fl)-Quartz

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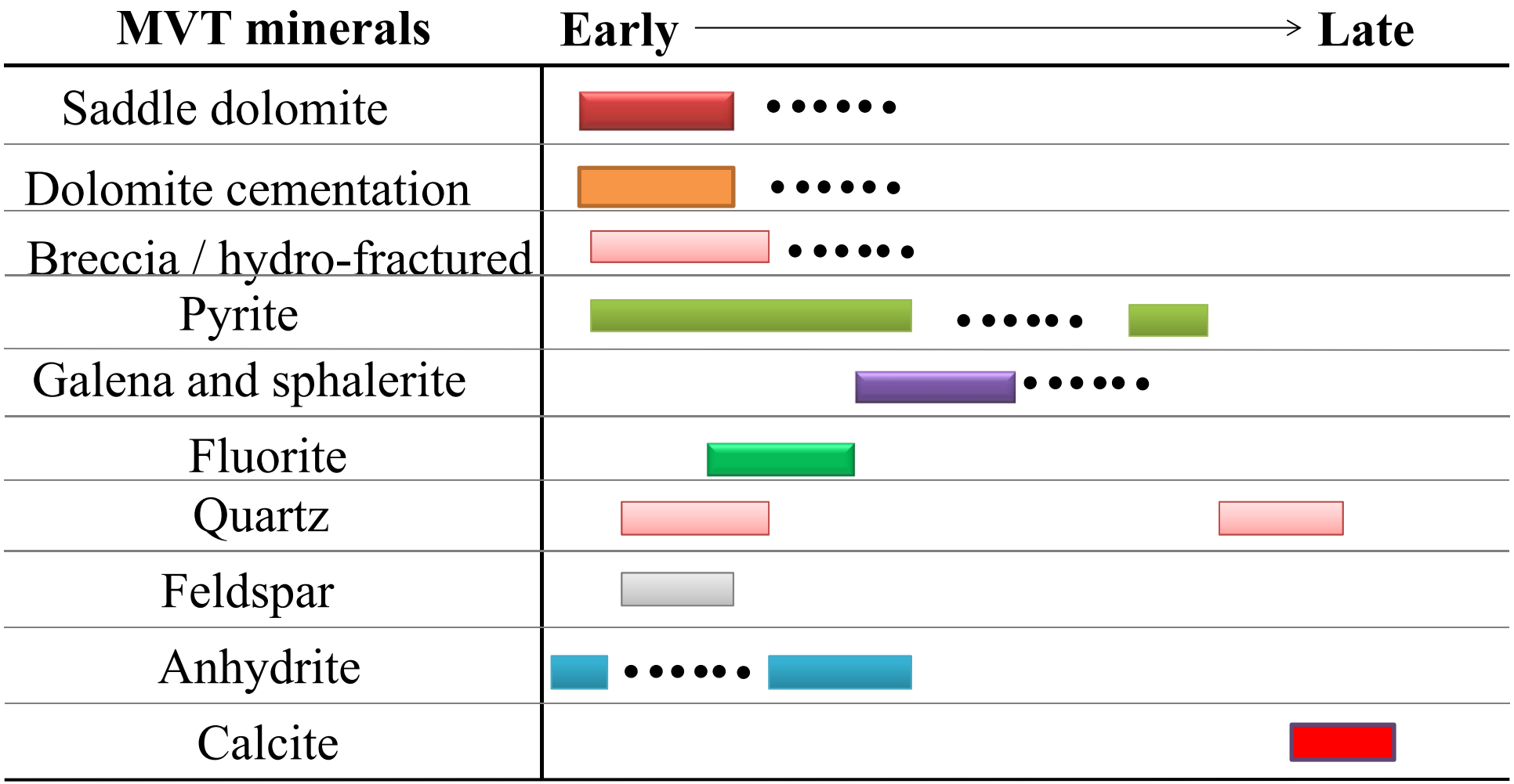
The MVT mineralization of Dengying Formation in G-M area , Sichuan Basin, Southwestern China



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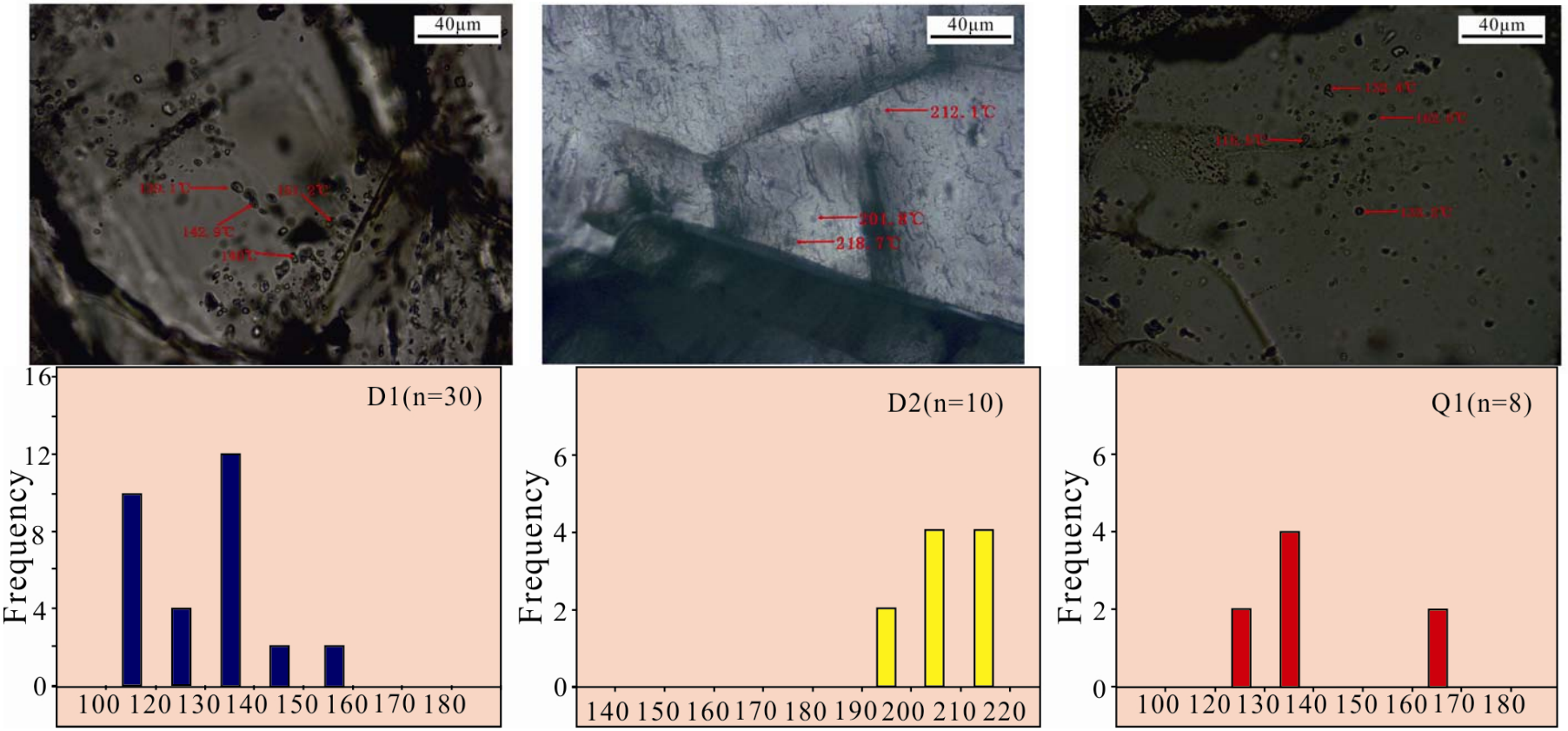
Secondary fluid inclusions from the saddle dolomite have obviously higher homogenization temperatures than surrounding rocks



- **Matrix dolomites**(D1): 101- 151 ℃(average **125** ℃).**Saddle dolomite**(D2): 196 - 218 ℃(Average **207** ℃) . Quartz cements(Q1): 125 -165 ℃(average 136℃).
- The **salinities** of the primary fluid inclusions in both the coarse and saddle dolomite with an average of approximately **12.0 wt.%** , show that the **fluid were saline brines**.

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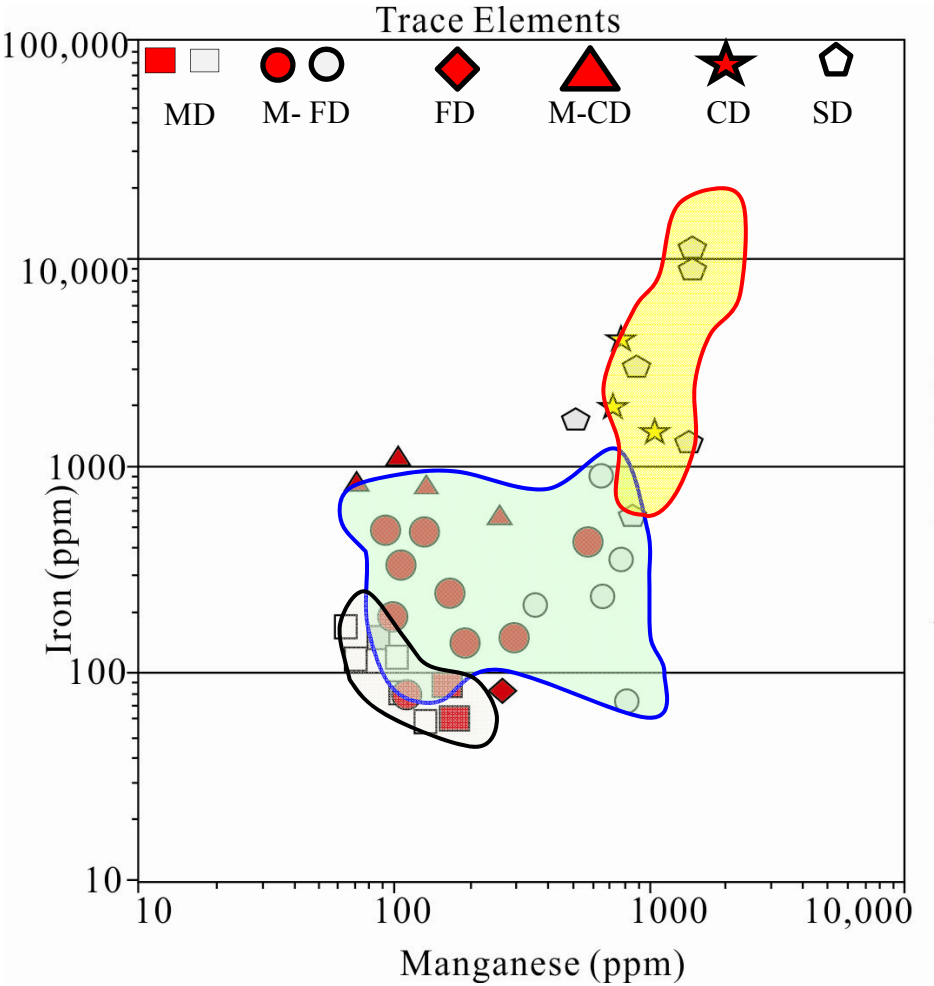
Trace-element data show that the SD and coarse dolomites are enriched in Fe and Mn relative to the micritic matrix dolomites



- **The iron content (Fe)**

Saddle and coarse dolomites
ranges from 736 to 11,601 ppm.
median value: **3895** ppm.

Micritic matrix dolomites
ranges from 59 to152 ppm.
median value: **95** ppm.

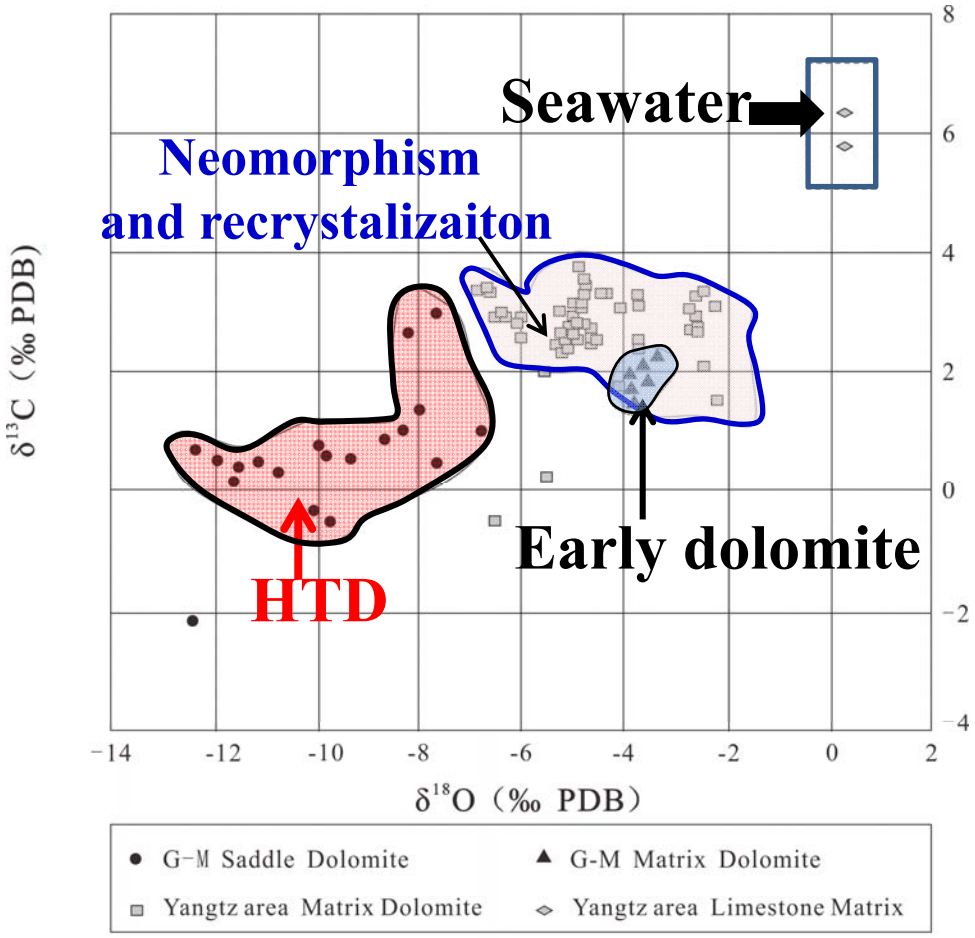
- **The manganese content (Mn)**

Saddle and coarse dolomites
median value: **1064** ppm.

Micritic matrix dolomites
median value: **123** ppm.

The relatively high Mn and Fe values of the saddle and coarse dolomites in Dengying Formation imply a subsurface genesis for the dolomites.

Oxygen and carbon isotopes show the $\delta^{18}O$ are depletion by the source of increased temperature



$\delta^{18}O$ and $\delta^{13}C$ of Seawater in Late Proterozoic：
$\delta^{18}O$= -0.5 ~ +0.9 ‰ （Fairchild et al，1987）
$\delta^{13}C$= +5 ~ +7 ‰ （Beeunas and Knauth，1985）

Elevated temperature and pressure mostly result in the depletion of $\delta^{18}O$ and $\delta^{13}C$ values.
The replacive saddle dolomite phases are marked **by very negative $\delta^{18}O_{VPDB}$** values (between -12.4 and −6.8‰) and **negative $\delta^{13}C_{VPDB}$** values (between −2.16 and 2.94‰).
The dolomite phase originated from Neomorphism and recrystalizaiton with positive $\delta^{18}O_{VSMOW}$ values (-6 and -2‰), whereas the calcite precipitated from seawater with lower $\delta^{18}O_{VSMOW}$ values (-0.5 and +0.9‰).

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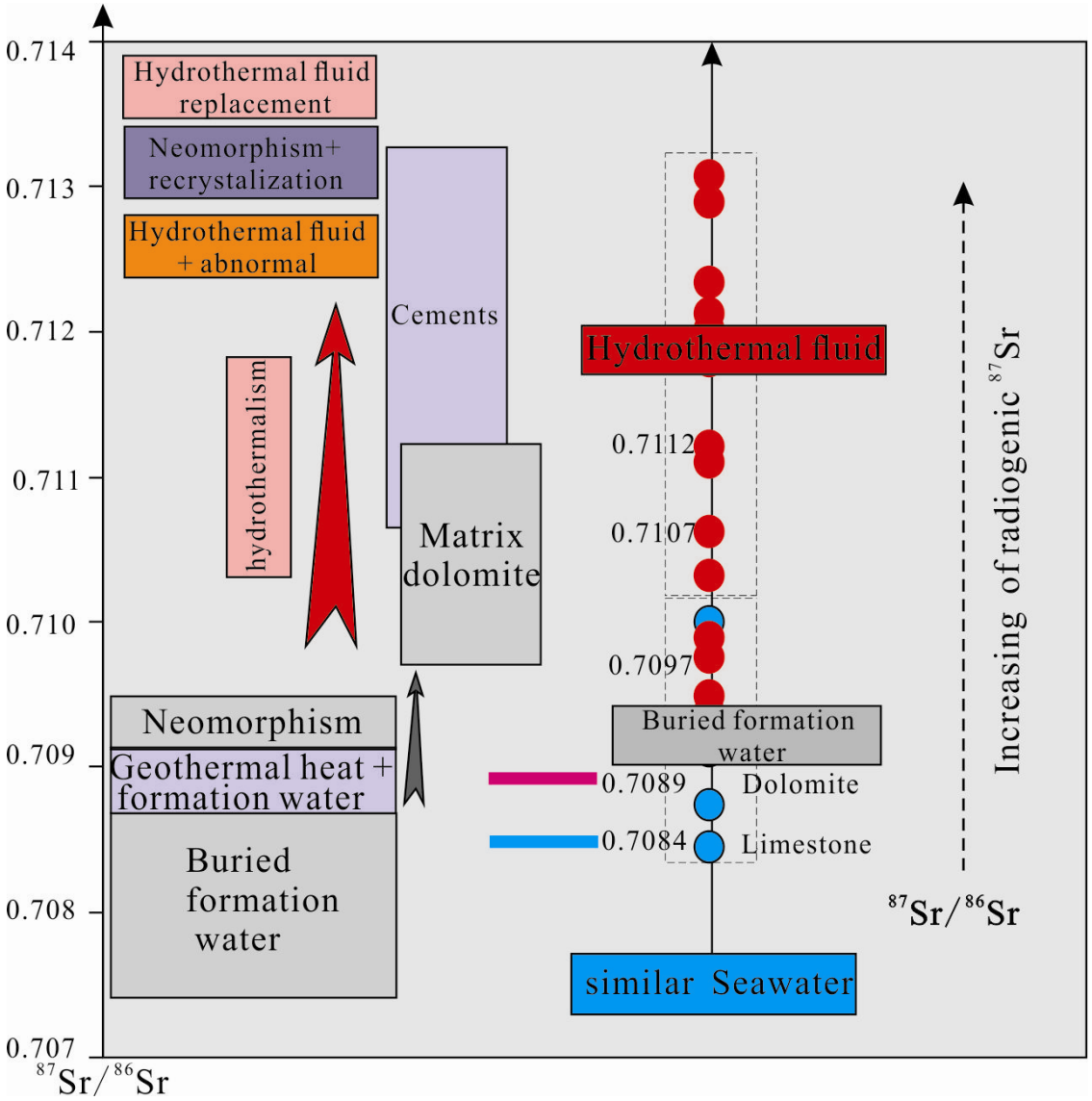
Strontium(Sr) isotopes enriched in ^{87}Sr suggests fluid that formed the dolomite is origined from more radiogenic deep basement rocks



Dolomites that formed from subsurface brines commonly have $^{87}Sr/^{86}Sr$ ratios that are higher (more radiogenic) than seawater for the time that they formed.

The range of $^{87}Sr/^{86}Sr$ ratios of seawater for Precambrian time is between **0.70845 and 0.70855**, The strontium isotope values for the dolomites in the Dengying range from **0.7097 to 0.7132**, suggests that the fluid that formed the dolomites passed through basement rocks or immature silici-clastics prior to precipitating the dolomite.

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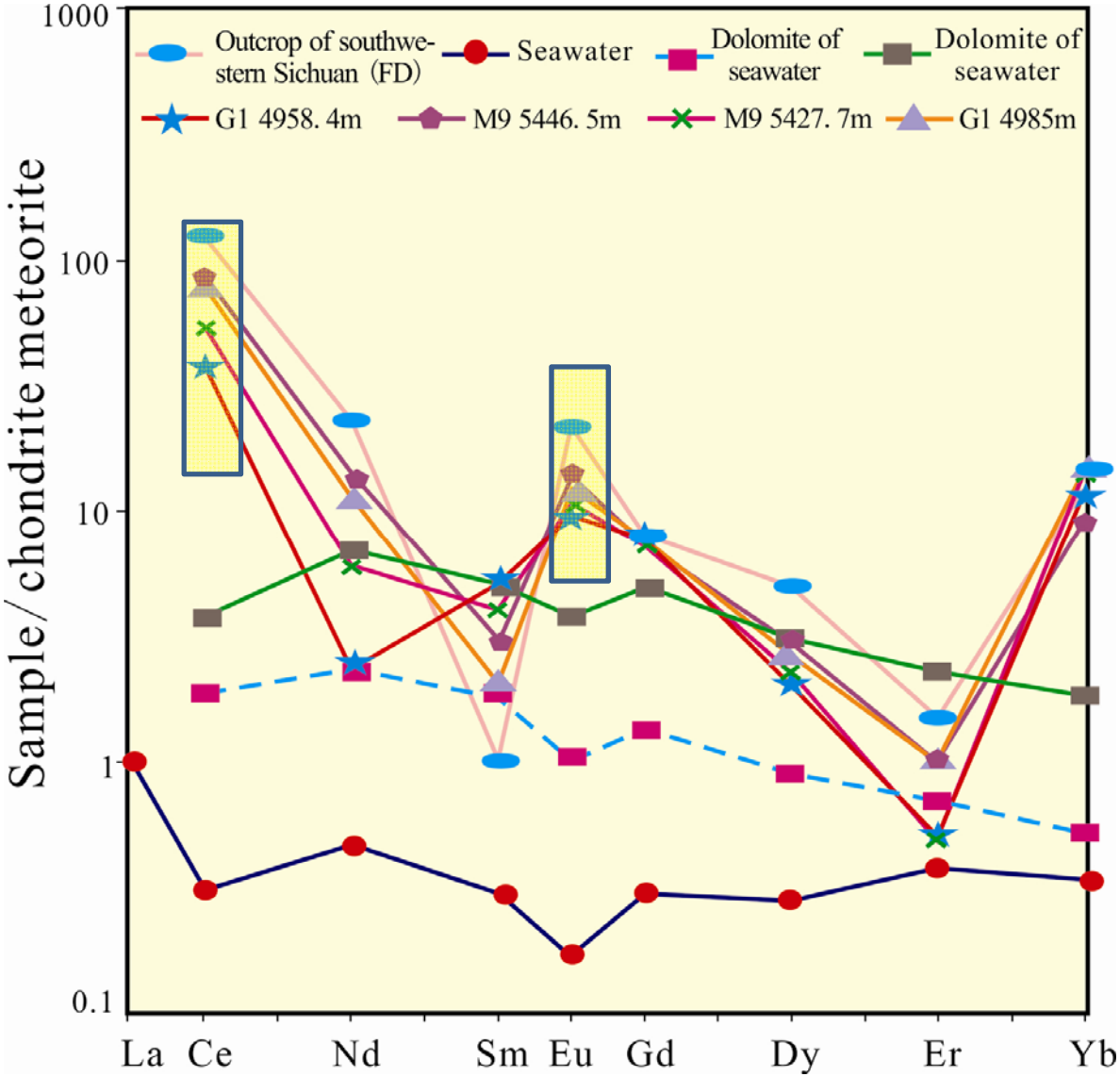
REE Data show the Eu and Er positive anomaly of medium-coarse dolostone in G-M area



The rare earth element components of medium-coarse dolomites in G-M area are characterized by huge **positive anomaly** of **cerium (Ce)** and **europium (Eu),** which was distinctly higher than that of seawater positive abnormity.

The average value of δCe was 1.92, the average value of δEu was 1.15

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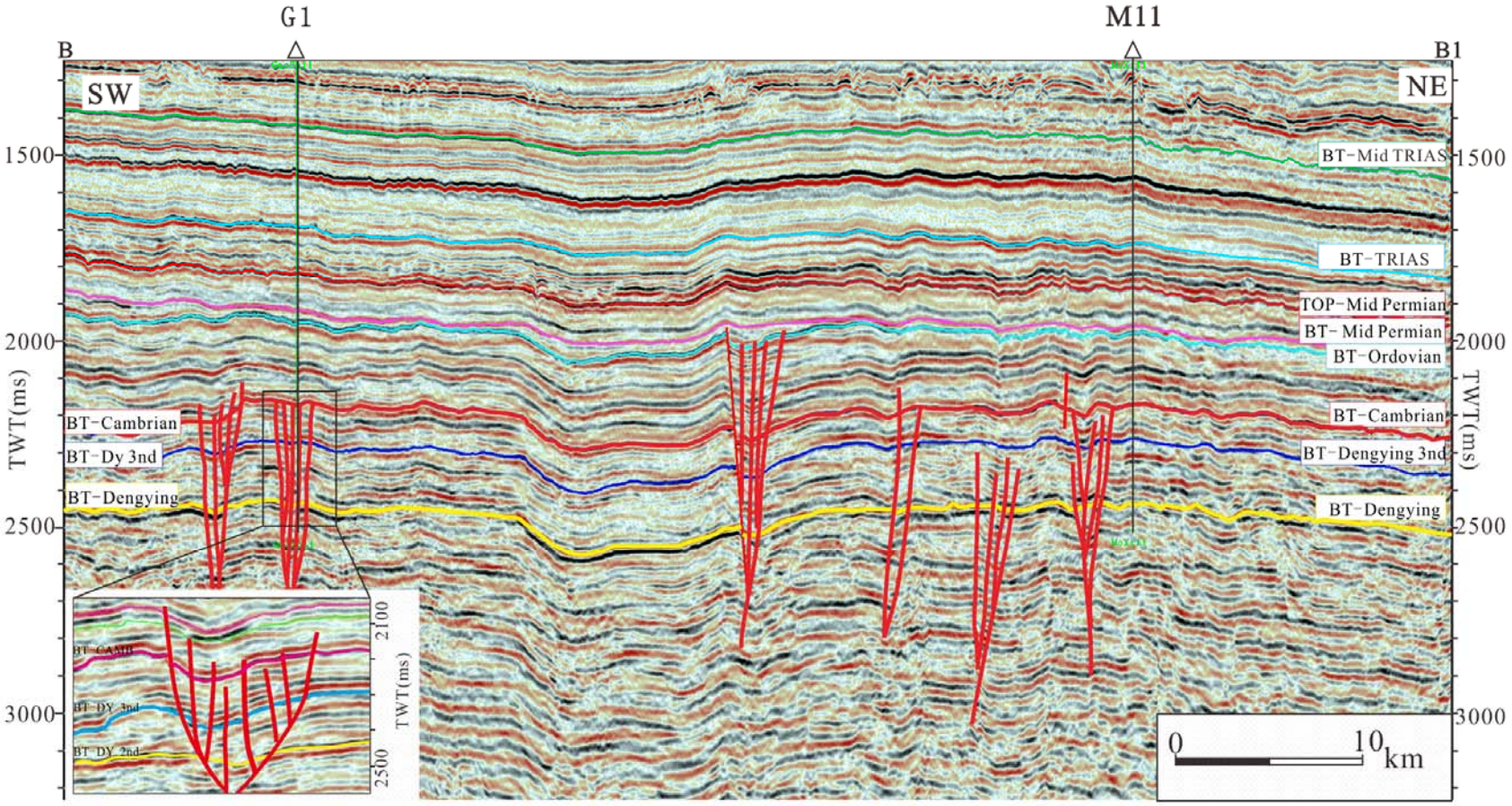
Seismic data： The dolomites of the Dengying in G-M area form around basement-rooted wrench faults that are detectable



The grabens are interpreted to be negative flower structures formed as a result of intracratonic rift in the Sinian–early Cambrian by transtensional faulting, and the Taphrogeny can be extended to the Ordovician Formation.

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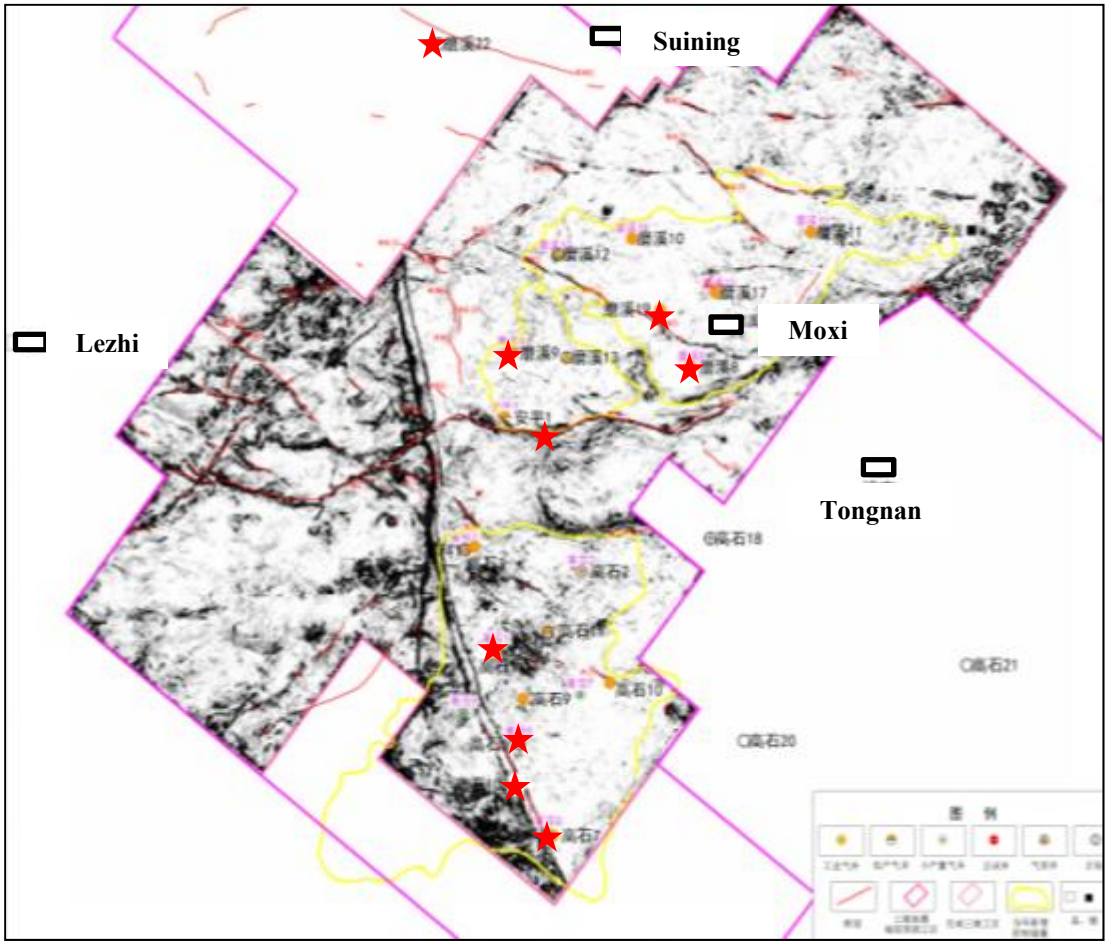

Overlay chart of Faults and coherence slice along Dengying 2nd

(Seismic data By EDRIP of Southwest Oil and Gas Field Company,2015)

Seismic interpretation results of coherence slices also confirmed that **two large N-S and E-W deep faults** developed in the G-M area, and associated with several NW-SE and SW-NE faults. The wells drilled in MVT associated minerals occur most in and around the deep fault zones.

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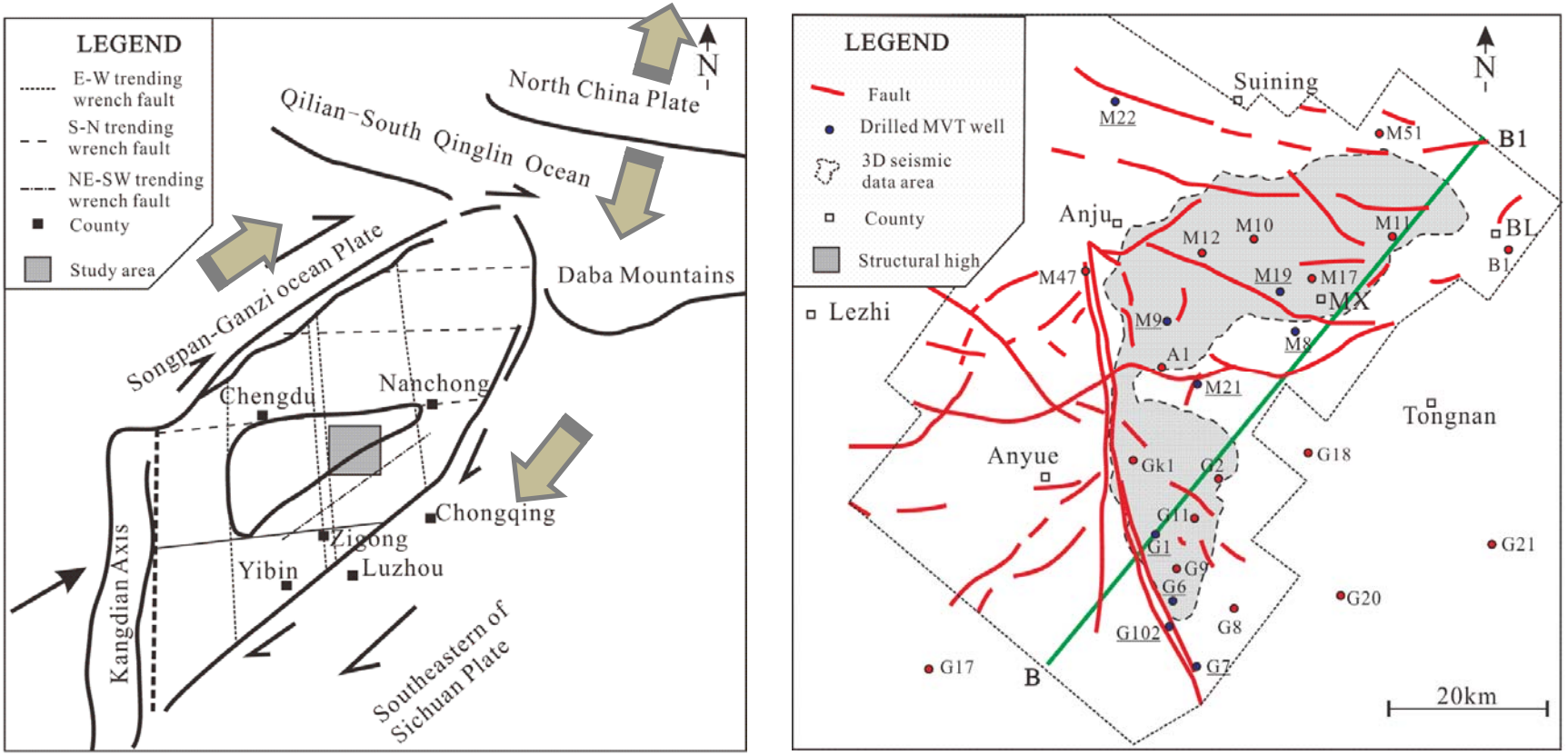
Regional "Xingkai taphrogeny" tectonic breakup led to basement faulting of oriented North-South and East-West strike



Precambrian Dengying dolomites were deposited on a relatively stable craton. A major breakup of "ancient China platform" between North China and the Yangtze block began during the terminal Proterozoic time due to "Xingkai taphrogeny" (LUO ZL, 2005). This breakup led to basement faulting of oriented North-South and East-West strike.

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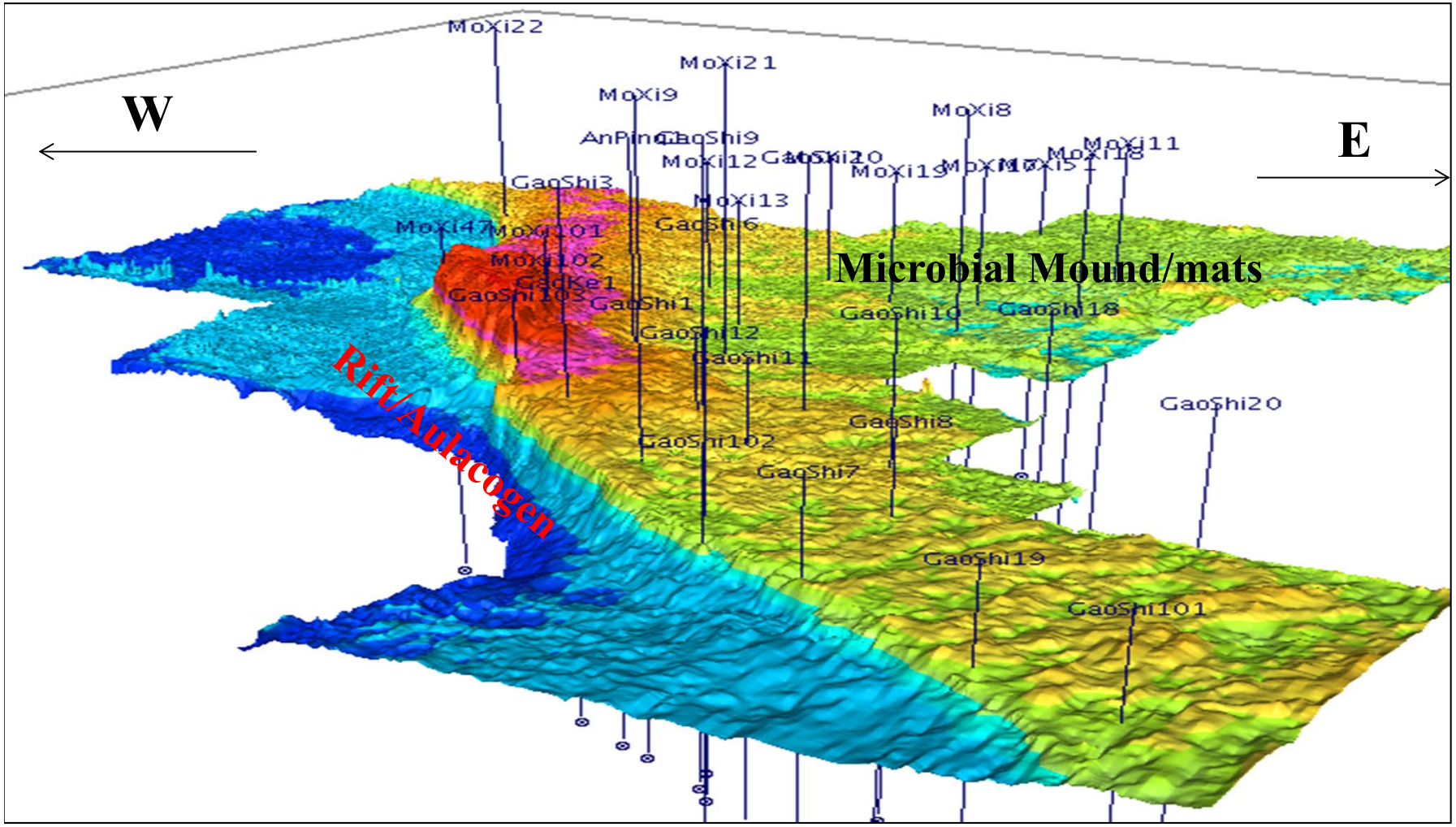
The inherited rift by basement-rooted wrench tectonic setting is the key of HTD develop in G-M area



Sketch Map of depositional environments in Dengying Formation

(Seismic data By EDRIP of Southwest Oil and Gas Field Company,2015)

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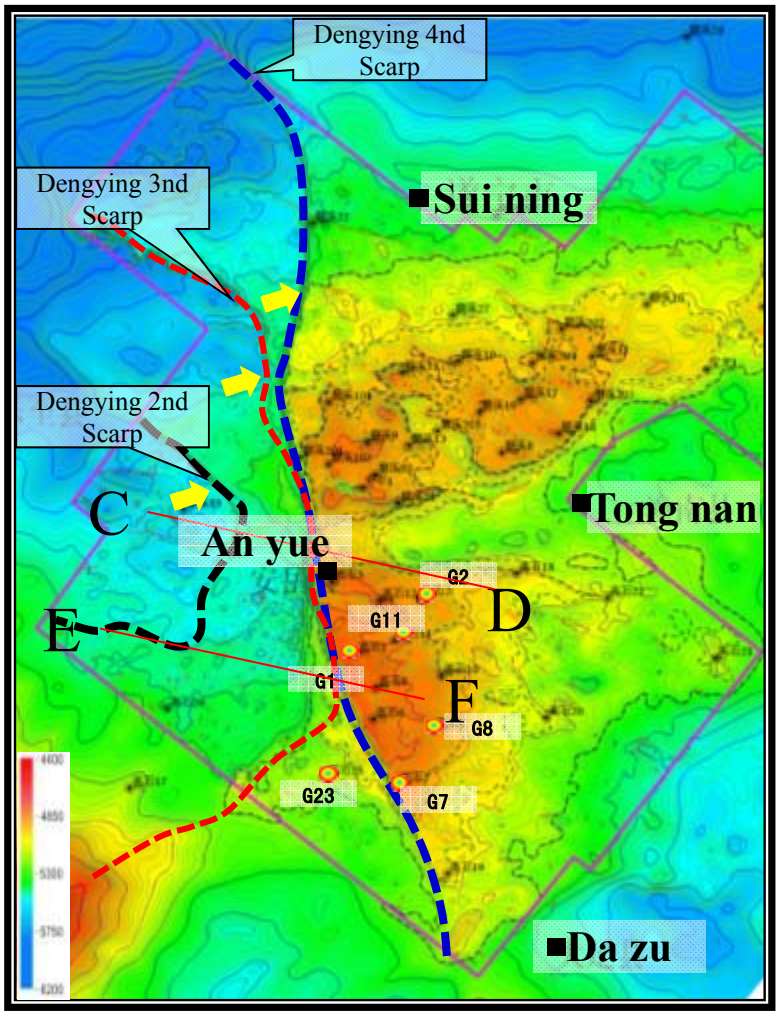
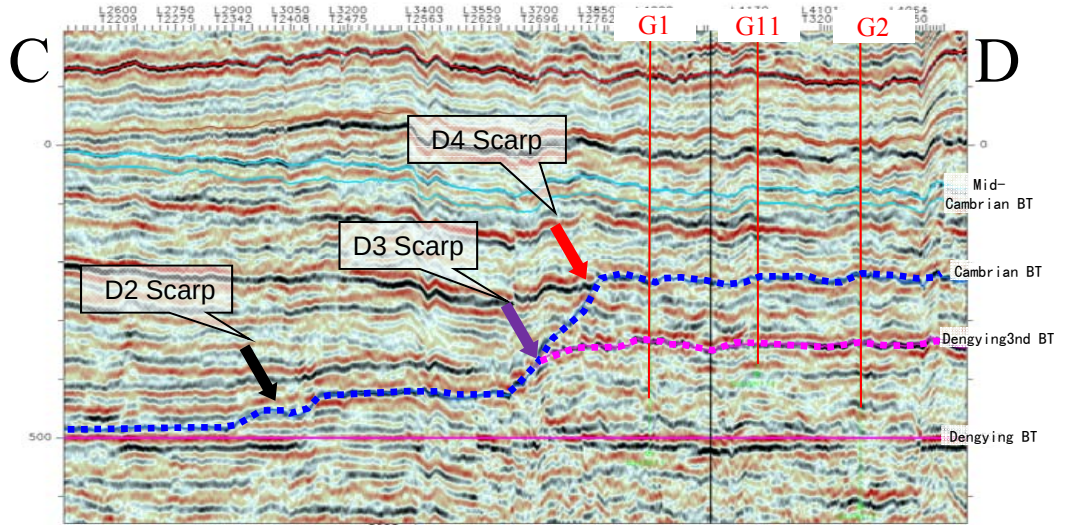
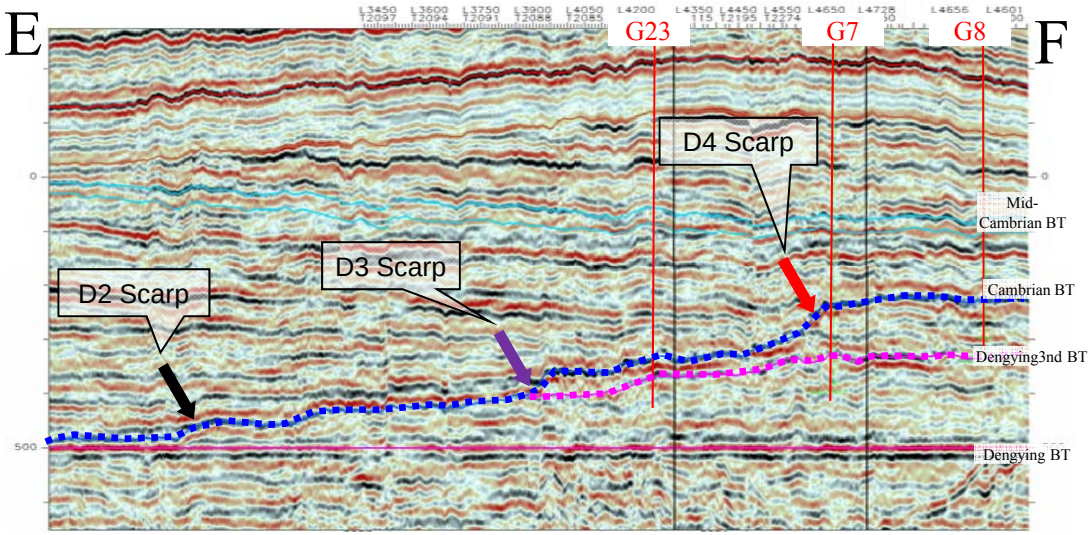


structural map of the Top Dengying in G-M area





Seismic data By EDRIP of Southwest Oil and Gas Field Company,2015

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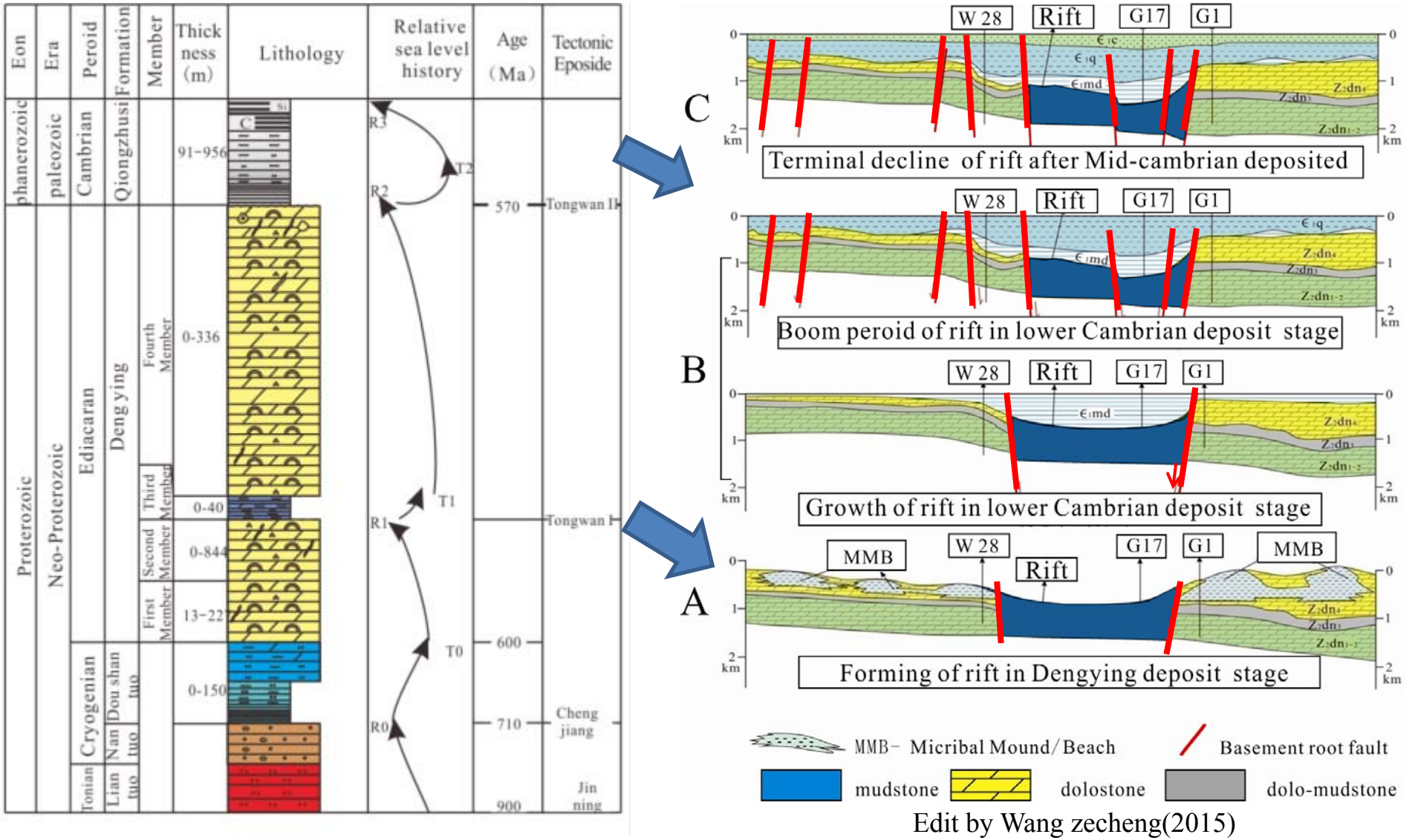

Edit by Wang zecheng(2015)

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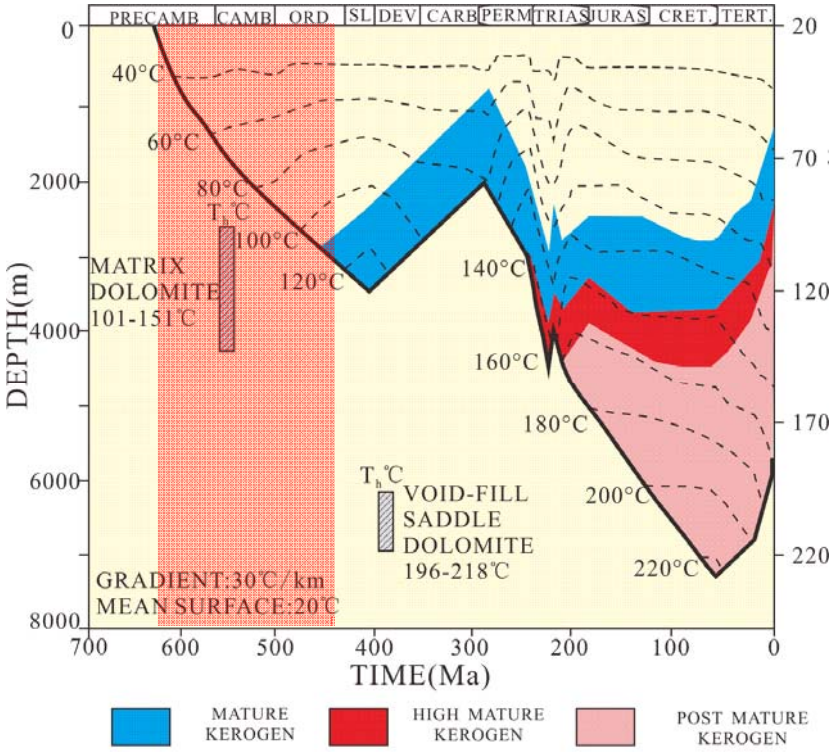
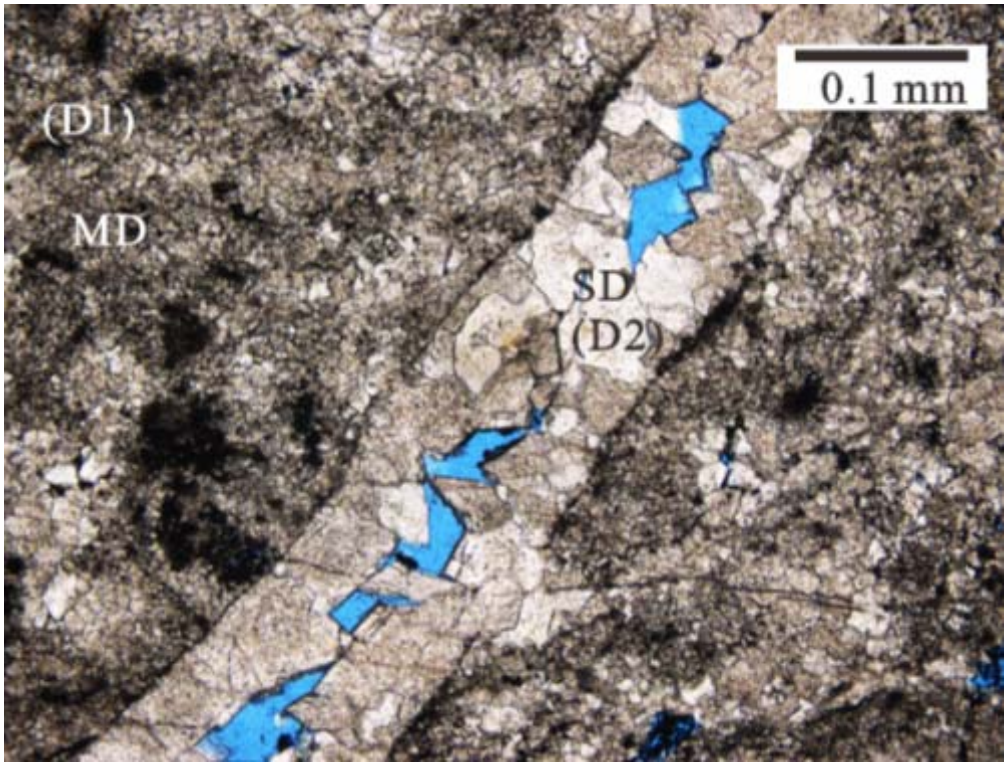
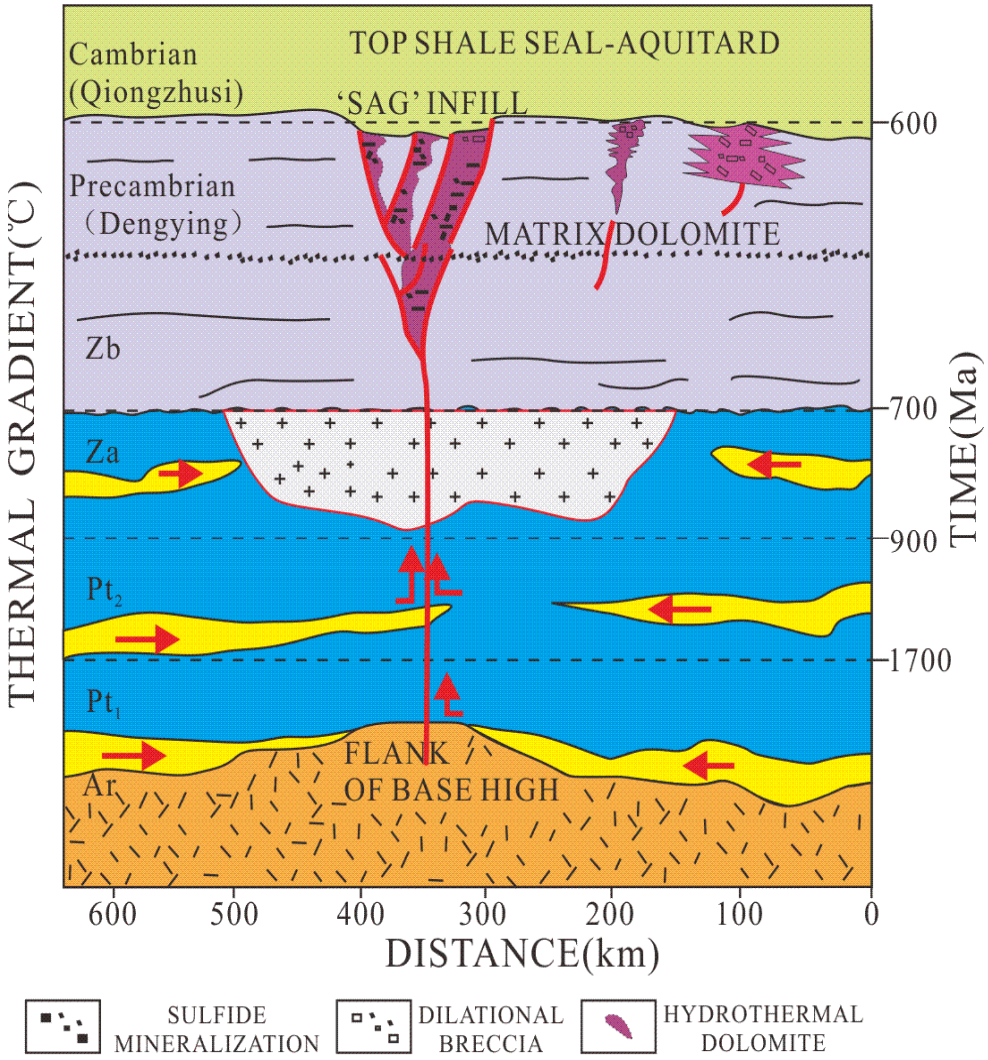
Fault-related hydrothermal alteration Time





- A regional geological study hints that the Dengying petrographical reflectance data are consistent with the presence of a 5-km stratigraphic succession of Dengying strata and maximum geothermal gradient of 20-30 ℃/km, all of which would **generate a maximum 150 ℃burial temperature** in G-M area. Obviously, normal burial condition is not responsible for the **high temperature (up to 218.7 ℃) by inclusions of saddle dolomite cement**. The high temperature conditions indicate that hydrothermal dolomitization is the result of locally geothermal abnormally.
- Integrated with the geothermal history, burial history and minerals ' paragenetic sequence of MVT minerals, the formation time of HTD is about **Late Sinian to Ordovician**.

Fault-related hydrothermal alteration Model



- High-pressure, high-temperature fluids flowed up active basement-rooted strike-slip and transtensional faults during the time of Dengying and Qiongzhusi deposition, and flowed out laterally into the early formed more permeable dolomites of the Dengying that are experienced epidiagenesis solution.
- Cooling hydrothermal fluids first leached the dolostone and produced vugs and pores in a migrating front, moving away from the fault/fracture zone.
- As permeability was enhanced by fracturing and leaching, warmer dolomite-supersaturated fluids migrated farther from the fault/fracture zone and precipitating saddle dolomite. These fluids first produced a halo of matrix dolomite, particularly on the downthrown sides of faults in negative flower structures.

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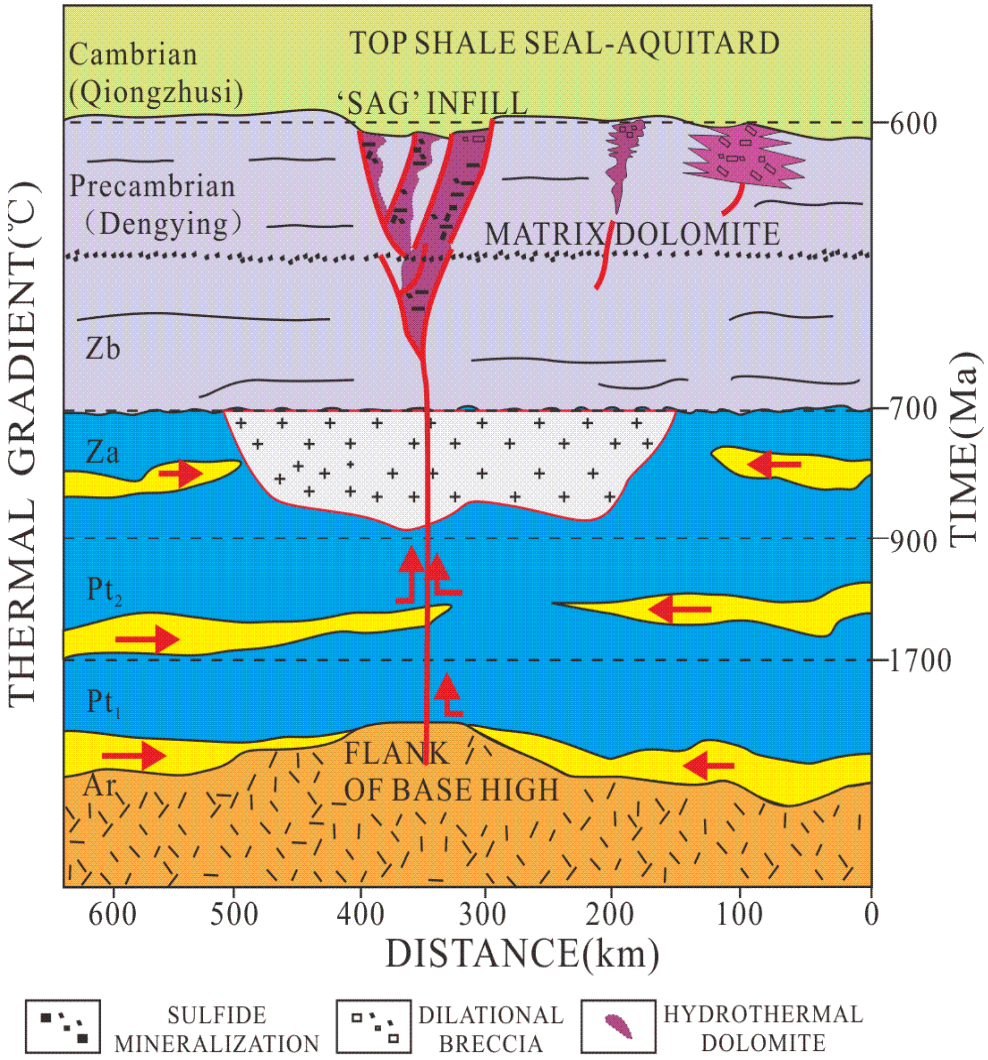
Fault-related hydrothermal alteration Model



- Because the fluids flowed up from greater depths where pressures are higher, the elevated pressure of the fluids may have led to hydrofracturing, enlargement of existing fractures, and further brecciation.
- Some dissolution vugs may have formed prior to and during matrix dolomitization. Matrix dolomitization was followed by further fracturing, brecciation, and vug development as tectonic activity continued. Fractures and vugs were lined or filled with saddle dolomite soon after their formation.

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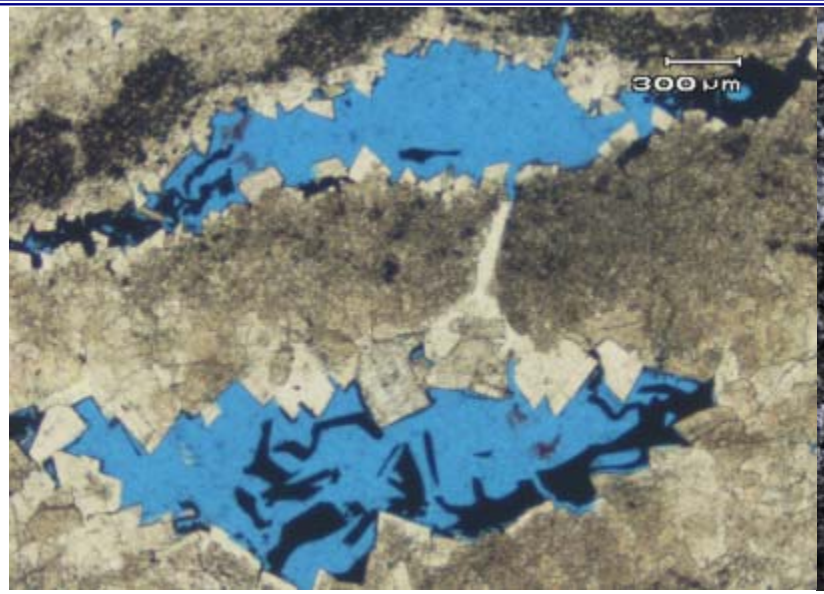
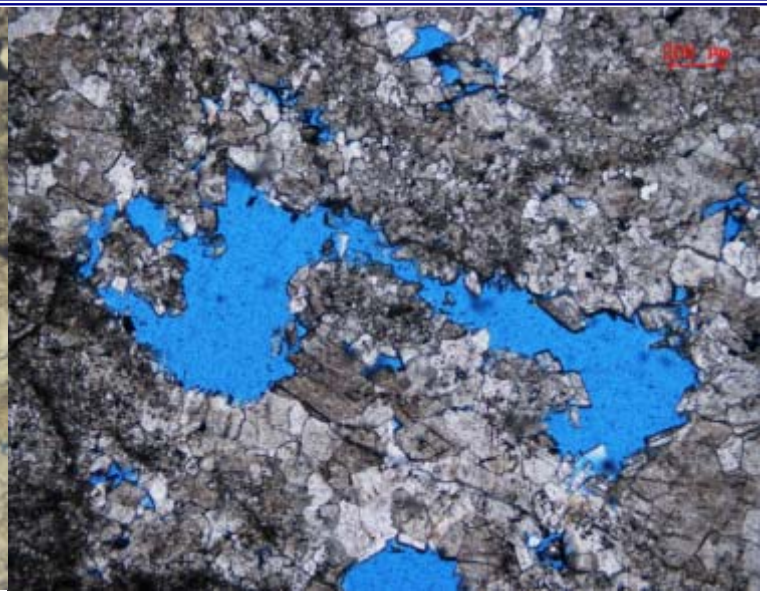
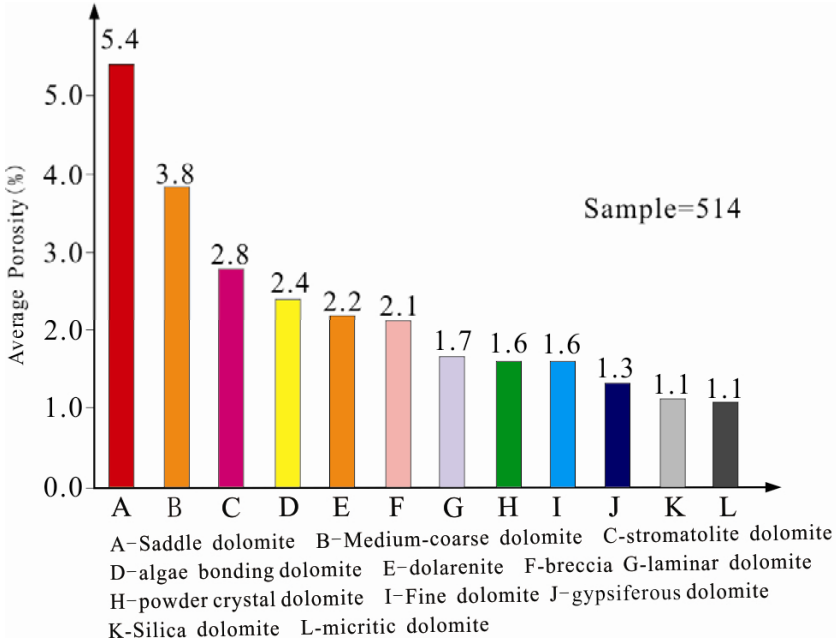
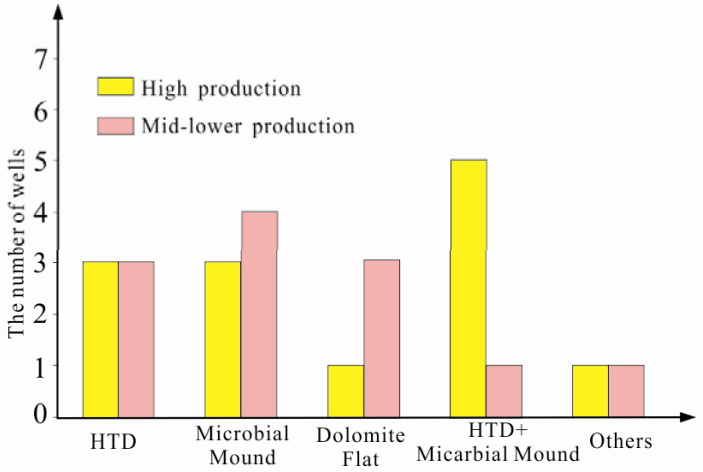
Reservoirs of hydrothermal dolomite-Dissolved pores and vugs developed









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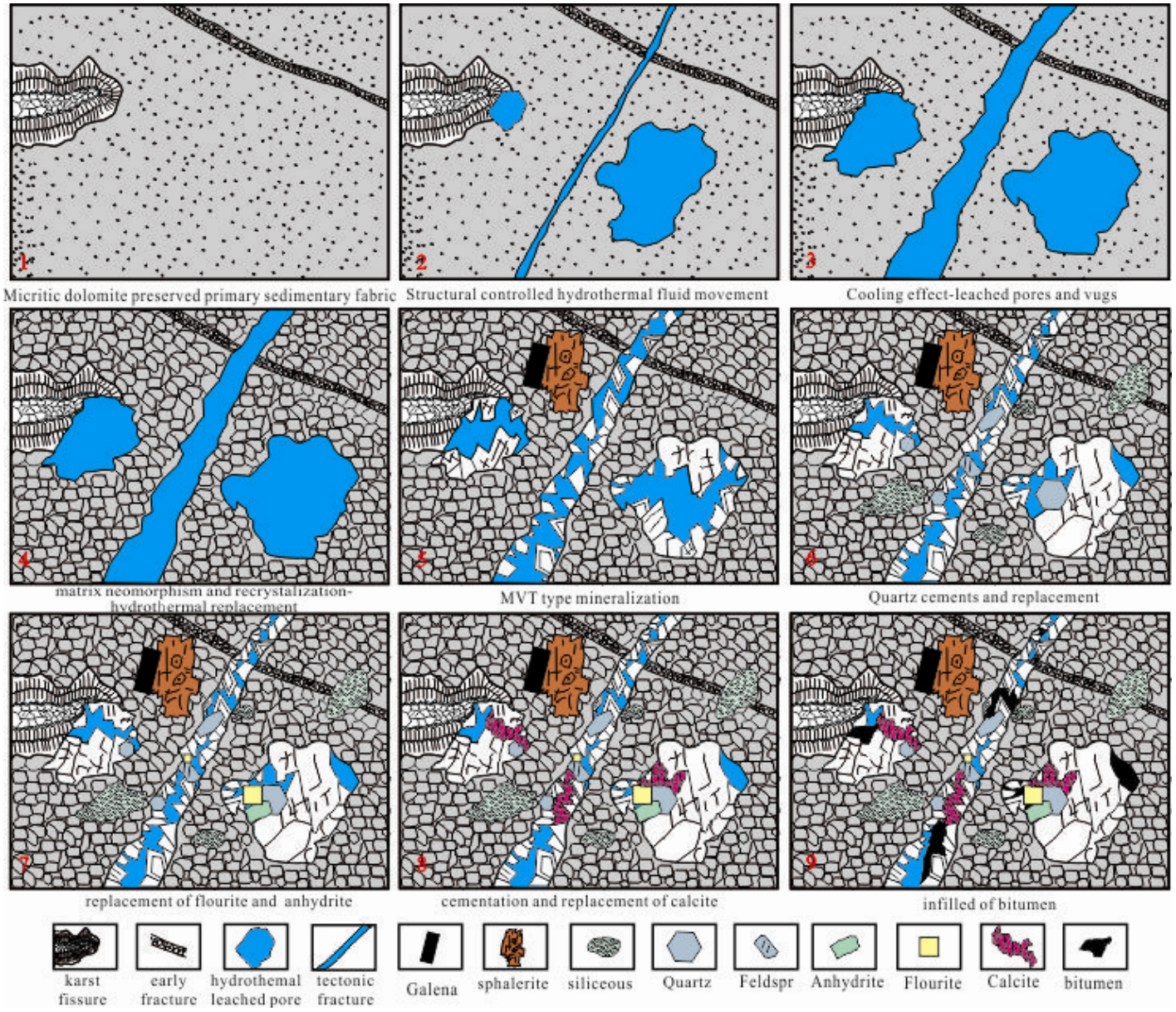
Model of HTD reservoir In Precambrian Dengying Formation



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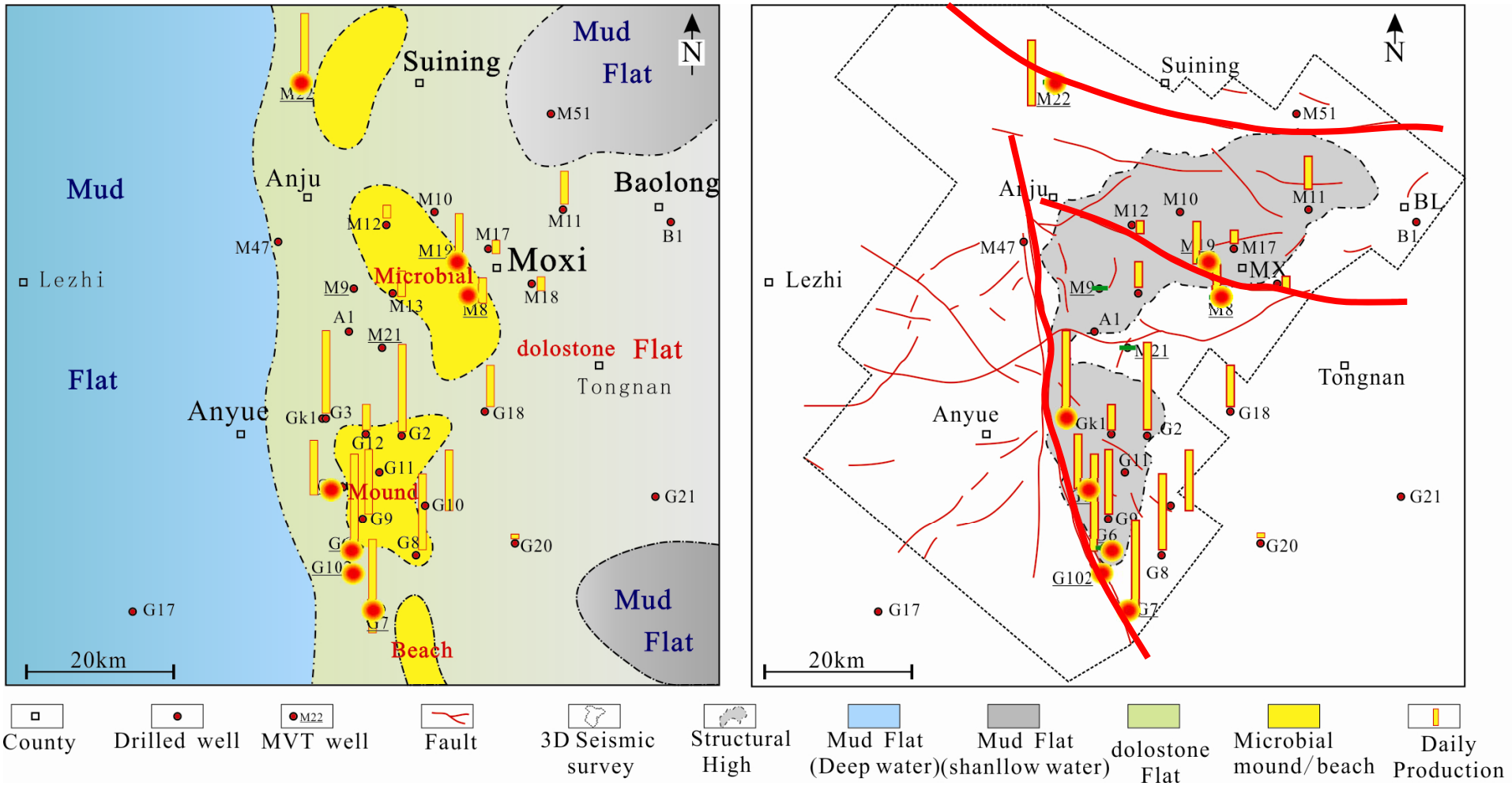
High production of Dengying are not directly controlled by sedimentary facies or structural high, but obviously effected by basement-root faults



Overlay chart of daily productivity and sedimentary facies in Dengying Formation(Left), daily productivity and basement faults of Dengying Formation in G-M area (Right)

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Some problems needing solving

- The **scale** of the HTD reservoir is almost difficult to predict
- The **recognition** of basement-root faults due to multi-stage tectonic movements
- The **risk** of the conflict between tectonic high and faults

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CONCLUSION

1.Petrography, fluid infusion, geochemistry and seismic data shows the evidence of hydrothermal dolomite in Precambrian Dengying Formation G-M area, central of Sichuan Basin.

2. Integrated with the geothermal history, burial history and minerals ' paragenetic sequence of MVT minerals, the formation time of HTD is about Late Sinian to Ordovician.

3.HTD reservoirs along basement-rooted wrench faults are probably the best candidates in Dengying Formation and have good hydrocarbon exploration prospect.

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