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Citation for final published version:

Zhu, Yanxian, He, Zhiliang, Guo, Xiaowen, Alves, Tiago M. , Lu, Xuesong, He, Sheng, Gao, Jian, Tao, Ze, Li, Huili and Li, Shuangjian 2024. Hydrocarbon-charge history of hydrothermally altered reservoirs: The Tailai gas field, east Sichuan Basin, China. AAPG Bulletin 108 (11) , pp. 2159-2188. 10.1306/08082423036

Publishers page: <https://doi.org/10.1306/08082423036>

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**Hydrocarbon-charge history of hydrothermally altered reservoirs: The Tailai Gas Field,
east Sichuan Basin, China**

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Acknowledgments

This study was financially supported by the Joint Funds of the National Natural Science Foundation
of China (no. U20B6001) and National Natural Science Foundation of China (no. 42002137). We
would like to thank AAPG Editor Dr. Matthew J. Pranter, Associate Editor Dr. Kenneth Peters and
well-qualified reviewers for the constructive suggestions. We thank Chunhui Zhu for help with in-
situ U-Pb dating. The Petroleum Exploration and Production Research Institute of SINOPEC is
thanked for providing background geological data.

Abstract: Hydrothermal dolomite reservoirs near basement strike-slip faults are major gas exploration targets in the Sichuan Basin, China. This work addresses the hydrocarbon generation and accumulation histories of the hydrothermal dolomite reservoirs within the Maokou Formation in the Tailai Gas Field. Diagenetic veining sequences and the hydrocarbon charge history are investigated through fluid inclusion analysis, geochemical data, and radiometric U-Pb dating of calcite cements. All these data are integrated by tying the geochemical results to the evolution of the nearby No. 15 Fault System and burial/thermal models for key wells. The interpreted seismic data indicate that the No. 15 Fault System provided major migration pathways for hydrocarbons. The hydrocarbon charge history of the Tailai Gas Field can be summarized as follows: (1) activity of the No.15 Fault System led to the migration of oil from the Wufeng-Longmaxi Formation source rocks into hydrothermal dolomite reservoirs from ~246.9 Ma to 245.3 Ma; (2) reactivation of the No.15 Fault System fed natural gas from the Wufeng-Longmaxi Formation source rocks into the Tailai Gas Field around ~222.4 Ma, with a small contribution from source rock in the first member of the Maokou Formation; (3) in-situ cracking of oil into gas occurred in the hydrothermal dolomite reservoirs from ~143 Ma to 110 Ma. The results in this work show that the oil and gas charge (Stages 1 and 2) was controlled by the No. 15 Fault System. The combination of fault-derived gas and cracking of oil (Stages 2 and 3) fed the prolific Tailai Gas Field.

Keywords: Hydrocarbon charge; Calcite cements; U-Pb dating; Hydrothermal dolomite; Sichuan Basin

42 **1. Introduction**

43 The Sichuan Basin of southern China had experienced multiple tectonic episodes, which: 1)
44 controlled the evolution of a marine carbonate platform from the Ediacaran to Late Triassic, 2) led to
45 the development a foreland basin in southern China during the Indosinian and Yanshanian orogenies
46 (Late Triassic to Late Cretaceous), and 3) promoted tectonic uplift and deformation at a regional scale
47 from the Late Cretaceous to the Quaternary (He et al., 2011; Liu et al., 2017; He et al., 2018; Liu et
48 al., 2021). This complex tectonic setting generated large basement faults, which became reactivated
49 in successive tectonic episodes with distinct magnitudes and time spans (Ma et al., 2018; Su et al.,
50 2020). This is an important aspect as fault reactivation can influence the permeability of fault zones,
51 fluid-flow patterns and fluid-focusing locations (Zhang et al., 2011; Li et al., 2017; Duwiquet et al.,
52 2022).

53 In the Sichuan Basin, Mid-Permian hydrothermal dolomites are often associated with basement
54 faults offsetting rocks older than 539 Ma, i.e. Ediacaran in age (Wang et al., 2014; Yang et al., 2015).
55 Such faults have attracted the attention of both industry and academia due to their impact on nearby
56 hydrocarbon reservoirs; they are able to enhance porosity and permeability when compared to
57 undeformed carbonate units (Xiao et al., 2020; S. J. Li et al., 2021). Basement faults also provided
58 pathways for migrating fluid in the Sichuan Basin, having controlled the subsequent hydrothermal
59 dolomitization in the northwestern, central and eastern parts of the basin during the Permian (Dong
60 et al., 2020; S. J. Li et al., 2021). Faults propagating into and offsetting source rocks thus played an
61 important role in the migration and distribution of oil and gas within the Permian units of the Sichuan
62 Basin (Yang et al., 2017; Ma et al., 2018; Y. J. Li et al., 2021; Jiao et al., 2022).

63 The Tailai Gas Field is a major hydrocarbon producing assets in the Sichuan Basin, being
64 located along the No.15 Fault System (Figure 1). It comprises a hydrothermal dolomite reservoir with
65 a production rate of $153.2 \times 10^3 \text{ m}^3/\text{d}$ (Zhang et al., 2020). The thickness of its dolomite reservoir -
66 part of the third member of the Maokou Formation - varies from 10.7 m to 23.1 m. Reservoir porosity
67 reaches a maximum value of 8.63% (Pan et al., 2020), and both calcite and dolomite cements have
68 been recently identified in it by S. J. Li et al. (2021) and T. Yang et al. (2022). These cements can
69 provide key information on the timings of hydrocarbon accumulation in the Tailai Gas Field.

70 In-situ radiometric U-Pb dating of carbonate cements has recently gathered significant interest
71 in isotope geochronology (Roberts et al., 2020, 2021). It was successfully used to determine the age
72 of: a) carbonate minerals in oceanic crust drilled by the International Ocean Discovery Program
73 (IODP) (Coogan et al., 2016), b) Urgonian carbonate reservoirs from France (Godeau et al., 2018),
74 and c) hydrocarbon prospects in the Tarim Basin, China (Chen et al., 2022). In addition, Micro-Laser
75 Raman spectroscopy (LRM) is a micro-analytical technique used to analyze fluid inclusions in rocks
76 which, when combined with microthermometric measurements, can provide information on the
77 composition, formation temperature and salinity of reservoir fluids (Burke, 2001; Goldstein, 2001;
78 Zhang et al., 2016). Finally, $^{87}\text{Sr}/^{87}\text{Sr}$, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopes can be efficiently applied to understand
79 the origin of vein-filling minerals (Bau et al., 2014; Worden et al., 2016; Tostevin et al., 2016). Based
80 on the dating and geochemical characterization of the cements and trapped fluid inclusions in rock,
81 one can identify discrete phases of calcite and dolomite veining, as well as the timings of oil and gas
82 charge (Guo et al., 2016; P. Yang et al., 2022).

83 This work uses carbonate rock core samples from three wells drilled in the Tailai Gas Field,

84 Sichuan Basin, to address the hydrocarbon-charging history of the hydrothermal dolomite reservoirs
85 in the third member of the Maokou Formation (Figures 1 and 2). The core samples, which include
86 veins and pyrobitumen in the hydrothermal dolomite reservoirs, were petrographically analyzed.
87 Fluid inclusion and Raman Spectroscopy data were obtained to investigate its composition, trapped
88 temperature and pressure. In parallel, radiometric U-Pb dating of calcites with pyrobitumen and
89 methane inclusions was employed to determine absolute charging ages for the Tailai Gas Field. This
90 is an important addition to the present knowledge of the field, as previous research was focused either
91 on the origin and source of natural gas (Y. J. Li et al., 2021; Huang et al., 2023), or on the hydrocarbon
92 accumulation models for the hydrothermal dolomite reservoirs in the third member of the Maokou
93 Formation (Pan et al., 2020). Hydrocarbon accumulation processes, and their relationship to basement
94 faults, are yet documented for this same unit. The aims of this paper are to:

95 1) Investigate the relationship between oil/gas charging processes and multi-phase veining in the
96 Tailai Gas Field;

97 2) Determine the timings of oil and gas charge by in-situ U-Pb data combined with
98 homogenization temperatures (T_h) of aqueous inclusions coeval with pyrobitumen and methane
99 inclusions;

100 3) Identify the main phases of faulting, and its reactivation periods, near the Tailai Gas Field;

101 4) Characterize fault-related hydrocarbon accumulation processes in hydrothermal dolomite
102 reservoirs.

103

104 2. Geological Setting

105 The Sichuan Basin has a total area of $180 \times 10^3 \text{ km}^2$ and is located in southern China (Figure 1).
106 It forms the eastern margin of the Qinghai-Tibet Plateau. The Sichuan Basin is surrounded by a series
107 of fold-and-thrust belts and associated structures; the Dabashan belt to the north, the Daloushan belt
108 to the south, the Longmenshan belt to the west, and the Qiyueshan fault to the east (Figure 1B). The
109 basin is rhombic in shape, being characterized by a vast depression to the west and a paleo-high in its
110 center (Figure 1B). At a local scale, the Tailai Gas Field is located in the Bashansi syncline of the east
111 Sichuan Basin, near the No. 15 Fault System (Zhang et al., 2020) (Figure 1C). The east Sichuan Basin
112 is itself bounded by the Huayingshan and Qiyueshan faults (Figure 1B). The east Sichuan Basin is a
113 typical thin-skinned Jura-type fold belt with tight anticlines and wide synclines (Li et al., 2015; Gu et
114 al., 2021) (Figure 1D). Triassic strata are exposed in the core of most anticlines, with Permian strata
115 outcropping in places. Most strata outcropping in the synclines are Jurassic in age.

116 Seismic and borehole data indicate that the east Sichuan Basin was first filled with marine strata
117 from the Sinian to the Middle Triassic, followed by continental deposits from the Late Triassic to the
118 present (Figure 2). Main source rocks are structurally placed under the third member of the Maokou
119 Formation and comprise shales in Qiongzhusi Formation and Wufeng-Longmaxi Formation, together
120 with marlite in the first member of the Maokou Formation (Figure 2). Hydrothermal dolomite
121 reservoirs in the third member of the Maokou Formation are widespread in the Sichuan Basin (Figure
122 1C), and characterized by their high porosity and permeability (S. J. Li et al., 2021). The thickness of
123 hydrothermal dolomites can reach 50 m in parts of the basin and, consequently, more than 20 wells
124 are currently producing gas from such Mid-Permian dolomitic intervals (Figure 1C). Proven reserves

125 in these dolomites reach $85.2 \times 10^9 \text{ m}^3$, a value far lower than their estimated total resource of 2,000
126 $\times 10^9 \text{ m}^3$ (Li et al., 2020). In the east Sichuan Basin, shales in the Upper Permian Longtan Formation
127 comprise the main regional seal for the hydrothermal dolomite reservoirs in the third member of the
128 Maokou Formation.

129 After the Sinian (Pre-Cambrian), the Sichuan Basin experienced multiple tectonic episodes,
130 which structurally controlled regional deformation and the reactivation of the No. 15 Fault System
131 (Mattaueer et al., 1985; Meng and Zhang, 1999; Yan et al., 2003; Charvet et al., 2010; He et al., 2011;
132 Li et al., 2019). In the Early Cambrian, Tongwan tectonics resulted in the formation of the Mianyang-
133 Changning intracratonic basin, and the No. 15 Fault System formed during discrete extensional
134 episodes (Liu et al., 2017, 2021; Su et al., 2020). Thereafter, Caledonian tectonics promoted tectonic
135 uplift and exhumation during the Silurian, Devonian and Carboniferous (Charvet, 2013; Huang et al.,
136 2017b; Su et al., 2020).

137 From the Late Carboniferous to the Early Permian, the Hercynian orogeny resulted in the uplift
138 and exhumation of the east Sichuan Basin (Huang et al., 2017a). Another phase of uplift and erosion
139 during the Dongwu tectonic episode (Permian) is marked by a prominent regional unconformity atop
140 the Maokou Formation (Horizon H3 in Figure 2). In addition, the Emeishan Large Igneous Province
141 (ELIP) is known to have broadly affected the Sichuan Basin during the Permian; it facilitated fluid
142 circulation within and through the No. 15 Fault System, driving hydrothermal dolomitization within
143 the third member of the Maokou Formation (Luo et al., 2012; Su et al., 2020; T. Yang et al., 2022).

144 During the Indosinian orogeny, the Yangtze plate collided with the North China platform in the
145 Triassic (~250 – 225 Ma), and with the Songpan block in the Late Triassic to Early Jurassic, from

146 ~225 Ma to 190 Ma (He et al., 2011; Zhang et al., 2013; Wang et al., 2021). The east Sichuan Basin
147 was deformed as recorded by the marked uplift of the Luzhou-Kaijiang High and resulting in an
148 angular unconformity at the base of the Xujiache Formation - T₃x (Horizon H5 in Figure 2; Huang et
149 al., 2019). Structural deformation during the Indosinian orogeny saw the development of detachment
150 and fault-propagation folds. Such orogeny resulted in the dextral strike-slip reactivation of the No.15
151 Fault System (Zeng et al., 2023).

152 The Yanshanian orogeny was associated with subduction of Paleo-Pacific Plate under the
153 Eurasian Plate (Jin et al., 2009; Li et al., 2012). Fold-and-thrust belts were formed in the east Sichuan
154 Basin in the early stages of the Yanshanian orogeny (189 –142 Ma), from the Early Jurassic to the
155 earliest Cretaceous, and were later deformed during the Late Cretaceous (~125 – 80 Ma) to form Jura-
156 type fold-and-thrust belts. Main structures formed at this time comprise fault-propagation folds,
157 detachment folds, pop-up structures and a few duplex structures (Shi et al., 2016; Zheng et al., 2019;
158 Su et al., 2020). The No. 15 Fault System was again reactivated near the Tailai Gas Field (Zeng et al.,
159 2023). Finally, the Himalayan orogeny – spanning from the end of the Cretaceous to the Holocene -
160 promoted the exhumation of the Songpan Block. Tectonic uplift, erosion, and extensive folding
161 occurred in the east Sichuan Basin at this time (Shi et al., 2016; He et al., 2022).

162 **3. Methods and Samples Analyzed**

163 **3.1. Geochemical analysis**

164 This study focuses on the geochemical analysis of 10 core samples of carbonate rocks from the
165 third member of the Maokou Formation (Table 1). These samples were collected from three producing
166 wells in the Tailai Gas Field. In these wells were collected one (1) vein-bearing sample (Well TL6),

167 five (5) samples with veins and pyrobitumen development (Well TL7), and four (4) samples with vein
168 and pyrobitumen filling (Well TL601) (Table 1). The samples collected from these three wells have
169 a wide range of depths, from 5,094.70 m [16,715 ft] to 5,534.05 m [18,156 ft]. They sampled fractures
170 and vugs in hydrothermal dolomites that were filled with dolomite, calcite, quartz cements and
171 pyrobitumen, so they provide relevant information regarding cement-forming fluid and hydrocarbon
172 fluid activity. The samples were processed and cut into double-polished thin sections, with a thickness
173 of approximately 100 μm , ready for petrographic analysis, fluid inclusion analysis, and Raman
174 spectroscopy.

175 The techniques utilized in this work include cathodoluminescence (CL), in-situ Rare Earth
176 Elements and Yttrium (REEY) analysis, and $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ measurements, all used with the
177 aim of understanding the diagenetic sequence of cements in the 10 processed samples. In addition,
178 microthermometric measurements and Raman spectroscopy were employed on fluid inclusions to
179 obtain their gas compositions, Homogenization Temperatures (Th) and Melting Temperatures (Tm).
180 Radiometric U-Pb analysis of calcites with primary pyrobitumen and methane inclusions were also
181 performed to determine the absolute ages of oil and gas charging episodes. A petrographic study of
182 veins and fluid inclusions was completed using a Nikon-LV100 microscope. Cathodoluminescence
183 images of thin sections were acquired using a CL8200 MK5 cathodoluminescence instrument at the
184 Key Laboratory of Tectonics and Petroleum Resources of Ministry of Education, China University of
185 Geosciences (Wuhan). A Leica DM2500 microscope was used for the imaging of the thin sections.

186 Fluid inclusions were studied based on the fluid inclusion assemblages (FIA) definition of
187 Goldstein (2001). Hence, the parameters Th (Homogenization Temperature) and Tm (Melting

Temperature) of aqueous inclusions were measured using a Zeiss Axiovert 200 M microscope equipped with a Linkam THMS600 heating-freezing stage. The Th values were determined using a heating rate of 5 °C/min, while Tm data were obtained using a heating/cooling rate of 1 °C/min. Measured temperature accuracy for Th and Tm are respectively ± 1 °C and ± 0.1 °C.

The corresponding salinity of fluid inclusions was calculated from the Tm values obtained for our samples (Bodnar, 1993):

$$\text{Salinity} = 0.00 + 1.78\theta - 0.0442\theta^2 + 0.000557\theta^3 \quad (1)$$

where θ is the melting temperature of the aqueous inclusion in degrees Celsius. The method of Bodnar (1993) compares the entrapment temperature of fluid inclusions with estimates of the samples' burial history, and has been widely used to determine the timings of hydrocarbon charge in many a prospect (Goldstein, 2001).

Rare Earth Elements and Yttrium (REEY) analysis were completed using a Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) at Wuhan SampleSolution Analytical Technology Co., Ltd. Laser sampling was performed using a GeolasPro laser ablation system that consists of a COMPexPro 102 ArF excimer laser (with a wavelength of 193 nm and maximum energy of 200 mJ) and a MicroLas optical system. An Agilent 7900 ICP-MS instrument was used to acquire ion-signal intensities. Prior to such an elemental analysis, helium was used as the carrier gas, and laser spot was set at 160 μm . The experimental procedure for each sample included the acquisition of background data for approximately 20 – 30 s and detailed measurements for 50 s. In addition to an internal calibration standard, the experimental compositions and concentration of major and trace elements were calibrated against the artificial silicate glass NIST610. The ICP-MS DataCal Excel-

209 based program was used off-line in the selection and integration of background and analytical data
210 (Liu et al., 2008). At the end of our analysis, the REEY contents of the host rocks and cements were
211 normalized to Post-Archaean Australian Shale (PAAS) compositions (McLennan, 1989).

212 Analysis $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ were undertaken at the State Key Lab of Geological Processes
213 and Mineral Resources, China University of Geosciences (Wuhan). Samples were taken with a
214 microdrill and crushed into a 200 mesh. Samples were first reacted with 100% H_3PO_4 in a vacuum at
215 25 °C, carbon and oxygen isotopes measurements were completed using a MAT253 gas stable isotope
216 mass spectrometer. The values for carbon and oxygen isotopes were given by the VPDB standard,
217 whose analytical uncertainties are better than $\pm 0.1\text{‰}$.

218 Strontium isotope tests were determined using a Nu Instruments Multi-Collector-Inductively
219 Coupled Plasma-Mass Spectrometer. Samples were centrifuged, purified, and separated, and Sr
220 isotope data were corrected for mass fractionation using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. The International
221 Standard Sample SRM-987 was used to monitor data quality.

222 Fluid inclusion Laser Raman experiments were completed using a JY/Horiba LABRAM HR800
223 (532 nm green laser; 300 mW output power) at the China University of Geosciences (Wuhan).
224 Pyrobitumen and gas inclusions were examined using a 200- μm confocal aperture and 300-gr. mm^{-1}
225 grating, with a grating center of 2650 cm^{-1} . For a better resolution, accurate Raman shifts of individual
226 gas-phase inclusions were measured using a 50- μm confocal aperture and 1800-gr. mm^{-1} grating, with
227 a grating center of 2900 cm^{-1} . Data acquisition times varied from 10 to 20 s so as to obtain the best
228 signal-to-noise ratios possible, while precise Raman symmetric stretching peak position of CH_4 was
229 corrected using a neon lamp (Lin et al., 2007). The equivalent vitrinite reflectance (VReq) of

pyrobitumen inclusions was calculated using the formula proposed by Liu et al. (2013). The density of pure methane inclusions was calculated using the C-H symmetric stretching band of methane at a room temperature (Lu et al., 2007). The trapped pressure of single-phase methane inclusions was calculated using the equations of state of Duan et al. (1992) and fluid inclusion data, including their density and trapped temperature. The homogenization temperature of the coexisting aqueous inclusions has been widely used to determine the trapped temperature of single-phase methane inclusions (Lin and Bodnar, 2010; Gao et al., 2019). The detailed procedures of PVT modeling of single-phase methane inclusions are listed in Supplementary File S1.

The radiometric U-Pb dating of calcite containing primary pyrobitumen/oil/gas inclusions has been recently applied to determine the absolute ages of oil and gas charge in particular fields (Chen et al., 2022). Our U-Pb dating of calcite in veins was completed using a RESOLUTION SE-S155 Laser Ablation System coupled to a Thermo Fisher iCAP RQ ICP-MS in Guizhou Tongwei Analytical Technology Co., Ltd and Key Laboratory of Basin Structure and Hydrocarbon Accumulation, CNPC. Calcite samples were made into standard 2.5-cm-diameter mounts with epoxy resin, which were then washed with ultrasound and ultrapure water (MQ), dried, and placed into the sample holder for U-Pb analysis. Before performing our LA-ICP-MS U-Pb dating, all measured points were ablated 15 shots with a uniform-sized laser beam so to eliminate potential contamination of the mineral surface. The LA-ICP-MS U-Pb dating was performed using a laser spot set with a diameter of 120 μm . The repetition rate of the laser pulse was set at 15 Hz and its fluence at $\sim 2.5 \text{ J/cm}^2$. The measurement cycle comprised a pre-ablation background of 15 s, an ablation period of 20 s and a washout time of 5 s.

251 After this measurement cycle, the samples produced by laser erosion were extracted from the
252 sample cell using gaseous He mixed with Ar gas, sent out to the ICP-MS in order to complete the test.
253 Our samples were measured together with a NIST 614 glass standard and several working matrix-
254 matched laboratory calcite standards, such as AHX-1d and PTKD-2 (Pan et al., 2021; Kendrick et al.,
255 2022). Repeated measurements of the NIST 614 glass and calcite standards were used to correct for
256 $^{207}\text{Pb}/^{206}\text{Pb}$ fractionation and instrument-related drift in the $^{206}\text{Pb}/^{238}\text{U}$ ratios. An in-house carbonate
257 standard AHX-1d with a cross-calibrated age of 238.2 ± 2.4 Ma was used for bias corrections of the
258 measured $^{238}\text{U}/^{206}\text{Pb}$ ratios. We adopted the built-in “U-Pb geochronology” data reduction schemes
259 (DRS) embedded in the IOLITE package of Paton et al. (2011) to calculate U-Pb isotope ratios,
260 apparent U-Pb ages, and U-Th-Pb concentration calculations. Later, the data were regressed on Tera-
261 Wasserburg concordia plots using the ISOPLOT version 3.75 of Ludwig (2012) so to determine each
262 sample’s U-Pb age (Chen et al., 2022).

263 3.2. Basin modeling

264 Burial and thermal models for the study area (and samples analyzed) were computed using
265 BasinMod-1D[®]. Parameters such as lithology, stratigraphic and erosional thickness, measured
266 maturity data and borehole temperatures were taken into consideration in our models (He and
267 Middleton, 2002). Lithology, stratigraphic thickness, measured maturity data and borehole
268 temperatures were obtained from SINOPEC. The absolute ages of key tectonic episodes and erosional
269 thickness were used to constrain the tectonic evolution of the study area (Deng et al., 2009; He et al.,
270 2011; Liu et al., 2021). Present-day heat flow values were calculated based on rock thermal
271 conductivity and geothermal gradients as determined from the measured borehole temperatures.

272 Paleo-heat flow values were reconstructed by geothermometer data, including vitrinite reflectance
273 and apatite fission track (Jiang et al., 2018; Qiu et al., 2022).

274 Recent work has confirmed that important source rocks under the third member of the Maokou
275 Formation include the Qiongzhusi Formation, the Wufeng-Longmaxi Formation and the first member
276 of the Maokou Formation (Guo et al., 2020; Y. J. Li et al., 2021; Qiu et al., 2021). However, the
277 gypsum-salt rocks are widely developed in the Middle Cambrian strata with the cumulative thickness
278 ranging from 100 m to 300 m in the study area (Xu et al., 2016). The gypsum-salt rocks have the
279 characteristics of strong plasticity and poor physical properties, which provide regional seal
280 conditions preventing the upward migration of hydrocarbon from the Lower Cambrian Qiongzhusi
281 Formation (Gu et al., 2015). Therefore, the source rocks in the Wufeng-Longmaxi Formation and the
282 first member of the Maokou Formation are considered as the main source intervals in our basin
283 models. The thickness of Wufeng-Longmaxi Formation source rocks with TOC of more than 2.0 wt%
284 varies from 40 m to 80 m in the research region (Y. J. Li et al., 2021). The thickness of the source
285 rock in the first member of the Maokou Formation ranged from 40 m to 70 m (S. Li, 2021), with its
286 TOC varying from 0.75 wt% to 1.50 wt% in the study area (Y. J. Li et al., 2021). At the end of our
287 calculations, the basin models were calibrated by the existing bottom-hole temperatures and vitrinite
288 reflectance values.

289 **3.3. Seismic data interpretation**

290 The interpreted 3D seismic data in the Tailai Gas Field covers an area of approximately 1500
291 km², with a sampling interval of 1 ms, and a bin spacing of 20 m × 20 m. Vertical resolution can
292 reach 25 m. Seismic data were interpreted to understand the structural style and reactivation history

of the No. 15 Fault System, including associated faults, during multiple tectonic episodes. The horizons interpreted in this work were selected based on previous studies in the Sichuan Basin (Zhang et al., 2020; Gu et al., 2021). Included in our interpretation was the use of variance time slices to effectively identify faults with small fault throws and high angles (Liao et al., 2020; Zhao et al., 2021). We selected, on Schlumberger's Petrel®, an inline range of 3, a crossline range of 3 and vertical smoothing of 6 to better image subtle structures. To avoid the influence of dipping structures, a dip correlation was set when extracting the variance attribute. The variance attribute was also used to interpret the geometry and structural style of the No. 15 Fault System. Seismic profiles were interpreted so as to identify strata growth and thickness differences across the No. 15 Fault System and its splayed segments. Thickness changes in strata may record the reactivation periods of a given fault (Shiroodi et al., 2015).

4. Results

4.1. Petrography

Figures 3 and 4 show photographs and photomicrographs of core samples taken from the third member of the Maokou Formation. As revealed in the Figure 3, vugs, stylolites and fractures are widely developed in the carbonate rocks. These vugs, stylolites and fractures are partly or completely filled by dolomite, calcite, quartz and, in some cases, pyrobitumen (Figure 3). In particular, stylolites are fully filled by pyrobitumen (Figure 3E). Fractures are predominantly low-angle (30° - 40°) or high-angle structures (70° - 90°), with no intermediate dips (Figure 3A, B, C, D). Low-angle fractures are 1 to 20 mm wide and filled by dolomite, calcite, quartz, and pyrobitumen (Figure 3A, B). High-angle fractures show a relatively narrow width (3 to 9 mm) and are filled with dolomite and calcite

314 cements (Figure 3B, C).

315 Microscopic observations of thin sections reveal fractures and vugs to be filled by saddle
316 dolomite (SD), calcite (Cal) and quartz (Qtz) cements. Five veining stages were identified based on
317 these microscopic data: Stage 1 (SD-1 cements), Stage 2 (SD-2 cements), Stage 3 (Cal-1 cements),
318 Stage 4 (Cal-2 cements), and Stage 5 (Qtz cements) (Figure 4). The mineral diagenetic sequence was
319 corrected by in-situ U-Pb dating of the carbonate cements.

320 SD-1 cements developed in vertical fractures and dissolved vugs, which typically show an
321 undulose extinction and bright pink cathodoluminescence (CL) colors (Figure 4A, B, C). SD-2
322 cements also show an undulose extinction, but rugged edges and dark pink CL colors (Figure 4D, E,
323 F). Cal-1 cements with dark orange CL colors are developed in the center of low-angle, vertical
324 fractures and dissolved vugs (Figure 4G, H, I). Cal-1 cements grow on euhedral SD-1 crystals and
325 are, therefore, younger than the SD-1 cements (Figure 4G). Cal-2 cements show coarse crystals and
326 have dark orange CL colors (Figure 4J, K, L). They filled the fractures and vugs after the SD-2
327 cements (Figure 4D). The similar Fe/Mn ratios of Cal-1 and Cal-2 cements caused their similar CL
328 colors but, nonetheless, Cal-1 and Cal-2 cements can be distinguished by their differing REEY
329 distribution patterns (Figure 10). The youngest stage comprises cements with coarse-grained quartz
330 with dark CL colors (Figure 4 J, K, L). The Carbonate rock samples in this paper were taken from the
331 same area, same wells, and same reservoir with T. Yang et al. (2022). Given the microscopic
332 characteristics, the SD-2 cements in this paper and D5 cements from T. Yang et al. (2022) both were
333 saddle dolomites with similar coarse crystal, undulose extinction and dark pink CL colors. It
334 suggested that SD-2 cements in this paper were the D5 cements from T. Yang et al. (2022).

335 **4.2. Fluid inclusions**

336 **4.2.1. Fluid inclusion petrography**

337 Abundant fluid inclusions occur in calcite and quartz cements; they include pyrobitumen
338 inclusions, single-phase gas inclusions and two-phase aqueous inclusions (Figure 5). Primary
339 inclusions were trapped on the growing face of the host crystal during their precipitation, while
340 secondary inclusions were entrapped in the crystal cracks after the formation of the host mineral (Chi
341 et al., 2021).

342 In Cal-1 cements, primary (and coexisting) aqueous and pyrobitumen inclusions are isolated or
343 oriented inside the crystals. Aqueous inclusions are 3 – 7 μm in size and elliptical. The pyrobitumen
344 inclusions are also elliptical (Figure 5A, B).

345 The Cal-2 cements contain coexisting primary aqueous and single-phase gas inclusions.
346 Aqueous inclusions are randomly distributed with diameters ranging from 4 to 7 μm . They show
347 elliptical and square shapes. Single-phase gas inclusions are densely to directionally distributed in
348 Cal-2 cements, with diameters ranging from 3 to 14 μm . They also show elliptical and square shapes
349 (Figure 5C, D). Secondary single-phase gas inclusions are also identified in Cal-2 cements. These
350 secondary single-phase gas inclusions occur along crystal cracks, with diameters varying from 3 to
351 10 μm , and elliptical shapes (Figure 5E).

352 Quartz cements contain coexisting primary aqueous and single-phase gas inclusions. The
353 aqueous inclusions are isolated in the quartz cements, with diameters ranging from 5 to 8 μm . They
354 show elliptical shapes. Single-phase gas inclusions are random and densely distributed in these quartz
355 cements, with diameters ranging from 2 to 17 μm , and elliptical shapes (Figure 5F).

356 4.2.2. Raman spectrum data from fluid inclusions

357 Figure 6 shows the Laser Raman spectra of primary pyrobitumen inclusions in Cal-1 cements.
358 Two first-order characteristic bands, namely the D and G bands, are highlighted in the figure. The
359 positions of the D and G bands appear respectively in Raman Shift values of $1314.54 - 1338.28 \text{ cm}^{-1}$
360 1 and $1584.57 - 1608.31 \text{ cm}^{-1}$ (Table S1). The equivalent vitrinite reflectance of pyrobitumen
361 inclusions in Cal-1 cements varies from 3.13 to 3.61% using the formula proposed by Liu et al. (2013).
362 The equivalent vitrinite reflectance of pyrobitumen inclusions indicates that pyrobitumen in
363 hydrothermal dolomite reservoirs reached an overmature state.

364 The Laser Raman spectra of single-phase gas inclusions in Cal-2 and quartz cements show a
365 typical Raman peak shift in CH_4 (Figure 7). The density of the methane inclusions was determined
366 by Raman spectroscopic analysis (Lu et al., 2007). The trapped pressure of single-phase methane
367 inclusions was calculated using the equations of state of Duan et al. (1992). Calibrated Raman shifts
368 of primary methane inclusions in the Cal-2 cements range from 2910.73 cm^{-1} to 2912.12 cm^{-1} , with
369 their density values of 0.217 cm^{-1} to 0.284 cm^{-1} (Table S2). The trapped pressure of primary methane
370 inclusions in the Cal-2 cements vary from 49.02 Mpa to 93.26 Mpa, with corresponding pressure
371 coefficients of 1.50 to 2.21 (Table S2). The calibrated Raman shifts of secondary methane inclusions
372 in the Cal-2 cements reach values of 2911.42 cm^{-1} to 2913.51 cm^{-1} (Figure 7D). Calibrated Raman
373 shifts of primary methane inclusions in quartz cements range from 2910.38 cm^{-1} to 2910.73 cm^{-1} ,
374 while the densities of the primary methane inclusions range from 0.283 g/cm^3 to 0.301 g/cm^3 . The
375 trapped pressure of primary methane inclusions in quartz cements is higher than those of primary
376 methane inclusions in the Cal-2 cements, with the values of 116.28 Mpa to 141.64 Mpa (Table S2).

377 The corresponding pressure coefficients range from 1.90 to 2.14 (Table S2).

378

379 **4.2.3. Fluid inclusion microthermometry**

380 Homogenization temperatures (T_h) values of aqueous inclusions coeval with primary
381 pyrobitumen inclusions in Cal-1 cements and primary methane inclusions in Cal-2 and quartz cements
382 show a characteristic range concentration (Figure 8). Aqueous inclusions associated with primary
383 pyrobitumen inclusions in Cal-1 cements have T_h from 84.7 to 110.0 °C (Figure 8A). Aqueous
384 inclusions associated with primary methane inclusions in Cal-2 and quartz cements have T_h values
385 ranging from 93.5 to 126.3 °C and 179.1 to 205.0 °C, respectively (Figure 8B, C).

386 Aqueous inclusions that are paragenetic relative to hydrocarbon inclusions can record the true
387 temperature of fluid entrapment without any pressure correction (Hanor, 1980). The entrapment
388 temperature of fluid inclusions coeval with hydrocarbon inclusions were therefore used to estimate
389 the timings of hydrocarbon charge. Both pairs of inclusions show a narrow range of salinity (Figure
390 9). In addition, the T_m values of the aqueous inclusions that were coeval with primary pyrobitumen
391 inclusions in Cal-1 cements range from −15.9 to −9.9 °C, values that are consistent with NaCl
392 concentrations of 13.83 wt% to 19.37 wt%. The aqueous inclusions coeval with primary methane
393 inclusions in Cal-2 and quartz cements record T_m values ranging from −10.5 to −5.6 °C and −4.7 to
394 −1.2 °C, respectively, and salinity equivalents of 8.68 wt% to 14.46 wt% NaCl and 2.07 wt% to 7.45
395 wt% NaCl, respectively.

396 **4.3. REEY (Rare Earth Element and Yttrium) and element composition**

397 The distribution pattern and anomalies of REEY can be used to effectively distinguish different

398 stages of calcite cements and the origin of their diagenetic fluids (Robbins et al., 2016). The PAAS-
399 normalized REEY patterns for host rocks (limestone and matrix dolomite) and the two types of calcite
400 cements in the reservoirs of our interest are shown in Figure 10. REEY patterns for the limestone and
401 matrix dolomite show negative Ce anomalies and positive Y anomalies. In contrast, the Cal-1 and
402 Cal-2 cements have different PAAS-normalized REEY patterns, with weak Eu anomalies in REEY
403 values of Cal-1 cements and remarkably positive Eu anomalies in the REEY values obtained for Cal-
404 2 cements. Cal-1 cements have also a higher content of heavy REEs when compared to Cal-2 cements.

405 The $\sum$ REEY of limestone varies from 6.59 to 18.97 ppm, presenting negative Ce anomalies
406 ($\delta\text{Ce}_{(\text{SN})} = 0.23 - 0.50$), positive Y anomalies ($\delta\text{Y}_{(\text{SN})} = 2.09 - 2.49$), but no Eu anomalies. The
407 $\sum$ REEY of matrix dolomite (2.83 – 5.76 ppm) is lower than the values recorded for limestone, but
408 also presents negative Ce anomalies ($\delta\text{Ce}_{(\text{SN})} = 0.20 - 0.53$) and positive Y anomalies ($\delta\text{Y}_{(\text{SN})} = 1.99$
409 – 2.56).

410 The REEY patterns of Cal-1 cements record negative Ce anomalies ($\delta\text{Ce}_{(\text{SN})} = 0.19 - 0.48$),
411 partial positive Eu anomalies ($\delta\text{Eu}_{(\text{SN})} = 0.89 - 1.78$) and positive Y anomalies ($\delta\text{Y}_{(\text{SN})} = 1.85 - 3.99$),
412 suggesting that the diagenetic fluid of Cal-1 cements originates from the surrounding host rock. Cal-
413 2 cements have negative Ce anomalies ($\delta\text{Ce}_{(\text{SN})} = 0.18 - 0.27$), distinct positive Eu anomalies ($\delta\text{Eu}_{(\text{SN})}$
414 = 5.27 – 36.47) and positive Y anomalies ($\delta\text{Y}_{(\text{SN})} = 2.12 - 7.28$). Positive Eu anomalies in carbonate
415 cements are likely caused by high-temperature or reducing hydrothermal fluids (Robbins et al., 2016).
416 High-temperature fluids (> 200 °C) are able to chemically reduce Eu^{3+} to Eu^{2+} (Bau, 1991). Eu in
417 reducing hydrothermal fluid is in a +2 valence state, and thus Eu^{2+} is more likely to replace Ca^{2+} in
418 carbonate rocks (Zhao et al., 2019). At low temperatures, Eu is insensitive to the redox environment,

419 and Eu^{3+} can be reduced to Eu^{2+} only under extremely low oxygen fugacity ($f_{\text{O}_2} < 10^{-80}$ bar) (Bau,
420 1991). Therefore, it is difficult for carbonate cements to have positive Eu anomalies even in strongly
421 reducing natural conditions, under low temperatures. The distinct positive Eu anomalies show that
422 the formation of Cal-2 cements was affected by abnormally high temperatures or, instead, the
423 diagenetic fluids of Cal-2 cements originated from a reducing hydrothermal fluid.

424 **4.4. $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ analysis**

425 Nine (9) $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were obtained for Cal-1 and Cal-2 cements in wells TL6, TL7 and
426 TL601, as well as for the surrounding host rock (Table 2). Values of $\delta^{13}\text{C}_{\text{VPDB}}$ ($^{13}\text{C}/^{12}\text{C}$ relative to
427 Vienna Pee Dee belemnite) range from 2.08‰ to 3.95‰ for limestone, 3.28‰ to 3.62‰ for matrix
428 dolomite, 1.52‰ to 2.75‰ for Cal-1 cements, and 1.16‰ to 2.38‰ for Cal-2 cements. Matrix
429 dolomite has the heaviest average $\delta^{13}\text{C}_{\text{VPDB}}$. The recorded $\delta^{18}\text{O}_{\text{VPDB}}$ values for limestone range from
430 -6.77‰ to -6.96‰, -6.76‰ to -7.03‰ for matrix dolomite, -8.40‰ to -8.60‰ for Cal-1 cements,
431 and -6.12 ‰ to -6.66‰ for Cal-2 cements. Clearly, the $\delta^{18}\text{O}_{\text{VPDB}}$ values for Cal-1 cements are lower
432 than those for limestone.

433 The $^{87}\text{Sr}/^{86}\text{Sr}$ values of limestone and matrix dolomite range from 0.707047 to 0.707232 and
434 0.707541 to 0.707845, respectively (Table 2). The $^{87}\text{Sr}/^{86}\text{Sr}$ values of Cal-1 cements vary from
435 0.707396 to 0.707645, while Cal-2 cements show values from 0.707443 to 0.707995 (Table 2). The
436 $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Middle Permian seawater vary from 0.70695 to 0.70752 (McArthur et al., 2001).

437 The above data reveal the $^{87}\text{Sr}/^{86}\text{Sr}$ values for matrix dolomite to be higher than those of
438 limestone, which are in turn partly higher than those of contemporaneous seawater. The $^{87}\text{Sr}/^{86}\text{Sr}$
439 values of Cal-1 cements are similar to those of limestone. The $^{87}\text{Sr}/^{86}\text{Sr}$ values of Cal-2 cements are

440 slightly higher than those of contemporaneous seawater.

441 **4.5. U-Pb Geochronology**

442 The absolute ages of carbonate cements can be determined using in-situ U-Pb dating (Roberts et
443 al., 2020, 2021). The U-Pb ages of SD-2 cements ranges from 263 ± 4.2 to 255.8 ± 6.9 Ma (T. Yang
444 et al., 2022).

445 Cal-1 cements show variable U concentrations (0.056 – 4.909 ppm) and low Pb concentrations
446 (0.007 – 0.250 ppm) in Sample T4. The $^{238}\text{U}/^{206}\text{Pb}$ ratios of Cal-1 cements in Sample T4 vary from
447 12.40 to 28.28, and the corresponding $^{207}\text{Pb}/^{206}\text{Pb}$ ranges from 0.05 to 0.51, allowing for a precise age
448 estimation with a 2σ error of 1.71%. The U-Pb ages of Cal-1 cements in Sample T4 return a value of
449 245.3 ± 4.2 Ma on the Tera-Wasserburg concordia diagram (Early-Middle Triassic; Figure 11). In our
450 analysis, the mean square of weighted deviation (MSWD) is as low as 2.0, indicating a data scatter
451 that is mainly caused by analytical uncertainties.

452 In Sample T7, Cal-1 cements show a higher variability in U concentrations (0.002 – 1.764 ppm)
453 when compared to Sample T4, while low Pb concentrations are still recorded (0.005 – 0.104 ppm).
454 The $^{238}\text{U}/^{206}\text{Pb}$ ratios of Cal-1 cements in Sample T7 vary from 0.17 to 26.40, and the corresponding
455 $^{207}\text{Pb}/^{206}\text{Pb}$ ranges from 0.05 to 0.88, again allowing for a precise age estimation with a 2σ error of
456 1.94%. The U-Pb age of Cal-1 cements in Sample T7 is 246.9 ± 4.8 Ma on the Tera-Wasserburg
457 concordia diagram, spanning the Early to Middle Triassic (Figure 11). The mean square of weighted
458 deviation (MSWD = 0.74) is relatively low.

459 The Cal-2 cements in Sample T10 reveal low concentrations of U and Pb, ranging from 0.005
460 to 1.31 ppm and from 0.015 to 0.331 ppm, respectively. The wide range of $^{238}\text{U}/^{206}\text{Pb}$ ratios ($0.17 \leq$

461 $^{238}\text{U}/^{206}\text{Pb} \leq 25.71$) and corresponding $^{207}\text{Pb}/^{206}\text{Pb}$ ratios ($0.13 \leq ^{207}\text{Pb}/^{206}\text{Pb} \leq 0.67$) of Cal-2 cements
462 in Sample T10 returned an age estimate with a 2σ error of 3.87%. The calculated U-Pb age is 222.4
463 ± 8.6 Ma on the Tera-Wasserburg concordia diagram, or Upper Triassic (Figure 11). The mean square
464 of weighted deviation (MSWD = 1.7) is relatively low.

465 5. Basin Modeling

466 Measured temperature data from drill-stem tests (DSTs) show that the average geothermal
467 gradient for the Tailai Gas Field is 23.2 °C/km, for an average present-day surface temperature of
468 15 °C. The present-day heat-flow values for this same field are estimated as 41.88 mW/m². Such
469 values return a positive correlation among measured and calculated R_o and temperatures in well
470 TL601 (Figure 12), suggesting that the thermal history models in this paper are consistent.

471 The Tailai Gas Field is located in the Bashansi syncline of the east Sichuan Basin, and its
472 deformation is minor. Wells TL6, TL7 and TL601 were drilled along this same structure, so the burial
473 history diagram of Well TL601 can be considered as representative of the whole study area. Burial
474 curves for well TL601 indicate the Tailai Gas Field suffered slight uplift during Dongwu tectonics
475 (late Middle Permian) and experienced rapid subsidence from Late Permian to Early Triassic.
476 Subsequently, the Tailai Gas Field underwent minor uplift during the early stage of Indosinian
477 orogeny. Slow subsidence and slight uplift respectively occurred during the Late Triassic and the late
478 stage of Indosinian orogeny in the Tailai Gas Field. Following the Indosinian orogeny, the study area
479 experienced long-term overall subsidence throughout the Jurassic-Early Cretaceous, with minor
480 superimposed erosion events due to the early stage of Yanshanian Orogeny (Figure 12). Gradual, slow
481 uplift occurred during the late stage of the Yanshanian orogeny (Late Cretaceous) in the study area

(Figure 12; Shi et al., 2016). This was followed by persisted and increased uplift with its value of approximately 1600 m during Himalayan orogeny (Neogene to the present day), owing to the collision of the Songpan Block (Figure 12; Shi et al., 2016; He et al., 2022). In well TL601, burial depths for the third member of the Maokou Formation reached a maximum of ~8075 m around 110 Ma, while temperatures approached 223.7°C.

6. Discussion

6.1. Timing of hydrocarbon charge

In this study, the timings of oil/gas charging for hydrothermal dolomite reservoirs in the third member of the Maokou Formation were determined using in-situ U-Pb datings combined with the Homogenization Temperatures (Th) of aqueous inclusions coexisting with pyrobitumen and methane inclusions. The main question is how these timings correlate with the basin modeling results shown in Figure 12, as suggested in the previous section. Our approach follows the principle that the measured Th values of aqueous inclusions may increase due to aqueous inclusions becoming trapped in minerals and veins undergoing stretching, fluid leakage, refilling, and rebalancing (Bourdet et al., 2008). The better-preserved inclusions are those that have the minimum Th (Chen et al., 2022) and these were the ones used in this work to determine the timings of hydrocarbon charge.

Cements, in the study area, were the product of paleofluid precipitation, recording the information of the cement-forming fluid, including composition, precipitation time and temperature. Hydrocarbon inclusions in minerals record information about hydrocarbon fluid activity, including the time of hydrocarbon charge and its composition. Primary hydrocarbon inclusions in minerals can be used to indicate that hydrocarbon charge was earlier than, or synchronous with, the precipitation

503 of the minerals. Secondary hydrocarbon inclusions in minerals show that hydrocarbon charge
504 occurred later than mineral precipitation.

505 No pyrobitumen inclusions were observed within SD-2 cements in this paper, indicating the oil
506 charge postdated the formation of SD-2 cements with the age from 263 Ma to 255.8 Ma (T. Yang et
507 al., 2022). Based on these data, we suggest that the cement-forming fluid of Cal-1 mainly originated
508 from the surrounding host rock with the contribution from pore fluids outside the Maokou Formation.
509 This is also proven by the REEY patterns of Ca-1 cements, which are similar to those of surrounding
510 rocks. Furthermore, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Cal-1 cements are partly greater than those of Middle
511 Permian seawater (Figure 13 and Table 2). The Cal-1 cements containing primary pyrobitumen
512 inclusions reveal one single oil-charging episode in the third member of the Maokou Formation
513 (Figure 5A, B), which predated or was synchronous with the formation of Cal-1 cements. The U-Pb
514 dates indicate that Cal-1 cements were formed in the Middle Triassic at approximately 246.9 – 245.3
515 Ma (Figure 12), while the crystallization of the Cal-1 cements can be inferred at about 246 Ma using
516 the fluid inclusion method (Figure 12). Based on these U-Pb dates and fluid inclusion data, the
517 primary pyrobitumen inclusions in Cal-1 cements reveal an oil-charging episode spanning 245.3 Ma
518 to 246.9 Ma, i.e., after the Dongwu tectonic episode. This age is contemporaneous with deposition of
519 the Leikoupou Formation.

520 Cal-2 cements are marked by their positive Eu and Y anomalies, suggesting the fluid that filled
521 such cements originated from deep hydrothermal sources (Bau et al., 2014). The $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ plots
522 in Figure 13A reveal that fluids filling the Cal-2 cements derived from marine carbonates. However,
523 for the same Cal-2 cements, the recorded $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are higher than those of Middle Permian

524 seawater (McArthur et al., 2001). Such an information indicates that the cement-forming fluid of the
525 Cal-2 originated from pore fluids outside the Middle Permian Maokou Formation. In addition,
526 primary methane inclusions are observed inside the crystals of Cal-2 cements, revealing that the first
527 gas-charging episode predated, or was synchronous with, the precipitation of the Cal-2 cements. The
528 U-Pb information suggests that Cal-2 cements formed at 222.4 ± 8.6 Ma (Late Triassic), while the
529 fluid inclusion method points out to an age of 210-227 Ma (Late Triassic) (Figure 12). Gas was present
530 at about 222.4 Ma - according to both the U-Pb results and fluid inclusion method – when the
531 precipitation of the Cal-2 cements occurred, i.e., during the Indosinian orogeny. Cementation was
532 during deposition of the Xujiahe Formation.

533 The formation of quartz cements could be inferred as 143 Ma (Early Cretaceous) using the fluid
534 inclusion method (Figure 12). Secondary methane inclusions are aligned with the cracks of Cal-2
535 cement crystals, indicating that the second episode of gas charge postdated the formation of these
536 (Cal-2) cements. The primary methane inclusions within quartz cements show that the second gas-
537 charging episode was earlier than, or synchronous with, the formation of quartz cements. Secondary
538 methane inclusions in the Cal-2 cements, and primary methane inclusions within quartz cements,
539 show that this gas-charging episode occurred from 222.4 to 143 Ma based on U-Pb data and the fluid
540 inclusion method.

541 In summary, the oil-charging timing for the hydrothermal dolomite reservoirs in the third
542 member of the Maokou Formation is consistent with the early stage of the Indosinian Orogeny, while
543 the timing of the first gas-charging episode coincided with the late stage of the Indosinian Orogeny.

544 **6.2. Fault reactivation and impact on the Tailai Gas Field**

545 The No. 15 Fault System was formed under regional extensional tectonics during the Early
546 Cambrian Tongwan orogeny (Liu et al., 2017, 2021; Su et al., 2020). The No. 15 Fault System and
547 associated structures were subsequently reactivated in multiple tectonic episodes (Zeng et al., 2023).
548 Variance time slices show that the No. 15 Fault System comprises multiple fault segments (Figure
549 14A), with vertical connectivity above and below the Lower Triassic gypsum-salt layer deemed to be
550 poor (Figure 14B, C, D).

551 Variance data in Figure 14A show that the No. 15 Fault System is composed of eight (8) distinct
552 fault segments, whose strike is mostly to the NW-SE except for segment 5, which strikes in a direction
553 close to the north. In this same Figure 14A, fault segments 1, 2, 3, and 4 splay out, and fault segments
554 5, 6, 7, and 8 developed linear structures (Figure 14A). Few fault segments continue across the lower
555 Triassic evaporite layer. Their orientation and style change across this layer (Figure 14B, C, D) Under
556 the Triassic evaporites interval, the No. 15 Fault System is an alternating negative and positive flower
557 structure, with some vertical faults (Figure 14B, C, D). Above these evaporites, the No. 15 Fault
558 System is composed of vertical and high-angle faults. Well TL7, for instance, was drilled next to fault
559 segment 6, a vertical fault (Figure 14B). Well TL601 is close to fault segment 3, which is formed by
560 a superimposed structure comprising a lower positive flower structure and an upper negative flower
561 structure (Figure 14C). Well TL6 is near fault segment 7, a relatively simpler positive flower structure
562 (Figure 14D).

563 The No.15 Fault System developed dextral transtensional activities during the early stage of
564 Indosinian orogeny, owing to the clockwise rotation of the Sichuan Basin (Zhang et al., 2013; Li et

al., 2023). Figure 15A depicts the two-way time (TWT) thickness of the Mid-Triassic Leikoupo Formation (T_{2l} , between H4 and H5 reflectors). This unit is significantly thicker near fault segments 2, 3, and 4 of the No. 15 Fault System, indicating that small pull-apart structures were formed near these segments during the Middle Triassic. The permeability of fault segments 2, 3 and 4 likely increased rapidly, which were the main pathways of hydrocarbon migration, owing to their development and reactivation during the early stage of Indosinian orogeny. The South China continent collided with the Songpan block during the late stage of Indosinian orogen (Wang et al., 2021). The direction of minimum principal stress (extensional stress) is NE-SW in the Sichuan Basin (Zhang et al., 2013; Wang et al., 2021). Figure 15B shows TWT thickness for the Upper Triassic Xujiahe Formation (T_{3x} , between horizons H5 and H6). This unit is thicker near fault segments 4 and 7, as well as the main fault of fault segment 2 and a minor splay fault of fault segment 3, suggesting that they formed local pull-apart structures and were conducive to the hydrocarbon migration during the Late Triassic. The change in stress orientation locked splay faults of fault segment 2 as well as the main fault of fault segment 3 by friction and unlocked other fault segments by reducing friction on the fault plane (Figure 15). This shows that the change of stress orientation during the early and late stage of Indosinian orogeny have critical influence on the hydrocarbon migration pathways, due to its control on the development and reactivation of different fault segments.

582

583 **6.3. Fault-related hydrocarbon accumulation processes**

584 The No.15 Fault System and associated fractures provided major migration pathways for
585 hydrothermal fluids in the Tailai Gas Field (Zhang et al., 2020; T. Yang et al., 2022). The $\delta^{13}C_2$ values

586 of natural gas within the hydrothermal dolomite reservoirs in the third member of the Maokou
587 Formation are generally lower than those of source rocks in the Wufeng-Longmaxi Formation and
588 the first member of the Maokou Formation, and greater than those of Qiongzhusi Formation source
589 rock (Xie et al., 2020; Y. J. Li et al., 2021; Huang et al., 2023). The $\delta^{13}\text{C}_2$ values of the natural gas
590 within the hydrothermal dolomite reservoirs in the third member of the Maokou Formation are
591 generally consistent with those of Carboniferous gas that was sourced from Wufeng-Longmaxi
592 Formation in the east Sichuan Basin (Huang et al., 2023). This shows that most natural gas within the
593 hydrothermal dolomite reservoirs in the third member of the Maokou Formation originated from the
594 Wufeng-Longmaxi Formation source rocks in the east Sichuan Basin (Y. J. Li et al., 2021; Huang et
595 al., 2023). The biomarker composition of pyrobitumen including terpane and sterane within the
596 hydrothermal dolomite reservoirs in the third member of the Maokou Formation are respectively
597 similar to terpane of source rock in the first member of the Maokou Formation and sterane of Wufeng-
598 Longmaxi Formation source rock, indicating that the natural gas has a contribution of the first
599 member of the Maokou Formation (Xie et al., 2020; Y. J. Li et al., 2021; Huang et al., 2023). Our
600 work shows that Cal-1 cements with primary pyrobitumen inclusions were mainly sourced from pore
601 fluids within the Maokou Formation, which crystallized during the early stage of Indosinian orogeny
602 (~250 – 225 Ma). In contrast, Cal-2 cements with primary methane inclusions precipitated from
603 hydrothermal fluids migrating during the late stage of Indosinian orogeny (~225 –190 Ma). The
604 formation of Cal-1 and Cal-2 cements, and the first oil and gas charging episodes coincided with
605 activity in the No. 15 Fault System, thus confirming that hydrothermal fluid migration and gas charge
606 were mainly controlled by deep-rooted basement faults. Based on the above data, hydrocarbon

607 accumulation processes in the third member of the Maokou Formation of the Tailai Gas Field can be
608 divided into three distinct stages (Figure 16):

609 (1) Stage 1: Charge of oil into the third member of the Maokou Formation from at least 246.9 to
610 245.3 Ma (Middle Triassic)

611 The third member of the Maokou Formation was tectonically uplifted and exhumed during the
612 Dongwu tectonics, with the study area recording extensive denudation (S. J. Li et al., 2021). A phase
613 of regional magmatism (the Emei magmatic episode) occurred at the start of the Late Permian (~259
614 Ma) as recorded by a large-scale basaltic eruption, ELIP (Shellnutt, 2014). The Emei magmatism was
615 associated with the reactivation of the No. 15 Fault System and facilitated hydrothermal
616 dolomitization in the third member of the Maokou Formation near the Tailai Gas Field (S. J. Li et al.,
617 2021). Oil charge occurred at about 246.9 – 245.3 Ma (Middle Triassic). The Wufeng-Longmaxi
618 Formation source rocks with sapropelic kerogen shows R_o values around 0.7% – 1.3%, hinting at the
619 generation of oil and minor volumes of wet gas (Y. J. Li et al., 2021). The source rock in the first
620 member of the Maokou Formation shows R_o values of 0.5% – 0.7% (Figure 12), corresponding to the
621 generation of little immature oil, all depending on the presence of humic-sapropelic kerogen (Y. J. Li
622 et al., 2021). The Wufeng-Longmaxi Formation source rocks generated large amounts of oil, while
623 the Middle Permian source rocks generated little oil.

624 Given these maturation data, the source rock in the first member of the Maokou Formation was
625 not likely to be a major contributor of oil to the Tailai Gas Field. Based on maturation timing, the
626 Wufeng-Longmaxi Formation was the source for most oil charging the Maokou Formation during the
627 Middle Triassic. Oil probably migrated up the No. 15 Fault System. The mudstones in the Longtan

628 Formation provided a good seal for these new oil accumulations.

629

630 (2) Stage 2: Accumulation of mixed oil and gas in available traps at ~ 222.4 Ma (Late Triassic)

631 Fluid inclusion data, as well as the U-Pb dates compiled in this work, reveal a first gas-charging
632 episode at ~ 222.4 Ma (Late Triassic), an age coinciding with the late stage of Indosinian orogeny
633 (~225 – 190 Ma) (Wang et al., 2021). In addition, the temperature estimated for the third member of
634 the Maokou Formation by our burial and thermal models was ~100 °C, a value lower than the
635 temperature necessary for the cracking of oil; thus indicating that in-situ cracking of oil in the third
636 member of the Maokou Formation did not occur at this time. The hydrothermal dolomite reservoirs
637 in the third member of the Maokou Formation should have hosted a mixture of oil and wet gas at
638 approximately 222.4 Ma (Late Triassic). Meanwhile, the R_o values of the Wufeng-Longmaxi
639 Formation source rocks entered the range of 1.3% to 2%, conditions deemed favorable to the
640 generation of condensate and wet gas. The R_o values of source rock in the first member of the Maokou
641 Formation reached the range of 0.7% to 1.3%, corresponding to the generation of oil and small
642 volumes of wet gas. Based on the maturity, the Wufeng-Longmaxi Formation was the main source of
643 wet gas charging into the hydrothermal dolomite reservoirs in the third member of the Maokou
644 Formation during the Late Triassic, with a small contribution of the source rock in the first member
645 of the Maokou Formation. Wet gas was trapped in gas inclusions within the Cal-2 cements around
646 222.4 Ma in the study area. The gas inclusions were likely altered, and C2-C5 within the gas
647 inclusions were cracked into methane, owing to the increasing burial depth and temperature of
648 Maokou Formation after the Indosinian orogeny (Figure 12). This increased the number of moles of

649 gas in the gas inclusions, thereby increasing their density and pressure.

650 Seismic data show the thickness change of Upper Triassic Xujiahe Formation, suggesting the
651 No. 15 Fault System was reactivated in the late stage of Indosinian orogeny (~225 Ma to 190 Ma).
652 The timing of the first episode of gas charge, the reactivation of No. 15 Fault System and the
653 formation of hydrothermal minerals (Cal-2 cements) are consistent in age, revealing that the wet gas
654 from source rocks in the Wufeng-Longmaxi Formation and the first member of the Maokou
655 Formation charged into the third member of the Maokou Formation via the No.15 Fault System during
656 the late stage of Indosinian orogeny.

657

658 (3) Stage 3: In-situ cracking of oil and subsequent accumulation of gas from at least 143 Ma to 110
659 Ma (Early Cretaceous)

660 Continued burial of the Maokou reservoir to a depth near 8 km altered all hydrocarbons to dry
661 gas. The modelled vitrinite reflectance (R_o) for the Maokou Formation reached ~2.0% around 143
662 Ma, and temperatures approached 180 °C, a value higher than the temperature necessary for the in-
663 situ cracking of oil (Figure 12). This means the crude oil accumulated in the hydrothermal dolomite
664 reservoirs in the third member of the Maokou Formation in Stages 1 began to crack into gas at ~ 143
665 Ma (Early Cretaceous). At about 110 Ma, the hydrothermal dolomite reservoirs in the third member
666 of the Maokou Formation reached its maximum burial depth, with the models returning a vitrinite
667 reflectance value of ~3.5% R_o , for maximum temperatures of 223.7°C (Figure 12). Any oil
668 accumulated in this formation was cracked into gas (Waples, 2000; Tian et al., 2008). The significant
669 volumes of pyrobitumen trapped in Maokou Formation samples, without liquid oil, appear to confirm

670 that all crude oil has been cracked into gas. Later, the Tailai Gas Field was mildly deformed in younger
671 tectonic episodes.

672 7. Conclusions

673 Based on the investigation of the petrography and diagenetic sequences of cements, fluid
674 inclusions, Rare Earth Elements and Yttrium (REEY), $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and U-Pb ratios in the
675 calcite cements, as well as on the seismic interpretation around the No. 15 Fault System, the following
676 conclusions can be drawn:

677 (1) One oil-charging episode and two gas-charging episodes were identified near the Tailai Gas Field
678 based on the diagenetic sequences of cements and hydrocarbon inclusions in the hydrothermal
679 dolomite reservoirs in the third member of the Maokou Formation.

680 (2) The calcite U-Pb dates and fluid-inclusion homogenization temperatures indicate that oil was
681 trapped in the reservoir from at least 246.9 Ma to 245.3 Ma (Middle Triassic), whereas the reservoir
682 was charged with gas from at least 222 Ma to 143 Ma (Late Triassic to Early Cretaceous).

683 (3) Based on the known time-span of the Indosinian orogeny, thickness changes in the Middle
684 Triassic Leikoupo and Upper Triassic Xujiahe formations indicate that the No. 15 Fault System
685 was active during the early and late stages of the Indosinian orogeny.

686 (4) The timings of oil and gas charge coincide with the reactivation of the No. 15 Fault System during
687 the early and late stage of the Indosinian orogeny. Hydrocarbon charge was mostly controlled by
688 the No. 15 Fault System, which formed the main migration path for both hydrocarbons and
689 hydrothermal fluids.

690 (5) Near the Tailai Gas Field, the accumulation of hydrocarbons in the hydrothermal dolomite

reservoirs in the third member of the Maokou Formation occurred in three stages: a) oil charging into the hydrothermal dolomite reservoirs in the third member of the Maokou Formation from at least 246.9 to 245.3 Ma, b) accumulation of mixed oil and gas in available traps at ~ 222.4 Ma, and c) in-situ cracking of oil and subsequent accumulation of gas from at least 143 Ma to 110 Ma.

712 **Appendixes**

713 The following are the Supplementary data to this article.

714 **Supplementary File S1:** PVT modeling of the single-phase methane inclusion.

715 **Supplementary Table S1.** Raman spectral parameters and equivalent vitrinite reflectance (VReq) of
716 pyrobitumen inclusions in the Sichuan Basin.

717 **Supplementary Table S2.** Raman spectral parameters, density and trapped pressure of single-phase
718 methane inclusions in the Sichuan Basin.

719 **Supplementary Table S3.** Microthermometry data for aqueous inclusions coeval with the primary
720 pyrobitumen inclusions in Cal-1 cements and primary methane inclusions in Cal-2 and quartz cements.

721 **Supplementary Table S4.** REEY data of the limestone, matrix dolomite, and calcite cements in the
722 hydrothermal dolomite reservoirs in the third member of the Maokou Formation in the Tailai Gas
723 Field.

724 **Supplementary Table S5.** Spot analysis data for U-Pb LA-ICP-MS.

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Figure Captions:

Figure 1. (A) Location of the Sichuan Basin in Central China. (B) Location of the east Sichuan Basin (Area III). (C) Map depicting the distribution of the dolomites in the third member of the Maokou Formation and associated basement faults. Figure modified after Zhang et al. (2020). (D) Simplified NW-SE cross-section from the east Sichuan Basin, highlighting its characteristic structural style with tight anticlines and broad synclines. FTB: fold-and-thrust belts.

Figure 2. Generalized neo-Proterozoic to Jurassic stratigraphy of the east Sichuan Basin highlighting main tectonic and depositional events, together with major petroleum elements recognized in the Tailai Gas Field.

Figure 3. Photos of characteristic samples of the different lithofacies observed in the hydrothermal dolomite reservoirs in the third member of the Maokou Formation. (A) Low-angle veins in matrix dolomite. (B) Vertical- and low-angle veins of hydrothermal dolomite in limestone. (C) high-angle veins in matrix dolomite. (D) Mineralized vugs with dolomite and calcite in matrix dolomite; (E) Pyrobitumen in a stylolite of matrix dolomite. (F) Pyrobitumen and calcite filling vugs in limestone. Lim: limestone; MD: matrix dolomite; Dol: dolomite; Cal: calcite; Qtz: quartz.

Figure 4. Photomicrographs of saddle dolomite, calcite and quartz cements from the Tailai Gas Field (the third member of the Maokou Formation) under transmitted and cathodoluminescence (CL) light. (A), (B) and (C) show photomicrographs of SD-1 and SD-2 cements in Sample T10. (D), (E) and (F): photomicrograph of SD-2 and Cal-2 of Sample T10. (G), (H) and (I): photomicrograph of SD-1 and Cal-1 cements of Sample T5. (J), (K) and (L): photomicrograph of SD-2, Cal-2 and Qtz cements of Sample T2. See Figure 3 for photos of core Samples T2, T5 and T10. Lim: limestone; MD: matrix

dolomite; SD-1 and SD-2: SD-1 and SD-2 cements; Cal-1 and Cal-2: Cal-1 and Cal-2 cements; Qtz: quartz.

Figure 5. Photomicrographs of fluid inclusions in Cal-1, Cal-2 and quartz cements from hydrothermal dolomite reservoirs in the third member of the Maokou Formation. (A) and (B) Primary pyrobitumen and coexisting aqueous inclusions in Cal-1 cements from Sample T4. (C) and (D) Primary single-phase gas and coexisting aqueous inclusions in Cal-2 cements from Sample T10. (E) Secondary single-phase gas inclusions in Cal-2 cements from Sample T2. (F) Primary single-phase gas and coexisting aqueous inclusions in quartz cements from Sample T1. See Figure 3 for photos of core Samples T2, T4 and T10. FIA: fluid inclusion assemblages.

Figure 6. Raman spectrum of primary pyrobitumen inclusions in Cal-1 cements acquired using a 300 gr/mm diffraction grating. (A) Raman spectrum of primary pyrobitumen inclusions in Cal-1 cements from Sample T4. (B) Raman spectrum of primary pyrobitumen inclusions in Cal-1 cements from Sample T7. See Figure 3 for photos of core Samples T4 and T7.

Figure 7. (A) Laser Raman spectrum of primary methane inclusions in Cal-2 cements using a 300 gr/mm diffraction grating; (B) Laser Raman spectrum of primary methane inclusions in Cal-2 cements using a 1800 gr/mm diffraction grating with a Ne lamp; (C) Laser Raman spectrum of secondary methane inclusions in quartz cements using a 300 gr/mm diffraction grating; (D) Laser Raman spectrum of secondary methane inclusions in quartz cements using a 1800 gr/mm diffraction grating with a Ne lamp. (E) Laser Raman spectrum of primary methane inclusions in quartz cements using a 300 gr/mm diffraction grating; (F) Laser Raman spectrum of primary methane inclusions in quartz cements using a 1800 gr/mm diffraction grating with a Ne lamp.

Figure 8. Histograms of homogenization temperatures (Th) for aqueous inclusions coeval with the primary pyrobitumen inclusions in Cal-1 cements and primary methane inclusions in Cal-2 and quartz cements. (A) Th for aqueous inclusions coeval with the primary pyrobitumen inclusions in Cal-1 cements from T4. (B) Th for aqueous inclusions coeval with the primary methane inclusions in Cal-2 cements from T2, T4 and T10. (C) Th for aqueous inclusions coeval with the primary methane inclusions in quartz cements from T1. FIA: fluid inclusion assemblages; PI: pyrobitumen inclusions; MI: methane inclusions.

Figure 9. Graph of homogenization temperature (Th) against salinity of aqueous inclusions coeval with the primary pyrobitumen inclusions in Cal-1 cements and primary methane inclusions in Cal-2 and quartz cements. AI: aqueous inclusions; PI: pyrobitumen inclusions; MI: methane inclusions.

Figure 10. Distributions of REEY in limestone, matrix dolomite, and calcite cements (Cal-1, Cal-2) from different locations. The concentrations shown are normalized to Post-Archaean Australian Shale (PAAS).

Figure 11. U-Pb Tera-wasserburg Concordia plots for calcite samples taken from hydrothermal dolomite reservoirs in the Tailai Gas Field (the third member of the Maokou Formation). MSWD: mean square of weighted deviates; LA-ICP-MS: laser ablation-inductively coupled plasma-mass spectrometer.

Figure 12. Burial and thermal history models for well TL601, including information on the timings of cement formation (calcite and quartz) and hydrocarbon charge.

Figure 13. $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ data for host rock (limestone and matrix dolomite) and cements (Cal-1, Cal-2) in the third member of the Maokou Formation near the Tailai Gas Field. (A) Cross

plots of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ for host rock and calcite cements (Wang et al., 2014); (B): Histograms showing $^{87}\text{Sr}/^{86}\text{Sr}$ data for host rock and cements. Data points for each vein are listed in Table 2.

Figure 14. Time slice of variance cube of 3D seismic data and seismic profiles across well TL7, TL601 and TL6 depicting the geometry of No. 15 Fault System in the study area. (A) The time slice (TWT = -2505 ms) of variance cube of 3D seismic data in the study area. (B) The seismic profile across well TL7. (C) The seismic profile across well TL601. (D) The seismic profile across well TL6. The Lower Triassic evaporate layer was interpreted referring to Gu et al. (2021). VF: vertical fault; NFF: negative flower structure; PFF: positive flower structure.

Figure 15. Formation thickness (TWT/ms) along the No. 15 Fault System in the Tailai Gas Field. (A): Thickness (TWT/ms) of the Middle Triassic Leikoupo Formation (T_{2l}); (B): Thickness (TWT/ms) of the Upper Triassic Xujiahe Formation (T_{3x}). Blue dotted rectangle in Figure 14 shows the location of Figure 15. Age of horizons are identified on Figure 2.

Figure 16. Hydrocarbon accumulation processes in the hydrothermal dolomite reservoirs in the third member of the Maokou Formation. (A) Formation and charge of oil into the third member of the Maokou Formation (B) Accumulation of mixed oil and gas in available traps. (C) In-situ cracking of oil and subsequent accumulation of gas.

Table Captions:

Table 1. Sampling information for the carbonate samples from the Tailai Gas Field analyzed in this work (the third member of the Maokou Formation, east Sichuan Basin).

Table 2. Calculated $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values for calcite cements and surrounding host rocks in hydrothermal dolomite reservoirs in the third member of the Maokou Formation of the Tailai Gas Field. $\delta^{13}\text{C}_{\text{VPDB}}$: $^{13}\text{C}/^{12}\text{C}$ relative to Vienna Peedee belemnite; $\delta^{18}\text{O}_{\text{VPDB}}$: $^{18}\text{O}/^{16}\text{O}$ relative to Vienna Peedee belemnite; $\delta^{18}\text{O}_{\text{SMOW}}$: $^{18}\text{O}/^{16}\text{O}$ relative to standard mean ocean water.

Sample	Well	Formation	Depth (m)	Lithology
T1	TL6	P ₂ m ³	5510.20	Dolomite, calcite and quartz cements filling fractures and vugs in matrix dolomite
T2	TL7	P ₂ m ³	5094.70	Dolomite, calcite and quartz cements filling a fracture in matrix dolomite
T3	TL7	P ₂ m ³	5095.35	Pyrobitumen filling a stylolite formed in matrix dolomite
T4	TL7	P ₂ m ³	5101.21	Dolomite and calcite cements filling fractures in limestone
T5	TL7	P ₂ m ³	5102.40	Dolomite and calcite cements filling fractures in limestone
T6	TL7	P ₂ m ³	5105.82	Dolomite and calcite cements filling fractures in limestone
T7	TL601	P ₂ m ³	5515.70	Calcite cements and pyrobitumen filling vugs in limestone
T8	TL601	P ₂ m ³	5521.00	Dolomite cements and pyrobitumen filling fractures in matrix dolomite
T9	TL601	P ₂ m ³	5521.10	Dolomite cements filling fractures in matrix dolomite
T10	TL601	P ₂ m ³	5534.05	Dolomite and calcite cements filling vugs in matrix dolomite

Sample	Type	$\delta^{13}\text{C}_{\text{VPDB}}(\text{‰})$	$\delta^{18}\text{O}_{\text{VPDB}}(\text{‰})$	$\delta^{18}\text{O}_{\text{SMOW}}(\text{‰})$	$^{87}\text{Sr}/^{86}\text{Sr}$
T1	MD	3.62	-6.76	23.94	0.707845
	Cal-2	2.38	-6.12	24.60	0.707995
T2	Cal-2	1.16	-6.66	24.05	0.707443
T4	Lim	2.08	-6.77	23.93	—
	Cal-1	1.52	-8.40	22.25	0.707645
T6	Lim	3.95	-6.95	23.74	0.707047
T7	Lim	3.43	-6.96	23.73	0.707232
	Cal-1	2.75	-8.60	22.04	0.707396
T10	MD	3.28	-7.03	23.66	0.707541

Lim: limestone; MD: matrix dolomite; Cal-1: Cal-1 cements; Cal-2: Cal-2 cements.

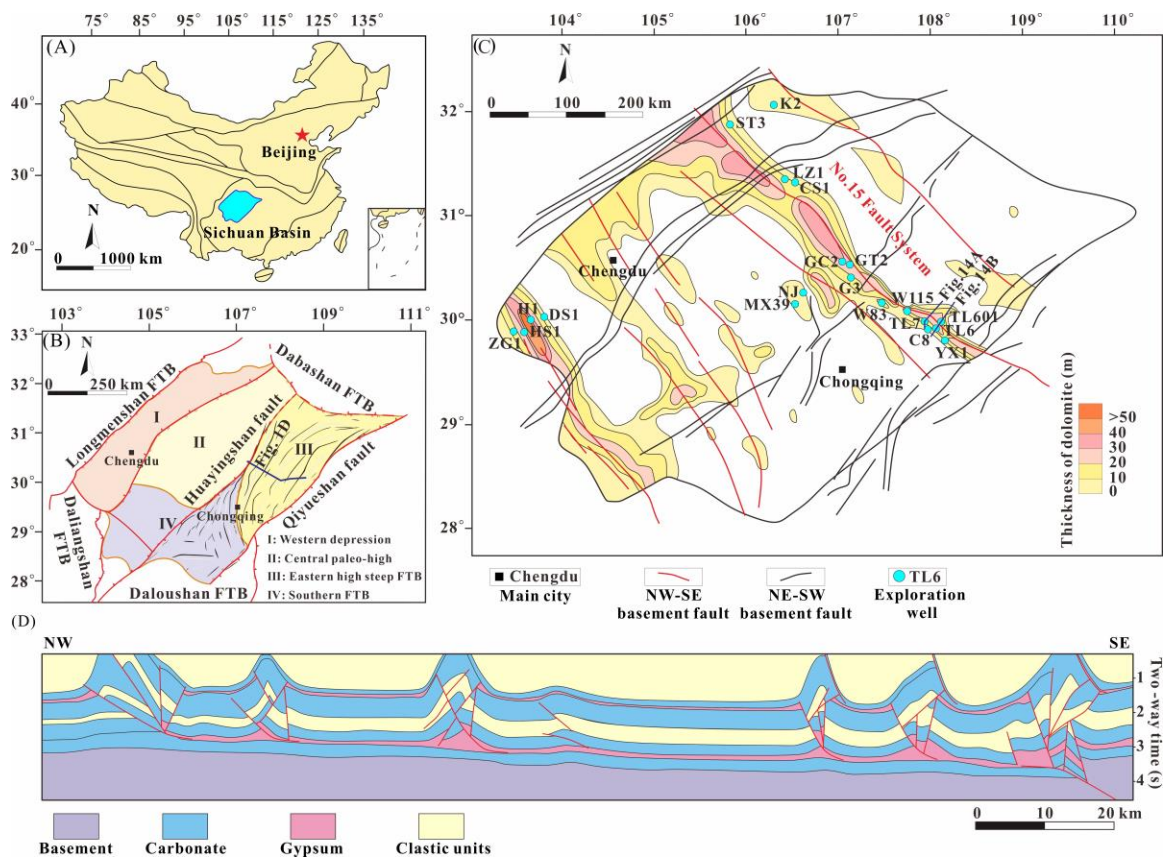


Figure 1

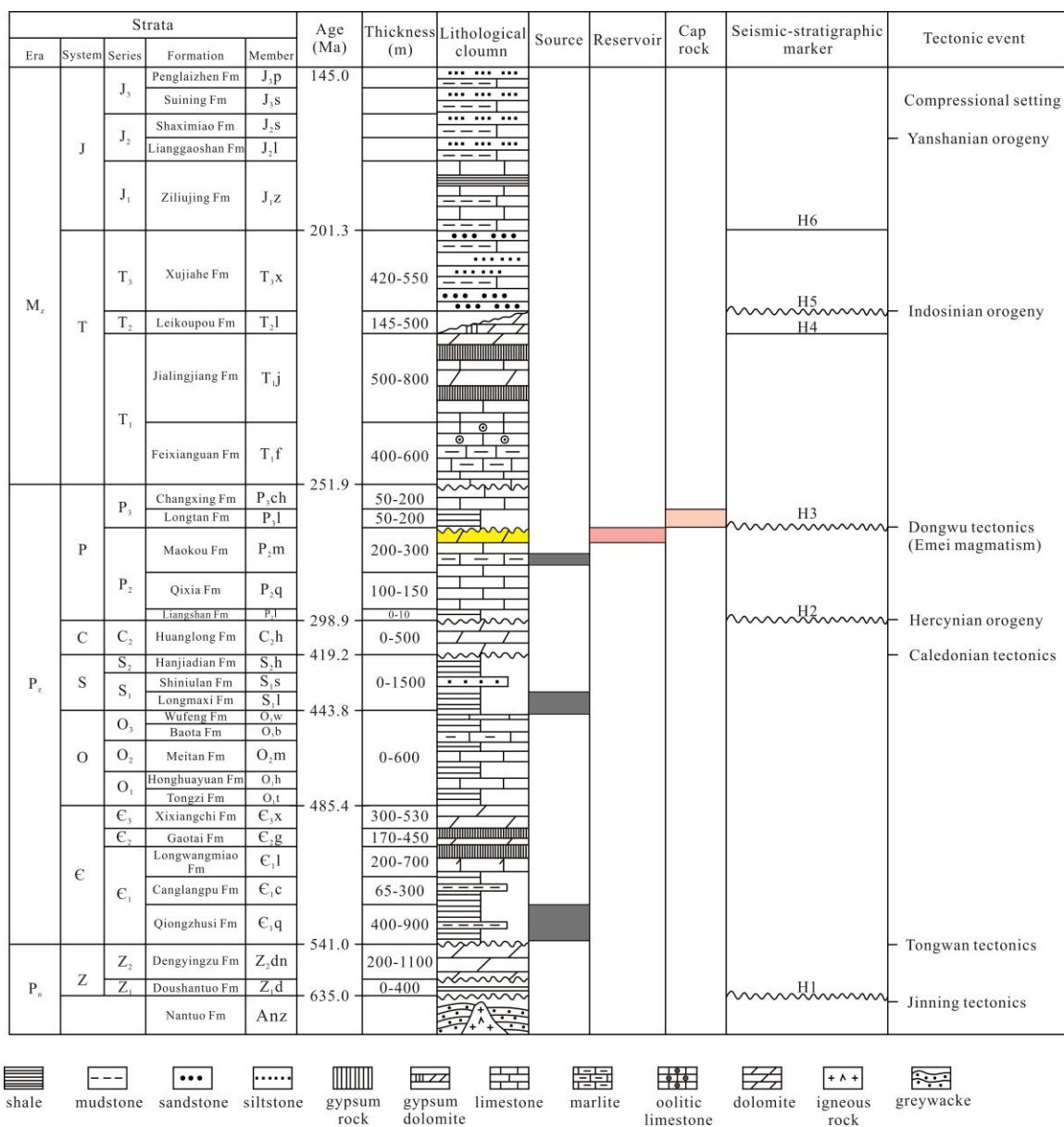


Figure 2

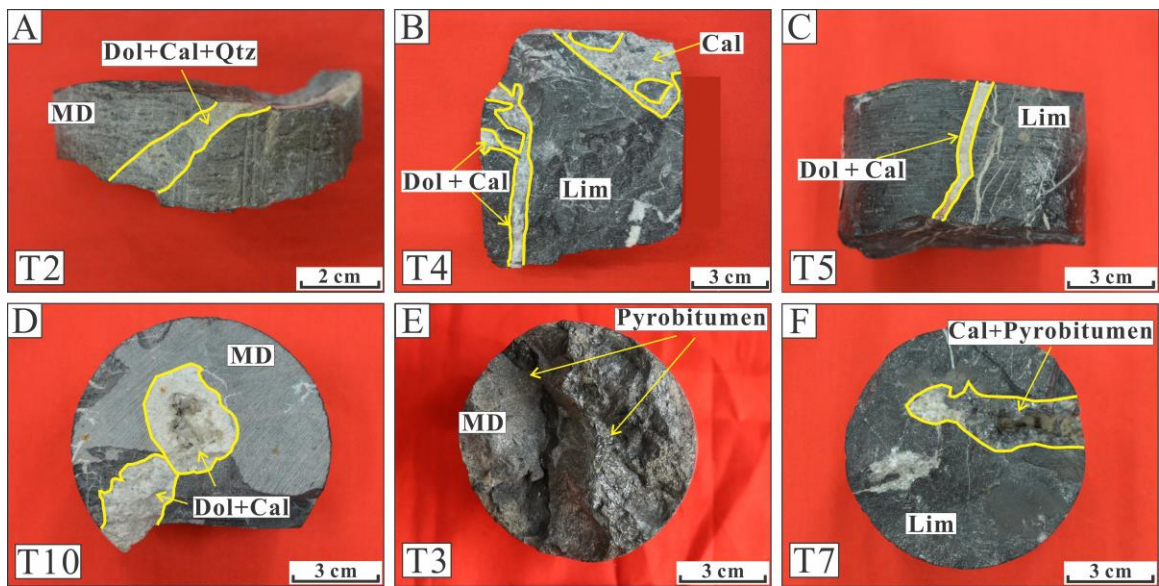


Figure 3

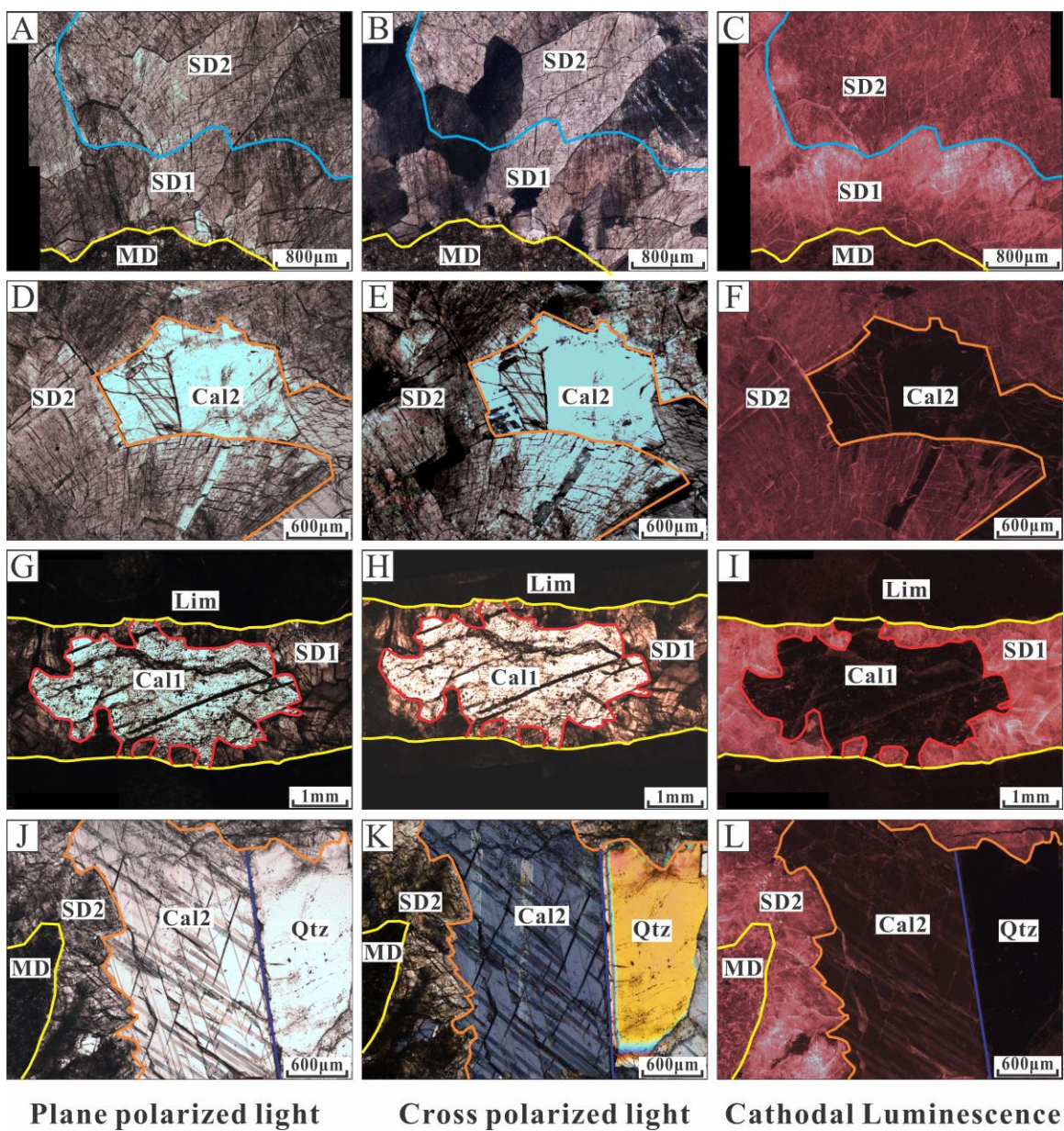


Figure 4

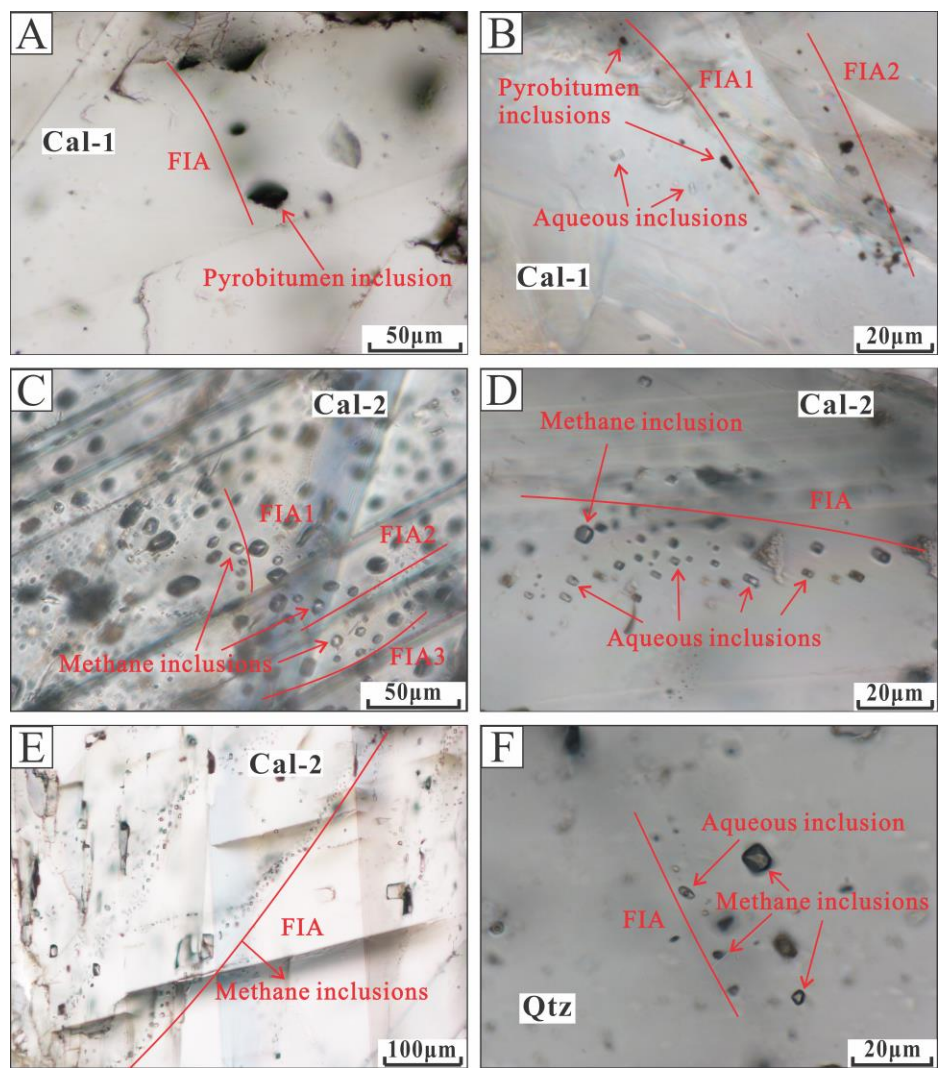


Figure 5

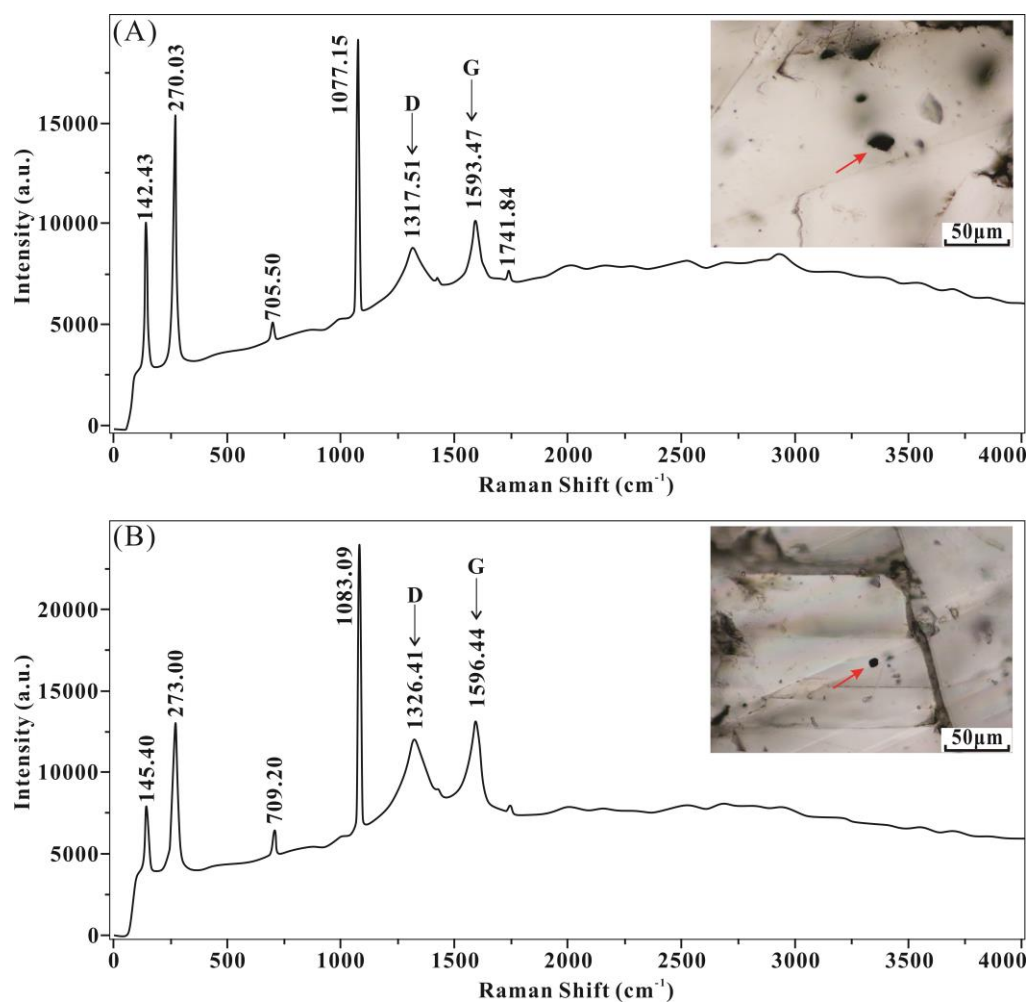


Figure 6

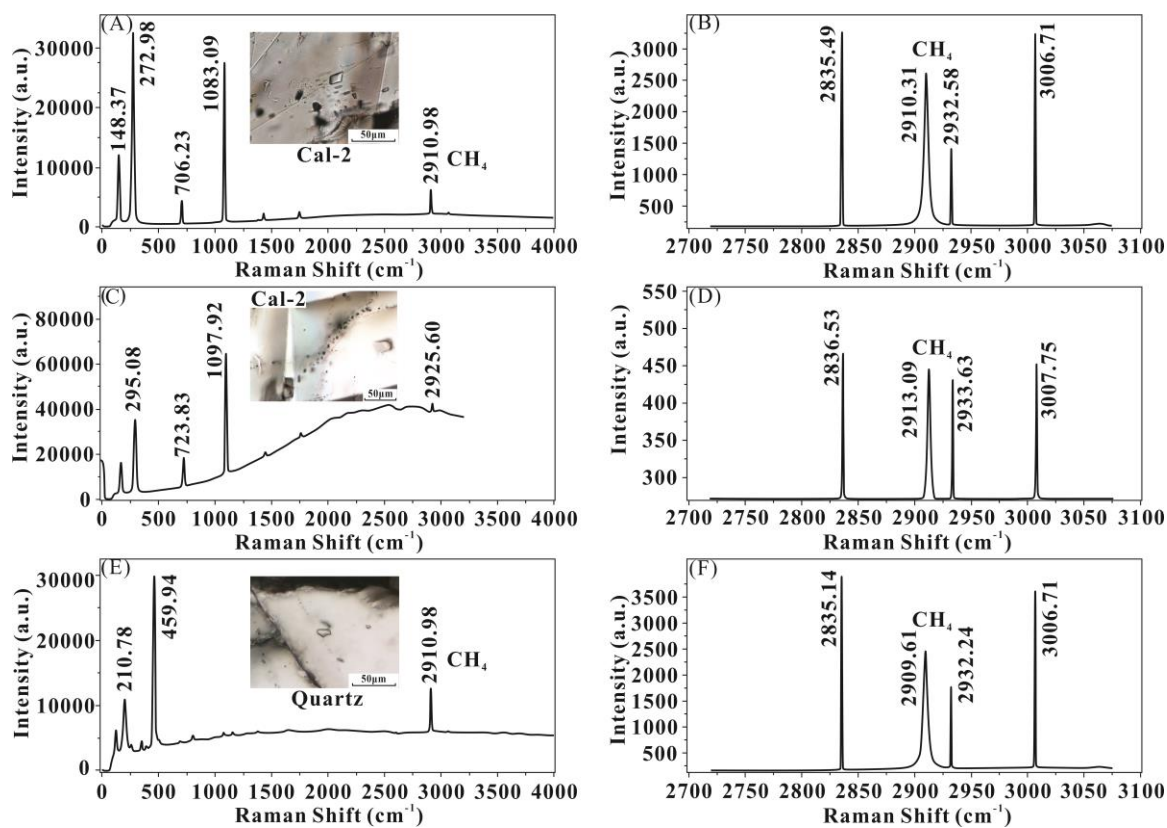


Figure 7

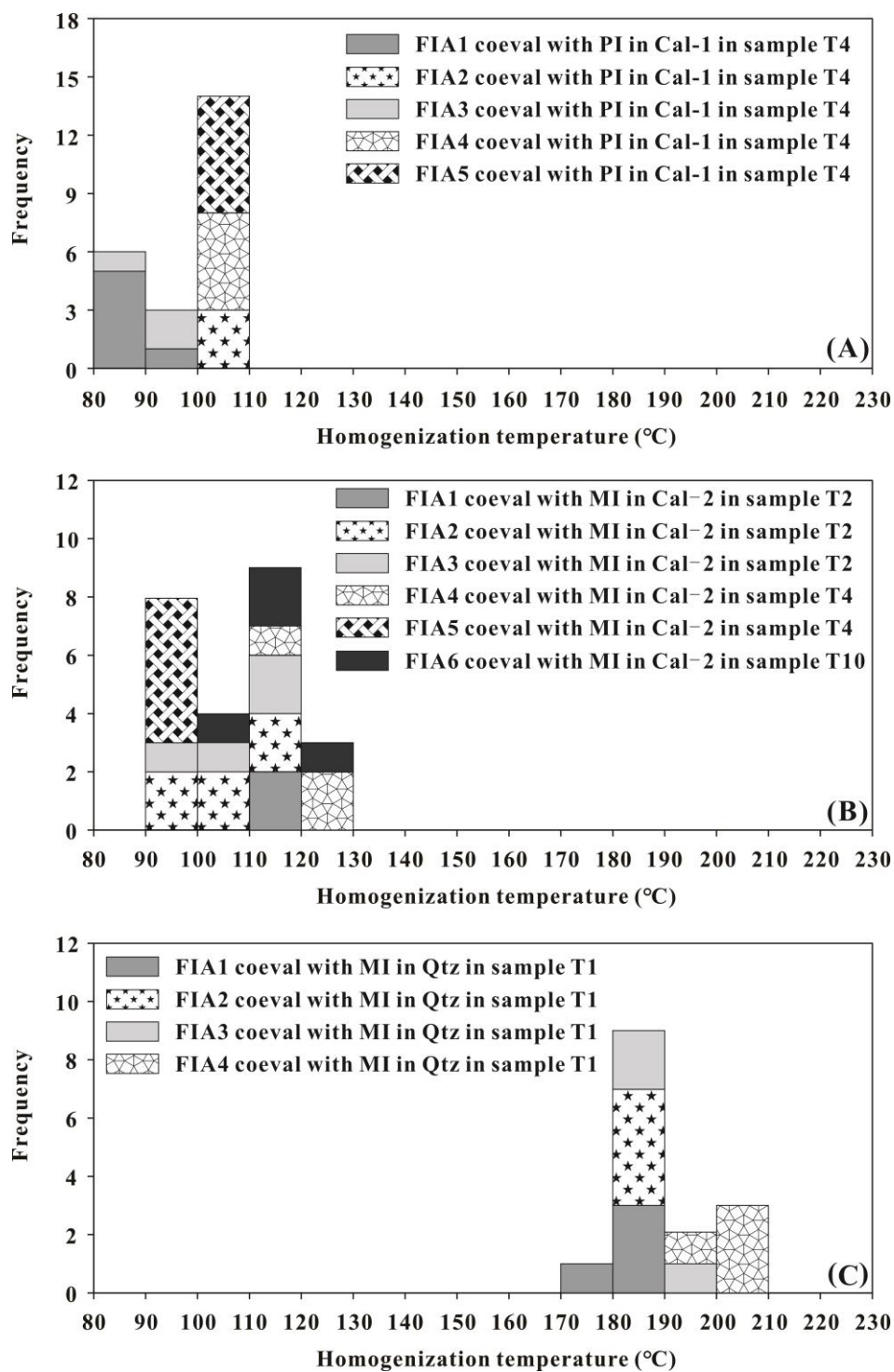


Figure 8

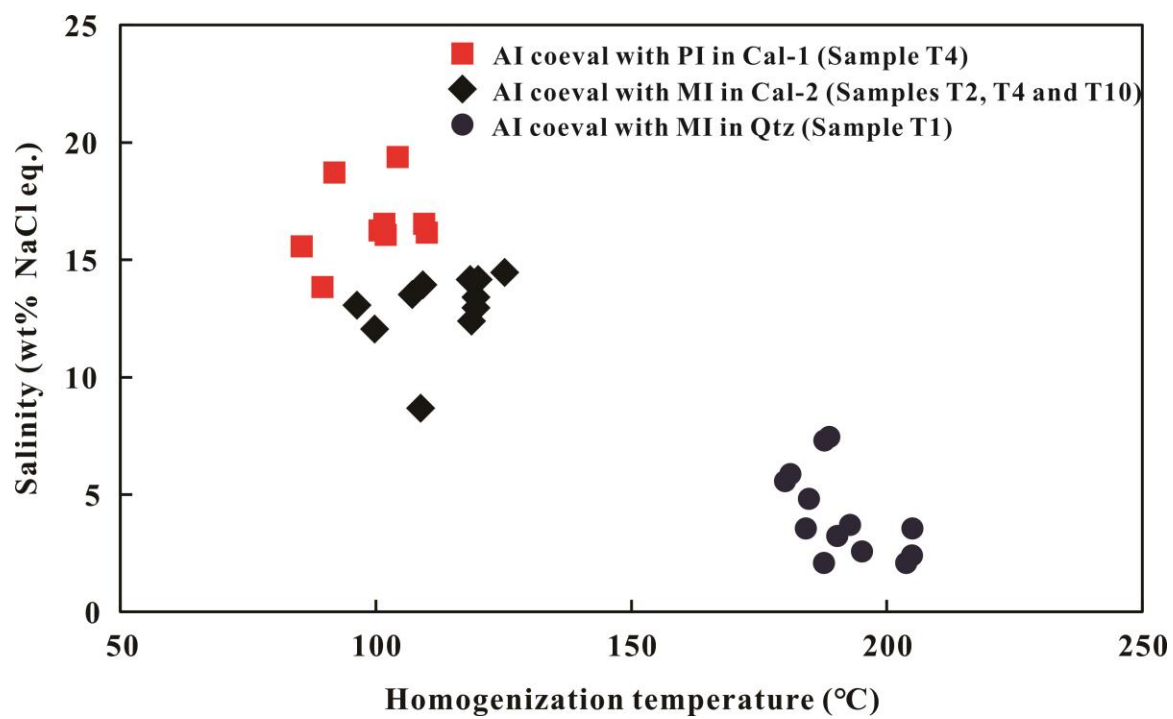


Figure 9

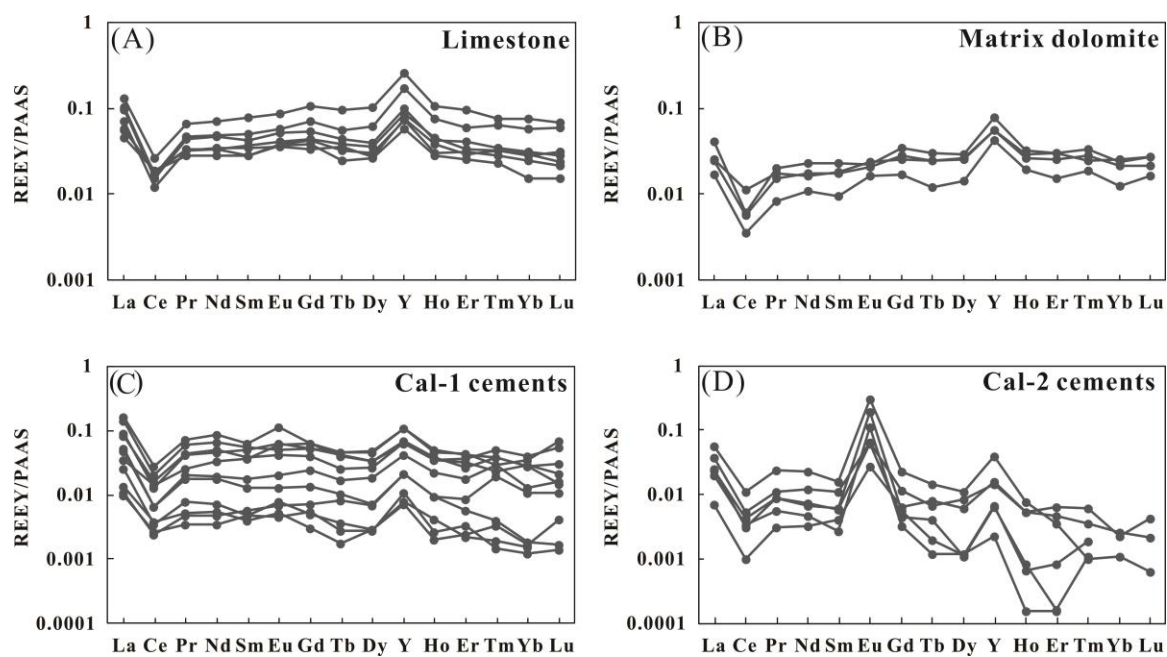


Figure 10

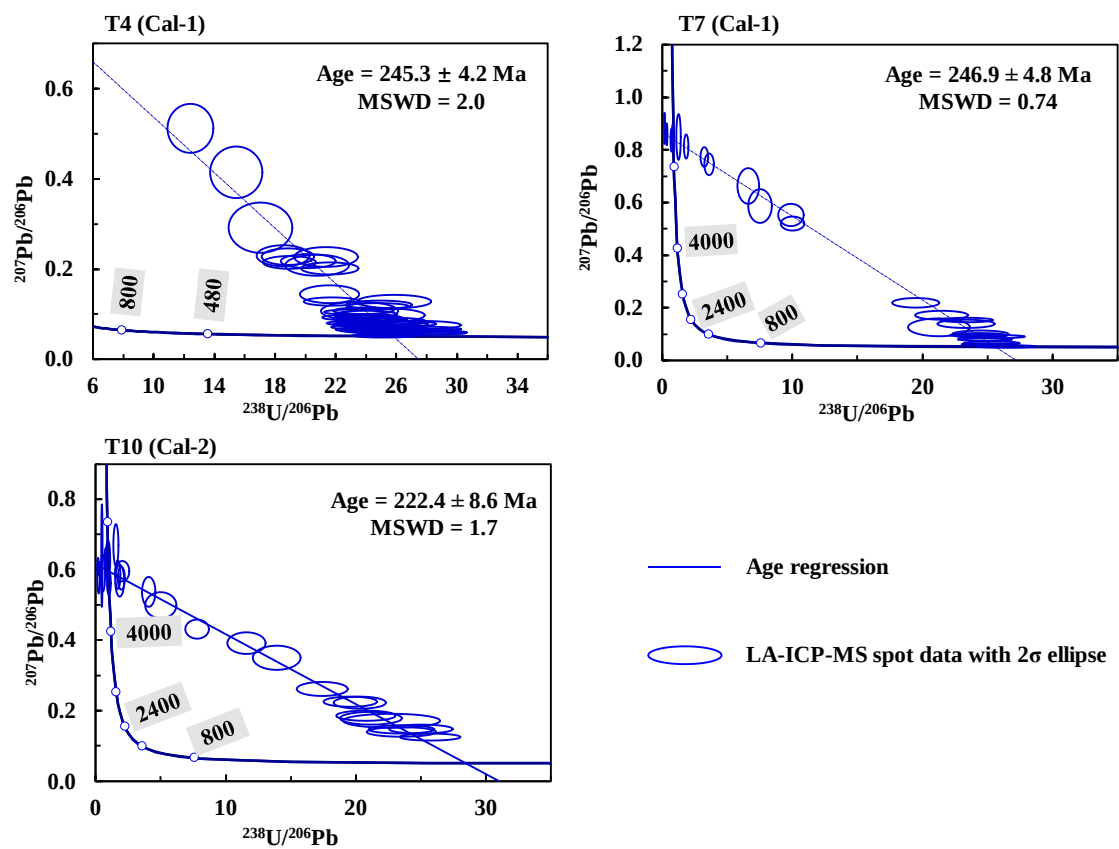


Figure 11

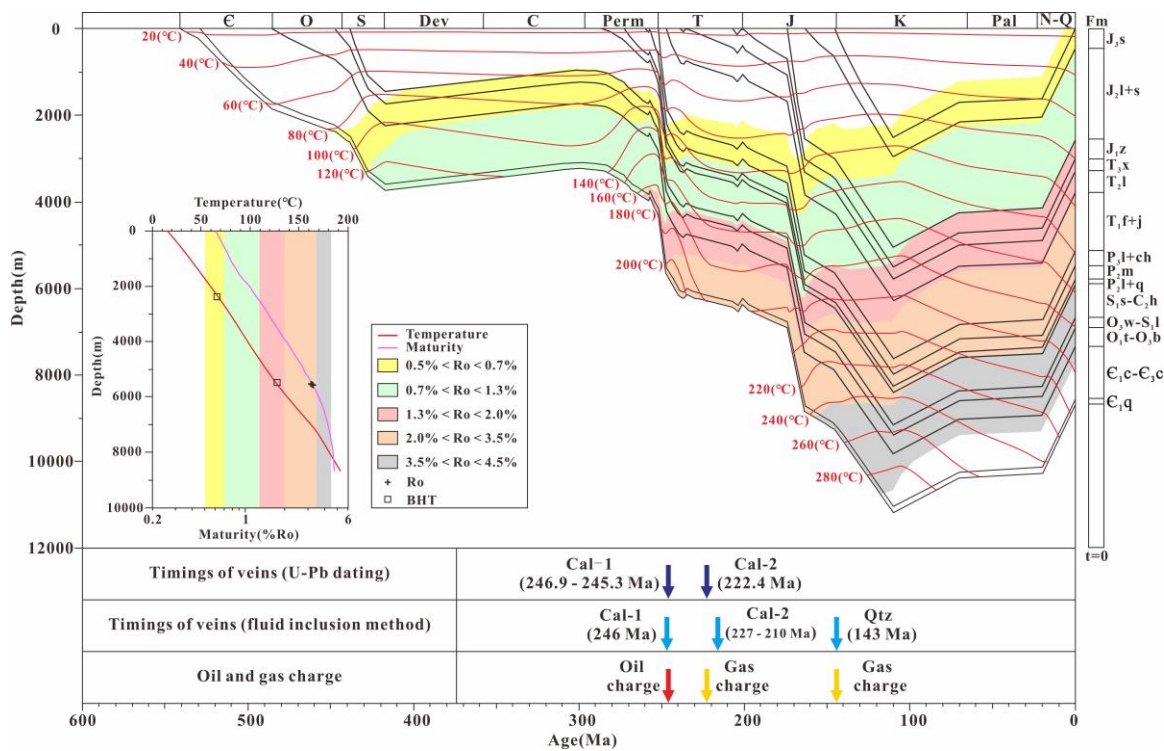


Figure 12

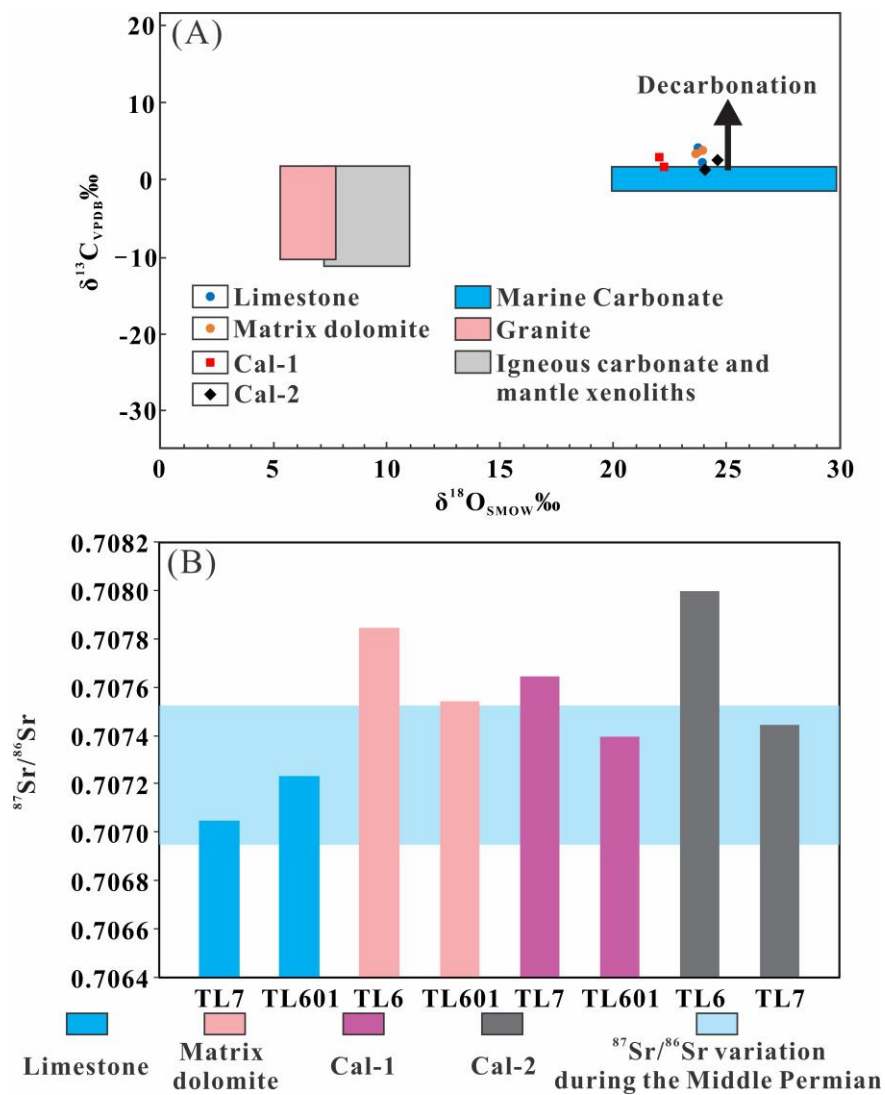


Figure 13

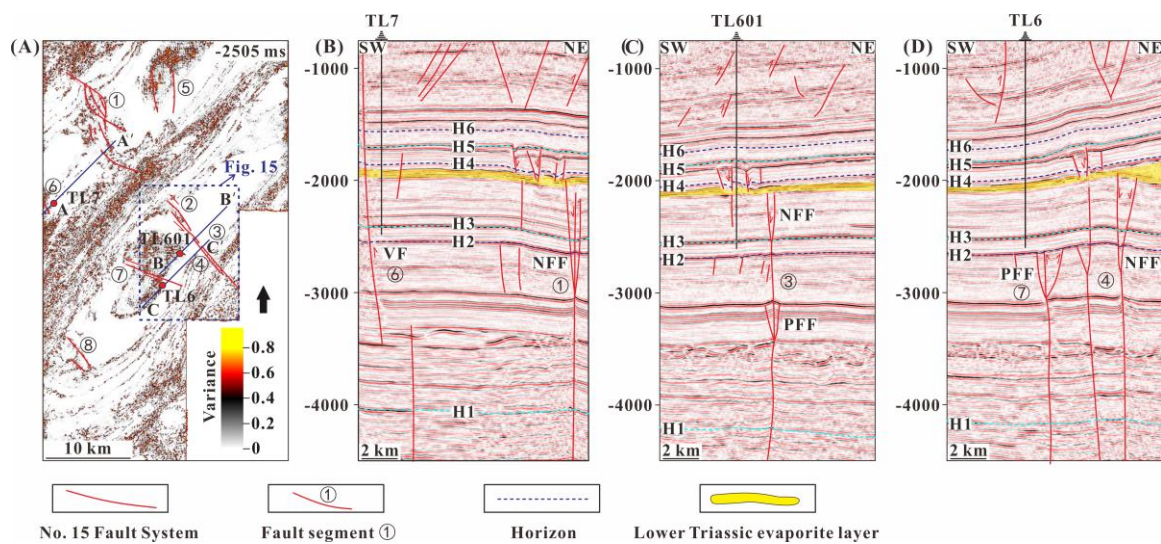


Figure 14

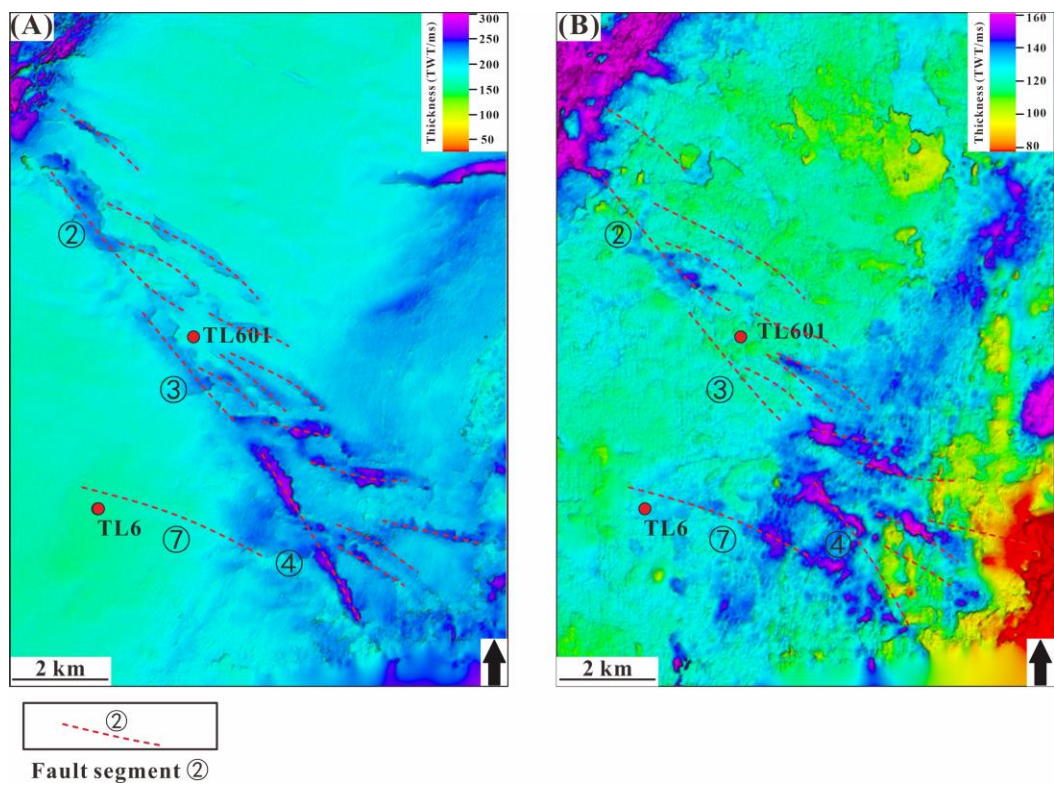


Figure 15

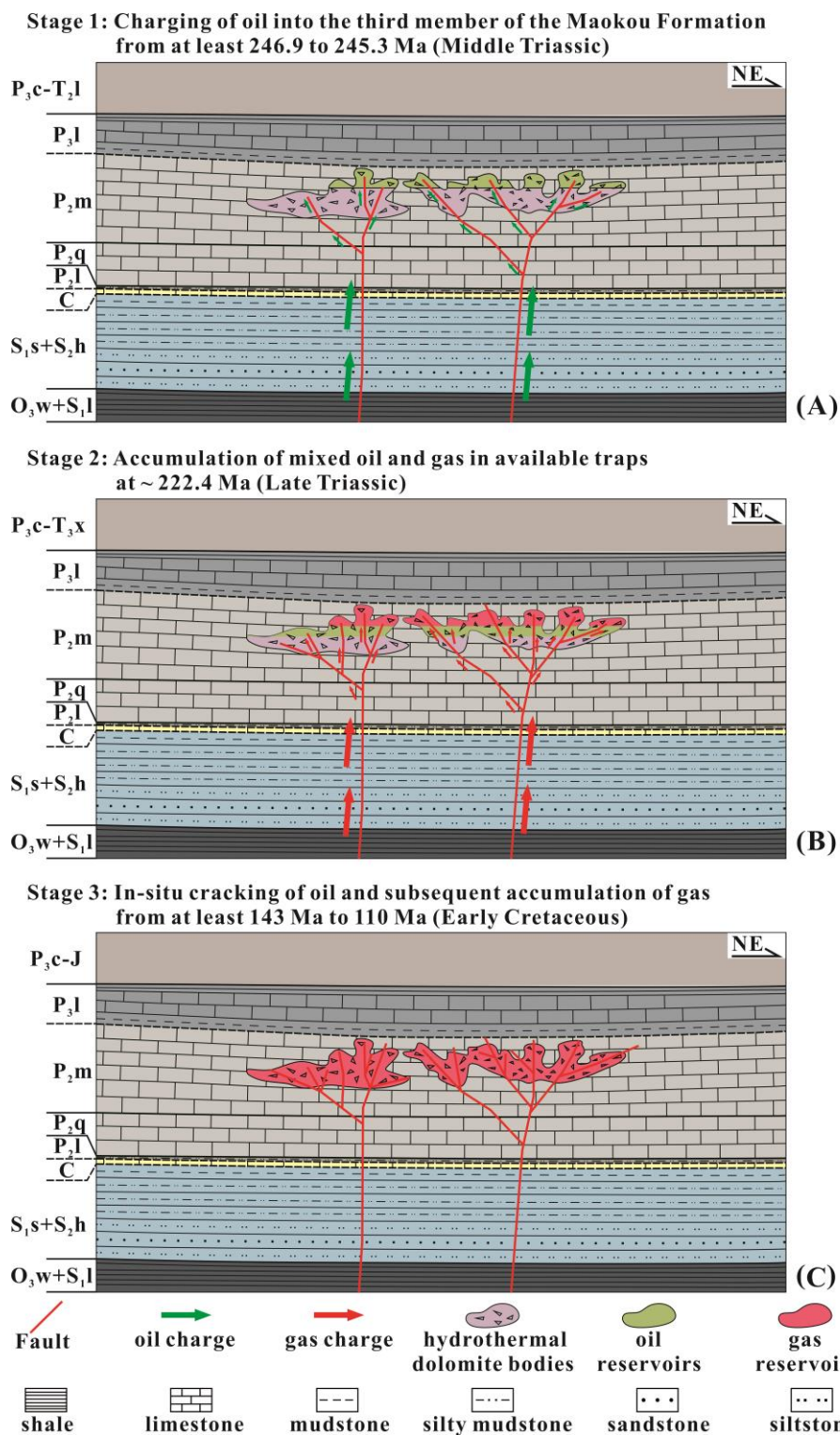


Figure 16