

# Maturity and Overpressure Evolution of the Lower Cambrian in the Central Paleo-Uplift, Sichuan Basin\*

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## Abstract

Sichuan basin is a prime gas-producing basin in China. The Central Paleo-Uplift, located in the middle of the basin, is always an important region for gas exploration. After the Weiyuan gas field was discovered in 1960s, another large gas field has been recently ascertained in the lower Cambrian (CNPC). Simultaneously, the lower Cambrian is promising for shale gas exploration. In this paper, maturity history of source rock and pore pressure evolution have been simulated, which are helpful for further gas exploration. The present geothermal gradient of the Central Paleo-Uplift is 24~30°C/km. According to the burial history and thermal history, maturity history of the Lower Cambrian source rock has been simulated by using Easy%Ro model in this paper. The source rock in the southern part became mature with Ro>1.0% in the early Caledonian (~420Ma), but was still immature in other regions. After a sluggish development caused by tectonic uplift during S~C, the thermal maturity increased again in mid-Permian (~270Ma), and Ro reached the peak of 2%~4% in late Cretaceous (~80Ma). The maturity evolution stopped as the regional uplift during Yanshan and Himalayan movement. The Central Paleo-Uplift has two overpressure systems: Permian-Triassic sequences and lower Cambrian. Based on the DST measurement, the overpressure coefficient is 2.0 in the upper system; and it is 1.5~1.75 in the lower. Anomalously high mudstone acoustic time in the Permian and Triassic reveals that disequilibrium compaction is the mainly mechanism for the overpressure. However, the combination of the normal acoustic time and geologic history analysis indicates that overpressure in the lower Cambrian is mainly resulted from fluid expansion, most like gas generation. 1D and 2D geopressure models demonstrate that surplus pressure in the lower Cambrian appeared during Triassic, and reached the maximum at about 80Ma. In conclusion, the lower Cambrian source rock in the Central Paleo-Uplift experienced twice hydrocarbon generation, and oil cracking is during 220~100Ma. Evolution of the pore pressure in the lower Cambrian includes three phases - normal pressure, overpressure and pressure releasing. Overpressure provides the motivation for hydrocarbon migrate laterally and downward into Sinian series. Furthermore, pressure releasing contributes to gas release from formation water.

## Introduction

Sichuan basin is a prime gas-producing basin in China. The Central Paleo-Uplift, located in the middle of the basin, is always an important region for gas exploration ([Figure 1](#)). After the giant Neoproterozoic Weiyuan gas field was discovered in the 1960s, another large gas field has

been recently ascertained in the Lower Cambrian (CNPC). Simultaneously, the Lower Cambrian is promising for shale gas exploration. In this paper, maturity history of source rock and pore pressure evolution have been simulated, which are helpful for further gas exploration.

### **Geologic Setting**

The Sichuan Basin is a composite superimposed basin with multi-cycle evolution. There is 8,000-12,000 m (26,250-39,370 ft) thick marine carbonate and continental clastic sediments overlying the pre-Sinian Proterozoic basement. Including several important tectonic episodes, the tectonic evolution of the basin can be divided into two main stages. (1) Intracratonic stage, before the Yanshanian tectonic movement (~190Ma). Tectonic activities were dominated by integral subsidence and uplift without intensive lateral compression. (2) Foreland stage, since the Yanshanian tectonic movement. Tectonic activity has been characterized by intensive lateral compression, and several fold belts were formed in the periphery area.

The Lower Cambrian source rock, which consists of black mudstones and shales, is considered as the most important hydrocarbon source rock in the Lower Paleozoic, in the Sichuan Basin (Dai, 2003; Huang et al. 2012). According to the burial history and thermal history, maturity history of the Lower Cambrian source rock has been simulated by using Easy%Ro model (Figure 2). The source rock in the southern part became mature with  $Ro > 1.0\%$  in the early Caledonian (~420Ma), but was still immature in other regions. After a sluggish development caused by tectonic uplift during S~C, the thermal maturity increased again in mid-Permian (~270Ma), and  $Ro$  reached the peak of 2%~4% in late Cretaceous (~90Ma). The maturity evolution ended as the regional uplift during Yanshan and Himalayan movement.

### **Thermal Maturity**

Cracking of crude oil should be influenced by temperature and pressure. Jackson et al. (1995) and Waples (2000) suggested that just a little crude oil cracked when temperature lower than 160°C, and the cracking was almost completed at 200°C. Based on the temperature histories of the Cambrian reservoirs (Figure 3), it can be determined that the oil cracking started from the end of the Triassic and finished up in the Early Cretaceous.

Overpressures are commonly encountered in the central of the Central Paleo-Uplift (Moxi area, Figure 1). Combining pressure measure data (DSTs, mud weights and sonic transit time) with seals analysis, five pressure systems, including three overpressure compartments, should be recognized in the central of the Central Paleo-Uplift (Figure 4). System I is normally pressured in the Lower Jurassic and upper; System II, spanning from the bottom of the Lower Jurassic to the Upper Triassic Xujiahe Formation, is the first overpressure compartment, with relatively higher overpressure in the upper part, and reducing in the bottom (approximately 2800m). System III is a high overpressured compartment ( $r > 2.0$ ) spanning from 3,000 m to 4,000 m. System IV is the third overpressured compartment, located in 4,000-5,000 m, with some lower pressure coefficient ( $r$ ) than the upper overpressure compartment (system III). Below 5,000 m, system V is almost normally pressured.

Overpressure mechanisms can be broadly separated into two categories of disequilibrium compaction mechanisms and fluid expansion mechanisms. The petrophysical properties of overpressuring sequences are different in above two categories (van Ruth et al., 2004; Tingay et al., 2009, 2013; Lahann and Swarbrick, 2011; Zhang, 2013). Analyzing the origins for overpressure systems in the Central Paleo-Uplift should

be contributed to understanding forming conditions and evolution characteristics of overpressure in the old Early Paleozoic strata. The sonic transit time-effective stress analysis indicates multiple origins for overpressure in the Central Paleo-Uplift (Figure 5). Overpressure data of the Upper Triassic Xujiahe Formation lie closed to the loading curve, which demonstrates that disequilibrium compaction is a key factor in this formation. However, the sonic transit time-effective stress analysis highlights the presence of overpressures generated by a fluid expansion mechanism in the Cambrian Formation. Although DSTs are absent in the Permian Formation, a higher overpressure caused by disequilibrium compaction must exist because of the abnormal high sonic transit time, which represents anomalous high porosity. As the absence of shales in the Lower Triassic Formation in the Sichuan Basin, disequilibrium compaction is not the mechanism for the high overpressure. We suggest that the primary origin for the high overpressure is oil cracking, added the contribution of dewater of the thick gypsolyte. In actuality, the good sealing capacity of anhydrite is the key for high overpressure preservation.

### **Discussion**

Combining the overpressure mechanisms with the burial and hydrocarbon generation histories, the evolution model of the pore pressure for the Cambrian overpressured formation in the Central Paleo-Uplift in the Sichuan Basin has been constructed (Figure 6). The pore pressure in the Cambrian Formation in the Central Paleo-Uplift in the Sichuan Basin was generally normal before 220Ma. Overpressuring occurred since 220Ma, and reached maximum at 90Ma. Pore pressure and overpressure have been decreased gradually to present state since 90Ma. In the Weiyuan structure, with the largest denudation quantity, the fluid pressure has been back to normal pressure; however, a middle magnitude overpressure is still preserved in the Cambrian Formation in the Moxi area.

### **Conclusions**

The Lower Cambrian source rock in the Central Paleo-Uplift experienced hydrocarbon generation twice, and oil cracking occurred during 220~100Ma. Five pressure systems, including three overpressure systems, have been recognized. Mechanisms for various overpressure systems may be different. The Cambrian overpressure system is predominantly associated with fluid expansion which mainly resulted by gas generation. Furthermore, we suggest that late gas generation is a key factor for gas and overpressure preservation in old strata. Evolution of the pore pressure in the Lower Cambrian includes three phases - normal pressure, overpressure and pressure releasing.

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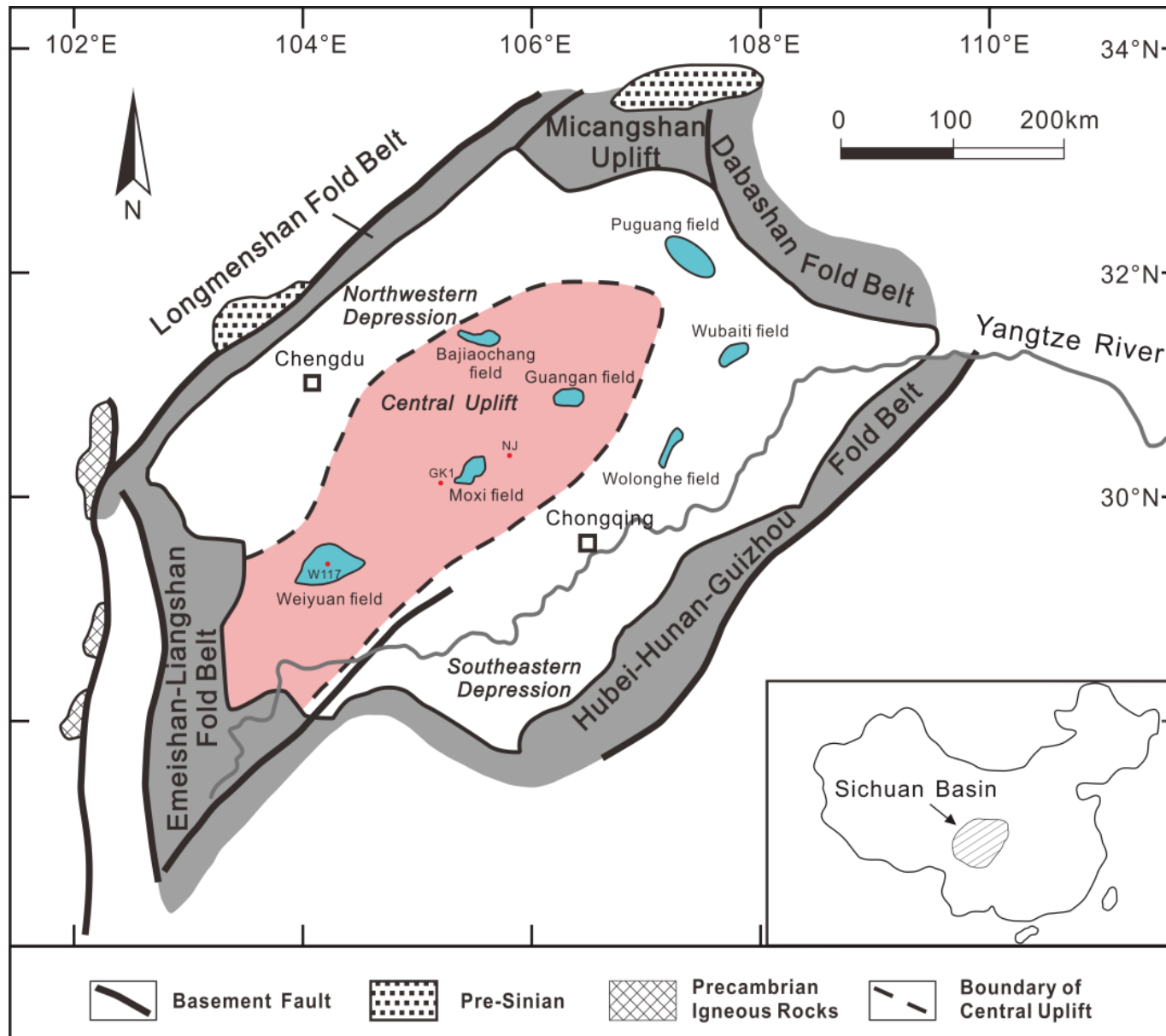


Figure 1. Main structural elements of the Sichuan Basin (modified from Ma et al., 2007) and the location of the giant gas fields and study wells.

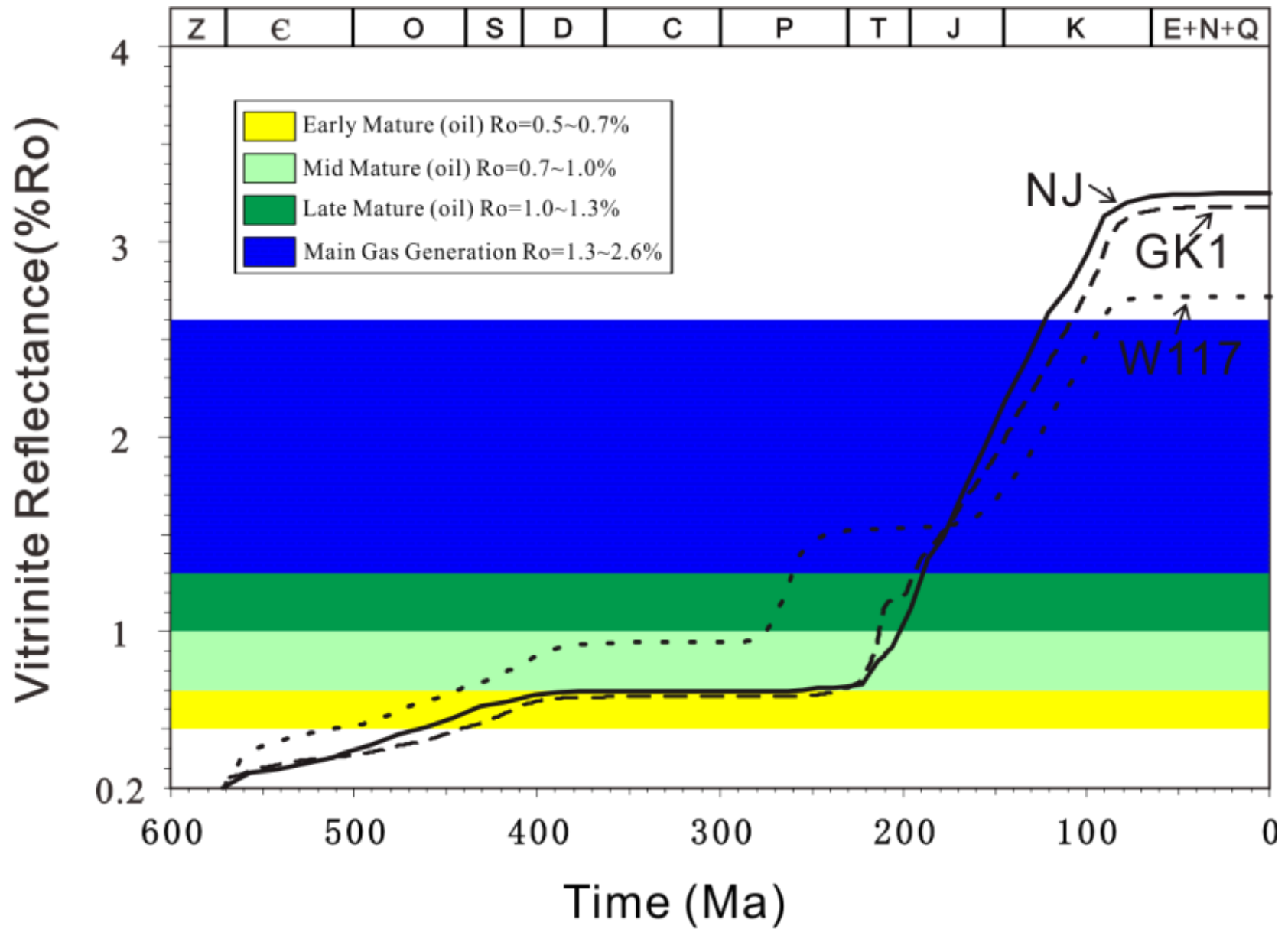


Figure 2. Maturity histories for the bottom of the Lower Cambrian Qiongzhusi Formation (Є1q) source rock in Well W117, Well GK1 and Well NJ.

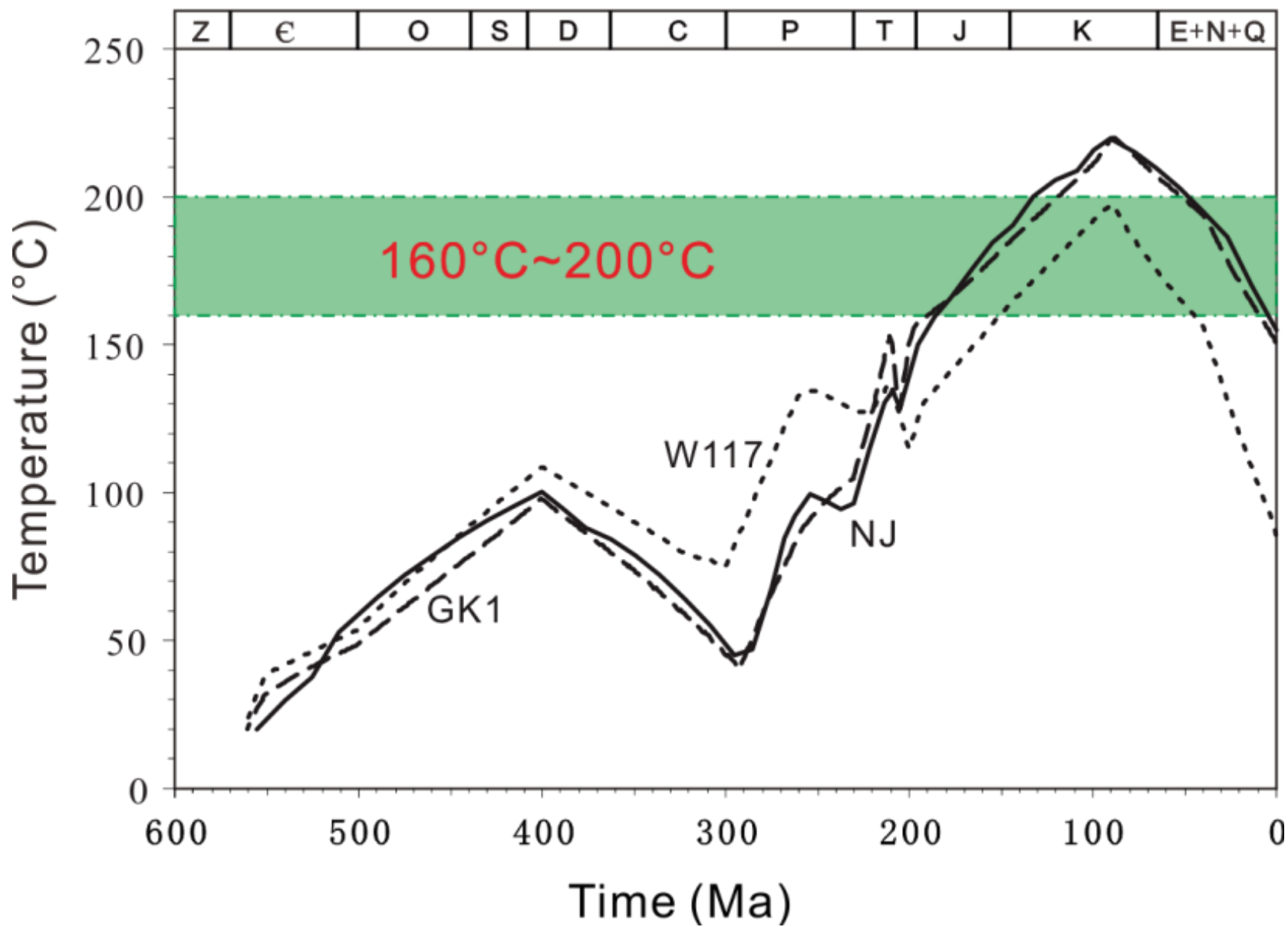


Figure 3. Temperature histories of the bottom of the Cambrian for three wells.

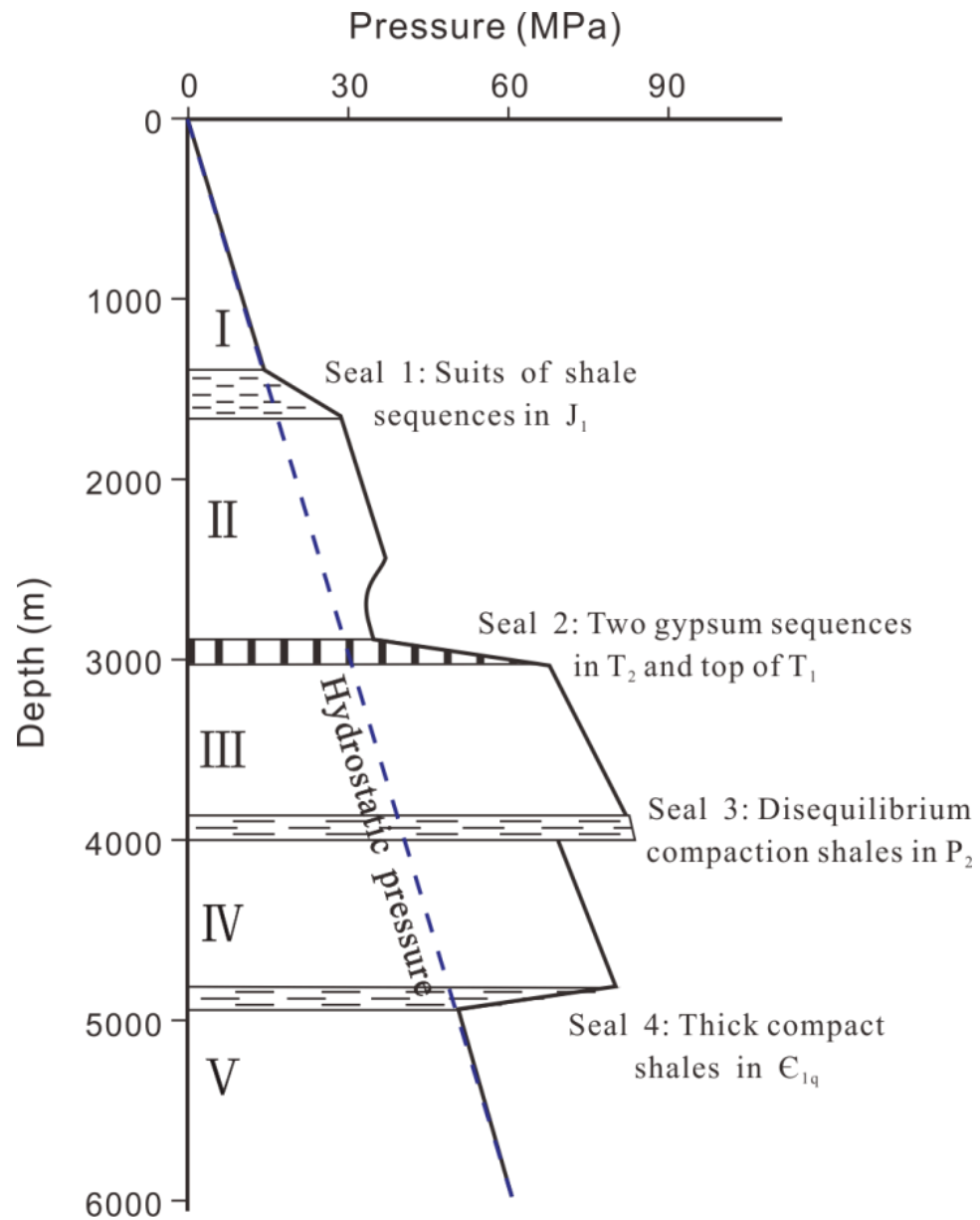


Figure 4. Profile of pressure systems and seals in the central of the Central Paleo-Uplift. Systems I and V are normally pressured, however, II, III and IV are overpressured.



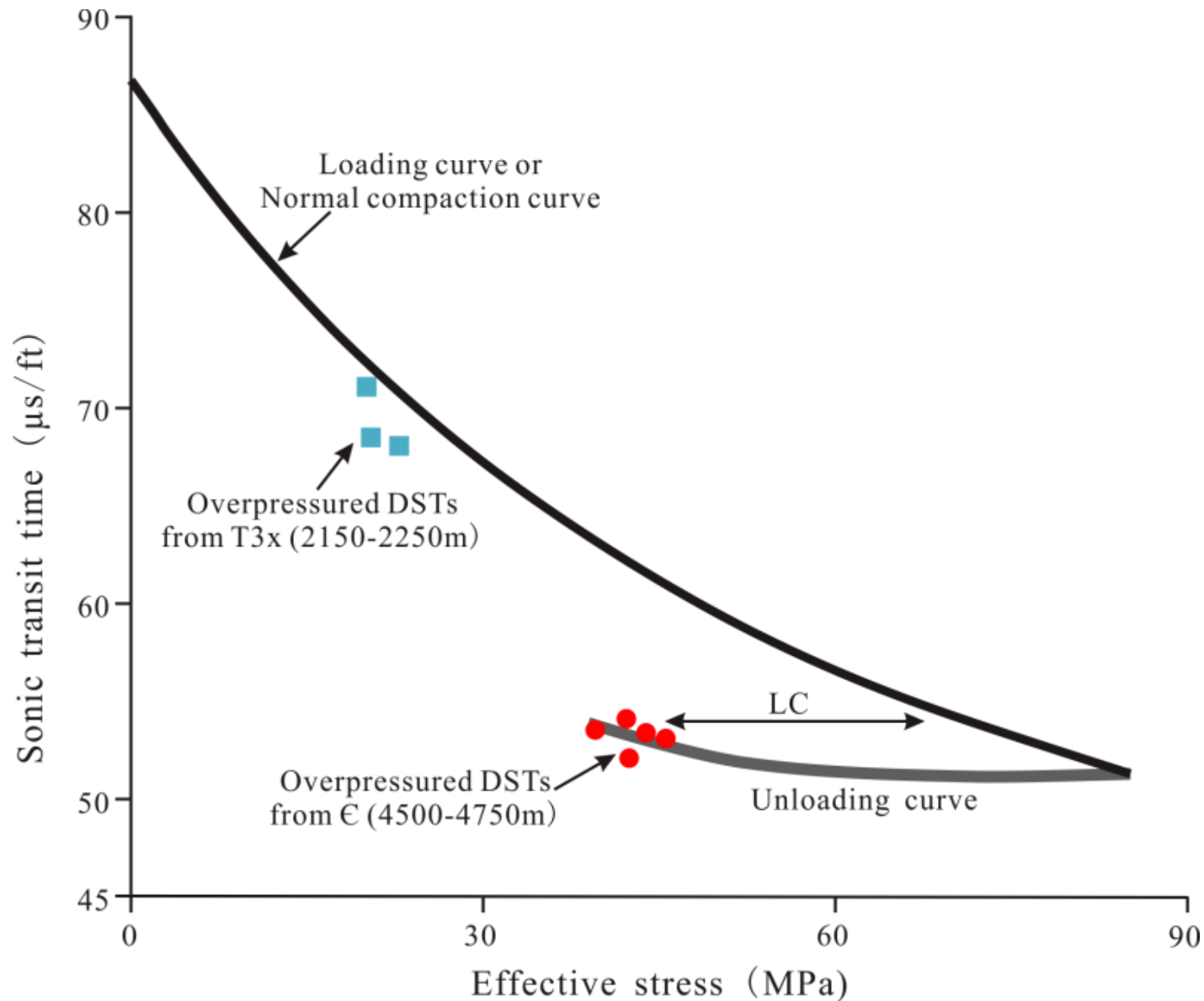


Figure 5. The relationship between sonic transit time and the effective in the Central Paleo-Uplift. Loading curve is calculated based on normally pressured sequences. Solid dots and squares are present the overpressured Cambria Formation and Upper Triassic Xujiache Formation. The Cambrian overpressured formation lies off the loading curve obviously, and the distance LC can reflect the contribution of fluid expansion for the overpressure.

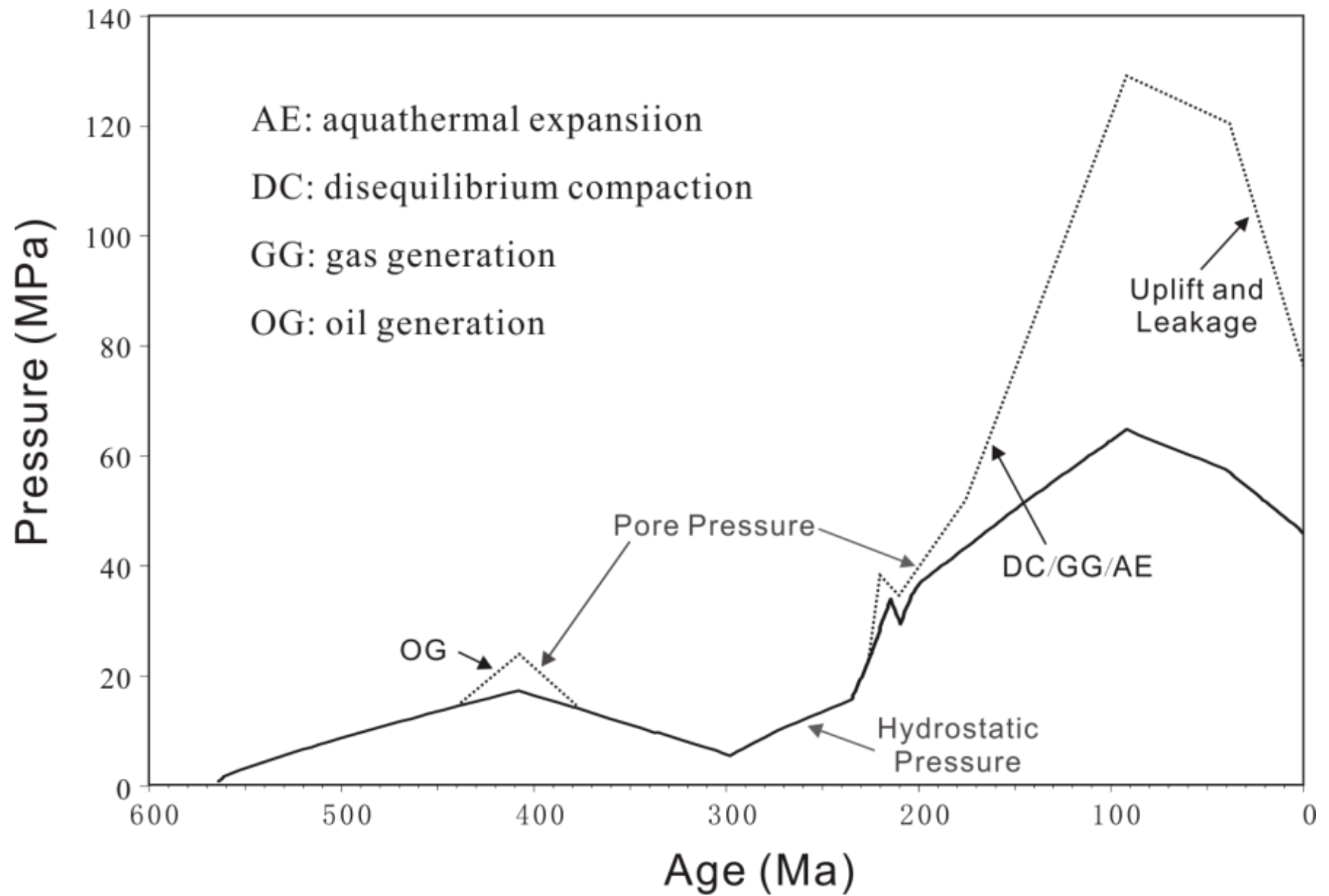


Figure 6. The pressure evolution model of the Cambrian Formation in the Central Paleo-Uplift in the Sichuan Basin and main overpressure mechanisms at various periods.