

PS Thermal Evolution of the Paleozoic Hydrocarbon Source Rocks in the Sichuan Basin*

Chuanqing Zhu¹, Nansheng Qiu¹, Shengbiao Hu², and Song Rao²

Search and Discovery Article #10503 (2013)**

Posted July 31, 2013

*Adapted from poster presentation given at AAPG 2013 Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013

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¹College of Geosciences, China University of Petroleum, Beijing, 102249, China (chuanqingzhu@yahoo.com)

²Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China

Abstract

The Sichuan Basin is one of the most important oil-gas bearing basins in SW China. A recently discovered large gas field, Puguang gas field, sheds some light on the petroleum exploration prospect in this basin. The thermal history of the Sichuan Basin has been reconstructed based on a large paleo-thermal indicators (Ro, AFT) dataset. The Ro profiles of some deep boreholes in the basin show ‘dog-leg’ shapes at the unconformity between the upper and middle Permian. The inversion result based on the Ro data suggests two historic different thermal regimes since the Paleozoic in the Sichuan Basin, the earlier one ending at the beginning of late Permian, the later one began since the last denudation. The low-T thermochronological modelling result suggests that the last denudation in different regions started at almost the same time (~100-80Ma), except for the western Sichuan Basin, in which the denudation started much later (~60-50Ma). This provides significant information supplementary to the thermal history reconstruction that based on the Ro data: the cooling started at ~60-50 Ma (Paleocene) in the west, and at ~100-80 Ma (late Cretaceous) in the other regions.

The maturation history of the hydrocarbon source rocks of some deep boreholes in the Sichuan Basin have been modeled based on the thermal evolution modeling results, the burial history of the source rocks, and the effect of the geological events on the evolution of the source rocks, especially the Paleozoic source rocks are also evaluated. In the southwestern part of the Sichuan Basin, which was closed to the Emeishan Large Igneous Province (ELIP), most Paleozoic source rock organic matter matured in the middle Late Permian. Lower Permian source rocks were heated to its peak maturity (maximum Ro > 3.0%) at around 260 Ma. There was no secondary hydrocarbon generation in the later time. This indicates that the thermal evolution of the Paleozoic source rocks was strongly affected by the Emeishan Mantle Plume (EMP) in this area. However, in the regions that are far away from the ELIP, including the Puguang gas field, secondary hydrocarbon generation of the source rocks existed, the thermal evolution of the source rocks was related to the Mesozoic foreland basin evolution. Therefore, the latter appears to be prospective to hydrocarbon reservoir accumulation.



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CHUANQING ZHU¹, NANSHENG QIU¹, SHENGBIAO HU², SONG RAO²

1. College of Geosciences, China University of Petroleum, Beijing, 102249, China

2. Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China

1. Geological setting

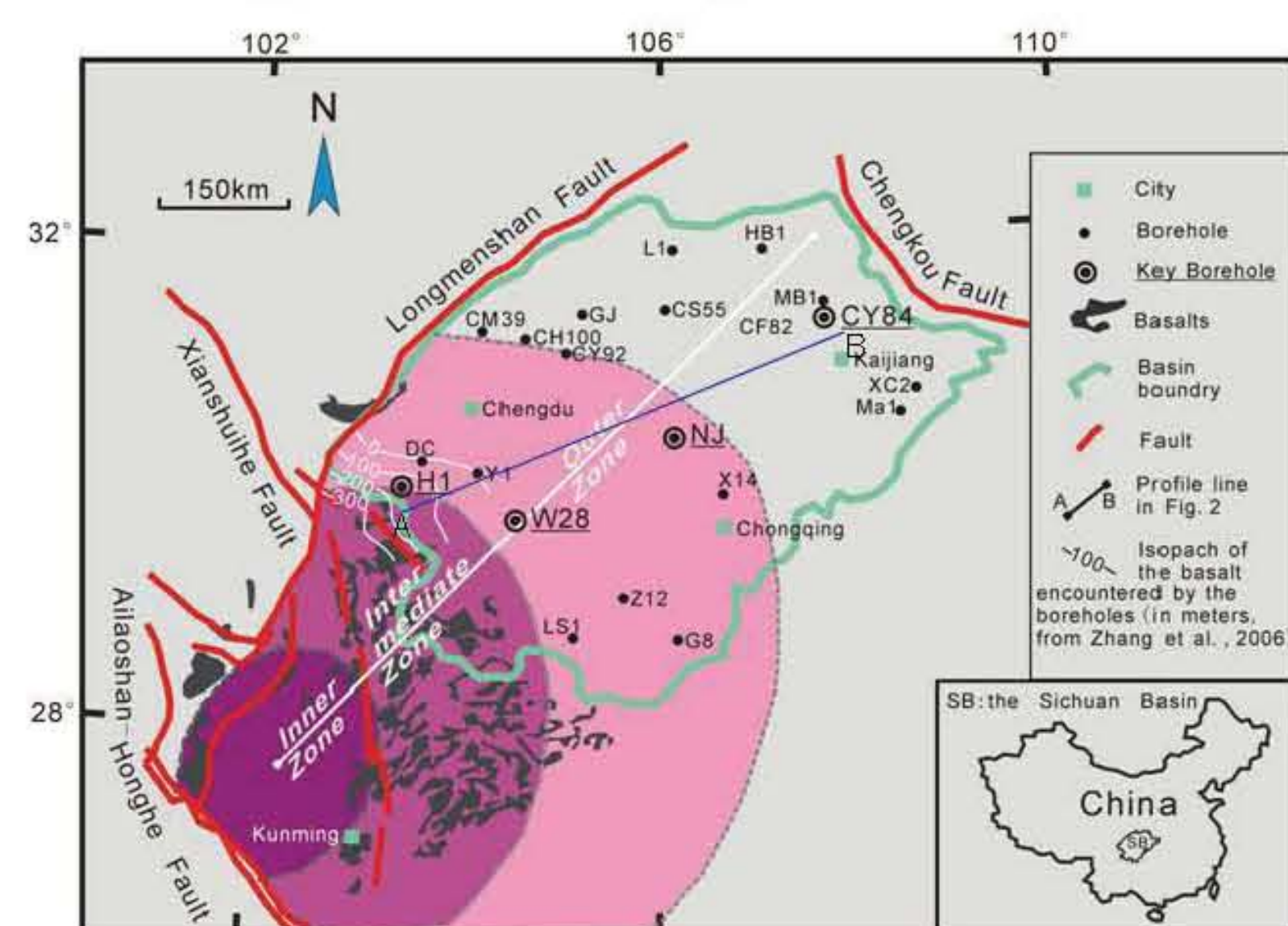


Fig. 1 Geology of the Sichuan Basin and the location of boreholes

The Sichuan Basin in southwestern China is an oil and gas bearing basin developed on the Yangtze Craton, which depressed in Paleozoic-early Mesozoic and bended in late Triassic-late Cenozoic. The Emeishan Large Igneous Province (ELIP) is partly located in the southwest of the Sichuan basin. Based on the distribution of the unconformity in Permian and magmatic rocks, the erosion thickness of the underlying Maokou limestone, the sedimentary successions and other lithofacies-paleogeographic information, He et al. (2007) divided the ELIP into the inner, intermediate and outer zones. The intermediate zone of the ELIP covers part of the southwestern Sichuan Basin. The outer zone covers part of the central and southern areas of Sichuan Basin (Fig.1).

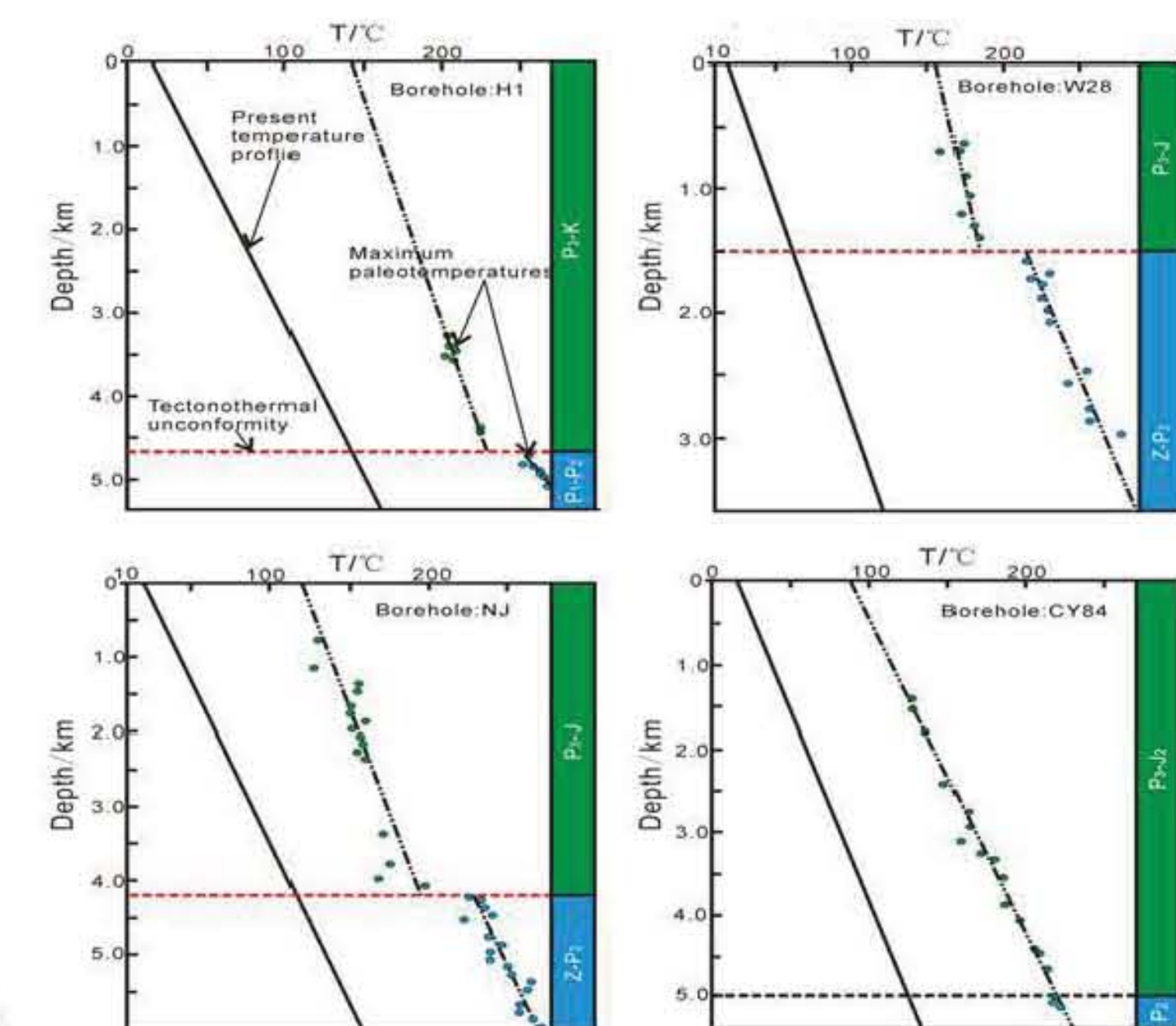


Fig.2 Maximum paleotemperature profiles of the key boreholes

2. Paleo-thermal regimes: insights from maximal paleotemperature profiles

Fig. 2 shows the paleotemperature profiles for 4 representative boreholes in the Sichuan basin from the Ro data based on the chemical kinetic model of vitrinite reflectance (Easy%Ro). No borehole existed in the inner zone of the ELIP as it is located out of the Sichuan basin (see Fig. 1). A representative borehole, H1, is located in the intermediate zone and two typical holes, W28 and NJ, in the outer zone. Another borehole, CY84, represents the boreholes out of the zones affected by the ELIP. The paleotemperature gradients for each independent subsections can be achieved for the four typical paleotemperature profiles of H1, W28, NJ and CY84 using a linear regression method. For the lower subsection, the temperature gradient is $\sim 43^\circ\text{C}/\text{km}$ for H1 in the intermediate zone, $35^\circ\text{C}/\text{km}$ and $23^\circ\text{C}/\text{km}$ for W28 and NJ, respectively, in the outer zone. A much lower, uniformed temperature gradient ($26^\circ\text{C}/\text{km}$) for the whole borehole section of CY84 is observed in the northeast of the Sichuan basin out of the zones; it is close to the paleotemperature gradient in the lower subsection of well NJ, which is located nearby the northeast boundary of the outer zone, and similar to that of the upper subsection within the zones and also to the present temperature gradients ($20\text{--}25^\circ\text{C}/\text{km}$). It could be concluded that the background temperature gradient out of the zones is much lower ($20\text{--}26^\circ\text{C}/\text{km}$) from late Permian than that ($23\text{--}43^\circ\text{C}/\text{km}$) in the zones heated by Emeishan mantle plume. Thus, the paleogeothermal gradients at the different geological times are obtained. Using the reconstructed eroded thickness and the present thermal conductivity of the core samples, the burial history can be reconstructed. The palaeo-porosity, the palaeo-thermal conductivity for each formation can then be subsequently evaluated, and the palaeo-heat flow can be determined accordingly.

3. Low-T Thermochronological modeling results

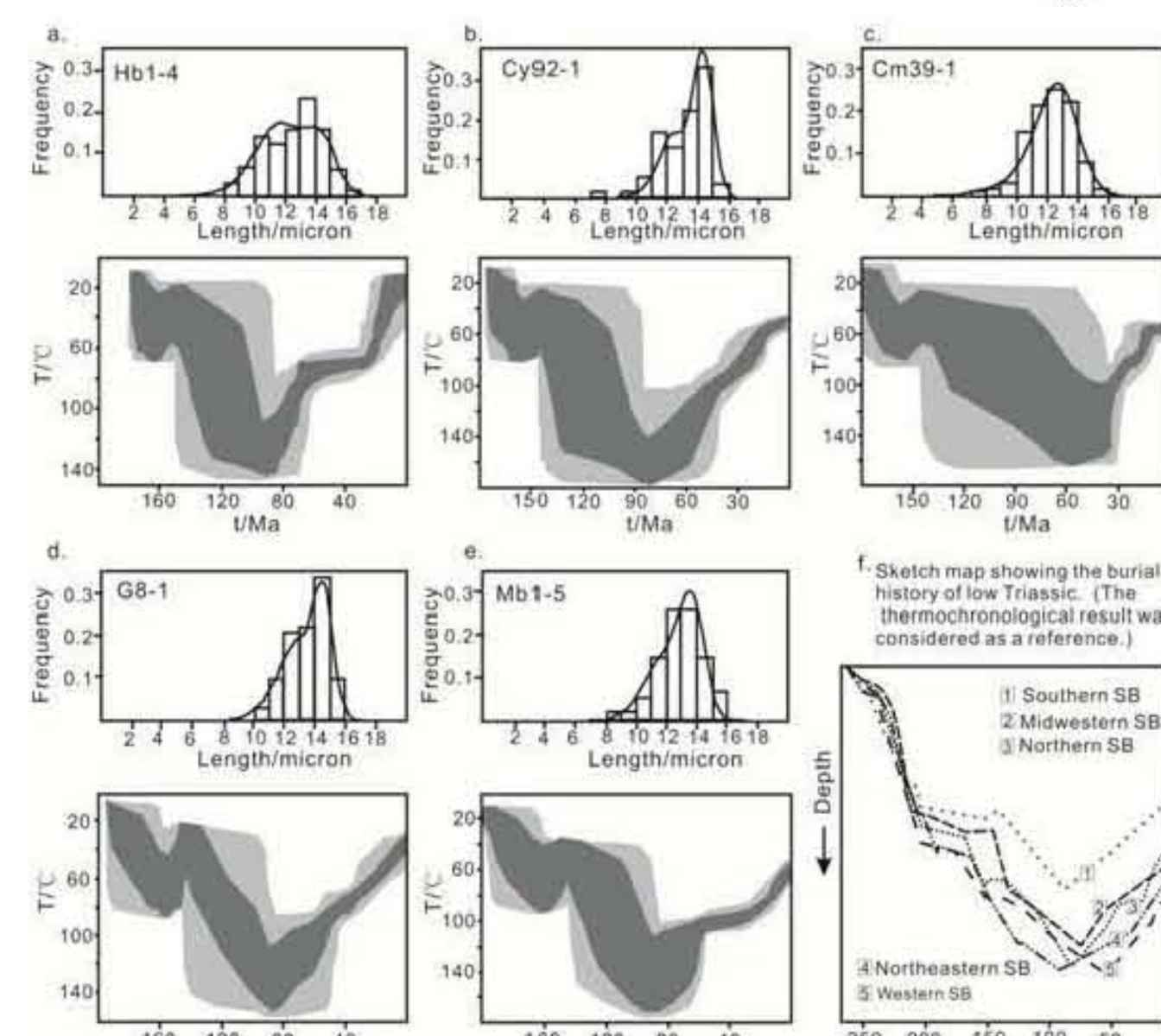


Fig. 3 Low-Thermochronological modeling results of some core samples in the Sichuan Basin

Many works have been done in this basin to assess the Cenozoic thermal history using apatite fission track (AFT) and (U-Th)/He. These modeling results which our works (Tian et al., 2011, 2012) are included suggested that the denudation in different regions started at almost same time ($\sim 100\text{--}80\text{Ma}$), except for the western Sichuan Basin where the denudation started much later ($\sim 60\text{--}50\text{Ma}$) (see Fig.3). This provided significant information supplementary to the thermal history reconstruction based on the Ro data: the strata buried deepest at $\sim 60\text{--}50\text{Ma}$ (Paleocene) in the west, and at $\sim 100\text{--}80\text{Ma}$ (late Cretaceous) in the other regions.

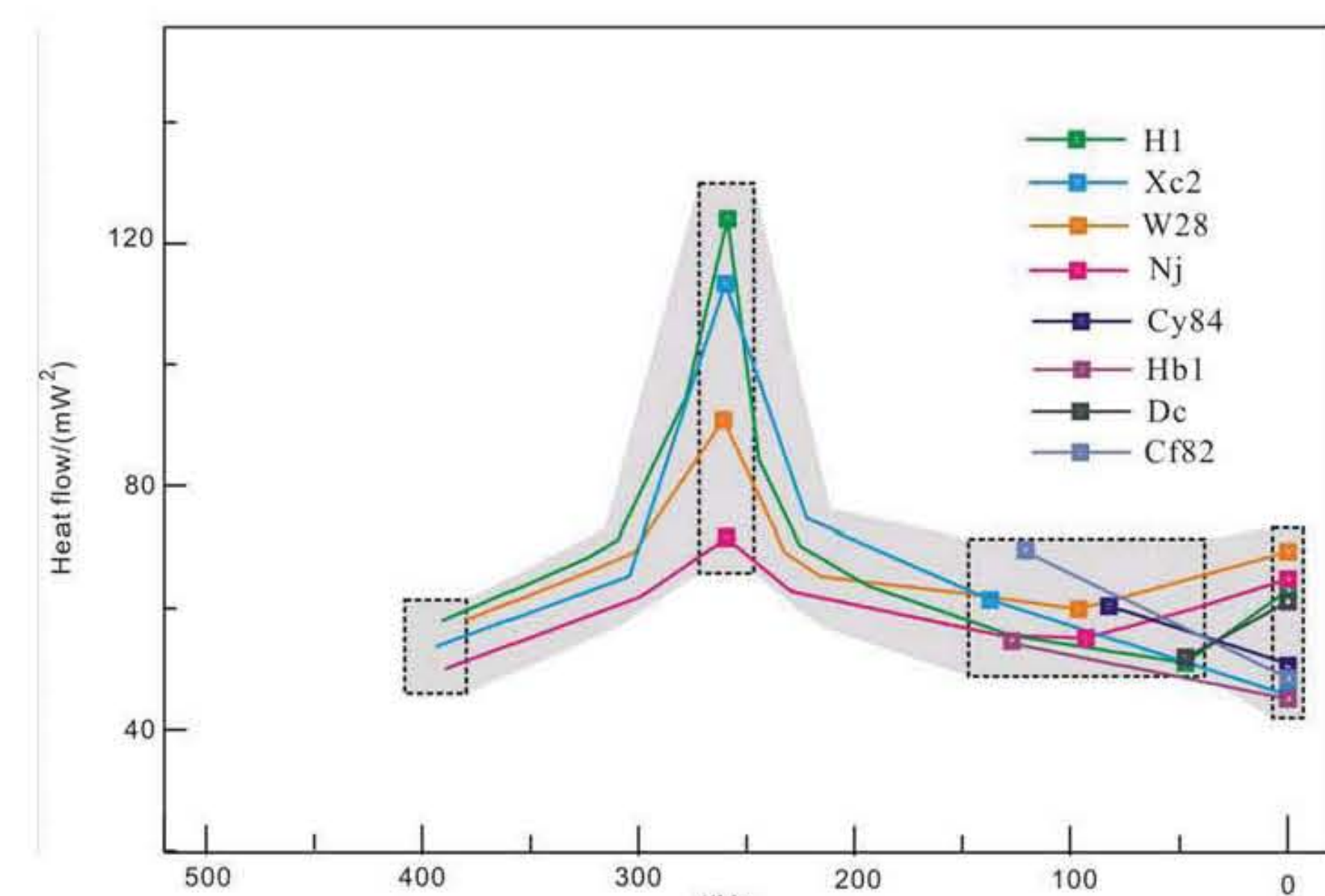


Fig. 4 Heat flow history of research boreholes in the Sichuan basin

4. Heat flow history of the Sichuan Basin

Two distinct paleogeothermal states have been reconstructed by the Ro data, and the paleotemperature recorded times could be constrained by the unconformity (i.e. the unconformity between upper and middle Permian which related to the Emeishan mantle plume) and the thermochronological modeling results. According to these reconstructed paleo-heat flows and the measured present ones, the heat flow history of the deep boreholes in the Sichuan Basin can be revealed in general (see Fig.4). For most of the boreholes involved, the maximum heat flow ($\sim 70\text{--}124\text{mW}/\text{m}^2$) occurred at around 260 Ma (the end of Middle Permian); the paleo-heat flow was low in the Caledonian ($\sim 40\text{--}60\text{mW}/\text{m}^2$), Yanshanian ($\sim 45\text{--}70\text{mW}/\text{m}^2$) and the present ($\sim 40\text{--}70\text{mW}/\text{m}^2$). The Permian thermal event was likely caused by the Emeishan mantle plume and characterized with zoned high heat flow; the Mesozoic thermal stage is weaker, and possibly related to the foreland basin evolution.

5. Thermal evolution of the Paleozoic hydrocarbon source rocks

The maturation history of the hydrocarbon source rocks of some deep boreholes in the Sichuan basin have been modeled based on the thermal evolution modeling results and the burial history of the source rocks, and the effect of the geological events on the evolution of the source rocks, especially the Paleozoic source rocks are also evaluated. In the southwestern part of the Sichuan Basin which closed to the Emeishan Large Igneous Province (ELIP), the organic matter of the most Paleozoic source rocks became mature in middle Late Permian, the source rocks of lower Permian were heated to its peak maturity (maximum Ro $> 3.0\%$) at around 260 Ma and there was no secondary hydrocarbon generation in the later time. This indicates that the thermal evolution of the Paleozoic source rocks was strongly affected by the Emeishan Mantle Plume (EMP) in this area. However, in the regions that far away from the ELIP, the Puguang gas field included, secondary hydrocarbon generation of the source rocks existed, the thermal evolution of the source rocks was related to the Mesozoic foreland basin evolution (see Fig. 5). Therefore, the latter appears to be more prospective to hydrocarbon reservoir accumulation.

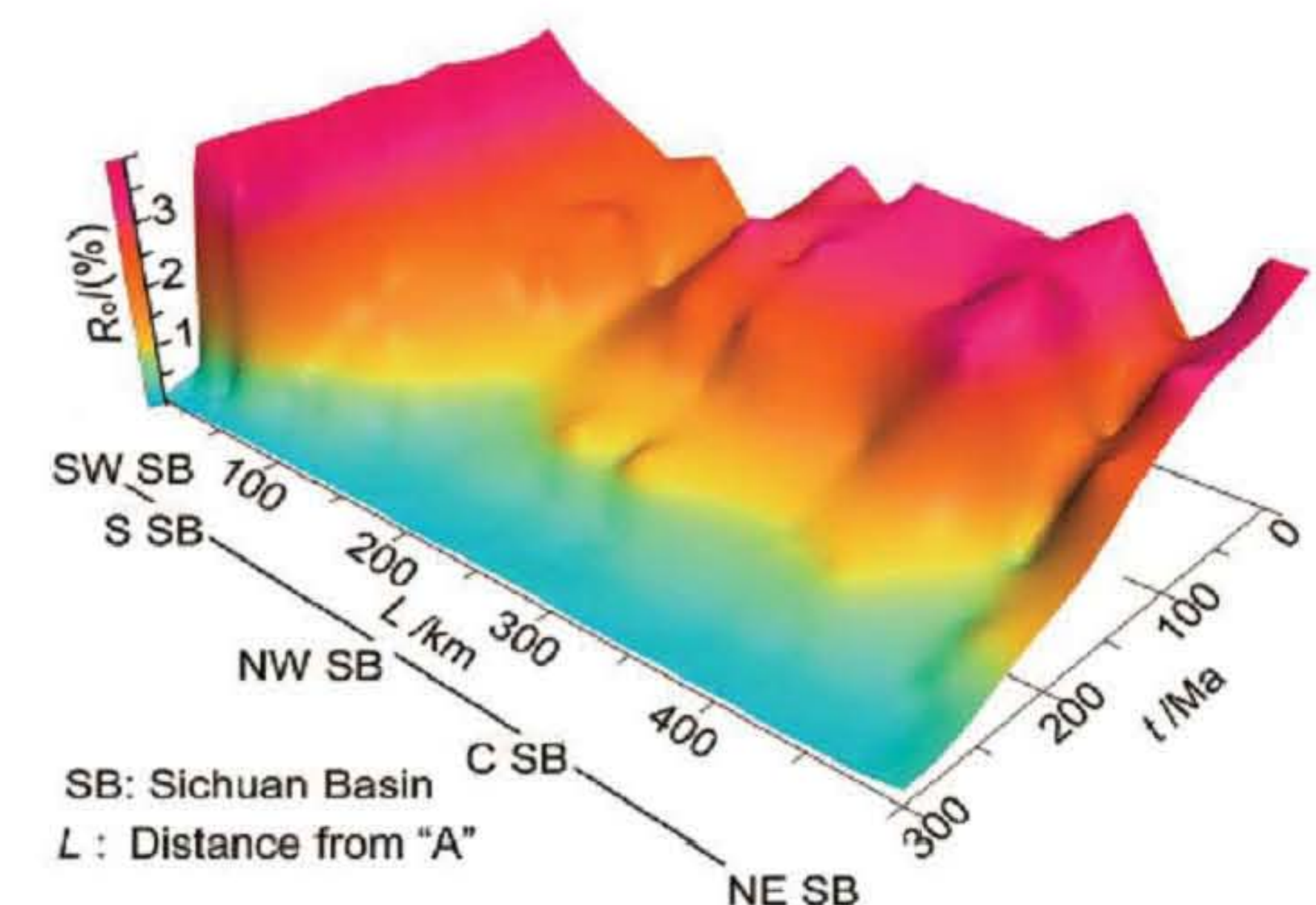


Fig. 5 Maturation history of the low Permian source rocks of the section crossing H1, NJ and CY84

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