PS Paleo-Heat Flow Evolution and Thermal History of the Baiyun Sag, the Pearl River Mouth Basin*

Yajun Li[1,2], Zhenglong Jiang[2], Shu Jiang[3], and Kangning Xu[2]

Search and Discovery Article #10952 (2017)**
Posted June 12, 2017

*Adapted from poster presentation given at AAPG 2017 Annual Convention and Exhibition, Houston, Texas, April 2-5, 2017

[1]School of Energy Resources, China University of Geosciences, Beijing, China (liyajun_daliu@sina.com)
[2]School of Marine Sciences, China University of Geosciences, Beijing, China
[3]Energy and Geoscience Institute, University of Utah, Salt Lake City, Utah, United States

Abstract

The Baiyun Sag (BYS) is located in the continental margin of the northern South China Sea (SCS). It has been one of the key areas to characterize geothermal field and thermal evolution of passive continental margin. The geological evolution of the BYS was driven by the plate tectonic interactions between the Philippine Sea plate, the Eurasian plate, and the Indo-Australian plate and was influenced by seafloor spreading of the South China Sea (SCS) in the Late Early Oligocene. Heat flow measurements show that the BYS is characterized by a high background heat flow, ranging from 72 mW/m^2 to 94 mW/m^2. The present-day heat flow of the northern South China Sea increases from the northern shelf with thick crust to the southern slope with thinned crust.

This study employs forward and inverse modelling to simulate the rift and post-rift processes exampled by three wells covering shelf to slope. Two new thermal evolution models of the BYS are established for continental shelf and continental slope. The new heat flow model of continental shelf is generally in agreement with the model of McKenzie. While heat flow of the new continental slope model continuously increases rather than decreases in previous models, which is resulted from lithospheric thinning and mantle upwelling during the Neogene passive continental margin stage. Heat flow gradually reduced after the cessation of the sea floor spreading (10 Ma).

Igneous rocks are generally formed after the late Miocene in the north margin of the SCS, which covered dozens of kilometers (Yan et al., 2006). The intrusion of magma into the brittle crust and mantle drastically heated the lithosphere and led the BYS to deform strongly through lithosphere thinning. The local multi-staged magmatic activities mainly contribute to the high level of maturity in the Liwan Sag located in the lower slope.

In addition, thermal state and thermo-rheological structure of the crust and mantle during the period of rifting and drifting are key factors controlling the thermal evolution of the BYS. The Panyu low uplift on the shelf is born from a normal lithosphere. For areas located in the continental slope, the lithosphere of BYS has thinned stepwise and became hotter during the passive continental margin stage.

Selected References

Beardsmore, G.R., and J.P. Cull, 2001, Crustal Heat Flow: A Guide to Measurement and Modelling: Cambridge University Press, Cambridge, UK, 321 p.

Pang, X., C. Chen, L. Shao, C. Wang, M. Zhu, M. He, J. Shen, S. Lian, and X. Wu, 2007, Baiyun Movement, A Great Tectonic Event on the Oligocene–Miocene Boundary in the Northern South China Sea and Its Implications: Geological Review, v. 53/2, p. 145-151.

Shao, L., X. Li, P. Wang, Z. Jian, G. Wei, X. Pang, and Y. Liu, 2004, Sedimentary Record of the Tectonic Evolution of the South China Sea Since the Oligocene - Evidence from Deep Sea Sediments of ODP Site 1148: Advances in Earth Science, v. 19, p. 539-544.

White, N., M. Thompson, and T. Barwis, 2003, Understanding the Thermal Evolution of Deep-Water Continental Margins: Nature, v. 426, p. 334-343.

Yan, P., H. Deng, H. Liu, Z. Zhang, and Y. Jiang, 2006, The Temporal and Spatial Distribution of Volcanism in the South China Sea Region: Journal of Asian Earth Sciences, v. 27, p. 647-659.

Zhao, Q., 2005, Late Cenozoic Ostracod Faunas and Paleoenvironmental Changes at ODP Site 1148, South China Sea: Marine Micropaleontology, v. 54, p. 27-47.

Paleo-heat flow evolution and thermal history of the Baiyun Sag, the Pearl River Mouth Basin

Yajun Li[a,b], Zhenglong Jiang[b,*], Shu Jiang[c,*], Kangning Xu[b]

a. School of Energy Resources, China University of Geosciences, Beijing 100083, China.
b. School of Marine Sciences, China University of Geosciences, Beijing 100083, China.
c. Energy and Geoscience Institute, University of Utah, Salt Lake City, UT 84108, USA.

Introduction

As there is limited amount of hydrocarbon left to produce in existing reserves, the hydrocarbon industry is now pursuing to explore frontier areas. The major unexplored area is the ocean. Explorations have been focused in the deepwater to ultra-deepwater passive margins, especially base of slope or the continent-ocean boundary area (White et al., 2003).

Explotation at deep-water margins

Continental margin models

"HOT" MARGIN

Mantle plumes upwell during the lithopheric thinning.
Location: the North Atlantic Ocean on the either side of the Iceland Plume.

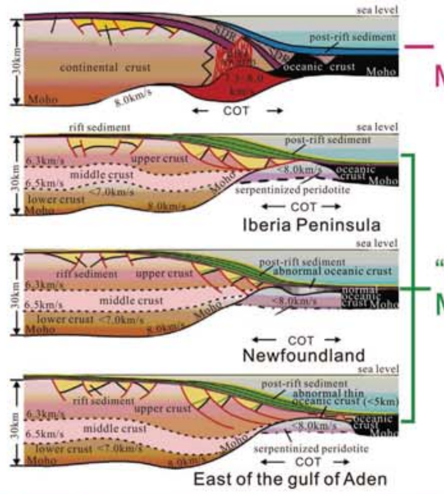
"COLD" MARGIN

Magmatism is poor until oceanic crust formed.

Location: the west of the Iberian Peninsula.

"WARM" MARGIN

A magma-poor margin but with volcanic rocks in the thick upper/middle crust.
Location: the northern continental margin of the South China Sea (NMSCS).



A series of Meso-Cenozoic sedimentary basin have been developed in the NMSCS, which contained abundant petroleum resources in the deep-water area. The Pearl River Mouth Basin (PRMB) is located in the continent-ocean transition of the NMSCS, which was influenced by seafloor spreadingof the SCS in the late Early Oligocene.

Geological Setting

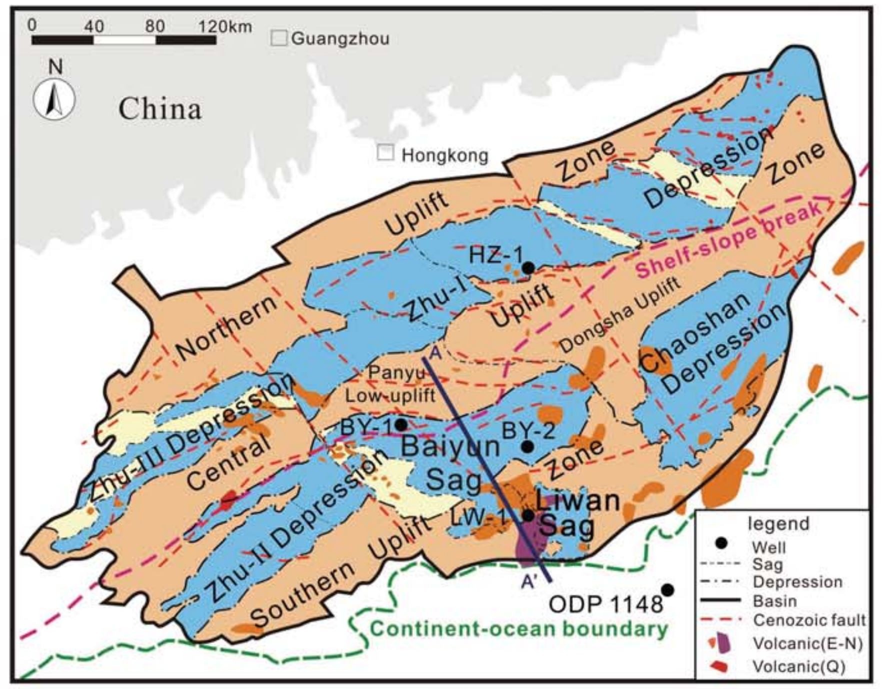
The geological evolution of the PRMB was driven by the plate tectonic motions between the Philippine Sea plate, the Eurasian plate and the Indo-Australian plate , and was influenced by seafloor spreading of the South China Sea (SCS) in the late Early Oligocene. The PRMB experienced Cretaceous pre-rift stage, Paleogene rift stage, Neogene passive continental margin stage (post-rift stage) and Pliocene-Quaternary Neotectonic stage.

Deepwater area: Baiyun Sag

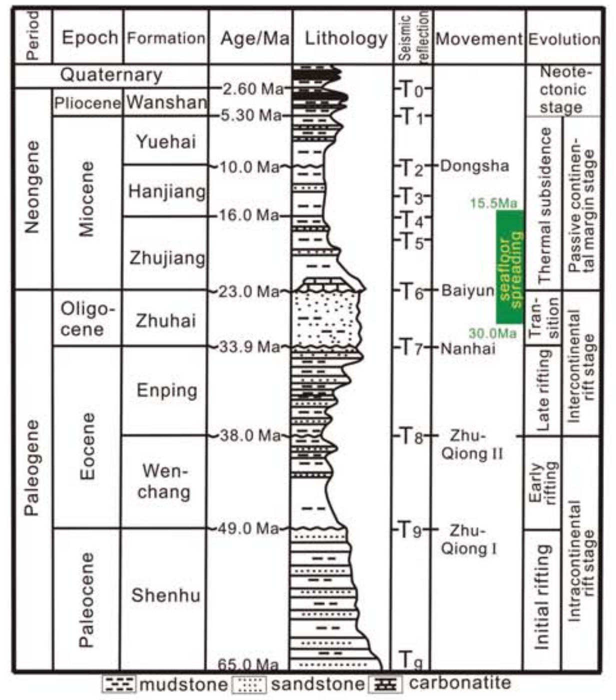
The Baiyun (BYS) is characterized by composite graben controlled by several boundary faults with 3 to 4 km of vertical offset. The inner faults are mostly c.20 km in length with small vertical offset. During the Paleogene rift stage, the BYS developed thick lacustrine organic-rich source rocks. After that, the BYS became the center of subsidence and deposition, and experienced the post-rift abnormal subsidence due to lithosphere cooling.

Ultra-deepwater area: Liwan Sag

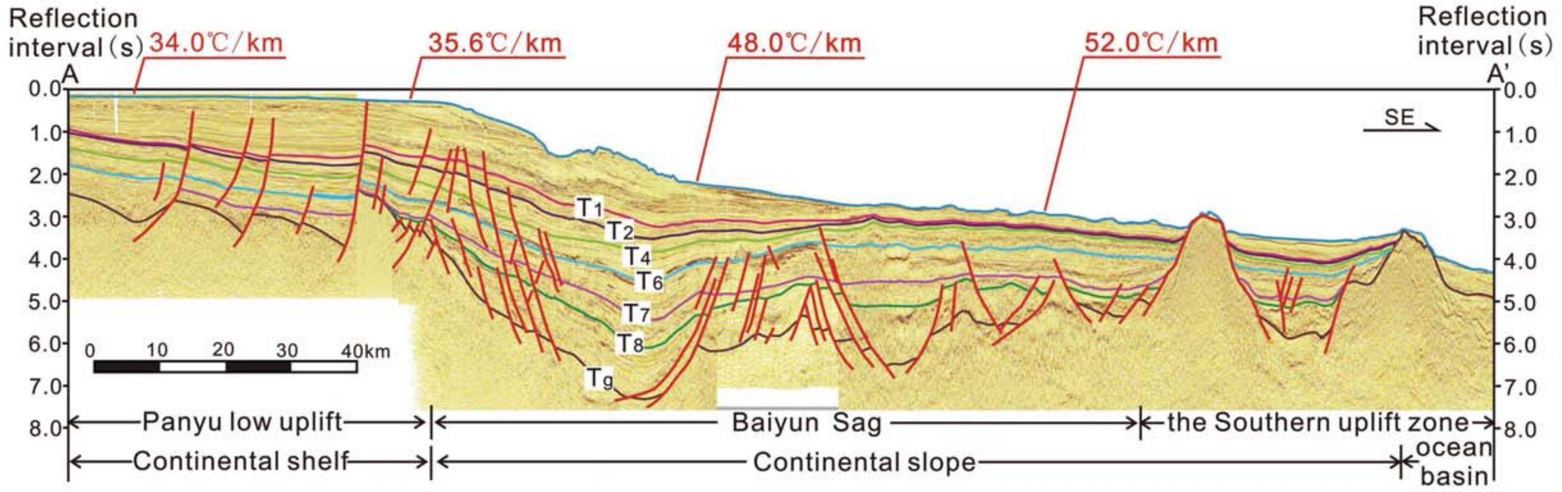
The Liwan Sag (LWS)is mainly characteristic of rift-depression without typical basin-controlling faults. There are multiple episodes of local magmatic activities during evolution of the sag. The multi-staged magmatism not only have generated domes, but also provide heat to ambient strata. The present structural framework of the LWS was rebuilt by the large-scale diapirism at ~32Ma.



Regional location of the Preal River Mouth basin



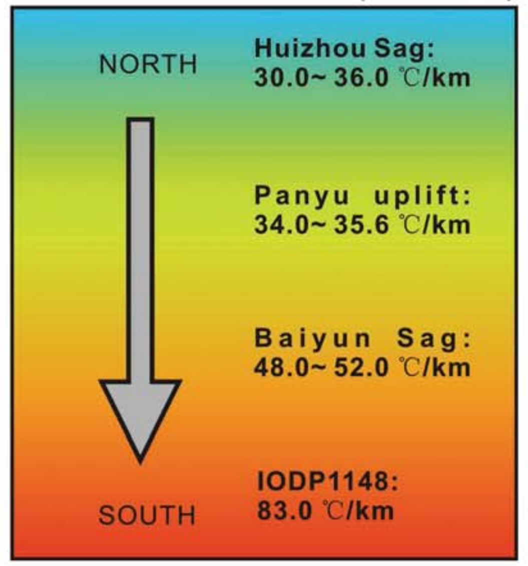
Lithostratigraphic sequence

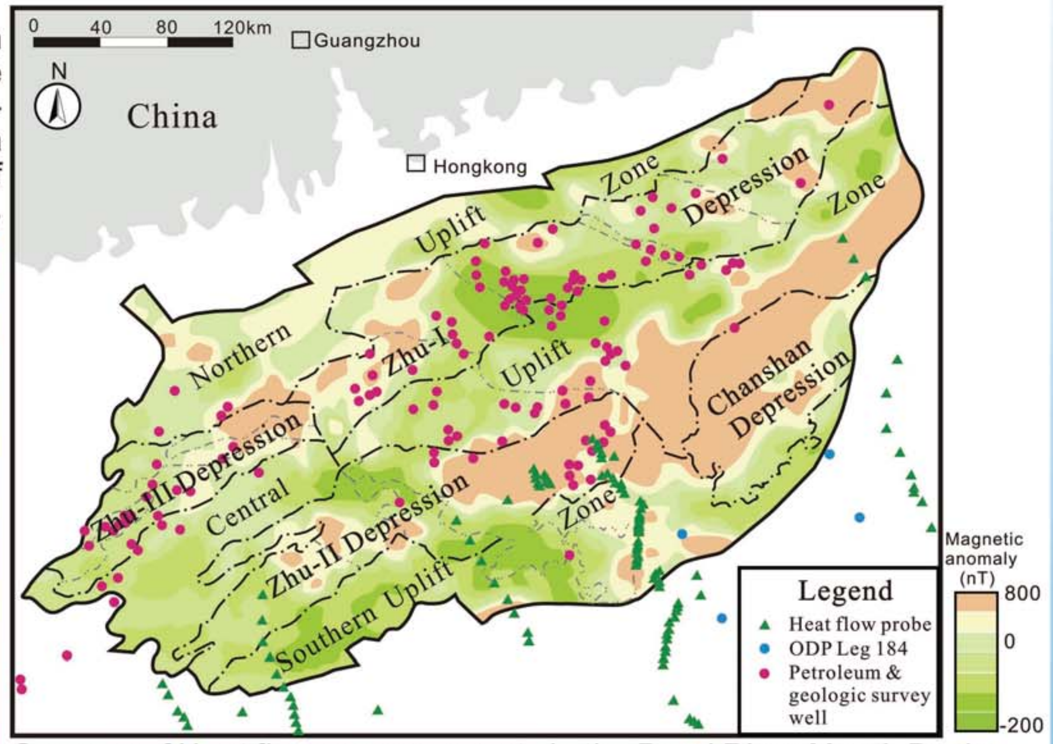


Geothermal field

A typical "hot basin" with average heat flow of 71.8±13.6 mW/m², ranging from 24.2 mW/m² to 121.0 mW/m².

Thermal gradient ranges from 24.7 to 60.8℃/km, with the average value of 37.9±7.4℃/km. The geothermal gradient value of shallow area in the PRMB is higher than that of the East China Sea Shelf (30.0℃/km).





Sources of Heat flow measurements in the Pearl River Mouth Basin (Magnetic anomaly modified from Pan et al., 2007)

The rock mixing principle (Beardsmore et al., 2001) is used to estimate the conductivity of the mixed lithology, the heat flow arecalculated by using the follow equations:

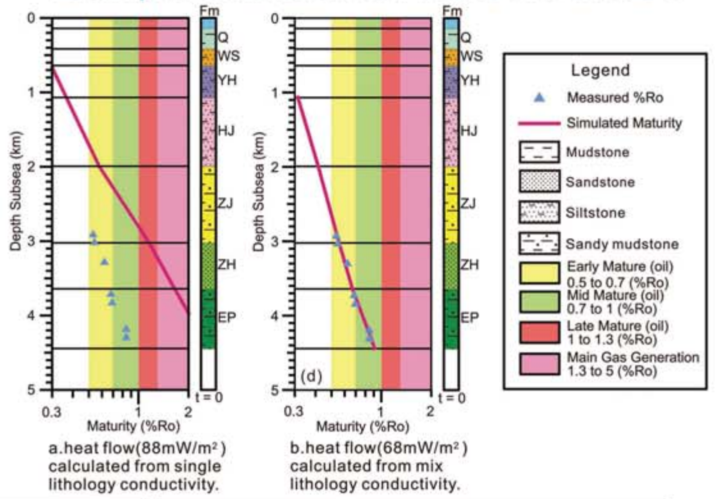
$$\lambda_{mix}=\frac{\sum d_i}{\sum \frac{d_i}{\lambda_i}}$$

where λ mix is the average conductivity of the sediment column (W/m˚C),d_i is the thickness of each lithology (m); λ i is the conductivity of each lithology (W/m˚C).

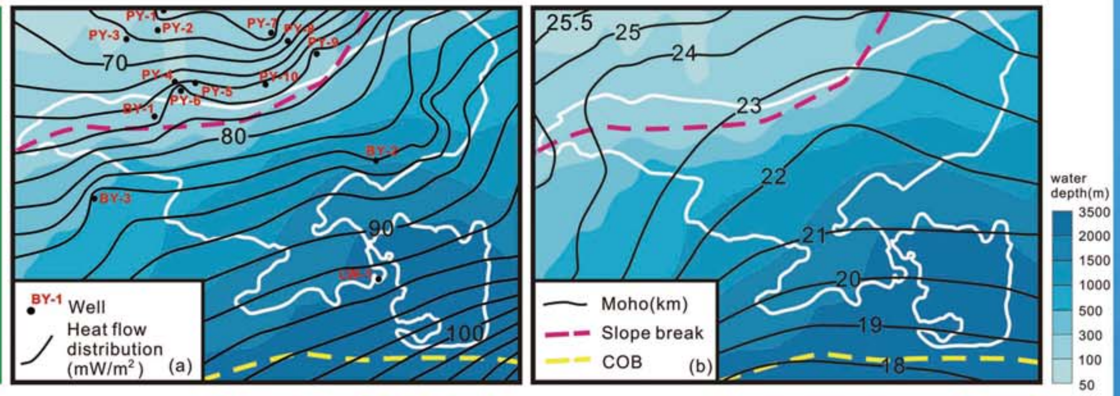
$$Q=\lambda_{mix}\times(T_o-T_b)/\Delta Z$$

where Q is the heat flow (mW/m²), T_o is the temperature at the surface of the sediment column (˚C). T_b is the temperature at the base of the sediment column (˚C) and ΔZ is the sedimentary thickness from the surface to the base of the stratigraphic column (m).

Example: simulated Ro results in well HZ-1



The heat flow values, ranging from 72 mW/m² to 94 mW/m² in the BYS are much higher than that in normal rift basin (50~65 mW/m²). The heat flow increase from the shelf in the north to the COB in the south, this trend is opposite to that Moho depth decreases from shelf to COB.



Paleo-heat flow evolution and thermal history of the Baiyun Sag, the Pearl River Mouth Basin

中國地質大學(北京)
CHINA UNIVERSITY OF GEOSCIENCES

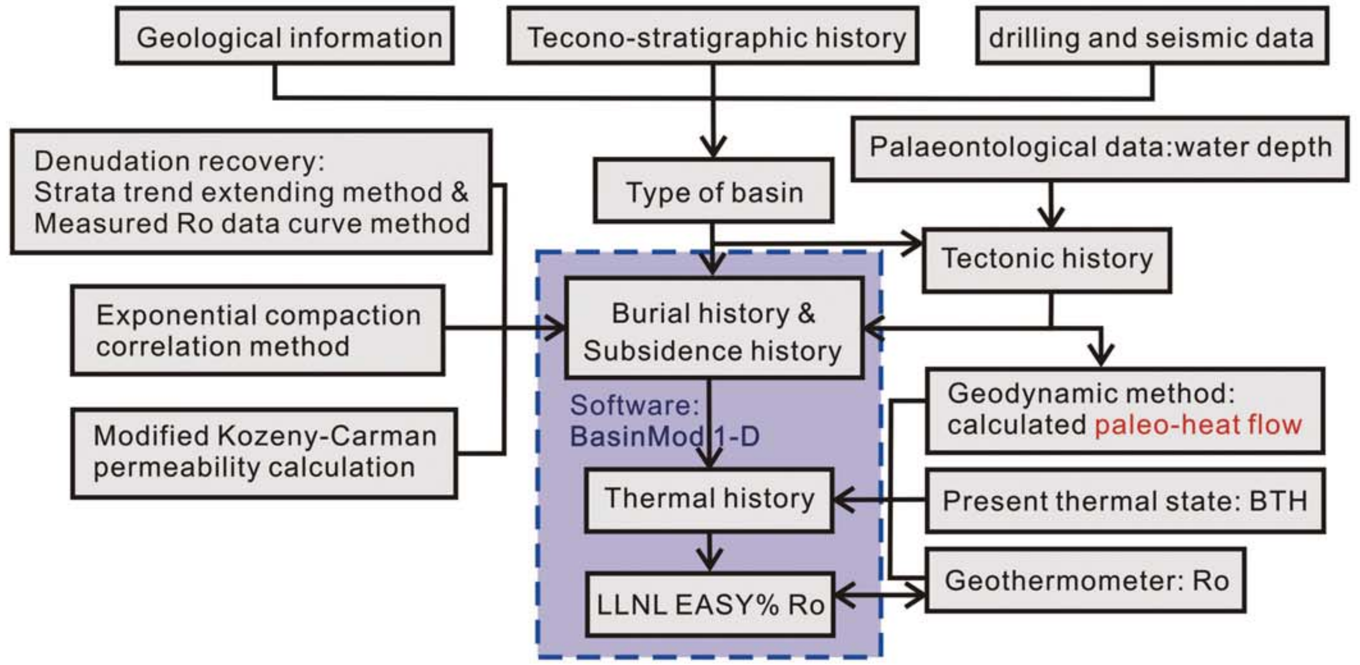
Yajun Li[a,b], Zhenglong Jiang[b,*], Shu Jiang[c,*], Kangning Xu[b]

a. School of Energy Resources, China University of Geosciences, Beijing 100083, China.
b. School of Marine Sciences, China University of Geosciences, Beijing 100083, China.
c. Energy and Geoscience Institute, University of Utah, Salt Lake City, UT 84108, USA.

THE UNIVERSITY OF UTAH
EGI Energy & Geoscience Institute AT THE UNIVERSITY OF UTAH

Panel 2

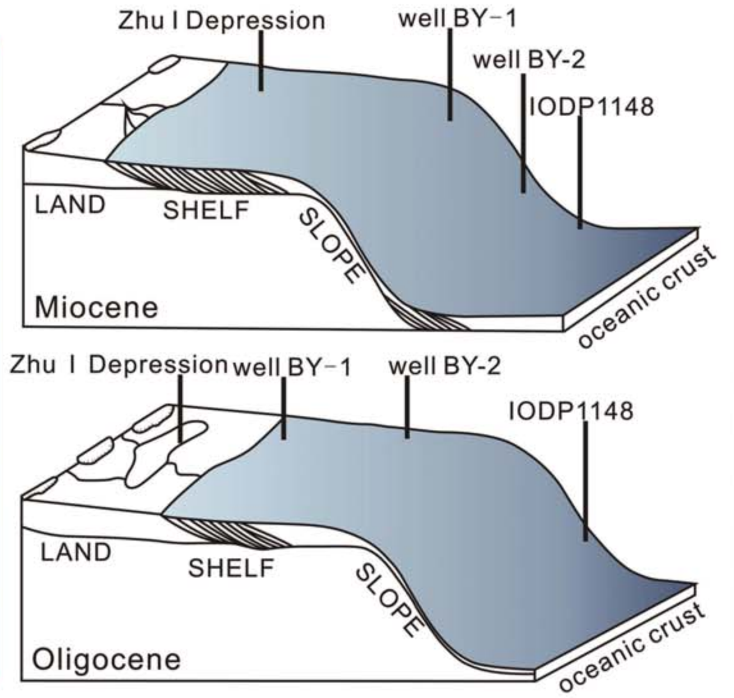
Method



Age, tectonic events, and lithology of formation of the Baiyun Sag from drilling and seismic data

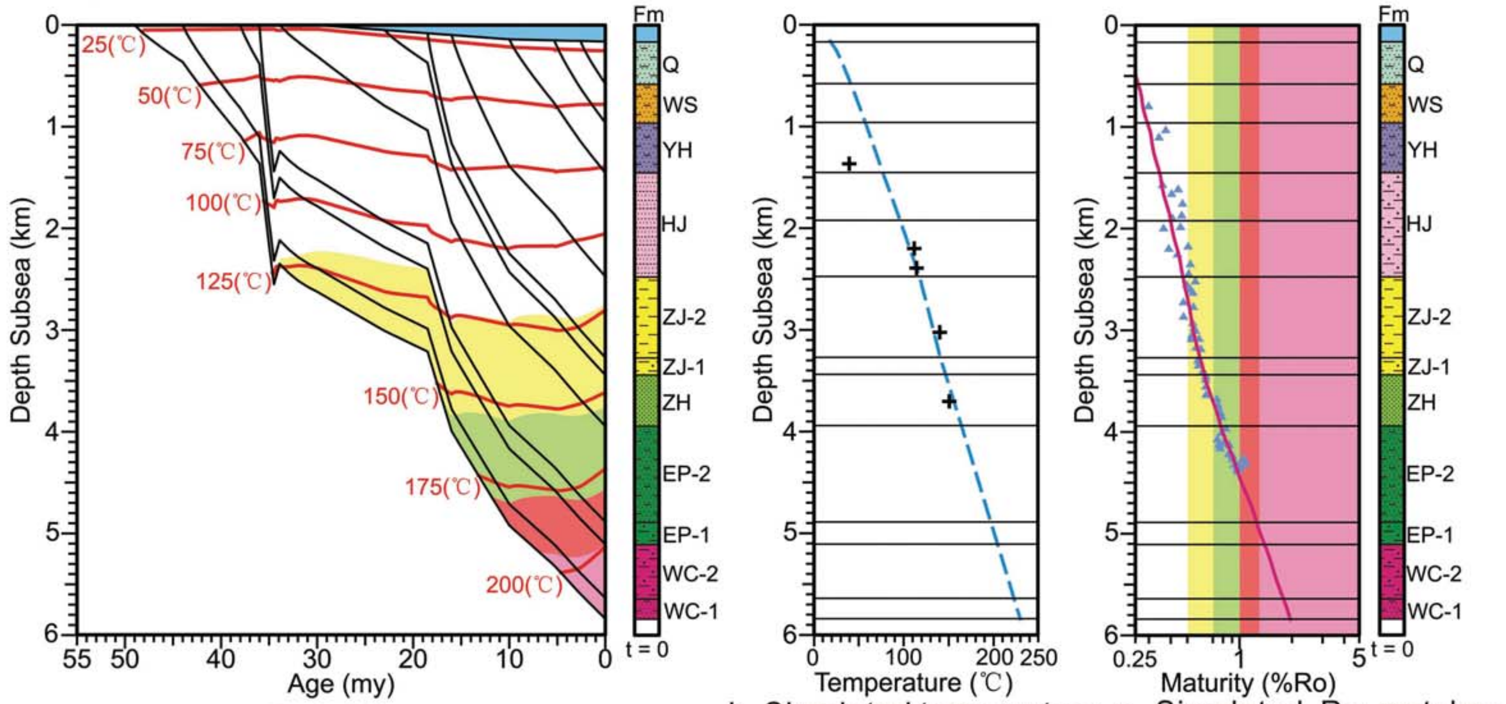
Deposion age		Teconic movement (Age/Ma)	Formation	Lithology
From/Ma	To/Ma			
2.60	0		Quaternary	nonconsolidated sand ans clay
5.30	2.60		Wanshan	neritic sand-mudstone
10.0	5.30	Dongsha(10.0 Ma)	Yuehai	marine mudstone
16.0	10.0		Hanjiang	littoral-neritic sand-mudstone
23.0	16.0	Baiyun(23.0 Ma)	Zhujiang	neritic mudstone
33.9	23.0	Naihai(33.9 Ma)	Zhuhai	littoral sand-mudstone
38.0	33.9	Zhu-Qiong II(49.0 Ma)	Enping	fluvial-lacustrine coal-bearing series
49.0	38.0	Zhu-Qiong I(49.0 Ma)	Wenchang	medium-deep lacustrine sand-mudstone

During the Late Oligocene, the BYS was in a rift to thermal subsidence stage, and then the water depth increased gradually. The BYS was in the inner continental shelf, and the water depth is less than 50m . A substantial research shows that palaeo-environment of IODP1148 site was bathyal environment in the Late Oligocene (Shao et al., 2004; Zhao, 2005), and water depth was deeper than 1000m. The water depth of the BYS increased with fluctuations, the palaeoenvironment evolved into continental slope in the early period of Early Miocene. In the late period of Early Miocene, the water depth was deeper than 1000m, and the environment of the BYS kept in continental slope and bathyal settings during the mid-Miocene to present.

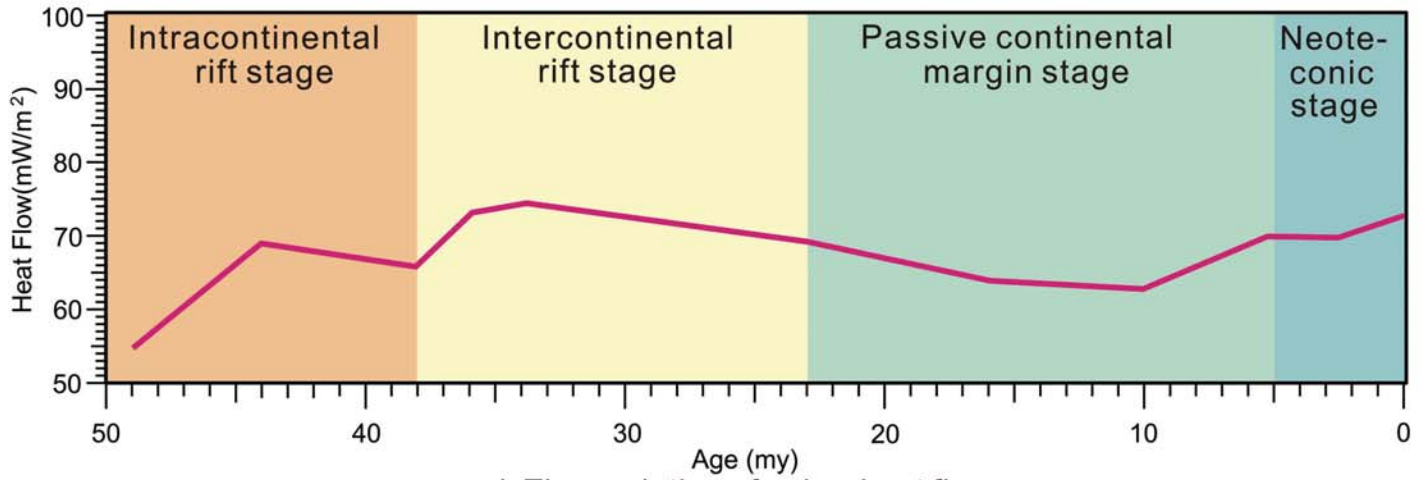


1-D modeling results

The well BY-1 with a total depth of 5094 m, located in the south of the Panyu low uplift and close to the shelf break area, has drilled into the Eocene Enping Fm. The thickness of the Eocene Wenchang and Enping Fm are obtained from drillingwell and seismic data, which were used to establish geologic model for studying thermal history.

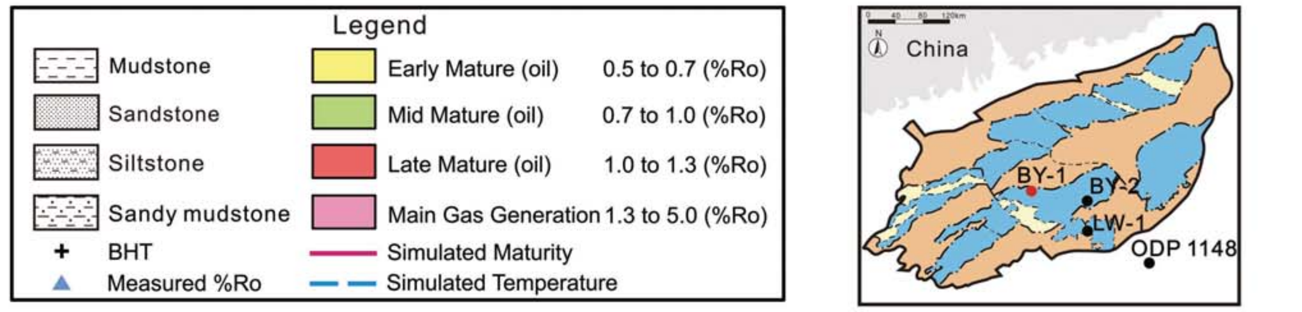


a. Burial history
b. Simulated temperature matches with the BHT
c. Simulated Ro matches with the measured Ro data

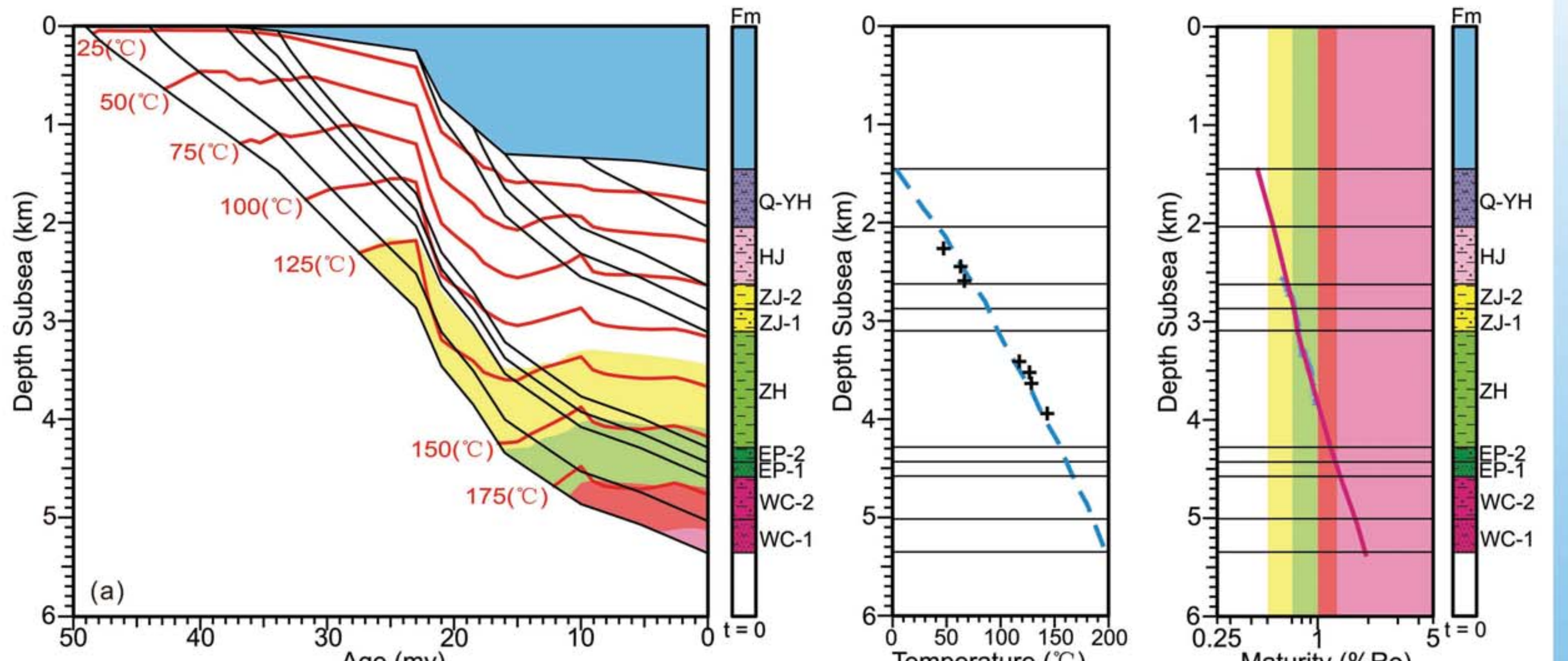


d. The evolution of paleo-heat flow

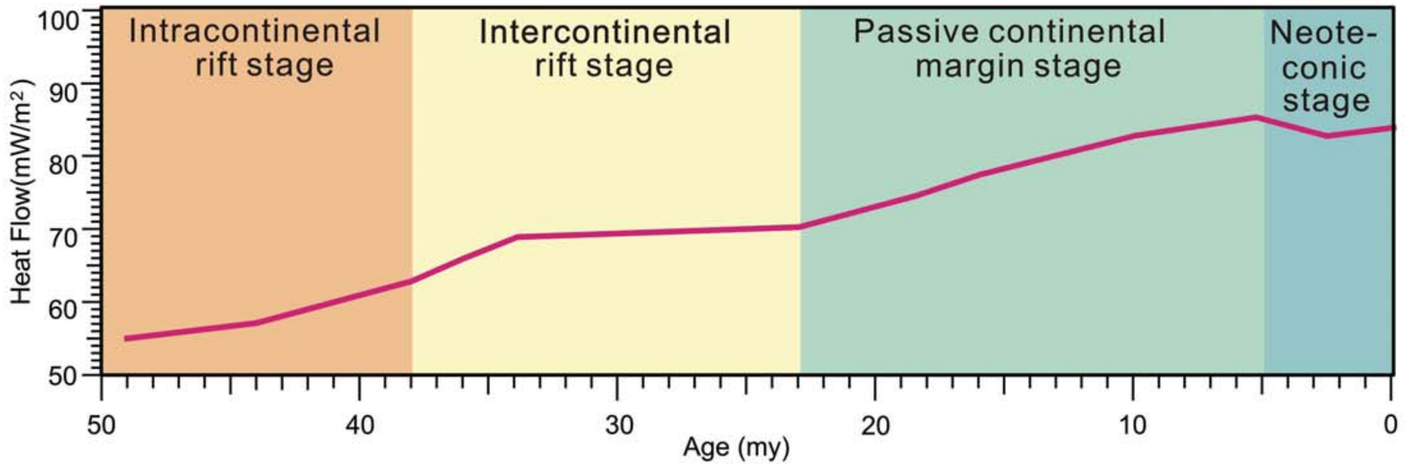
(Formation names: WC-1 = the lower part of the Wenchang Fm; WC-2 = the upper part of the Wenchang Fm; EP-1 = the lower part of the Enping Fm; EP-2 = the upper part of the Enping Fm; ZH = the Zhuhai Fm; ZJ-1 = the lower part of the Zhujiang Fm; ZJ-2 = the upper part of the Zhujiang Fm; HJ = the Hanjiang Fm; YH = the Yuehai Fm; WS = the Wanshan Fm; and Q= Quaternary.)



The well BY-2 is much deeper than well BY-1, which lies on the upper slope. The oldest layer is the Oligocene Zhuhai Fm with a total drilling depth of 3843m. The thickness of the Eocene Enping and Wengchang Fm are estimated from seismic data.

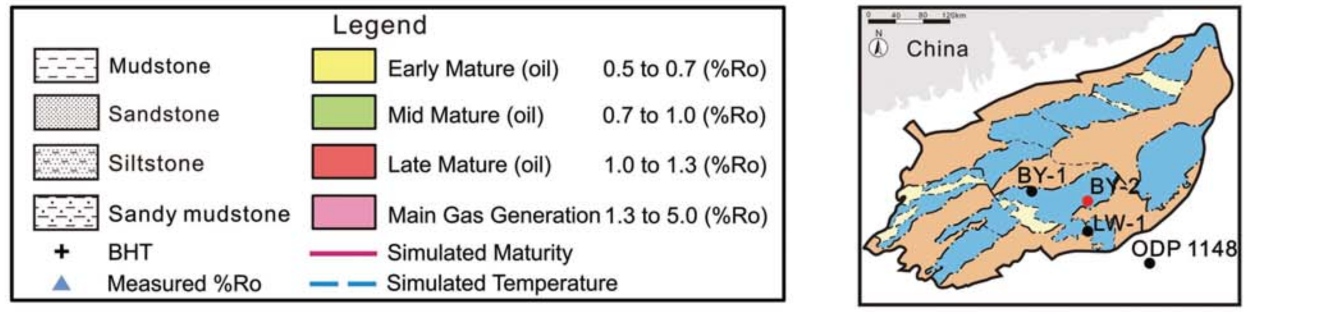


a. Burial history
b. Simulated temperature matches with the BHT
c. Simulated Ro matches with the measured Ro data



d. The evolution of paleo-heat flow

(Formation names: WC-1 = the lower part of the Wenchang Fm; WC-2 = the upper part of the Wenchang Fm; EP-1 = the lower part of the Enping Fm; EP-2 = the upper part of the Enping Fm; ZH = the Zhuhai Fm; ZJ-1 = the lower part of the Zhujiang Fm; ZJ-2 = the upper part of the Zhujiang Fm; HJ = the Hanjiang Fm; Q-YH = the Yuehai, Wanshan Fm and Quaternary.)



Paleo-heat flow evolution and thermal history of the Baiyun Sag, the Pearl River Mouth Basin

Yajun Li[a,b], Zhenglong Jiang[b,*], Shu Jiang[c,*], Kangning Xu[b]

a. School of Energy Resources, China University of Geosciences, Beijing 100083, China.
b. School of Marine Sciences, China University of Geosciences, Beijing 100083, China.
c. Energy and Geoscience Institute, University of Utah, Salt Lake City, UT 84108, USA.

中國地質大學(北京) CHINA UNIVERSITY OF GEOSCIENCES

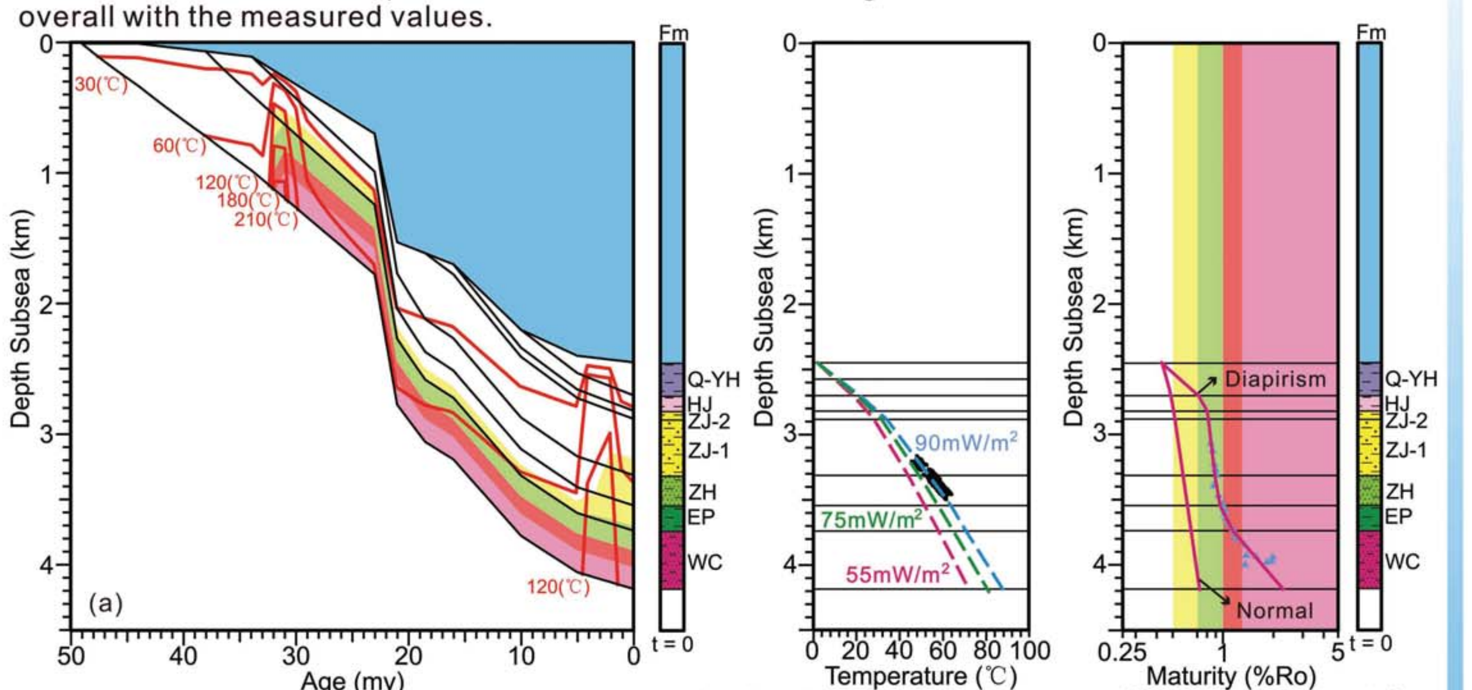
THE UNIVERSITY OF UTAH

EGI Energy & Geoscience Institute AT THE UNIVERSITY OF UTAH

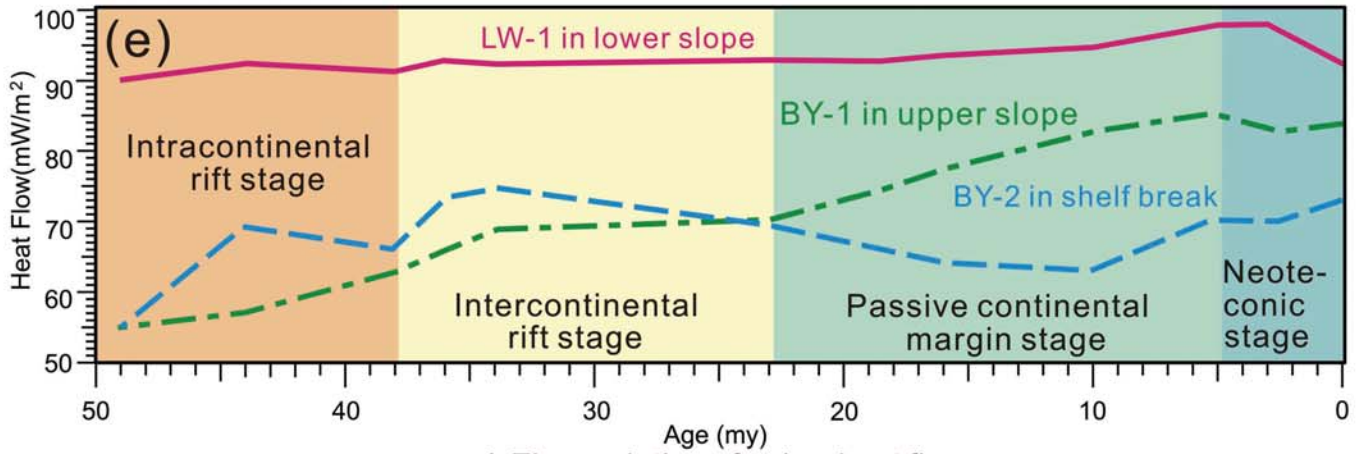
Panel 3

1-D modeling results

The well LW-1 with a total depth of 4185.4m is located in the lower slope with water depth of 2450 m. It has drilled into the Eocene Wenchang Fm. The drilling data are used to build up the geologic model. Considering the well area is close to the LWS, local multi-staged magmatic activities (Dome-like uplifts or diapirs) are likely to have contributed to the present maturity drgree of well LW-1 (Pang et al., 2007; Sun et al., 2013; Zhou et al., 2012). When the additional heat by the volcanic intrusion was inputted into the thermal modelling, the simulated %Ro was consistent overall with the measured values.



a. Burial history   b. Simulated temperature matches with the BHT   c. Simulated Ro matches with the measured Ro data

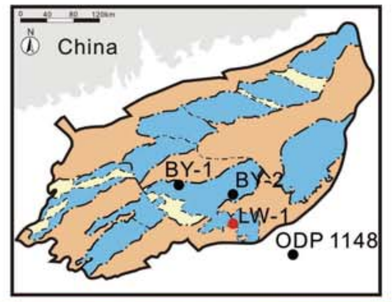


d. The evolution of paleo-heat flow

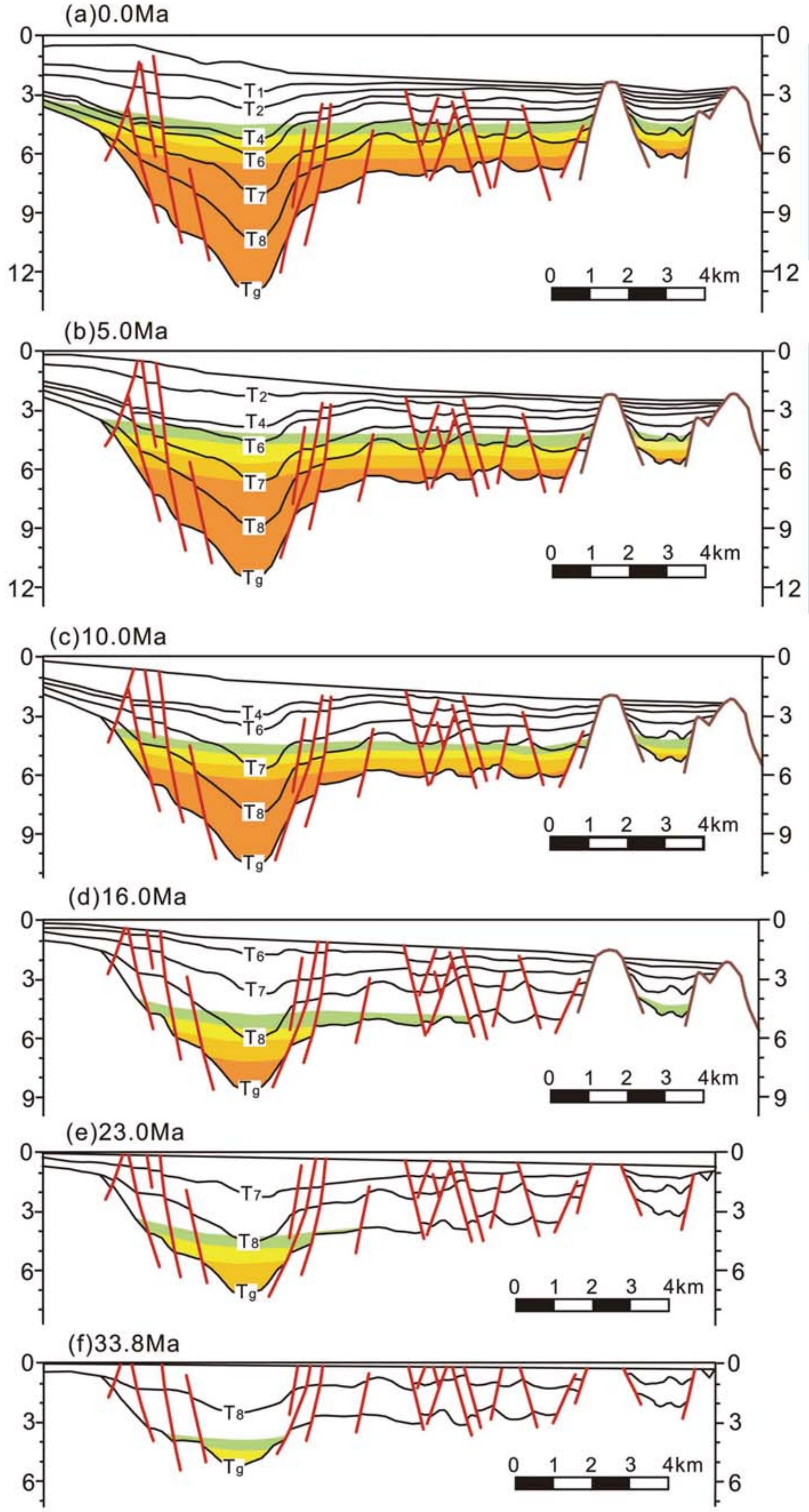
(Formation names: WC = the Wenchang Fm; EP= the Enping Fm; ZH = the Zhuhai Fm; ZJ-1 = the lower part of the Zhujiang Fm; ZJ-2 = the upper part of the Zhujiang Fm; HJ = the Hanjiang Fm; Q-YH = the Yuehai, Wanshan Fm and Quaternary.)

Legend

Mudstone	Early Mature (oil)	0.5 to 0.7 (%Ro)
Sandstone	Mid Mature (oil)	0.7 to 1.0 (%Ro)
Siltstone	Late Mature (oil)	1.0 to 1.3 (%Ro)
Sandy mudstone	Main Gas Generation	1.3 to 5.0 (%Ro)
+ BHT	Simulated Maturity	
▲ Measured %Ro	Simulated Temperature	



Thermal history reconstruction



Present

High maturity values are observed in the deep of the BYS and the Southern uplift zone, and relatively low maturity values in the Panyu low-uplift at present day.

5.0 Ma

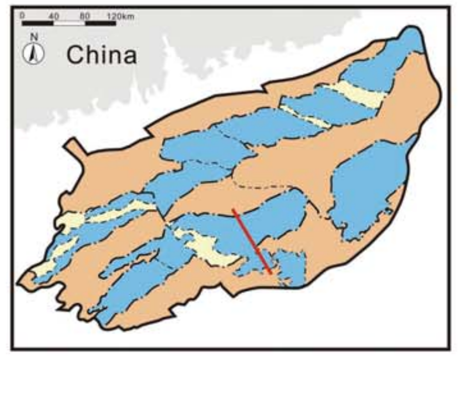
The Zhuhai Fm was in the peak period of hydrocarbon generation (the Ro% values ranging from 0.75% to 2.20%), with a large amount of gas generated. The Wenchang and Enping Fm were in over-mature stage with the Ro% values being higher than 2.0% .

10.0 Ma

Thermal evolution degree increased with thesedimentation of overlying formations. The Zhuhai Fm evolved into early-mature and mid-mature stage at 10.0 Ma

16.0 Ma

The Wenchang and Enping Fm were successively in the main period of hydrocarbon generation with gas generated.



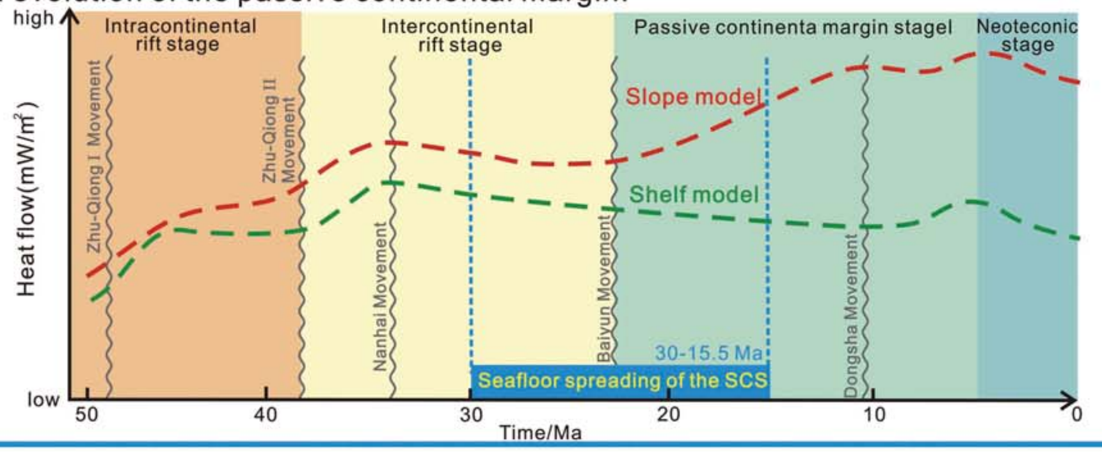
Tectonic thermal history reconstruction of the part of line AA'

Early-mature (Ro=0.75~0.1.00%)   Mid-mature (Ro=1.00~1.25%)   Late-mature (Ro=1.25~2.00%)   Over-mature (Ro=2.00~5.00%)

Discussion & Conclusion

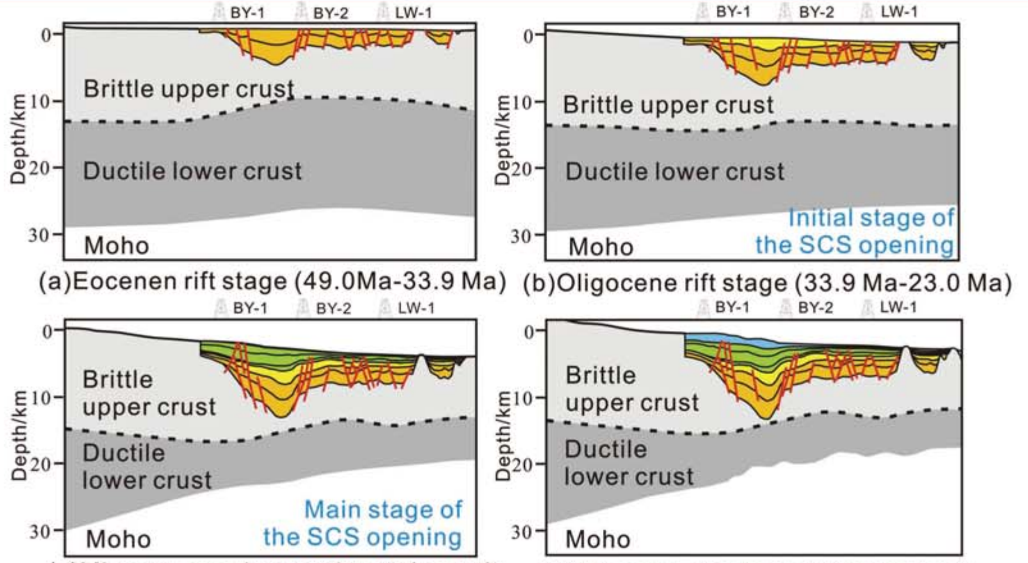
1 The PRMB is characterized by a high background heat flow. The present-day heat flow increases from the north to south of the northern SCS where the crustal thickness decreases from the continental shelf to slope.

2 Two new thermal evolution models for continental shelf and continental slope of the PRMB are established. The new continental shelf model is generally in agreement with the model of Mckenzie, while the slope model is quite different from previous models during the Neogene passive continental margin stage. With multiple episodes of seafloor spreading of the SCS, heat flow in the slope did not decrease but continuously increased as a result of lithospheric thinning and mantle upwelling. Heat flow gradually reduced after the cessation of the sea floor spreading (10 Ma). Tectonic settings and magmatism in deep mantle control the differential evolution of the passive continental margin.



3 Thermal state and thermo-rheological structure of the crust and mantle during the period of rifting and drifting are key factors controlling the thermal evolution of the Baiyun Sag. The Panyu low-uplift on the shelf is born from a normal lithospere. For areas located in the continental slope, the lithosphere of Baiyun Sag has thinned stepwisely and the Liwan Sag started rifting from a hot lithosphere during the passive continental margin stage. This is the reason why the thermal evolutions of the BYS and the LWS in the south are so different from that of the Panyu low-upliftin the north.

4 The thermal evolution of the Baiyun Sag is mainly controlled by tectonic activities such as magmatism, lithospheric thinning and upwelling of Moho. Lithospheric thinning and upwelling of Moho are main control factors of thermal evolution during the rift and drift stage, magmatic activity dominated the fluctuation of heat flow during the Neotectinic stage. Moreover, local multiple episodes of magmatic activities and diapirism led to the high maturity of source rocks in the Liwan Sag since 32 Ma.



(a)Eocenen rift stage (49.0Ma-33.9 Ma) (b)Oligocene rift stage (33.9 Ma-23.0 Ma) (c)Miocene passive continental margin stage (23.0Ma-5.0Ma) (d)Pliocene-Quaternary Neotectonic stage (5.0Ma-Prensent)

ACKNOWLEDGMENTS: This work was supported by "Research on Origin and Accumulation of Petroleum in the deepwater area of Northern South China"(Grant No.2011ZX05025-003-004) and National Natural Science Foundation of China (Grant No. 91328201).