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## 渤海盆地秦南凹陷新生代以来构造-热演化史

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### Cenozoic tectonic-thermal history reconstruction of the Qinnan Depression, Bohai Basin

**Abstract:** [Objective] Tectono-thermal history is important to understand basin evolution and its geodynamic mechanism and is the key question to be solved for source rock maturation study. With the increasing energy demand and difficulty in oil and gas discovery on land, sea basins have gradually become an important alternative for oil and gas exploration and a hotspot of national energy strategy research. The Qinnan Depression, located in the northwest of the Bohai Sea, has good exploration prospects. However, owing to the low level of exploration, research on the tectono-thermal evolution of Qinnan Depression is still limited. [Methods] In this study, 25 artificial wells have been established based on 3 seismic profiles of the Qinnan Depression, and their tectonic subsidence and thermal history have been modeled to reconstruct the tectonic-thermal evolution history using a multi-stage finite stretching model. [Results] The results indicate that since the Cenozoic era, the Qinnan Depression has undergone three stages of rifting and stretching during the sedimentary periods of the Kongdian Formation to fourth member of the Shahejie Formation (65–42 Ma), the third member of the Shahejie Formation (42–38 Ma), and the third member of the Dongying Formation (32.8–30.3 Ma), with a total stretching factor of 1.27–2.05. Corresponding to the three stages of stretching, the basal heat flow of the Qinnan Depression has experienced three stages of increase, reaching a peak of 64.0–89.0 mW/m<sup>2</sup> at the end of the deposition of the third member of the Dongying Formation (~30.3 Ma), and then decreased gradually until present. [Conclusion] The Qinnan Depression underwent three phases of heating and two stages of cooling since the Cenozoic period. There is a good coupling relationship between the tectonic-thermal evolution process and fault activity in the Qinnan Depression. [Significance] The parameters such as tension system and basement heat flow history obtained in this study are of great significance for understanding the deep

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dynamic mechanisms of basin tectonic evolution and guiding oil and gas exploration.

**Keywords:** Bohai Basin; Qinnan Depression; structure subsidence; thermal history; Cainozoic

**摘 要:** 构造-热演化史是认识盆地形成及其动力学机制的重要窗口, 也是烃源岩成熟生烃研究的核心问题。随着能源需求的增长以及陆地油气发现难度的增加, 海域逐渐成为我国油气勘探的重要接替区与国家能源战略研究的重要领域。秦南凹陷位于渤海海域西北部, 勘探前景良好, 但勘探程度低, 构造-热演化研究尚属空白。文章选取秦南凹陷3条地震剖面, 建立25口人工井, 进行了构造沉降史和热史模拟, 恢复了秦南凹陷构造-热演化历史。研究结果表明: 秦南凹陷新生代以来于孔店组—沙河街组四段沉积时期(65~42 Ma)、沙河街组三段沉积时期(42~38 Ma)以及东营组三段沉积时期(32.8~30.3 Ma)分别经历了3期裂陷拉张, 总拉张系数为1.27~2.05; 对应这3期拉张作用, 秦南凹陷基底热流经历3期升高, 在东营组三段沉积末期(30.3 Ma)基底热流达到峰值64.0~89.0 mW/m<sup>2</sup>, 之后逐渐降低至今; 秦南凹陷构造-热演化过程与断裂活动具有良好的耦合关系。研究获得的拉张系数、基底热流等参数对于了解渤海盆地构造演化的深部动力学机制以及指导研究区油气勘探具有重要意义。

**关键词:** 渤海盆地; 秦南凹陷; 构造沉降; 热史演化; 新生代

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## 0 引言

20世纪50年代以来, 海洋油气资源逐渐成为全球油气储量新的增长点。渤海盆地是渤海湾含油气盆地的重要组成部分, 是目前中国海域石油产量最大的含油气盆地。随着一系列大—中型油气田在渤海盆地边缘凹陷的不断探明, 边缘凹陷逐渐成为油气勘探的热点(庄新兵等, 2011; 王冠民等, 2018; 赵子斌等, 2018)。作为渤海盆地的边缘凹陷, 秦南凹陷的勘探程度迄今为止是渤海海域最低的凹陷之一。多年来, 秦南凹陷未取得较大规模的商业发现, 该区域烃源岩的生烃能力一直受到质疑, 直至近年来秦南凹陷东南斜坡秦皇岛29-2油气田的发现, 初步展现了秦南凹陷良好的勘探前景(徐长贵等, 2010)。大规模的油气勘探发现是保证油气田开发具备经济效益的关键。然而, 边缘凹陷勘探程度低、不确定因素多, 导致勘探难度高、勘探风险较大。

构造-热演化模拟是一种从岩石圈尺度来研究盆地热演化史的方法。该方法不仅可以恢复盆地基底热流史、温度史, 还可以获得不同时期的应变速率以及拉张系数, 从而探讨盆地演化的地球动力学背景(胡圣标等, 1999; 何丽娟和汪集旻, 2007; Tang et al., 2014a; 胡杰等, 2021)。盆地不同时期的热状态与油气生成、运移和聚集成藏有着十分密切的关系, 不仅影响着烃源岩的成熟生烃能力, 还控制着其与圈闭的匹配关系(任战利等, 2008; Tang et

al., 2014b, 2023; 常甜甜等, 2022; 张云逸等, 2023)。鉴于构造-热演化研究在盆地动力学与油气勘探开发中的重要作用, 相关学者针对渤海湾盆地热历史研究方面开展了丰富的研究工作, 取得了较丰硕的成果, 其中包括基于裂变径迹、镜质体反射率等古温标约束的热历史(胡圣标等, 1999; Hu et al., 2001; Zuo et al., 2017; Chang et al., 2018; Jiang et al., 2021), 也包括基于数值模拟重建的热历史(Liu et al., 2018; 刘琼颖等, 2019)。但已发表的大部分成果主要集中在油气勘探程度较高、基础较丰富的地区, 如东濮凹陷(Tang et al., 2019)、济阳坳陷(Qiu et al., 2014)等。由于勘探程度较低, 目前关于秦南凹陷的研究主要集中在断层活动、油气地质特征、沉积相类型及分布以及烃源岩类型等方面(赖维成等, 2007; 石文龙等, 2014; 庞小军等, 2017; 王冠民等, 2018; 杨传超等, 2019; 刘丹丹等, 2020), 构造-热演化研究尚属空白。

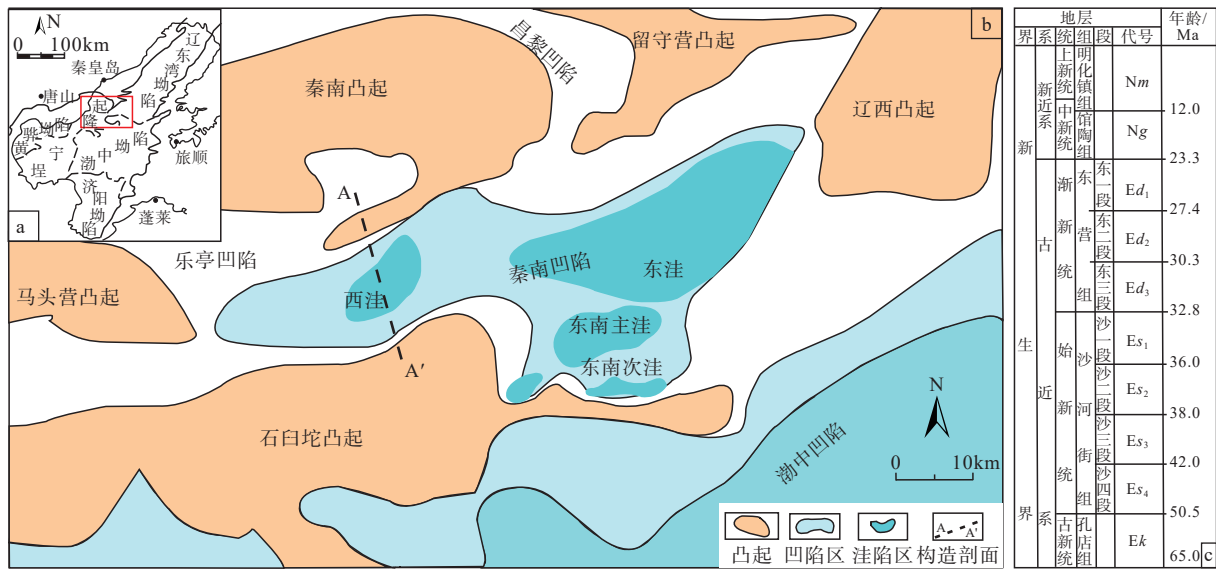
通过收集秦南凹陷最新的三维地震剖面与钻井岩芯数据, 基于3条地震解释剖面建立人工井, 并采用多期有限拉张模型进行构造-热演化模拟, 获得秦南凹陷新生代各裂陷幕的构造沉降, 进而预测盆地基底热流演化史。研究成果可为探讨渤海盆地构造演化及深部动力过程提供启示, 还能与研究区油气资源预测和有利勘探区带优选提供依据, 从而具有重要的理论意义和应用价值。

## 1 地质背景

渤海湾盆地是发育在华北克拉通基底上的中

—新生代断陷盆地 (Li et al., 2000)。渤海盆地是渤海湾盆地的海域部分, 秦南凹陷位于渤海盆地西北部 (图 1a), 被东部辽西凸起、南部石白坨凸起、西部马头营凸起和北部秦南凸起所围限。秦南凹陷整体呈近东西走向, 可划分为 3 个次级构造单元, 西洼、东南洼 (包括东南主洼和东南次洼) 和东洼 (王德英等, 2015; 图 1b)。整体上, 秦南凹陷经历了古近纪裂陷与新近纪以来的拗陷阶段 (蔡少武等, 2018; 谢玉洪等, 2018; 康海亮等, 2021), 具有明显的

断—拗双层结构 (图 2)。秦南凹陷发育完整的古近系孔店组、沙河街组 (沙四段、沙三段、沙二段、沙一段)、东营组 (东三段、东二段、东一段), 新近系馆陶组、明化镇组, 第四系平原组 (图 1c; 赖维成等, 2007)。凹陷内共发育 3 套烃源岩, 分别为古近系沙三段、沙一段和东三段, 其中沙三段烃源岩为该区域油气的主要来源, 已发现的油气藏主要分布于沙一段、沙二段储层中 (庞小军等, 2017; 牛成民等, 2018)。

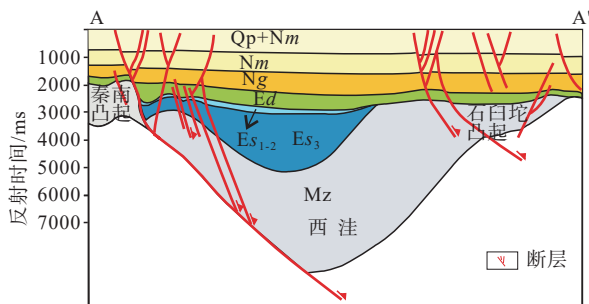


a—研究区位置; b—秦南凹陷构造单元; c—秦南凹陷新生代地层

图 1 秦南凹陷位置、构造单元与地层

Fig. 1 Map showing location, tectonic units, and stratigraphy of the Qinnan Depression

(a) The location of the Qinnan Depression; (b) The tectonic units of the Qinnan Depression; (c) The Cenozoic strata of the Qinnan Depression



注: Mz—基底; Qp—更新统; 其他地层符号同图 1c

图 2 秦南凹陷构造剖面图 (剖面位置见图 1b; 据胡志伟等, 2019 修改)

Fig. 2 Structural section of the Qinnan Depression (The cross-sectional position is shown in Fig. 1b; modified from Hu et al., 2019)

Notes: Mz—basement; Qp—Pleistocene; other stratigraphic symbols are the same as Fig. 1c.

## 2 方法和参数

### 2.1 基础资料

在秦南凹陷共选取 3 条地震测线, 并识别出 T8 (65 Ma)、T6 (42 Ma)、T5 (38 Ma)、T3 (32.8 Ma)、T3m (30.3 Ma)、T2 (23.3 Ma) 和 T0 (12 Ma) 共 8 个反射界面。根据地震解释层位, 参考实际钻井岩性数据, 共建立 25 口人工井, 位置分布见图 3, 计算其构造沉降及热流史。

### 2.2 多期有限拉张模型

针对秦南凹陷新生代以来经历多幕式裂陷过程的演化特征, 选取了多期有限拉张模型来计算其基底热演化史 (Chen, 2014; Tang et al., 2014a)。该模型是基于 Jarvis and Mckenzie (1980) 提出的一维有限

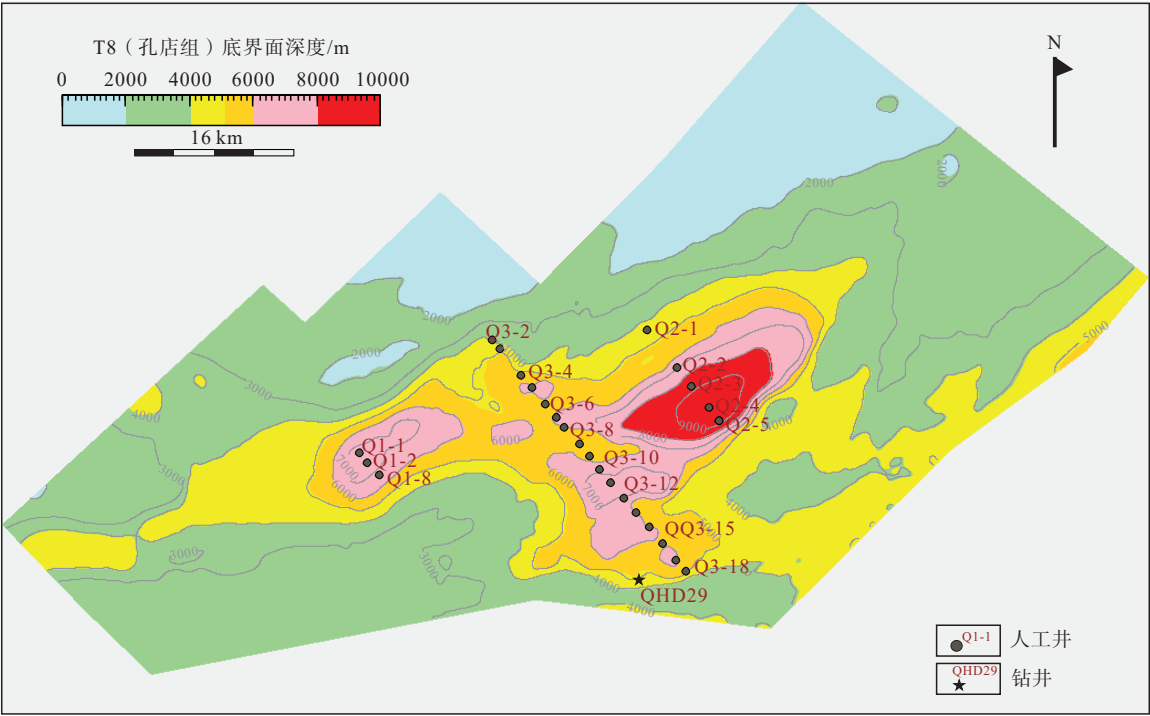


图 3 秦南凹陷孔店组底界面深度图以及模拟井分布

Fig. 3 Map showing the depth of the bottom interface of the Kongdian Formation of the Qinnan Depression and the distribution of modelling wells

拉张模型发展起来的。模型考虑了拉张期间应变速率呈指数衰减以及各期拉张事件温度前后的继承性,适用于前期拉张热扰动没有完全消失又开始新的拉张事件的情况。

多期有限拉张模型计算的基本流程为: 首先通过回剥法获得构造沉降曲线(观测构造沉降), 根据构造沉降曲线, 参考盆地构造演化过程初步划分裂陷期与裂后期; 然后不断地改变各期次的拉张因子, 根据多期有限拉张模型计算得到预测构造沉降量; 再将预测构造沉降曲线量与回剥法得到的观测构造沉降曲线进行对比, 直到满足拟合要求, 便可确定拉张因子; 确定拉张因子后, 便可计算各时期温度及热流值, 从而恢复其热演化史。计算过程中, 模型的上边界设置为恒温(0℃), 下边界温度设为 1330℃。其他模型参数见表 1。

2.3 构造沉降恢复

回剥法恢复构造沉降的基本原理如下: 根据沉积压实原理和质量守恒法则, 以地层分层为基础, 按地质年代逐层回剥至地表, 从而得到各个地层在不同地质时期的真实埋藏深度与构造沉降量。该回剥过程中需要经历压实校正、沉积物负荷校正、古水深校正以及古海平面变化校正(Scater and

表 1 模型参数及取值

Table 1 Definitions and values of parameters used in this study

| 参数符号     | 参数名称      | 取值                   | 单位                |
|----------|-----------|----------------------|-------------------|
| $a$      | 岩石圈厚度     | 125                  | km                |
| $t_c$    | 初始地壳厚度    | 35                   | km                |
| $\rho_w$ | 海水密度      | 1030                 | kg/m <sup>3</sup> |
| $\rho_c$ | 地壳密度      | 2800                 | kg/m <sup>3</sup> |
| $\rho_m$ | 地幔密度      | 3330                 | kg/m <sup>3</sup> |
| $\rho_a$ | 软流圈密度     | 3200                 | kg/m <sup>3</sup> |
| $\kappa$ | 岩石圈热扩散率系数 | $1.0 \times 10^{-6}$ | m <sup>2</sup> /s |
| $\alpha$ | 岩石圈热膨胀系数  | $3.2 \times 10^{-5}$ | ℃ <sup>-1</sup>   |
| $K_c$    | 地壳热导率     | 3.1                  | W/(m · K)         |
| $K_m$    | 地幔热导率     | 2.9                  | W/(m · K)         |

注: 模型参数取值参考刘琼颖和何丽娟(2019)、Chen(2014)

Christie, 1980)。

恢复构造沉降史需要大量的基础参数, 其中包括地层年代、地层分层、岩性、密度和孔隙度等。计算过程中, 地层年代与分层数据参考实际钻井资料及地震解释成果; 岩性数据来自中海油天津分公司的地质录井、测井资料, 由于研究区地层岩性主要为泥岩和砂岩, 因此计算时只考虑了这 2 种岩

性;不同地层密度按地层统计的砂岩、泥岩百分含量加权确定;孔隙度与深度的关系采用指数形式,初始孔隙度、压实系数等参数参考刘琼颖和何丽娟(2019)。由于古近纪以来,渤海盆地几乎为陆相沉积,只有短时间海侵,且海平面变化不大(Xie et al., 2007),所以计算过程中不考虑古水深与古海平面校正。

利用回剥法获得的构造沉积曲线(观测构造沉降)如图4所示。由于裂陷过程的复杂性和地壳成分的非均质性,很难用统一的模式来描述所有钻井的沉降历史。然而从构造沉降曲线的总体趋势可以看出,渤海盆地秦南凹陷新生代以来经历了3期裂陷幕和2期热沉降幕。第1期裂陷幕发生孔店组至沙四段沉积期(65~42 Ma),第2期裂陷幕为沙三段沉积期(42~38 Ma),之后为沙二段至沙一段沉积期的裂后热沉降幕(38.0~32.8 Ma)。第3期裂陷幕发生于东三段沉积期(32.8~30.3 Ma),随后凹陷进入区域热沉降阶段,直至今今。

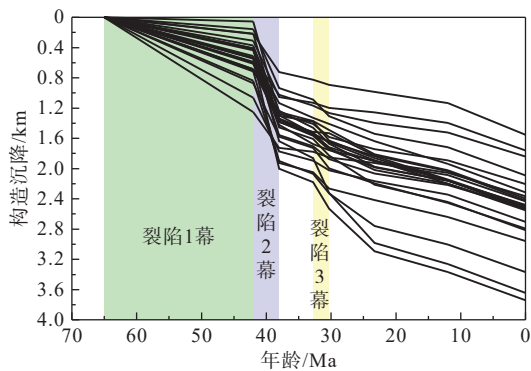
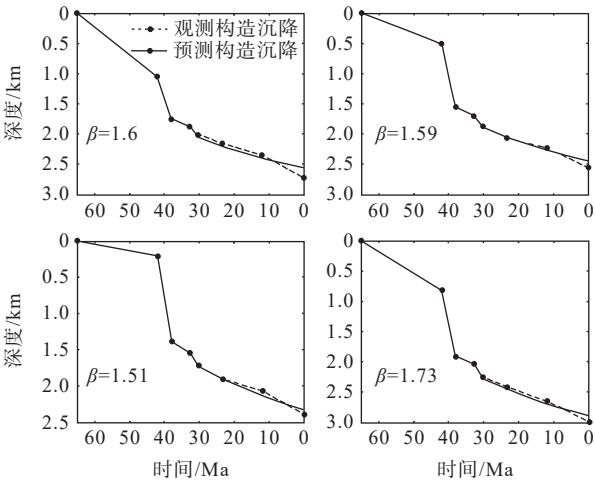


图4 渤海盆地秦南凹陷构造沉降曲线  
Fig. 4 Back-stripped tectonic subsidence curves for the 25 artificial wells of the Qinnan Depression

3 秦南凹陷构造-热演化过程

3.1 拉张因子

明确秦南凹陷的裂陷期与热沉降期后,采用多期有限拉张模型,通过不断改变每期裂陷拉张的拉张因子,将计算得到的预测构造沉降曲线与回剥获得的观测构造沉降曲线进行拟合(图5)。拟合成功后,即可得到每期裂陷拉张的拉张因子,总的拉张因子为每期拉张因子的乘积。从计算结果来看,秦南凹陷3期裂陷拉张的平均拉张因子分别为1.15、1.30和1.06(表2),其中第2期裂陷拉张最为强烈。



β—总拉张因子  
图5 渤海盆地秦南凹陷观测构造沉降曲线与预测沉积曲线拟合  
Fig. 5 Subsidence analysis for the 25 artificial wells in the Qinnan depression.

The circles connected by the dashed lines indicate observed subsidence (from back-stripping), while the dark solid lines represent the theoretical subsidence predicted by the multi-episodic finite stretching model; β—total stretching factor.

表2 渤海盆地秦南凹陷拉张因子

| Table 2 Stretching factors of the Qinnan Depression |       |                   |                   |                      |           |
|-----------------------------------------------------|-------|-------------------|-------------------|----------------------|-----------|
| 注陷                                                  | 井号    | 第1期<br>(65~42 Ma) | 第2期<br>(42~38 Ma) | 第3期<br>(32.8~30.3Ma) | 总拉张<br>因子 |
| 西洼                                                  | Q1-1  | 1.05              | 1.16              | 1.04                 | 1.27      |
|                                                     | Q1-2  | 1.07              | 1.24              | 1.01                 | 1.34      |
|                                                     | Q1-8  | 1.41              | 1.09              | 1.01                 | 1.55      |
| 东洼                                                  | Q2-1  | 1.04              | 1.28              | 1.08                 | 1.44      |
|                                                     | Q2-2  | 1.11              | 1.37              | 1.08                 | 1.64      |
|                                                     | Q2-3  | 1.19              | 1.43              | 1.08                 | 1.84      |
|                                                     | Q2-4  | 1.14              | 1.62              | 1.11                 | 2.05      |
|                                                     | Q2-5  | 1.10              | 1.51              | 1.18                 | 1.96      |
| 东南洼                                                 | Q3-2  | 1.13              | 1.14              | 1.04                 | 1.34      |
|                                                     | Q3-3  | 1.01              | 1.54              | 1.02                 | 1.59      |
|                                                     | Q3-4  | 1.05              | 1.49              | 1.03                 | 1.61      |
|                                                     | Q3-5  | 1.13              | 1.37              | 1.03                 | 1.59      |
|                                                     | Q3-6  | 1.10              | 1.36              | 1.05                 | 1.57      |
|                                                     | Q3-7  | 1.10              | 1.33              | 1.07                 | 1.57      |
|                                                     | Q3-8  | 1.09              | 1.32              | 1.08                 | 1.55      |
|                                                     | Q3-9  | 1.18              | 1.16              | 1.08                 | 1.48      |
|                                                     | Q3-10 | 1.18              | 1.21              | 1.05                 | 1.50      |
|                                                     | Q3-11 | 1.32              | 1.18              | 1.03                 | 1.60      |
|                                                     | Q3-12 | 1.23              | 1.35              | 1.04                 | 1.73      |
|                                                     | Q3-13 | 1.24              | 1.20              | 1.09                 | 1.62      |
|                                                     | Q3-14 | 1.15              | 1.21              | 1.10                 | 1.53      |
|                                                     | Q3-15 | 1.16              | 1.28              | 1.03                 | 1.53      |
|                                                     | Q3-16 | 1.15              | 1.25              | 1.06                 | 1.52      |
|                                                     | Q3-17 | 1.18              | 1.19              | 1.07                 | 1.50      |
|                                                     | Q3-18 | 1.13              | 1.19              | 1.07                 | 1.44      |
| 平均值                                                 |       | 1.15              | 1.30              | 1.06                 | 1.57      |

3.2 热流演化史

基底热流结果表明,秦南凹陷新生代以来经历了3期加热、2期冷却(图6,表3)。65 Ma时,初始基底热流约为54.9 mW/m<sup>2</sup>,在经历孔店组一沙四段第1期拉张裂隙后(65~42 Ma),基底热流升高为55.2~68.8 mW/m<sup>2</sup>。接着经历沙三段第2期强烈拉张裂隙(42~38 Ma),至沙三段沉积末期基底热流升高至62.4~83.9 mW/m<sup>2</sup>。2期裂隙后,秦南凹陷于沙二段一沙一段沉积期间(38~32.8 Ma)经历短暂裂

后热沉降,基底热流稍有冷却,降至62.3~83.0 mW/m<sup>2</sup>。凹陷于东三段沉积期间(32.8~30.3 Ma)经历第3期加热,基底热流升高至64.0~89.0 mW/m<sup>2</sup>。东二段沉积开始,秦南凹陷进入裂后热沉降阶段,基底热流冷却至今,为61.4~73.6 mW/m<sup>2</sup>,平均为66.7 mW/m<sup>2</sup>。相较于西洼与东南洼,秦南凹陷东洼经历了较强的热史演化过程,具有更高的古热流值(图6,表3)。

秦南凹陷现今基底热流为61.4~73.6 mW/m<sup>2</sup>。

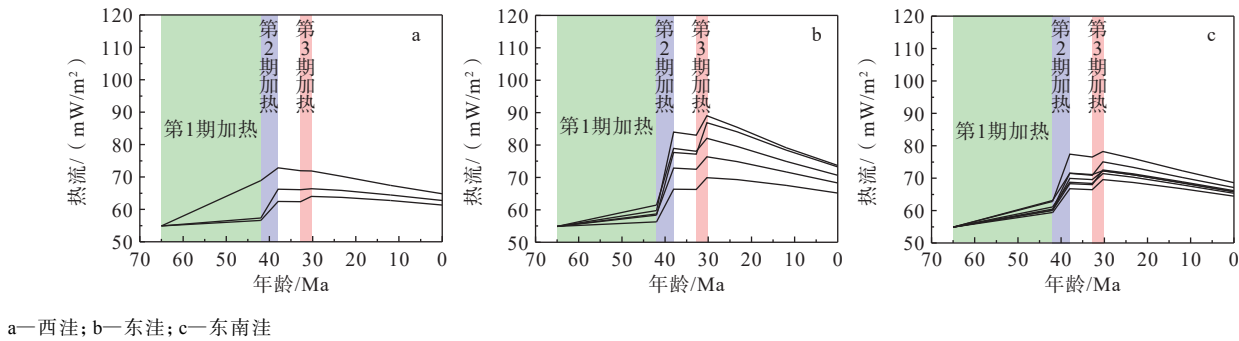


图 6 渤海盆地秦南凹陷基底热流史

Fig. 6 Reconstructed basal thermal history for the artificial wells in the Qinnan Depression

(a) Xi subsea; (b) Dong subsea; (c) Southwest subsea.

表 3 渤海盆地秦南凹陷人工井基底热流史 (单位: mW/m<sup>2</sup>)

Table 3 Calculated basal heat flow data for all the artificial wells in Qinnan Depression

| 洼陷  | 井名    | 65Ma | 42Ma | 38Ma | 32.8Ma | 30.3Ma | 23.3Ma | 12Ma | 0Ma  |
|-----|-------|------|------|------|--------|--------|--------|------|------|
| 西洼  | Q1-1  | 54.9 | 56.6 | 62.4 | 62.4   | 64.0   | 63.7   | 62.7 | 61.4 |
|     | Q1-2  | 54.9 | 57.3 | 66.2 | 66.0   | 66.4   | 65.9   | 64.5 | 62.7 |
|     | Q1-8  | 54.9 | 68.9 | 72.8 | 71.9   | 71.9   | 70.2   | 67.4 | 64.8 |
|     | 平均值   |      | 60.9 | 67.1 | 66.8   | 67.4   |        |      | 63.0 |
| 东洼  | Q2-1  | 54.9 | 56.3 | 66.4 | 66.3   | 69.9   | 69.3   | 67.5 | 65.2 |
|     | Q2-2  | 54.9 | 58.7 | 72.8 | 72.5   | 76.3   | 74.9   | 71.7 | 68.3 |
|     | Q2-3  | 54.9 | 61.4 | 78.9 | 78.1   | 82.0   | 79.5   | 74.9 | 70.6 |
|     | Q2-4  | 54.9 | 59.7 | 83.9 | 83.0   | 89.0   | 85.4   | 79.2 | 73.7 |
|     | Q2-5  | 54.9 | 58.3 | 77.7 | 77.2   | 86.9   | 84.0   | 78.4 | 73.2 |
|     | 平均值   |      | 58.9 | 75.9 | 75.4   | 80.8   |        |      | 70.2 |
| 东南洼 | Q3-2  | 54.9 | 59.4 | 64.8 | 64.6   | 66.2   | 65.6   | 64.1 | 62.4 |
|     | Q3-3  | 54.9 | 55.2 | 74.1 | 74.1   | 75.0   | 74.1   | 71.2 | 68.0 |
|     | Q3-4  | 54.9 | 56.6 | 74.4 | 74.2   | 75.6   | 74.4   | 71.4 | 68.1 |
|     | Q3-5  | 54.9 | 59.4 | 73.8 | 73.3   | 74.6   | 73.2   | 70.3 | 67.2 |
|     | Q3-6  | 54.9 | 58.3 | 72.0 | 71.7   | 74.0   | 72.8   | 70.1 | 67.1 |
|     | Q3-7  | 54.9 | 58.3 | 70.9 | 70.6   | 73.9   | 72.7   | 70.0 | 67.0 |
|     | Q3-8  | 54.9 | 58.0 | 70.0 | 69.8   | 73.5   | 72.5   | 69.9 | 66.9 |
|     | Q3-9  | 54.9 | 61.1 | 67.5 | 67.2   | 70.7   | 69.6   | 67.4 | 64.9 |
|     | Q3-10 | 54.9 | 61.1 | 69.6 | 69.1   | 71.3   | 70.1   | 67.8 | 65.2 |
|     | Q3-11 | 54.9 | 65.9 | 73.7 | 72.9   | 73.9   | 72.2   | 69.1 | 66.2 |
|     | Q3-12 | 54.9 | 62.8 | 77.4 | 76.6   | 78.2   | 76.1   | 72.3 | 68.6 |
|     | Q3-13 | 54.9 | 63.1 | 71.5 | 70.9   | 75.0   | 73.4   | 70.3 | 67.1 |
|     | Q3-14 | 54.9 | 60.1 | 68.3 | 68.0   | 72.5   | 71.4   | 68.9 | 66.2 |
|     | Q3-15 | 54.9 | 60.4 | 71.5 | 71.1   | 72.3   | 71.1   | 68.5 | 65.8 |
|     | Q3-16 | 54.9 | 60.1 | 69.9 | 69.6   | 72.2   | 71.1   | 68.6 | 65.9 |
|     | Q3-17 | 54.9 | 61.1 | 68.7 | 68.3   | 71.4   | 70.3   | 67.9 | 65.4 |
|     | Q3-18 | 54.9 | 59.4 | 66.8 | 66.5   | 69.5   | 68.7   | 66.7 | 64.5 |
|     | 平均值   |      | 60.2 | 69.0 | 68.7   | 71.6   |        |      | 65.6 |

根据人工井信息,新生代沉积物厚度为 3.0~9.8 km。考虑到新生界沉积物的平均生热率为  $1.2 \mu\text{W}/\text{m}^3$  (彭波和邹华耀, 2013), 新生界沉积物的热流贡献为  $3.6\sim 8.9 \text{ mW}/\text{m}^2$ 。因此,秦南凹陷大地热流为  $64.9\sim 77.5 \text{ mW}/\text{m}^2$ , 这与唐晓音等 (2023) 报道的热流值一致。

## 4 讨论

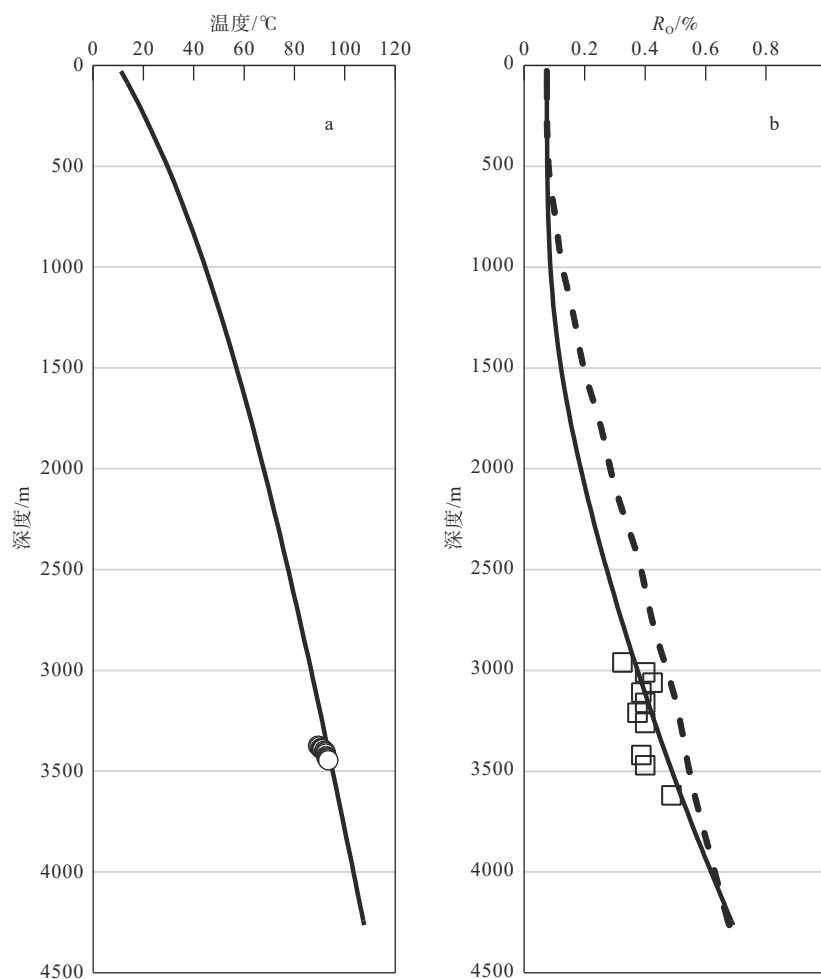
### 4.1 模拟结果的验证与约束

钻井实测温度与镜质体反射率 ( $R_o$ ) 是 2 个常用来检验热史模拟结果的指标 (Rodon and Littke, 2005; Zuo et al., 2015)。文章选取位于秦南凹陷东南

洼的实际钻井 QHD29 (位置见图 3), 采用 Genesis 软件 (version 4.91, ZetaWare, Inc.), 基于模拟计算得到的基底热流值, 计算其理论镜质体反射率与温度, 并将计算结果与实测值进行对比 (图 7)。计算值与实测值具有良好的拟合关系, 表明文中获得的基底热流值较为合理。

### 4.2 构造-热演化的动力学机制

古新世孔店组沉积期 (65~42 Ma), 秦南凹陷进入初期裂陷 (平均构造沉降速率为  $0.02 \text{ km}/\text{Ma}$ ; 图 8a), 热流开始缓慢升高; 始新世沙三段沉积期 (42~38 Ma), 盆地进入第 2 期裂陷 (平均构造沉降速率为  $0.21 \text{ km}/\text{Ma}$ ), 热流再次升高; 渐新世沙一段—沙二段沉积期 (38.0~32.8 Ma), 凹陷经历了短暂的



a—温度模拟值与实测值 (实线为模拟得到的温度曲线, 圆圈为实测的温度值); b—镜质体反射率模拟值与实测值 (实线为 ARCO 模型计算而得的  $R_o$  曲线, 虚线为 LLNL 模型计算而得的  $R_o$  曲线, 方框为实测  $R_o$ )

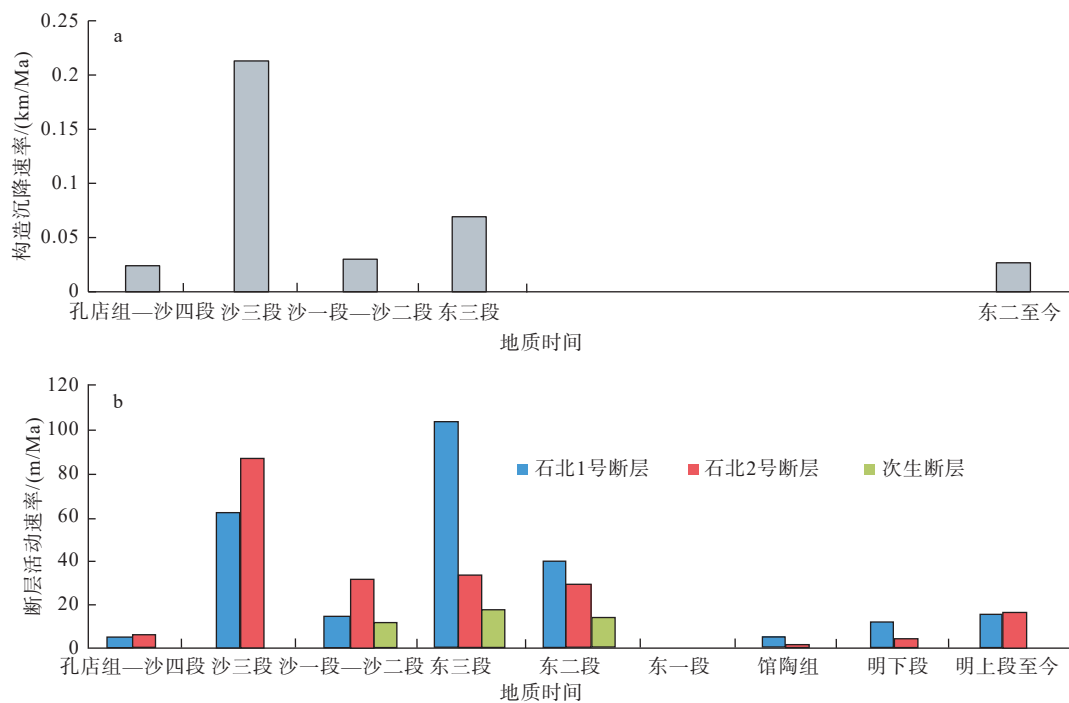
图 7 模拟温度及镜质体反射率与实测值拟合图

Fig. 7 Simulated and measured values of temperature and vitrinite reflectance

(a) Simulated and measured values of temperature (the solid line represents the simulated temperature curve, and the circle represents the measured temperature value); (b) Simulated and measured values of vitrinite reflectance (the solid line represents the  $R_o$  value curve calculated by the ARCO model, the dashed line represents the  $R_o$  value curve calculated by the LLNL model, and the box represents the measured  $R_o$  value)

热沉降(平均构造沉降速率为 0.02 km/Ma);东三段沉积期(32.8~30.3 Ma),秦南凹陷经历第 3 次短暂的裂陷(平均构造沉降速率为 0.07 km/Ma),热流升高并达到最高值;随后盆地进入热沉降期(平均构造沉降速率为 0.26 km/Ma),热流逐渐降低。而秦南凹陷边界断层活动性研究结果表明,虽然不同沉积时期,各断层活动存在差异性,但总体上,秦南凹陷边界断层的活动性表现为:孔店组—沙四段对应秦南凹陷初始裂陷期,断层开始活动;沙三段为盆地的强裂陷期,断层活动增强;沙一段—沙二段沉积期断层活动减弱;东三段沉积期断层活动再次加强;东二段沉积开始,断层活动减弱(庞小军等, 2017; 刘丹丹等, 2020; 图 8b)。由此可以看出,秦南

凹陷多幕裂陷加热的演化过程与断层活动的旋回性十分吻合,其构造沉降整体上可能受断层作用的控制。在渤海盆地,莫霍面、软流圈顶面形态呈上隆状态,与新生代断陷盆地的形态呈镜像关系(张成科等, 2002; Huang and Zhao, 2006; 邢作云等, 2006; 黄忠贤等, 2009; 郑洪伟等, 2012; Hao et al., 2013; 姜迪迪等, 2013),说明软流圈上隆的伸展作用是渤海新生代盆地最主要的深部动力来源,这可能是由于太平洋板块向欧亚板块俯冲引起的(刘琼颖等, 2019)。太平洋板块向欧亚板块的汇聚速率与渤海新生代盆地的沉积、沉降速率呈负相关关系正说明了这一点,即俯冲速率越小时,沉积、沉降速率越大(信延芳等, 2015; 刘琼颖和何丽娟, 2019)。



a—平均构造沉降速率; b—断层平均活动速率(刘丹丹等, 2020)

图 8 秦南凹陷各沉积时期平均构造沉降速率与断层平均活动速率

Fig. 8 Average tectonic subsidence rate and fault activity rate during different sedimentary periods in the Qinnan Depression

(a) Average tectonic subsidence rate; (b) Average fault activity rate(Liu et al.,2020)

## 5 结论

(1)新生代以来秦南凹陷经历 3 期裂陷拉张过程,分别为孔店组—沙四段沉积时期(65~42 Ma)、沙三段沉积时期(42~38 Ma)以及东三段沉积时期(32.8~30.3 Ma)。新生代期间,秦南凹陷总拉张系数平均为 1.57,沙三段沉积时期拉张系数最大,平均为 1.30。

(2)秦南凹陷基底热流自新生代初开始升高,经过 3 期加热,整体在东三段沉积末期(~30.3Ma)达到峰值,介于 64.0~89.0 mW/m<sup>2</sup>,平均为 73.9 mW/m<sup>2</sup>。秦南凹陷构造-热演化过程与断裂活动具有良好的耦合关系。

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