doi: 10.12029/gc20190517

赵金环,邹长春,王稳石,张小环,朱永宜,张金昌,张恒春,丁娱娇,林峰,秦宇星,周海,孙文龙. 2019. 松科二井东孔营城组火山岩测井响应特征及岩性评价[J]. 中国地质, 46(5): 1174−1183.

Zhao Jinhuan, Zou Changchun, Wang Wenshi, Zhang Xiaohuan, Zhu Yongyi, Zhang Jinchang, Zhang Hengchun, Ding Yujiao, Lin Feng, Qin Yuxing, Zhou Hai, Sun Wenlong. 2019. Log response characteristics and lithological evaluation of volcanic rocks in Yingcheng Formation from the second scientific drilling borehole (SK−2 east borehole) in Songliao basin of Northeast China[J]. Geology in China, 46(5): 1174−1183(in Chinese with English abstract).

松科二井东孔营城组火山岩测井响应特征及岩性评价

赵金环[1,2],邹长春[1,2],王稳石[3],张小环[1,2],朱永宜[3],张金昌[3],张恒春[3],
丁娱娇[4],林峰[4],秦宇星[4],周海[4],孙文龙[4]

(1.中国地质大学(北京)地下信息探测技术与仪器教育部重点实验室,北京 100083;
2.中国地质大学(北京)地球物理与信息技术学院,北京 100083;3.中国地质调查局勘探技术研究所,河北 廊坊 065300;
4.中国石油集团测井有限公司天津分公司,天津 300280)

提要:为开展松辽盆地深部长期观测、流体实验和探索白垩纪火山事件,利用松科二井东孔丰富、齐全的测井资料,对营城组火山岩岩性进行评价。通过测井响应特征分析发现,松科二井东孔营城组凝灰岩具有最强的放射性和导电性,高孔隙度的集块熔岩密度为低值,流纹岩表现出高密度和低导电性。利用测井交会图和成像识别模式,识别出松科二井东孔营城组火山岩以流纹岩、凝灰熔岩和集块熔岩为主,少量的凝灰岩。结合凝灰岩处测井曲线变化特点,证明了火山喷发间断的存在。流纹岩具有高碱、高Si、低Fe和低黏土矿物特征。T_2谱分析认为流纹岩有利于后期深部长期观测和流体实验的开展。研究成果对松科二井东孔后续火石岭组火成岩及整个松辽盆地火山岩研究具有一定的参考价值。

关 键 词:深地勘查工程;松科二井东孔;火山岩;测井响应特征;岩性评价

中图分类号:P588.14;P613.8 **文献标志码**:A **文章编号**:1000−3657(2019)05−1174−10

Log response characteristics and lithological evaluation of volcanic rocks in Yingcheng Formation from the second scientific drilling borehole (SK−2 east borehole) in Songliao basin of Northeast China

ZHAO Jinhuan[1,2], ZOU Changchun[1,2], WANG Wenshi[3], ZHANG Xiaohuan[1,2],
ZHU Yongyi[3], ZHANG Jinchang[3], ZHANG Hengchun[3], DING Yujiao[4], LIN Feng[4],
QIN Yuxing[4], ZHOU Hai[4], SUN Wenlong[4]

(1.*Key Laboratory of Geo−detection, Ministry of Education, China University of Geosciences (Beijing), Beijing* 100083*, China;* 2. *School of Geophysics and Information Technology, China University of Geosciences, Beijing* 100083*, China;* 3. *Institute of*

收稿日期:2019−03−12;**改回日期**:2019−09−06

基金项目:中国地质调查局地质调查专项(12120113017600)、国家自然科学基金重大项目专题(41790455−1)和中国地质调查局公益性基础地质调查项目(DD20179362)联合资助。

作者简介:赵金环,女,1987年生,博士生,地球探测与信息技术专业;E−mail: 446103042@qq.com。

通讯作者:邹长春,男,1969年生,教授,博士生导师,主要从事岩石物理、测井与井中物探、油气勘探和科学钻探等领域的教学和科研工作;E−mail:zoucc@cugb.edu.cn。

Exploration Techniques, China Geological Survey, Langfang 065000, *Hebei, China;* 4. *Tianjin Branch, CNPC Logging, Tianjin* 300280*, China*)

Abstract: In order to conduct long-term deep observation, fluid experiments and investigate volcanic events in Songliao basin, the authors carried out lithological evaluation of volcanic rocks in Yingcheng Formation by using abundant and complete geophysical logs from SK-2 east borehole. The log response analysis of volcanic rocks shows that the radioactivity and electric conductivity of tuffs are the strongest. Agglomeratic lavas have low density because of high porosity. The density of rhyolites is the highest and the electric conductivity is the weakest. Volcanic rocks of Yingcheng Formation along SK-2 east borehole consist of rhyolites, transitional tuffl lavas, agglomeratic lavas and a little tuffs by using cross plots and imaging models. A volcanic eruptive gap may exist, as evidenced by tuff with high GR, low RD and low DEN. Rhyolites are characterized by high alkali, high Si, low Fe and low clay mineral. T_2 analysis suggests that the rhyolites are favorable for carrying out long-term observations and fluid experiments. The results provide a reference of interpretation for subsequent volcanic rock in Huoshilin Formation and research of volcanic rocks in the whole basin.

Key words: deep exploration engineering; SK-2 east borehole; volcanic rocks; log response characteristics; lithological evaluation

About the first author: ZHAO Jinhuan, female, born in 1987, doctor candidate, majors in geo- detection and information technology; E-mail: 446103042@qq.com.

About the corresponding author: ZOU Changchun, male, born in 1969, professor, supervisor of doctor candidates, mainly engages in the teaching and scientific research of petrophysics, logging, borehole geophysical prospecting, hydrocarbon exploration and scientific drilling ; E-mail: zoucc@cugb.edu.cn.

Found support: Supported by China Geological Survey Project (No. 12120113017600), Key Project of National Natural Science Foundation of China (No. 41790455-1) and Public Welfare Fundamental Geological Survey Project of China Geological Survey (No. DD20179362).

1 引 言

松辽盆地作为白垩纪时期亚洲古陆上发育的最大内陆含油气沉积盆地,也是全球范围内保存最为完整的陆相沉积盆地之一(吴怀春等,2008;黄清华等,2011)。无论是资源勘探开发,还是白垩纪全球古气候、古环境变化研究,松辽盆地已经成为全国乃至全球的重点研究区域。白垩纪松辽盆地资源与环境深部钻探工程(CCSD-SK)第二阶段松科二井东孔钻穿了整个白垩纪陆相地层,该工程的实施对实现油气勘探新突破、开展深部长期观测、实验和探索白垩纪火山事件具有重要意义(邹长春等,2016;Sun et al.,2016;侯贺晟等,2018;朱永宜等,2018)。松科二井东孔营城组(2952~3342 m)埋藏较深。钻井取心表明在营城组钻遇火山岩,总厚度约160 m。火山岩的岩性评价是探索白垩纪火山事件的首要任务。

火山岩的矿物成分、结构、构造以及物性特征的差异导致其测井响应特征存在一定的差异(潘保芝等,2009)。但由于火山岩的矿物成分复杂、结构和构造特征繁多、物性差异大,同一类型火山岩测井响应特征不同,变化范围比较大,既有高值,也有低值。松科二井东孔测井项目丰富,采用国内外先进的测井仪器,获取了常规、电阻率成像、新型岩性元素扫描(Litho Scanner)、核磁共振等优质的测井资料,蕴含了大量、连续的地质信息。连续、丰富、齐全的测井资料有助于火山岩岩性评价工作的开展。

本文分析了松科二井东孔营城组火山岩测井响应特征。建立了岩性交会识别图版和成像识别模式,得到松科二井东孔营城组火山岩岩性剖面。在此基础上,开展岩性特征、孔隙特性和流纹岩的化学特征分析,为松科二井东孔后续火石岭组火山岩以及整个松辽盆地火山岩研究提供参考。

2 松科二井东孔营城组火山岩测井响应特征

经过多年的地质调查与油气勘探,松辽盆地营城组火山岩类型从基性岩到酸性岩均存在,以酸性岩为主(刘万洙等,2003;戴亚权,2007;王璞珺等,2008;李宁等,2009;吴杰,2015)。松科二井东孔营

城组主要钻遇的火山岩类型包括流纹岩、集块熔岩、凝灰熔岩和凝灰岩。根据王璞珺等(2007)的火山岩分类方案，流纹岩属于火山熔岩类；集块熔岩和凝灰熔岩属于火山碎屑熔岩类；凝灰岩属于火山碎屑岩类。不同地区同一类型的火山岩的测井响应特征不同，但大体上表现为火山碎屑熔岩的自然伽马和密度测井值既有高值也有低值，电阻率则皆为低值；火山熔岩的电阻率和密度皆为高值，火山碎屑熔岩则多是呈现出中间值的特征(Khatchikian, 1983; Bartetzko et al., 2003; 邵维志等, 2006; Ikeda, 2008; 刘俊田等, 2009; 吴颜雄等, 2012; 王泽华等, 2015)。根据归位后的精准岩心资料，分析了松科二井东孔营城组火山岩的测井响应特征。

2.1 常规测井响应特征

营城组火山岩的常规测井响应特征存在不同程度上的差别(图1)。流纹岩呈现高电阻率(R)、低声波时差(AC)和低中子(CN)的响应特征；集块熔岩呈现低密度(DEN)的响应特征；凝灰岩呈现高自然伽马(GR)、高声波时差、高中子的响应特征；对于凝灰熔岩，其常规测井响应皆处在中间值的范围内。由此可见，凝灰岩的放射性和导电性最强；流纹岩具有高密度和低导电性；集块熔岩的密度最低。自然伽马、电阻率和密度对松科二井东孔营城组火山岩岩性变化最为敏感，从火山熔岩、火山碎屑熔岩到火山碎屑岩，电阻率逐渐降低；而对于自然伽马和密度，火山熔岩和火山碎屑岩呈现高值、火山碎屑熔岩呈现低值的特征。

2.2 电阻率成像测井响应特征

电阻率成像测井在垂向上的分辨率达到毫米级，可获得地层的结构、构造、裂缝等特征的信息(Ekstrom et al., 1987)。松科二井东孔营城组电阻率成像图像上，清晰地反映出流纹岩的流纹构造、集块熔岩的集块结构以及凝灰熔岩的凝灰结构(图2)。

2.3 新型岩性元素扫描测井响应特征

新型岩性元素扫描测井可以获得岩石中Si、Ca、Al、Fe、S、Ti、K、Na等造岩元素的百分含量，以及SiO_2、K_2O+Na_2O百分含量和矿物含量。随着岩性的变化，松科二井东孔火山岩Si、Ca、Al、Mg、Ti、K和Na元素的百分含量无明显的差别。流纹岩、凝灰熔岩和集块熔岩具有较高的SiO_2百分含量，高达82%；凝灰岩的SiO_2百分含量只有12%~32%，但其K_2O+Na_2O百分含量高达38%。流纹岩的Fe元素百分含量较低0.5%~1.5%，而凝灰熔岩、集块熔岩和凝灰岩的Fe元素百分含量在2%左右。

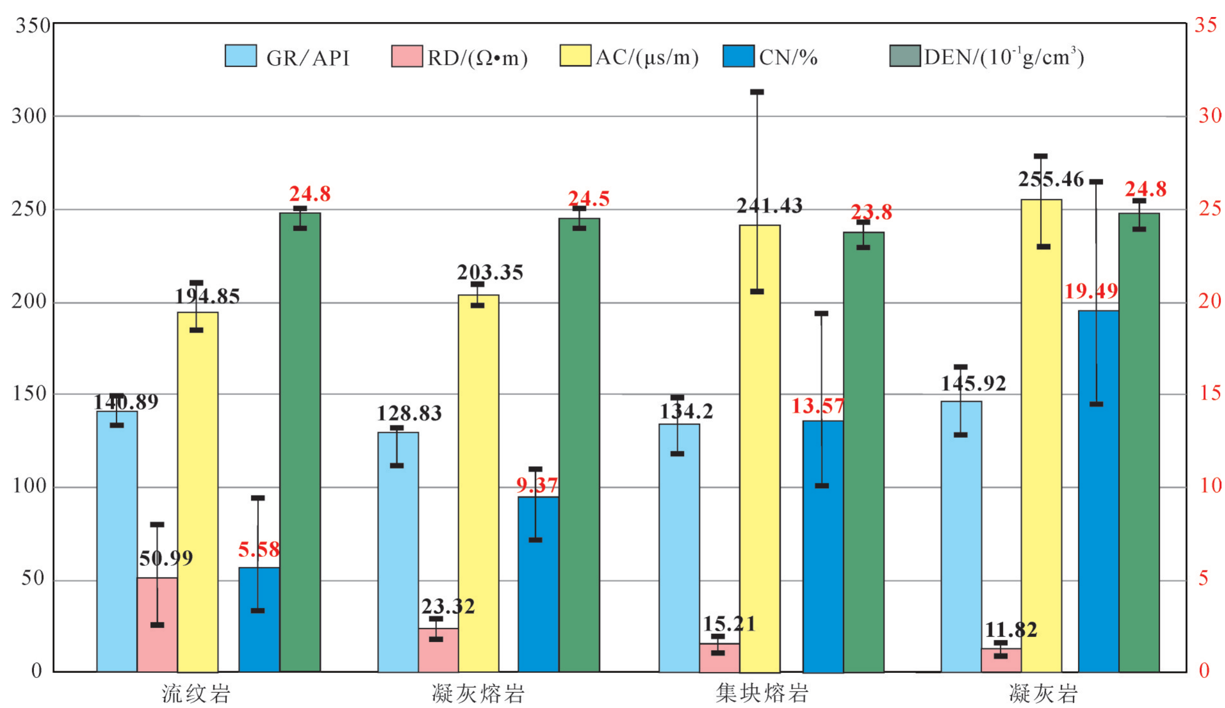

图1 松科2井东孔营城组火山岩常规测井响应特征

Fig.1 Conventional log response of volcanic rocks of Yingcheng Formation in SK-2 east borehole

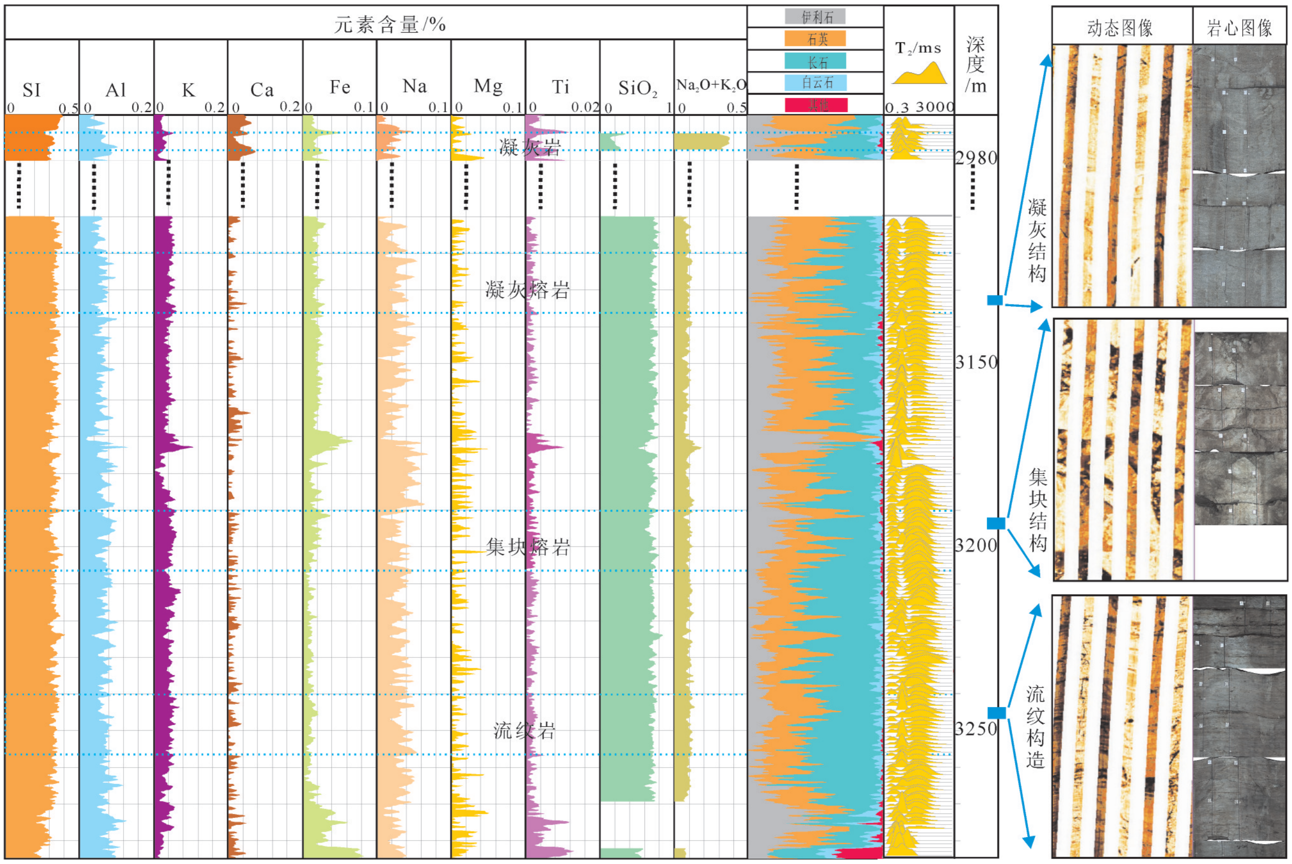

图2　松科二井东孔营城组火山岩新型岩性元素扫描、核磁共振、电阻率成像测井响应特征

Fig.2 Litho scanner, resistivity image and NMR log responses of volcanic rocks in Yingcheng Formation from SK−2 east borehole

2.4 核磁共振测井响应特征

核磁共振测井通过T_2谱探测岩石的孔隙结构以及孔隙度的大小。整体上,松科二井东孔营城组凝灰熔岩和集块熔岩T_2谱多为双峰形态,两峰明显;凝灰岩T_2谱则呈现出单峰形态;流纹岩T_2谱双峰分布为主,第一个峰相对较小,且有单峰存在(图2)。

3　松科二井东孔营城组火山岩剖面的建立

3.1 火山岩剖面建立的方法

交会图法是国内外最为常用的,也是最为简单的一种方法。但由于不同地区同一类型的火山岩的测井响应特征不同,且同一岩性测井响应特征为一分布范围,交会图法具有局限性。通过火山岩测井响应特征的分析,在优选出对岩性变化敏感的测井项目的基础上,建立了岩性识别交会图版(图3)。流纹岩、凝灰熔岩、集块熔岩和凝灰岩在交会图中的重叠区域,反映出火山岩岩性过渡的特点(王泽华等,2015)。

国际地质科学联合会(IUGS)推荐使用的TAS图版,根据不同岩石类型的SiO_2和Na_2O+K_2O含量不同,对火山岩进行岩性的细分。按照SiO_2的含量不同,火山岩分为超基性、基性、中性和酸性四大类(Le Bas et al.,1986)。TAS图主要用于火山熔岩类的岩性识别,凝灰熔岩和集块熔岩是介于火山熔岩和火山碎屑岩之间的过渡性岩石,凝灰岩则属沉积岩范畴,TAS图版不适用于该两类岩石的识别。将来自松科二井东孔营城组流纹岩样本点投影到TAS图,酸性的流纹岩基本上都落在流纹岩区域(图4)。

根据凝灰熔岩和集块熔岩的定义,碎屑粒径<2 mm的火山碎屑熔岩称为凝灰熔岩,表现出凝灰结构;碎屑粒径>64 mm的火山碎屑熔岩称为集块熔岩,具有集块结构(王璞珺等,2007;李宁等,2009)。松科二井东孔营城组微电阻率成像图像上,流纹岩的流纹构造、凝灰熔岩的凝灰结构和集块熔岩的集块结构清晰可见。根据火山岩在微电

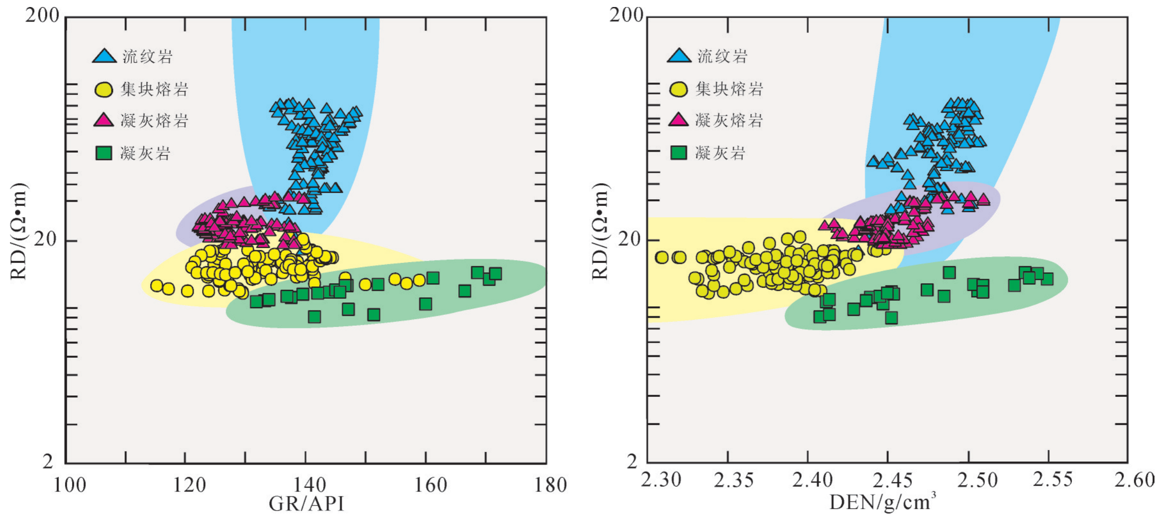

图3 松科二井东孔营城组火山岩常规测井交会图

Fig.3 Cross plots of volcanic rocks based on conventional logs

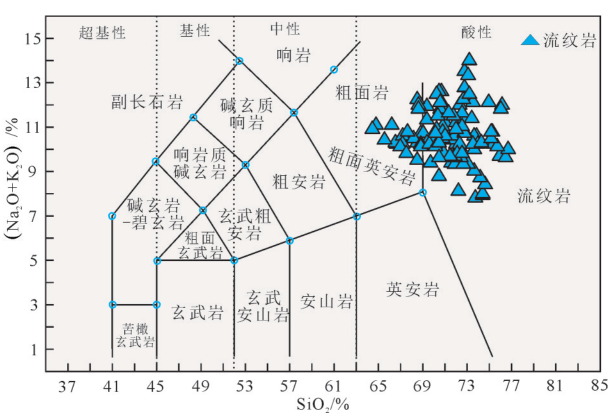

图4 松科二井东孔营城组火山岩利用TAS图识别岩性实例

Fig.4 Distribution of logs from Litho scanner log in TAS

阻率成像图像上的这些特征，建立了区分流纹岩、凝灰熔岩和集块熔岩的电阻率成像识别模式（图5）。针对常规测井交会图中重叠的区域，采用上述3种模式，通过识别结构和构造特征进一步区分。

3.2 松科二井东孔营城组火山岩岩性剖面

综合各种测井资料，利用交会图版和成像识别模式，得到松科二井东孔营城组火山岩剖面（图6）。松科二井东孔营城组以酸性的流纹岩为主，主要发育在3210~3270 m；其次为凝灰熔岩和集块熔岩，分别发育在3110~3140 m和3180~3210 m；少量的凝灰岩发育在2974.1~2977.0 m、3173.7~3174.2 m。与钻井取心对比发现，测井识别3178~3215 m为集块熔岩，钻井取心定义该深度处为集块岩。松科二井东孔营城组取心直径为214 mm，大直径岩心导致肉眼观测到的火山碎屑成分不准确。现场岩心观察发现同一深度岩性有交叉，既有集块岩，也有集块熔岩。结合录井岩屑描述结果，定义该深度段岩性为集块熔岩。当两种岩性统一，识别正确率大幅度提高。

松科二井东孔营城组火山岩岩性识别表明，同一类型火山岩测井响应特征变化范围大，交会图法具有一定的局限性，应选择对岩性变化反应敏感的测井项目进行交会；当各类火山岩结构和构造特征区分明显时，可以利用成像测井资料，通过识别火山岩的结构和构造特征识别火山岩岩性；松辽盆地火山熔岩类、火山碎屑熔岩和火山碎屑岩均有，不利于使用化学元素进行岩性识别；火山岩成分和类型十分复杂，命名的不统一是影响火山岩岩性识别效果的又一因素。因此，应在充分了解区域岩性特点和分类的基础上，综合利用各种测井资料，开展火山岩的岩性识别。

火山岩纵向上岩性的变化有利于重构火山事件（Paulick et al., 2005; Busby and Bassett., 2007; Wildner et al., 2010; Waichel et al., 2012）。松科二井东孔所在的徐家围子断陷营城组火山岩是多期次火山喷发-间歇形成的产物（贺电等，2008；王玲等，2009；姜传金等，2010）。火山碎屑沉积物的存在标志着火山喷发的间断（Wildner et al., 2002）。火山喷发的间断在测井响应特征上表现为GR增加、R和

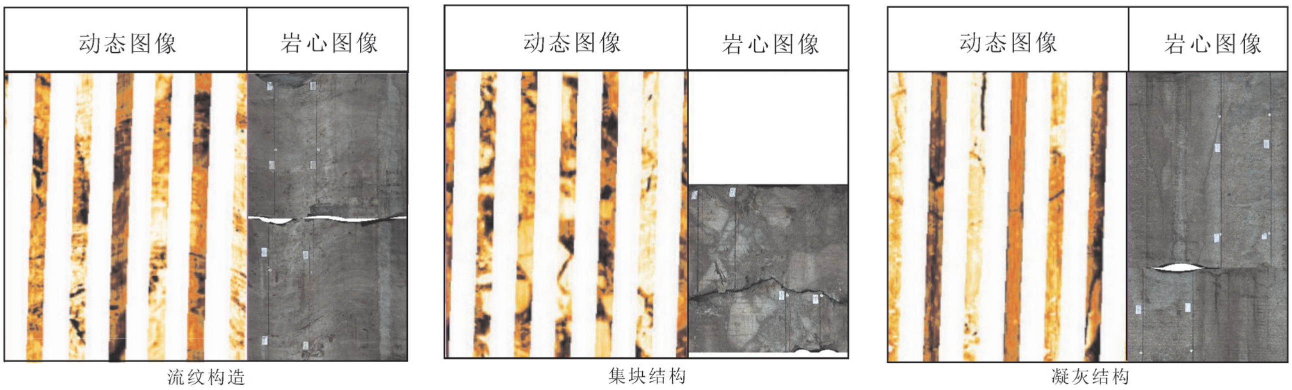

图5 松科二井东孔营城组流纹岩、集块熔岩和凝灰熔岩电成像识别模式
Fig.5 Models of rhyolites, agglomeratic lavas and tuffl lavas in images from resistivity image logs

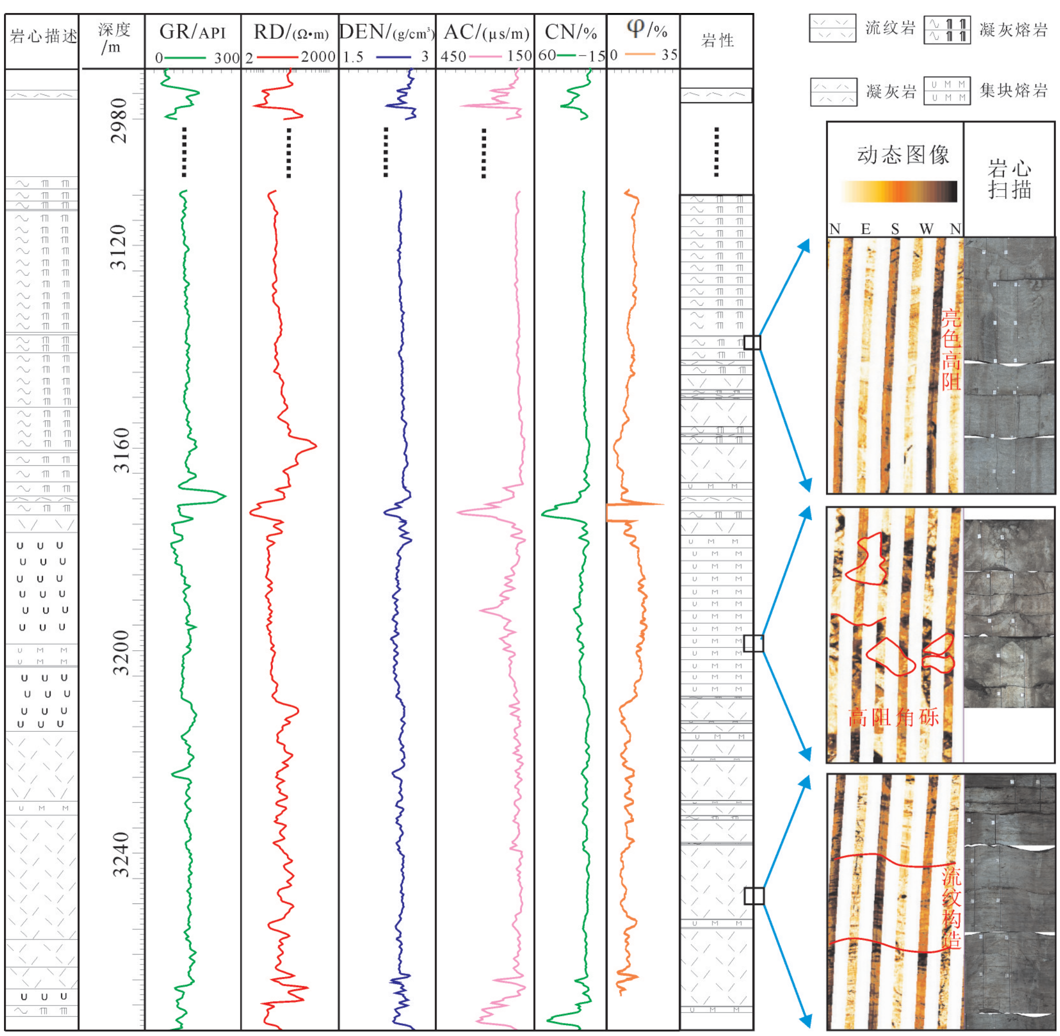

图6 松科二井营城组火山岩岩性剖面
Fig.6 Lithological profile of Yingcheng Formation in SK−2 east borehole

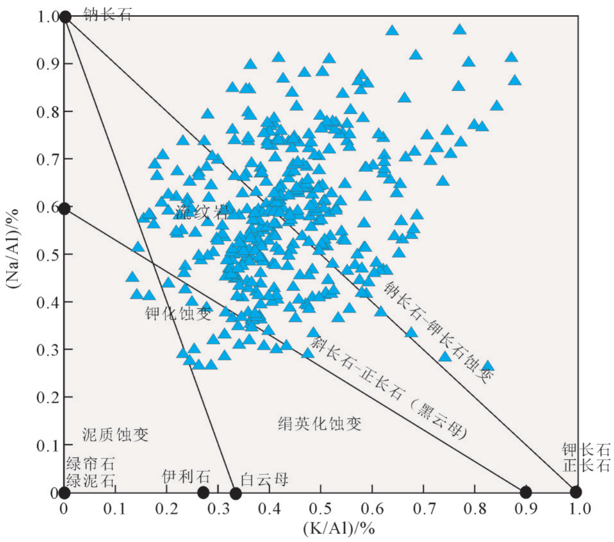

图7 松科二井东孔营城组流纹岩K/Al−Na/Al摩尔比交会图
Fig.7 Plot showing K/Al−Na/Al from Litho Scanner data in SK−2 east borehole

DEN降低（Planke，1994；Bartetzko et al.，2001）。松科二井东孔营城组火山岩序列中发育凝灰岩，伴随着GR增加、RD和DEN降低的测井响应特征，指示着火山喷发间断的存在。

4 流纹岩化学元素特征

徐家围子断陷内流纹岩广泛发育（孟凡超等，2010；姜传金等，2010）。岩性测井识别结果表明，流纹岩是松科二井东孔营城组发育厚度最大的火山岩。分异、同化、混染和蚀变作用使得长英质火山岩的化学成分发生了一定的变化。松辽盆地火山岩经历了长期的热液蚀变作用（孟凡超等，2010）。K/Al−Na/Al的摩尔比交会图有助于理解蚀变类型（Davies and Whitehead, 2006；Davies and Whitehead, 2009；Mauriohooho et al., 2016）。利用新型岩性元素扫描测井得到的岩石的K、Na和Al的百分含量，建立了流纹岩的K/Al−Na/Al的摩尔比交会图（图7）。K/Al比大于0.45指示含钾矿物的增加。将近一半样点的K/Al比大于0.45，表明岩石主要经历了较强的钾化蚀变，泥质蚀变和绢英质蚀变作用较弱。矿物计算结果在流纹岩层段黏土矿物的含量相对较低，与K/Al−Na/Al的摩尔比交会图中反映的弱泥质蚀变作用相对应。

火山岩中，岩系的划分对研究火山岩源区的组成和岩浆的演化过程十分重要。徐家围子断陷流纹岩化学分析结果表明流纹岩多呈现高碱、高硅特征，为地壳部分熔融的产物（孟凡超，2010，2013；刘玮等，2013；程银行等，2016）。松科二井东孔营城组流纹岩多位于钠长石−钾长石线以上，指示流纹岩具有高碱特征。火山岩化学成分受源区成分、熔融温度、压力、挥发分以及熔融程度的影响。松科二井东孔营城组流纹岩具有高碱、高SiO_2和低Fe的特征，为开展流纹岩的成因分析提供一定的支持。

5 有利岩性优选

核磁共振T_2谱反映了岩石内孔径分布特征，大T_2值对应着半径大的孔隙，小T_2值对应着半径小的孔隙（肖立志，1998；何雨丹等，2005；肖亮，2008；肖立志等，2012）。核磁共振测井资料显示，流纹岩T_2谱双峰分布为主，两峰区别明显，第一个峰相对较小，第二个峰为主；凝灰熔岩和集块熔岩T_2谱多为双峰形态，与流纹岩相比，第一个峰的面积增大，且集块熔岩T_2谱第一个峰增大更为明显（图8）。孔喉半径的分布特征与核磁共振T_2谱分布特征有很好的相似性（Coates et al., 2000；赵彦超等，2006；Xiao et al.，2016）。可见，流纹岩的孔径分布相对均匀，大孔隙比例高，孔喉半径偏大，孔隙连通性相对较好，凝灰熔岩次之。密度、中子和声波时差测井主要反映岩石孔隙特性影响。由图6可知，集块熔岩的孔隙度最大，呈现出低密度、高中子和高声波时差的

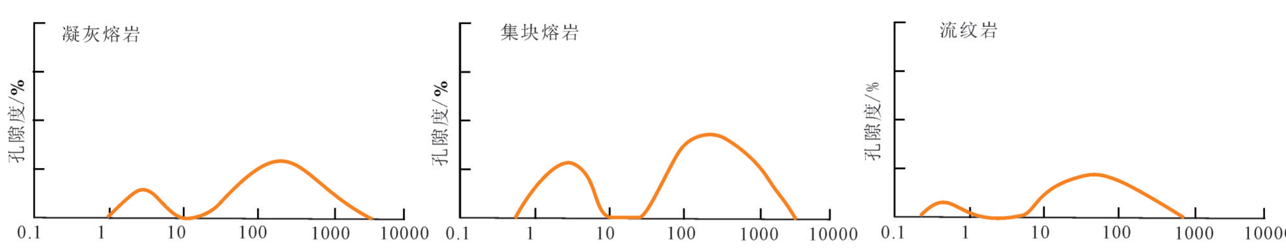

图8 不同岩性的T_2谱形态
Fig.8 The T_2 configurations of volcanic rocks

特征。但T_2谱反映其连通性较差。大孔隙比例高、孔喉尺寸大的流纹岩适合流体的存储和运移,可作为深部流体活动观测和物质实验研究的有利场所。

6 结 论

(1)松科二井东孔营城组凝灰岩具有最强的放射性和导电性,高孔隙度的集块熔岩表现出密度最低的特征,流纹岩的密度最高、导电性最差。从火山熔岩、火山碎屑熔岩到火山碎屑岩,电阻率测井值呈现降低的趋势。流纹岩具有低Fe、高碱和高SiO_2的特征。

(2)根据火山岩物理性质、结构和构造的差别,建立了岩性识别交会图版和成像识别模式,识别出松科二井东孔营城组火山岩以流纹岩、凝灰熔岩和集块熔岩为主,少量的凝灰岩。GR增加、RD和DEN降低的凝灰岩,表明了火山喷发间断的存在。

(3)松科二井东孔营城组流纹岩黏土矿物含量较低,蚀变作用以钾化蚀变为主。T_2谱分析表明,流纹岩的孔径分布相对均匀,大孔隙比例高,孔喉半径偏大,孔隙连通性相对较好,有利于开展深部长期观测和流体实验。

References

Bartetzko A, Pezard P, Goldberg D, Sun Y F, Becker K. 2001. Volcanic stratigraphy of DSDP/ODP Hole 395A: An interpretation using well−logging data [J]. Marine Geophysical Researches, 22: 111−127.

Bartetzko A, Paulick H, Iturrino G, Arnold J. 2003. Facies reconstruction of a hydrothermally altered dacite extrusive sequence: Evidence from geophysical downhole logging data (ODP leg 193) [J]. Geochemistry Geophysics Geosystems, 4(10)：429−432.

Busby C J, Bassett K N. 2007. Volcanic facies architecture of an intra−arc strike−slip basin, Santa Rita Mountains, Southern Arizona [J]. Bull. volcano, 70: 85−103.

Cheng Yinhang, Li Ying, Liu Yongshun, Teng Xuejian, Li Yanfeng, Yang Juanquan, Ao Cong. 2016. The tectonic extensional event during the early Cretaceous in the west margin of Songliao Basin: U−Pb dating, geochemistry and petrogenesis of rhyolites [J]. Acta Geologica Sinica, 90(12)：3492− 3507 (in Chinese with English abstract).

Coates G R, Xiao L Z, Primmer M G. 2000. NMR logging principles and applications [M]. Gulf Publishing Company, Houston, USA, 1−256.

Davies J F, Whitehead R E. 2006. Alkali−alumina and mgo−alumina molar ratios of altered and unaltered rhyolites [J]. Exploration and Mining Geology, 15(1/2): 75−88.

Davies J F, Whitehead R E. 2009. Alkali/alumina molar ratio trends in altered granitoid rocks hosting porphyry and related deposits [J]. Exploration and Mining Geology, 19(1/2): 13−22.

Dai Yaquan, Luo Jinglan, Lin Tong, Yang Zhisheng, Zhang Jun, Liu Shuyuan, Xia Huiping. 2007. Reservoir characteristics and petrogenesis of volcanic rocks in the Yingcehng Formation of the Shengping gas field, northern Songliao basin [J]. Geology in China, 34 (3):528−535 (in Chinese with English abstract).

Ekstrom M P，Dahan C A，Chen M, Lioyd P M, Rossi D J. 1987． Formation imaging with microelectrical scanning arrays[C]// SPWLA 27rd Annual Logging Symposium, 1−21.

He Dian, Li Jianghai, Liu Shoujie, Han Liang. 2008. Discovery of a giant caldera in the Yingcheng Formation in the Xujiaweizi fault depression, northern Songliao basin[J]. Geology in China, 35 (3)：463−471 (in Chinese with English abstract).

He Yudan, Mao Zhiqiang, Xiao Lizhi, Ren Xiaojun. 2005. An improved method of using NMR T2 distribution to evaluate pore size distribution [J]. Chinese Journal of Geophysics, 48(2): 373−378 (in Chinese with English abstract).

Hou Hesheng, Wang Chengshan, Zhang Jiaodong, Ma Feng, Fu Wei, Wang Pujun, Huang Yongjian, Zou Changchun, Gao Yongfeng, Gao Yuan, Zhang Laiming, Yang Jin, Guo Rui. 2018. Deep continental scientific drilling engineering in Songliao Basin: Progress in earth science research [J]. Geology in China, 45 (4)：641−657 (in Chinese with English abstract).

Huang Qinghua, Wu Huaichun, Wan Xiaoqiao, He Huaiyu, Deng Chenglong. 2011. New progress of integrated chronostratigraphy of the Cretaceous in Songliao basin [J]. Journal of Stratigraphy, 35(3): 250−257 (in Chinese with English abstract).

Ikeda R, Kajiwara T, Omura K, Hickman S. 2008. Physical rock properties in and around a conduit zone by well− logging in the Unzen Scientific Drilling Project, Japan [J]. Journal of Volcanlolgy and Geothermal Research, 175: 13−19.

Jiang Chuanjin, Chen Shumin, Chu Lilan, Zhang Guangying, Ju Linbo. 2010. A new understanding about the volcanic distribution characteristics and eruption mechanism of Yingcheng Formation in Xujiaweizi fault depression [J]. Acta Petrologica Sinica, 26(1): 63−72 (in Chinese with English abstract).

Khatchikian A. 1983. Log evaluation of oil−bearing igneous rocks [C]// Corpus Christi，Texas: SPWLA 23rd Annual Logging Symposium, 1−35.

Le Bas M J，Le Maitre R W，Streckeisen A，Zanettin B. 1986. A chemical classification of volcanic rocks based on the Total Alkali−Silica diagram [J]. Journal of Petrology，27(3): 745−750.

Li Ning, Qiao Dexin, Li Qingfeng, Wu Hongliang, Fu Yousheng, Dong Lixin, Feng Qingfu, Wang Kewen. 2009. Theory on logging interpretation of igneous rocks and its application Petroleum [J]. Exploration and Development, 36(6): 683− 692(in Chinese with English abstract).

Liu Juntian, Zhang Daisheng, Huang Weidong, Li Zaiguang, Qin

Xinping, Wei Cheng. 2009. Volcanic rock lithology recognition technique and its application in Malang Depression, Santanghu Basin[J]. Lithologic Reservoirs, 21(4): 87- 91(in Chinese with English abstract).

Liu Wanzhu, Wang Pujun, Men Guangtian, Bian Weihua, Yin Xiuzhen. 2003. Characteristics of deep volcanic reservoirs in Northern Songliao Basin [J]. Oil & Gas Geology, 24(1): 28−31 (in Chinese with English abstract).

Liu Wei, Sun Deyou, Li Rilei, Liu Manli, Wen Shengfu, Zhang Xi, Guo Jun, Wang Tianhao, Wu Pengfei, Liu Xiaoming. 2013. Chronology and petrogenesis of volcanic rocks in Yingcheng Formation from Changling depression in Songliao Basin [J]. Global Geology, 32(2): 522−530 (in Chinese with English abstract).

Mauriohooho K, Barker S L L，Rae A. 2016. Mapping lithology and hydrothermal alteration in geothermal systems using portable X−ray fluorescence (PXRF): A case study from the Tauhara geothermal system, Taupo volcanic zone [J]. Geothermics, 64: 125−134.

Meng Fanchao, Liu Jialin, Li Ming, Liu Xiao, Yin Changhai, Lu Jiamin, Cui Yan. 2010. Geochemistry and tectonic implications of rhyolites from Yingcheng Formation in Xujiaweizi, Songliao Basin [J]. Acta Petrologica Sinica, 26(1): 227- 241 (in Chinese with English abstract).

Meng Fanchao，Lu Yulin，Liu Jiaqi, Cui Yan. 2013. Geochemical characteristics and petrogenesis of two types of acid volcanic rocks from Yingcheng Formation in Songliao Basin [J]. Acta Petrologica Sinica, 29(8): 2731−2745 (in Chinese with English abstract).

Pan Baozhi, Li Zhoubo, Fu Yousheng, Wang Hongjian, Yang Xiaoling, Xu Shumei. 2009. Application of logging data in lithology identification and reservoir evaluation of igneous rock in Songliao Basin[J]. Geophysical Prospecting for Petroleum, 48(1): 48−52 (in Chinese with English abstract).

Paulick H, Breitkreuz C. 2005. The Late Paleozoic felsic lava−dominated large igneous province in northeast Germany: Volcanic facies analysis based on drill cores [J]. International Journal of Earth Sciences, 94: 834−850.

Planke S. 1994. Geophysical response of flood basalts from analysis of wire line logs: Ocean drilling program site 642, Vøring volcanic margin [J]. Journal of Geophysical research, 99: 9279−9296.

Shao Weizhi, Liang Qiaofen, Li Junguo, Deng Lin. 2006. On log response characteristics of igneous reservoir in Huanghua Depression [J]. Well Logging Technology, 30(2): 149- 153 (in Chinese with English abstract).

Sun Yonghong，Zhang Feiyu, Wang Qingyan, Gao Ke. 2016. Application of "Crust 1" 10k ultra−deep scientific drilling rig in Songliao Basin Drilling Project (CCSD- AKII) [J]. Journal of Petroleum Science and Engineering, 145: 222−229.

Waichel B L, de Lima E F, Viana A R, Scherer C M, Bueno G V. 2012. Gabriel dutra stratigraphy and volcanic facies architecture of the Torres Syncline, Southern Brazil, and its role in understanding the Paraná−Etendeka Continental Flood Basalt Province [J]. Journal of Volcanology and Geothermal Research, 215−216: 74−82.

Wang Ling，Jin Jiuqiang，Zhang Yan. 2009. Division of volcanic eruption periods of the first and third members of Yingcheng formation in Xujiaweizi fault depression in Songliao basin [J]. China Petroleum Exploration，14(2)：6- 13(in Chinese with English abstract).

Wang Pujun, Zheng Changqing, Shu Ping, Liu Wanzhu, Huang Yulong, Tang Huafeng, Cheng Rihui. 2007. Classification of deep volcanic rocks in Songliao Basin [J]. Petroleum Geology & Oilfield Development in Daqing, 26(4): 17- 22 (in Chinese with English abstract).

Wang Pujun, Feng Zhiqiang, Liu Wanzhu. 2008. Volcanic Rocks in Petroliferous Basins: Petrograghy, Facies, Riservoir, Pool, Exploration [M]. Beijing: Science Press, 18−34 (in Chinese).

Wang Zehua, Zhu Xiaomin, Sun Zhongchun, Luo Xingping, Dai Xiongjun, Dai Yong. 2015. Lithofacies classification in the basin using logging data: Taking Junggar Basin as an example [J]. Earth Science Frontiers, 22(3): 254- 268 (in Chinese with English abstract).

Wildner W, Lima E F, Nardi L V S, Sommer C A. 2002. Volcanic cycles and setting in the Neoproterozoic III to Ordovician Camaqu ã Basin succession in southern Brazil: Characteristics of post−collisional magmatism [J]. Journal of Volcanology and Geothermal Research, 118: 261−283.

Wildner W L, Nardi V S, De Lima E F. 2010. Post- Collisional alkaline magmatism on the Taquarembó Plateau: A well−reserved Neoproterozoic- Cambrian Plutono- volcanic association in Southern Brazil [J]. International Geology Review, 41: 1082−1098.

Wu Huaichun, Zhang Shihong, Huang Qinghua. 2008. Establishment of floating astronomical time scale for the terrestrial Late Cretaceous Qingshangkou Formation in the Songliao baisn of Northeast China [J]. Earth Science Frontiers, 15(4): 159- 169 (in Chinese with English abstract).

Wu Jie. 2015. Identification of volcanic lithology and reservoir with petrophsical elastic parameters: An example of Yingcheng Formation in Xujiaweizi Fault Depression, North of Songliao Basin [J]. Geological Science and Technology Information, 34(4): 15−19 (in Chinese with English abstract).

Wu Yanxiong, Wang Pujun, Bian Weihua, Gao Youfeng, Lang YuanQiang. 2012. Log responses and its corresponding geological interpretation of deep volcanic reservoir in Songliao Basin [J]. Journal of Jinlin University (Earth Science Edition), 42(6): 1927−1934 (in Chinese with English abstract).

Xiao Liang. 2008. Application of NMR log data to formation pore structure evaluation [J]. Xinjiang Petroleum Geology, 29(2): 260−263 (in Chinese with English abstract).

Xiao Liang, Wang Hua, Zou Changchun, Mao Zhiqiang, Guo

Haopeng. 2016. Improvements on "Application of NMR logs in tight gas reservoirs for formation evaluation: A case study of Sichuan basin in China" [J]. Journal of Petroleum Science Engineering, 138:11−17.

Xiao Lizhi. 1998. NMR Logging and Rock NMR and Its Application [M]. Beijing: Science Press, 56−69 (in Chinese with English abstract).

Xiao Lizhi, Xie Ranhong, Liao Guangzhi. 2012. Theory and Method of NMR Logging in Complicated Hydrocarbon Reservoir of China [M]. Beijing: Science Press,105−136 (in Chinese).

Zhao Yanchao, Chen Shuhui, Guo Zhenhua. 2006. Application of nuclear magnetic resonance technology to pore structure in tight sandstone: A case from Third Member of Shihezi Formation Upper Paleozoic in Daniudi Gas Field, Ordos basin [J]. Geological Science and Technology Information, 25(1): 109−112 (in Chinese with English abstract).

Zhu Yongyi, Wang Wenshi, Zhang Hengchun, Yan Jia, Cao Longlong, Xu Jie, Meng Qinghong, Tan Xiaoli. 2018. Implementation overview of Chinese continental scientific drilling (CCSD) project and technical systems of core boring. [J]. Acta Geologica Sinica, 92 (10): 1971−1984 (in Chinese with English abstract).

Zou Changchun, Xiao Liang, Niu Yixiong, Hou Jie, Peng Cheng. 2016. General design of geophysical logging of the CCSD−SK−2 east borehole in the Songliao Basin of Northeast China [J]. Earth Science Frontiers, 23(3): 279−287 (in Chinese with English abstract).

附中文参考文献

程银行,李影,刘永顺,腾学建,李艳锋,杨俊泉,奥琮. 2016. 松辽盆地西缘早白垩世伸展事件:流纹岩锆石U−Pb年龄、地球化学研究[J]. 地质学报,90(12):3492−3507.

戴亚权,罗静兰,林潼,杨知盛,张军,刘淑云,夏惠萍. 2007. 松辽盆地北部升平气田营城组火山岩储层特征与成岩演化[J]. 中国地质,34(3):528−535.

贺电,李江海,刘守偈,韩亮. 2008. 松辽盆地北部徐家围子断陷营城组大型破火山口的发现[J]. 中国地质,35(3):463−471.

何雨丹,毛志强,肖立志,任小军. 2005. 核磁共振T_2分布评价岩石孔径分布的改进方法[J]. 地球物理学报,48(2): 373−378.

侯贺晟,王成善,张交东,马峰,符伟,王璞珺,黄永建,邹长春,高有峰,高远,张来明,杨瑨,国瑞. 2018. 松辽盆地大陆深部科学钻探地球科学研究进展[J]. 中国地质,45(4):641−657.

黄清华,吴怀春,万晓樵,贺怀宇,邓成龙. 2011. 松辽盆地白垩系综合年代地层学研究新进展[J]. 地层学杂志,35(3):250−257.

姜传金,陈树民,初丽兰,张广颖,鞠林波. 2010. 徐家围子断陷营城组火山岩分布特征及火山喷发机制的新认识[J]. 岩石学报,26(1):63−72.

李宁,乔德新,李庆峰,武宏亮,付有升,董丽欣,冯庆付,王克文. 2009. 火山岩测井解释理论与应用[J]. 石油勘探与开发,36(6):683−692.

刘俊田,张代生,黄卫东,李在光,覃新平,魏成. 2009. 三塘湖盆地马朗凹陷火山岩岩性测井识别技术及应用[J]. 岩性油气藏,221(4):87−91.

刘万洙,王璞珺,门广田,边伟华,尹秀珍,许利群. 2003. 松辽盆地北部深层火山岩储层特征[J]. 石油与天然气地质,24(1):28−31.

刘玮,孙德有,李瑞磊,刘曼丽,温升福,张玺,苟军,王天豪,武鹏飞,柳小明. 2013. 松辽盆地长岭断陷营城组火山岩的时代与岩石成因[J]. 世界地质,32(3):522−532.

孟凡超,刘嘉麟,李明,刘晓,印长海,陆加敏,崔岩. 2010. 松辽盆地徐家围子营城组流纹岩地球化学特征及构造指示意义[J]. 岩石学报,26(1):227−241.

孟凡超,路玉林,刘嘉麒,崔岩. 2013. 松辽盆地营城组两类酸性火山岩地球化学特征与成因[J]. 岩石学报,29(8):2731−2745.

潘保芝,李舟波,付有升,王宏建,杨晓玲,许淑梅. 2009. 测井资料在松辽盆地火成岩岩性识别和储层评价中的应用[J]. 石油物探,48(1):48−52.

邵维志,梁巧峰,李俊国,邓林. 2006. 黄骅凹陷火成岩储层测井响应特征研究[J]. 测井技术,30(2):149−153.

王玲,靳久强,张研. 2009. 松辽盆地徐家围子断陷营城组一、三段火山喷发期次划分及意义[J]. 中国石油勘探,14(2):6−13.

王璞珺,郑长青,舒萍,刘万洙,黄玉龙,唐华风,程日辉. 2007. 松辽盆地深层火山岩岩性分类方案[J]. 大庆石油地质与开发,26(4):17−22.

王璞珺,冯志强,刘万洙. 2008. 盆地火山岩:岩性、岩相、储层、气藏、勘探[M]. 北京:科学出版社,18−34.

王泽华,朱筱敏,孙中春,罗兴平,戴雄军,戴勇. 2015. 测井资料用于盆地中火成岩岩性识别及岩相划分:以准噶尔盆地为例[J]. 地学前缘,22(3):254−268.

吴怀春,张世华,黄清华. 2008. 中国东北松辽盆地晚白垩世青山口组浮动天文年代标尺的建立[J]. 地学前缘,15(4):159−169.

吴杰. 2015. 火山岩岩性、储层的岩石物理弹性参数判别:以松辽盆地北部徐家围子断陷营城组为例[J]. 地质科技情报,34(4):15−19.

吴颜雄,王璞珺,边伟华,高有峰,郎元强. 2012. 松辽盆地深层火山岩储层测井响应特征及地质解译[J]. 吉林大学学报(地球科学版),42(6):1927−1934.

肖亮. 2008. 利用核磁共振测井资料评价储集层孔隙度结构的讨论[J]. 新疆石油地质,29(2): 260−263.

肖立志. 1998. 核磁共振成像测井与岩石核磁共振及其应用[M]. 北京: 科学出版社,56−69.

肖立志,谢然红,廖广志. 2012. 中国复杂油气藏核磁共振测井理论与方法[M]. 北京: 科学出版社,105−136.

赵彦超,陈淑慧,郭振华. 2006. 核磁共振方法在致密砂岩储层孔隙结构中的应用——以鄂尔多斯大牛地气田上古生界石盒子组3段为例[J]. 地质科技情报, 25(1):109−112.

朱永宜,王稳石,张恒春,闫家,曹龙龙,许洁,孟庆鸿,谈晓丽. 2018. 我国大陆科学钻探工程实施概况及其取心钻进技术体系[J]. 地质学报,92(10): 1971−1984.

邹长春,肖亮,牛一雄,侯颉,彭诚. 2016. 松辽盆地科学钻探工程松科二井东孔测井设计[J]. 地学前缘,23(3): 279−287.