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青藏高原如角高温地热系统构造−热耦合成热模式

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提要:【研究目的】地表热异常的形成无外乎两方面原因:异常的热源及异常的热传递方式。"厚壳"与"热壳"共存,是青藏高原高温地热系统与一般汇聚板缘型地热系统的最大差异。部分熔融(热)作为"热壳"中的异常热源,断裂系统(构造)作为"厚壳"中的对流传热通道,清晰刻画两者空间关系,探讨构造−热耦合成热模式,可能是完善"厚壳"与"热壳"共存下青藏高原特色成热理论的重要途径。**【研究方法】**本次研究以萨嘎县如角沸泉为例,运用大地电磁测深、音频大地电磁测深。**【研究结果】**探测断裂系统与部分熔融的空间关系;结合已有地球物理、地热地球化学研究,建立如角沸泉构造−热耦合成热模式;并以断裂系统的交汇处为目标体,布设两口生产井。**【结论】**如角式构造−热耦合成热模式具有普适性,对于完善青藏高原特色成热理论及提高地热勘查成功率具有重要意义。

关 键 词:构造−热耦合成热模式;如角沸泉;高温地热系统;地热成因机制;地热勘查实践;地热地质调查工程;青藏高原

创 新 点:(1)通过综合分析,提出断裂系统(构造)与部分熔融(热)的耦合成热模式研究,是解释"厚壳"与"热壳"共存特征下青藏高原高温地热系统成因的有效途径;(2)多尺度地球物理构建了如角高温地热系统构造−热空间结构,并通过多学科交叉融合,建立了如角构造−热耦合成热模式。

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Structure−thermal coupling model of the high temperature geothermal system in Rujiao on the Xizang Plateau

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Abstract: This paper is the result of geothermal survey engineering.

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[Objective] There are two reasons for the formation of surface thermal anomaly: abnormal heat source and abnormal heat transfer mode. The coexistence of "Thick Crust" and "Hot Crust" is the biggest difference between the high temperature geothermal system on the Xizang Plateau and the common convergent plate margin geothermal system.Partial melting (Hotsource) is an abnormal heat source in the "HotCrust ", and fracture system (Structure) is a convective heat transfer channel in the "Thick Crust ". Clearly depicting the spatial relationship between the two and exploring the structural−thermal coupling model of heat generation may be an important approach to improving the characteristic heat generation theory of the Xizang Plateau under the coexistence of a "Thick crust" and a "Hot crust". **[Methods]** This study takes the Rujiao Boiling Spring in Saga County as an example, and uses magnetotelluric sounding and audio magnetotelluric sounding. **[Results]** To explore the spatial relationship between the fault system and partial melting; we combined with previous studies on geophysics, geochemistry and fluid dynamics, established Rujiao boiling spring structure−thermal couplingthermal model; and set up two production wells with the intersection of the fault system as the target. **[Conclusion]** The Rujiao tectonic−thermal coupled model of heat generation has universal applicability, which is of great significance for improving the formation theory of characteristic heat in the Xizang Plateau and enhancing the success rate of geothermal exploration.

Key words: construct−thermal coupled model; Rujiao boiling spring; geothermal mechanism; geothermal exploration practice; geothermal survey engineering; Tibet Plateau

Highlights: (1) Through comprehensive analysis, it is proposed that the coupling thermal model of fault system and partial melting is an effective way to explain the genesis of high−temperature geothermal system in Xizang Plateau under the co−existence of "Thick crust" and "Hot crust". (2) The structure−thermal spatial relation of Rujiao high−temperature geothermal system is constructed by multi−scale geophysics, and the structure−thermal coupling model of Rujiao high−temperature geothermal system is explored through multidisciplinary integration.

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1 引 言

地热能是一种稳定可靠的清洁能源（蔺文静等，2013）。随着碳达峰、碳中和“双碳目标”的提出，进行能源结构调整，发展低碳能源势在必行（Wang et al., 2021a）。中国地热资源开发利用，呈现地热发电（多吉等, 2007）、温泉开发（郭镜和夏时斌, 2022）、浅层地温能利用（蔺文静等, 2013）、干热岩开发利用（Zhang et al., 2022）等多点开花的良好态势。青藏高原有丰富的地热资源，特别是羊八井地热田的开发利用，为西藏电力发展做出重要贡献（多吉等，2007）。但自羊八井装机容量达25.18 MW后，西藏地热发电进展缓慢（廖志杰和吴方之，2010）。鉴于西藏800 MW的发电潜力（王绍亭和陈新民, 1999），以及羊八井开发过程中出现的地热田资源枯竭、回灌率不足、环境污染等问题，说明西藏地热发电潜力与问题并存。

探明青藏高原高温地热成因机制，是发挥“潜力”与解决“问题”的先决条件。青藏高原高温地热系统的形成机制还存在众多分歧。根据大地构造背景及前人地热成因机制研究，梳理青藏高原高温地热系统的特色成热背景：(1)“厚壳”与“热壳”共存（沈显杰等,1990），是青藏高原高温地热系统与一般汇聚板缘型地热系统的最大差异；(2)中下地壳广泛存在部分熔融（Brown et al., 1996; Nelson et al., 1996; Wei et al., 2001），是“热壳”的“源”（李振清，2002）。(3)热泉严格受断裂构造控制（张朝锋等，2018）。

地表热异常的形成原因无外乎两方面：异常的热源及异常的热传递方式（Egbert et al., 2021）。“热

壳”是地热异常形成的有利因素,但“厚壳”却是热传导的不利因素。我们在讨论地热成因时往往更关注热源,而对热传递方式研究不够。实际上,全世界75%的高温地热发电系统位于断裂构造复杂区(Curewitz and Karson,1997)。断裂构造之于高温地热系统的重要意义在于,其极高的渗透率利于深部热流体向浅部运移(郭镜和夏时斌,2021),以对流方式进行热传递(Bibby et al.,1995)。也就是说,相较于热源,断裂系统形成的高效热对流,对于高温地热系统的形成同样重要(Egbert et al., 2021)。

那么,阐明断裂系统使“热壳”深部的热穿透“厚壳”,在地表形成高温热异常的成热过程,是解释青藏高原高温地热系统形成机制的关键。根据上述分析,本次研究以如角高温地热系统为例,通过大地电磁及音频大地电磁,探测断裂系统与部分熔融的空间关系,探讨构造-热耦合成热模式,深化地热成因研究,指导地热勘查实践。

2 地热地质背景

2.1 青藏高原地热地质背景

青藏高原位于特提斯汇聚板缘型地热域(何治亮等,2017),有着中国陆内最大规模的地热异常,地热显示点664处(白嘉启等,2006),其中高温地热显示57处(张朝锋等,2018;图1)。地热类型多样,包括水热爆炸、间歇喷泉、高温沸泉等,泉华、水热蚀变岩发育(佟伟等,1978)。

2.1.1 热源

印度-欧亚陆陆碰撞形成青藏高原巨厚地壳(Beck et al., 1995; Searle et al., 1999; 侯增谦等,2006;许志琴等,2006;Zhao et al., 2021),用地幔传热可能很难解释青藏高原高温地热成因(沈显杰等,1990)。自1981年中法合作对羊八井—洛扎地区开展大地电磁测深,至INDEPTH计划探测青藏高原深部结构,发现中下地壳存在“低速高导体”(Brown et al., 1996; Nelson et al., 1996; Wei et al., 2001),一般认为是部分熔融体(Beaumont et al., 2001)或富水流体(Makovsky and Klemperer, 1999)。利用低速高导体反映的部分熔融体深度、规模、黏度等参数,进行数值模拟得出的“Channel flow”模式(Beaumont et al., 2001,2004;Jamieson et al., 2004,2006),能解释喜马拉雅造山过程中众多地质事件的形成机制(张进江等, 2013),说明低速高导体可能是中下地壳部分熔融层。通过对现在热泉气体的He同位素组成和热泉的地球化学特征研究表明,该低速高导体的性质为硅酸盐岩浆熔体,可能不是以水为主的流体,为部分熔融层的存在提供了佐证(李振清等, 2005)。通过喜马拉雅地表热流值、地热梯度、岩石物性等推断,地壳深部15 km处温度可达650℃,达到了湿花岗岩的熔融温度(赵文津等,2001)。虽然不能从理论上完全排除低速高导体是富水流体,但根据其他地质现象推断,其是部分熔融体的可能性较大。部分熔融体可能是青藏高原一种普遍存在的热源(李振清,2002; 李振清等,2005)。

2.1.2 流体来源

西藏地热水的氢氧同位素特征位于大气降水线附近,说明大气水是地热水的主要补给来源(王思琪,2017)。利用碳同位素初步判断羊八井地热水中的碳起源于念青唐古拉杂岩体的变质作用(赵平等,2002)。西藏古泉华和现代地热水中多富含硼(Tong and Zhang,1981;陈克造等,1981;于昇松和唐渊,1981;郑绵平等,1983;吴俐俐等,1984),随着硼同位素分析技术的发展(Spivack and Edmond, 1986; Aggarwal et al.,2003;吕苑苑等,2008),近年来在西藏地热水示踪中发挥了重要作用(吕苑苑等,2008,2012;刘明亮,2018)。如西藏地热区热水 δ^{11}B-B 二元混合关系表明,海相碳酸盐岩和富B的岩浆岩是西藏热水硼的主要来源(吕苑苑等,2014)。因此,大气水为西藏地热水的主要补给来源,同时有岩浆热液及地层建造水的加入。

2.1.3 流体运移通道

水热活动沿雅鲁藏布江缝合带两侧“东西成串”分布,同时在南北向裂谷中“南北成带”分布,从区域尺度上说明东西向及南北向大型断裂严格控制着青藏高原的地热分布(张朝锋等,2018)。众多地热显示多位于不同方向断裂的交汇部位(李振清,2002),从地热田尺度上说明地热异常严格受断裂控制。因此,青藏高原广泛分布的东西南北交错断裂系统(图1),可能是地热流体迁移的有利通道。

2.2 如角沸泉地热地质特征

西藏萨嘎县如角沸泉地热系统位于雅鲁藏布江北侧冈底斯弧岩浆带(图1),距如角乡约40 km。沸泉出露于北北东向与北西向断裂的交汇部位(图

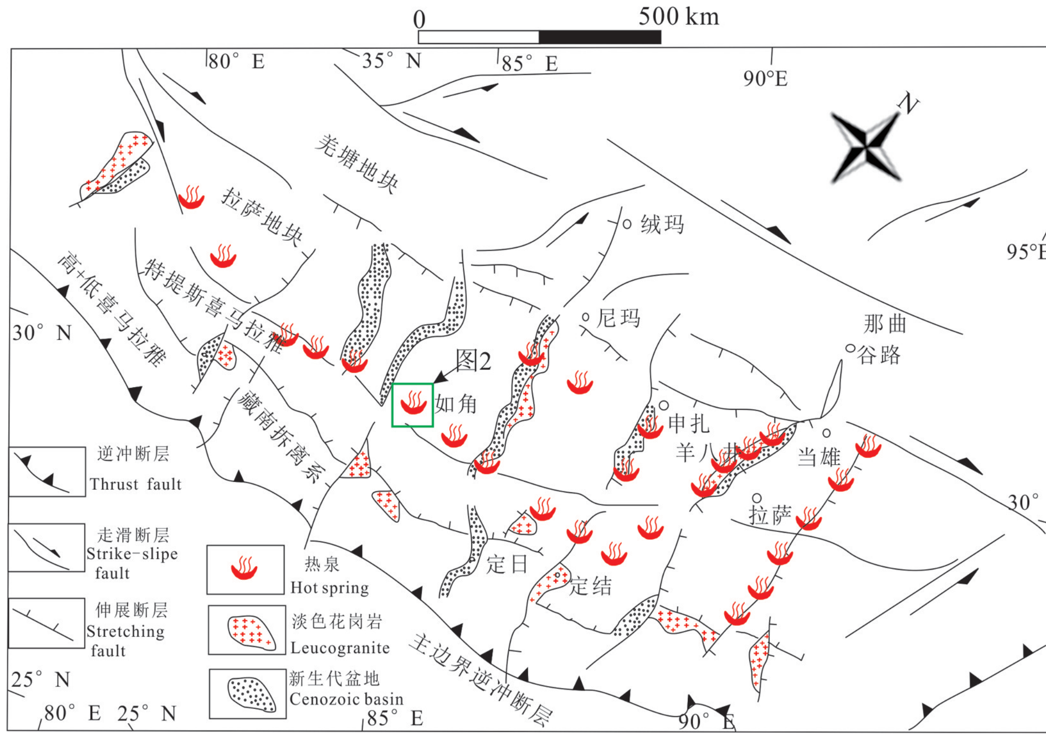

图1 青藏高原大地构造及高温热泉分布简图(底图据张进江等,2007)
Fig.1 Geotectonics and distribution diagram of high-temperature hot springs on the Xizang Plateau (base map after Zhang Jinjiang et al., 2007)

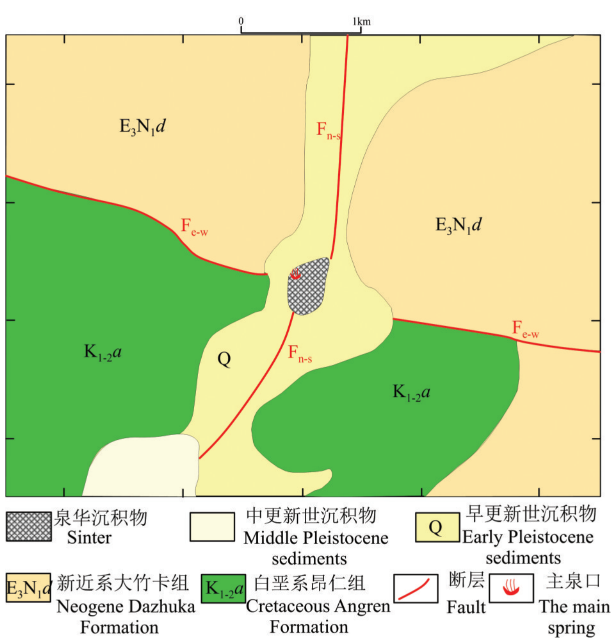

图2 西藏萨嘎县如角沸泉地质简图(据西藏地热队,2021❶)
Fig.2 Geological sketch of Rujiao boiling spring, Saga County, Xizang (after geothermal Team of Xizang Geological Survey Bureau, 2021❶)

2)。水热蚀变区约0.8 km²,出露大小温泉9个,天然流量约900 m³/d,主泉口温度81~83℃,利用SiO_2地球化学温标估算浅层热储温度为150.7℃,利用Na-K地球化学温标估算深部热储温度为205.2℃,具有较好的地热发电前景;水化学类型为$HCO_3\cdot Cl-Na$型水,可溶性总固体为2094 mg/L,pH值为7.5,硼(HBO_2:263.6 mg/L)及砷(As:6.27 mg/L)含量偏高(西藏地热队,2021❶)。

3 方　法

音频大地电磁(AMT)及大地电磁(MT)数据采用加拿大凤凰公司研制的V5系列仪器采集。AMT用于3 km以内的深部空间结构探测;MT用于30 km以内的深部空间结构探测。AMT数据处理时最低频率截取到1 Hz,MT数据处理时最低频率截取到0.01~0.0034 Hz。由于测区位于西藏农牧区,无明显干扰源,因而各测点数据质量高。AMT及MT数据处理与二维反演的相关算法、技术成熟,数据处理包括极化模式判别、静态校正(王家映,1992)

等,二维反演解释有快速松弛(RRI)(Smith and Booker, 1991)、OCCAM(Constable et al.,1987)和共轭梯度反演(Rodi and MacKie, 2001)等方法。本次研究运用Zongmt软件中的Smoothnessconstrained对数据进行二维反演。

4 结 果

4.1 如角高温地热系统的构造-热空间格架

如角沸泉东向90 km处的吉隆—措勤大地电磁测深剖面(图3a),显示深部存在大规模部分熔融体(魏文博等,2009)。据此,推测如角沸泉深部可能存在部分熔融。通过实施大地电磁测深剖面M_1(点距500~2000 m不等),解译两条深大断裂$F_Ⅰ$、$F_Ⅱ$,组成类似地堑式构造,可能是后碰撞伸展期南北向伸展作用的地质响应(图3b)。且断裂$F_Ⅰ$深度延伸较大,可能是来自部分熔融的岩浆热液向浅部运移的良好通道。$F_Ⅱ$处于地势较高区域,可能是大气水下渗的有利通道。通过布设近南北向音频大地电磁测深剖面SN_1(点距50~200 m不等),探测近东西向断裂,共解译4条断裂F_1、F_2、F_3、F_4(图3c)。4条断裂组成两组地堑式构造,从不同尺度说明伸展作用形成的地堑式构造在如角深部是普遍存在的。热泉与断裂F_2、F_3直接相关,但断裂F_1、F_4也是地热水运移不可或缺的组成部分。

根据如角沸泉出露于近南北及近东西向断裂交汇部位的实际现象,笔者推测不同方向的断裂组成相互连通的断裂网络是地热流体运移的必要条件。据此,布设两条近东西向音频大地电磁测深剖面,探测南北向的流体运移通道,并把南北向与东西向断裂在深部的交汇部位作为地热井实施的目标体。EW_2剖面(点距50~100 m不等)解译断裂F_5,EW_8剖面(点距50~100 m不等)解译断裂F_6及F_3(图3d)。EW2布设于断裂带F_1中,F_5既是南北及东西断裂的交汇部位。EW_8剖面中解译的F_3即为SN_1剖面中的F_3(图3e)。据此,布设400 m的地热井,生产井1及生产井2。

综上,本文在前人研究基础上,通过大地电磁测深与音频大地电磁测深,刻画了大气降水-部分熔融-地热田之间多尺度的流体运移通道,具象化了如角地热系统构造-热空间结构,并布设2口地热井。

4.2 如角高温地热系统构造-热耦合成热模式

如角地热水中硼(HBO_2)含量高达263.6 mg/L,为富硼地热水(西藏地热队,2021[1])。一般认为富硼地热水与壳内岩浆活动有关(佟伟等,1978)。喜马拉雅普遍存在富硼淡色花岗岩,且淡色花岗岩可能源自部分熔融(Zeng et al., 2011; 张进江等, 2013)。B易于在残余岩浆流体或其共存的气液相中富集的特性(吴俐俐等, 1984),说明部分熔融是富硼流体的硼源。结合多尺度的流体运移通道空间特征,建立如角地热系统的构造-热耦合成热模式(图4):部分熔融是如角沸泉的热源,且提供地热水中的岩浆流体组分;$F_Ⅰ$断裂为岩浆流体向上运移的重要通道,$F_Ⅱ$断裂为大气水下渗循环的重要通道,不同尺度的地堑式断裂系统组成了如角地热水的循环通道;南北向断裂起到连通东西向断裂$F_Ⅰ$与$F_Ⅱ$的作用,形成相互连通的断裂网络,利于地热流体长距离运移。

5 讨 论

5.1 如角式构造-热耦合成热模式的大地构造基础

印度-欧亚陆陆碰撞形成的青藏高原加厚地壳(Beck et al., 1995; Searle et al., 1999; 侯增谦等, 2006; 许志琴等, 2006),基本排除了地幔热异常对青藏高原高温地热系统的主导作用(沈显杰等, 1990)。地球物理发现青藏高原中下地壳存在部分熔融(Brown et al., 1996; Nelson et al., 1996; Wei et al., 2001),其有空间上大规模存在(魏文博等, 2009)及时间上持续发生的性质(Lee and Whitehouse, 2007; 张进江等, 2013);早期向南逆冲推覆和后期继承早期逆冲推覆构造面向北伸展拆离形成的东西向断裂(Hodges, 2000),及后期东西向伸展形成的南北向裂谷(Yin et al., 1999; Blisniuket al., 2001; Williams et al., 2001),交错形成断裂网络(图1),在不同的构造应力作用下,一直处于活动状态,有利于地热流体的迁移。空间上大规模存在、时间上持续发生的部分熔融与空间上广泛分布、时间上多期活动的断裂系统,为如角式构造-热耦合成热模式提供了大地构造基础。

5.2 青藏高原众多高温地热系统普遍有岩浆热液贡献

岩浆流体对地热水及其溶解组分的定量贡献,一直是地下水科学及相关学科最具挑战性的研究领域之一。通过C-H-O-S-B等多种同位素测试

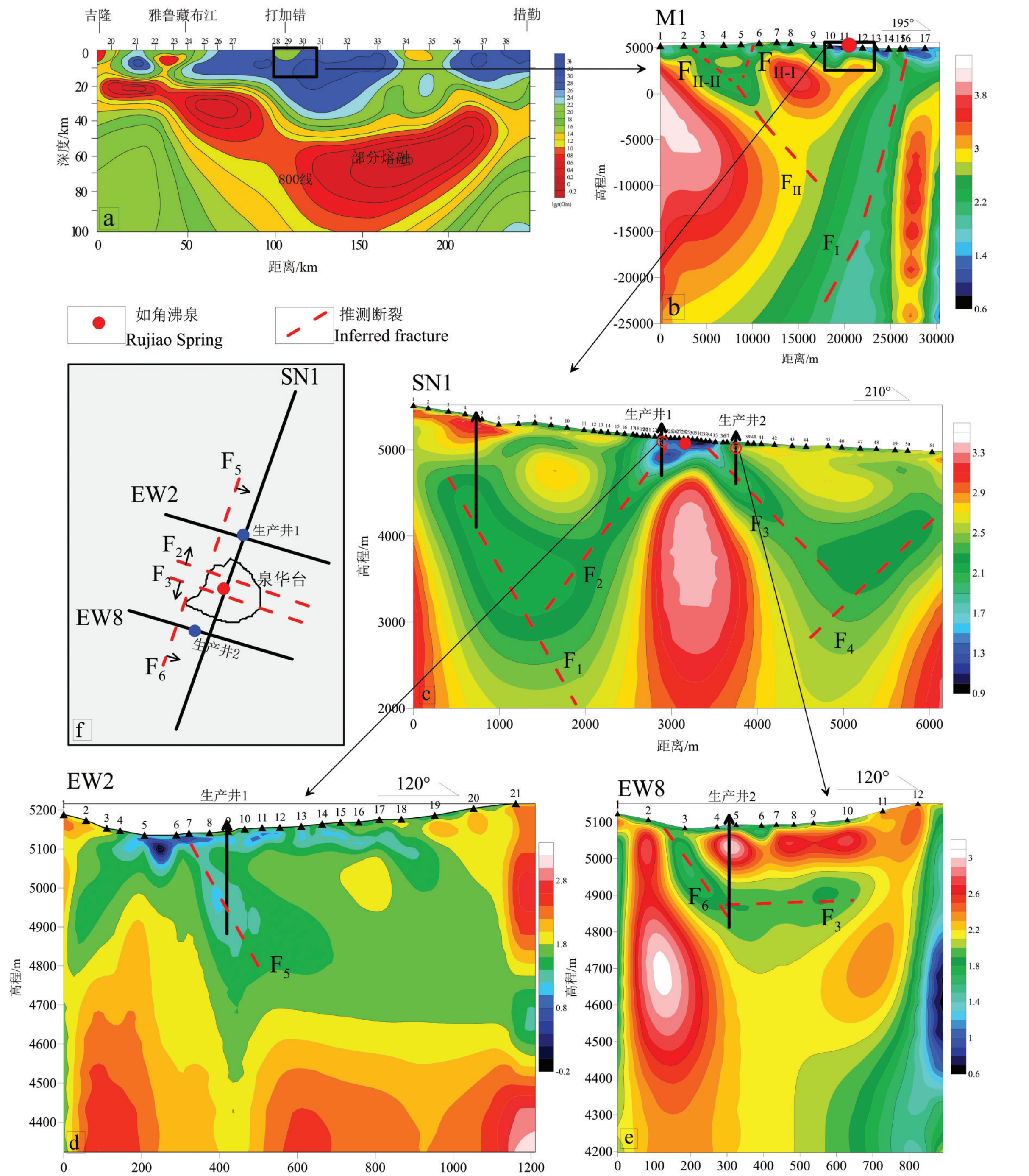

图3 多尺度大地电磁探测如角地热系统流体运移通道

a—吉隆—措勤大地电磁测深剖面(据魏文博等,2009);b—如角地热系统近南北向大地电磁测深剖面;c—如角地热系统近南北向音频大地电磁测深剖面SN1;d—如角地热系统近东西向音频大地电磁测深剖面EW2;e—如角地热系统近东西向音频大地电磁测深剖面EW8;f—如角地热系统音频大地电磁测深剖面相对位置及解译断裂平面展布图

Fig.3 Characterization of fluid migration channels in Rujiao geothermal system by multi−scale magnetotelluric exploration

a−Jilong−Cuoqin magnetotelluric sounding profile (after Wei Wenbo et al., 2009); b−Near S−N magnetotelluric sounding profile of Rujiao geothermal system; c−SN1 near S−N audio magnetotelluric sounding profile of Rujiao geothermal system; d−Near W−E audio magnetotelluric sounding profile EW2 of Rujiao Geothermal system; e−Near W−E audio magnetotelluric sounding profile EW8 of Rujiao Geothermal system; f−The relative position map ofthe audio magnetotelluric sounding profile and thefault plane in the Rujiao geothermal system

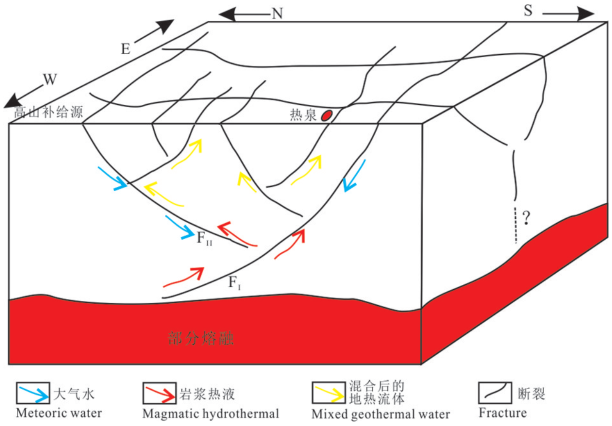

图4 如角高温地热系统构造-热耦合成热模式
Fig.4 Tectonic-thermal coupling model of Rujiao geothermal system

并与Li、Rb、Cs、B等特征元素进行综合分析,正在成为西藏地热水示踪的重要手段(刘明亮,2018)。如根据地热水中氧同位素漂移研究,发现扎西康温泉有约20%的岩浆水贡献(Wang et al., 2021b);卡乌、曲参岗、查巴曲珍、古堆、羊八井、羊易等热泉,以显著富集B、Li、As等元素为特征,可能与岩浆热液有关(Yuan et al., 2014; 许鹏等,2018)。因此,青藏高原众多高温温泉有着岩浆热液贡献,为如角式构造-热耦合成热模式提供物质基础。

5.3 如角式构造-热耦合成热模式流体动力学探讨

一般认为部分熔融为"热异常",其热驱流体运移(候增谦等,2006;梁维,2014)。但仔细思考会发现,部分熔融只是岩石状态的改变,其未向上侵位就不会产生温差,也就不存在热驱流体运移。那么,部分熔融的岩浆热液,如何被驱动至地表?

印度—欧亚陆陆碰撞,引起地壳增厚,产生部分熔融,南北向逆冲或伸展过程中形成断裂F_I。F_I断裂深达流体压力转换带以下的部分熔融(图5a),其每次活动与地层产生ΔP_1的压力差。根据部分熔融体在深部>15 km处,可知这是一巨大的流体驱动力。而断裂活动的抽吸作用产生压力差ΔP_2,是岩浆热液与熔体解耦的主要动力(图5b)。解耦的岩浆热液与地层水,沿F_I向浅部运移与沿F_{II}向下循环的大气水混合,形成如角地热水。ΔP_1作为整个渗流系统的源动力,ΔP_2作为岩浆热液解耦、大气水下渗、地层水混入的抽吸动力,两者与密度差造成的驱动力耦合组成了地热流体产生、混合、运移的动力系统。也就是说,部分熔融与其说为"热源",其更应该被称为高温岩浆热液的"物源",构造活动产生的压力差是岩浆热液向上运移的源动力。这为如角式构造-热耦合成热模式

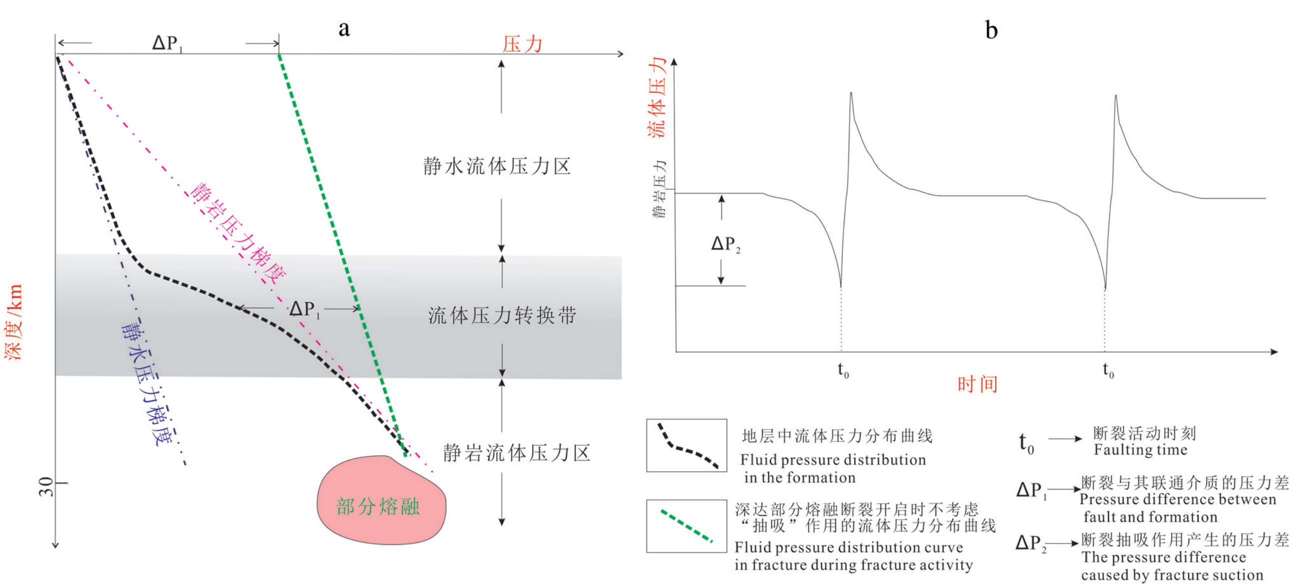

图5 如角地热系统流体动力学分析
a—断裂与其连通介质的流体压力变化示意图(据Cox, 2005修改);b—断裂"抽吸"作用的流体压力变化示意图
Fig.5 Fluid dynamics analysis of Rujiao geothermal system
a-Schematic diagram of fluid pressure variation between fault and formation (modified from Cox, 2005); b-Schematic diagram of fluid pressure variation during fracture "pumping"

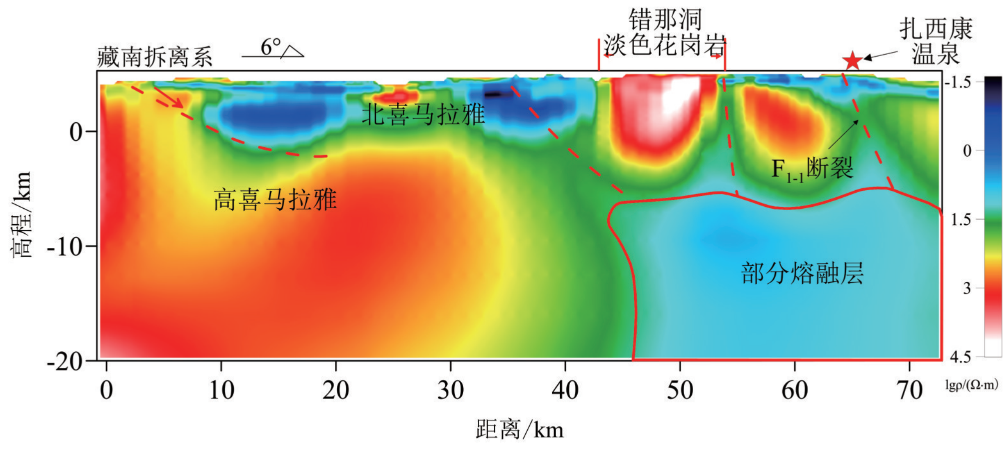

图6 穿过扎西康温泉的南北向大地电磁测深剖面(据Guo et al., 2019修改)
Fig.6 The north−south MT profile across Zhaxikang hot spring (modified from Guo et al., 2019)

提供了流体动力学基础。

5.4 如角式构造−热耦合成热模式是青藏高原普遍存在的一种地热成因机制

深大断裂连通部分熔融的成热模式,在青藏高原是否普遍存在? 自南向北点距1 km左右、长约72 km的大地电磁测深剖面(图6),揭示了北喜马拉雅扎西康温泉(43~69℃, Wang et al., 2021b)构造−热的空间关系。其一,北喜马拉雅及扎西康温泉深部15~20 km处存在低电阻率的部分熔融层(图6)。与前人发现藏南15~20 km深处存在低速高导体的研究结果一致(Brown et al., 1996; Nelson et al., 1996; Wei et al., 2001)。其二,北倾的东西向断裂F_{1-1}连通了部分熔融层和扎西康温泉(图6),是深部岩浆热液向上运移的有利通道。作为青藏高原为数不多点距1~2 km的两条大地电磁剖面,发现北喜马拉雅扎西康地热系统及拉萨地块如角地热系统具有相似的构造−热空间关系,说明如角式构造−热耦合成热模式可能在整个青藏高原具有普适性。

综上,如角式构造−热耦合成热模式,为解释青藏高原高温地热系统"厚壳"与"热壳"共存的矛盾提供了启示。本文对该模式的大地构造基础、物质基础、流体动力学基础及普适性进行了详尽讨论。

6 结 论

通过多尺度的大地电磁测深、音频大地电磁测深方法,较完整刻画了如角高温地热系统构造−热空间格架;结合构造背景、地热地球化学,提出了如角构造−热耦合成热模式;以东西及南北向断裂深部交汇处为勘查目标体,布设两口生产井;探讨了如角式构造−热耦合成热模式的大地构造基础、物质基础、流体动力学基础及其在青藏高原高温地热系统的普适性;对于完善青藏高原高温地热成热理论,提高地热资源勘查效率具有重要意义。

注释

❶西藏地热队. 2021. 西藏自治区萨嘎县如角沸泉高温地热资源预可行性勘查评价[R].

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