

doi: 10.12029/gc20190504

陈宣华, 邵兆刚, 熊小松, 高锐, 刘雪军, 王财富, 李冰, 王增振, 张义平. 2019. 祁连造山带断裂构造体系、深部结构与构造演化[J]. 中国地质, 46(5):995–1020.

Chen Xuanhua, Shao Zhaogang, Xiong Xiaosong, Gao Rui, Liu Xuejun, Wang Caifu, Li Bing, Wang Zengzhen, Zhang Yiping. 2019. Fault system, deep structure and tectonic evolution of the Qilian Orogenic Belt, Northwest China[J]. *Geology in China*, 46(5): 995–1020(in Chinese with English abstract).

祁连造山带断裂构造体系、深部结构与构造演化

陈宣华¹, 邵兆刚¹, 熊小松¹, 高锐², 刘雪军³, 王财富³, 李冰¹, 王增振¹, 张义平¹

(1. 中国地质调查局-中国地质科学院地球深部探测中心, 北京 100037; 2. 中国地质科学院地质研究所, 北京 100037;
3. 中国石油集团东方地球物理勘探有限责任公司综合物化探处, 河北 涿州 072751)

摘要:祁连造山带处在特提斯构造域的北缘, 经历了早古生代原特提斯洋发育以来的构造演化, 是青藏高原东北缘高原隆升与扩展的关键构造带。本文依据区域地质调查与构造地质填图, 结合前人地球物理场资料, 阐述了中国西北和祁连造山带断裂构造体系特征。通过超宽频大地电磁测深(MT)剖面数据采集处理, 以及浅、中—深层电性剖面反演与构造解释, 分析了祁连造山带全地壳深部结构特征与盆山耦合关系, 揭示了原特提斯洋构造域北祁连洋板块向南和向北进行双向俯冲的化石俯冲带深部结构特征; 俯冲消减的北祁连洋板块的宽度约在 600 km 以上。其中, 北祁连洋向南在柴达木—祁连地块之下的俯冲作用角度较缓, 俯冲带向南延伸的距离较远, 其俯冲断离的板片可以达到现今柴达木盆地的北缘; 北祁连洋向北的俯冲作用产状较陡, 其俯冲断离的板片具有向南陡倾的产状倒转特征, 可能与中生代以来、特别是印度—亚洲大陆碰撞的远程效应引起的挤压构造变形有关。大地电磁测深剖面的浅层反演与构造解释, 验证了祁连山北缘断裂以北发育的榆木山逆冲推覆构造, 榆木山构成飞来峰构造, 将早白垩世酒泉盆地的一个分支掩盖在外来的逆冲推覆体之下; 飞来峰之下具有油气勘查前景。根据早白垩世晚期普遍发育的伸展作用, 限定榆木山逆冲推覆构造发育的时间在早白垩世早期, 从而提供了青藏高原北缘早白垩世早期高原隆升与扩展的证据。综合前人资料和本研究成果, 建立了祁连造山带自新元古代以来的构造演化概念模型。

关键词:祁连山; 断裂构造体系; 超宽频大地电磁测深; 深部结构; 逆冲推覆构造; 构造演化; 深部地质调查工程
中图分类号: P542.3 文献标志码: A 文章编号: 1000-3657(2019)05-0995-26

Fault system, deep structure and tectonic evolution of the Qilian Orogenic Belt, Northwest China

CHEN Xuanhua¹, SHAO Zhaogang¹, XIONG Xiaosong¹, GAO Rui², LIU Xuejun³, WANG Caifu³,
LI Bing¹, WANG Zengzhen¹, ZHANG Yiping¹

(1. SinoProbe Center, Chinese Academy of Geological Sciences and China Geological Survey, Beijing 100037, China; 2. Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China; 3. Department of Geophysical and Geochemical Exploration, BGP INC., China National Petroleum Corporation, Zhuozhou 072751, Hebei, China)

Abstract: The Qilian Orogenic Belt (QLOB), located on the northern margin of the Tethyan tectonic domain, suffered from the

收稿日期: 2019-08-21; 改回日期: 2019-09-23

基金项目: 中国地质调查局公益性基础地质调查项目“祁连—天山及周缘盆地结合带深部地质调查”(DD20160083)资助。

作者简介: 陈宣华, 男, 1967年生, 博士, 研究员, 博士生导师, 主要从事构造地质学、深地探测与深地科学研究; E-mail: xhchen@cags.ac.cn。

development and evolution of the Early Paleozoic Proto-Tethyan Ocean (i.e., the North Qilian Ocean, NQO), and was the key orogenic belt for the uplift and expansion of the Tibetan Plateau on its northeastern margin. Based on regional geological survey and structure geological mapping and combined with previous geophysical data and newly completed super-broadband magnetotelluric (MT) sounding, this paper expounds the characteristics of the fault system in Northwest China and the QLOB. Through super-broadband MT data acquisition, processing, and inversion, and structural interpretation of shallow, medium and deep electrical structures along the MT profile across the QLOB, the distribution of Mesozoic and Cenozoic basins related to the fault system, and the deep crustal structure underneath the QLOB are analyzed. The deep electrical structure of the QLOB reveals a fossil bi-directional subduction of the NQO plate in the Proto-Tethyan tectonic domain. According to deep electrical structure, the original width of the subducted North Qilian Ocean plate was over 600 km. The southward subducted NQO plate probably reached the north margin of the Qaidam Block (the present Qaidam Basin) in the south, with a gentle subduction angle underneath the Central and South Qilian Block. Then, the melting-broken plate (or slab) might have migrated downward to the depth. In the north, the subducted NQO plate probably reached the southern margin of the Yin'e Basin of the present position, with a steep subduction angle. The dumpling melting-broken NQO plate was separated from the crustal retention plate in the north, through the northward extrusion of the upper mantle. The authors hold that the folding deformation of the subducted ocean plate was probably caused by the compressional tectonics in the Mesozoic and the Cenozoic, especially during the Late Cimmerian orogeny of Early Cretaceous and the India-Asian continental collision in Neogene. The shallow part of the electrical structure proves that the Yumushan thrust-*nappe* structure was developed northward to the North Qilian Fault, with the Yumushan as a *klippe* in the north. The concealed Early Cretaceous basin underneath the *klippe* should be a good area for oil and gas prospecting. According to the normal faulting developed in the Early Cretaceous, the authors constrain the main stage thrusting of the North Qilian Fault in the Early Cretaceous, which might provide the evidence for the uplift and expansion of the northern margin of the Tibetan Plateau in the Early Cretaceous. Based on combined data from previous researches and this study, the authors put forward a conceptual tectonic evolution model for the Qilian Orogenic Belt.

Key words: Qilian Mountain; fault system; super-broadband MT sounding; deep structure; thrust; tectonic evolution; deep geological survey engineering

About the first author: CHEN Xuanhua, male, born in 1967, doctor, professor, majors in structural geology, deep exploration and deep earth science; E-mail: xhchen@cags.ac.cn.

Fund support: Supported by China Geological Survey Program (No. DD20160083).

1 引 言

祁连造山带地处青藏高原东北缘(图1),是中国中央造山带或秦祁昆造山系的重要组成部分(杨经绥等,2010;潘桂棠和肖庆辉,2015)。祁连造山带是特提斯构造域最北部典型的增生型造山带,由北祁连造山带、中祁连地块和南祁连造山带等组成(陈宣华等,2010,2017)。祁连造山带经历了多期构造变形和复合造山过程,包括中元古代罗迪尼亚(Rodinia)超大陆的裂解(~1.5 Ga; Wang et al., 2016),新元古代大洋俯冲、大陆碰撞与裂解(杨经绥等,2009;夏林圻等,2016;Wu et al., 2016;Zuza et al., 2017),早古生代原特提斯洋(北祁连洋)弧盆系的形成演化与大洋俯冲、大陆俯冲和碰撞造山(杨经绥等,2009,2010;Song et al., 2014;潘桂棠和肖庆

辉,2015;夏林圻等,2016;Wu et al., 2016),晚古生代碰撞造山后的伸展垮塌(孙廷贵等,2004;吴才来等,2004;杨超等,2010)、大陆裂解与宗务隆有限洋盆的形成演化(郝国杰等,2004;孙娇鹏等,2014),中生代陆内伸展(Chen et al., 2003;李奋其,2003;陈宣华等,2010)和新生代陆内造山(Wu et al., 2016, 2017;Zuza et al., 2016, 2017;Li et al., 2019)等过程,在印度-亚洲大陆碰撞和青藏高原新生代造山过程中起着重要的作用(Yin and Harrison, 2000;Yin, 2010;Zheng et al., 2013a, b;Li et al., 2015;Zhang et al., 2017;Zuza et al., 2017, 2019;Wu et al., 2019),具有复杂造山带地壳结构和深部过程(Wang et al., 2011;Gao et al., 2013;赵文津等,2014;Ye et al., 2015, 2016;陈宣华等,2019a)。

前人在祁连造山带及周缘测制了多条大地电

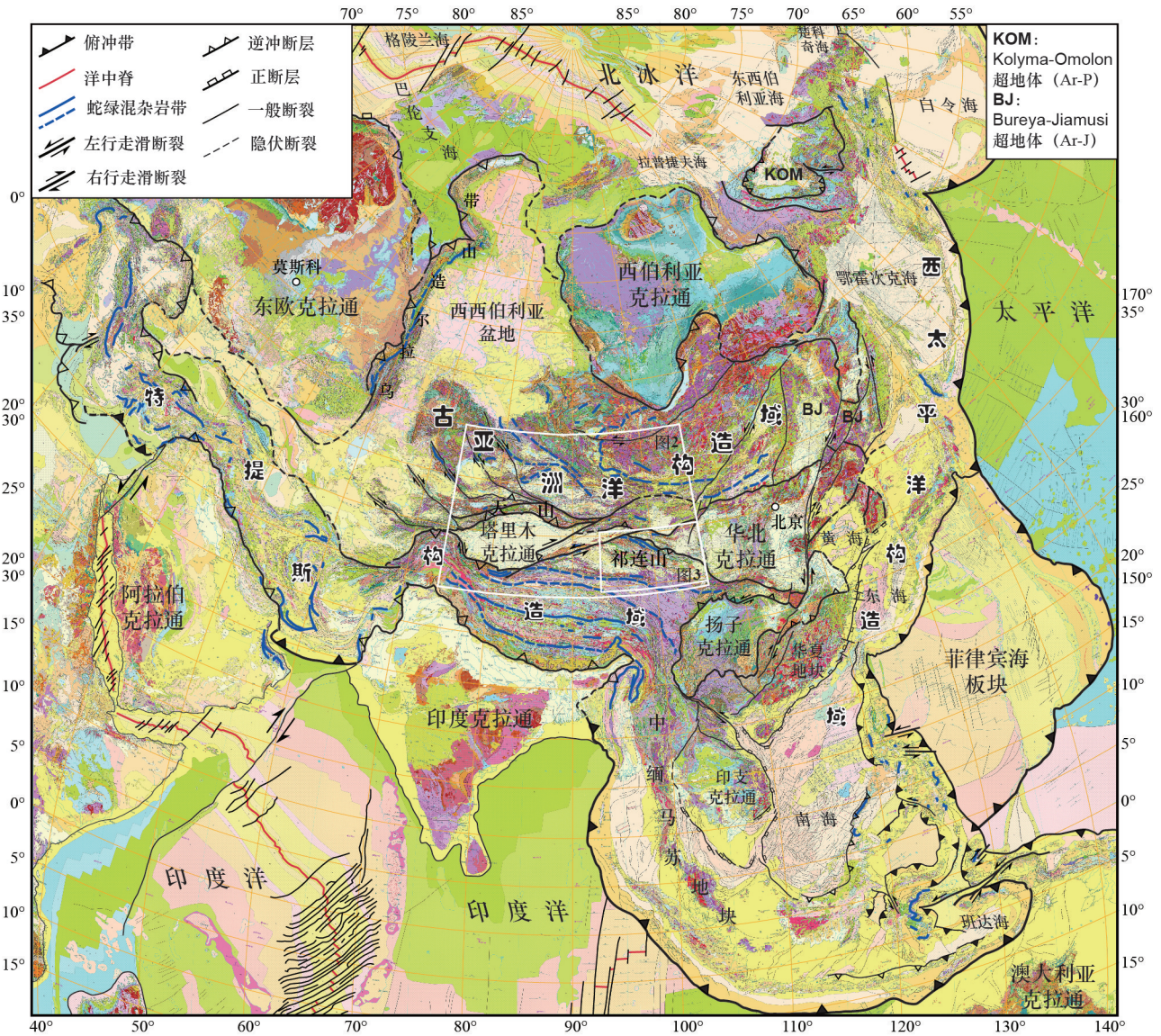


图1 亚洲构造简图(据任纪舜等,2013;陈宣华等,2017,2019b简化修改)

图中给出古亚洲洋构造域、西太平洋构造域和特提斯构造域的大致范围、主要克拉通和一些主要的大型断裂,以及图2和图3的位置

Fig.1 Sketch tectonic map of Asia (modified from Ren Jishun et al., 2013; Chen Xuanhua et al., 2017, 2019b)

The map shows general ranges of the Paleo-Asian Ocean, the Western Pacific and the Tethyan tectonic domains, the main cratons and some major large-scale faults, as well as the locations of Fig. 2 and Fig.3

磁测深剖面,包括格尔木—额济纳旗地学断面给出的电性结构,为研究祁连山带岩石圈电性结构与构造演化提供了重要的科学依据(高锐等,1995;朱仁学和胡祥云,1995;汤吉等,2005;詹艳等,2008;赵国泽等,2010;Xiao et al., 2011, 2012, 2013, 2015, 2016)。本文在中国地质调查局深部地质调查工程支持下(吕庆田等,2019),依据区域地质调查与构造地质填图,结合前人地球物理场资料,通过超宽频大地电磁测深(MT)剖面数据采集处理与浅、深层反演

剖面的构造解释,阐述了祁连山带断裂构造体系与深部结构特征,提出了构造演化的综合模型。

2 大地构造背景

祁连山带位于青藏高原东北缘,处在特提斯构造域的最北部,其北部以祁连山北缘断裂(NQLF)与河西走廊盆地为界,并通过阿拉善地块与古亚洲洋构造域接壤;南部以柴达木盆地北缘断裂(简称“柴北缘断裂”,NQDF)与柴达木盆地为界,

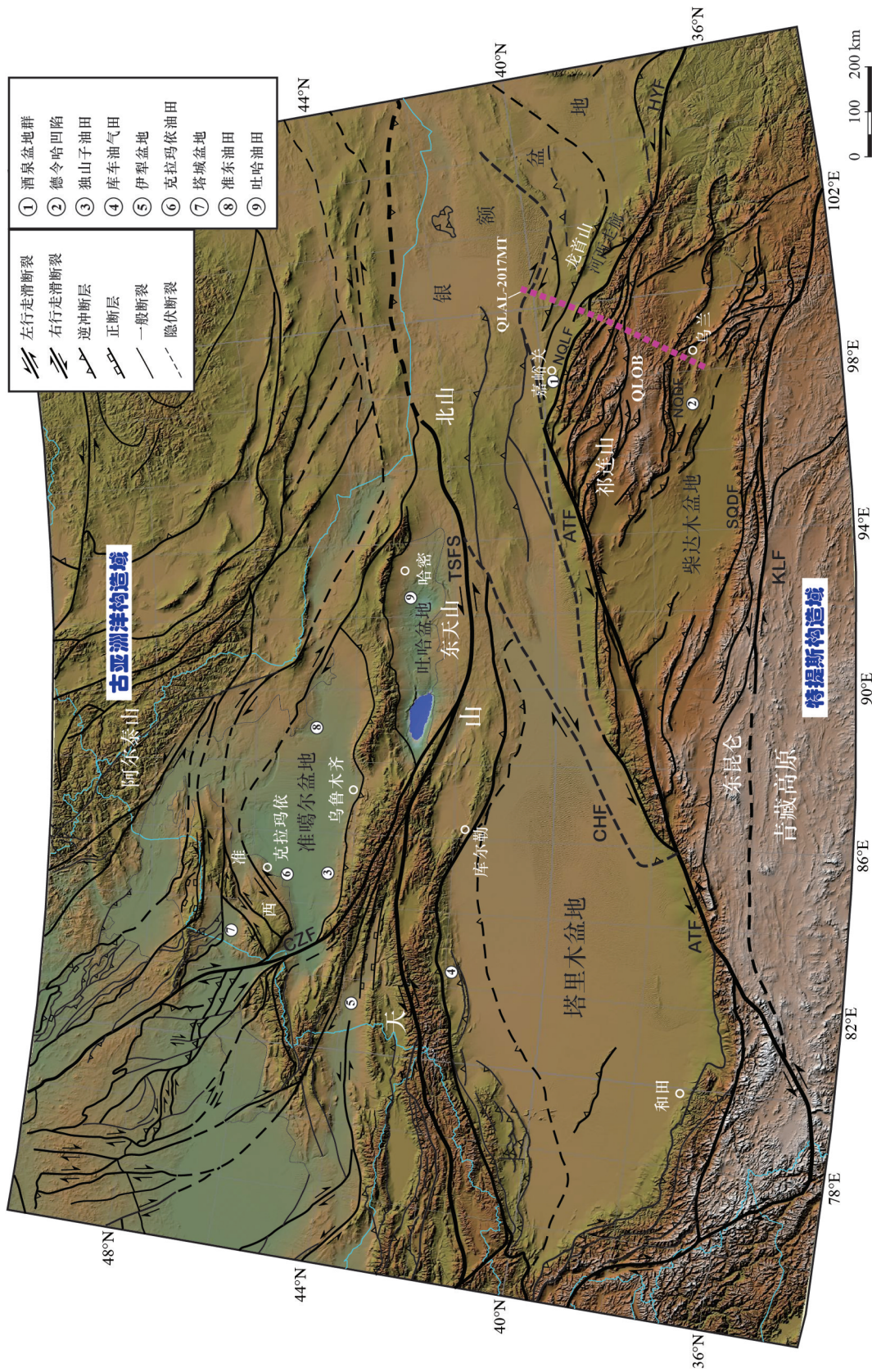


图2 中国西北及周边地区断裂构造体系略图(据陈宣华等, 2019a 修改)
 TSFS—天山走滑断裂系统; ATF—阿尔金山断裂; CZF—成吉斯—准噶尔断裂; KLF—昆仑—昆仑断裂; CHF—车尔臣河断裂; SQDF—柴达木南缘断裂; NQDF—柴达木北缘断裂; NQLF—祁连山北缘断裂; HYF—海原断裂; 图中给出超宽频大地电磁测深剖面(QLAL-2017MT)的位置

Fig.2 Sketch map of the fault system of Northwest China and surrounding areas (modified from Chen Xuanhua et al., 2019a)
 TSFS— Tianshan strike-slip fault system; ATF— Altun Fault; KLF— Kunlun Fault; CHF— Cheerchen Fault; SQDF— South Qaidam Fault; NQDF— North Qaidam Fault; NQLF— North Qilian Fault; HYF— Haiyuan Fault. The location of super-broadband magnetotelluric sounding profile (QLAL-2017MT) is shown in Fig. 2

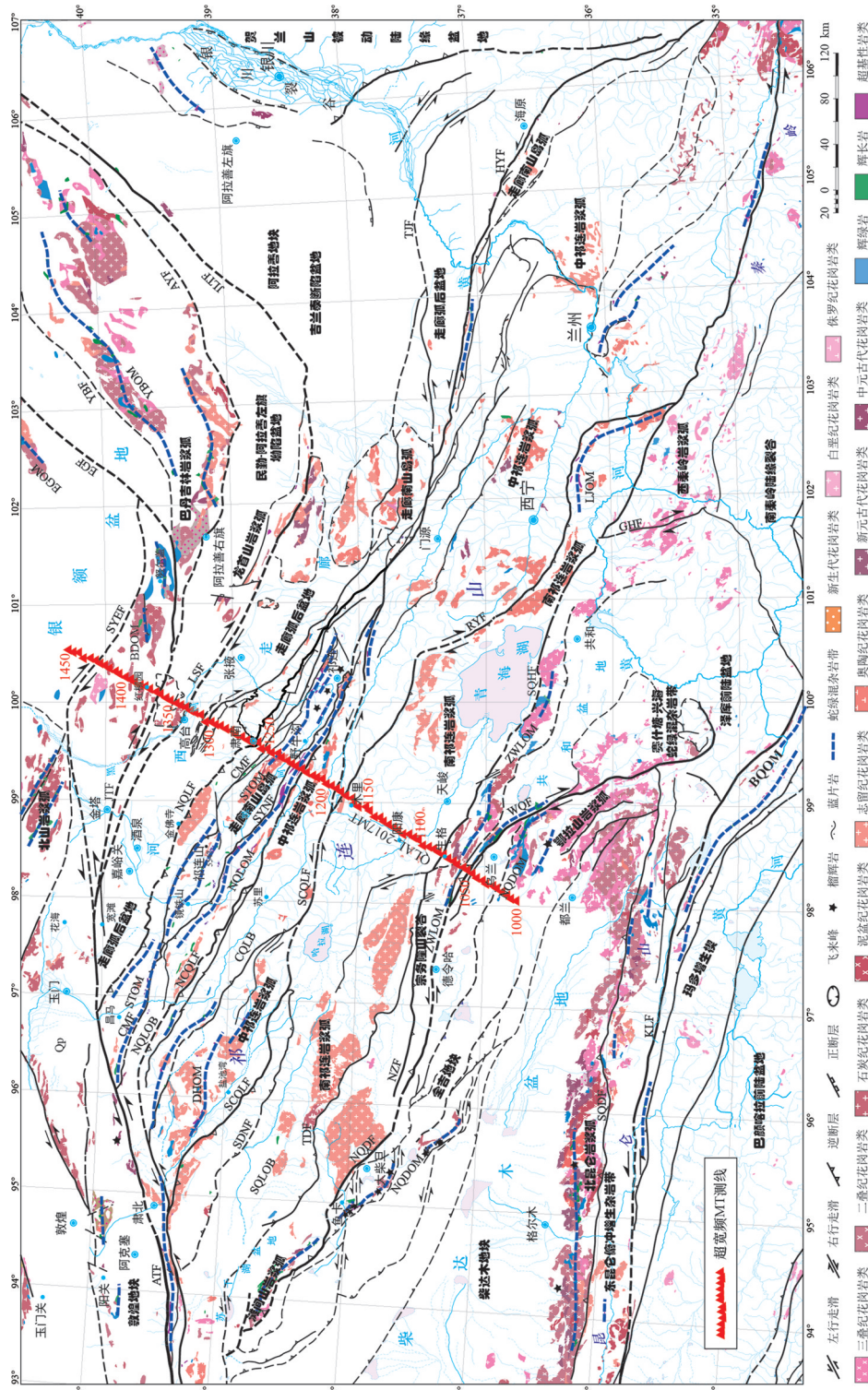


图3 祁连造山带及周缘断裂构造体系略图

SQLOB—南祁连造山带; CQLB—中祁连地块; NOLOB—北祁连造山带; ATF—阿尔金山断裂; KLF—昆仑断裂; NQDF—柴达木盆地北缘断裂; SDNF—党河南山南缘断裂; TDF—土耳其根达坂断裂; NZF—北宗务隆山断裂; SQHF—青海南山断裂; SCQLF—中祁连南缘断裂; NCQLF—中祁连北缘断裂; CMF—昌马—俄博断裂; NQLF—祁连山北缘断裂; HYF—海原断裂; TJF—天景山断裂; WQF—温泉断裂; RYF—日月山断裂; GHF—共和断裂; LSF—龙首山断裂; JTF—金塔断裂; AYF—阿拉善右旗断裂; YBF—雅布赖断裂; EGF—恩格尔苏南缘断裂; SYEF—银额盆地南缘断裂。图中给出超宽频大地电测深剖面(QLAL-2017MT)的位置

Fig.3 Sketch map of the fault system of the Qilian Mountain Orogenic Belt and its adjacent areas

SQLOB—South Qilian Orogenic Belt; CQLB—Central Qilian Block; NOLOB—North Qilian Orogenic Belt; ATF—Altun Fault; KLF—Kunlun Fault; NQDF—North Qaidam Fault; SDNF—South Danghe Nan Shan Fault; TDF—Tuergendaban Fault; NZF—North Zongwulong Shan Fault; SQHF—South Qinghai Fault; SCQLF—South Central Qilian Fault; NCQLF—North Central Qilian Fault; SYNF—South Yentiugou Fault; CMF—Changma-Ebo Fault; NQLF—North Qilian Fault; HYF—Haiyuan Fault; WQF—Wenquan Fault; RYF—Riyueshan Fault; YBF—Yabu Lai Fault; GHF—Gonghe Fault; LSF—Longshoushan Fault; JTF—Jinta Fault; AYF—Alxa Right Banner Fault; EGF—Ebo Fault; SYEF—South Enggeerwusu Fault; YEF—Yabulai Fault. The location of super-broadband magnetotelluric sounding profile (QLAL-2017MT) is also shown

西北部被阿尔金断裂(ATF)所切,东部与秦岭造山带等相接(图1,图2,图3)。祁连造山带是典型的增生型造山带,具有很厚的陆壳(可达72 km左右)和典型山根(由花岗质榴辉岩组成)特征(邓晋福等,1995);主要由复杂变形的早古生界岛弧和岩浆弧等组成,由南向北可分为南祁连造山带(褶皱带)、中祁连地块(隆起)和北祁连造山带(褶皱带)等3个近北西向展布的构造单元(图3;陈宣华等,2010;胡道功等,2018)。祁连造山带发育多条蛇绿混杂岩带,构造运动复杂多样。祁连造山带及邻区地层发育齐全,自太古宙至新生代地层普遍发育,记录了早期大陆地壳的形成、大陆岩石圈的伸展、裂解、大洋岩石圈俯冲消减和陆内造山与构造变形等系列过程中的地质信息。

南祁连造山带(SQLOB)处在柴北缘断裂(NQDF)与中祁连南缘断裂(SCQLF)之间(图3),主要由南祁连岩浆弧、滩间山岩浆弧、宗务隆山构造带裂谷和蛇绿混杂岩带等组成(王立全等,2013;潘桂棠和肖庆辉,2015)。南祁连造山带发育新太古代末期—古元古代早期构造岩浆活动(裴先治等,2007)。南祁连党河南山地区早古生代发育岛弧岩浆活动(赵虹等,2004)。柴达木盆地北缘发育沙柳河蛇绿岩组合(宋述光等,2009)。天峻南山地区经历了从晚古生代俯冲作用(246 Ma)到中生代后碰撞(215 Ma)的花岗岩类岩浆活动(郭安林等,2009)。宗务隆山构造带西起阿尔金山,向东经苏干湖盆地被第四系覆盖后,于土尔根大坂、达肯大坂又出露,继续东延,经南祁连南侧的宗务隆山延至青海南山的野马湖一带,呈北西西走向的窄条楔入南祁连加里东构造带与柴达木地块之间;主要为石炭—二叠纪裂谷(潘桂棠和肖庆辉,2015)。宗务隆山构造带石炭系为浅海碎屑岩—碳酸盐岩—火山岩沉积组合。

中祁连地块(CQLB)处在中祁连南缘断裂(SCQLF)与中祁连北缘断裂(NCQLF)之间(图3),由中祁连—湟源地块以及叠置在其上的中祁连岩浆弧、党河南山—拉脊山蛇绿混杂岩带北带(大道尔吉—拉脊山—永靖蛇绿混杂岩带;C-S)等组成(王立全等,2013;潘桂棠和肖庆辉,2015);主要为前寒武系片麻岩基底,其东段的马街山岩群是祁连造山带古老变质基底岩系之一。中祁连东段(湟源)经历了新元古代

岩浆活动;中祁连西段(野马南山)发育早古生代I型花岗岩类岩浆活动(黄增保等,2015)。早志留世(441~434 Ma)进入后碰撞的伸展环境。

北祁连造山带(NQLOB)呈狭长带状展布于托莱南山与河西走廊之间,处在祁连山北缘断裂(NQLF)与中祁连北缘断裂(NCQLF)之间(图3);主要由北祁连蛇绿混杂岩带主带(熬油沟—玉石沟—柏木峡蛇绿混杂岩带;C-S)、走廊南山岛弧(O)、北祁连蛇绿混杂岩带北带(九个泉—大岔大坂—老虎山蛇绿混杂岩带;C-S)和走廊弧后盆地(O-S)等组成(王立全等,2013;潘桂棠和肖庆辉,2015;张义平等,2015),其基底主要由太古宙和古元古界的结晶变质岩系组成。北祁连造山带是在新元古代Rodinia联合大陆(Pangen-850 Ma)基础上裂解,经由寒武纪裂谷盆地、奥陶纪初期成熟洋盆(北祁连洋)、奥陶纪中晚期北祁连活动大陆边缘、志留纪—早、中泥盆世碰撞造山而形成的。奥陶纪中、晚期,北祁连、河西走廊地区发育中、上奥陶统洋壳—岛弧—弧后火山岩,形成典型的沟—弧—盆构造—沉积体系。主造山阶段北祁连洋俯冲消减、增生,洋盆闭合、弧—陆碰撞,形成早古生代造山楔,下古生界发生强烈构造变形变质;伴随有大量的花岗岩类(500~400 Ma)侵位(许志琴等,1999;吴才来等,2006)。北祁连洋盆地接受了巨厚的寒武—奥陶系沉积,发育蛇绿岩套。下、中志留统为典型复理石浊流沉积,上志留统为滨浅海相磨拉石沉积;志留纪末期为北祁连的主造山期。泥盆系主要为典型的前陆盆地磨拉石建造;晚泥盆世进入后碰撞(造山)的伸展作用环境,造山带地壳开始减薄。石炭系以滨海沼泽相沉积为主。

北祁连造山带和祁连山南侧的柴达木北缘构造带发育以榴辉岩为代表的高压—超高压变质带,是国际地学研究的热点地区之一(Yang et al., 1998, 2002; 杨经绥等, 2000; 张建新, 2000; Song et al., 2003a, 2003b, 2005, 2006, 2009, 2013, 2014)。北祁连中段清水沟—百经寺一带发育早古生代高压超高压变质作用,俯冲—增生杂岩带中的低温榴辉岩以透镜体形式产于蓝片岩和多硅白云母片岩中;榴辉岩相变质时代为463~468 Ma。柴北缘构造带中的榴辉岩及其围岩片麻岩中发育超高压变质矿物,如柯石英、金刚石和超高压微结构等(杨经绥等,

2001; Song et al., 2005), 成为早古生代原特提斯洋壳俯冲和陆-陆碰撞的重要记录。

3 断裂构造体系特征

3.1 总体特征

中国西北地区以显著的逆冲推覆构造和走滑断裂系的发育为特征, 断裂构造体系错综复杂(图2)。其中, 逆冲推覆构造主要发育在祁连山和天山造山带的内部和山前, 是青藏高原向NE扩展和祁连山、天山等山脉隆升的构造主因; 走滑断裂系主要有天山走滑断裂系统(TSFS)和阿尔金山走滑断裂系(ATF; Yin et al., 2002; Chen et al., 2004), 前者与古亚洲洋构造域及中亚造山带的演化有关, 后者与特提斯构造域及喜马拉雅—青藏高原造山带的演化有关。西北地区发育大量的蛇绿混杂岩带, 一般与大型断裂构造相伴出现, 是该地区从古亚洲洋和特提斯洋构造环境向大陆转换以及大陆显著增生的重要标志。

祁连造山带及其盆山结合带以发育显著的前新生代和新生代逆冲断裂系为特征, 最主要的断裂系统包括祁连南山—柴北缘、中祁连和北祁连等逆冲断层系, 以及走滑断裂系统等(图3; 陈宣华等, 2010)。

祁连造山带及其盆山结合带以发育显著的新生代逆冲断裂系为特征, 最主要的断裂带包括北祁连山山前断裂带、北祁连山南缘断裂带、中祁连山南缘断裂带、北宗务隆山断裂带、南祁连山山前断裂带(即柴北缘逆冲断层系的柴达木山逆冲断层带)、欧龙布鲁克山—牦牛山断裂带和赛什腾山—锡铁山断裂带等。其中, 南祁连山—柴达木盆地北缘断裂系统为一组呈带状分布的断裂带, 总体走向为NW—NWW向, 以向柴达木盆地内部的逆冲推覆断裂为主, 控制着祁连山和柴达木盆地北缘新生代盆-山构造的发育(陈宣华等, 2010)。

3.2 祁连南山—柴北缘逆冲断层系

祁连南山—柴北缘逆冲断层系为一组呈带状分布的断裂带, 主要包括柴北缘和祁连南山等逆冲断层系, 总体走向为NW—NWW向, 以向柴达木盆地内部的逆冲推覆断裂为主, 控制着祁连南山和柴北缘新生代盆-山构造的发育。祁连南山—柴北缘逆冲断层系构成由现今柴达木盆地与可可西里盆

地构成的古柴达木盆地的北部边界, 其启动时间不晚于始新世早期(Wu et al., 2019)。其中, 柴北缘逆冲断层系形成于~49 Ma(Yin et al., 2002); 祁连南山逆冲断层系可能形成于~33 Ma之前(Yin et al., 2002)。

柴达木盆地北缘可能是在奥陶纪晚期俯冲闭合的早古生代古洋盆(崔军文等, 1999)和碰撞造山带(王惠初等, 2005)基础上发育而来的。新生代柴北缘逆冲断层系由一系列北倾的基底卷入叠瓦状逆冲断层组成, 主要断裂(带)为柴北缘断裂、大赛什腾山北逆冲断层、小赛什腾山北逆冲断层、赛南逆冲断层带、鱼卡—绿梁山断裂带(包括西绿梁山和东绿梁山等逆冲断层)、锡铁山断裂带和欧龙布鲁克山—牦牛山断裂带(包括欧龙布鲁克和埃姆尼克山等逆冲断层带)等, 将古生代变质沉积岩、变质火山岩和含超高压(UHP)榴辉岩的片麻岩逆冲推覆到新生代地层之上, 是祁连南山—柴北缘逆冲断层系的南缘部分(陈宣华等, 2010)。柴达木盆地北缘的赛什腾、绿梁山、锡铁山是向南斜向逆覆于新近纪沉积岩之上的无根推覆体(王根厚等, 2001)。

祁连南山逆冲断层系主要由党河南山南缘断裂(SDNF)、土尔根达坂断裂(TDF)、北宗务隆山断裂(NZF)和青海南山断裂(SQHF)等组成(图3)。其中, 党河南山南缘断裂和土尔根达坂断裂均为北倾的逆冲断层, 将达肯大坂岩群和古生代地层逆冲推覆在新近系之上, 与柴北缘断裂一起构成祁连南山—柴北缘逆冲断层系的主体。北宗务隆山断裂为南倾的韧性剪切带, 具有左行剪切特征; 其将达肯大坂岩群和宗务隆蛇绿混杂岩逆冲推覆在三叠系隆务河群之上(郭安林等, 2009)。青海南山断裂可能具有与北宗务隆山断裂类似的逆冲极性, 它们同时构成祁连南山—柴北缘逆冲断层系的反向逆冲断层。

3.3 中祁连逆冲断层系

主要由中祁连南缘断裂(SCQLF)和中祁连北缘断裂(NCQLF)等组成, 分别构成中祁连地块的南、北边界(图3)。

中祁连南缘断裂: 主断裂由SW向NE方向逆冲, 倾角 $50^{\circ}\sim 70^{\circ}$; 其逆冲方向与祁连造山带断裂构造体系的主逆冲方向相一致。局部可见前寒武纪基底和古生界强烈逆冲推覆在中—新生界(新近系)之上。在疏勒南山的东南端, 由于受到野马山

一疏勒南山南缘断裂自NE向SW方向的逆冲推覆作用影响,该断裂表现为自NE向SW的反向逆冲。在构造地貌方面,该断裂可能是形成党河谷地地貌的主因。由于新生代阿尔金断裂和海原断裂、天景山断裂等左行走滑断裂活动的影响和改造,该断裂兼具左行走滑性质。

中祁连北缘断裂:西起野马山北麓,向东经托莱南山北麓、托莱河谷至托莱山一线展布,主断裂由SW向NE方向逆冲。向东或继续向大坂山延伸,或归并到祁连山北缘断裂之中,并在经过冷龙岭南坡之后,发散为海原断裂和天景山断裂构成的左行走滑断裂系。该断裂显著的构造地貌特征是形成野马山、托莱南山和托莱河谷,将中祁连地块前寒武纪变质岩系逆冲推覆在北祁连蛇绿混杂岩带之上。在托莱南山北麓,可见前寒武纪变质岩系逆冲推覆在白垩系之上。

3.4 北祁连逆冲断层系

主要由野牛沟南缘断裂(SYNF)、昌马—俄博断裂(CMF)、祁连山北缘断裂(NQLF)、榆木山逆冲推覆构造系统(YMTS)和河西走廊活动断裂系等组成(国家地震局地质研究所、国家地震局兰州地震研究所,1993;陈宣华等,2010,2019a;Zuza et al.,2019)。

野牛沟南缘断裂:西起镜铁山西侧,向东横穿北大河而进入黑河流域,沿托莱山北麓展布,在祁连县南东一侧归并到中祁连北缘断裂。它与中祁连北缘断裂分别构成北祁连蛇绿混杂岩带主要的北、南边界。该断裂具有由SW向NE方向逆冲的构造极性,控制了野牛沟和祁连等多个早白垩世盆地的发育,并将北祁连蛇绿混杂岩(含前寒武纪变质岩系和早古生代蛇绿岩套)逆冲推覆在早白垩世沉积盆地之上。

昌马—俄博断裂:也被称为昌马—祁连断裂带,主要由西段的昌马断裂和中东段的肃南—祁连断裂等连接而成;从昌马盆地的南缘向东经红窑子、月牙大坂、大泉口、臭水柳河、白泉门、大台子等地区,总体走向为N60~80°W,断面倾向SW,倾角55~60°(国家地震局兰州地震研究所,1992;国家地震局地质研究所和国家地震局兰州地震研究所,1993)。该断裂向东自俄博之后,归并到祁连山北缘断裂的冷龙岭断裂段,向东与海原断裂及天景山

断裂相接。昌马—俄博断裂具有多期活动,可能最初形成于印支期,控制了白泉门三叠纪沉积盆地的发育;早白垩世以来活动加剧,将前新生代地层逆冲推覆在新生代地层之上,晚第四纪和全新世仍有活动。该断裂可能为超岩石圈断裂,以挤压逆冲为主,兼具左行走滑性质(国家地震局兰州地震研究所,1992)。

祁连山北缘断裂:也被称为北祁连北缘断裂(胡道功等,2018),为祁连山主逆冲断层,构成北祁连榆木山逆冲推覆构造系统的根带。该断裂主要由佛洞庙—红崖子断裂和冷龙岭断裂等各段组成,主要为第四纪活动构造(国家地震局地质研究所和国家地震局兰州地震研究所,1993)。主要沿祁连山北部边缘展布,西起昌马北部的疏勒河口(昌马河口),向东经金佛寺、肃南、民乐扁都口、俄博、金瑶岭、冷龙岭至雪龙横山以北;其东段通过雷公山—毛毛山断裂与左行走滑的海原断裂相接。可作为北祁连造山带(祁连山)与河西走廊盆地的大致边界,控制了河西走廊盆地早白垩世沉积。断层呈波状弯曲或锯齿状,总体走向NW,倾向SW,倾角为45~80°;以挤压逆冲为主,兼具左行走滑性质。断裂具多期活动,其形成可追溯到早古生代,晚古生代、中生代和新生代均有活动,第四纪(全新世)构造活动强烈。

榆木山逆冲推覆构造系统:榆木山及周边地区主要发育北祁连逆冲断层系(NQLTS)北部的构造要素,可称为榆木山逆冲推覆构造系统(YMTS),由一系列北西向、北西西向逆冲断层和系列褶皱组成,其根带为祁连山北缘断裂(NQLF)。该系统主要由榆木山南缘断裂(SYMF)、肃南断裂(SNF)、榆木山北缘断裂(NYMF;国家地震局兰州地震研究所,1992;Ren et al.,2019)、梨园堡断裂(LYF;陈宣华等,2019a)等组成,具有多期活动的特点,主要为早白垩世早期的逆冲推覆构造。其中,榆木山南缘断裂和榆木山北缘断裂分别构成榆木山飞来峰的南、北边界;梨园堡断裂为挤压逆冲过程中引发的右行走滑断裂,相伴发育走滑双重构造(陈宣华等,2019a)。

河西走廊活动断裂系:河西走廊是青藏高原向北东扩展的最前缘,是现今构造变形和地震活动最为强烈的地区之一(Tapponnier et al.,1990;Hetzl

et al., 2004; 陈柏林等, 2008; 张培震等, 2014; 陈干等, 2017; Yang et al., 2018a, 2018b); 同时产出有作为我国最早石油基地的玉门油田(杨树锋等, 2007; Cheng et al., 2019)。河西走廊活动断裂系主要包括榆木山北部山前的大更子断裂(DGF)、小更子断裂(XGF)、张掖断裂(ZF), 以及河西走廊西部的嘉峪关—文殊山断裂(JWF)、宽滩山断裂(KF)等。大更子断裂和小更子断裂等构成榆木山北部山前的活动隐伏逆冲断层系, 是榆木山逆冲推覆构造系统的重要组成部分(陈宣华等, 2019a)。嘉峪关—文殊山断裂位于酒泉东部盆地的西侧, 将酒泉盆地分割成酒西和酒东两个盆地; 断裂呈NNW向展布, 倾向SW, 倾角陡立, 具强烈的挤压逆冲特征, 兼具右行走滑性质, 为新生代和晚第四纪强烈活动的断裂(李玉龙, 1984)。宽滩山断裂为南倾的隐伏逆冲断裂, 其动力学与青藏高原南缘主边界逆冲断裂(MBT)类似, 被称为青藏高原“北边界断裂”(North Boundary Thrust, 即NBT), 沿NBT阿拉善地块可能向青藏高原之下俯冲(高锐等, 1998)。

3.5 走滑断裂系统

主要包括由海原断裂(HYF)和天景山断裂(TJF)等构成的左行走滑断裂系统, 以及由温泉断裂(WQF)、日月山断裂(RYF)和共和断裂(GHF)等组成的右行走滑断裂系统(图3)。

海原断裂: 是青藏高原东北缘最显著的边界断裂之一, 整体呈现向NE凸出的宽缓弧形特征; 其东起六盘山东麓, 与NNW向六盘山逆冲断层相连接; 向西北经月亮山—南华山—西华山北麓、黄家洼山南麓、哈思山—哈拉山南麓、米家山北麓和甘肃景泰兴泉堡, 向西进入乌鞘岭, 与雷公山—毛毛山断裂斜接, 并归并到祁连山腹地WNW向逆冲断层系之中。海原断裂具有多阶段演化历史, 其初始阶段强烈的NE向逆冲推覆始于(12±3)Ma, ~5.4 Ma以来以不断增强的左行走滑为特征(王伟涛等, 2014); 第四纪表现为强烈的左行走滑和强震特征, 记录了高原向NE扩展的构造过程(施炜等, 2013)。海原断裂切过上、中地壳, 具有多个分支, 并归集到下地壳低角度拆离剪切带之中(Gao et al., 2013)。

天景山断裂: 发育在青藏高原的东北缘, 为青藏高原的东北边界, 具有向NE凸出的弧形特征。

该断裂向东与六盘山逆冲断层相接; 自中卫南部向西经古浪进入冷龙岭, 与海原断裂一起, 归并到祁连山逆冲断层系之中。该断裂具有第四纪左行走滑特征。

温泉断裂: 主要沿哇洪山一线分布, 呈NNW向延伸达200 km以上, 构成柴达木盆地—东昆仑与共和盆地—西秦岭的边界。断裂北端斜接柴北缘断裂, 南端切断柴达木南缘断裂(即昆中断裂)。断裂总体走向330~350°, 多数断面倾向SW, 倾角50°~70°。该断裂具有右行走滑特征, 为一条壳内转换断层, 其右行走滑视位移量为~10 km; 断裂作用发生在上新世时期, 与左行走滑的阿尔金断裂构成共轭剪切断裂体系(陈宣华等, 2010)。

4 地球物理场特征及其对断裂构造体系的反映

4.1 区域重力场特征

祁连造山带具有与周缘盆地及造山带明显不同的区域重力场特征。其中, 南祁连为NW向展布的重力低异常带, 布格重力值为(-460 ~ -320)×10⁻⁵ m/s²; 中祁连为NNW向展布的梯级带, 幅值为(-440 ~ -360)×10⁻⁵ m/s², 局部为重力高或重力低异常; 北祁连为NNW向展布的梯级带, 北祁连南部为(-350 ~ -400)×10⁻⁵ m/s², 河西走廊为(-350 ~ -260)×10⁻⁵ m/s²; 银额盆地南部等地区为重力高异常区, 布格重力值为(-255 ~ -180)×10⁻⁵ m/s²(冯治汉等, 2018)。

在剩余重力异常方面, 祁连造山带与河西走廊盆地一起, 构成被周缘剩余重力高所围限的相对低值区, 剩余重力最低值出现在中祁连及之南的地区, 与断裂构造体系的展布特征相一致(图4a)。西宁盆地西侧的祁连山西部地区, 其剩余重力异常表现为周缘高、中间低, 呈NWW向展布; 其上叠加局部负异常形态不规则, 主要是中—新生代沉积盆地和古生代中酸性岩体的综合反映。河西走廊西部的酒西、酒东和民乐盆地, 剩余重力异常表现为与祁连山走向大致平行, 异常为NWW走向。银额盆地南部剩余重力异常表现为两组异常的迭合, 以NEE向的重力异常为主, 可能主要受前中生代构造格局控制; NNE向异常次之。在阿尔金山地区, 剩余重力异常呈NE走向, 南北均为重力高, 中部发育局部负异常,

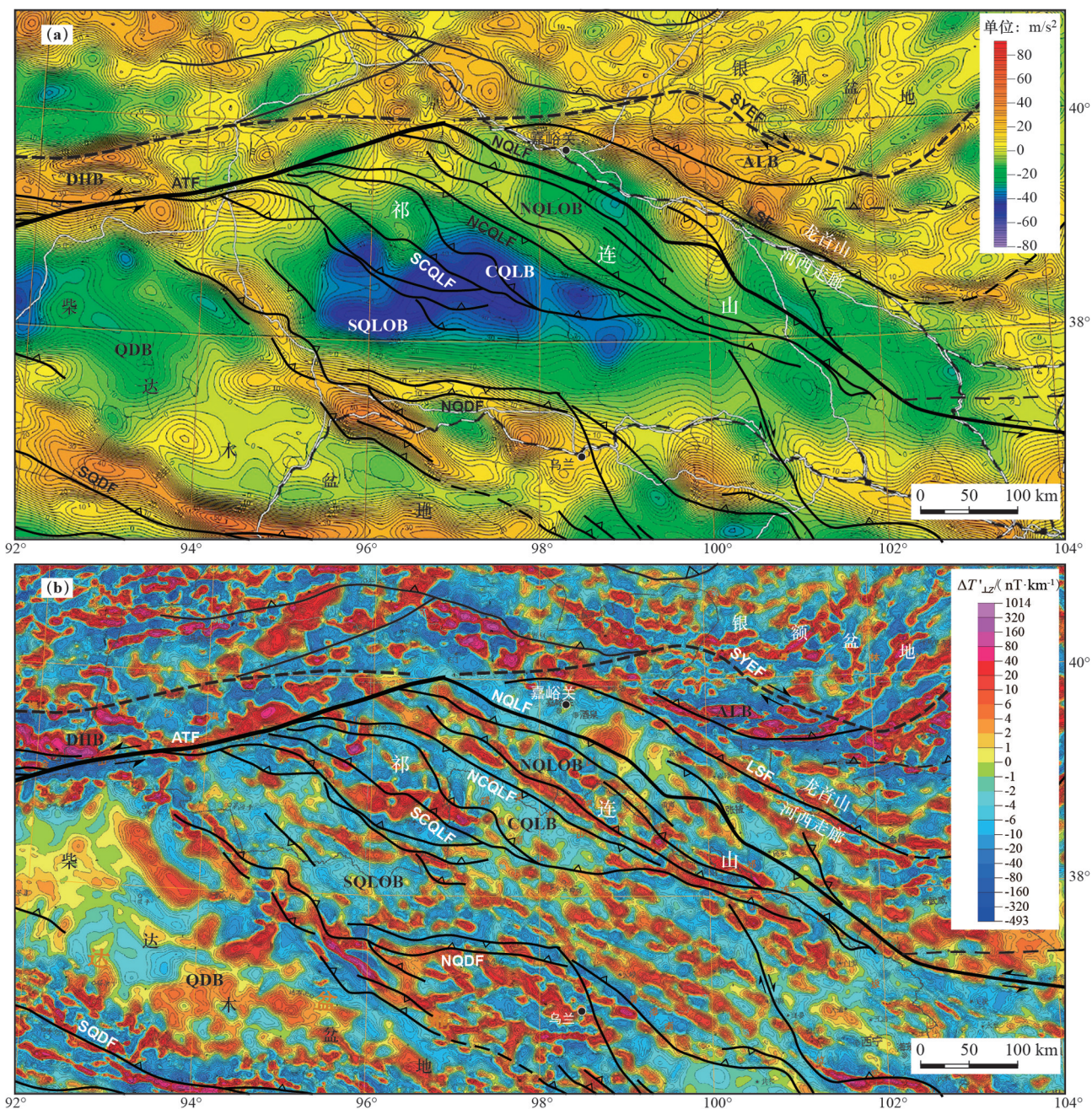


图4 祁连山及周缘地球物理场异常及其与断裂构造体系的关系

a—剩余重力异常及其与断裂构造体系的关系, 剩余重力异常据冯治汉等(2018); b—航磁 ΔT 场化极垂直一阶导数异常及其与断裂构造体系的关系, 航磁 ΔT 场化极垂直一阶导数异常据熊盛青等(2015); ALB—阿拉善地块; NQLOB—北祁连造山带; CQLB—中祁连地块; SQLOB—南祁连造山带; QDB—柴达木地块; DHB—敦煌地块

Fig.4 Sketch maps showing the relationships between the geophysical field anomalies and the fault system in the Qilian Mountain and surrounding areas

a—Residual gravity anomaly (after Feng Zhihan et al., 2018) and its relationship with fault system; b—First vertical derivative anomaly of the aeromagnetic ΔT field polarization (after Xiong Shengqing et al., 2015) and its relationship with fault system; ALB—Alxa Block; NQLOB—North Qilian Orogenic Belt; CQLB— Central Qilian Block; SQLOB—South Qilian Orogenic Belt; QDB—Qaidam Block; DHB—Dunhuang Block

可能与中—新生代地层的加厚有关。柴达木盆地也表现为被周缘重力高所围限的相对重力低值区,并具有东、西分区特征,西部为低值区。

4.2 区域航磁特征

祁连造山带航磁异常总体呈NW至NWW走向,由多条NW向线性正磁异常带组成(图4b),磁异常强度为50~200 nT;当磁场上延10 km、20 km后,反映为宽缓的区域性正负磁场(熊盛青等,2015)。其中,柴北缘—南祁连航磁异常由一连串等轴状、长条状高磁异常组成,西段为平稳磁场背景上叠加区域性负异常和局部磁异常;中祁连地块磁异常区,磁异常平静,幅值变化不大;北祁连为NWW走向的高磁异常带,局部为长条状、椭圆状,异常强度为100~200 nT;河西走廊地区为相对平静的磁场,仅有少量几处局部磁异常。银额南部为负磁异常区,包括宗乃山、特罗西滩以南、雅布赖山以西地区,磁力异常以NEE向展布为主;北部为正磁异常区,与特罗西滩隆起、宗乃山隆起带相对应(熊盛青等,2015;冯治汉等,2018)。区域航磁异常的展布与断裂构造体系具有较好的一致性。

与祁连造山带不同,柴达木盆地航磁异常呈磁场镶嵌特征,为宽阔、平缓、正负伴生异常,强度80~100 nT,以正磁异常为主;磁异常宽阔平缓之原因可能与古元古界结晶岩系埋深有关,异常的次级波动跳跃,反映出基底的不均一性(熊盛青等,2015)。

5 超宽频大地电磁测深揭示的深部结构特征

5.1 数据采集

超宽频大地电磁测深法是在常规大地电磁测深(MT)测量基础上,结合长周期大地电磁、音频大地电磁等方法的探测优势,综合发展起来的深层、超深层大地电磁探测方法。与常规MT方法相同,超宽频MT方法以天然平面电磁波作为场源,通过高频和低频的双向扩频,弥补了常规MT方法对高频和低频信号响应的不足,以获得有用的深部信息。超宽频MT方法高频采集频率达到10000 Hz,尽可能提高对浅部不均匀电性体的识别、控制;低频部分采样频率最大控制到0.0001 Hz,在兼顾调查效率的同时,实现了对地下深部电性体的控制,其探测深度可达下地壳及上地幔。实验研究表明,采

用长周期仪器设备和稳定性好的不极化电极,合理布置测站,能够采集到最长周期达几万秒的长周期大地电磁场信号(叶高峰等,2013)。

2017年6—7月,本项目组部署采集了柴北缘—祁连山—河西走廊盆地—合黎山—大青山—银额盆地南缘的超宽频MT剖面(图2,图3),测线编号为QLAL-2017MT,施工号为QL2017MT。剖面从南到北经过的大地构造单元包括柴达木地块(含柴达木盆地、德令哈坳陷和乌兰坳陷)、祁连造山带(包括南祁连造山带、中祁连地块、北祁连造山带,含天峻坳陷、木里坳陷等)、河西走廊过渡带(含酒泉盆地和民乐盆地)和阿拉善地块(包括阿拉善弧形构造带和银额盆地)。

超宽频MT测量的野外施工采用大间距张量观测方式,共采集 E_x 、 E_y 、 H_x 、 H_y 、 H_z 5个分量,测深点距平均约5 km。投入使用的电法仪器及磁棒包括8台MTU-5A,19台V5-2000(含1台备用),14根AMTC-30和MTC-80H磁棒、40根MTC-50磁棒。通过仪器性能检测标定、一致性试验和采集参数试验,确定了极距和采集时间等采集参数。在平坦区,野外电极布置采用“+”字型方式布极,两对电极组成一个正交十字形,采集站基本在中心位置,南北向(0°)的偶极子为 E_x ,东西向(90°)的偶极子为 E_y ;电极距长度布设在180~200 m。在山地、沼泽、高压线、公路、铁路等布极困难地区,适当采用“L”型或“T”型装置布极,电极长度布设在50~200 m,极困难山区不低于30 m。电极、磁棒布设利用全站仪配合森林罗盘仪进行定向、测距。高频数据采集时间大于30 min;宽频带低频数据采集时间大于10 h,施工中保证单点全天采集,超宽频测深点采集时间为6 d以上。仪器开始及结束MT采集施工的一致性均方误差小于4%。QLAL-2017MT剖面采集长度为464 km,共采集91个测点,其中超宽频测深点31个(频率范围10000~0.0001 Hz),宽频测深点60个(10000~0.0005 Hz);宽频测深点在全线分布均匀。

5.2 数据处理

超宽频MT资料处理包括数据预处理、资料反演、资料定性分析三个阶段。本次超宽频带大地电磁测深剖面测量中,每个测点数据采集分别使用了两种仪器,其中高频段使用MTU-5A仪器采集,频

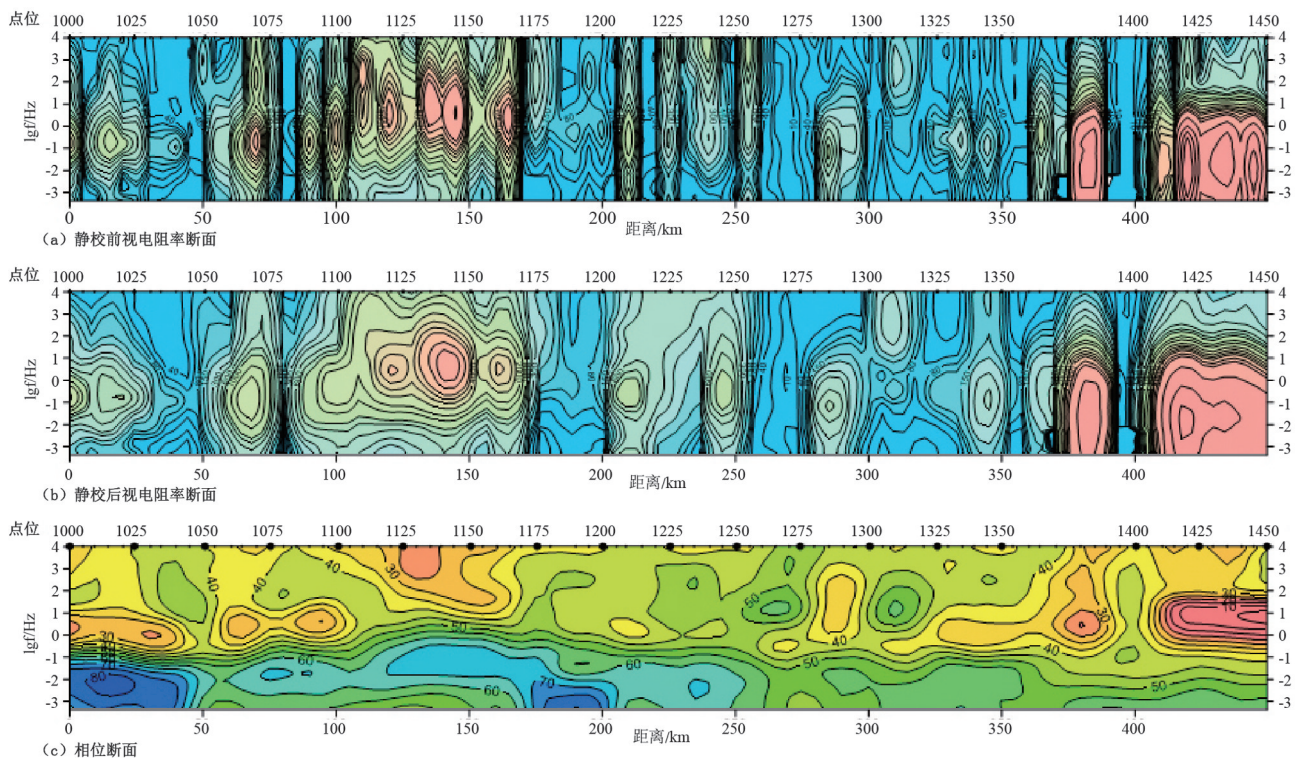


图5 大地电磁测深剖面(QLAL-2017MT)静态位移及静校正对比图

Fig.5 Comparison of static migration and static correction of magnetotelluric sounding profile (QLAL-2017MT)

率为10000~10 Hz;低频段使用V5-2000采集,频率为360~0.0005 Hz(超宽频的低频为0.0001 Hz),两种仪器采集的数据在360~10 Hz频段相互重叠。在后续的数据处理之前,先是将这两种仪器采集的高频和低频数据进行拼接叠合成全频段曲线,然后进行了去噪处理以压制采集噪声影响,进行了极化模式识别,利用各测点首支电阻率分析进行了静态位移校正,并将大地电磁场分量随时间的变化转换成频谱,得到视电阻率和阻抗相位等参数的频率响应,获得视电阻率与相位剖面图件(图5)。

利用相位剖面可以判断视电阻率静态改正的合理性。相位剖面等值线的横向变化可定性确定地层的起伏变化及断裂位置。在视电阻率剖面上(图5a,图5b),等值线横向分段特征明显,呈高阻、低阻相间分布的特征;在纵向上,有的显示低-高-低三层电性特征,有的显示高-低-高-低四层电性特征。由趋肤深度推断,在0.1 Hz附近相对连续的一套相对高阻层,是壳内高阻基底,该套层的厚度定性反映了高阻基底的厚度。而在该套高阻层下,出现一套相对连续的低阻,推测为壳内高导层。在1080、

1170、1270、1350、1400等测点附近,剖面等值线突变,呈陡直状,推测为大型断裂的反映。相位剖面形态(图5c)与视电阻率具有较好的一致性;由于相位不受静态效应影响,其形态在横向上更加连续。

5.3 电性结构反演

通过野外小极距电性测量、钻井、地震、重磁和区域地质资料对电性层进行地质推断解释,确定电性层与地层的对应关系。对测区内的构造、地层起伏变化等建立整体的认识,采用可视化人机交互数据预处理系统,根据MT数据资料的特点,参照已有地质、地球物理探测成果,重新进行人机交互资料编辑,压制各种干扰,突出有效信息,然后在定性分析认识的基础上进行定量的一维反演和二维反演解释,将频率域相位剖面转换成深度域的电阻率剖面。

根据测深点距大、沿测线构造复杂、相邻点构造跨度大、地表出露地层多、电性差异大等特点,本次研究采用以高频资料为标准、进行全频段手工智能校正的静态位移校正方法,对超宽频MT不同频段的数据分别进行有针对性的反演计算,获得浅层和中—深层两个深度的反演剖面并进行分析解

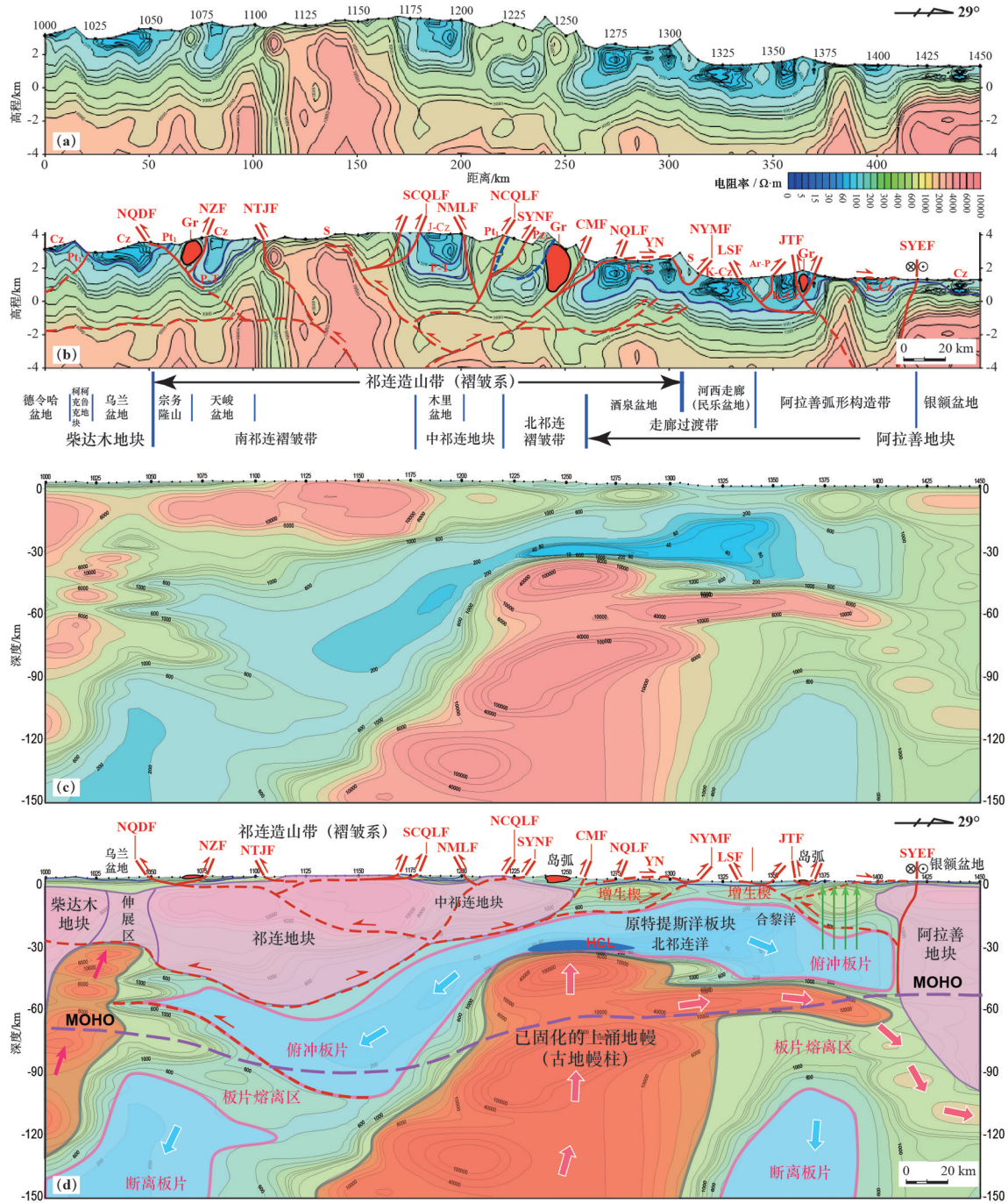


图6 大地电磁测深反演剖面(QLAL-2017MT)的构造解释

a—共轭梯度法浅层反演剖面;b—浅层反演剖面的构造解释;c—共轭梯度法中—深层反演剖面;d—中—深层反演剖面的构造解释;断裂名称: NQDF—柴达木盆地北缘断裂; NZF—北宗务隆山断裂; NTJF—天峻盆地北缘断裂; SCQLF—中祁连南缘断裂; NMLF—木里盆地北缘断裂; NCQLF—中祁连北缘断裂; SYNF—野牛沟南缘断裂; CMF—昌马—俄博断裂; NQLF—祁连山北缘断裂; YN—榆木山逆冲推覆构造; NYMF—榆木山北缘断裂; LSF—龙首山断裂; JTF—金塔断裂; SYEF—银额盆地南缘断裂; Gr—花岗岩

Fig.6 Structural geological explanation of magnetotelluric sounding profile (QLAL-2017MT)

a—Inversion profile of shallow layers using conjugate gradient method; b—Structural interpretation of inversion profile of shallow layers; c—Inversion profile of middle to deep layers using conjugate gradient method; d—Tectonic interpretation of inversion profile of middle to deep layers. Fault names: NQDF—North Qaidam Fault; NZF—North Zongwulong Shan Fault; NTJF—North Tianjun Fault; SCQLF—South Central Qilian Fault; NMLF—North Muli Fault; NCQLF—North Central Qilian Fault; SYNF—South Yeniugou Fault; CMF—Changma—Ebo Fault; NQLF—North Qilian Fault; YN—Yumushan Nappe; NYMF—North Yumushan Fault; LSF—Longshoushan Fault; JTF—Jinta Fault; SYEF—South Yin’e Fault; Gr—Granite

释。一维大地电磁测深曲线的近似反演采用Bostick法。二维反演采用共轭梯度法。

浅层精细反演采用的频率范围为10000~0.001 Hz,为常规MT频段加上向高频扩频部分,反演深度10 km,主要反映基底及以上沉积地层构造及展布特征(图6a)。本次研究尽可能多地收集和分析了地面地质及物性等资料,充分考虑了地层、岩性与电性的对应关系,对浅层反演结果进行标定和校正,提高了浅层反演的可靠性。按照由浅到深、由已知到未知的原则,在浅层反演结果可靠的条件下,也提高了中—深层的反演精度。

5.4 浅层结构特征

超宽频大地电磁测深剖面资料处理与反演结果显示了较为清晰的浅层地壳结构(图6b)。在剖面南部,MT浅层反演结果显示柴达木北缘乌兰盆地与北侧宗务隆山北缘断裂(NZF)的规模较小,宗务隆山底部与柴达木地块有着相似的电性特征,但往北电性界面的起伏明显增大,指示柴达木盆地北缘断裂(NQDF)、宗务隆山北缘断裂均与浅层新生代沉积盆地的挤压变形相关,往北挤压变形强度增大。在宗务隆山北缘断裂上盘出现的高阻异常表明,在宗务隆山存在岩体侵入,位置与地表出露的花岗岩及花岗闪长岩对应(郭安林等,2009)。宗务隆山北缘断裂北侧的新生代天峻盆地与柴达木北缘乌兰盆地具有非常相似的电性结构特征。

在新生代天峻盆地北侧,南祁连造山带出现显著的高阻电性体分布特征,高阻体在地表与出露的古生代次高阻层对应,地层岩性主要为志留系浅变质砂泥质岩石,岩石普遍发育片理及韧性变形,分布范围位于天峻盆地与中、新生代木里盆地之间,并在高阻体南北分界处形成电性快速变化的密集梯度带,南侧密集梯度带呈陡北倾,具有大型挤压逆冲构造特征,向下延伸规模较大。本次研究将之命名为天峻盆地北缘断裂(NTJF;图6b),可作为中、新生代柴达木盆地向北扩展的边界断裂。北侧过渡带同样具有北倾特征,但倾角较缓,具有北倾逆冲断层的特征,规模较大。

南祁连造山带北部的中、新生代木里盆地呈明显的低阻特征。木里盆地的南北两侧受挤压构造控制,具挤压拗陷盆地特征。木里盆地北缘断裂(NMLF)的南侧发育中祁连南缘断裂(SCQLF),总

体为南倾,构成南祁连造山带与中祁连地块的浅部边界。中祁连地块呈相对高阻特征,其中下元古界地层电阻率高于早古生界地层,与中祁连地表的元古界及北祁连早古生界地层的电性统计结果一致。中祁连北缘断裂(NCQLF)具有南倾特征,向下延伸规模较大,构成中祁连地块与北祁连造山带的浅部边界。

祁连山北缘断裂(NQLF)是祁连造山带与河西走廊过渡带的分界断裂,处在北祁连造山带的北缘,其北部以低阻的中、新生代盆地发育为主要特征。祁连山北缘断裂上盘主要为高阻地质体;断裂下盘主要为低阻的中、新生代沉积盆地,已发生强烈的挤压变形,盆地南缘被压伏在逆冲断层之下。由于断裂上盘强烈的逆冲挤压作用,在祁连山北缘断裂以北形成榆木山逆冲推覆构造(YN),祁连山北缘断裂构成逆冲推覆构造的根带。作为局部的高山,由志留系复理石建造为主的榆木山构成飞来峰构造,其之下均为电阻率较低的白垩系,说明在榆木山飞来峰之下为早白垩世酒泉盆地的一个分支;盆地基底发生明显压缩变形,底部具有隐伏断裂构造控制特征。榆木山北缘断裂(NYMF)构成逆冲推覆构造的前锋,也是该地区青藏高原的北界(陈宣华等,2019a)。

中—深层反演采用频率范围为320~0.0001 Hz,为常规MT加上低频扩频和超低频部分,反演深度可达150 km以深,主要反映地壳及上地幔的物性结构特征(图6c)。反演过程中采用了浅层静态位移校正的结果,对该频段曲线进行校正。

一维Bostick与二维共轭梯度反演结果的大体结构基本一致,二者在横向上结构相似,而在纵向上,共轭梯度比Bostick结果刻画精细,基本上可以划为高—低—高三套电性层,与地壳及上地幔的结构特征具有较好的一致性。因此,最终的地质构造解释主要依据二维共轭梯度反演结果。

在榆木山北缘断裂以北,中生代民乐盆地与榆木山南侧的酒泉盆地分支具有连续发育的特征,但盆地构造挤压变形幅度逐渐减弱;民乐盆地的白垩系和新生界沉积岩(K—Cz)最厚可达~4 km。

河西走廊盆地北侧的龙首山断裂(LSF)倾角较大,其向下部延伸的幅度不大,主要为走滑断裂特征,构成阿拉善地块的南界。阿拉善弧形构造带的

中部发育高阻基底隆起,分割了两侧的早白垩世拗陷盆地。南侧盆地发育的断裂及岩体规模进一步减弱,反映随着远离祁连造山带,阿拉善地块的刚性逐渐增强。在银额盆地南缘断裂(SYEF)处,出现明显的近直立基底电性扭折带,反映该断裂具有强烈走滑变形特征。SYEF北侧的银额盆地在剖面上具有较为稳定的基底和沉积盖层发育特征。

5.5 中—深层电性结构特征

祁连造山带及周缘深部电性结构差异较大,电性层起伏大,但具有一定的纵向成层性,可大致划分为4套电性层,分别为:上部高阻层,厚度一般小于40 km,主要对应上地壳;中上部低阻层,深度一般在20~70 km,低阻层断续分布,局部发育高阻团块异常,对应下地壳;中深部高阻层,一般埋深在50~120 km,高阻层断续分布,局部发育低阻异常,推测主要为上地幔的反映;深部低阻层,一般在120 km以深发育,连续性差,推测为软流圈的反映。

柴达木地块具有最厚的上地壳高阻层,电阻率高。南祁连造山带上地壳厚度大、电阻率高,中祁连地块、北祁连造山带与河西走廊过渡带的上地壳厚度小、电阻率低,并具有向北厚度变薄的趋势。阿拉善地块(银额盆地)的上地壳厚度较大,有一定的变化,电阻率中等。上地壳厚度变化反映了构造稳定性的变化;柴达木、南祁连和银额盆地的上地壳厚度大、电阻率高,具有较强的稳定性。

该剖面下地壳厚度变化在15~40 km。其中,柴达木地块的下地壳厚度最薄,只有18 km左右;向北厚度逐步增大,达40 km左右,在柴达木北缘断裂附近有明显上隆,至南祁连南部一直保持着较厚的下地壳。中祁连南部至河西走廊过渡带南部的下地壳逐渐变薄,发育有下地壳和MOHO(莫霍)面斜坡。河西走廊和龙首山之下的下地壳总体表现为一套电阻率极低的电性层,电阻率只有5~100 $\Omega \cdot m$,厚度较大。北部阿拉善地块的下地壳厚度一般在20~30 km。

从中—深层反演剖面来看,祁连造山带的莫霍面起伏较大,埋深在42~80 km,具有波状起伏特征。在柴达木地块的北缘和北祁连造山带—走廊过渡带南部地区,分别形成两个幔隆区。而在南祁连造山带—中祁连地块和阿拉善地块北部之下,则分别形成两个幔坳区;MOHO面最深处可能位于南

祁连造山带之下,最大可达80 km以深。

6 讨论

6.1 深部电性结构的构造指示意义

前人已有的多条大地电磁测深剖面显示,祁连造山带及周缘深部电性结构复杂多样,存在明显的横向变化和纵向分层(高锐等,1995;朱仁学、胡祥云,1995;汤吉等,2005;詹艳等,2008;赵国泽等,2010;Xiao et al., 2011, 2012, 2013, 2015, 2016)。其中,阿尔金断裂带为一个近于垂直的电阻率边界带;走廊过渡带总体显示为低阻(高速)异常,存在中、下地壳低阻异常区;走廊过渡带与北祁连之间存在“鳄鱼嘴”构造,其中、下地壳向北祁连下方俯冲,而上地壳有向南仰冲的构造样式;北祁连电性结构相对复杂,上地壳上部为高阻异常,上地壳下部局部存在低阻异常区,下地壳—上地幔顶部的低阻异常不发育;中祁连地块上地壳为明显的高阻异常,下地壳—上地幔顶部显示为低阻异常,不连续延伸至北祁连下方的上地幔之中;中、南祁连地块的上地壳以高阻异常为主,局部发育低阻异常区,下地壳发育低阻异常带,向南延伸至柴达木盆地内(Xiao et al., 2011, 2012, 2013, 2015, 2016)。

本研究给出的超宽频MT中—深层反演剖面显示,祁连造山带及周缘的岩石圈电性结构具有一个非常明显的特点,即广泛发育壳内和上地幔低阻(高导)层(HCL),其电阻率值较小;在北祁连造山带之下~30 km深度等局部地区的电阻率甚至小于10 $\Omega \cdot m$ 。这一高导层具有横向上的连续分布和间断特征,并在垂向上跨越了中、下地壳和上地幔,总体上表现为一个向南倾伏的倒转背形形态(图6c)。在中祁连地块—北祁连造山带—河西走廊过渡带地区,低阻高导层的上界面埋深最浅,可达上地壳的下部或地表浅层;向南,低阻高导层上界面的埋深逐渐加深,在南祁连造山带的宗务隆构造带之下~80 km深处发生断离,并继续向南在柴达木地块北缘之下迅速加深并向150 km以深延伸。在河西走廊过渡带下方,低阻高导层也在~80 km深处发生断离,并迅速向下进行垂向延伸,垂深可达150 km以深,导电性在20~40 $\Omega \cdot m$,接近于稳定大陆区的中、下地壳导电性。

祁连造山带及周缘的壳内和上地幔高导层成

因机制存在多种不同的观点。根据地质构造特征和流变学性质分析,含盐流体的填充、导电矿物的富集、壳内岩石的部分熔融等,均可引起中、下地壳电阻率的减小。但是,导电矿物的富集难以引起大范围连续分布壳内高导层的形成;而部分熔融多发生在火山发育区或具有较高热流值的区域,可能与地壳内部的局部热富集有关,要求有较高的温度,这与祁连造山带的情况相左。大地热流数据显示,中祁连地块的平均热流值为 68.3 mW/m^2 ,海原弧形构造区为 60 mW/m^2 ,均难以达到部分熔融的局部热富集要求。因此,用部分熔融来解释区内存在的高导体有一定的困难;部分作者倾向于含盐水流体成因(金胜等,2012)。也有的作者认为,祁连造山带的下地壳温度可达到或超过 $550 \text{ }^\circ\text{C}$,可能已发生部分熔融(李清河等,1998;涂毅敏等,2000)。一般认为,上地幔的高导层可能是岩石部分熔融与含盐水流体引起的。

现代海底之下 $50\sim 150 \text{ km}$ 处的大洋岩石圈上地幔具有高的电导率($0.02\sim 0.2 \text{ S/m}$; Naif, 2018)。与板块的年龄无关,亏损的洋中脊玄武岩地幔(DMM)在 $100\sim 300 \text{ km}$ 深处的电导率为 $10^{-1.2\sim -1.5} \text{ S/m}$ (Katsura et al., 2017)。考虑到大洋岩石圈的含水量较高和高温状态,而在通过俯冲碰撞导致大洋关闭而形成大陆之后,大洋岩石圈的残余(如蛇绿混杂岩带)经历了脱水和降温作用,其电导率应有所下降。Xu et al. (2016)认为,我国西北西准噶尔造山带的宽频带大地电磁测深剖面上存在晚古生代“化石”洋内俯冲带。Yin et al. (2017)在纵贯华北造山带(Trans-North China Orogen, 简称 TNCO)的MT阵列观测中,将电阻率为 $10\sim 100 \text{ } \Omega \cdot \text{m}$ 相对高导的岩石圈地幔解释为“化石”大洋俯冲带。本研究超宽频MT测深得到的祁连造山带壳内和上地幔高导层(HCL),与大洋岩石圈地幔的电导率相当,可能是大洋岩石圈板块的残余。

柴北缘—祁连造山带—走廊过渡带广泛出现的壳内和上地幔低阻高导层(HCL),除了该地区普遍存在的高含水量之外,也可能为早古生代双向俯冲的北祁连洋板块残余的反映(图6d);低阻高导层在局部可以通过逆冲断层连通到地表的蛇绿混杂岩带,也说明了其代表洋板块残余的可能性。同时,本研究提出的模式认为,祁连造山带之下发育

了大范围的层状低阻大洋俯冲板片的断裂构造,低阻大洋板片向南俯冲到巨厚的祁连造山带山根之下,出现大洋板片间断熔离区,并在熔离板片的前缘出现局部向上反冲的折返特征,这一构造特征与南祁连造山带中出现的蛇绿混杂岩带密切相关。在北祁连洋(原特提斯洋)板块的北部,向北俯冲的大洋板片以具有右行走滑性质的银额盆地南缘断裂(SYEF)为界与阿拉善地块对接,在对接带下部同样存在已断离的深俯冲古大洋板片,揭示了早古生代北祁连洋板块向南、北两个方向俯冲的双俯冲模式,以及加里东期古老造山带的山根和俯冲板片的断离构造。由于中生代以来挤压构造事件的影响,这一向南、北两侧双向俯冲构造的残余,也发生了严重的挤压缩短变形,构成向南倾伏的倒转背形形态。随着北祁连洋的俯冲、闭合,在双向古俯冲带的前缘分别出现了陆缘增生楔,以及其后部的岛弧岩浆带。由于后期区域挤压构造事件作用,在增生楔发育的地壳强度薄弱部位发育大规模的逆冲挤压和推覆,形成祁连山北缘的榆木山逆冲推覆和飞来峰构造(图6d)。

由于早古生代北祁连洋板块的消减而形成的祁连造山带,其南部边界为现今的柴达木盆地北缘,北部边界则为银额盆地的南缘,以银额盆地南缘断裂为界。俯冲消减的北祁连洋板块残片,包括断离板片、熔离板片和俯冲折返的板片,其累计的宽度可达 $\sim 600 \text{ km}$;如果再把出露地表的蛇绿混杂岩累计进来,北祁连洋板块残片的宽度将远远超过 $\sim 600 \text{ km}$,说明原特提斯北祁连洋的宽度远在 $\sim 600 \text{ km}$ 之上。

在双向俯冲的大洋板片下部,大型柱状高阻电性体一直向下延伸至上地幔深部,可能具有已固化的上涌古地幔柱的构造特征,推测为早古生代北祁连洋板块在南、北两个方向上进行双向俯冲的深部动力来源;上涌地幔大致在MOHO面深度出现向北的水平底辟扩展特征,并分割了向北俯冲的原特提斯洋板片。在剖面南部的柴达木地块与南祁连造山带交接部位,同样存在古老的地幔物质上涌构造残余,并在柴达木地块与南祁连造山带接触区域形成伸展变形区,但地幔上涌的规模较小,可能是该地区晚石炭世—二叠纪大陆裂谷与夭折了的宗务隆有限洋盆形成演化的深部记录。

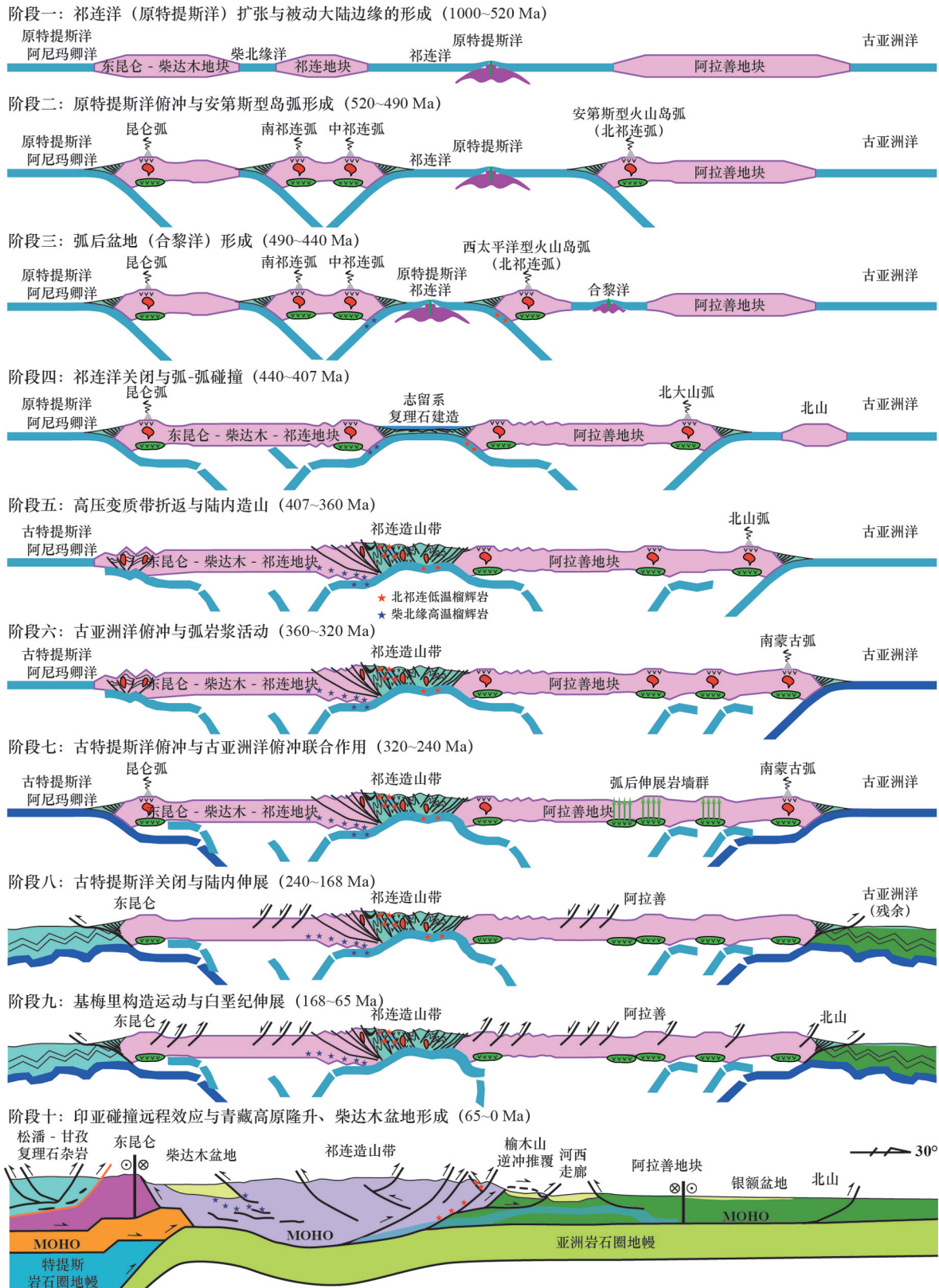


图7 祁连造山带及周缘新元古代以来构造演化模式
Fig.7 Tectonic evolution of the Qilian Orogenic Belt since Neo-Proterozoic

6.2 构造变形与构造演化

祁连造山带经历了早古生代原特提斯洋发育以来的构造演化,是青藏高原东北缘高原隆升与扩展的关键构造带。综合研究表明,祁连造山带可能经历了以下多个阶段的构造演化(图7)。

(1)北祁连洋扩张与被动大陆边缘的形成(1000~520 Ma):在经历中元古代罗迪尼亚(Rodinia)超大陆的裂解(~1.5 Ga; Wang et al., 2016)之后,祁连山地区又经历了新元古代大洋俯冲、大陆碰撞与裂解等过程(杨经绥等, 2009; 夏林圻等, 2016; Wu et al., 2016, 2017; Zuza et al., 2017)。新元古代以来,伴随着北祁连洋的扩张,形成了柴达木—祁连地块与阿拉善地块之间的原特提斯洋,其两侧发育被动大陆边缘。前奥陶纪时期,南祁连与中祁连—陇西地块和柴达木地块可能具有相同的地壳结构形式和物质组成特点(Song et al., 2013),属于同一个大陆板块;或者,柴达木地块与祁连造山带之间存在短暂的柴北缘洋。阿拉善地块构成古亚洲洋与特提斯洋两大构造域之间的分界,它既是原特提斯洋的北岸,又是古亚洲洋的南岸。

(2)北祁连洋俯冲、关闭与碰撞造山(520~407 Ma):早古生代,祁连山地区经历了原特提斯洋(北祁连洋)弧盆系的形成演化与大洋俯冲、大陆俯冲和碰撞造山等过程(Gehrels et al., 2003a, b; Xiao et al., 2009; 杨经绥等, 2009, 2010; Song et al., 2014; 潘桂棠、肖庆辉, 2015; 夏林圻等, 2016; 白建科等, 2016; Wu et al., 2016, 2017; 李冰等, 2017; Li et al., 2018)。原特提斯洋构造域北祁连洋板块向南和向北进行双向俯冲,在北祁连洋的北侧形成走廊南山岛弧和阿拉善南缘(北大山—大青山)早古生代岩浆弧,在南侧则形成中祁连岩浆弧(黄增保等, 2015)和南祁连岩浆弧(大陆弧; 朱小辉等, 2016)。此时,北祁连造山带肃南地区的下奥陶统沉积物源主要来自于其南侧的中祁连地块,也有少量来源于北部的北祁连岛弧等(李猛等, 2015)。柴北缘和北祁连的高压超高压(HP-UHP)变质作用同时形成,洋壳变质榴辉岩的年龄集中在470~460 Ma(Yang et al., 2002; Song et al., 2013, 2014; Zhang et al., 2017)。原特提斯(北祁连)洋板块向南和向北两个方向上的双向俯冲模式,可以较好地解释深地震反射、大地电磁测深等深部探测地球物理资料和该地

区花岗岩类侵入岩体的分布特征。

(3)陆内造山、弧后伸展与宗务隆有限洋盆(407~240 Ma):祁连山造山带和华北克拉通之间的碰撞使混杂堆积上冲到华北克拉通的被动大陆边缘地层之上。早泥盆世,祁连山地区广泛发育磨拉石建造;晚泥盆世进入后造山的伸展垮塌阶段(孙廷贵等, 2004; 吴才来等, 2004; 杨超等, 2010; 夏林圻等, 2016)。至石炭纪,祁连山及周缘继续处于区域性伸展环境,形成宗务隆有限洋盆(郝国杰等, 2004; 孙娇鹏等, 2014),可能是古特提斯洋(Gehrels et al., 2011)北部的一个分支。早二叠世(~276 Ma),古亚洲洋构造域南缘和阿拉善地块普遍发育与陆内伸展有关的基性岩墙群(Zhang et al., 2017)。河西走廊北侧大青山—北大山一带晚石炭世—早三叠世时期的岩浆侵入活动,可能与古亚洲洋南缘的边缘海在此关闭及洋壳俯冲的过程有关。晚二叠世—早三叠世以来,祁连山地区处在古特提斯洋向北俯冲形成的东昆仑—柴达木—西秦岭岩浆弧地体的北侧(Chen et al., 2015),构成东昆仑—柴达木—祁连—西秦岭地块的一部分。

(4)古特提斯洋的关闭、陆内伸展与早白垩世构造挤压(240~65 Ma):受古特提斯洋关闭的影响,祁连造山带及周缘普遍发育印支期挤压构造变形(Chen et al., 2015; Li et al., 2017)。祁连造山带内部发育的三叠纪盆地沉积,记录了印支期构造挤压事件。之后的晚三叠世晚期与早、中侏罗世,祁连造山带和柴达木盆地等地区整体处于伸展构造环境(郭召杰等, 1998; 金之钧等, 1999; 戴俊生等, 2000; 汤良杰等, 2000; 罗金海等, 2001; 曾联波等, 2001, 2002; Chen et al., 2003; Yin et al., 2008; 陈宣华等, 2010)。

在中国东部广泛发育的燕山运动(~165 Ma)与中国西部印度—亚洲大陆碰撞事件(~55 Ma; Yin and Harrison, 2000)之间,河西走廊北部地区曾发生了一次早白垩世早期的南北向构造挤压事件,可能是中特提斯洋关闭事件(或称之为基梅里运动,即班公湖—怒江洋俯冲和关闭事件)及其远程效应的具体表现。早白垩世构造挤压导致祁连造山带内部及周缘早白垩世大量类前陆盆地(如平山湖盆地; 邵浩浩等, 2019)的形成,祁连山北缘断裂等继续活动,形成榆木山逆冲推覆和飞来峰构造(陈宣

华等,2019a)。祁连山北缘及榆木山飞来峰之下掩伏有早白垩世早期的沉积盆地,是油气与水资源勘查的重要远景区(潘宏勋等,2000;陈宣华等,2019a)。早白垩世晚期普遍发育的伸展作用和伸展断陷盆地的形成(Chen et al., 2003; 陈宣华等, 2019a),改造了榆木山逆冲推覆构造及其逆掩断层之下的白垩系褶皱构造;白垩纪中期则是北祁连和酒西盆地等烃类形成的主要时期。早白垩世早期的构造挤压,是先于新生代青藏高原整体形成的一次高原雏形形成事件,具有重要的大陆动力学和大地构造意义。

(5)印度—亚洲碰撞远程效应(65~0 Ma):新生代在印度板块与欧亚大陆碰撞造山(始于~55 Ma)的大规模挤压构造背景下,柴达木地区发育大型压陷盆地(E₂-Qp; Yin and Harrison, 2000; Yin et al., 2002; 陈宣华等,2010)。在祁连造山带,新生代陆内造山作用强烈,发育逆冲断裂作用(Wu et al., 2016; Zusa et al., 2016, 2017, 2019; Li Bing et al., 2019; 陈宣华等,2019a),具有复杂的造山带地壳结构和深部过程(Wang et al., 2011; Gao et al., 2013; 赵文津等, 2014; Ye et al., 2015, 2016; 陈宣华等, 2019a)。祁连造山带复杂的逆冲断裂作用使得老的南倾俯冲带再次活动,在被动大陆边缘地层与基底之间产生新的滑脱构造,新生代逆冲作用使得蛇绿混杂岩带在造山带的不同部位重复出现,分割了原来作为整体的北祁连洋板块南、北两个俯冲造山带。中新世冷却历史(20~10 Ma)记录了北祁连造山带最初的剥露作用,与青藏高原—塔里木地区普遍的新生代隆升与剥露历史相一致(George et al., 2001)。

7 结 论

本文通过超宽频大地电磁测深剖面给出的全地壳深部结构特征,结合区域地质调查与构造解析,初步分析了青藏高原东北部祁连造山带深部地壳结构与构造变形特征,在前人基础上,进一步建立了区域构造演化模型,得到以下结论:

(1)超宽频大地电磁测深(MT)剖面的浅层反演与构造解释,揭示了祁连造山带盆山结构特征。祁连山北缘发育榆木山逆冲推覆构造和飞来峰,使得早白垩世沉积盆地被逆冲推覆体所掩埋,具有油

气勘查的前景。构造解析表明,榆木山逆冲推覆构造的发育可能在早白垩世的早期,并受到中新世以来印度—亚洲大陆碰撞远程效应引起的挤压构造变形的影响。

(2)MT剖面中深层反演显示,早古生代(原特提斯)北祁连洋板块具有向南和向北双向俯冲的化石俯冲带深部结构特征。中、南祁连之下的北祁连洋板块具有向南在柴达木—祁连地块之下低角度俯冲的深部结构特征,其俯冲断离的板片至少可以达到现今柴达木盆地北缘的位置。在祁连山北侧,北祁连洋板块向北的俯冲作用产状较陡,而其俯冲断离的板片甚至发生了产状倒转。中生代以来的构造挤压变形可能是其发生北翼倒转的背形褶皱作用的原因。

(3)深部结构特征显示,由于早古生代北祁连洋板块的消减而形成的祁连造山带,其南部边界为现今的柴达木盆地北缘,北部边界则为银额盆地的南缘,以银额盆地南缘断裂为界。通过俯冲消减的北祁连洋板块残片,计算得到原特提斯北祁连洋的宽度约600 km之上。

致谢:本文参加野外地质调查工作的还有徐盛林、张焱焱、王永超、邵浩浩、陈泓旭、韩建恩、史建杰、李江瑜、苗慧心、李杰、王洛娟、贺承广、韩乐乐、秦翔、余苇、丁伟翠、王叶、马飞宙、周琦等,研究工作得到中国地质调查局西北项目办和甘肃省张掖丹霞国家地质公园等的大力支持与帮助,东方地球物理公司综合物化探处协助完成QLAL-2017MT大地电磁剖面数据采集与资料处理,笔者在此一并表示衷心感谢。

References

- Bai Jianke, Wang Hongliang, Zhu Xiaohui, Xie Congrui. 2016. Characteristics of olistostromes from the Ordovician Zhongbao Group in Shihuigou area, North Qilian orogenic belt and their palaeogeographic implications[J]. *Geology in China*, 43 (3): 977-986 (in Chinese with English abstract).
- Chen Bailin, Wang Chunyu, Cui Lingling, Liu Jianmin. 2008. Developing model of thrust fault system in western part of northern Qilian Mountains margin-Hexi Corridor basin during late Quaternary[J]. *Earth Science Frontiers*, 15 (6): 260-277 (in Chinese with English abstract).
- Chen Gan, Zheng Wenjun, Wang Xulong, Zhang Peizhen, Xiong Jianguo, Yu Jinxing, Liu Xingwang, Bi Haiyun, Liu Jinrui, Ai

- Ming. 2017. Present kinematics characteristics of the northern Yumushan active fault and its response to the northeastward growth of the Tibetan Plateau[J]. *Seismology and Geology*, 39 (5): 871–888 (in Chinese with English abstract).
- Chen Xuanhua, Yin A, Gehrels G E, Cowgill E S, Grove M, Harrison T M, Wang X–F. 2003. Two phases of Mesozoic north–south extension in the eastern Altyn Tagh range, northern Tibetan Plateau[J]. *Tectonics*, 22 (5): 1053, DOI: 10.1029/2001TC001336.
- Chen Xuanhua, Dang Yuqi, Yin An, Wang Liqun, Jiang Wuming, Jiang Rongbao, Zhou Suping, Liu Mingde, Ye Baoyin, Zhang Min, Ma Lixie, Li Li. 2010. Basin–mountain Coupling and Tectonic Evolution of Qaidam Basin and its Adjacent Orogenic Belts[M]. Beijing: Geological Publishing House, 1–365 (in Chinese).
- Chen Xuanhua, Gehrels G, Yin A, Zhou Q, Huang P. 2015. Geochemical and Nd–Sr–Pb–O isotopic constrains on Permo–Triassic magmatism in eastern Qaidam Basin, northern Qinghai–Tibetan plateau: Implications for the evolution of the Paleo–Tethys[J]. *Journal of Asian Earth Sciences*, 114: 674–692.
- Chen Xuanhua, Chen Zhengle, Han Shuqin, Yang Yi, Wang Zhihong, Jia Muxin, Ye Baoying, Shi Wei, Nie Lanshi, Ding Weicui, Bai Yanfei, Li Yong, Shi Jianjie, Li Bing, Shao Zhaogang, Liu Chunyong, Liu Gang, Zhang Yiping, Xu Shenglin, Ma Feizhou. 2017. Tectonic, Magmatic, and Metallogenic Evolution of the Balkhash and West Junggar Metallogenic Belt, Central Asia[M]. Beijing: Geological Publishing House, 1–539 (in Chinese).
- Chen Xuanhua, Shao Zhaogang, Xiong Xiaosong, Gao Rui, Xu Shenglin, Zhang Yiping, Li Bing, Wang Ye. 2019a. Early Cretaceous overthrusting of Yumu Mountain and hydrocarbon prospect on the northern margin of the Qilian Orogenic Belt[J]. *Acta Geoscientica Sinica*, 40 (3): 377–392 (in Chinese with English abstract).
- Chen Xuanhua, Li Jiangyu, Dong Shuwen, Shi Wei, Bai Yanfei, Zbhang Yiping, Ding Weicui. 2019b. Tectonic deformation of Jurassic Ningwu–Jingle Basin and its implication for the beginning of Yanshanian Orogeny in Central North China Craton[J]. *Geotectonica et Metallogenia*, 43 (3): 389–408 (in Chinese with English abstract).
- Chen Zhengle, Wang Xiaofeng, Yin An, Chen Bailin, Chen Xuanhua. 2004. Cenozoic left–slip motion along the central Altyn Tagh fault as inferred from the sedimentary record[J]. *International Geology Review*, 46: 839–856.
- Cheng Feng, Garzzone C, Jolivet M, Wang Weitao, Dong Jibao, Richter F, Guo Zhaojie. 2019. Provenance analysis of the Yumen Basin and northern Qilian Shan: Implications for the pre–collisional paleogeography in the NE Tibetan plateau and eastern termination of Altyn Tagh fault[J]. *Gondwana Research*, 65: 156–171.
- Cui Junwen, Tang Zheming, Deng Jinfu, Yue Yongjun, Meng Lingshun. 1999. Altun Fault System[M]. Beijing: Geological Publishing House, 1–249 (in Chinese).
- Deng Jinfu, Wu Zongxu, Yang Jianjun, Zhao Hailing, Liu Houxiang, Lai Shaocong, Di Yongjun. 1995. Crust–Mantle petrological structure and deep processes along the Golmud–Ejin Qi geoscience section[J]. *Acta Geophysica Sinica*, 38 (Supp.II): 130–144 (in Chinese with English abstract).
- Fen Zhihan, Liu Kuanhou, Guo Peihong, Wang Yilin. 2018. Characteristics of Gravity and Magnetic Fields in Northwest China and its Applications[M]. Wuhan: China University of Geosciences Press, 1–235 (in Chinese).
- Gao Rui, Li Tingdong, Wu Gongjian. 1998. Lithospheric evolution geodynamic process of the Qinghai–Tibet Plateau: An inspiration from the Yadong–Golmud–Ejin Geoscience Transect[J]. *Geological Review*, 44 (4): 389–395 (in Chinese with English abstract).
- Gao Rui, Wang Haiyan, Yin An, Dong Shuwen, Kuang Zhaoyang, Zusa A V, Li Wenhui, Xiong Xiaosong. 2013. Tectonic development of the northeastern Tibetan Plateau as constrained by high–resolution deep seismic–reflection data[J]. *Lithosphere*, 5 (6): 555–574.
- Gehrels G E, Yin A, Wang X F. 2003a. Magmatic history of the northeastern Tibetan Plateau[J]. *Journal of Geophysical Research*, 108 (B9): 2423, doi: 10.1029/2002JB001876.
- Gehrels G E, Yin A, Wang X F. 2003b. Detrital–zircon geochronology of the northeastern Tibetan Plateau[J]. *Geological Society of America Bulletin*, 115: 881–896.
- Gehrels G, Kapp P, DeCelles P, Pullen A, Blakey R, Weislogel A, Ding L, Guynn J, Martin A, McQuarrie N, Yin A. 2011. Detrital zircon geochronology of pre–Tertiary strata in the Tibetan–Himalayan orogen[J]. *Tectonics*, 30: TC5016, doi:10.1029/2011TC002868.
- George A D, Marshallsea S J, Wyrwoll K–H, Chen J, Lu Y. 2001. Miocene cooling in the northern Qilian Shan, northeastern margin of the Tibetan Plateau, revealed by apatite fission–track and vitrinite–reflectance analysis[J]. *Geology*, 29: 939–942.
- Guo Anlin, Zhang Guowei, Qiang Juan, Sun Yangui, Li Guang, Yao Anping. 2009. Indosinian Zongwulong orogenic belt on the northeastern margin of the Qinghai–Tibet plateau[J]. *Acta Petrologica Sinica*, 25 (1): 1–12 (in Chinese with English abstract).
- IGCEA (Institute of Geology, China Earthquake Administration), LISCEA (Lanzhou Institute of Seismology, China Earthquake Administration). 1993. The Qilian Mountain – Hexi Corridor Active Fault System[M]. Beijing: Seismological Press, 1–340 (in Chinese with English abstract).
- LISCEA (Lanzhou Institute of Seismology, China Earthquake Administration). 1992. Changma Active Fault Zone[M]. Beijing: Seismological Press, 1–207 (in Chinese).
- Hao Guojie, Lu Songnian, Wang Huichu, Xin Houtian, Li Huaikun. 2004. The pre–Devonian tectonic framework in the northern margin of Qaidam basin and geological evolution of Olongbuluk

- palaeo-block[J]. *Earth Science Frontiers*, 11 (3): 115–122 (in Chinese with English abstract).
- Hetzl R, Tao Mingxin, Stokes S, Niedermann S, Ivy-Ochs S, Gao Bo, Strecker M R, Kubik P W. 2004. Late Pleistocene / Holocene slip rate of the Zhangye thrust (Qilian Shan, China) and implications for the active growth of the northeastern Tibetan Plateau[J]. *Tectonics*, 23: TC6006, doi:10.1029/2004TC001653.
- Hu Daogong, Qi Bangshen, Zhang Yaoling, Song Huanxin, Qi Shengsheng, Zhao Xitao, Zhang Xujiao, Wen Zhigang. 2018. Cenozoic Tectonic Environment Evolution and Uplift Process in Qilian Mountains[M]. Beijing: Geological Publishing House, 1–210 (in Chinese).
- Huang Zengbao, Zheng Jianping, Li Baohua, Wei Zhijun, Qi Wei, Chen Xu. 2015. Geochronology and geochemistry of Yemashan batholiths in western Central Qilian and its tectonic implications[J]. *Geology in China*, 42 (2): 406–420 (in Chinese with English abstract).
- Jin Sheng, Zhang Letian, Jin Yongji, Wei Wenbo, Ye Gaofeng. 2012. Crustal electrical structure along the Hezuo–Dajing profile across the Northeastern Margin of the Tibetan Plateau[J]. *Chinese Journal of Geophysics*, 55 (12): 3979–3990 (in Chinese with English abstract).
- Katsura T, Baba K, Yoshino T, Kogiso T. 2017. Electrical conductivity of the oceanic asthenosphere and its interpretation based on laboratory measurements[J]. *Tectonophysics*, 717: 162–181.
- Li Bing, Hu Daogong, Chen Xuanhua, Zhang Yaoling, Wu Huanhuan, Wang Chaoqun. 2017. Age and tectonic setting of the granite porphyry within Youhulugou ophiolite in the suture zone of the North Qilian Mountain[J]. *Geoscience*, 31 (5): 883–889 (in Chinese with English abstract).
- Li Bing, Chen Xuanhua, Andrew V. Zuzi, Hu Daogong, Ding Weicui, Huang Penghui, Xu Shenglin. 2019. Cenozoic cooling history of the North Qilian Shan, northern Tibetan Plateau, and the initiation of the Haiyuan fault: Constraints from apatite- and zircon-fission track thermochronology[J]. *Tectonophysics*, 751: 109–124.
- Li Fenqi. 2003. New evidence for the presence of the NS-trending extensional structures in northwestern China: An example from the Early Cretaceous half-graben fault depressions in Jiuquan, Gansu[J]. *Sedimentary Geology and Tethyan Geology*, 23 (2): 35–42 (in Chinese with English abstract).
- Li Meng, Wang Chao, Li Rongshe, Peng Yan. 2015. Age and provenance of the Yingou Group in Sunan area of North Qilian Mountain: Evidence from detrital zircon U–Pb dating[J]. *Geology in China*, 42 (3): 601–615 (in Chinese with English abstract).
- Li Qinghe, Zhang Yuansheng, Tu Yimin, Fan Bing. 1998. The combined interpretation of crustal velocity and electrical resistivity in Qilianshan Mountain – Hexi Corridor region[J]. *Chinese Journal of Geophysics*, 41 (2): 197–210 (in Chinese with English abstract).
- Li Sanzhong, Jahn Bor-ming, Zhao Shujuan, Dai Liming, Li Xiyao, Suo Yanhui, Guo Lingli, Wang Yongming, Liu Xiaochun, Lan Haoyuan, Zhou Zaizheng, Zheng Qiliang, Wang Pengcheng. 2017. Triassic southeastward subduction of North China Block to South China Block: Insights from new geological, geophysical and geochemical data[J]. *Earth-Science Reviews*, 166: 270–285.
- Li Sanzhong, Zhao Shujuan, Liu Xin, Cao Huahua, Yu Shan, Li Xiyao, Somerville I, Yu Shengyao, Suo Yanhui. 2018. Closure of the Proto-Tethys Ocean and Early Paleozoic amalgamation of microcontinental blocks in East Asia[J]. *Earth-Science Reviews*, 186: 37–75.
- Li Yalin, Wang Chengshan, Dai Jingen, Xu Ganqing, Hou Yunling, Li Xiaohan. 2015. Propagation of the deformation and growth of the Tibetan-Himalayan orogen: A review[J]. *Earth-Science Reviews*, 143: 36–61.
- Li Yulong. 1984. The characteristics and active period of Jiayuguan Fault[J]. *Journal of Lanzhou University (Natural Science Edition)*, 20 (2): 118–123 (in Chinese with English abstract).
- Lü Qingtian, Meng Guixiang, Yan Jiayong, Zhang Kun, Zhao Jinhua, Gong Xuejing. 2019. Multi-scale exploration of mineral system: Concept and progress — A case study in the middle and lower reaches of the Yangtze River Metallogenic Belt[J]. *Geology in China*, 46 (4): 673–689 (in Chinese with English abstract).
- Naif S. 2018. An upper bound on the electrical conductivity of hydrated oceanic mantle at the onset of dehydration melting[J]. *Earth and Planetary Science Letters*, 482: 357–366.
- Pan Guitang, Xiao Qinghui. 2015. Explanatory Note to the Tectonic Map of China (1 : 2 500 000) [M]. Beijing: Geological Publishing House, 1–160 (in Chinese).
- Pan Hongxun, Ge Xiaohong, Liu Junlai. 2000. Query to the Yumushan uplift on the north margin of Qilian Mountain[J]. *Journal of Changchun University of Science and Technology*, 30 (1): 9–13 (in Chinese with English abstract).
- Pei Xianzhi, Meng Yong, Ding Saping, Li Zuochen, Liu Zhanqing, Liu Huibin, Li Gaoyang, Li Ruibao. 2007. Identification of 2.5 Ga detrital zircons from Conjoint area between Qilian–Qinling Orogenic Belts and its geological implication[J]. *Journal of Earth Sciences and Environment*, 29 (2): 111–116 (in Chinese with English abstract).
- Ren Jishun, Niu Baogui, Wang Jun, Jin Xiaochi, Xie Liangzhen. 2013. International Geological Map of Asia (1 : 5 000 000) [M]. Beijing: Geological Publishing House.
- Ren Junjie, Xu Xiwei, Zhang Shimin, Ding Rui, Liu Hanyong, Liang Oubo, Zhao Junxiang. 2019. Late Quaternary slip rates and Holocene paleoearthquakes of the eastern Yumu Shan fault, northeast Tibet: Implications for kinematic mechanism and seismic hazard[J]. *Journal of Asian Earth Sciences*, 176: 42–56.
- Shao Haohao, Chen Xuanhua, Zhang Da, Shao Zhaogang, Li Bing, Wang Zengzhen, Zhang Yiping, Xu Shenglin, Shi Jianjie, Miao Huixin. 2019. The Lower Cretaceous tectonic deformation stages

- and detrital zircon U – Pb ages of Pingshanhu Basin in Hexi Corridor[J]. *Geology in China*, 46(5): 1079–1093(in Chinese with English abstract).
- Shi Wei, Liu Yuan, Liu Yang, Chen Peng, Chen Long, Cen Min, Huang Xingfu, Li Hengqiang. 2013. Cenozoic evolution of the Haiyuan fault zone in the northeast margin of the Tibetan Plateau[J]. *Earth Science Frontiers*, 20 (4): 1–17 (in Chinese with English abstract).
- Song S G, Yang J S, Xu Z Q, Liou J G, Shi R D. 2003a. Metamorphic evolution of the coesite-bearing ultrahigh-pressure terrane in the North Qaidam, Northern Tibet, NW China[J]. *Journal of Metamorphic Geology*, 21: 631–644.
- Song S G, Yang J S, Liou J G, Wu C L, Shi R D, Xu Z Q. 2003b. Petrology, geochemistry and isotopic ages of eclogites from the Dulan UHPM Terrane, the North Qaidam, NW China[J]. *Lithos*, 70: 195–211.
- Song S G, Zhang L F, Niu Y L, Su L, Jian P, Liu D Y. 2005. Geochronology of diamond-bearing zircons from garnet peridotite in the North Qaidam UHPM belt, Northern Tibetan Plateau: A record of complex histories from oceanic lithosphere subduction to continental collision[J]. *Earth and Planetary Science Letters*, 234: 99–118.
- Song S G, Zhang L F, Niu Y L, Su L, Song B A, Liu D Y. 2006. Evolution from oceanic subduction to continental collision: a case study from the Northern Tibetan Plateau based on geochemical and geochronological data[J]. *Journal of Petrology*, 47: 435–455.
- Song Shuguang, Niu Yaoling, Zhang Lifei, Wei Chunjing, Liou J G, Su Li. 2009. Tectonic evolution of early Paleozoic HP metamorphic rocks in the North Qilian Mountains, NW China: New perspectives[J]. *Journal of Asian Earth Sciences*, 35: 334–353.
- Song Shuguang, Niu Yaoling, Zhang Lifei, Zhang Guibin. 2009. Time constraints on orogenesis from oceanic subduction to continental subduction, collision, and exhumation: An example from North Qilian and North Qaidam HP–UHP belts[J]. *Acta Petrologica Sinica*, 25 (9): 2067–2077 (in Chinese with English abstract).
- Song Shuguang, Niu Yaoling, Su Li, Xia Xiaohong. 2013. Tectonics of the North Qilian orogen, NW China[J]. *Gondwana Research*, 23 (4): 1378–1401.
- Song S G, Niu, Y L, Su L, Zhang C, Zhang L F. 2014. Continental orogenesis from ocean subduction, continent collision/subduction, to orogen collapse, and orogen recycling: The example of the North Qaidam UHPM belt, NW China[J]. *Earth–Science Reviews*, 129: 59–84.
- Sun Jiaopeng, Chen Shiyue, Hu Zhongya, Liu Wenping, Guo Chen, Ma Shuai. 2014. Research on the mixed model and developmental characteristic of the clastic–carbonate diamictite facies in the northern Qaidam[J]. *Natural Gas Geoscience*, 25 (10): 1586–1593 (in Chinese with English abstract).
- Sun Yangui, Zhang Guowei, Wang Jin, Zhan Fayu, Zhang Zhiyong. 2004. $^{40}\text{Ar}/^{39}\text{Ar}$ age of the basic sill swarms of two periods in the Junction area of Qinling and Kunlun and its tectonic significance[J]. *Acta Geologica Sinica*, 78 (1): 65–71 (in Chinese with English abstract).
- Tang Ji, Zhan Yan, Zhao Guoze, Deng Qianhui, Wang Jijun, Chen Xiaobin, Zhao Junmeng, Xuan Fei. 2005. Electrical conductivity structure of the crust and upper mantle in the northeastern margin of the Qinghai–Tibet plateau along the profile Maqen–Lanzhou–Jingbian[J]. *Chinese Journal of Geophysics* (in Chinese), 48 (5): 1205–1216 (in Chinese with English abstract).
- Tapponnier P, Meyer B, Avouac J P, Peltzer G, Gaudemer Y, Guo Shunmin, Xiang Hongfa, Yin Kelun, Chen Zhitai, Cai Shuahua, Dai Huagang. 1990. Active thrusting and folding in the Qilian Shan, and decoupling between upper crust and mantle in northeastern Tibet[J]. *Earth and Planetary Science Letters*, 97: 382–403.
- Tu Yimin, Li Qinghe, Cheng Jin. 2000. Seismic velocity structure and electric resistivity on north segment of the North–South Seismic Zone[J]. *Northwestern Seismological Journal*, 22 (4): 353–360 (in Chinese with English abstract).
- Wang Chengshan, Gao Rui, Yin An, Wang Haiyan, Zhang Yuxiu, Guo Tonglou, Li Qusheng, Li Yalin. 2011. A mid-crustal strain-transfer model for continental deformation: A new perspective from high-resolution deep seismic-reflection profiling across NE Tibet[J]. *Earth and Planetary Science Letters*, 306: 279–288.
- Wang Genhou, Ran Shuming, Li Ming. 2001. The characteristics of Neogene Sertengshan–Xietieshan oblique thrust fault in the northern margin of Qaidam Basin[J]. *Journal of Geomechanics*, 7 (3): 224–230 (in Chinese with English abstract).
- Wang Huichu, Lu Songnian, Mo Xuanxue, Li Huaikun, Xin Houtian. 2005. An Early Paleozoic collisional orogen on the northern margin of the Qaidam basin, northwestern China[J]. *Geological Bulletin of China*, 24 (7): 603–612 (in Chinese with English abstract).
- Wang Liquan, Pan Guitang, Ding Jun, Yao Dongsheng. 2013. *Geological Map of the Qinghai–Tibet Plateau and Explanatory Notes (1 : 500 000)* [M]. Beijing: Geological Publishing House, 1–288 (in Chinese).
- Wang Lu, Wang Heng, He Chuan, Chen Nengsong, Santosh M, Sun Min, Wang Qinyan, Jin Lanlan, Liao Fanxi. 2016. Mesoproterozoic continental breakup in NW China: Evidence from gray gneisses from the North Wulan terrane[J]. *Precambrian Research*, 281: 521–536.
- Wang Weitao, Zhang Peizhen, Zheng Dewen, Pang Jianzhang. 2014. Late Cenozoic tectonic deformation of the Haiyuan fault zone in the northeastern margin of the Tibetan Plateau[J]. *Earth Science Frontiers*, 21 (4): 266–274 (in Chinese with English abstract).
- Wu Cailai, Yang Jingsui, Yang Hongyi, Wooden J L, Shi Rendeng, Chen Songyong, Zheng Qiuguang. 2004. Dating of two types of granite from north Qilian, China[J]. *Acta Petrologica Sinica*, 20 (3): 425–432 (in Chinese with English abstract).

- Wu Cailai, Yao Shangzhi, Yang Jingsui, Zeng Lingsen, Chen Songyong, Li Haibing, Qi Xuexiang, Wooden J L, Mazdab F K. 2006. Double subduction of the Early Paleozoic North Qilian oceanic plate: Evidence from granites in the central segment of North Qilian, NW China[J]. *Geology in China*, 33 (6): 1197–1208 (in Chinese with English abstract).
- Wu Chen, Yin An, Zuza A V, Zhang Jinyu, Liu Wencan, Ding Lin. 2016. Pre-Cenozoic geologic history of the central and northern Tibetan Plateau and the role of Wilson cycles in constructing the Tethyan orogenic system[J]. *Lithosphere*, 8 (3): 254–292.
- Wu Chen, Zuza A V, Yin An, Liu Changfeng, Reith R C, Zhang Jinyu, Liu Wencan, Zhou Zhiguang. 2017. Geochronology and geochemistry of Neoproterozoic granitoids in the central Qilian Shan of northern Tibet: Reconstructing the amalgamation processes and tectonic history of Asia[J]. *Lithosphere*, 9 (4): 609–636.
- Wu Chen, Zuza A V, Chen Xuanhua, Ding Lin, Levy D A, Liu Changfeng, Liu Wencan, Jiang Tian, Stockli D F. 2019. Tectonics of the Eastern Kunlun Range: Cenozoic reactivation of a Paleozoic–Early Mesozoic Orogen[J]. *Tectonics*, 38. doi: 10.1029/2018TC005370.
- Xia Linqi, Li Xiangmin, Yu Jiyuan, Wang Guoqiang. 2016. Mid–Late Neoproterozoic to Early Paleozoic volcanism and tectonic evolution of the Qilian Mountain[J]. *Geology in China*, 43 (4): 1087–1138 (in Chinese with English abstract).
- Xiao Q B, Zhao G Z, Dong Z Y. 2011. Electrical resistivity structure at the northern margin of the Tibetan Plateau and tectonic implications[J]. *Journal of Geophysical Research*, 116 (B12): 401.
- Xiao Q B, Zhang J, Wang J J, Zhao G Z, Tang J. 2012. Electrical resistivity structures between the Northern Qilian Mountains and Beishan Block, NW China, and tectonic implications[J]. *Physics of the Earth and Planetary Interiors*, 200–201: 92–104.
- Xiao Q B, Zhang J, Zhao G Z, Wang J. 2013. Electrical resistivity structures northeast of the Eastern Kunlun fault in the Northeastern Tibet: Tectonic implications[J]. *Tectonophysics*, 601: 125–138.
- Xiao Q, Shao G, Liu–Zeng J, Oskim M E, Zhang J, Zhao G, Wang J. 2015. Eastern termination of the Altyn Tagh Fault, western China: Constraints from a magnetotelluric survey[J]. *Journal of Geophysical Research – Solid Earth*, 120: 283–2858.
- Xiao Qibin, Shao Guihang, Yu Guo, Cai Juntao, Wang Jijun. 2016. Electrical resistivity structures of the Kunlun–Qaidam–Qilian system at the northern Tibet and their tectonic implications[J]. *Physics of the Earth and Planetary Interiors*, 255: 1–17.
- Xiao Wenjiao, Windley B F, Yong Yong, Yan Zhen, Yuan Chao, Liu Chuanzhou, Li Jiliang. 2009. Early Paleozoic to Devonian multiple–accretionary model for the Qilian Shan, NW China[J]. *Journal of Asian Earth Sciences*, 35: 323–333.
- Xiong Shengqing, Fan Zhengguo, Zhang Hongrui, Ding Yanyun, Huang Xuzhao, Li Zhankui, Guo Zhihong, Yang Xue, Tong Jing, Liu Qiankun, Zhou Daoqing, Tan Lin, Zhang Junwei. 2015. Introduction to Aeromagnetic Map Series of Continental China (1:2 500 000) [M]. Beijing: Geological Publishing House, 1–19 (in Chinese).
- Xu Yixian, Yang Bo, Zhang Sheng, Liu Ying, Zhu Lupei, Huang Rong, Chen Chao, Li Yongtao, Luo Yinhe. 2016. Magnetotelluric imaging of a fossil paleozoic intraoceanic subduction zone in western Junggar, NW China[J]. *Journal of Geophysical Research: Solid Earth*, 121: 4103–4147.
- Xu Zhiqin, Yang Jingsui, Zhang Jianxin, Jiang Mei, Li Haibing, Cui Junwen. 1999. A comparison between the tectonic units on the two sides of the Altun sinistral strike–slip fault and the mechanism of lithospheric shearing[J]. *Acta Geologica Sinica*, 73 (3): 193–205 (in Chinese with English abstract).
- Yang Chao, Cen Qinghua, Wang Guanmin, Pang Xiaojun, Ma Tingting. 2010. Sedimentary and tectonic evolution of Qaidam areas in Late Paleozoic[J]. *Journal of China University of Petroleum*, 34 (5): 38–49 (in Chinese with English abstract).
- Yang Haibo, Yang Xiaoping, Zhang Huiping, Huang Xiongnan, Huang Weiliang, Zhang Ning. 2018a. Active fold deformation and crustal shortening rates of the Qilian Shan Foreland Thrust Belt, NE Tibet, since the Late Pleistocene[J]. *Tectonophysics*, 742–743: 84–100.
- Yang Haibo, Yang Xiaoping, Huang Xiongnan, Li An, Huang Weiliang, Zhang Ling. 2018b. New constraints on slip rates of the Fodongmiao–Hongyazi fault in the Northern Qilian Shan, NE Tibet, from the ¹⁰Be exposure dating of offset terraces[J]. *Journal of Asian Earth Sciences*, 151: 131–147.
- Yang Jingsui, Xu Zhiqin, Li Haibing, Wu Cailai, Cui Junwen, Zhang Jianxin, Chen Wen. 1998. Discovery of eclogite at northern margin of Qaidam Basin, NW China[J]. *Chinese Science Bulletin*, 43: 1755–1760.
- Yang Jingsui, Xu Zhiqin, Song Shuguang, Wu Caikai, Shi Rendeng, Zhang Jianxin, Wan Yusheng, Li Haibing, Jin Xiaochi, Jolivet M. 2000. Discovery of eclogite in Dulan, Qinghai Province and its significance for studying the HP–UHP metamorphic belt along the Central Orogenic Belt in China[J]. *Acta Geologica Sinica*, 74 (2): 156–168 (in Chinese with English abstract).
- Yang Jingsui, Song Shuguang, Xu Zhiqin, Wu Caikai, Shi Rendeng, Zhang Jianxin, Li Haibing, Wan Yusheng, Liu Yan, Qiu Haijun, Liu Fulai, Maruyama S. 2001. Discovery of coesite in the North Qaidam Early Paleozoic ultrahigh–high pressure (UHP–HP) metamorphic belt, NW China[J]. *Acta Geologica Sinica*, 75 (2): 175–179 (in Chinese with English abstract).
- Yang J S, Xu Z Q, Zhang J X, et al. 2002. Early Palaeozoic North Qaidam UHP metamorphic belt on the northeastern Tibetan plateau and a paired subduction model[J]. *Terra Nova*, 14 (5): 397–404.
- Yang Jingsui, Xu Zhiqin, Zhang Jianxin, Zhang Zeming, Liu Fulai, Wu Caikai. 2009. Tectonic setting of main high– and ultrahigh–pressure metamorphic belts in China and adjacent region and discussion on their subduction and exhumation mechanism[J]. *Acta*

- Petrologica Sinica, 25 (7): 1529–1560 (in Chinese with English abstract).
- Yang Jingsui, Xu Zhiqin, Ma Changqian, Wu Cailai, Zhang Jianxin, Wang Zhongqi, Wang Guocan, Zhang Hongfei, Dong Yunpeng, Lai Shaocong. 2010. Compound orogeny and scientific problems concerning the Central Orogenic Belt of China[J]. *Geology in China*, 37 (1): 1–11 (in Chinese with English abstract).
- Yang Shufeng, Chen Hanlin, Cheng Xiaogan, Xiao Ancheng, He Guangyu, Chen Jianjun, Tian Duowen. 2007. Deformation characteristics and rules of spatial change for the Northern Qilianshan thrust belt[J]. *Earth Science Frontiers*, 14 (5): 211–221 (in Chinese with English abstract).
- Ye Gaofeng, Wang Hui, Guo Zeqiu, Xie Chengliang, Gong Xiugang. 2013. Data acquisition and processing technology of long-period magnetotellurics[J]. *Progress in Geophysics*, 28 (3): 1219–1226 (in Chinese with English abstract).
- Ye Zhuo, Gao Rui, Li Qiusheng, Zhang Hongshuang, Shen Xuzhang, Liu Xuzhou, Gong Chen. 2015. Seismic evidence for the North China plate underthrusting beneath northeastern Tibet and its implications for plateau growth[J]. *Earth and Planetary Science Letters*, 426: 109–117.
- Ye Zhuo, Li Qiusheng, Gao Rui, Zhang Hongshuang, Shen Xuzhang, Liu Xuzhou, Gong Chen. 2016. Anisotropic regime across northeastern Tibet and its geodynamic implications[J]. *Tectonophysics*, 671: 1–8.
- Yin An, Harrison T M. 2000. Geologic evolution of the Himalayan–Tibetan orogen[J]. *Annual Review of Earth and Planetary Sciences*, 28: 211–280.
- Yin An, Rumelhart P E, Butler R, Cowgill E, Harrison T M, Foster D A, Ingersoll R V, Zhang Q, Zhou X Q, Wang X F, Hanson A, Raza A. 2002. Tectonic history of the Altyn Tagh fault system in northern Tibet inferred from Cenozoic sedimentation[J]. *Geological Society of America Bulletin*, 114: 1257–1295.
- Yin An, Dang Yuqi, Zhang Min, Chen Xuan–Hua, McRivette M W. 2008. Cenozoic tectonic evolution of Qaidam basin and its surrounding regions (Part 3): Structural geology, sedimentation, and regional tectonic reconstruction[J]. *Geological Society of America Bulletin*, 120: 847–876.
- Yin An. 2010. Cenozoic tectonic evolution of Asia: A preliminary synthesis[J]. *Tectonophysics*, 488: 293–325.
- Yin Yaotian, Wei Wenbo, Jin Sheng, Santosh M. 2017. Fossil oceanic subduction zone beneath the western margin of the Trans–North China Orogen: Magnetotelluric evidence from the Lüliang Complex[J]. *Precambrian Research*, 303: 54–74.
- Zhan Yan, Zhao Guoze, Wang Jijun, Chen Xiaobin, Xiao Qibin, Huang Zhe, Zhen Guojun. 2008. Deep electric structure beneath the epicentre of the 1927 Gulang M8 earthquake and its adjacent areas from magnetotelluric sounding[J]. *Chinese Journal of Geophysics* (in Chinese), 51 (2): 511–520 (in Chinese with English abstract).
- Zhang Cong, Bader T, Zhang Lifei, van Roermund H. 2017. The multi-stage tectonic evolution of the Xitieshan terrane, North Qaidam orogen, western China: From Grenville–age orogeny to early–Paleozoic ultrahigh–pressure metamorphism[J]. *Gondwana Research*, 41: 290–300.
- Zhang Huiping, Zhang Peizhen, Prush V, Zheng Dewen, Zheng Wenjun, Wang Weitao, Liu Caicai, Ren Zhikun. 2017. Tectonic geomorphology of the Qilian Shan in the northeastern Tibetan Plateau: Insights into the plateau formation processes[J]. *Tectonophysics*, 706–707: 103–115.
- Zhang Peizhen, Zhang Huiping, Zheng Wenjun, Zheng Dewen, Wang Weitao, Zhang Zhuqi. 2014. Cenozoic tectonic evolution of continental eastern Asia[J]. *Seismology and Geology*, 36 (3): 574–585 (in Chinese with English abstract).
- Zhang Yiping, Xiao Wenxia, Zhang Jin, Chen Xuanhua, Zhang Beihang, Zhao Heng, Wang Yannan, Li Jiangyu, Shi Jianjie. 2015. A discussion on the provenance and age of Xiangshan Group in Eastern Hexi Corridor[J]. *Geology in China*, 42 (6): 1774–1792 (in Chinese with English abstract).
- Zhang Yiping, Zhang Jin, Chen Xuanhua, Wang Yannan, Zhao Heng, Nie Fengjun, Zhang Beihang. 2017. Late Palaeozoic tectonic setting of the southern Alxa Block, NW China: constrained by age and composition of diabase[J]. *International Geology Review*, 59 (8): 1028–1046.
- Zhao Guoze, Zhan Yan, Wang Lifeng, Wang Jijun, Tang Ji, Chen Xiaobin, Xiao Qibin. 2010. Electric structure of the crust beneath the Ordos fault block[J]. *Seismology and Geology*, 32 (3): 346–359 (in Chinese with English abstract).
- Zhao Hong, Dang Ben, Wang Chongli. 2004. The geochemical characteristics of Ordovician volcanic rocks in southern Danghe Mountain in southern Qilian Mountains, Gansu Province[J]. *Geoscience*, 18 (1): 64–69 (in Chinese with English abstract).
- Zhao Wenjin, Mechie J, Feng Mei, Shi Danian, Xue Guangqi, Su Heping, Song Yang, Yang Hongwei, Liu Zhi–wei. 2014. Cenozoic orogenesis of the Qilian Mountain and the lithosphere mantle tectonic framework beneath it[J]. *Geology in China*, 41 (5): 1411–1423 (in Chinese with English abstract).
- Zhang Jianxin, Yang Jingsui, Xu Zhiqin, Zhang Zemin, Chen Wen, Li Haibing. 2000. Peak and retrograde age of eclogite at the northern margin of Qaidam basin, northwestern China: Evidences from U–Pb and Ar–Ar dates[J]. *Geochimica*, 29 (3): 217–222 (in Chinese with English abstract).
- Zheng Wenjun, Zhang Peizhen, Ge Weipeng, Molnar P, Zhang Hui–Ping, Yuan Daoyang, Liu Jianhui. 2013a. Late Quaternary slip rate of the South Heli Shan Fault (northern Hexi Corridor, NW China) and its implications for northeastward growth of the Tibetan Plateau[J]. *Tectonics*, 32: 271–293.
- Zheng Wenjun, Zhang Huiping, Zhang Peizhen, Peter Molnar, Liu

- Xingwang, Yuan Daoyang. 2013b. Late Quaternary slip rates of the thrust faults in western Hexi Corridor (Northern Qilian Shan, China) and their implications for northeastward growth of the Tibetan Plateau[J]. *Geosphere*, 9 (2): 342–354.
- Zhu Renxue, Hu Xiangyun. 1995. Study on the resistivity structure of the lithosphere along the Golmud–Ejin Qi geoscience transect[J]. *Acta Geophysica Sinica*, 38 (s II): 46–57 (in Chinese with English abstract).
- Zhu Xiaohui, Wang Hongliang, Yang Meng. 2016. Zircon U–Pb age of the monzogranite from the middle segment of the Qaidam Mountain composite granite on the south margin of the Qilian Mountain[J]. *Geology in China*, 43 (3): 751–767 (in Chinese with English abstract).
- Zuza A V, Cheng Xiaogan, Yin An. 2016. Testing models of Tibetan Plateau formation with Cenozoic shortening estimates across the Qilian Shan–Nan Shan thrust belt[J]. *Geosphere*, 12 (2): 501–532.
- Zuza A V, Wu Chen, Reith R C, Yin An, Li Jianhua, Zhang Jinyu, Zhang Yuxiu, Wu Long, Liu Wencan. 2017. Tectonic evolution of the Qilian Shan: An early Paleozoic orogen reactivated in the Cenozoic[J]. *Geological Society of America Bulletin*, 130 (5/6): 881–925.
- Zuza A V, Wu Chen, Wang Zengzhen, Levy D A, Li Bing, Xiong Xiaosong, Chen Xuanhua. 2019. Underthrusting and duplexing beneath the northern Tibetan Plateau and the evolution of the Himalayan–Tibetan orogen[J]. *Lithosphere*, 11 (2): 209–231.
- 附中文参考文献**
- 白建科,王洪亮,朱小辉,谢从瑞. 2016. 北祁连石灰沟奥陶纪中堡群滑塌堆积特征及其古地理环境意义[J]. *中国地质*, 43(3): 977–986.
- 陈柏林,王春宇,崔玲玲,刘建民. 2008. 祁连山北缘—河西走廊西段晚新生代逆冲推覆断裂发育模式[J]. *地学前缘*, 15(6): 260–277.
- 陈干,郑文俊,王旭龙,张培震,熊建国,俞晶星,刘兴旺,毕海芸,刘金瑞,艾明. 2017. 榆木山北缘断裂现今构造活动特征及其对青藏高原北东扩展的构造地貌响应[J]. *地震地质*, 39(5): 871–888.
- 陈宣华,党玉琪,尹安,汪立群,蒋武明,蒋荣宝,周苏平,刘明德,叶宝莹,张敏,马立协,李丽. 2010. 柴达木盆地及其周缘山系盆山耦合与构造演化[M]. 北京:地质出版社, 1–365.
- 陈宣华,陈正乐,韩淑琴,杨屹,王志宏,贾木欣,叶宝莹,施炜,聂兰仕,丁伟翠,白彦飞,李勇,史建杰,李冰,邵兆刚,刘春涌,刘刚,张义平,徐盛林,马飞宙. 2017. 巴尔喀什—西准噶尔及邻区构造—岩浆—成矿作用演化[M]. 北京:地质出版社, 1–539.
- 陈宣华,邵兆刚,熊小松,高锐,徐盛林,张义平,李冰,王叶. 2019a. 祁连山北缘早白垩世榆木山逆冲推覆构造与油气远景[J]. *地球学报*, 40(3): 377–392.
- 陈宣华,李江瑜,董树文,施炜,白彦飞,张义平,丁伟翠[J]. 2019b. 华北克拉通中部宁武—静乐盆地侏罗纪构造变形与燕山期造山事件的启动[J]. *大地构造与成矿学*, 43(3): 389–408.
- 崔军文,唐哲民,邓晋福,岳永君,孟令顺. 1999. 阿尔金断裂系[M]. 北京:地质出版社, 1–249.
- 邓晋福,吴宗絮,杨建军,赵海玲,刘厚祥,赖绍聪,狄永军. 1995. 格尔木—额济纳旗地学断面走廊地壳—上地幔岩石学结构与深部过程[J]. *地球物理学报*, 38(增刊II): 130–144.
- 冯治汉,刘宽厚,郭培虹,王艺霖. 2018. 西北地区重磁场特征及其应用研究[M]. 武汉:中国地质大学出版社, 1–235.
- 高锐,李廷栋,吴功建. 1998. 青藏高原岩石圈演化与地球动力学过程——亚东—格尔木—额济纳旗地学断面的启示[J]. *地质论评*, 44(4): 389–395.
- 郭安林,张国伟,强娟,孙延贵,李广,姚安平. 2009. 青藏高原东北缘印支期宗务隆造山带[J]. *岩石学报*, 25(1): 1–12.
- 国家地震局地质研究所,国家地震局兰州地震研究所. 1993. 祁连山—河西走廊活动断裂系[M]. 北京:地震出版社, 1–340.
- 国家地震局兰州地震研究所. 1992. 昌马活动断裂带[M]. 北京:地震出版社, 1–207.
- 郝国杰,陆松年,王惠初,辛后田,李怀坤. 2004. 柴达木盆地北缘前泥盆纪构造格架及欧龙布鲁克古陆块地质演化[J]. *地学前缘*, 11(3): 115–122.
- 胡道功,戚帮申,张耀玲,宋焕新,祁生胜,赵希涛,张绪教,文志刚. 2018. 祁连山新生代构造环境演化与隆升过程[M]. 北京:地质出版社, 1–210.
- 黄增保,郑建平,李葆华,魏志军,漆玮,陈旭. 2015. 中祁连西段野马山岩基年代学、地球化学特征及地质意义[J]. *中国地质*, 42(2): 406–420.
- 金胜,张乐天,金永吉,魏文博,叶高峰. 2012. 青藏高原东北缘合作—大井剖面地壳电性结构研究[J]. *地球物理学报*, 55(12): 3979–3990.
- 李冰,胡道功,陈宣华,张耀玲,吴环环,王超群. 2017. 北祁连缝合带油葫芦沟蛇绿岩中花岗岩锆石U–Pb年龄及地质意义[J]. *现代地质*, 31(5): 883–889.
- 李奋其. 2003. 中国西北部南北向伸展构造存在的新证据——酒泉早白垩世半地堑断陷成因初探[J]. *沉积与特提斯地质*, 23(2): 35–42.
- 李猛,王超,李荣社,彭岩. 2015. 北祁连南地区阴沟群形成时代及沉积源区讨论——碎屑锆石U–Pb年龄证据[J]. *中国地质*, 42(3): 601–615.
- 李清河,张元生,涂毅敏,范兵. 1998. 祁连山—河西走廊地壳速度结构及速度与电性的联合解释[J]. *地球物理学报*, 41(2): 197–210.
- 李玉龙. 1984. 嘉峪关断层的性质和活动时期[J]. *兰州大学学报(自然科学版)*, 20(2): 118–123.
- 吕庆田,孟贵祥,严加水,张昆,赵金花,龚雪婧. 2019. 成矿系统的多尺度探测: 概念与进展——以长江中下游成矿带为例[J]. *中国地质*, 46(4): 673–689.
- 潘桂棠,肖庆辉. 2015. 中国大地构造图说明书(1:2500000)[M]. 北京:地质出版社, 1–160.
- 潘宏勋,葛肖虹,刘俊来. 2000. 对祁连山北缘榆木山隆起的质疑. *长春科技大学学报*, 30(1): 9–13.
- 裴先治,孟勇,丁仁平,李佐臣,刘战庆,刘会彬,李高阳,李瑞保. 2007. 祁连—秦岭造山带交接部位25亿年碎屑锆石的发现及其地质意义[J]. *地球科学与环境学报*, 29(2): 111–116.

- 任纪舜,牛宝贵,王军,金小赤,谢良珍.2013.国际亚洲地质图(1:5000000)[M].北京:地质出版社.
- 邵浩浩,陈宣华,张达,邵兆刚,李冰,王增振,张义平,徐盛林,史建杰,苗慧心.2019.河西走廊平山湖盆地早白垩世构造变形期次及其碎屑锆石U-Pb年龄约束[J].中国地质,46(5):1079-1093.
- 施炜,刘源,刘洋,陈鹏,陈龙,岑敏,黄兴富,李恒强.2013.青藏高原东北缘海原断裂带新生代构造演化[J].地质前缘,20(4):1-17.
- 宋述光,牛耀龄,张立飞,张贵宾.2009.大陆造山运动:从大洋俯冲到大陆俯冲、碰撞、折返的时限——以北祁连山、柴北缘为例[J].岩石学报,25(9):2067-2077.
- 孙娇鹏,陈世悦,胡忠亚,刘文平,郭晨,马帅.2014.柴北缘古生代碎屑岩-碳酸盐岩混积相发育特征及组合模式研究[J].天然气地球科学,25(10):1586-1593.
- 孙延贵,张国伟,王瑾,詹发余,张智勇.2004.秦昆结合区两期基性岩墙群⁴⁰Ar/³⁹Ar定年及其构造意义[J].地质学报,78(1):65-71.
- 汤吉,詹艳,赵国泽,邓前辉,王继军,陈小斌,赵俊猛,宣飞.2005.青藏高原东北缘玛沁—兰州—靖边剖面地壳上地幔电性结构研究[J].地球物理学报,48(5):1205-1216.
- 涂毅敏,李清河,成瑾.2000.华北地震带北段速度结构与电阻率特征[J].西北地震学报,22(4):353-360.
- 王根厚,冉书明,李明.2001.柴达木盆地北缘赛什腾—锡铁山左行逆冲断裂及地质意义[J].地质力学学报,7(3):224-230.
- 王惠初,陆松年,莫宣学,李怀坤,辛后田.2005.柴达木盆地北缘早古生代碰撞造山系统[J].地质通报,24(7):603-612.
- 王立全,潘桂棠,丁俊,姚东生.2013.青藏高原及邻区地质图及说明书(1:1 500 000)[M].北京:地质出版社,1-288.
- 王伟涛,张培震,郑德文,庞建章.2014.青藏高原东北缘海原断裂带晚新生代构造变形[J].地质前缘,21(4):266-274.
- 吴才来,杨经绥,杨宏仪,Wooden J L,史仁灯,陈松永,郑秋光.2004.北祁连山东部两类I型花岗岩定年及其地质意义[J].岩石学报,20(3):425-432.
- 吴才来,姚尚志,杨经绥,曾令森,陈松永,李海兵,戚学祥,Wooden J L, Mazdab F K.2006.北祁连山早古生代双向俯冲的花岗岩证据[J].中国地质,33(6):1197-1208.
- 夏林圻,李向民,余吉远,王国强.2016.祁连山新元古代中—晚期至早古生代火山作用与构造演化[J].中国地质,43(4):1087-1138.
- 熊盛青,范正国,张洪瑞,丁燕云,黄旭钊,李占奎,郭志宏,杨雪,佟晶,刘前坤,周道卿,谭林,张俊伟.2015.中国陆域航磁系列图(1:2 500 000)(说明书)[M].北京:地质出版社,1-19.
- 许志琴,杨经绥,张建新,姜枚,李海兵,崔军文.1999.阿尔金断裂两侧构造单元的对比及岩石圈剪切机制[J].地质学报,73(3):193-205.
- 杨超,陈清华,王冠民,庞小军,马婷婷.2010.柴达木地区晚古生代沉积构造演化[J].中国石油大学学报(自然科学版),34(5):38-49.
- 杨经绥,许志琴,宋述光,吴才来,史仁灯,张建新,万渝生,李海兵,金小赤, Jolivet M.2000.青海都兰榴辉岩的发现及对中国中央造山带内高压-超高压变质带研究的意义[J].地质学报,74(2):156-168.
- 杨经绥,宋述光,许志琴,吴才来,史仁灯,张建新,李海兵,万渝生,刘焰,邱海峻,刘福来,Maruyama S.2001.柴达木盆地北缘早古生代高压-超高压变质带中发现典型超高压矿物——柯石英[J].地质学报,75(2):175-179.
- 杨经绥,许志琴,张建新,张泽明,刘福来,吴才来.2009.中国主要高压-超高压变质带的大地构造背景及俯冲/折返机制的探讨[J].岩石学报,25(7):1529-1560.
- 杨经绥,许志琴,马昌前,吴才来,张建新,王宗起,王国灿,张宏飞,董云鹏,赖绍聪.2010.复合造山作用和中国中央造山带的科学问题[J].中国地质,37(1):1-11.
- 杨树锋,陈汉林,程晓敢,肖安成,何光玉,陈建军,田多文.2007.祁连山北缘冲断带的特征与空间变化规律[J].地质前缘,14(5):211-221.
- 叶高峰,王辉,郭泽秋,谢成良,巩秀钢.2013.长周期大地电磁测深数据采集及处理技术[J].地球物理学进展,28(3):1219-1226.
- 詹艳,赵国泽,王继军,陈小斌,肖骑彬,黄哲,镇国钧.2008.1927年古浪8级大地震及其周边地块的深部电性结构[J].地球物理学报,51(2):511-520.
- 张建新,杨经绥,许志琴,张泽明,陈文,李海兵.2000.柴北缘榴辉岩的峰期和退变质年龄:来自U-Pb及Ar-Ar同位素测定的证据[J].地球化学,29(3):217-222.
- 张培震,张会平,郑文俊,郑德文,王伟涛,张竹琪.2014.东亚大陆新生代构造演化[J].地震地质,36(3):574-585.
- 张义平,肖文霞,张进,陈宣华,张北航,赵衡,王艳楠,李江瑜,史建杰.2015.河西走廊东部香山群时代和物源讨论[J].中国地质,42(6):1774-1792.
- 赵国泽,詹艳,王立凤,王继军,汤吉,陈小斌,肖骑彬.2010.鄂尔多斯地块地壳电性结构[J].地震地质,32(3):346-359.
- 赵虹,党彝,王崇礼.2004.甘肃南祁连党河南山中奥陶世火山岩的地球化学特征[J].现代地质,18(1):64-69.
- 赵文津,Mechie J,冯梅,史大年,薛光琪,宿和平,宋洋,杨宏伟,刘志伟.2014.祁连山造山作用与岩石圈地幔的特型结构构造[J].中国地质,41(5):1411-1423.
- 朱仁学,胡祥云.1995.格尔木—额济纳旗地学断面岩石圈电性结构的研究[J].地球物理学报,38(s II):46-57.
- 朱小辉,王洪亮,杨猛.2016.祁连南缘柴达木山复式花岗岩体中部二长花岗岩锆石U-Pb定年及其地质意义[J].中国地质,43(3):751-767.