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榆木山构造带深部结构及隆升成因

熊小松[1],高锐[2,3],酆少英[4],李英康[5],黄兴富[3],陈宣华[1],常玉举[6]

(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. 中山大学地球科学与工程学院,广东 广州 510275; 4. 中国地震局地球物理勘探中心,河南 郑州 450002; 5. 国土资源实物地质资料中心,河北 三河 065201; 6. 中石化石油工程地球物理有限公司华北分公司,河南 郑州 450016)

提要:新生代以来,欧亚与印度两大板块间的碰撞拼合及后续的汇聚挤压塑造了现今青藏高原的高海拔地形地貌和巨厚地壳。位于青藏高原最北缘的榆木山构造带,其内部构造变形的几何学和运动学特征记录了地球最新演化历史过程中,构造、剥蚀和气候变化之间的复杂关系。长期以来,其构造成因和属性一直存在争议。本文通过对最近完成的深地震反射剖面的初步处理,其反射剖面初步揭示了榆木山构造带的深部地壳结构:榆木山构造带之下莫霍面深度为45~48 km,整体由北向南加深;同时,深部反射和地表层析速度成像结果显示榆木山下方存在明显的反射透明区、高速异常体,结合地表地质调查,推测其可能为花岗岩体,同早古生代祁连洋的闭合有关;在榆木山构造带之下存在明显的壳内滑脱面,推测其隆升受控于两条背向逆冲断裂带的控制。本文同时结合其他地质地球物理资料,初步提出了青藏高原北缘的演化模型,为青藏高原北缘的向北扩展、盆山耦合及块体间关系提供了新的思路。

关 键 词:祁连造山带;榆木山构造带;深部结构;隆升成因;深地勘查工程

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Deep structure of Yumushan tectonic zone and genesis of the uplift

XIONG Xiaosong[1], GAO Rui[2,3], FENG Shaoying[4], LI Yingkang[5], HUANG Xinfu[3],
CHEN Xuanhua[1], CHANG Yuju[6]

(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. *School of Earth Science and Geological Engineering, Sun Yat−Sen University, Guangzhou* 510275*, Guangdong, China;* 4. *Geophysical Exploration Center, China Earthquake Administration, Zhengzhou* 450002*, Henan, China;* 5. *Geological Information Center, Ministry of Land and Resources, Yanjiao,* 065201*, Hebei, China;* 6. *North China Branch, Petroleum Engineering Geophysics Co., Ltd., SINOPEC, Zhengzhou* 450016*, Henan, China*)

Abstract: Since early Cenozoic, the collision and ongoing continuous convergence of the Indian and Eurasian plates have resulted in

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作者简介:熊小松,男,1983年生,博士,副研究员,主要从事深部构造与大陆岩石圈演化研究; E−mail: benxung@126.com。

通讯作者:高锐,男,1950年生,院士,研究员,从事深部构造研究;E−mail: ruigao126@126.com。

the high elevation and thick crust of the Tibetan Plateau. Yumushan thrust belt is located at the north front of the Qilian Mountain, and is the newest joined part of the Tibetan Plateau. Its geometry and kinematics of the crustal deformation recorded the complex relationship between the tectonics, erosion and climate change of the newest evolution of the earth. The deep structure and uplift mechanism have been controversial for a long time. In this paper, the authors unraveled the crustal structure of the Yumushan thrust belt by the newest acquired deep seismic reflection profile. The Moho depth beneath the Yumushan belt is 45−48 km with a shallower trend to the north; the deep reflection structure and subsurface tomography velocity structure show the apparent transparent zone and high velocity zone beneath the Yumushan, which may represent the intrusion of a large amount of granitoids beneath the Yumushan related to the closure of the Qilian Ocean in early Paleozoic, and the uplift was driven by two back−back thrust faults. Combined with other geological and geophysical data, the authors propose a new growth pattern in the northmost Tibetan Plateau, which may shed some light on the northward growth as well the basin−range coupling relation.

Key words: Qilian orogeny; Yumushan thrust belt; deep structure; uplift mechanism; deep exploration engineering

About the first author: XIONG Xiaosong, male, born in 1983, associate professor, mainly engages in the study of deep structure and evolution of the continental lithosphere; E−mail: benxung@126.com.

About the corresponding author: GAO Rui, male, born in 1950, academician/professor, mainly engages in the study of the structure of deep earth; E−mail: ruigao126@126.com.

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1 引 言

新生代以来,欧亚与印度两大板块间的碰撞拼合及后续的汇聚挤压塑造了现今青藏高原的高海拔地形地貌和巨厚地壳。一直以来,青藏高原地壳变形、地壳增厚和隆升机制问题,是全球地球科学界研究和争论的焦点(Molnar et al.,1975,1993,2009; Tapponnier et al.,1982,2001;Harrison et al.,1992;钟大赉等, 1996;许志琴等, 1999; Yin et al., 2000; Molnar,2005;Clark et al.,2010;Clark,2012;Yuan et al., 2013; Gao et al., 2016; Zuza et al., 2016, 2018)。地质地球物理研究均表明,目前青藏高原仍然处在持续向外扩张生长之中(Métivier et al., 1998; 王成善等, 2004; 张培震等, 2006; Wang et al., 2011, 郑文俊等, 2016; Wang et al.,2018; Zhang et al., 2018)。青藏高原的周缘地区是高原向外扩展的最前线,是研究青藏高原隆升和地壳加厚变形的关键地带。北祁连和河西走廊是印度和欧亚两大板块南北向碰撞挤压应力在高原北缘最易集中的区域,其内部构造变形的几何学和运动学特征记录了地球最新演化历史过程中,构造、剥蚀和气候变化之间的复杂关系,是研究青藏高原隆升、高原向北扩展,进而理解正在进行中的印度与欧亚大陆碰撞的大陆内部构造作用的关键部位(图1)。

榆木山构造带位于祁连山最北缘,自南向北由榆木山前到北侧前陆盆地—河西走廊盆地群海拔从3 km骤降到1.5~2 km。介于河西走廊前陆盆地系中酒东、民乐盆地之间,总体走向北北西向,长约70 km,宽20~40 km。主体由古生代奥陶纪和志留纪低绿片岩相地层组成,零星出露中生代地层,在西北端为新生代地层,地层之间多以角度不整合或断层接触(甘肃地调局,1971;图2,图3)。东缘和北缘受断裂控制,南侧为祁连山北缘断裂。长期以来,榆木山构造带的成因和构造属性一直存在争议(王多杰, 1990; 潘宏勋等, 2000; Tappnnier et al., 1990; Palumbo et al., 2009a, 2009b; Seong et al., 2011; Fang et al., 2012; Wang et al., 2018)。有学者根据榆木山周缘地层间的接触关系、褶皱变形样式、地形地貌以及对周缘沉积盆地的特征开展研究,认为其是燕山运动晚期形成的北北西向分割酒东、民乐盆地的断隆(王多杰等,1990),后有学者通过对边缘断裂带的识别,并结合对地块的构造属性及相邻两侧盆地中、新生代沉积演化特征的分析,认为其是古近纪—新近纪逆冲推覆到中新生代盆地之上的1个推覆体(李玉龙等,1988;潘宏勋等,2000)。陈宣华等(2019)通过地球物理和野外地质调查,认为榆木山北缘山系构成飞来峰,榆木山之下是被掩盖的白垩纪酒泉盆地的一个分支。对于

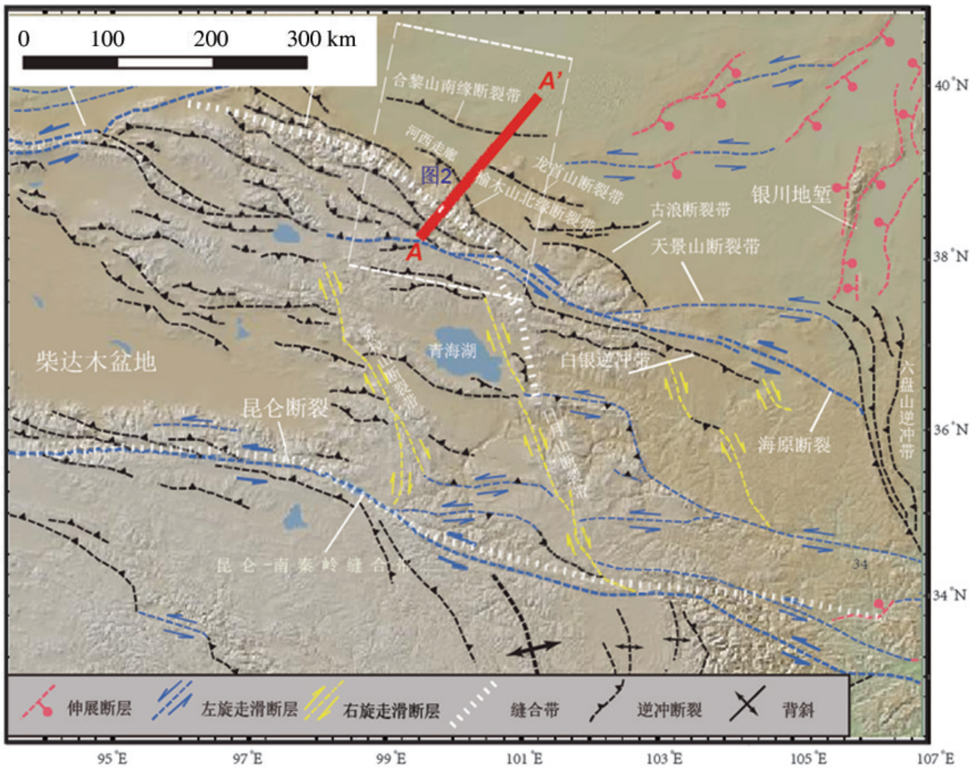

图1 青藏高原东北缘及周缘构造位置图（修改自 Duvall et al., 2013;Yuan et al., 2013; Gao et al., 2013; Zuza and Yin, 2016；红线为2016年采集的深地震反射剖面位置）

Fig.1 Tectonic sketch map of the northeastern Tibet and adjacent regions（modified from Duvall et al., 2013; Yuan et al., 2013; Gao et al., 2013; Zuza and Yin, 2016；Red line represents the deep seismic reflection profile acquired in 2016）

榆木山的抬升和扩展过程，不同学者也有不同的认识。Tapponnier et al.（1990）通过对榆木山及其北缘的逆冲断层陡坎的研究认为榆木山整体是一个底部为壳内解耦面的断坡相关背斜；边庆凯等（2001）发现榆木山卷入褶皱变形的地层由西向东逐渐变老，认为这是活动构造由东向西逐渐发展的反映。Palumbo et al.（2010）通过地形剖面、断层滑动速率、古流域以及风口的研究，认为榆木山的抬升是1个侧向和垂向生长的过程。Jeong et al.(2011)通过地貌学的研究认为榆木山受向东传播的隐伏断层的驱动，从而垂向抬升和横向褶皱生长。对于上述关键问题的认识亟需高分辨率的地球物理探测资料来进行揭示。

2016年，中国地质科学院在中国地质调查项目的支持下，完成了一条从野牛沟—肃南—高台—喇叭井（戈壁—沙漠）近南北向长200 km的深地震反射剖面，横跨北祁连造山带、河西走廊盆地和阿拉善地块南缘，横穿了整个榆木山构造带（图2）。本文通过地震反射获取的初步成果和单炮初至层析反演获取的浅部速度结构，获得了榆木山构造带的深部结构，并通过综合地球物理和地质相结合的方法，探讨了榆木山构造带的深部结构和抬升成因。

2 地质背景

榆木山构造带位于青藏高原北缘，是组成北祁连造山带的最外侧部分，向北以榆木山北缘断裂分割了河西走廊坳陷盆地群（图2，图3）。

北祁连造山带位于青藏高原北缘，呈北西西–南东东向展布，夹持于祁连地块和河西走廊之间，向西止于阿尔金走滑断裂带，向东与西秦岭构造带相接，其长近1000 km（图2）。作为青藏高原构造变形和向北推挤的最前缘，北祁连是青藏高原北部边缘新构造和活动构造的变形特征记录最为敏感的部位（Tapponnier et al.，1990）。同时，北祁连作为一条多旋回造山带，记录了北祁连自新元古代裂解以来多次的地块拼合的演化历史（任纪舜等，1981）。

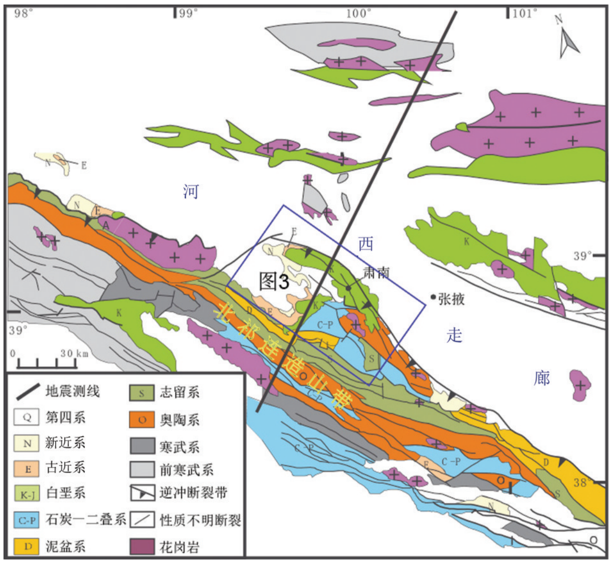

图2 祁连造山带及周缘地质简图
Fig.2 Geological sketch map of the Qilian orogeny and adjacent regions

其经由寒武纪裂谷盆地、奥陶纪初期成熟洋盆（古祁连洋）、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（王荃等, 1981; 左国朝等, 1987; 肖序常等, 1988; 许志琴等, 1994; 宋述光等, 1997; 夏林圻等, 1998, 2001; Yin et al., 2000; Gehrels et al., 2003a, 2003b, 2011; 吴才来等, 2004, 2006; Song et al., 2006, 2013; Yin et al., 2007; Xiao et al., 2009; Xu et al., 2014）；在中生代侏罗纪和白垩纪处于稳定的伸展环境（Horton et al., 2004）；随后在新生代伴随印度—欧亚板块之间的碰撞又逐渐复活成为褶皱逆冲造山带，内部广泛发育新生代褶皱、逆冲和走滑断裂（Tapponnier et al., 1990, 2001; Burchfiel et al., 1991; 国家地震局地质研究所, 1993; Yin et al., 2000; Zheng et al., 2010）。北祁连出露地层主要有寒武系、下奥陶统、下志留统、石炭系，零星出露二叠系和三叠系(表1)。区内主要发育古生代地层。下古生界为一套海相碎屑岩及中、基性火山岩建造，是典型的地槽沉积。上古生界以后，主要沉积陆相碎屑岩。

河西走廊位于祁连造山带以北和阿拉善地块以南，近NWW-SEE走向，延伸超过1000 km，是青藏高原边缘主要的汇聚构造带之一。其与以南平均海拔达4500 km的北祁连形成了将近3000 km的海拔落差。其形成演化与北祁连造山带的构造演化息息相关，大致经历了早古生代活动陆缘、晚古生代—早中生代前陆盆地、中生代中晚期伸展断陷和新生代挤压变形和前陆盆地演化4个阶段（戴霜, 2003; 杜远生等, 2004）。尤其是新生代以来印度板块和欧亚板块持续的碰撞和向北推挤所导致的高原隆升和大规模的走滑断裂作用，形成了典型的新生代压陷盆地（国家地震局阿尔金活动断裂带课题组, 1992；国家地震局地质研究所等, 1993；葛肖虹等, 2006；郑文俊等, 2016）。同时，其内部又被一组活动性很强的NNW-NW向断裂所控制的隆起分割成几个次级盆地，包括酒西盆地、酒东盆地、潮水盆地等。其基底具双层性质，下部基底为早古生代寒武纪、奥陶纪、志留纪火山-沉积岩系。寒武系出露中统黑茨沟群和上统香毛山群；奥陶系主要出露下统阴沟组和肮脏沟组；志留系出露中统脑沟组和上统旱峡组；上部基底为泥盆系下中统雪山群和上统沙流水组；石炭系下统臭牛沟组和上统太原组；下二叠统大黄沟组和上统窑沟组。盖层则由中新生代地层组成，中生代地层三叠系发育不全，侏罗系和白垩系下统仅仅零星出露。新生代地层广泛发育，尤其是第四纪以来，受控于青藏高原的隆升剥蚀和向北扩展生长，河西走廊盆地普遍接受沉积。

3 深地震反射剖面

3.1 数据采集

野外地震数据采集过程中，采用大中小炮不同药量进行深井激发兼顾地壳的上中下反射信息获取。三种药量（500 kg、96 kg和36 kg，分别称为大炮、中炮和小炮）的炸药震源激发并同时接收，以获得高分辨率的地震数据。野外采用法国SERCEL428XL数字地震仪进行数据采集。小炮炮间距240 m，井深25 m，接收道数720道；中炮炮间距5000 m，井深25 m，双井组合激发，接收道数720道。最小偏移距为140 m，最大偏移距为14500 m。采样间隔为2 ms；采用SM-24超级检波器进行接收，其组合方式为单串12个检波器，沿测线线性组合方式埋置，组内距1 m，道间距40 m。全剖面记录长度30 s，具体观测系统和采集参数见表1。

3.2 数据处理

本次处理采用CGG、OMEGA和GRISYS多个

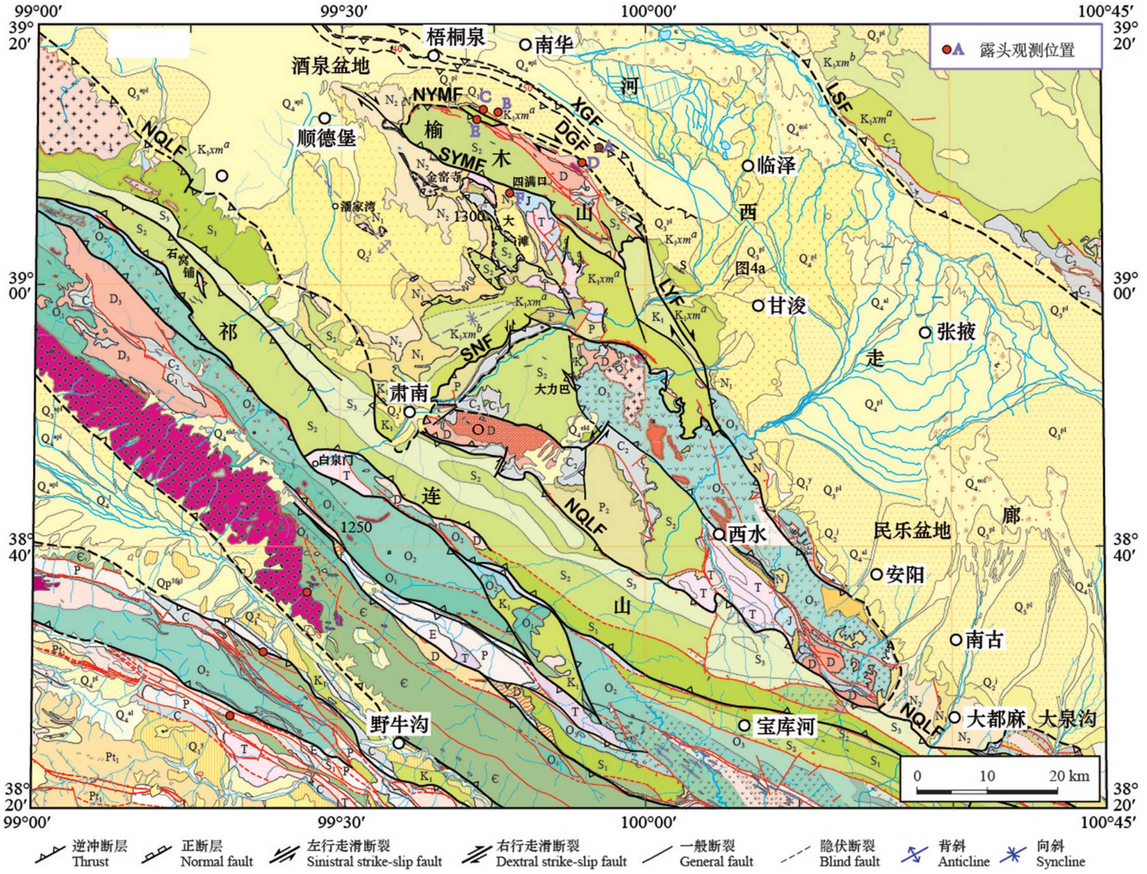

图3 榆木山构造带地质简图（修改自陈宣华等，2019）

Q_4—全新统; Q_3—上更新统; Q_2—中更新统; Q_1—下更新统; N_2—上新统; N_1—中新统; E—古近系; K_1—下白垩统; J—侏罗系; T—三叠系;P—二叠系; C_2—上石炭统; C_1—下石炭统; D—泥盆系; S_3—上志留统; S_2—中志留统; S_1—下志留统; O_3—上奥陶统; O_2—中奥陶统;O_1—下奥陶统; Є—寒武系; Pt_1—古元古界;NQLF—祁连山北缘断裂; NYMF—榆木山北缘断裂; SYMF—榆山南缘断裂;LSF—龙首山断裂; LYF—梨园堡断裂; SNF—肃南断裂; DGF—大更子断裂; XGF—小更子断裂

Fig. 3 Geological sketch map of the Yumushan thrust belt (modified from Chen et al., 2019)

Q_4−Holocene; Q_3−Upper Pleistocene; Q_2−Middle Pleistocene; Q_1−Lower Pleistocene; N_2−Pliocene; N_1−Miocene; E−Paleogene; K1−Lower Cretaceous; J−Jurassic; T−Triassic; P−Permian; C_2−Upper Carboniferous; C1−Lower Carboniferous; D−Devonian; S_3−Upper Silurian; S_2−Middle Silurian; S_1−Lower Silurian; O_3−Upper Ordovician; O_2−Middle Ordovician; O_1−Lower Ordovician; Є−Cambrian; Pt1−Paleoproterozoic; NQLF−North Qilian Mountain fault; NYMF−North Yumushan Mountain fault; SYMF−SouthYumushan Mountain Fault; LSF−Longshoushan Mountain fault; LYF−Liyuanpu Fault; SNF−Sunan Fault; DGF−Dagengzi Fault; XGF−Xiaogengzi Fault

处理软件相结合的手段，在对地表地质条件分析、静校正分析、原始单炮品质分析和能量分析等详细分析的基础上，对处理方法和参数进行了大量的测试工作，确定了处理流程，其中关键处理技术包括地表一致性静校正、子波一致性处理和叠前去噪等。经过精细的数据处理，最终获得了叠加和偏移剖面。本文的研究采用了叠加剖面。由于本文仅探讨榆木山的深部结构特征，因此仅展示该段的深部反射剖面（图4a）。

3.3 深地震反射剖面特征

在图4a的剖面上可见一些显著的强反射同向轴。纵轴表示双程走时(TWT)。本文采用6 km/s的地壳平均速度来进行时−深转换，剖面的浮动基准面为4 km。

剖面显示，榆木山构造带之下，在上地壳（0~8 s）内，介于CDP号100 ~ 2100，在CDP号1000最深可达6 s（18 km）存在一明显的反射透明体；在CDP号100附近，存在一条向北倾斜的反射体，而在CDP号2600附近，存在另外一条明显的向南倾斜的反射体。

在中下地壳（8 s之下），在剖面最北端8 s存在一条向南倾斜的反射，向南可延伸到16 s，推测其可能为上地壳同中下地壳的滑脱面；在剖面北段10 s

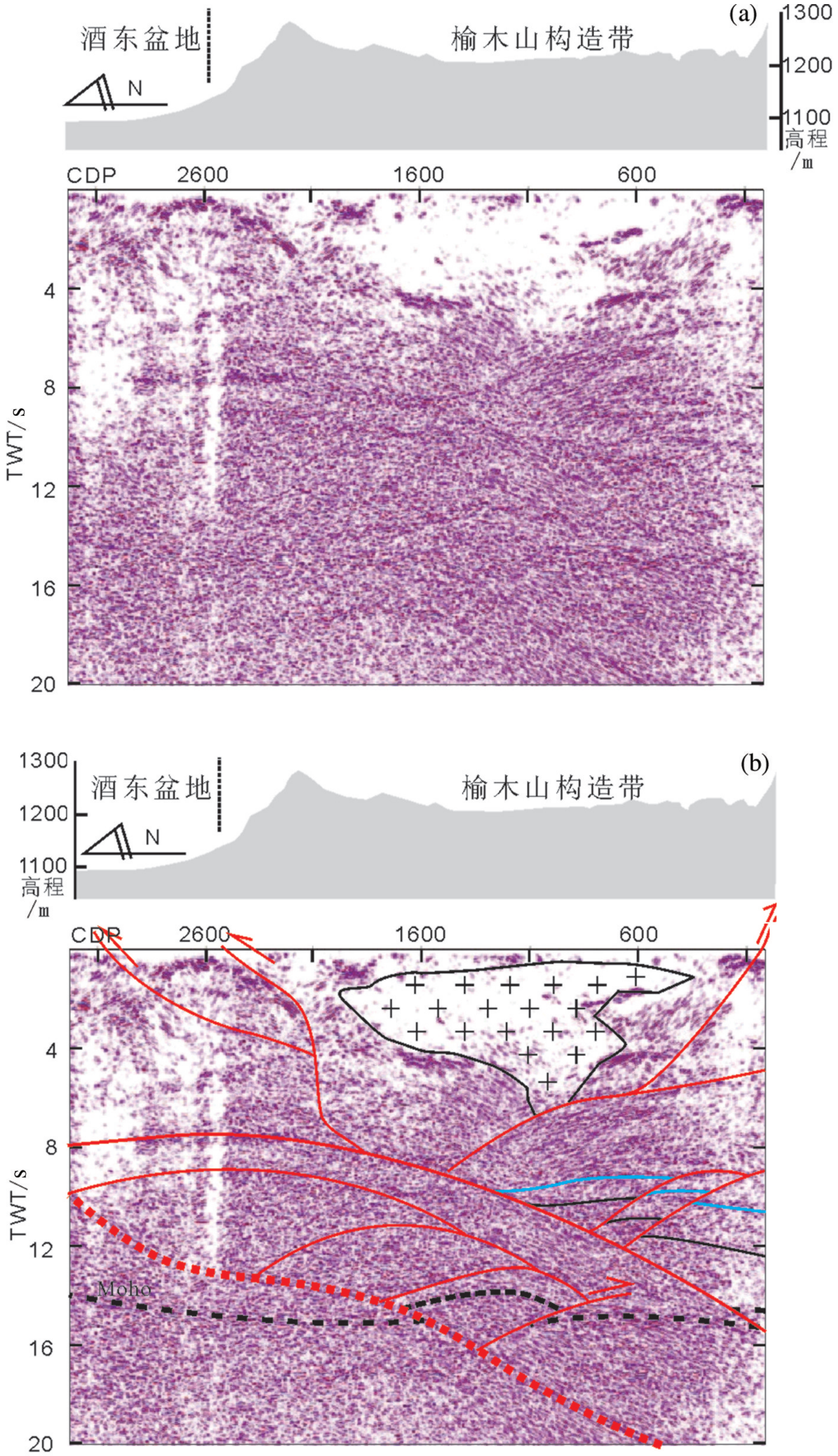

图4 榆木山构造带地震反射剖面及解释(a:未解释的叠加地震剖面;b:地震剖面的反射特征)
Fig. 4 The deep seismic reflection across the Yumushan thrust belt
(a: un-interpreted profile;b: Preliminary interpretation of the profile)

表1 采集参数表

Table1 Acquisition parameters

采集		激发	
采集系统	Sercel 428XL	炸药类型	动力源
采样间隔	2 ms（小炮）	单井深度	25 m（小炮）
接收道数	720		25 m×2（中炮）0
道间距	40 m		50 m×4（大炮）
检波器/道	24（组内距1 m）	激发能量	36 kg（小炮）
排列方式	中间接受（小炮）		96 kg（中炮）
	单边接受（大炮）		500 kg（大炮）
最小偏移距	140 m	炮间距	240 m（小炮）
最大偏移距	14500 km		5000 m（中炮）
叠加次数	72		25 km（大炮）
记录			
记录格式	SEG-D	记录长度	30 s（小炮，中炮） 60 s（大炮）

TWT往南存在一条明显的自下地壳到上地幔的一条反射；在剖面中北段，8 s滑脱层之下，可见中下地壳有弧形反射叠置；而在剖面南段，滑脱面之上，也存在弧形反射。

莫霍面显示从北向南逐渐从14 s TWT加深到16.6 s TWT，但是莫霍面并非连续的，而是被南倾的下地壳-上地幔反射体切割，其中在榆木山构造带中心之下，显示有局部隆起。

3.4 浅层速度结构模型

根据大炮初至进行层析反演表层初始模型，用计算的初至波和实际拾取的初至波进行比较，计算地表模型的修正量，经过几次迭代反演得到比较精确的地表模型（图5）。模型显示在剖面的南段和北段，榆木山之下均发育有高速体，速度可达4.0 km/s以上。

4 讨 论

4.1 榆木山的深部结构

前人研究认为榆木山主体部分为古生界及岩体组成，下古生界以奥陶纪—志留纪低绿片岩相变质岩系为主；上古生界是一套陆源碎屑岩和海相地层。不同时代的地层间主要以不整合或断层接触。此外，局部出露有下、中三叠统，下、中侏罗统，下白垩统和新生界，南北两侧以及西北角出露新生代以来地层，包括白杨河组、疏勒河组、玉门砾岩层、酒泉砾岩层、戈壁砾岩层（刘栋梁等，2012）。他们之间多以不整合或断层接触（甘肃省地调局，1971；潘宏勋等，2000；图3）。传统认为，榆木山岩体出露较少，主要为侵位于奥陶纪地层中的早古生代晚期的3个二长花岗岩岩体出露，规模不大，包括红崖子西北部金佛寺地区、大力巴东部和榆木山之南的金窑寺（陈宣华等，2019）。3个岩体长轴方向均为北西西向，岩体内北东向陡斜节理发育，多被方解石脉和石英脉填充，显示岩体在新生代以来受强烈的区域挤压作用。

深地震反射剖面表层结构速度模型显示（图5），沿测线地表到地下1.2 km深在测线的南段、中段和北段均显示显著的高速体存在，其地震波速度最高可达6 km/s，由测线出露的基岩可以对比得知，在测线南段和北段出露有大面积的花岗岩体，其中南段以走廊南山出露的早奥陶世二长花岗岩为主

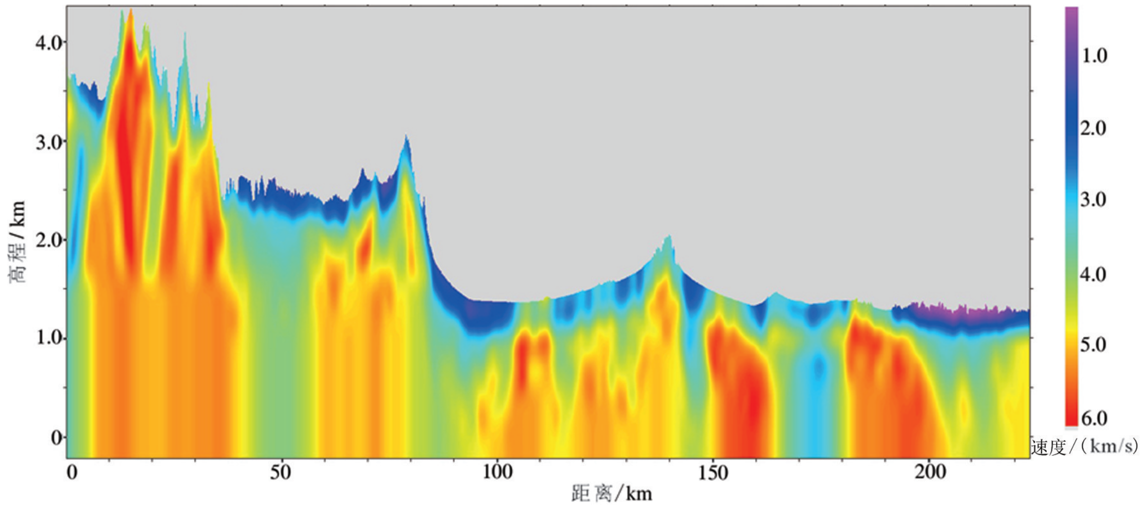

图5 层析静校正获得的浅部速度结构模型

Fig. 5 The shallow velocity structure model obtained by tomographic static correction

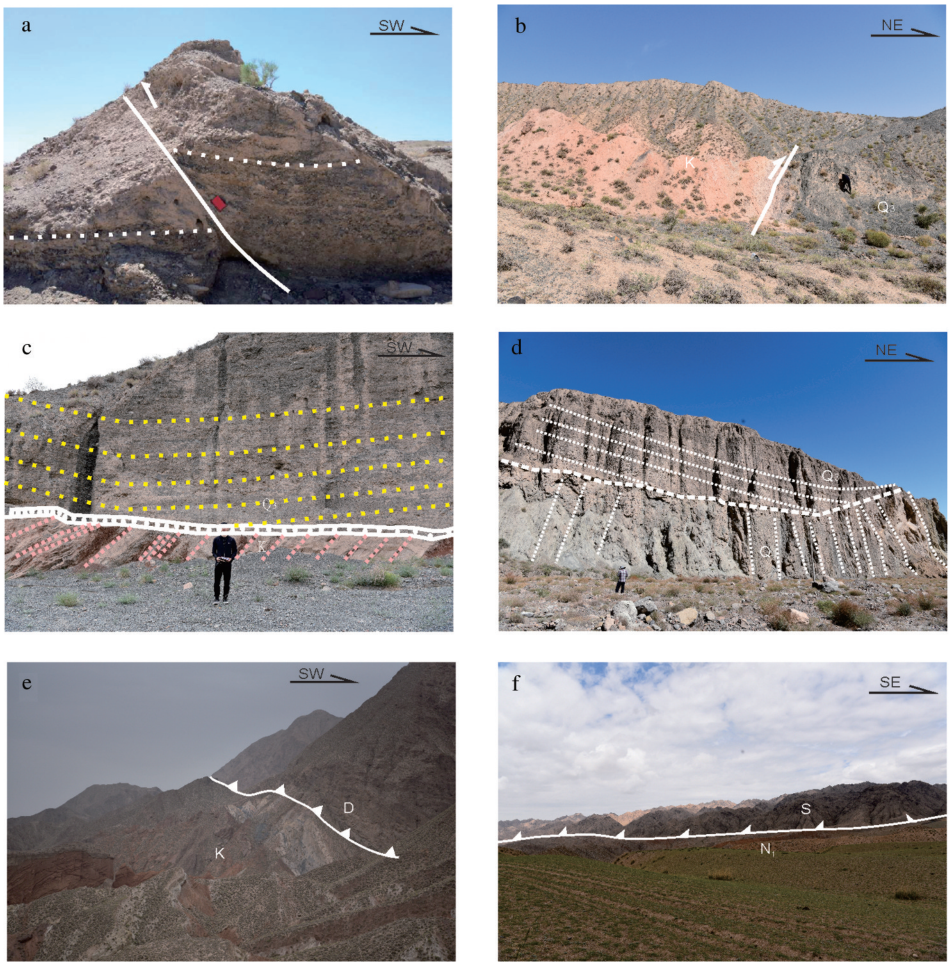

图6 榆木山构造带及邻区地表露头（详细位置见图3）
a—酒东盆地内发育的逆冲断层；b—白垩纪逆冲于Q_1之上；c—Q_3不整合覆盖于K之上；d—Q_1与Q_3角度不整合；e—泥盆系逆冲于白垩系之上；f—榆木山反冲断裂

Fig.6 The outcropped thrust deformation in the Yumushan tectonic belt (the locations shown in Fig. 3)
a-Thrust faults in Jiudong basin; b- Cretaceous strata overthrusted on the Q_1 strata; c-Q_3 unconformably covering Cretaceous strata; d- Angular unconformity between the Q_1 and Q_3; e- Devonian strata overthrusted on the Cretaceous strata; f- The Yumushan back thrust faults

(吴才来等, 2004; 2010)，在河西走廊以北在合黎山和大青山地区则出露石炭纪和二叠纪斜长花岗岩和花岗闪长岩(赖新荣等, 2007)，因此笔者推测在榆木山之下的高速体也应代表侵位的大面积花岗岩。同时，深地震反射剖面也清晰地显示在榆木山构造带之下有透明反射区，根据前人对于深地震反射剖面透明区的构造解释，一般认为其应代表侵入的花岗岩体。但榆木山之下的花岗岩因为两侧边缘的逆冲断层对中部的物质的仰冲运移影响较两侧低，未大面积出露于地表，其时代根据榆木山构造带零星出露的志留纪花岗岩体，推测该区出露的花岗岩应该为早古生代侵位岩体，可能与加里东期祁连洋的向北闭合相关，在北祁连造山带发育的铜铁矿床，可能在榆木山构造带之下也有发育。另据陈宣华等（2019）研究表明，推覆的基底岩石之下还存在白垩纪沉积的可能，说明该推覆作用应该晚于白垩纪。

4.2 榆木山构造带隆升成因

前人曾推测榆木山构造带整体是由于冲断背斜作用(Tapponnier et al., 1990)，但缺乏明显的深部地球物理数据支持。榆木山深部结构特征显示，榆木山构造带受控于两条背向的逆冲断裂带，北为榆木山北缘断裂带，南为祁连—肃南断裂带。其中，榆木山北缘断裂带研究较为详细，地表地质研究表明，该断裂带由多条次级断裂组成，总体产状为275°~300°SW∠45°~61°（国家地震局地质研究所等，

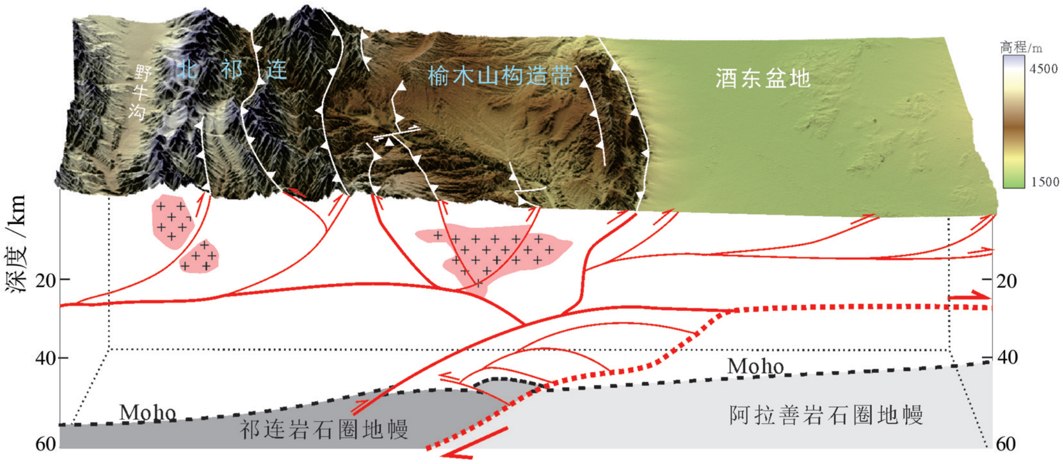

图7 青藏高原东北缘深部结构及扩展抬升初步模式图
Fig. 7 The deep structure and preliminary uplift model of northeast Tibetan Plateau

1993；边庆凯等，2001；金卿，2011；陈干等，2017）。野外露头可见泥盆纪地层逆冲于白垩纪地层之上（图6e）。榆木山南缘断裂带为一条向南仰冲的逆冲断裂带，其分割了北祁连和榆木山两个构造块体。前人研究表明榆木山的垂直抬升速率在0.4~0.8 mm/a（Palumbo et al., 2009; 郑文俊，2009; Seong et al., 2011）。其中，Palumbo et al.(2009b)利用原地宇宙成因核素^{10}Be测年方法，认为榆木山中部的隆升速率在770 mm/ka，而边部的隆升速率在500 mm/ka，中部隆升速率明显高于两侧，也说明了中部的隆升叠加了南北两侧背向逆冲的结果。根据地质反射剖面特征并结合地表地质，笔者推测在榆木山内部同时发育有多条次级的逆冲断裂带，且最终都收敛于壳内的滑脱面上。但在榆木山之下，北侧的滑脱面是主滑脱面，且该滑脱面向南倾并最终切割莫霍，应该同阿拉善地块的向南被动楔入有关。泊松比是了解地球内部物质组成的重要参数，榆木山构造带的泊松比较低（李永华等，2014；王兴臣等，2017）说明该区中上地壳长英质含量较高，该区的地壳增厚方式以中上地壳的逆冲褶皱为主。

在榆木山构造带最北缘，邻近酒东盆地可见多条逆冲断层，包括白垩纪地层逆冲于第四纪地层之上（图6b），在盆地内部，也发育有条逆冲断裂（图6a），说明青藏高原的北缘物质已经越过榆木山北缘断裂带继续向北以逆冲的方式进行扩展。前人通过平衡剖面恢复技术估算河西走廊盆地群在早白垩世的原始边界位于现今边界的30~50 km(何光玉等,2004)，也证实了榆木山构造带在一直向北扩展。

5 结　论

结合前人在榆木山北缘断裂和酒泉盆地等地开展的热年代学、地貌学等研究工作，笔者通过对榆木山构造带深地震反射剖面的详细解释，认为：

(1)榆木山构造带之下莫霍面深度在45~48 km；在上地壳存在大面积分布的花岗岩体，可能与早古生代祁连洋的闭合有关。

(2)榆木山构造带的抬升受控于两条主要的背向的逆冲断裂带，上地壳和中下地壳之间存在明显的滑脱面，上地壳以逆冲褶皱变形为主，而在中下地壳，阿拉善地块的向南楔入致使中下地壳叠瓦状逆冲为主（图7），上地壳的逆冲褶皱在整个地壳抬升过程中起到主要作用。

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