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胶东金矿集中区深部结构研究进展

Research progress on the deep structure of Jiaodong gold deposit concentration area

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摘要 华北克拉通东部金矿床与克拉通破坏作用具有密切的时空与成因联系,也被称之为“克拉通破坏型金矿床”.普遍认为华北克拉通破坏与“克拉通破坏型金矿床”成矿作用发生的主要动力背景为古太平洋板块向欧亚大陆下的西向(现今方位)俯冲引发的地幔非稳态流动,即矿床的形成受克拉通破坏过程中的深部作用过程控制.胶东是目前我国最大的金矿集区与黄金生产基地,也是“克拉通破坏型金矿床”成矿模式建立的最典型地区.为揭示这克拉通破坏过程中深部作用过程及其对金成矿的控制作用,前人运用不同方法,在该区开展了大量的地球物理探测研究,取得了丰富成果,但是上述成果多为分散的、局部的,尚缺乏系统性认识.鉴于此,本文根据近年来的探测结果,系统总结了胶东金矿集中区及邻区深部结构特征,包括岩石圈各圈层结构及壳幔各向异性与流变学特征等,以期对全面深入认识“克拉通破坏型金矿”成矿系统及深部找矿突破等提供重要参考.

关键词 胶东金矿; 岩石圈结构; 地壳结构; 浅部结构; 壳幔各向异性

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Abstract The gold deposits in the eastern North China Craton are closely related to craton destruction in time, space and origin, and are also known as “Decratonic gold deposits”. It is generally believed that the main dynamic background for the North China Craton destruction and the mineralization of the “Decratonic gold deposits” is the unsteady flow of the mantle caused by the westward (present-day azimuth) subduction of the paleo-Pacific plate under the Eurasian continent. This means that the formation of the gold deposits was controlled by deep processes during the craton destruction. Jiaodong is currently the largest gold ore concentration area and gold production base in China. It is also the most typical area where the metallogenic model of the “Decratonic gold deposits” was established. In order to reveal the deep dynamic process and its controlling effect on gold mineralization during the destruction of this craton, a large number of geophysical exploration studies by using different methods have been carried out in this area, with abundant achievements acquired, but these results are mostly scattered, local and lacking in systematic understanding. Therefore, based on the detection results in recent years, this paper systematically summarizes the deep structural characteristics of the Jiaodong gold-concentrated area and its adjacent regions, including the lithosphere structure, crust-mantle anisotropy and rheological characteristics, etc. It will provide an important reference for understanding the metallogenic system of the “Decratonic gold deposits” and breakthroughs in deep ore prospecting.

Keywords Jiaodong gold deposit; Lithospheric structure; Crust structure; Shallow structure; Crust-mantle seismic anisotropy

0 引言

华北克拉通是全球最古老的克拉通之一,但与世界其他古老克拉通相比,华北克拉通不论是在构造演化还是金成矿作用方面均具有鲜明的“中国特色”。大量研究表明,华北克拉通在古生代以来遭受到强烈的破坏,其最主要表现是华北克拉通大约 120 km 厚的岩石圈根“丢失”(Fan and Menzies, 1992; Menzies *et al.*, 1993; 吴福元等, 2008);同时与克拉通破坏相伴,华北克拉通发生了广泛而强烈的构造-岩浆-成矿作用(翟明国等, 2004; Yang *et al.*, 2005; 张田和张岳桥, 2007; Chen, 2009, 2010; Zhu *et al.*, 2015)。研究还揭示,华北克拉通破坏与金成矿作用具有密切的空间、时间和成因联系。空间上,两者均发生在华北克拉通东部,即南北重力梯度带以东地区;时间上,金成矿作用集中爆发于晚中生代,与华北克拉通破坏作用峰期的时间大体一致(Yang and Zhou, 2001; Yang *et al.*, 2003);成因上,金成矿作用与克拉通破坏诱发的构造-岩浆-流体作用过程密切相关。鉴于此,华北克拉通东部的金矿被称为“克拉通破坏型金矿床”(朱日祥等, 2015)。

对于华北“克拉通破坏型金矿床”,前人已从区域成矿构造背景、区域构造样式与构造过程、矿田构造、矿床地质地球化学特征、流体包裹体等方面开展了大量的研究,并提出了一系列相关的金成矿模式(卢冰等, 1995; 杨金中等, 2000; 李洪奎等, 2012; 翟明国等, 2004; 范宏瑞等, 2005; 邓军等, 2004; Deng *et al.*, 2015; Li *et al.*, 2015)。另一方面,为了认识华北克拉通破坏及“克拉通破坏型金矿床”形成的深部背景,前人也开展了大量的地球物理探测研究(Chen *et al.*, 2008, 2009, 2014; Chen, 2009, 2010; Zhao *et al.*, 2009, 2012; Zheng *et al.*, 2009, 2012, 2017),并认为古太平洋板块向欧亚大陆下的西向(现今方位)俯冲引发的地幔非稳态流动是导致华北东部克拉通破坏及“克拉通破坏型金矿床”成矿作用发生的主要动力学背景(朱日祥和郑天愉, 2009; 朱日祥等, 2011, 2012)。

作为我国最主要的金矿集中区和最大的黄金生产基地(Fan *et al.*, 2003; Yang *et al.*, 2003; Song *et al.*, 2015; 宋明春等, 2020),胶东地区位于华北克拉通东部,是克拉通破坏或岩石圈减薄最为强烈的地区,因此也被认为是研究华北东部克拉通破坏与“克拉通破坏型金矿床”形成过程的理想场所(Carlson *et al.*, 2005; 吴福元等, 2008; 翟明国等, 2004; 朱日祥等, 2015; Yang *et al.*, 2021; Zhu and Sun, 2021)。另一方面,随着地表与浅部矿被开发利用殆尽,矿山面临着向深部要资源的挑战(Harrison and Urosevic, 2012)。勿庸置疑,随着找矿对象由浅表转向深部、由出露区转向覆盖区及由老区转向新区,深部探测技术将发挥越来越重要的作用。近些年,为揭示华北东部克拉通破坏区金成矿带的深部结构与深部过程,在国家重点研发计划项目“华北克拉通成矿系统的深部过程与成矿机理”资助下,中国科学院地质与地球物理研究所在胶东地区跨主要断裂的一条 NW 向剖面同时进行短周期密集台阵观测(共 340 套短周期地震仪)和宽频带台阵观测(NCISP-9 台阵, 共 20 套宽频带地震仪)(图 1),分别开展了接收函数成像(Yu *et al.*, 2020)、背景噪

声成像(俞贵平等, 2020)、剪切波分裂和壳幔各向异性研究(Wu *et al.*, 2020, 2021)等综合地球物理探测。本文主要针对已开展的成像研究,对胶东矿集区的岩石圈各圈层结构及壳幔各向异性与流变学特征的研究进展进行总结,以期对全面深入认识“克拉通破坏型金矿床”形成的深部背景、矿床成因及指导深部找矿等提供地球物理约束。

1 区域构造背景

胶东地区位于华北克拉通东南缘(图 1),西以北北东向的郯庐断裂带为界,是我国最重要的金矿集中区(Qiu *et al.*, 2002; Mao *et al.*, 2008)。胶东地区可以划分为三个构造单元,即胶北隆起、胶莱盆地和苏鲁造山带(李金良等, 2007; Zhou *et al.*, 2008; 李洪奎等, 2012),胶北隆起主要出露太古宙变质岩和中生代花岗岩为主。其中,太古代变质岩以胶东岩群为主,主要由高级变质的 TTG 和以斜长角闪岩类为主的变质表壳岩组成,而中生代花岗岩主要为侏罗-白垩纪花岗岩-花岗闪长岩-花岗斑岩等。胶莱盆地是早白垩世断陷盆地(Zhang *et al.*, 2003; 周建波等, 2016),发育白垩纪陆相火山-沉积岩。胶北隆起与胶莱盆地均属胶北地体。苏鲁造山带是一条含榴辉岩的高压-超高压变质岩带(Li *et al.*, 1993; Yin and Nie, 1993; Xu *et al.*, 2009),代表华北与华南地块的缝合带,属胶南地体的组成部分。在胶东地区,五莲—烟台断裂带被认为是胶北与胶南地体的分界断裂,是一条晚中生代的走滑断裂带(翟明国等, 2000; 林伟等, 2003; 张岳桥等, 2007)。

按金矿床空间分布特点,胶东地区通常被划分三个矿集中区,其中胶北隆起上有两个,即胶西北与栖蓬福两个金矿集中区;苏鲁造山带内有一个,分布于牟平—乳山地区,即牟乳矿集中区/成矿带。此外,胶莱盆地内金矿化较差,目前仅在盆地与变质基底的结合部位发现有少量小规模的构造角砾岩型和砾岩型金矿(杨立强等, 2014; 宋明春, 2015)。胶东金矿化主要有两种端元类型:石英脉型和蚀变岩型。胶西北矿集中区主要以蚀变岩型金矿为主,而栖蓬福和牟乳两个矿集中区则以石英脉型金矿为主(杨立强等, 2014; 宋明春, 2015)。

胶东地区构造以 NE-NNE 向断列构造为主,对该区金矿床空间分布具明显控制作用。如三山岛断裂、焦家断裂、招平断裂、栖霞断裂、五莲—烟台断裂等分别控制着三山岛金矿床、焦家—新城矿田、玲珑—大尹格庄矿带、栖蓬福矿田和牟乳成矿带(图 1)。

2 岩石圈地幔结构

胶东地区所处的华北克拉通东部自中生代以来发生了广泛的伸展构造变形和岩浆活动,造成岩石圈显著减薄,由古生代时的 180 km 以上减薄至今的 60~100 km(Chen *et al.*, 2008; Chen, 2010)。早期在该区及附近的 P 波层析成像结果显示扬子块体向华北克拉通下方俯冲,扬子块体上地壳与下地壳拆离,呈现“鳄鱼嘴”构造(Xu *et al.*, 2001, 2002)。在郯庐断裂带胶东地区部分,S 波接收函数得到的岩石圈厚度为 60~80 km,横跨断裂的 LAB 呈现弧形,顶端位置大致位于郯庐断裂下方,Moho 面在断裂下方也存在 36~32 km 的明显抬升,这种一致性表明郯庐断裂区存在深部物

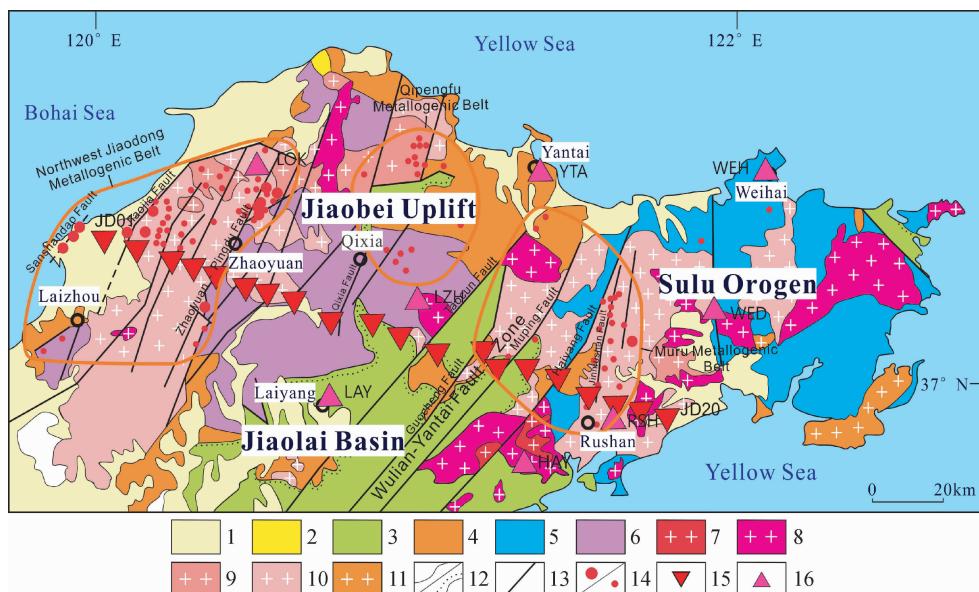


图1 胶东地区地质图和台站分布(修改自 Yu et al., 2020)

1. 第四纪松散沉积物; 2. 古近纪-新近纪陆相火山沉积地层; 3. 白垩纪陆相火山沉积地层; 4. 古元古代-新元古代滨浅海相地层;
5. 新元古代榴辉岩花岗质片麻岩; 6. 太古宙花岗绿岩带; 7. 白垩纪崂山花岗岩; 8. 白垩纪伟德山花岗岩; 9. 白垩纪郭家岭花岗闪长岩;
10. 侏罗纪花岗岩; 11. 三叠纪花岗岩类; 12. 确认的/不确认的边界; 13. 断层; 14. 大-超大型金矿/中型金矿; 15. 宽频带地震台;
16. 短周期地震台; 17. 33 km 深度处的射线穿透点(参考模型: $V_p = 6.3 \text{ km/s}$, $V_p/V_s = 1.76$). 粉色实线 AB 表示 CCP 叠加剖面的位置.

CAOB: 中亚造山带; NCC: 华北克拉通; SCB: 华南板块; WB: 西部陆块; EB: 东部陆块; TNCO: 中部造山带; JLJB: 胶辽吉构造带.

Fig. 1 Geological map of the Jiaodong Peninsula and distribution of stations (modified from Yu et al., 2020)

1. Quaternary loose sediments; 2. Paleogene-Neogene terrestrial volcanic-sedimentary strata; 3. Cretaceous continental volcanic-sedimentary strata; 4. Paleoproterozoic-Neoproterozoic shore-shallow marine facies strata; 5. Neoproterozoic with eclogite granitic gneiss; 6. Archean granite-greenstone belt; 7. Cretaceous Laoshan granite; 8. Cretaceous Weideshan Granite; 9. Cretaceous Guojialing granodiorite; 10. Jurassic granite; 11. Triassic granitoids; 12. conformity/unconformity; 13. fault; 14. large to super-large gold deposit/medium gold deposit; 15. broadband seismic station; 16. short-period seismic station; 17. piercing points of rays at 33 km depth (reference model: $V_p = 6.3 \text{ km/s}$, $V_p/V_s = 1.76$). Pink solid line AB denotes the position of CCP stacking profile.

CAOB: Central Asian orogenic belt; NCC: North China Craton; SCB: South China Block;

WB: Western Block; EB: Eastern Block; TNCO: Trans-North China Orogen; JLJB: Jiao-Liao-Ji Belt.

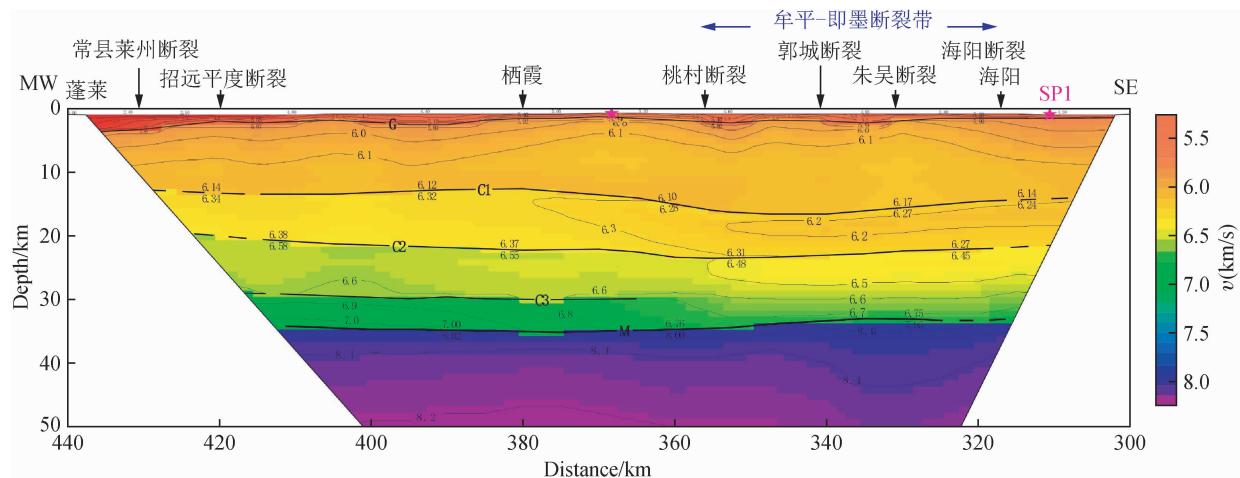


图2 胶东宽角反射/折射地震探测速度剖面(潘素珍等, 2015)

Fig. 2 Deep seismic sounding velocity profile across the Jiaodong Peninsula (Pan et al., 2015)

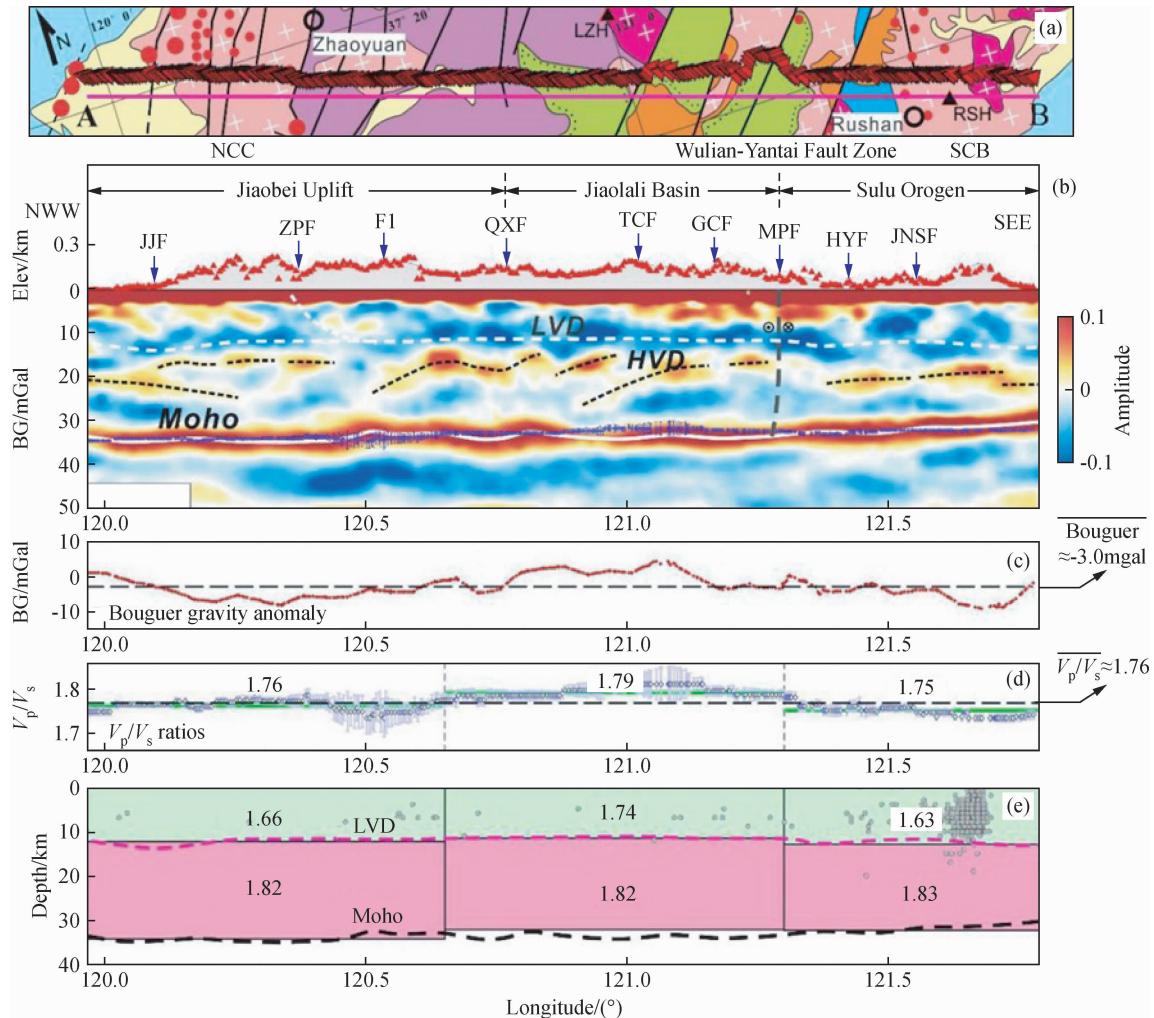


图3 接收函数地壳结构成像(Yu et al., 2020)

(a) 地质简图(粉色实线AB表示CCP叠加剖面位置);(b)一次转换波Ps震相的CCP叠加剖面;(c)布格重力异常;(d)黄色菱形为 $H-\kappa$ 扫描得到的纵横波速度比,绿色实线为构造单元的平均值,黑色虚线为整个地区的平均值;(e)分层 $H-\kappa$ 扫描获得的上下地壳的波速比和厚度.NCC:华北克拉通;SCB:华南板块;LVD:低速间断面;HVD:高速间断面;JJF:焦家断裂;ZPF:招远—平度断裂;QXF:栖霞断裂;TCF:桃村断裂;GCF:郭城断裂;MPF:牟平断裂;HYF:海阳断裂;JNSF:金牛山断裂.

Fig. 3 Receiver function imaging of the crust (Yu et al., 2020)

(a) Simplified geology map along the survey line;(b) CCP image of Ps phase (0.01 ~ 2.4 Hz);(c) Bouguer gravity anomalies based on a global Earth gravitational model (EGM2008);(d) Crustal V_p/V_s ratios of each station (yellow diamond). Green solid line denotes the average of each tectonic unit; the black dotted line denotes the regional average;(e) V_p/V_s ratios and thicknesses of upper and lower crust.

JJF, Jiaojia fault; ZPF, Zhaoyuan-Pingdu fault; QXF, Qixia fault; TCF, Taocun fault; GCF, Guocheng fault; MPF, Muping fault; HYF, Haiyang fault; JNSF, Jinniushan fault.

质侵入,在中生代到新生代的大陆伸展和岩石圈减薄过程中提供了软流圈物质上涌通道(Chen et al., 2006). 利用该区P波接收函数反演S波速度结构显示,郯庐断裂两侧地壳结构、岩石圈速度分层以及剪切波分裂参数存在明显差异,这种差异性结构成因有两种可能性:(1)岩石圈尺度郯庐断裂为软流圈物质上涌通道,促进了华北克拉通活化;(2)郯庐断裂带两侧分属于碰撞于早中生代的华北克拉通和扬子地块,古老的块体在后期华北克拉通活化中仍保存了下来(Zheng et al., 2008). P波层析成像也显示郯庐断裂西侧上地幔明显的低速异常,指示存在地幔物质上涌(Lei et al.,

2020). 胶东半岛Pn波成像显示上地幔速度结构沿着五莲烟台断裂带两侧存在明显差异,断裂西侧速度约为7.8 km/s,而东侧速度偏高,达到8.1 km/s(胥颐等,2008).

中岩石圈不连续面(Mid-Lithosphere Discontinuity,简称MLD)代表整体上刚性克拉通岩石圈内部古老的薄弱带,在华北克拉通西部、中部与东部均发现了MLD的存在(Meng et al., 2021),值得注意的是其深度与华北克拉通东部较薄的岩石圈厚度相对应(Zhang et al., 2020). 在中生代以前MLD可能也同时存在于华北克拉通东部,这样的薄弱带促进了东部华北克拉通岩石圈底部和内部同时的改造,尤其是在中生

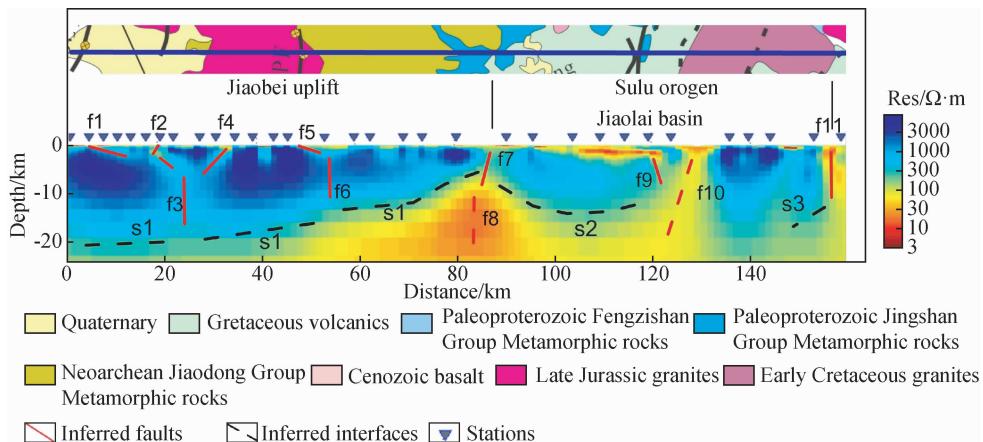


图4 胶东大地电磁测深视电阻率剖面(Zhang et al., 2018)

剖面西起三山岛,东至乳山。f1:三山岛断裂;f2:焦家断裂;f4,f5:招平断裂;f7:桃村断裂。

Fig. 4 Apparent resistivity profile of magnetotelluric across the Jiaodong Peninsula (Zhang et al., 2018)

The profile starts from Sanshandao in the west to Rushan in the east. f1: Sanshandao fault;

f2: Jiaojia fault; f4, f5: Zhaoping fault; f7: Taocun fault.

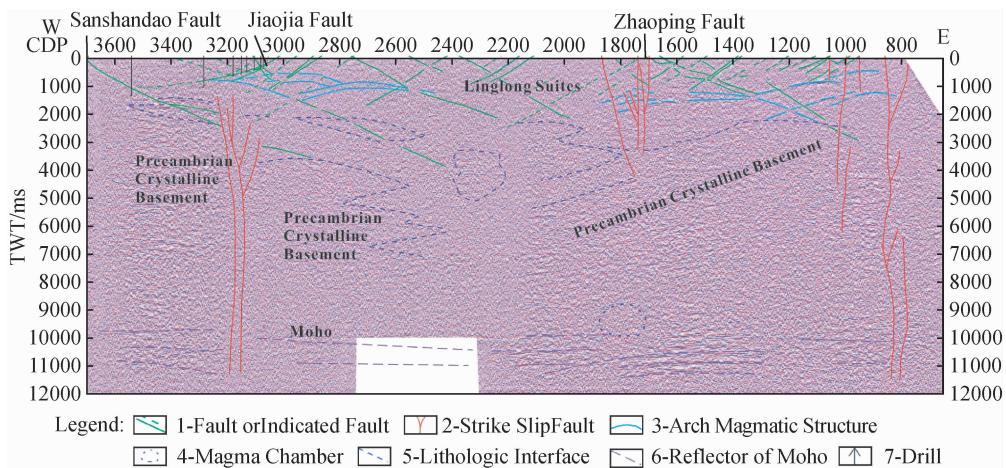


图5 跨胶西北矿集区的浅层反射地震剖面(Yu et al., 2018)

Fig. 5 Shallow reflection seismic profile across the northwest Jiaodong metallogenic belt (Yu et al., 2018)

代太平洋板块俯冲的强烈影响下,导致了该区域克拉通的减薄和破坏,但该薄弱带并未明显影响华北克拉通中部和西部的演化(Chen et al., 2014)。胶东区域南部地幔过渡带的660 km界面向下凹陷30 km,明显厚于周边区域,反映了太平洋板块深俯冲滞留以及零星的穿透入下地幔对于中生代以来华北克拉通东部活化的影响(Chen et al., 2009)。该区660 km界面还出现了双速度间断面特征,可能是非橄榄石成分相变造成,例如从石榴石到钙钛矿的相变(Ai and Zheng, 2003)。

3 地壳结构

在晚中生代以来华北克拉通破坏、岩石圈减薄的背景下,胶东地区地壳结构的差异导致了区域性成矿的差异(Yu et al., 2020)。目前,在胶东及其邻区已经开展了大量的地壳结构研究(杨文采等,1999;胥颐等,2008,2009;Jia et al.,

2014; Tian et al., 2014; 刘志等,2015; 潘素珍等,2015; 段永红等,2016; Zhang et al., 2018; Yu et al., 2020)。胶东地区南部的深反射地震研究发现了扬子块体向华北克拉通下方俯冲的特征,五莲烟台断裂带为强烈改造过的三叠纪华北华南陆-陆碰撞缝合带(Yang et al., 2002)。胶东半岛北向地震宽角反射/折射海陆联测剖面得到的地壳P波速度结构显示(图2):胶东地区基底埋深普遍较浅,从东到西呈逐渐变深趋势;整个胶东地区地壳结构具有明显的横向分层、纵向分块特征,地壳厚度呈现中间厚两侧薄的特征,在栖霞附近地壳达到约34 km,两侧约31 km左右,但上下地壳存在解耦特征,上地壳厚度呈现明显的西薄东厚的特征,而下地壳则呈现出东薄西厚的变化特征;五莲烟台断裂作为胶东半岛非常重要的断裂,其东西两侧的地壳结构特征具有明显差异,其东侧速度偏低,西侧偏高,地壳各分层界面形态在该断裂两侧起伏变化明显,且苏鲁造山带上地壳P波速度较胶莱

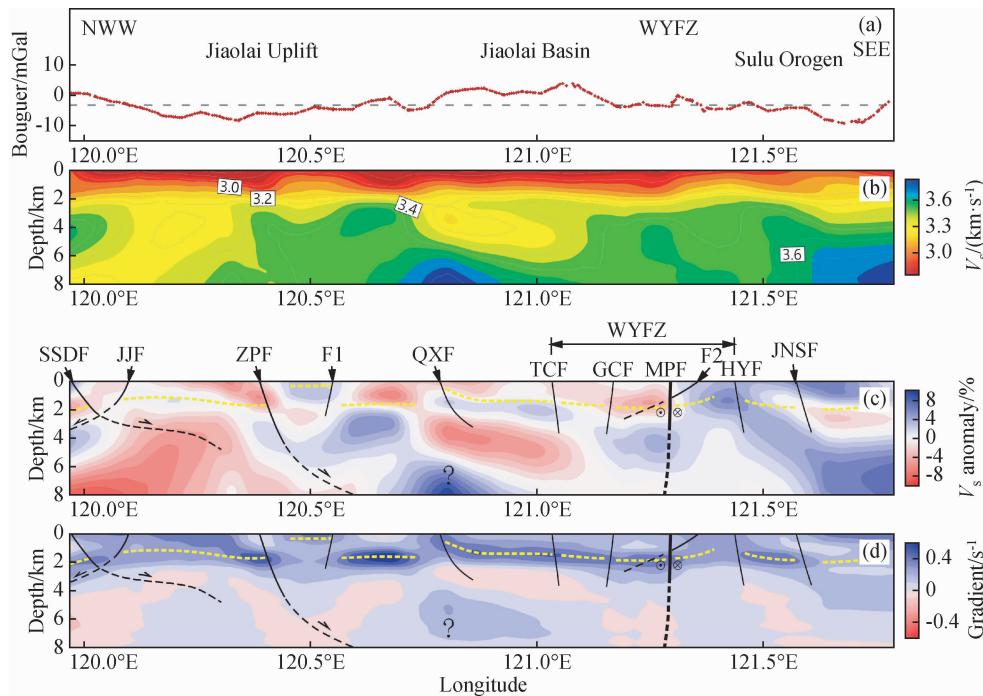


图 6 S 波速度成像结果(俞贵平等, 2020)

(a) 布格重力异常, 数据来自 EGM2008 全球重力场模型, 灰色虚线为平均值; (b) S 波速度剖面; (c) S 波速度扰动; (d) S 波垂向速度梯度, 其中黑色实线表示地表观测到的主要断层, 黑色虚线表示推测的断层, 箭头表示拆离断层的运动方向, 黄色虚线表示高速间断面.

Fig. 6 S-wave velocity imaging results(Yu et al., 2020)

(a) Bouguer gravity anomalies using data from the EGM2008 global gravity model. Gray dashed line denotes the average value;
 (b) S-wave velocity profile; (c) S-wave velocity disturbances; (d) S-wave vertical velocity gradient profile. The black solid line denotes the main fault observed on the surface; the black dotted line denotes the predicted fault; the arrow denotes the movement direction of the detachment fault, and the yellow dashed line denotes the high-velocity discontinuity.

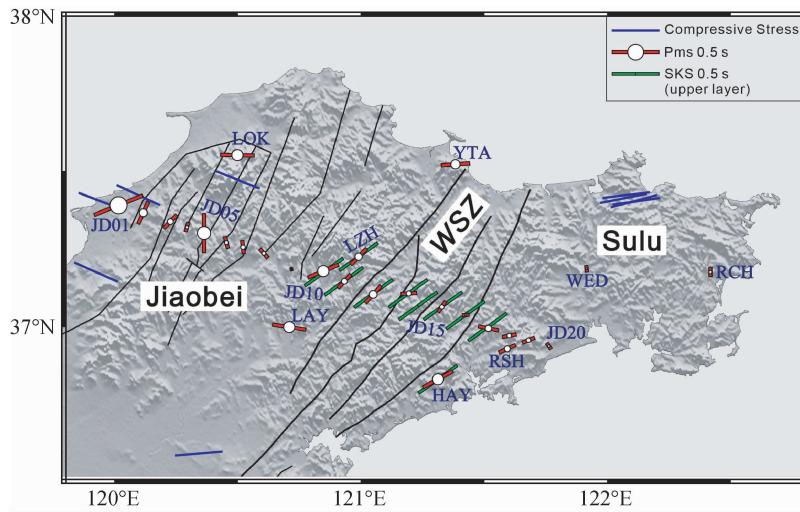


图 7 胶东半岛 SKS 各向异性结果(Wu et al., 2020)

五莲缝合带(WSZ)为双层各向异性结构, 蓝棒代表上层分裂参数, 红棒代表下层分裂参数.

Fig. 7 Station-averaged SKS anisotropy results for the Jiaodong Peninsula (Wu et al., 2020)

A two-layer model allows estimating anisotropy in the WSZ, blue bars represent the splitting parameters for the upper layer, while red bars are the splitting vectors for the lower layer.

盆地和胶北隆起偏高, 这些特征与西太平洋板块对其的俯冲挤压有着密切的关联(潘素珍等, 2015).

中国东部 P 波层析成像结果显示胶东地区呈现出构造隆起区的地壳速度特征, 其局部异常与主要构造走向趋于一

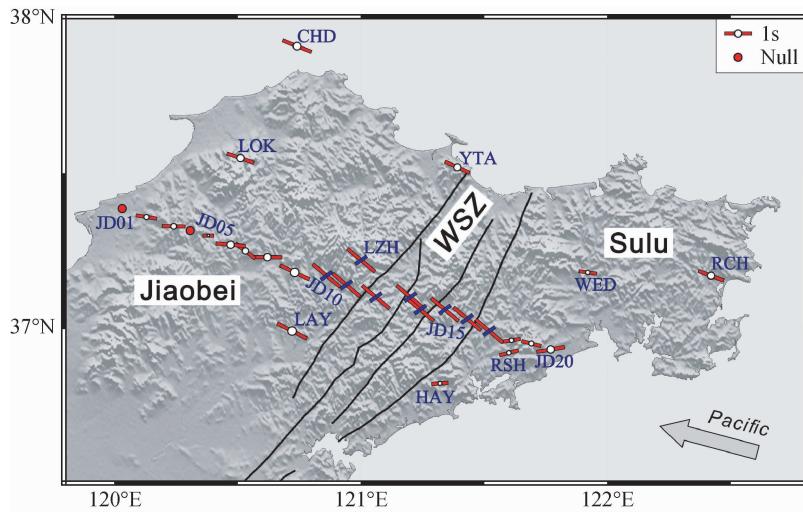


图 8 地壳各向异性结果 (Wu et al., 2021)

红棒为 Pms 分裂参数, 绿棒为 XKS 上层分裂参数.

Fig. 8 The estimated crust azimuthal anisotropy (Wu et al., 2021)

The red bars indicate the splitting parameters derived from Pms phase, the green bars represent the upper layer anisotropy based on XKS splitting analysis.

致(胥颐等, 2009). 基于胶东地区国家地震台网的背景噪声成像研究得到了该区三维 S 波速度结构, 在安丘和蓬莱附近的新生代玄武岩下方发现了 Moho 面的抬升以及上地幔低速异常, 可能是滞留的太平洋板片造成的软流圈物质上涌造成 (Li et al., 2018). 利用短周期密集台阵记录的远震 P 波接收函数数据得到了胶东半岛的精细地壳结构(图 3), 结果显示:

(1) 平均地壳厚度为 33 km, 平均波速比 V_p/V_s 约为 1.76; 低速层发育在 12~16 km, 可能是含水或含盐流体的脆韧性过渡带, 为晚中生代大规模金成矿提供了流体来源 (Hou et al., 2022); 胶莱盆地下方一组北倾界面可能是三叠纪陆-陆碰撞期间形成的一系列逆冲推覆构造, 其后期进一步活化, 成为超高压变质岩折返通道; 中地壳低速层的形成以及早期逆冲推覆构造的活化可能与晚中生代强烈伸展构造背景有关, 它们均代表胶东地区可能经历了广泛的地壳伸展.

(2) 在胶西北矿集区地壳伸展尤为强烈, 从地表到壳幔过渡带均存在曾发生伸展作用的证据, 例如脆性上地壳存在以拆离断层为主的横向拉张, 成像结果刻画了招平断裂等缓倾拆离断层, 且最终汇聚于中地壳脆韧性过渡带, 其次胶西北中下地壳强度弱、垂向速度梯度小, 壳幔过渡带较厚, 可能和横向伸展引起的岩浆/成矿热液作用相关.

(3) 牛乳成矿带主要受控于走滑性质的五莲烟台断裂带, 断裂带两侧 Moho 面、中地壳低速层顶、底界面均存在不同程度的错断, 且壳幔过渡带厚度、上地壳纵横波速度比和布格重力异常也存在显著差异, 均表明五莲烟台断裂带为切穿地壳的深大断裂, 同时也是苏鲁造山带与胶北地体之间的构造边界.

(4) 结构差异导致胶东半岛东部和西部地区的成矿差异, 在华北克拉通破坏的峰期, 胶西北地区巨量金矿的形成

与强烈的地壳伸展、巨量的岩浆活动、以及古西太平洋滞留板片的脱水密切相关, 受控于大规模缓倾的拆离断层; 而东部的牛乳成矿带以高角度的脆性断裂为主, 尽管其成矿动力学机制等与胶西北地区相同, 但可能因为伸展程度相对较低且断层倾角较大而不利于金的沉淀和富集 (Yu et al., 2020).

大地电磁测深技术由于精度高、探测深度大、对高导层反应敏感等优点, 成为研究地球壳幔电性结构的主要地球物理方法之一 (Zhang et al., 2018; 胡浩等, 2020). 穿过胶北隆起和胶莱盆地 NW 向剖面大地电磁测深结果显示(图 4), 以剖面 85 km 和 125 km 处为界有三个宽且不连续的高电阻率层, 且近地表的高导异常与地表出露的主要断裂对应良好, 并最终与中地壳高导层相连通, 可能与上涌的玄武质岩浆有关, 85 km 处深部高导异常为胶北隆起和胶莱盆地边界 (Zhang et al., 2018).

4 浅层结构

除上述深部地球物理探测以外, 胶东地区还开展了浅部结构的探测研究. 开展地壳精细结构, 特别是 10 km 以浅的上地壳结构研究, 有助于查明控矿构造的规模、深部延展及构造样式等, 对认识构造控矿规律及指导深部找矿等具有重要意义 (张明辉等, 2019). 焦家金成矿带是胶东地区最重要的成矿带之一, 其金资源储量已经成为我国最大的金矿带, 其成矿受控于焦家断裂, 且其展布与断裂带吻合 (于学峰等, 2019). 胶东莱州深钻 ZK01 资料显示, 焦家金矿带深部从破碎特征、蚀变矿化特征、构造岩类型等方面与浅部存在差异, 具有分带性, 其深部矿体主要位于主断裂面(断层泥)上部, 打破以往研究认为断层泥在成矿过程中起隔挡成矿热液的作用、矿体位于其下的局限认识; 该断裂具有多期性, 成矿流体显示多源性, 成矿物质总体来源于中生代活化再造的前寒

武纪变质基底(于学峰等, 2019). 跨三山岛断裂、焦家断裂和招平断裂的三条反射地震剖面, 揭示了三山岛断裂带、焦家断裂带和招平断裂带三大控矿构造的精细结构(图5)(Yu *et al.*, 2018), 地震剖面显示, 该区的地质体结构样式叠加了挤压、走滑和伸展多阶段活动. 玲珑岩体呈碟形剖面, 浅部发育大量X状共轭断层的多期岩浆侵入体, 与岩浆侵入位置相匹配; 三山岛断裂和招平断裂带为SE倾向的铲状断层, 认为三山岛断裂早期可能受到挤压和逆冲作用, 晚期可能发生伸展拆离, 而焦家断裂为NW倾向, 在深部与三山岛断裂斜交, 这些断层均表现为地壳浅层结构, 随着深度增加倾角变缓; 玲珑岩体内部有多个类似“拱弧构造”的岩浆侵入形成的弧形界面, 存在2~3期的岩浆活动(单伟等, 2018); 玲珑岩体东西两侧为切穿地壳的大型走滑断裂, 其中招平断裂东部的走滑断裂束, 使得新太古代变质岩和晚侏罗纪毕郭岩体发生位错, 该位错对应于Moho面断裂和下地壳的岩浆房, 为岩浆和成矿热液上涌提供了重要通道. 该研究认为胶东地块可能由几个倾斜排列的地块组合而成, 地块间强烈的岩浆作用和热液活动导致了大规模的矿化, 该结果为认识中生代克拉通的破坏和大规模金矿形成提供了新的视角(Yu *et al.*, 2018).

由于成本高, 以浅层地震勘探为代表的高分辨率成像方法测线一般较短, 且主要布设在矿区内部. 随着便携式一体化短周期地震仪的发展和完善, 短周期密集台阵被动源探测技术逐渐成为探测浅部精细结构的重要手段(Lin *et al.*, 2013; Liu *et al.*, 2017a, b; 张明辉等, 2020; 俞贵平等, 2020; Yu *et al.*, 2020). 俞贵平等(2020)利用布设在胶东地区跨胶北隆起、胶莱盆地和苏鲁造山带的一条NNW-SEE向的短周期密集台阵剖面(图1), 采用地震背景噪声分析方法提取台站对间的面波经验格林函数信号, 开展了背景噪声成像研究, 基于S波速度反演, 获得胶东地区8 km以浅的上地壳S波速度结构(图6a, b), 结果显示, 胶东地区沉积层普遍较薄, 在约1~2 km深度处存在一个高速间断面, 其速度迅速增加, 推断可能是浅层沉积层、花岗岩风化层或太古宙基底风化层与深部致密基岩之间的速度间断面; 胶西北地区的S波速度结构呈现很强的非均一性. 为了突出S波速度的横向和垂向变化特征, 又分别计算了相对S波速度扰动(图6c)和垂向S波速度梯度(图6d). 其中, 垂向S波速度梯度进一步刻画了上述高速间断面, 且该高速间断面在胶西北地区错断显著, 错断位置与地表断层出露位置吻合良好, 表明这些断层为大规模的伸展拆离断层; 相对S波速度扰动结果显示, 胶北隆起及其周缘存在一些呈铲状且高低速相间的异常条带, 认为是低角度断层构造, 造成S波局部低速异常的原因可能是断层在伸展背景下的岩石破碎或流体蚀变等. 在五莲烟台断裂带地区的牟乳成矿带及以东的苏鲁造山带, 上地壳S波偏高, 且具有显著的横向分块特征, 指示控矿断裂为高角度走滑断裂(杨立强等, 2014). 相比牟乳成矿带高角度脆性断裂控矿, 胶西北低角度拆离断层更有利于形成大规模蚀变岩型矿化, 控矿构造的不同是胶东成矿区域性差异的主控因素.

焦家断裂带北段展布已基本查明, 为了解焦家断裂带南部延伸特征, 胡浩等(2020)开展了面积性音频大地电磁测深工作, 并构建了该区拟三维电阻率模型, 结果显示测区浅

表(0~100 m)普遍存在低阻薄层, 主要为第四系沉积以及风化岩体层, 下伏有厚度变化的高阻层, 高阻层在西部表现为不连续缓倾层状分布, 且被中部低阻体分隔, 而中部低阻体发生近EW向错断. 厘定了焦家断裂带南延位置和形态, 认为该断裂受后期NW-SE向断裂改造发生错断, 并指出焦家断裂的低电阻率特征表明其发育于伸展背景之下, 该断裂是岩浆活动的浅部通道, 为金成矿提供了有利条件.

5 壳幔各向异性与流变学特征

晚三叠期间, 华南块体向北俯冲到华北块体之下, 形成东西延展超过1500 km的不规则的缝合带(Hacker *et al.*, 1998, 2000). Li(1994)提出的地壳拆离模型认为华南块体的上地壳从下地壳拆离并逆冲向华北克拉通内400 km; Faure等(2001, 2003)和Zhai(2002)通过构造分析认为胶北块体属于华南范围, 华北与华南的边界位于胶东半岛的北部; Wu等(2004)和Zheng等(2005)的研究发现, 五莲花岗岩为晚三叠纪大陆俯冲期间华南块体上部刮下来的构造碎屑, 推断缝合带位于胶东半岛地区的五莲烟台断裂带的北侧; 更多地研究认为, 五莲烟台断裂带(即五莲缝合带WSZ)是华北克拉通和华南块体的边界(曹国权和王致本, 1990; Yin and Nie, 1993; Zhai *et al.*, 2000; Zhou *et al.*, 2008), 然而深部壳幔变形证据依然缺乏. 大陆碰撞会导致块体边界岩石圈的强烈变形, 并产生化石各向异性(Silver and Chan, 1988). 胥颐等(2008)基于国家台网地震资料, 反演得到的黄海及其邻区Pn波各向异性结果显示, 胶东地区的Pn波快波方向近东西方向, 而五莲烟台断裂带东、西两侧的各向异性存在较明显的差异, 认为可能是中朝与扬子块体的拼合边界的一部分. Wu等(2020)利用跨五莲烟台断裂带布设的NW向宽频带台阵(NCISP-9)及附近固定台站开展了SKS剪切波分裂研究, 分析了胶东半岛地震波各向异性(图7), 结果表明胶东半岛不同构造单元的分裂模式存在差异, 胶北和苏鲁块体为单层各向异性, 快波方向为WNW-ESW或E-W向, 而在五莲烟台断裂带, 分裂参数随后方位角呈现 $\pi/2$ 周期性变化, 表明存在双层各向异性模式, 通过对观测结果拟合得到其下层快波方向WNW-ESE向, 平行于太平洋板块现今俯冲方向, 与前人在胶东半岛的研究结果相一致(Shi *et al.*, 2015; Tian & Santosh, 2015; Zhao & Xue, 2010), 各向异性由太平洋板块俯冲引起的大地幔楔中的软流圈回流所引起; 其上层快波方向为NE-SW向, 与五莲烟台断裂带走向大致平行, 尽管经历了晚中生代以来岩石圈的减薄, 岩石圈仍保留了晚三叠纪华北克拉通和华南块体碰撞导致的化石各向异性. 该研究认为五莲烟台断裂带为华北克拉通和华南地块之间的碰撞缝合带.

地壳各向异性所反映的地壳变形特征同样会记录陆-陆碰撞过程, Wu等(2021)利用宽频带台阵(NCISP-9)数据, 采用径向接收函数Pms到时余弦拟合及切向接收函数按方位角加权叠加两种手段获取了胶东半岛的地壳方位各向异性(图8), 结果显示, 在五莲断裂带, 观测到NE向快波方向, 大致与断裂走向平行, 并与XKS得到的双层各向异性的上层快波方向吻合, 地壳各向异性来自于晚三叠纪华北和华南的碰撞, 这次碰撞事件导致了两块体边界缝合带区域的地壳和

岩石圈地幔垂直连贯边形,本研究支持五莲烟台断裂带为华北华南陆-陆碰撞缝合带。胶北块体地壳各向异性主要受控于E-W向地壳应力及NNE向拆离断层,北苏鲁块体地壳各向异性较弱,分裂时差均小于0.2 s,可能是广泛分布的超高压变质岩在内部较难产生强烈变形导致(Wu et al., 2021)。

6 结 论

本文对胶东金矿集区及邻区深部结构进行了初步总结,在岩石圈各圈层结构及壳幔各向异性特征等方面获得主要认识如下:

(1) 华北克拉通东部自晚中生代以来发生广泛的伸展构造变形和岩浆活动,胶东地区岩石圈厚度减薄至60~80 km,郯庐断裂为岩石圈尺度断裂,为大陆伸展和岩石圈减薄过程中软流圈物质上涌重要通道。

(2) 胶东地区地壳平均厚度约33 km,平均纵横波速度比为1.76,12~16 km的中地壳普遍发育低速层,可能是含水或含盐流体的脆韧性过渡带,为晚中生代大规模金成矿提供了流体来源。

(3) 接收函数CCP成像与上地壳S波速度结构显示,胶北成矿带控矿构造表现为大规模拆离断层,而东部半乳成矿带则以高角度的脆性(走滑)断裂为主;控矿断裂性质的不同可能是胶东区域性成矿差异的重要控制因素。

(4) 胶东地区SKS和Pms震相得到的壳幔各向异性结果显示,五莲烟台断裂带地壳和岩石圈地幔快波方向均平行于断裂走向,表明该断裂带岩石圈可能保存了三叠纪华北与华南陆-陆碰撞的化石各向异性,推测五莲烟台断裂带为华北克拉通和华南块体在东部的碰撞缝合带。

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References

- Ai Y S, Zheng T Y, Xu W W, et al. 2003. A complex 660 km discontinuity beneath northeast China. *Earth and Planetary Science Letters*, 212(1-2): 63-71.
- Carlson R W, Pearson D G, James D E. 2005. Physical, chemical, and chronological characteristics of continental mantle. *Reviews of Geophysics*, 43, RG1001, doi: 10.1029/2004RG000156.
- Chen L. 2009. Lithospheric Structure variations between the eastern and central North China Craton from S- and P-Receiver Function Migration. *Phys. Earth Planet. Inter.* 173(3-4): 216-227.
- Chen L. 2010. Concordant structural variations from the surface to the base of the upper mantle in the North China Craton and its tectonic implications. *Lithos*, 120(1-2): 96-115.
- Chen L, Cheng C, Wei Z G. 2009. Seismic evidence for significant lateral variations in lithospheric thickness beneath the central and western North China Craton. *Earth and Planetary Science Letters*, 286: 171-183.
- Chen L, Jiang M M, Yang J H, et al. 2014. Presence of an intralithospheric discontinuity in the central and western North China Craton: Implications for destruction of the craton. *Geology*, 42(3): 223-226.
- Chen L, Tao W, Zhao L, et al. 2008. Distinct lateral variation of lithospheric thickness in the Northeastern North China Craton. *Earth Planet Sci Lett*, 267: 56-68.
- Chen L, Zheng T Y, Xu W W. 2006. A thinned lithospheric image of the Tanlu Fault Zone, eastern China: Constructed from wave equation based receiver function migration. *J Geophys Res*, 111: B09312.
- Deng J, Liu X F, Wang Q F, et al. 2015. Origin of the Jiaodong-type Xinli gold deposit, Jiaodong Peninsula, China: Constraints from fluid inclusion and C-D-O-Sr isotope compositions. *Ore Geology Reviews*, 65: 674-686.
- Deng J, Wang Q F, Yang L Q, et al. 2004. The geological settings to the gold metallogeny in northwestern Jiaodong Peninsula, Shandong Province. *Earth Science Frontiers* (in Chinese), 11(4): 527-533.
- Duan Y H, Wang F Y, Zhang X K, et al. 2016. Three dimensional crustal velocity structure model of the middle-eastern North China Craton (HBCrust1.0). *Science China Earth Sciences*, 59: 1477-1488.
- Fan H R, Hu F F, Yang J H, et al. 2005. Fluid evolution and large-scale gold metallogeny during Mesozoic tectonic transition in the eastern Shandong province. *Acta Petrologica Sinica* (in Chinese), 21(5): 1317-1328.
- Fan H R, Zhai M G, Xie Y H, et al. 2003. Ore-forming fluids associated with granite-hosted gold mineralization at the Sanshandao deposit, Jiaodong gold province, China. *Mineralium Deposita*, 38: 739-750.
- Fan W M, Menzies M A. 1992. Destruction of aged lower lithosphere and accretion of asthenosphere mantle beneath eastern China. *Geotectonica et metallogenica*, 16: 171-180.
- Faure M, Le Breton N, Lin W, et al. 2001. Where is the North China-South China block boundary in eastern China?. *Geology*, 29(2): 199-222.
- Faure M, Wei L, Monie P, et al. 2003. Exhumation tectonics of the ultrahigh-pressure metamorphic rocks in the Qinling orogen in east China: New petrological-structural-radiometric insights from the Shandong Peninsula. *Tectonics*, American Geophysical Union (AGU), 22(3): 1018.
- Hacker B R, Ratschbacher L, Webb L, et al. 1998. U/Pb zircon ages constrain the architecture of the ultrahigh-pressure Qinlin-Dabie Orogen, China. *Earth and Planetary Science Letters*, 161: 215-230.
- Hacker B R, Ratschbacher L, Webb L, et al. 2000. Exhumation of ultrahigh-pressure continental crust in east central China: Late Triassic-Early Jurassic tectonic unroofing. *Journal of Geophysical Research: Solid Earth*, 105: 13339-13364.
- Harrison C B, Urosevic M. 2012. Seismic processing, inversion, and AVO for gold exploration—Case study from Western Australia. *Geophysics*, 77(5): 235-243.
- Hou J, Xu T, Ai Y S, Yu GP, Yang YJ, Xu B, Wang QF, 2022, Crustal controls on the formation of the Jiaodong supergiant gold province: evidence from ambient noise tomography, *Journal of Geophysical Research: Solid Earth*, under review.
- Hu H, Zhang K, Yan J Y, et al. 2020. Electrical structures in the southern reach of the Jiaoja fault belt inferred from audio-frequency magnetotelluric sounding in the Jiaodong Peninsula, Shandong Province. *Acta Geologica Sinica* (in Chinese), 94(2): 661-674.
- Jia S X, Wang F Y, Tian X F, et al. 2014. Crustal structure and tectonic study of North China Craton from a long seismic sounding profile. *Tectonophysics* 627, 48-56.
- Lei J S, Zhao D P, Xu X W, et al. 2020. P-wave upper-mantle tomography of the Tanlu fault zone in eastern China. *Physics of the Earth and Planetary Interiors*, 299: 106402.
- Li C L, Chen C X, Dong D D, et al. 2018. Ambient noise tomography of the Shandong province and its implication for Cenozoic intraplate volcanism in eastern China. *Geochemistry, Geophysics, Geosystems*, 19: 3286-3301.
- Li H K, Zhuo C Y, Geng K, et al. 2012. Study on tectonic background of gold mineralization in Jiaodong area. *Shandong land and resources* (in Chinese), 28(1): 5-13.
- Li J L, Zhang Y Q, Liu Z Q, et al. 2007. Sedimentary-subsidence history and tectonic evolution of the Jiaolai basin, eastern China. *Geology in China* (in Chinese), 34(2): 240-250.
- Li L, Santosh M, Li S R. 2015. The ‘Jiaodong type’ gold deposits:

- Characteristics, origin and prospecting. *Ore Geology Reviews*, 65: 589-611.
- Li S G, Xiao Y L, Liou D L, et al. 1993. Collision of the North China and Yangtze Blocks and formation of coesite-bearing eclogites: timing and processes. *Chem. Geol.*, 109: 89-111.
- Li S X, Liu C C, An Y H, et al. 2007. Geology of gold deposits in Shandong Peninsula. Beijing: Geological Publishing House (in Chinese).
- Li Z X. 1994. Collision between the North and South China blocks: a crustal-detachment model for suturing in the region east of the Tanlu fault. *Geology*, 22: 739-742.
- Lin F C, Li D Z, Clayton R W, et al. 2013. High-resolution 3D shallow crustal structure in Long Beach, California: Application of ambient noise tomography on a dense seismic array. *Geophysics*, 78(4): Q45-Q56.
- Lin W, Michel F, Wang Q C. 2003. Mesozoic geometry and kinematics in the Jiaodong peninsula and its tectonic evolution. *Chinese Journal of Geology* (in Chinese), 38(4): 495-505.
- Liu Y N, Niu F L, Chen M, et al. 2017a. 3-D crustal and uppermost mantle structure beneath NE China revealed by ambient noise adjoint tomography. *Earth and Planetary Science Letters*, 461: 20-29.
- Liu Z, Tian X B, Gao R, et al. 2017b. New images of the crustal structure beneath eastern Tibet from a high-density seismic array. *Earth and Planetary Science Letters*, 480: 33-41.
- Liu Z, Wang F Y, Zhang X K, et al. 2015. Seismic structure of the lithosphere beneath Eastern North China craton: results from long distance deep seismic sounding. *Chinese J. Geophys.* (in Chinese), 58(4): 1145-1157.
- Lu B, Hu S X, Zhou S Z, et al. 1995. Terrane tectonics and tectonic setting of gold deposits in the Shandong Peninsula. *Geological Review* (in Chinese), 41(1): 7-14.
- Mao J W, Wang Y T, Li H M, et al. 2008. The relationship of mantle-derived fluids to gold metallogenesis in the Jiaodong Peninsula: Evidence from D-O-C-S isotope systematics. *Ore Geology Reviews*, 33(3-4): 361-381.
- Meng FC, Ai YS, Xu T, et al. 2021. Lithospheric structure beneath the boundary region of North China Craton and Xing Meng Orogenic Belt from S-receiver function analysis. *Tectonophysics*, 818, 229067.
- Menzies M A, Fan W M, Zhang M. 1993. Palaeozoic and Cenozoic lithoprobes and the loss of > 120 km of Archaean lithosphere, Sino-Korean craton, China. *Geological Society, London, Special Publications*, 76(1): 71-81.
- Pan S Z, Wang F Y, Zheng Y P, et al. 2015. Crustal velocity structure beneath Jiaodong Peninsula and its tectonic implications. *Chinese J. Geophys.* (in Chinese), 58(9): 3251-3263.
- Qiu Y M, Groves D I, McNaughton N J, et al. 2002. Nature, age, and tectonic setting of granitoid-hosted, orogenic gold deposits of the Jiaodong Peninsula, eastern North China Craton, China. *Mineralium Deposita*, 37(3-4): 283-305.
- Shi Y T, Gao Y, Tai L X, et al. 2015. The shear-wave splitting in the crust and the upper mantle around the Bohai Sea, North China. *Journal of Asian Earth Sciences*, 111: 505-516.
- Silver P G, Chan W W. 1988. Implications for continental structure and evolution from seismic anisotropy. *Nature*, 335(6185): 34-39.
- Song M C, Li S Z, Santosh M, et al. 2015. Types, characteristics and metallogenesis of gold deposits in the Jiaodong Peninsula, Eastern North China Craton. *Ore Geology Reviews*, 65(3): 612-625.
- Song M C, Lin S Y, Yang L Q, et al. 2020. Metallogenic model of Jiaodong Peninsula gold deposits. *Mineral Deposits* (in Chinese), 39(2): 215-236.
- Tian X B, Santosh M. 2015. Fossilized lithospheric deformation revealed by teleseismic shear wave splitting in eastern China. *GSA Today*, 25(2): 4-10.
- Tian X F, Zelt C A, Wang F Y, et al. 2014. Crustal structure of the North China Craton from a long-range seismic wide-angle reflection/refraction data. *Tectonophysics*, 634: 237-245.
- Wu C L, Xu T, Ai Y S, et al. 2020. XKS splitting-based upper-mantle deformation in the Jiaodong Peninsula records the boundary between the North China Craton and South China Block. *Geophys. J. Int.*, 222: 956-964.
- Wu C L, Xu T, Ai Y S, et al. 2021. Crustal azimuthal anisotropy in the Jiaodong Peninsula: Evidence for the suture between the North China Craton and South China Block. *Physics of the Earth and Planetary Interiors*, 314: 106705.
- Wu F Y, Xu Y G, Gao S, et al. 2008. Lithospheric thinning and destruction of the North China Craton. *Acta Petrologica Sinica* (in Chinese), 24(6): 1145-1174.
- Wu Y B, Zheng Y F, Zhou J B. 2004. Neoproterozoic granitoid in northwest Sulu and its bearing on the North China - South China Blocks boundary in east China. *Geophysical Research Letters*, 31(7).
- Xu P F, Liu F T, Wang Q C, et al. 2000. Seismic tomography beneath the Dabie-Sulu collision orogen-3-D velocity structures of lithosphere. *Chinese Journal of Geophysics* (in Chinese), 43(3): 377-385.
- Xu P F, Liu F T, Wang Q C, et al. 2001. Slab-like high velocity anomaly in the uppermost mantle beneath the Dabie-Sulu orogeny. *Geophys. Res. Lett.*, 28(9): 1847-1850.
- Xu P F, Liu F T, Ye K, et al. 2002. Flake tectonics in the Sulu orogeny in eastern China as revealed by seismic tomography. *Geophys. Res. Lett.*, 29(10): 23-1-23-4.
- Xu Y, Li Z W, Kim Kwanghee, et al. 2009. Crustal velocity structure and collision boundary between the Sino-Korea and Yangtze blocks in the Yellow Sea. *Chinese J. Geophys.* (in Chinese), 52(3): 646-652.
- Xu Y, Li Z W, Liu J S, et al. 2008. Pn wave velocity and anisotropy in the Yellow Sea and adjacent region. *Chinese J. Geophys.* (in Chinese), 51(5): 1444-1450.
- Xu Z Q, Yang W C, Ji S C, et al. 2009. Deep root of a continent-continent collision belt: Evidence from the Chinese Continental Scientific Drilling (CCSD) deep borehole in the Sulu ultrahigh-pressure (HP-UHP) metamorphic terrane, China. *Tectonophysics*, 475(2): 204-219.
- Yang J H, Wu F Y, Chung S L, et al. 2005. Petrogenesis of Early Cretaceous intrusions in the Sulu ultrahigh-pressure orogenic belt, east China and their relationship to lithospheric thinning. *Chemical Geology*, 222(3-4): 200-231.
- Yang J H, Wu F Y, Wilde S A. 2003. A review of the geodynamic setting of large-scale Late Mesozoic gold mineralization in the North China Craton: An association with lithospheric thinning. *Ore Geology Reviews*, 23(3-4): 125-152.
- Yang J H, Xu L, Sun J F, et al. 2021. Geodynamics of decratonization and related magmatism and mineralization in the North China Craton. *Science China Earth Sciences*, 64(9): 1409-1427.
- Yang J H, Zhou X H. 2001. Rb-Sr, Sm-Nd, and Pb isotope systematics of pyrite: implications for the age and genesis of lode gold deposits. *Geology*, 29: 711-714.
- Yang J Z, Shen Y C, Liu T B. 2000. Gold mineralization associated with detachment structure in Jiaodong region. *Gold Geology* (in Chinese), 2: 21-25.
- Yang W C. 2002. Geophysical profiling across the Sulu ultra-high-pressure metamorphic belt, eastern China. *Tectonophysics*, 354(3): 277-288, doi:10.1016/S0040-1951(02)00386-4.
- Yin A, Nie S Y. 1993. An indentation model for the North and South China collision and the development of the Tan-Lu and Honam Fault Systems, eastern Asia. *Tectonics*, 12: 801-813.
- Yu G P, Xu T, Ai Y S, et al. 2020. Significance of crustal extension and magmatism to gold deposits beneath Jiaodong Peninsula, eastern North China Craton: Seismic evidence from receiver function imaging with a dense array. *Tectonophysics*, 789: 228532.
- Yu G P, Xu T, Liu J T, et al. 2020. Late Mesozoic extensional structures and gold mineralization in Jiaodong Peninsula, eastern North China Craton: an inspiration from ambient noise tomography on data from a dense seismic array. *Chinese J. Geophys.* (in Chinese), 63(5): 1878-1893, doi: 10.6038/cjg2020N0446.
- Yu X F, Shan W, Xiong Y X, et al. 2018. Deep structural framework and genetic analysis of gold concentration areas in the northwestern Jiaodong Peninsula, China: A new understanding based on high-

- resolution reflective seismic survey. *Acta Geologica Sinica*, 92(5): 1823-1840.
- Zhao L, Allen R M, Zheng T, Zhu R X. 2012. High-resolution body wave tomography models of the upper mantle beneath eastern China and the adjacent areas. *Geochemistry Geophysics Geosystems*, 13: Q06007.
- Zhao L, Allen R M, Zheng T Y, Hung S H. 2009. Reactivation of an Archean craton: Constraints from P- and S-wave tomography in North China. *Geophysical Research Letters*, 36: doi: 10.1029/2009GL039781.
- Zhao L, Xue M. 2010. Mantle flow pattern and geodynamic cause of the North China Craton reactivation: Evidence from seismic anisotropy. *Geochemistry, Geophysics, Geosystems*, 11(7).
- Zhai M G. 2002. Where is the North China-South China block boundary in eastern China? Comment and Reply. *Geology*, 30(7): 667.
- Zhai M G, Guo J H, Wang Q C, et al. 2000. Division of petrological-tectonic units in the Northern Sulu ultra-high pressure zone: An example of thick-skin thrust of crystalline units. *Sci. Geol. Sin. (in Chinese)*, 35(1): 16-26.
- Zhang K, Lü Q T, Yan J Y, et al. 2018. Crustal structure beneath the Jiaodong Peninsula, North China, revealed with a 3D inversion model of magnetotelluric data. *Journal of Geophysics and Engineering*, 15: 2442-2454.
- Zhang M H, Liu Y S, Hou J, et al. 2019. Review of seismic tomography methods in near-surface structures reconstruction. *Progress in Geophysics (in Chinese)*, 34(1): 48-63.
- Zhang M H, Wu Z B, Ma L X, et al. 2020. Research progress of passive source detection technology based on short-period dense seismic array. *Progress in Geophysics (in Chinese)*, 35(2): 0495-0511.
- Zhang T, Zhang Y Q. 2007. Geochronological sequence of Mesozoic intrusive magmatism in Jiaodong Peninsula and its tectonic constraints. *Geological Journal of China Universities (in Chinese)*, 13(2): 323-336.
- Zhang Y Q, Dong S W, Shi W. 2003. Cretaceous deformation history of the middle Tan-Lu fault zone in Shandong Province, eastern China. *Tectonophysics*, 363: 243-258.
- Zhang Y Q, Li J L, Zhang T, et al. 2007. Late Mesozoic kinematic history of the Muping-Jimo fault zone in Jiaodong Peninsula, Shandong Province, East China. *Geological Review (in Chinese)*, 53(3): 289-300.
- Zhao L, Allen R M, Zheng T Y, et al. 2012. High-resolution body wave tomography models of the upper mantle eastern China and the adjacent areas. *Geochemistry Geophysics Geosystems*, 13, 6007.
- Zheng T Y, Duan Y H, Xu W W, Ai Y S. 2017. A seismic model for crustal structure in North China Craton. *Earth and Planetary Physics*, 1: 26-34.
- Zheng T Y, Zhao L, Xu W W, et al. 2008. Insight into modification of North China Craton from seismological study in the Shandong Province. *Geophys. Res. Lett.*, 35(22): L22305, doi:10.1029/2008GL035661.
- Zheng T Y, Zhao L, Zhu R X. 2009. New evidence from seismic imaging for subduction during assembly of the North China craton. *Geology*, 37: 395-398.
- Zheng T Y, Zhu R X, Zhao L, Ai Y S. 2012. Intra-lithospheric mantle structures recorded continental subduction. *Journal of Geophysical Research*, 117: B03308.
- Zheng Y F, Zhou J B, Wu Y B, et al. 2005. Low-grade metamorphic rocks in the Dabie-Sulu orogenic belt: A passive-margin accretionary wedge deformed during continent subduction. *International Geology Review*, 47(8): 851-871.
- Zhou J B, Han W, Song M C. 2016. The exhumation of the Sulu Terrane and the forming of the Tancheng-Lujiang Fault: Evidence from detrital zircon U-Pb dating of the Mesozoic sediments of the Laiyang Basin, Central China. *Acta Petrol. Sin. (in Chinese)*, 32(04): 1171-1181.
- Zhou J B, Wilde S A, Zhao G C, et al. 2008. SHRIMP U-Pb zircon dating of the Wulian complex: Defining the boundary between the North and South China Cratons in the Sulu Orogenic Belt, China. *Precambrian Res.*, 162: 559-576.
- Zhou X H, Yang J H, Zhang L C. 2002. The formation of Jiaodong super large gold deposit and the deep lithospheric process of North China in Mesozoic. *Science in China (Series D)*, 32: 11-20.
- Zhu G, Liu C, Gu C C, et al. 2018. Oceanic plate subduction history in the western Pacific Ocean: Constraint from late Mesozoic evolution of the Tan-Lu Fault Zone. *Science China Earth Sciences*, 61: 386-405.
- Zhu R X, Chen L, Wu F Y, et al. 2011. Timing, scale and mechanism of the destruction of the North China Craton. *Sci. China Earth Sci. (in Chinese)*, 54: 789-797.
- Zhu R X, Fan H R, Li J W, et al. 2015. Decratonic gold deposits. *Science China Earth Sciences*, 45(8): 1153-1168.
- Zhu R X, Sun W D. 2021. The big mantle wedge and decratonic gold deposits. *Science China Earth Sciences*, 64(9): 1451-1462.
- Zhu R X, Xu Y G, Zhu G, et al. 2012. Destruction of the North China Craton. *Science China Earth Sciences*, 55: 1565-1587.
- Zhu R X, Zheng T Y. 2009. Destruction geodynamics of the North China Craton and its Paleoproterozoic plate tectonics. *Chinese Sci. Bull. (in Chinese)*, 54(14), 1950-1961.

附中文参考文献

- 曹国权, 王致本. 1990. 山东胶南地体及其边界断裂五莲: 荣成断裂的构造意义. *山东地质*, 6(1): 1-15.
- 邓军, 王庆飞, 杨立强, 等. 2004. 胶西北金矿集区成矿作用发生的地质背景. *地学前缘*, 11(4): 527-533.
- 段永红, 王夫运, 张先康, 等. 2016. 华北克拉通中东部地壳三维速度结构模型(HBCrust1.0). *中国科学: 地球科学*, 46: 845-856.
- 范宏瑞, 胡芳芳, 杨进辉, 等. 2005. 胶东中生代构造体制转换过程中流体演化和金的大规模成矿. *岩石学报*, 21(5): 1317-1328.
- 胡浩, 张昆, 严加永, 等. 2020. 山东胶东半岛焦家断裂带南缘电性结构研究. *地质学报*, 94(2): 661-674.
- 李洪奎, 祁传源, 耿科, 等. 2012. 胶东金矿成矿构造背景探讨. *山东国土资源*, 28(1): 5-13.
- 李金良, 张岳桥, 柳宗泉等. 2007. 胶莱盆地沉积-沉降史分析与构造演化. *中国地质*, 34(2): 240-250.
- 林伟, Michel F, 王清晨. 2003. 胶东半岛中生代构造演化的几何学和运动学. *地质科学*, 38(4): 495-505.
- 刘志, 王夫运, 张先康, 等. 2015. 华北克拉通东部地壳与地幔盖层结构—长观测距深地震测深剖面结果. *地球物理学报*, 58: 1145-1157.
- 卢冰, 胡受奚, 周顺之, 等. 1995. 山东半岛的地体构造及金矿成矿的区域地质背景. *地质评论*, 41(1): 7-14.
- 潘素珍, 王夫运, 郑彦鹏, 等. 2015. 胶东半岛地壳速度结构及其构造意义. *地球物理学报*, 58(9): 3251-3263.
- 单伟, 于学峰, 李洪奎, 等. 2018. 招平断裂带中段深部结构构造来自地震剖面的证据. *山东国土资源*, 34(5): 49-58.
- 宋明春. 2015. 胶东金矿深部找矿主要成果和关键理论技术进展. *地质通报*, 34(9): 1758-1771.
- 宋明春, 林少一, 杨立强, 等. 2020. 胶东金矿成矿模式. 矿床地质, 39(2): 215-236.
- 吴福元, 徐义刚, 高山, 等. 2008. 华北岩石圈减薄与克拉通破坏研究的主要学术争论. *岩石学报*, 24(6): 1145-1174.
- 胥颐, 李志伟, Kim Kwanghee, 等. 2009. 黄海的地壳速度结构与中朝-扬子块体拼合边界. *地球物理学报*, 52(3): 646-652.
- 胥颐, 李志伟, 刘劲松, 等. 2008. 黄海及其邻近地区的Pn波速度与各向异性. *地球物理学报*, 51(5): 1444-1450.
- 杨金中, 沈远超, 刘铁兵. 2000. 胶东地区滑脱构造与金矿成矿浅析. *黄金地质*, 2: 21-25.

- 杨立强, 邓军, 王中亮, 等. 2014. 胶东中生代金成矿系统. 岩石学报, 30(9): 2447-2467.
- 杨文采, 程振炎, 陈国九, 等. 1999. 苏鲁超高压变质带北部地球物理调查(I)—深反射地震. 地球物理学报, 42(1): 41-52.
- 俞贵平, 徐涛, 刘俊彤, 等. 2020. 胶东地区晚中生代伸展构造与金成矿:短周期密集台阵背景噪声成像的启示. 地球物理学报, 63(5): 1878-1893, doi: 10.6038/cjg2020N0446.
- 于学峰, 杨德平, 李大鹏, 等. 2019. 胶东焦家金矿带 3000 m 深部成矿特征及其地质意义. 岩石学报, 35(9): 2893-2910.
- 翟明国, 范宏瑞, 杨进辉, 等. 2004. 非造山带型金矿-胶东型金矿的陆内成矿作用. 地学前缘, 11(1): 85-98.
- 翟明国, 郭敬辉, 王清晨等. 2000. 苏鲁变质带北部的岩石构造单元及结晶块体推覆构造. 地质科学, 35(1): 16-26.
- 张田, 张岳桥. 2007. 胶东半岛中生代侵入岩浆活动序列及其构造制约. 高校地质学报, 13(2): 323-336.
- 张岳桥, 李金良, 张田等. 2007. 胶东半岛牟平-即墨断裂带晚中生代运动学转换历史. 地质评论, 53(3): 289-300.
- 张明辉, 刘有山, 侯爵, 等. 2019. 近地表地震层析成像方法综述. 地球物理学进展, 34(1): 48-63.
- 张明辉, 武振波, 马立雪, 等. 2020. 短周期密集台阵被动源地震探测技术研究进展. 地球物理学进展, 35(2): 0495-0511.
- 周建波, 韩伟, 宋明春. 2016. 苏鲁地体折返与郯庐断裂活动:莱阳盆地中生界碎屑锆石年代学的制约. 岩石学报, 32(04): 1171-1181.
- 朱日祥, 陈凌, 吴福元, 等. 2011. 华北克拉通破坏的时间、范围与机制. 中国科学: 地球科学, 41: 583-592.
- 朱日祥, 范宏瑞, 李建威, 等. 2015. 克拉通破坏型金矿床. 中国科学: 地球科学, 45(8): 1153-1168.
- 朱日祥, 徐义刚, 朱光, 等. 2012. 华北克拉通破坏. 中国科学: 地球科学, 42: 1135-1159.
- 朱日祥, 郑天渝. 2009. 华北克拉通破坏机制与古元古代板块构造体系. 科学通报, 54(14), 1950-1961.