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中国北方新生代大陆变形及其动力学机制分析

徐芹芹[1,2] 季建清[2] 涂继耀[2] 侯建军[2]

(1. 中国地质科学院地质研究所,北京 100037;2. 造山带与地壳演化教育部重点实验室,
北京大学地球与空间科学学院,北京 100871)

提要:大陆变形研究是大陆动力学的基本内容之一,对断裂构造及盆山演化进行研究是认识与了解大陆变形最直接有效的途径。中生代晚期—新生代,中国北方受到印度板块向北俯冲、太平洋板块向西运动与西伯利亚板块阻挡所导致的复杂构造动力系统的长期作用,地壳变形复杂,是研究大陆变形理想的天然实验室。本文在详细野外构造解析基础上,结合遥感与数字地貌技术、地震反射资料解释以及低温热年代学方法,通过对中国北方新生代断裂作用和山脉隆升历史研究,理清了断裂发育序次、断裂作用与构造应力场的对应关系,掌握了现今构造地貌格局东西差异的成因,并探讨了大陆变形的动力学机制。古新世—早始新世,中国北方普遍发育一组NNE向的断裂构造,该组断裂并非全区均匀发育,东部断裂规模较大,地貌特征明显,向西规模逐渐变小。NNE向断裂具有左行走滑的运动学特征,大致对应NW−SE向挤压应力场,推测NNE向左行走滑断裂的发育与新生代早期太平洋板块NNW向运动有关。NNE向断裂发育之后,东部渤海湾周边发育了NE向右行、NW向左行共轭走滑断裂,大致对应近EW向挤压应力场。西准噶尔地区发育了NE向左行、NW向右行走滑断裂,大致对应近NS向挤压应力场。东、西部的NE、NW向断裂都叠加在NNE向断裂之上,改造和破坏了早期NNE向断裂。本文推测东部后期断裂的发育与43~42 Ma太平洋板块运动由NNW转变为WNW向有关,而西部NE、NW向断裂发育与印度−欧亚大陆碰撞远程效应有关。随着印度板块持续北向运动并发生顺时针旋转,西部地区保持NNE向挤压应力场,发育了一系列NW、NNW向断裂。东部地区依然呈现近EW向挤压应力场。受到新生代以来各组断裂构造的影响,中国北方山脉和盆地呈现出线状与面状结合的网格状特征。磷灰石裂变径迹年龄统计显示,东部地区普遍经历了古新世—早始新世(66~42 Ma)的隆升−剥露,该期构造事件为现今东部地区构造地貌格局的形成奠定了基础。与东部地区不同,西部地区则存在8~6 Ma等时面,且8~6 Ma整体隆升−剥露为西部地区现今构造地貌格局的形成做出了主要的贡献。

关 键 词:NNE走滑断裂;构造地貌;大陆变形;新生代;中国北方
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Cenozoic continental deformation in northern China and its geodynamic mechanism

XU Qin−qin [1,2], JI Jian−qing [2], TU Ji−yao[2], HOU Jian−jun[2]

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作者简介:徐芹芹,女,1984年生,博士,构造地质学专业;E−mail: qinqin2002dz1@163.com。
通讯作者:季建清,男,1968年生,博士,教授,岩石学、构造地质学与同位素年代学专业;E−mail: grsange@pku.edu.cn。

(1. *Institute of Geology, Chinese Academy of Geological Sciences, Beijing* 100037*, China;* 2. *Laboratory of Orogenic Belts and Crustal Evolution, Peking University, Beijing* 100871*, China*)

Abstract: Continental deformation is one of the basic contents of continental dynamics. Researches on the faults and basin−mountain evolution are the most direct and effective way to understand the continental deformation. During the late Mesozoic—Cenozoic, northern China was long influenced by northward subduction of Indian plate, westward movement of Pacific plate and blocking of Siberia plate. The crustal deformation was complex, which made northern China an ideal natural laboratory for the study of continental deformation. In this paper, based on the detailed analysis of field structures, combined with remote sensing and digital geomorphology, seismic reflection data interpretation, and low temperature thermochronology, the authors clarified the fault development sequence and tectonic stress field with the help of studying the Cenozoic faulting and the uplift history of mountain ranges in northern China. The causes of the present tectonic landform pattern difference between eastern and western China were found and the geodynamic mechanism of continental deformation was explored. NNE−striking faults were widely developed in northern China during Paleocene—Early Eocene, but they were not uniform, with larger scale and clear geomorphological features in the east. These NNE−trending faults were characterized by sinistral strike−slip, indicating NW—SE compressive stress field. The authors infer that the forming of NNE strike−slip faults was related to the NNW movement of Pacific plate in early Cenozoic. The NE dextral strike− slip and NW sinistral strike−slip faults, forming a conjugate fault system, developed in Bohai Bay region after the NNE strike−slip faults, and the direction of corresponding compressive stress field was nearly east—west. On the contrary, there were conjugate faults with NE sinistral strike−slip and NW dextral strike−slip in the west of Junggar Basin. The direction of compressive stress field was nearly north—south. These conjugate faults were superimposed on and cut the early NNE strike−slip faults. It is held that the formation of later faults in the east was related to the conversion of the movement direction of Pacific plate from north—northwest to west−northwest in 43~42 Ma. In the west, the later faults resulted from distant effect of the collision between India and Eurasia plates. With the continued northward movement of Indian plate together with the clockwise rotation, the western region maintains experienced north—northeast compressive stress field and developed a series of NW and NNW trending faults, whereas the eastern region still exhibited the EW compressive stress field. Affected by these Cenozoic faults, the mountains and basins in northern China showed a grid pattern assembled by lines and planes. Statistical analysis of apatite fission track ages shows that the eastern region experienced regional uplift−exhumation during Paleocene—Early Eocene (ca. 65~42 Ma). This tectonic event made a major contribution to the formation of present tectonic landform pattern in the east. Different from the east, the western region had undergone regional uplift−exhumation in about 8~6 Ma, hence forming the present tectonic landform pattern.

Key words: NNE strike−slip fault; tectonic landforms; continental deformation; Cenozoic; Northern China

About the first author: XU Qin−qin, female, born in 1984, doctor, mainly engages in the study of structural geology; E−mail: qinqin2002dz1@163.com.

About the corresponding author: JI Jian−qing, male, born in 1968; doctor, professor, engages in the study of petrology, structural geology and isotopic chronology; E−mail: grsange@pku.edu.cn.

1 引 言

大陆变形研究是大陆动力学的基本内容之一，通过大陆变形的方式、机制的解析，可以解决构造单元状态、演化规律等科学问题。

大陆变形事实上是地球运转造成的甚为壮观的景象。按照不同情况下地壳出现的位移，变形又可分为由水平运动形成的走滑断裂以及由垂直运动形成的山脉与盆地。

断裂构造是传递岩石圈构造演化、深部动力学过程和物质组成信息的最重要的构造类型，也是阐明大陆地壳演化、建立大陆动力学模式的核心研究内容[1-3]，同时走滑断裂还是板块间相互作用的一种重要调节方式，是陆内变形的一种重要方式[4]。山脉和盆地代表了地貌垂向的起伏，是构造形态在地表的直接反映，同时也是地貌格局的主要表现形式，因此山脉隆升与盆地形成代表了构造地貌格局的形成。

中国大陆及邻区位于欧亚大陆东部，处于印度板块、西伯利亚板块与太平洋板块所围限的三角形

区域，属于全球构造关键部位，受到印度板块北向运动、太平洋板块西向运动与西伯利亚板块南向运动所导致的三向挤压[5]的长期作用，地壳变形复杂，是最具典型意义的地区，是研究大陆变形理想的天然实验室。

本文所述中国北方是指阴山—燕山以南，秦岭—大别以北，从中国东部渤海湾盆地周边到新疆地区，大体呈WNW—NW方向延伸的区域(图1)。

中国北方及邻区现今构造-地貌展布具有显著的东西差异性(图2)。大致以102°E为界，东部断裂构造方向以NNE和NE向为主，西部断裂方向以ENE、WNW、NW以及NNW向为主。西部的盆地被ENE、WNW以及NW向山脉所围限，表现为压扁的菱形状，总体呈近EW向展布。中部鄂尔多斯盆地、东部的渤海湾—下辽河盆地等均受NNE向山脉所围限，也表现为菱形块状，但总体走向呈NNE向展布(图1)。

关于中国东部和西部构造方向性的显著差异，曾有过多种解释：李四光[7]认为，在亚洲大陆向南移动中，亚洲东部大陆和太平洋地块之间产生一对左旋的扭力，在这样一对力偶作用下，中国东部出现了显著的从NE到NNE向的断裂与褶皱，以及不太明显的从NW到NNW向的断裂，相互交切，并且把这一系列NNE向的构造带，称为“新华夏构造体系”。中国科学院地质研究所[8]着重用X型断裂来概括中国的构造格式，认为在长期的NS向挤压应力场作用下，由NS向构造带划分开的西部，盛行钝角对着挤压力的X型交叉断裂，东部盛行锐角对着挤压力的X型交叉断裂。根据室内模拟实验，钟嘉猷[9]认为中国的“地台”在地球不均匀的自转条件下，受到NS向的压力，由于西部与东部的地质条件不同，所以发生不均一的变形。西部地壳厚，并受到冈瓦纳古陆块更直接、更强大的压力，而且周围有连续的硅铝层的围限，所以挤压效果等明显。东部地壳较薄，又濒临太平洋，受冈瓦纳古陆块的影响小，而且不受硅铝层的围限，可以自由地向东南伸展或蠕散。在上述因素的综合影响下，虽然两方同处在NS向的挤压应力作用下，却出现西部的交

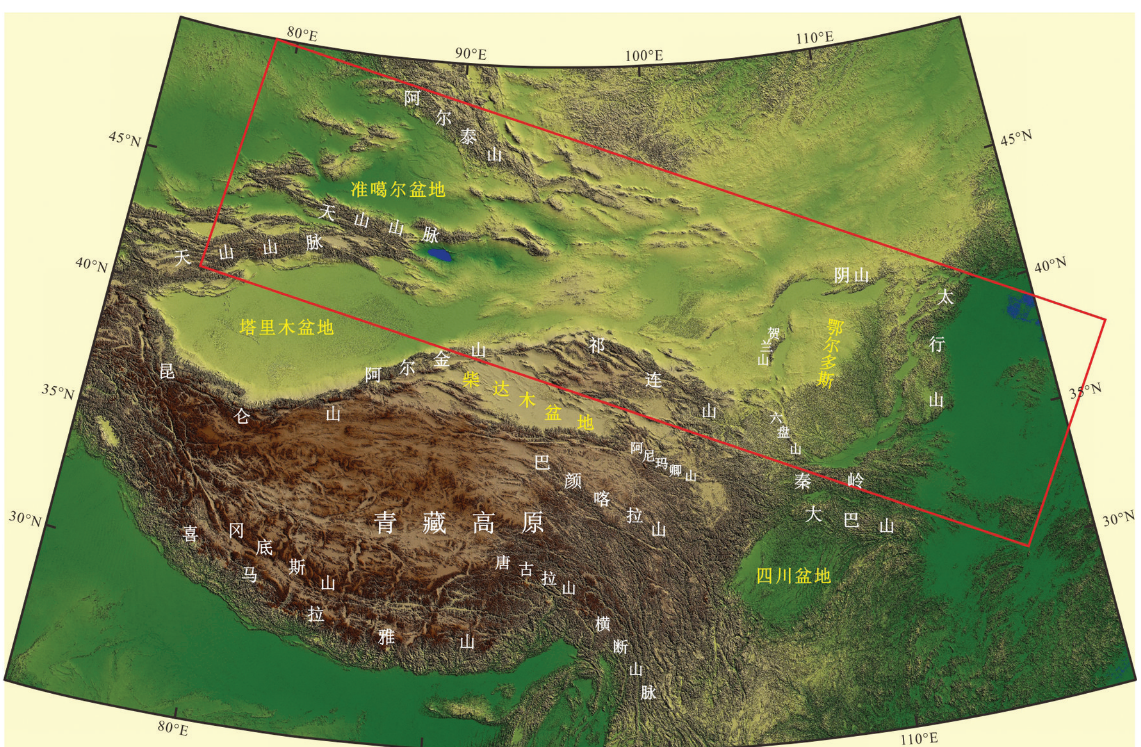

图1 中国北方及邻区现今构造地貌及主要构造体系图
红框示本文主要研究区及图3数字地貌解译范围
Fig.1 Tectonic landform map of northern China and adjacent areas
Red rectangle shows the study area and location of Fig. 3

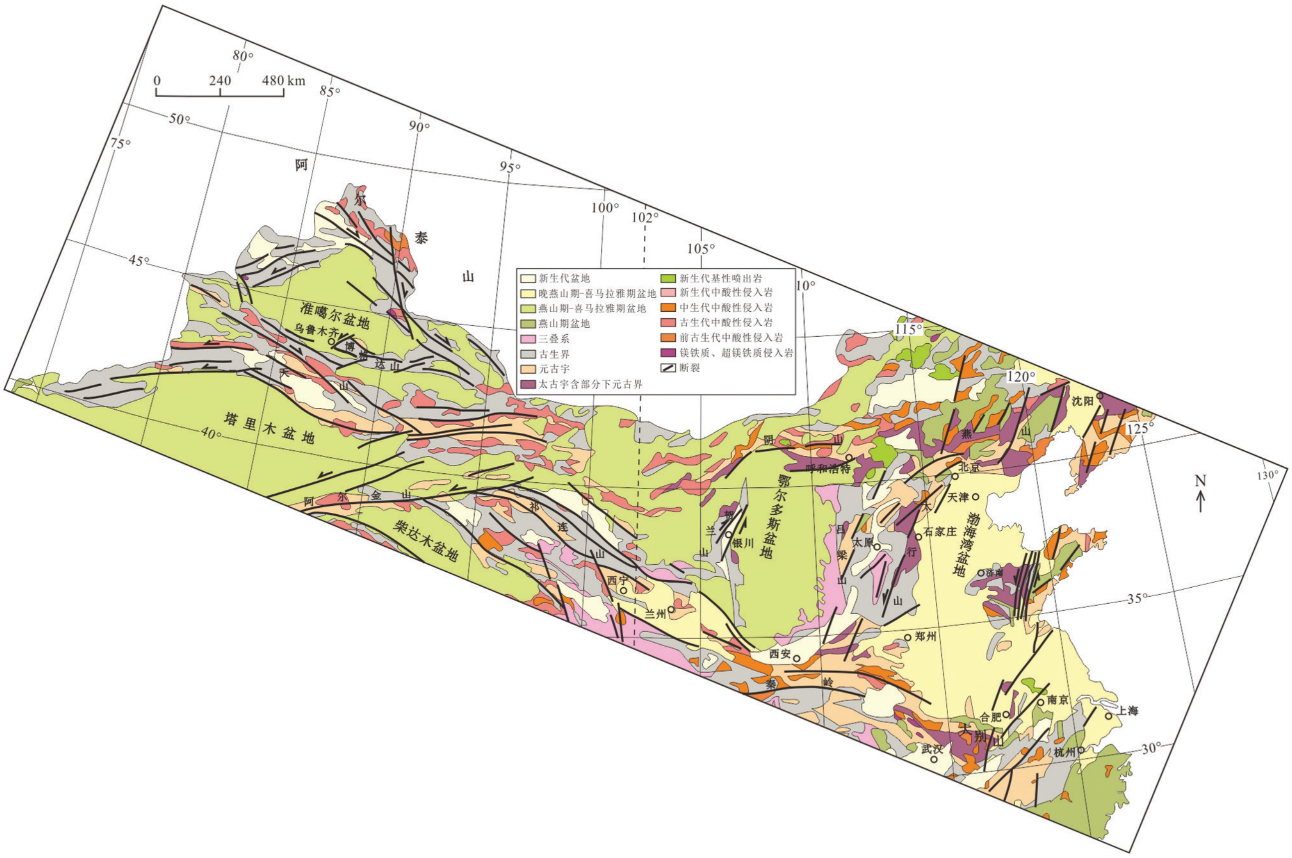

图2 中国北方及邻区主要构造体系图（据文献[6]修改）
Fig.2 Tectonic system of northern China and adjacent areas (after reference [6])

叉断裂以钝角对着挤压方向，东部的交叉断裂以锐角对着挤压力方向。葛肖虹等[10-11]认为，中国东部从华南到东北NNE向为主的挤压褶皱与推覆构造是发生于渐新世末期（24.6 Ma）的“四川运动”构造变形的产物，而且“四川运动”与中国东部NNE向的宏观盆-山地貌是在始新世中期—渐新世太平洋板块运动转向的背景下形成的。

对于中国东部和西部在构造地貌上的差别，显然上述解释还不够全面、合理。但是，应用板块构造理论进行解释，颇值得注意[12]。

新生代，中国大陆及邻区发生了一期最重要的构造事件——印度-欧亚大陆碰撞，这一构造事件引起了两大陆之间巨大的地壳缩短量[13-17]，深刻影响了中国构造地貌格局乃至全球气候环境的演变[18-23]。印度-欧亚大陆碰撞之后，碰撞带以北2000~3000 km的广大地区受到了明显的远程效应影响[24-29]，目前普遍认为这种远程效应影响是通过走滑断裂和地壳增厚[30-35]两种方式来实现的，而且这种远程效应被认为是中国大陆变形主要的动力学机制[36]。吴珍汉等[37]、Wu et al. [38]认为，中国大陆现今地势呈现的西高东低的特点，就是由印度-欧亚大陆碰撞引起近NS向强烈挤压，并使得青藏高原及其邻区隆升造成的，而且这种地势是由早期东高西低的地势逐步反转的结果。

然而，印度-欧亚大陆碰撞对中国大陆变形的影响主要是从碰撞之后开始的，那么两大陆碰撞之前，中国大陆变形主要是由什么因素引起的？上述断裂构造、构造地貌特征呈现的都是现今的差异，印度-欧亚大陆碰撞之前它们具有怎样的特征，是否也存在东西差异？这些问题，前人研究很少，值得进一步深入开展工作。另外，前人对中国北方地区的断裂构造进行了大量的研究，但大部分集中在某一个特定区域[39-62]，整个北方地区断裂的系统研究相对比较薄弱。

对断裂构造及盆山演化进行研究是认识与了解大陆变形与构造地貌形成及演化最直接有效的途径。另外，山脉是最容易开展地壳变形研究的对象[63]。热史演化对山脉隆升与构造地貌形成具有独到的优势。所以，本文选取中国北方新生代断裂作用与山脉隆升作为主要研究对象，通过野外地质构造分析、遥感与数字地貌技术、地震反射资料解释以及低温热年代学方法，了解中国大陆变形特征与构造地貌格局形成过程，为中国断裂构造发育以及构造地貌演化的动力学机制研究提供一个全新的视角和窗口，并为中国大陆变形的研究提供基础资料。由于本文是针对中国北方大陆变形进行的整体性研究，资料丰富，工作量大，因此研究过程中需要综合利用前人的相关资料，对这些资料进行归纳、融合，获得系统性研究成果。

2　中国北方新生代断裂作用特征

2.1　中国北方及邻区新生代断裂系统

中国北方及邻区新生代断裂构造非常发育，具有东西分异的特征（图2~图3）。

大致以102°E为界，东西两侧新生代断裂有明显的差异。东部环渤海湾地区，以NNE向、NE向走滑断裂为主，辅以NW向断裂。其中NNE向断裂包括郯庐断裂带、太行山山前断裂带等，且NNE向断裂多被后期NE向断裂改造[64–67]。贺兰山—六盘山地区也发育有NNE向断裂，但规模和延伸性都不及环渤海湾地区。

西部地区总体以发育NWW、NW、NNW以及NEE向走滑或逆冲走滑断裂为主，各个地区又稍有不同。其中准噶尔西部以发育NW和NEE断裂为主，辅以NE向断裂。东准噶尔地区断裂方向以NW和NNW向为主，且NNW断裂发育最晚，第四纪仍存在强烈活动，如富蕴断裂。天山地区断裂以WNW向右旋走滑和ENE向左行走滑为主，呈网格状分布。阿尔金地区断裂由一系列NEE向左行走滑断裂组成，祁连山地区断裂主要为NW向，并且被阿尔金断裂带切断和改造。

2.2　中国北方NNE向断裂作用

2.2.1 NNE向断裂分布特征

为了便于研究工作的开展，本文把研究区划分为四个重点区域，分别为：渤海湾盆地周边（包括郯

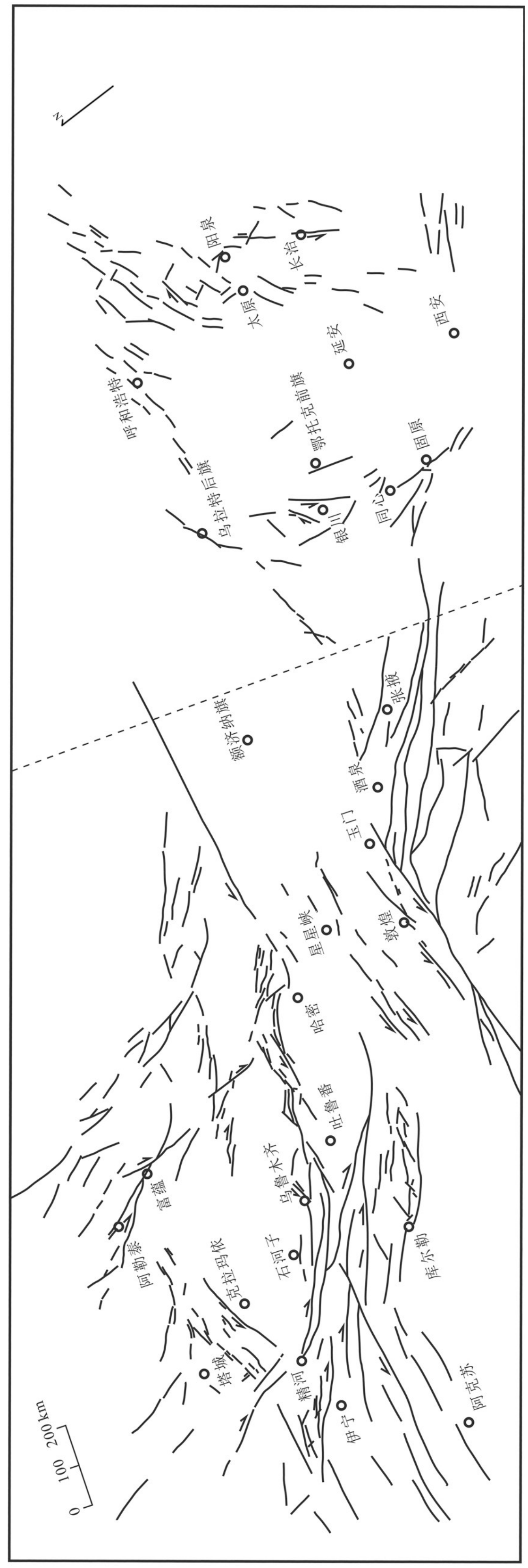

图3 中国北方及邻区新生代断裂系统发育图（根据图1数字地貌图解译）
Fig.3 Fault system of northern China (derived from Fig.1 by geological interpretation)

庐断裂带、燕山东段及太行山山前断裂带）、中部地区（包括狼山、贺兰山及六盘山）、阿尔金—祁连山地区以及新疆北部地区。

位于研究区东部最著名的NNE向断裂是郯庐断裂带（图2），它是纵贯中国东部大陆边缘的一条巨型断裂带[49]，是世界上最宏大的走滑断裂带之一[39-40, 68-69]。然而野外调查发现，除了郯庐断裂带之外，中国北方其他地区都有NNE向断裂构造存在（图3）。另外中国二三级地貌的分界线大兴安岭—太行山—武陵山构造带，也呈现NNE向。由此可见，NNE走向断裂构造在整个中国北方是普遍发育的，这种现象并非偶然，应该是区域性变形作用的结果。

对各个地区劈理野外产状玫瑰花图进行对比，可以发现NNE向断裂作用存在差异。东部地区与其他地区相比，NNE向断裂的优势更加明显。包括郯庐断裂带、燕山东段以及太行山山前断裂带在内的中国东部NNE向断裂构造，规模相对较大，透入性更好，地貌特征表现非常明显，在数字地貌图上呈明显的线性延伸（图1~图2），通过野外地质观测（图4、图5）、数字地貌图解译（图3、图6）等可以准确识别。

中部狼山、贺兰山地区NNE向断裂规模相对东部地区，规模变小，地貌特征表现比东部地区弱，可能由于受到后期断裂的改造和破坏，零星、断续发育，延伸不远，但是通过野外地质观测、数字地貌解译、结合地质图以及其他相关资料可以识别（图3~图5,图7~图8）。六盘山地区的NNE向断裂构造相对于狼山、贺兰山地区，受到后期断裂改造作用更加强烈，在数字地貌图上没有清晰表现，只有通过详细野外地质观测并结合大比例尺地质图才可识别（图5）。

阿尔金、祁连山以及新疆北部的NNE向断裂规模更小，在数字地貌图上几乎没有显示，只能通过详细的野外构造解析以及地质图来确认（图4~图5）。

根据各个地区NNE向断裂作用的特征，可以发现，整个研究区内的变形作用以剪切作用为主，发生的深度应该在2~3 km范围内（图9-a），在贺兰山石炭井地区（图9-b）变形深度相对较较大（在3~5 km），出现了褶皱，但褶皱轴面方向也呈NNE向，应

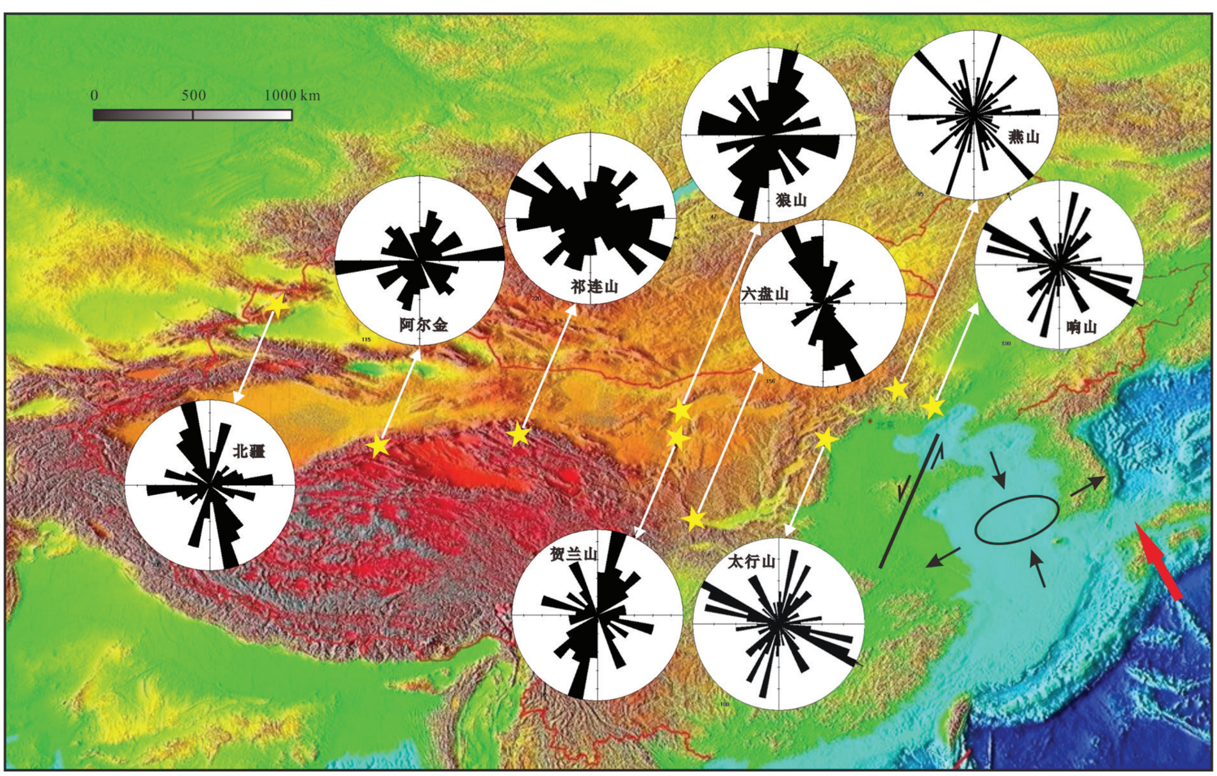

图4 研究区劈理野外产状玫瑰花图
Fig.4 Rose diagrams of cleavages in the study area

图5 研究区NNE向断裂野外照片

a—郯庐断裂带；b—燕山东段；c—太行山南段NNE向劈理；d—贺兰山汝淇沟地区；e—马东山，马东山断裂使马东山山脊呈NNE走向；f—阿尔金山东北部东巴兔山，NNE向小型破裂面；g—祁连山旱峡煤矿，NNE向密集陡立劈理；h—新疆达尔布特断裂北侧NNE向密集陡立劈理

Fig.5 Field photographs of the NNE-trending faults in the study area

a-Tan-Lu fault zone; b-Eastern segment of Yanshan; c-NNE-trending cleavages in the southern segment of Taihang Mountain; d-Ruqigou region in the Helan Mountain; e-NNE-striking Ridge of Madong Mountain influenced by Madong Mountain fault; f-Small NNE-striking fracture in Dongbatu Mountain, northeast of Altun Mountain; g-Intensive and steep NNE-striking cleavages in the Hanxia coal mine, Qilian Mountain; h-Intensive and steep NNE-striking cleavages in the north of Daerbute fault, Xinjiang

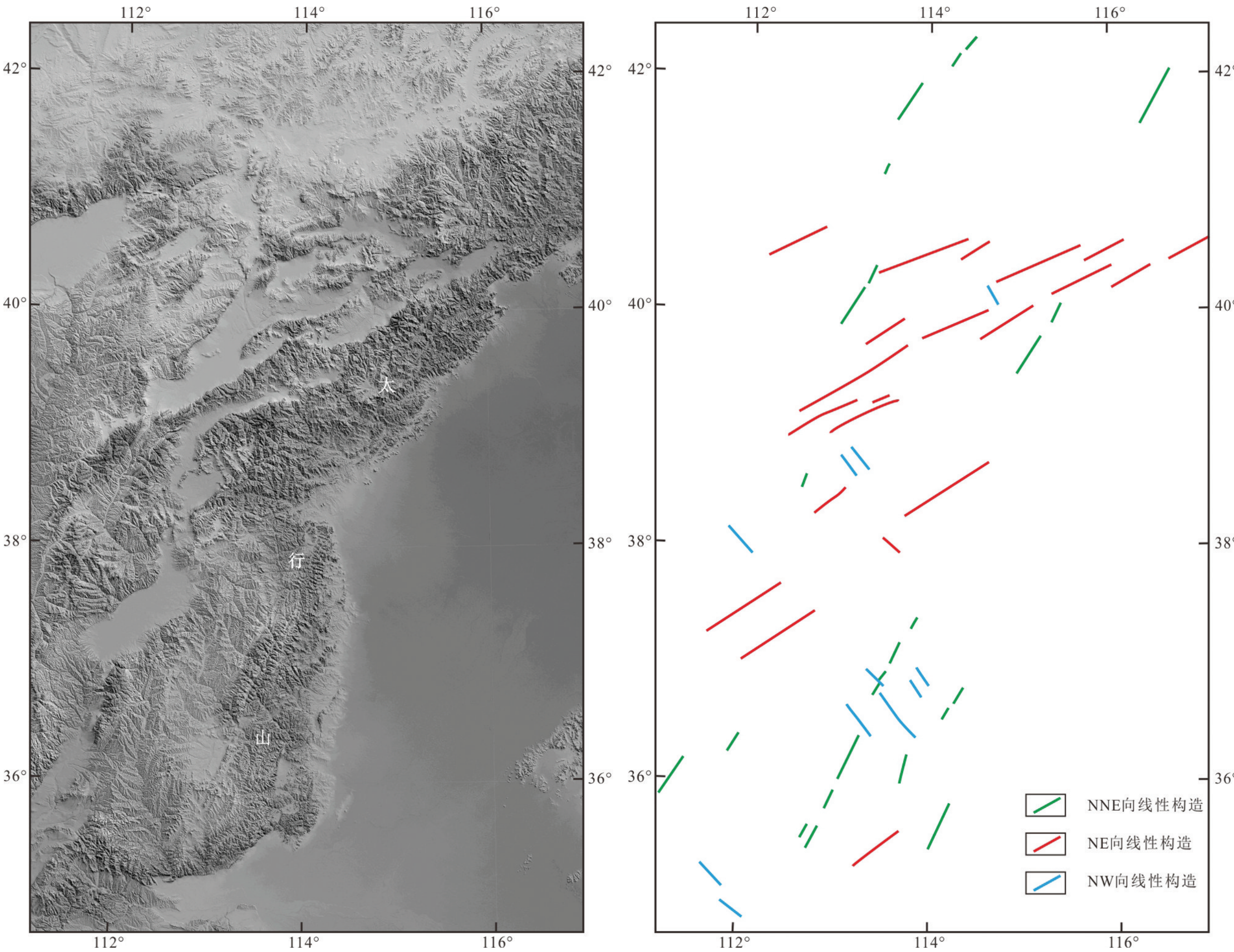

图6 太行山地区数字地貌及解译图
Fig. 6 Digital geomorphological map and interpretation of Taihang Mountains

该是同一构造应力场条件下的产物。

2.2.2 NNE向断裂作用时间

断裂多是在一定构造激化阶段形成的[70]，可以利用与断裂同期变形的地层和褶皱等的相互关系来确定其形成时期。

关于郯庐断裂带的形成时间，观点纷繁，争论颇多[39−40, 49, 59, 62, 66, 69, 71−82]。本文前期研究工作揭示，郯庐断裂带的形成时间是早新生代，大约在古新世—早始新世[66]。

庆建春[83]根据太行山北段小五台山、中段五台山、南段临城、内邱一带的磷灰石裂变径迹研究，认为与NNE向山前断裂体系相关的太行山岩体冷却和隆起的时限集中在63~52 Ma，这说明太行山山前NNE向断裂的活动时间即为古新世—早始新世。李越等[67]通过对河北省秦皇岛市响山—柳江盆地地区的构造解析以及响山隆升裂变径迹年龄的测定，认为响山的隆升以及柳江盆地的沉降都受到一条NNE走向断裂控制，该断裂是郯庐断裂系的组成部分，活动时代为白垩世末—古新世。

贺兰山地区NNE向黄河断裂的逆冲分量使得前古生代地层直接覆盖在中生代地层之上(图8)，说明NNE向断裂活动时间应该是中生代之后。六盘山地区被NNE向断裂改造和破坏的最新地层是白垩系乃家河组与马东山组(图10)，说明NNE向断裂活动的时间在白垩纪之后。

新疆北部NNE向断裂作用的时间同样是在早新生代，大约在古近纪[84]。

根据区域对比分析，本文认为中国北方NNE向

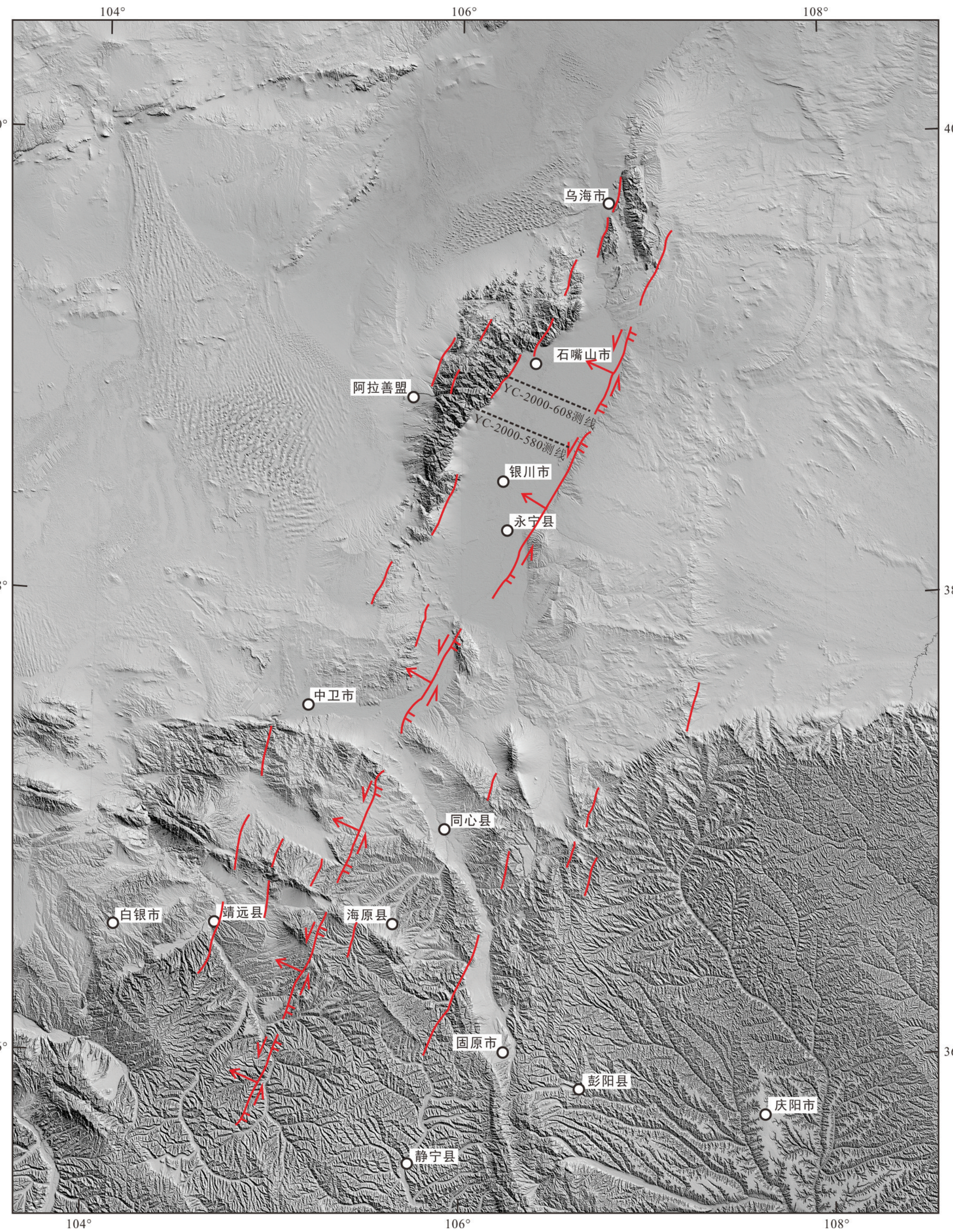

图7 贺兰山及其邻区早新生代断裂发育图
Fig. 7 Early Cenozoic fault system of Helan Mountain and adjacent areas

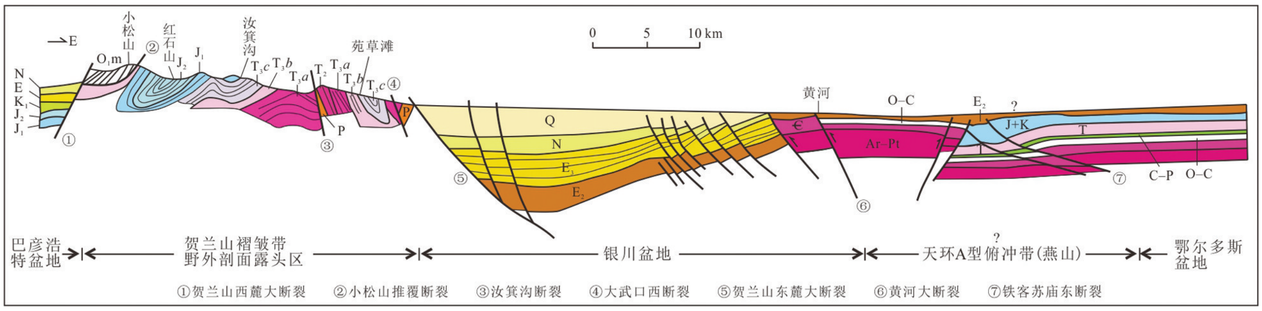

图8 鄂尔多斯盆地西缘贺兰山盆地—银川盆地—铁克苏庙地质剖面❶
Fig. 8 Geological section of Helan Mountain Basin—Yinchuan Basin—Tiekesumiao on the western margin of Ordos Basin❶

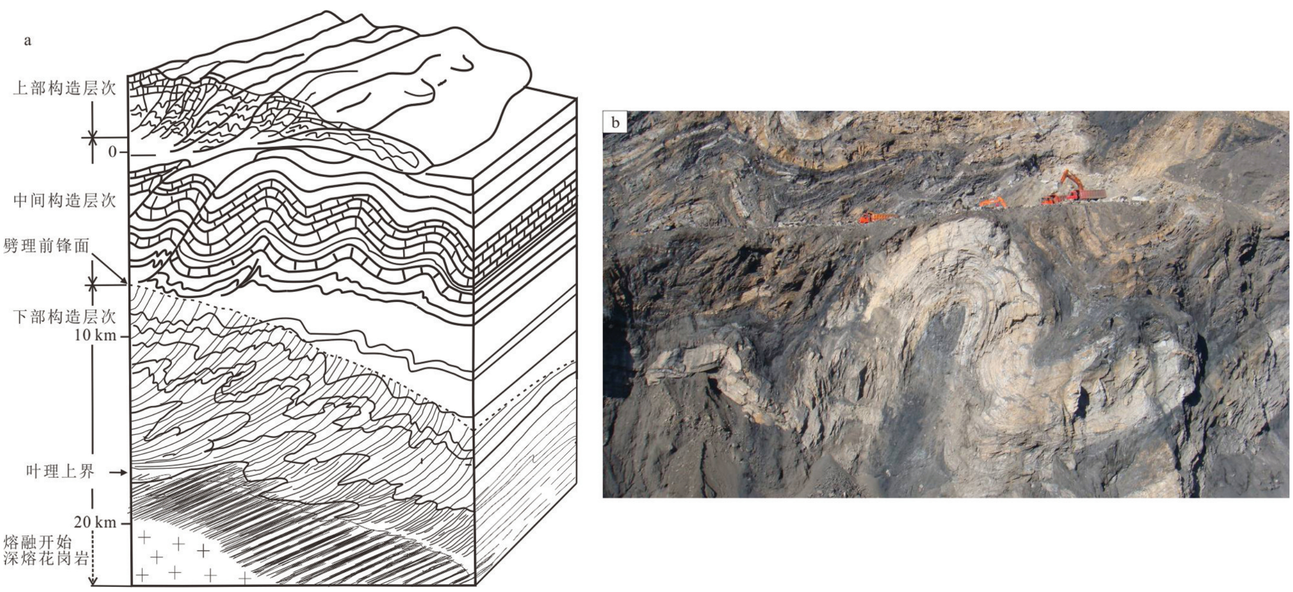

图9 研究区变形深度
a—地壳理想构造层次示意图[63]；b—贺兰山石炭井地区褶皱野外露头，镜头南西，褶皱轴面大致NNE方向
Fig. 9 Deformation depth of the study area
a−Ideal crust profile with tectonic level [63]; b−Fold in Shitanjing region, Helan Mountain, with NNE-striking axial plane (lens facing southwest)

断裂作用的时间大约在古新世—早始新世。

2.2.3 NNE向断裂运动学性质及应力场特征

根据研究区各个区域NNE向断裂作用特征，断裂一侧牵引褶皱、羽裂、断裂两盘地层的运动方向（图11），可以判定，中国北方NNE向断裂为左行走滑断裂，大致对应NW−SE向挤压应力场（图4、图12−a），那么NW−SE向挤压应力场是在什么背景条件下形成的呢？需要从中国北方大陆所处的大地构造位置来考虑。

中国大陆及邻区位于欧亚大陆东部，处于印度板块、西伯利亚陆块与太平洋板块所围限的三角形区域，太平洋板块西向运动与印度−欧亚大陆碰撞远程效应影响导致了中国大陆内部的强烈变形。印度−欧亚大陆碰撞发生在55~40 Ma[85−94]。NNE向左行走滑断裂作用发生的时间在古新世—早始新世，当时印度−欧亚板块还没有开始大规模的碰撞，而中生代末期—古新世，太平洋板块作NNW向运动[36, 95−96]，因此当时变形作用的力源应该来自东部的太平洋板块。万天丰[36]认为，造成岩石变形的构造应力主要集中在岩石圈上部，尤其在上地壳，且各板块

❶季建清. 中卫地区构造演化及圈闭条件研究[R]. 北京大学科技开发部, 2012.

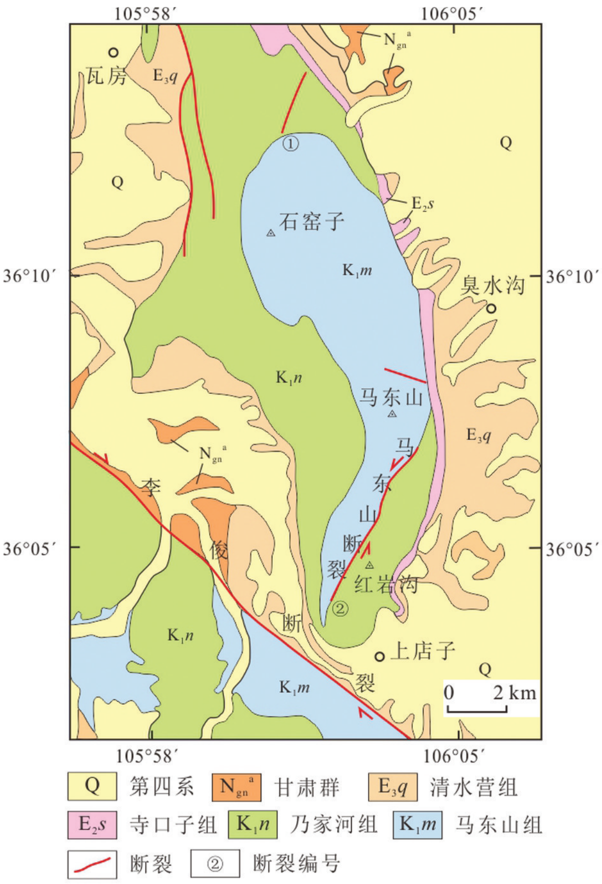

图10 马东山及邻区地质图❶❷

①—马东山北NNE断裂；②—马东山断裂

Fig. 10 Geological map of Madong Mountain and adjacent areas❶❷

①–NNE-striking fault in the north of Madong Mountain; ②–Madong Mountain fault

的构造应力的最大主压应力方向是与板块运移方向一致的。因此太平洋板块NNW方向的运动，形成了NW–SE向挤压应力场[97]（图4、图12–a），NW–SE向的挤压使中国北方大陆产生一系列NNE向断裂，辅以近EW向右行走滑断裂（图4、图12–a）。

2.3 变形序列

通过野外构造解析（图4~图5、图11）、数字地貌解译（图3、图6），本文发现：中国东部及贺兰山地区主要发育两期断裂构造，第一期是前文论述的NNE向左行走滑断裂，辅以近EW向右行走滑断裂；第二期是NE向和NW向共轭断裂（图3、图6、图13）。根据野外观察到的各走向断裂构造相互切割改造关系可以进一步确定出两期断裂构造发育先后关系（图13–a~e）。早期为NNE向和近EW向断裂构造共轭发育，NNE向断裂构造的发育程度明显强于近EW向，所以早期的断裂构造以NNE向发育为主；晚期为NE向和NW向断裂构造共轭发育，发育程度相近。

另外，地震反射剖面资料也揭示了NE向断裂后期发育的特征（图13–f）。图13–f是渤海湾地区所有断裂构造行迹在T_1反射层面上的投影图，相当于面T_1面上断裂分布的平面图。该构造图显示郯庐断裂被后期的NE向断裂右旋错动，即NE向为右行走滑断裂。根据库伦–莫尔破裂准则，后期NE向右行、NW向左行共轭断裂大致对应近EW向挤压应力场（图12–b）。

从早期的NNE向左行到后期NE向右行走滑断裂，两期断裂构造体系之间存在一个转换过程，该转换过程是中国东部非常重要的构造事件。其具体时限可以由中国东部地区山脉的新生代隆起历史以及周边盆地的断裂构造演化史来确定。

庆建春[83]对太行山北段岩体的磷灰石裂变径迹研究认为，与NNE向山前断裂体系相关的太行山岩体冷却和隆起的时限集中在63~52 Ma，而与NE向山前断裂体系相关的岩体冷却和隆起时限为46 Ma以来。李越等[67]对河北省秦皇岛市响山柳江盆地地区进行的磷灰石裂变径迹研究结果也揭示，NNE走向断裂的活动时限为70~50 Ma，与太行山地区的研究结果相似。

李理和钟大赉[98]通过泰山磷灰石裂变径迹研究认为，新生代以来泰山存在两期快速抬升，分别为44~37 Ma、23~20 Ma。44~37 Ma快速抬升大致对应济阳凹陷中的济阳运动[99–100]，还明显地反映在渤海湾盆地黄骅坳陷的孔店地区，如43 Ma期间的“孔店升降”[101]。东濮凹陷文留背斜在43~38 Ma期间形成，整个凹陷也随之整体抬升[102]。与泰山同属一个泰沂山系的蒙山，王振兰等[103]做的裂变径迹分析结果表明，蒙山发生了两期抬升事件，54~50 Ma和

❶地质部甘肃省地质局区域地质测量队. 1:20万海原幅地质图. 1965.

❷地质部甘肃省地质局区域地质测量队. 1:20万固原幅地质图. 1965.

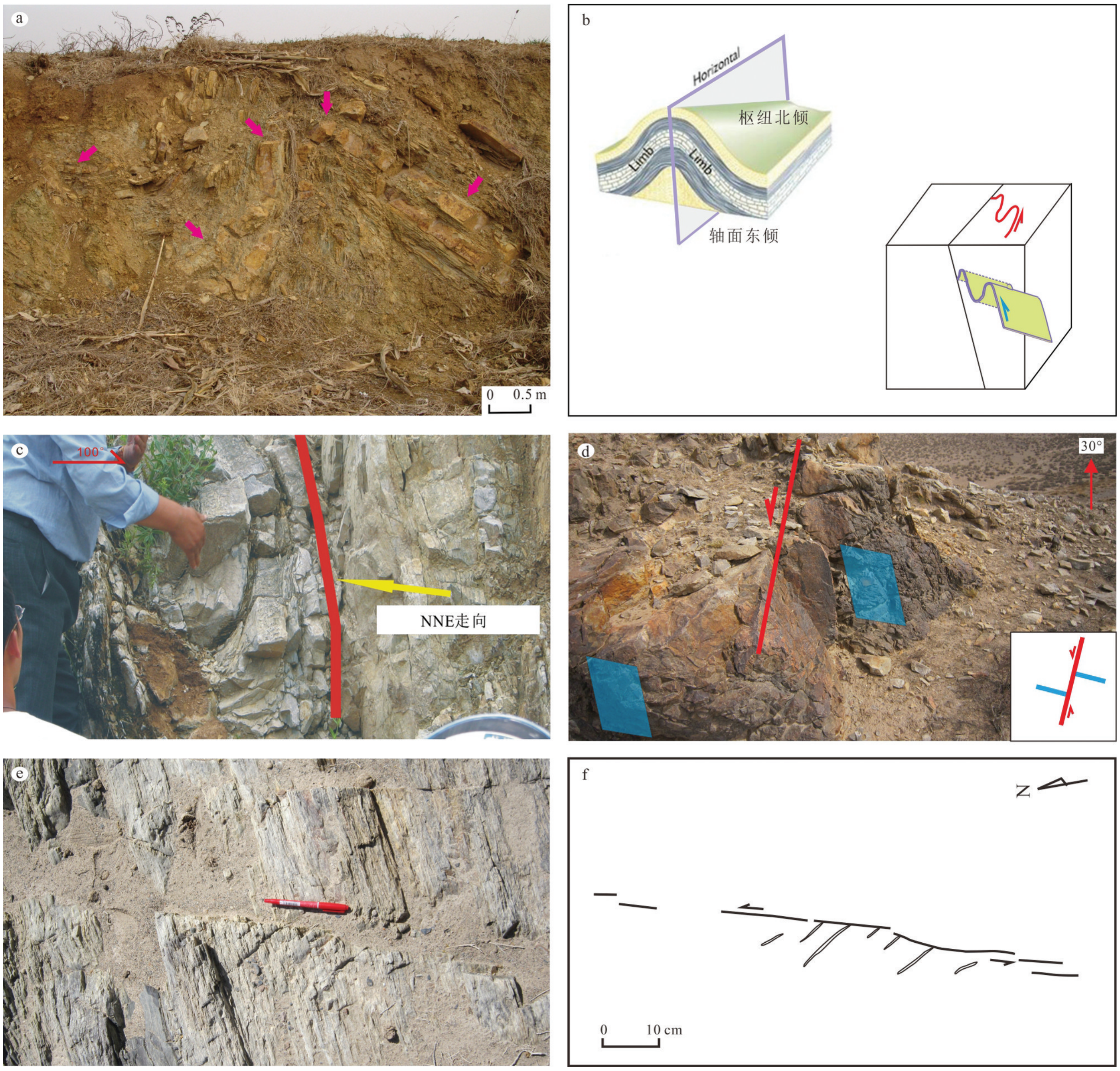

图11 中国北方NNE向断裂运动学特征

A、b—沂水县北西方向6 km处郯庐断裂一侧牵引褶皱野外照片与构造解析示意图；c—燕山东段NNE向强烈变形带中发育的牵引褶皱，变形带略向西倾，褶皱枢纽向南倾，表明变形带的左旋逆冲性质；d—贺兰山南部NNE向断裂左行走滑证据；e、f—甘肃阿尔金北东巴兔山地区NNE向走滑断裂的野外照片及示意图

Fig.11 Kinematic characteristics of the NNE-striking faults in the study area

A、b−Photograph and structural analysis of the drag fold on one side of Tan-Lu fault, 6 km northwest of Yishui County; c−Drag fold in the NNE strongly deformed zone, eastern segment of Yanshan. The deformed zone dips west and the fold hinge dips south, indicating the sinistral strike−slip and thrust movement of the deformed zone. d−Photograph shows the sinistral strike−slip of the NNE-striking fault in the south of Helan Mountain. E, f− Photograph and sketch map of the NNE strike−slip fault in Dongbatu Mountain, northeast ofAltun Mountain

42~38 Ma。上述资料表明，在距今42~38 Ma，鲁西隆起经历了一期大的构造抬升事件，而且这一时限与济阳坳陷箕状断陷的形成时代一致。

以上事实说明，43~42 Ma中国东部出现一期非常重要的构造事件，这一时限与新生代太平洋板块运动方向的改变的时间[97, 104−106]是一致的。

太平洋板块运动方向的改变，即由NNW向转变为WNW向，相应的挤压应力场方向由NW−SE

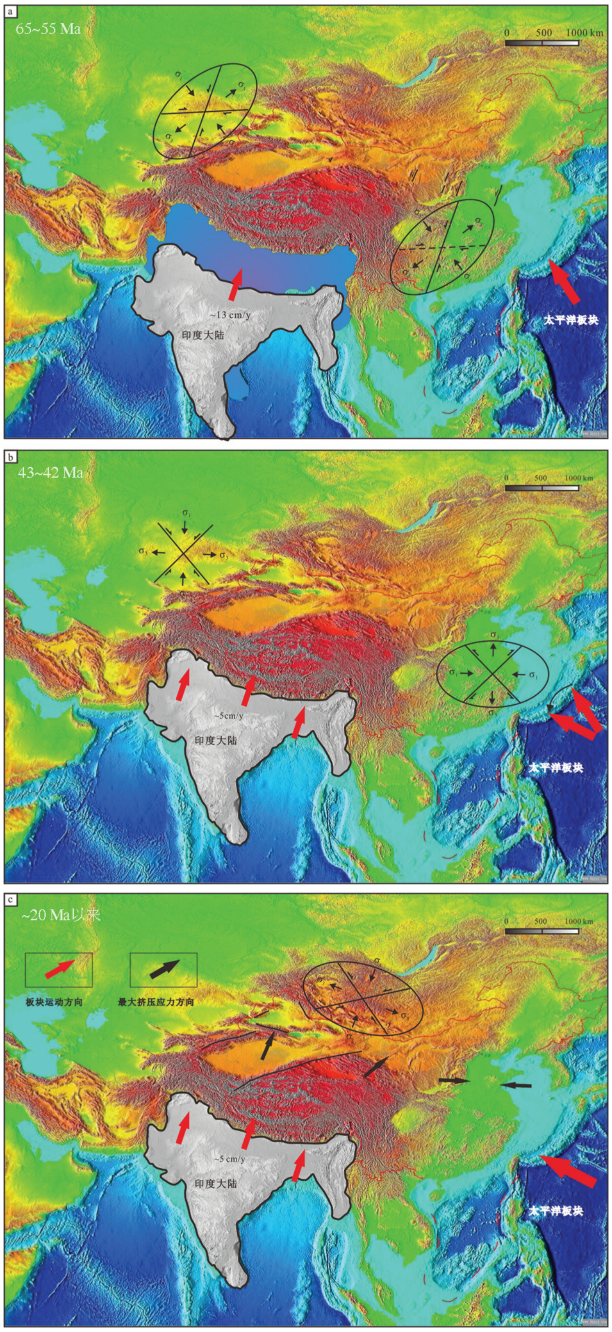

图12 中国北方及邻区应力场特征示意图
a—古新世—早始新世；b—中始新世；c—中新世以来
Fig. 12 Sketch map showing the stress field in northern China and adjacent areas
a−Paleocene—Early Eocene; b−Middle Eocene; c−Since Miocene

向转变为近EW向（图12−b），进而产生一系列上文论述的NE、NW向断裂（以NE为主）。

同样地，受到印度−欧亚大陆NNE向碰撞的影响，西部地区形成了近NS向挤压应力场（图12−b），形成了两组NE向左行、NW向右行共轭走滑断裂（详见文献[84]；图12−b）。

渐新世—中新世以来，印度大陆持续向北运动，并发生顺时针旋转[30−31]，中国西北部（包括阿尔金、天山地区）发育了一系列ENE向左行走滑断裂（图3），显示了后期应力场发生了小角度顺时针转变（图12−c）。响应应力场方向的顺时针改变，六盘山地区发育了一系列310°、330°、350°走向的右行走滑断裂（图14）。

随着印度板块的持续挤入以及太平洋板块的西向运动，现今中国北方大陆应力场大约以阿尔金断裂为界，西北主要形成近NNE向的挤压应力场，而阿尔金断裂以东，主压应力方向由NE向逐渐转变为中国东部的近EW向（图12−c）。

3 中国北方新生代构造地貌格局形成

3.1 盆−山构造地貌格局

宏观的地貌格局，是指大的地貌单元，即山脉、高原、盆地、平原等，在平面上的排列组合形式与垂向上的高低起伏形态。地貌的平面轮廓与垂向起伏，是构造形态在地表的直接反映，同时也是地貌格局的主要表现形式。

山脉是正向单元，是地壳垂直上升运动的结果；盆地是负向单元，是地壳垂直下降运动的结果。山脉和盆地代表了地貌垂向的起伏。因此，山脉和盆地是构造地貌格局主要的表现形式，山脉隆升与盆地形成直接反映了构造地貌格局的形成。

中国大陆盆地与山脉纵横交错，相互穿插，看似杂乱无章，但实际上它们的平面布局上却是按一定规律排列的。其中，山脉走向与新生代断裂构造的走向几乎完全一致，呈现出线状构造、面状盆地的特点，即不同形式的网格状地貌结构（图1）。西北部地区，在NW、WNW以及ENE断裂系统控制下，山脉走向与断裂方向几乎一致（图1），并形成几个大型压扁菱形盆地，如塔里木盆地、柴达木盆地、准噶尔盆地，盆地整体走向呈近EW向。中部的四川盆地、鄂尔多斯盆地和中国东部的华北盆地、渤海湾—下辽河盆地等均受NE—NNE向和近EW向断裂所围限，也都表现为菱形块状，总体呈NE—NNE向展布。

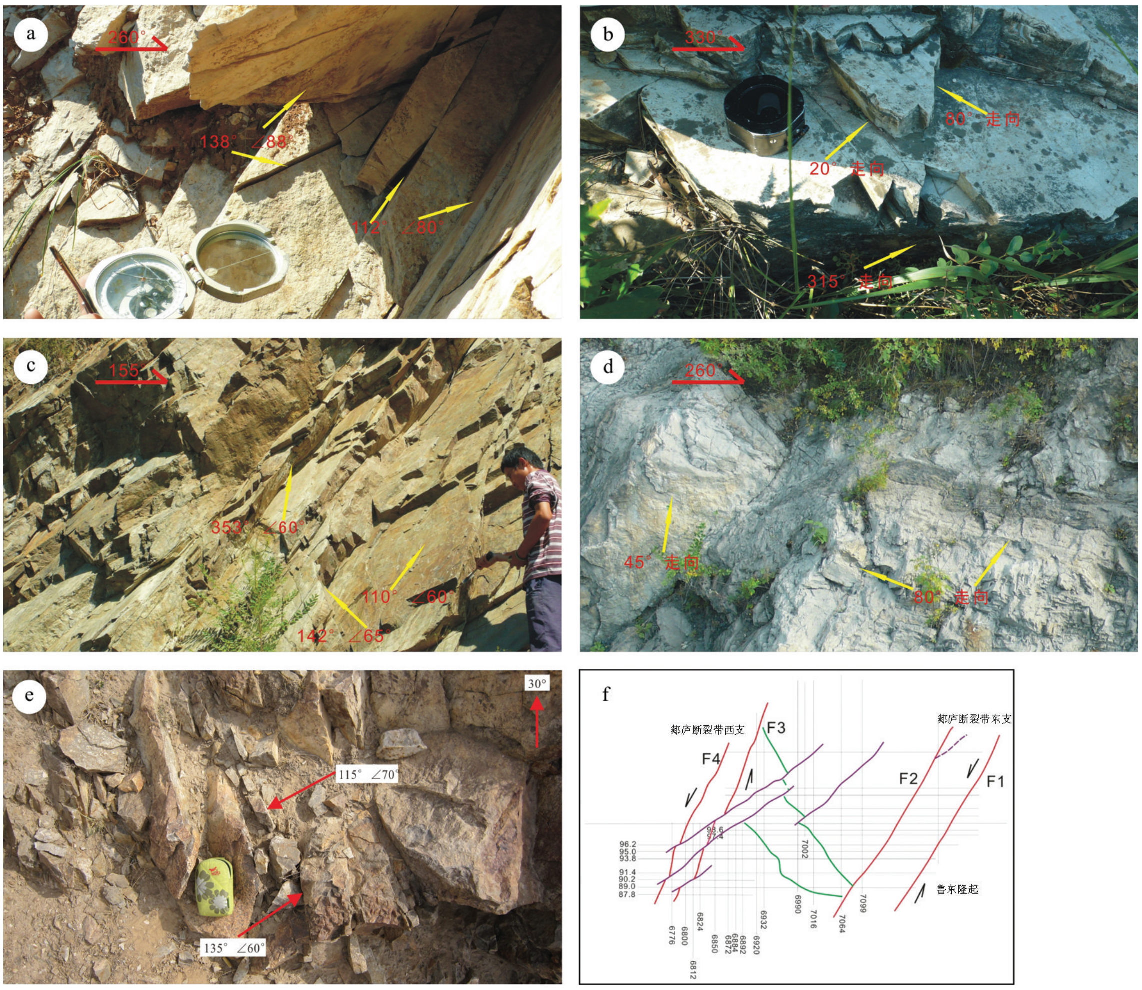

图13 研究区变形序列

a~d—燕山东段断裂构造发育野外照片：a—48°(NE)走向破裂面切割早期22°(NNE)走向破裂面；b—315°(NW)走向破裂面切割早期共轭的20°(NNE)、80°(近EW)走向破裂；c—在原始地层中发育早期的83°(近EW)走向破裂以及晚期的52°(NE)走向破裂；d—80°(近EW)走向的破裂被45°(NE)走向的破裂所切割、改造；e—贺兰山南部断裂野外露头，NNE向断裂被后期NE向断裂切断；f—青东凹陷东部地区古近—新近纪构造行迹在T_1构造面上的投影图[64]，T_1—新近系馆陶组上段底，F_1—F_4为郯庐断裂分支

Fig.13 Deformation sequence of the study area

a—d−Photographs of faults developed in the eastern segment of Yanshan. a−Old NNE-trending fracture cut by the NE-trending one; b− Conjugate fractures striking NNE and EW cut by the young NW-trending fracture; c−Old EW- and young NE-trending fractures developed in the original strata. d− EW- trending fracture cut by the young NE-trending one. e− Old NNE-trending fracture cut by the NE−trending one in the south of Helan Mountain. f−Tertiary structures in the east of Qingdong Sag projected onto the T_1 surface[64]. T_1−Bottom of upper member of the Guantao Formation; F_1−F_4: Branches of the Tan—Lu fault

3.2 天山隆升过程与热史演化

现代的天山，即地理意义上的天山，是中新生代以来板内造山作用的产物[107−138]。

对于中新生代天山地壳演化和隆升过程，使用磁性地层学以及低温年代学方法进行研究的很多，尤其是磷灰石裂变径迹方法[108, 113, 118, 123−125, 129−131, 136−141]。前人研究成果揭示出天山山脉存在多阶段、多期次的隆升−剥露特征(图15)，尤其是中新世以来的隆升被广泛报道(图15)。

本文与王丽宁等[134]合作采用河床砂岩屑裂变径迹测年方法对西南天山隆升历史进行了初步研究，认为西南天山山体是8~6 Ma以来形成的。另外，王丽宁[143]采用同样方法对南天山、北天山、东天山隆升历史进行了详细的研究。结果显示，南天山和北天山在新生代以来都经历了多个阶段的冷却抬升，但最近一期抬升都发生在8~6 Ma，且8~6 Ma

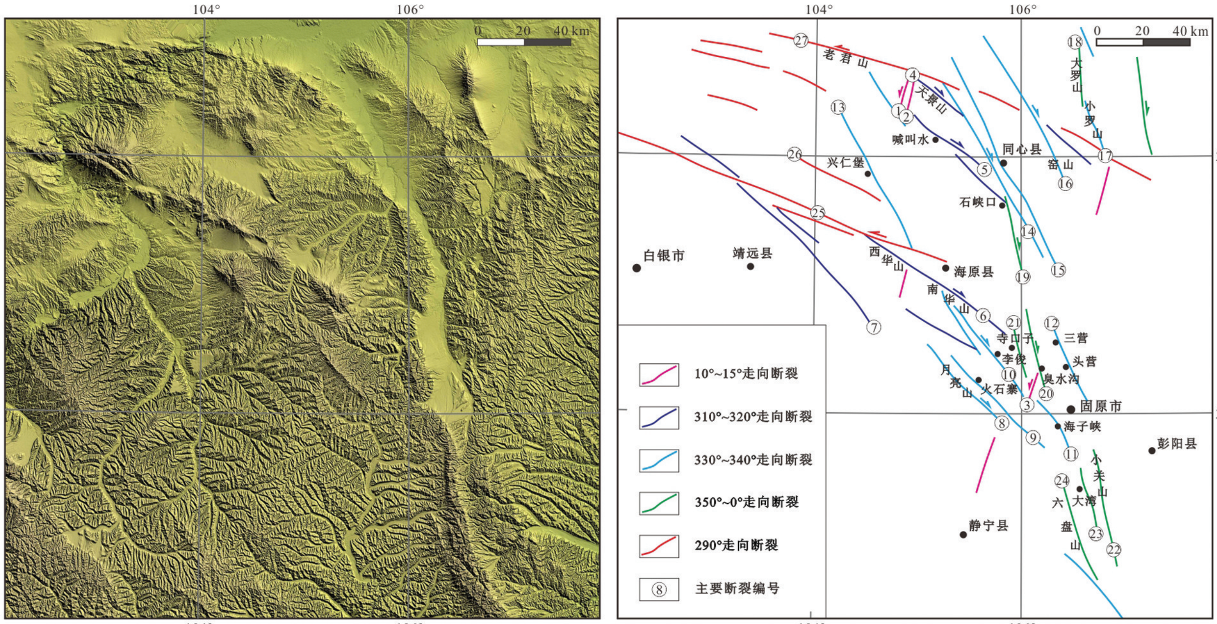

图14 六盘山及邻区数字地貌及解译图

①—寺口子沟西缘断裂;②—寺口子沟东缘断裂;③—马东山山前断裂;④—天景山断裂;⑤—喊叫水断裂;⑥—南华山山前断裂;⑦—宝积断裂;⑧—月亮山断裂;⑨—火石寨断裂;⑩—李俊断裂;海子峡断裂;三营—头营断裂;兴仁堡断裂;桃山断裂;清水河断裂;窑山断裂;小罗山断裂;大罗山断裂;石峡口断裂;臭水沟—寺口子断裂;寺口子断裂;小关山断裂;大湾断裂;六盘山断裂;海原断裂;兴仁堡南断裂;老君山断裂

Fig. 14 Digital geomorphological map and interpretation of Liupan Mountain and adjacent areas

①−Fault in the west of Sikouzigou; ②−Fault in the east of Sikouzigou; ③−Madong Mountain piedmont fault; ④−Tianjing Mountain fault; ⑤−Hanjiaoshui fault; ⑥−Nanhua Mountain piedmont fault; ⑦−Baoji fault; ⑧−Yueliang Mountain fault; ⑨−Huoshizhai fault; ⑩−Lijun fault; −Haizixia fault; Sanying−Touying fault; Xingrenpu fault; Taoshan fault; Qingshuihe fault; Yashan Mountain fault; −Xiaoluo Mountain fault; −Daluo Mountain fault; −Shixiakou fault; Choushuigou−Sikouzi fault; − Sikouzi fault; −Xiaoguan Mountain fault; −Dawan fault; −Liupan Mountain fault; −Haiyuan fault; −Fault in the south of Xingrenpu;−Laojun Mountain fault

时期的退火封闭面现今已经抬升至河流切割的地表位置(详见文献[143])。裂变径迹封闭温度的上限为110°C,下限为70°C,如果取地温梯度为30°C/km,则部分退火带所在的深度为4~2 km。裂变径迹年龄峰值代表了颗粒源区山体抬升至部分退火带之上(即4~2 km之上)的时间。这说明天山山体剥露的厚度达到4~2 km,且隆升速率在0.67~0.25 mm/a。目前天山山体的平均海拔高度是5~3 km,可以推断,8~6 Ma以来的天山的抬升贡献几乎是现代山体高程的主要构成。因此,本文认为8~6 Ma以来的山体隆升是形成现代天山地貌的原因。

3.3 阿尔泰山隆升过程与热史演化

阿尔泰造山带位于中亚造山带南缘,跨越哈萨克斯坦、俄罗斯、中国,向东南延入到蒙古戈壁阿尔泰,为典型的显生宙增生造山带[144]。

前人采用不同手段、从不同角度,对包括中国阿尔泰山在内的整个阿尔泰造山带中新生代的陆内造山作用展开了一系列的研究[43, 134, 145−161],探讨了阿尔泰山的隆升过程和热史演化。

前人利用裂变径迹方法对中国境内阿尔泰山的隆升−剥露过程以及热史展开过一些研究[149−153, 161]。

刘顺生等[149]对阿尔泰哈巴河岩体进行了磷灰石和锆石裂变径迹研究,年龄分别为76.9~51.1 Ma和149~141 Ma,存在两个快速冷却期,分别是276~96 Ma和17 Ma以后。袁万明等[150]、Yuan et al.[153]从对新疆阿尔泰造山带西部构造活动的研究中获得一批较为系统的磷灰石裂变径迹分析结果。32个磷灰石裂变径迹年龄为(46.9±7.2)Ma~(163.0±6.4)Ma,热模拟结果显示了白垩纪与中新世两期的快速冷却过程。保增宽等[151]获得的阿尔泰青河附近闪长岩体3个样品的磷灰石裂变径迹年龄为95~78 Ma,热历史反演的结果表明青河地区具有115~85 Ma、10~8 Ma以来两次快速冷却过程。郭召杰等[152]通过对阿尔泰可可托海地区花岗岩体的磷灰石裂

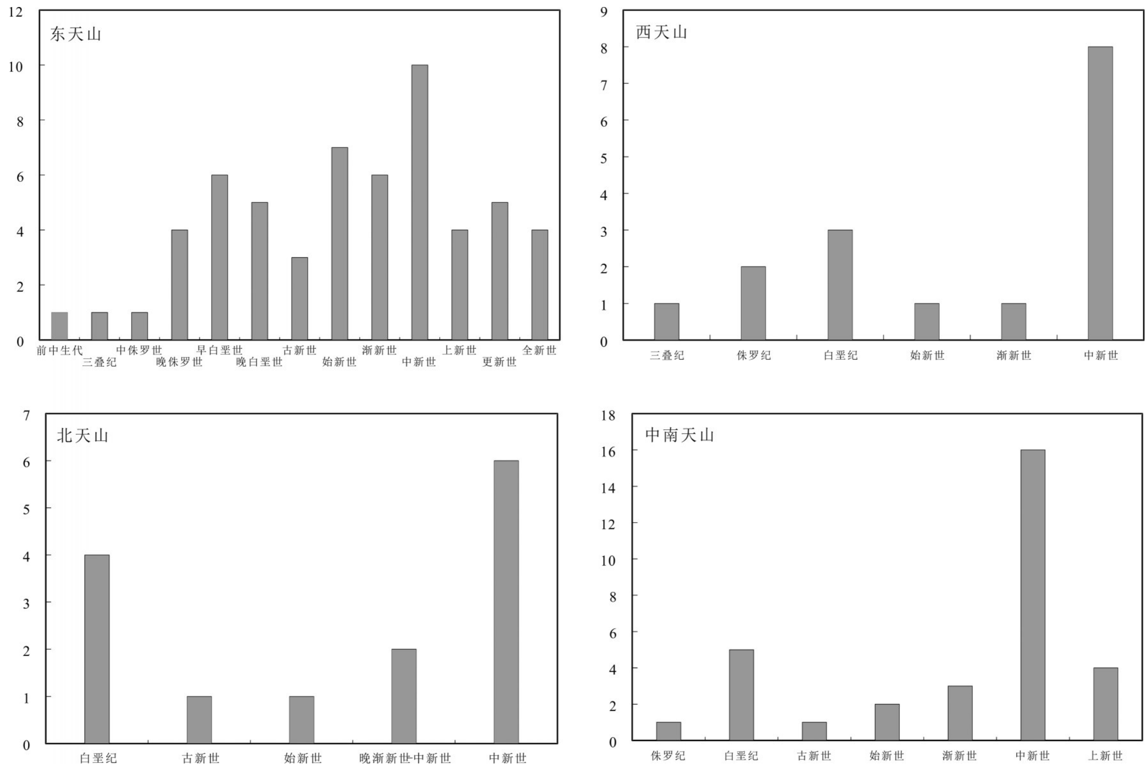

图15 天山隆升阶段统计

数据来源：文献[107−115, 117, 119−133, 136−138, 140−142]

Fig. 15 Uplifting phases of Tianshan Mountains

Data source: references [107−115, 117, 119−133, 136−138, 140−142]

变径迹研究认为，阿尔泰地区存在晚侏罗世—早白垩世的冷却事件，可能是古中亚造山带解体剥露事件的反映。赵文菊等[161]获得的阿尔泰东南部地区磷灰石样品的裂变径迹年龄为（59.4±5.8）Ma~（109.7±8.1）Ma。热史模拟结果揭示了108 Ma之前的初始整体隆升、108~28 Ma的缓慢冷却阶段以及28 Ma以来的快速冷却过程。

前人对中国阿尔泰地区山脉隆升以及热史的研究显示，阿尔泰地区主要经历了晚侏罗世—早白垩世[152]、白垩纪[150−151, 153]、以及晚渐新世—早中新世[149, 153, 161] 3个阶段的快速冷却过程。其中，晚侏罗世—早白垩世的冷却可能与蒙古—鄂霍次克洋的闭合有关[147]，白垩世的冷却过程可能与西伯利亚板块向西南方向的挤压作用引起的隆升剥蚀有关[150]。然而，现代阿尔泰山的形成具体对应于哪一阶段的隆升，前人研究中没有明确表示。

笔者对阿尔泰青河—富蕴地区花岗岩与片麻岩样品进行了裂变径迹研究（图16），获得的磷灰石裂变径迹年龄为（18.7±1.6）Ma~（22.7±2.2）Ma[162]。热史模拟表明，阿尔泰青河—富蕴地区存在两期主要的快速抬升和冷却过程，分别是28~18 Ma和8~6 Ma以来，且8~6 Ma以来是本区剥露最快时期。其中，28~18 Ma与前人揭示的晚渐新世—早中新世的快速冷却一致。对于8~6 Ma以来的抬升冷却，除了保增宽等[151]曾报道青河地区存在10~8 Ma以来的快速冷却过程以外，其他研究中并未提及。

实际上，8~6 Ma以来的抬升冷却不仅仅在中国阿尔泰地区存在。De Grave and Van den haute[147]、De Grave et al. [154−155]对西伯利亚阿尔泰进行了磷灰石裂变径迹研究，认为阿尔泰山造山带是晚中新世到上新世形成的；Gurvan Bogd地体的磷灰石热模拟显示，戈壁阿尔泰存在晚新生代（(5±3)Ma）的抬升冷却，这一阶段的快速隆升是对印度-欧亚大陆碰撞的响应[157]。因此，本文认为阿尔泰地区普遍经历了晚新生代（8~6 Ma）的抬升冷却过程，且8~6 Ma以来的快速抬升，形成了现代阿尔泰山的地貌。

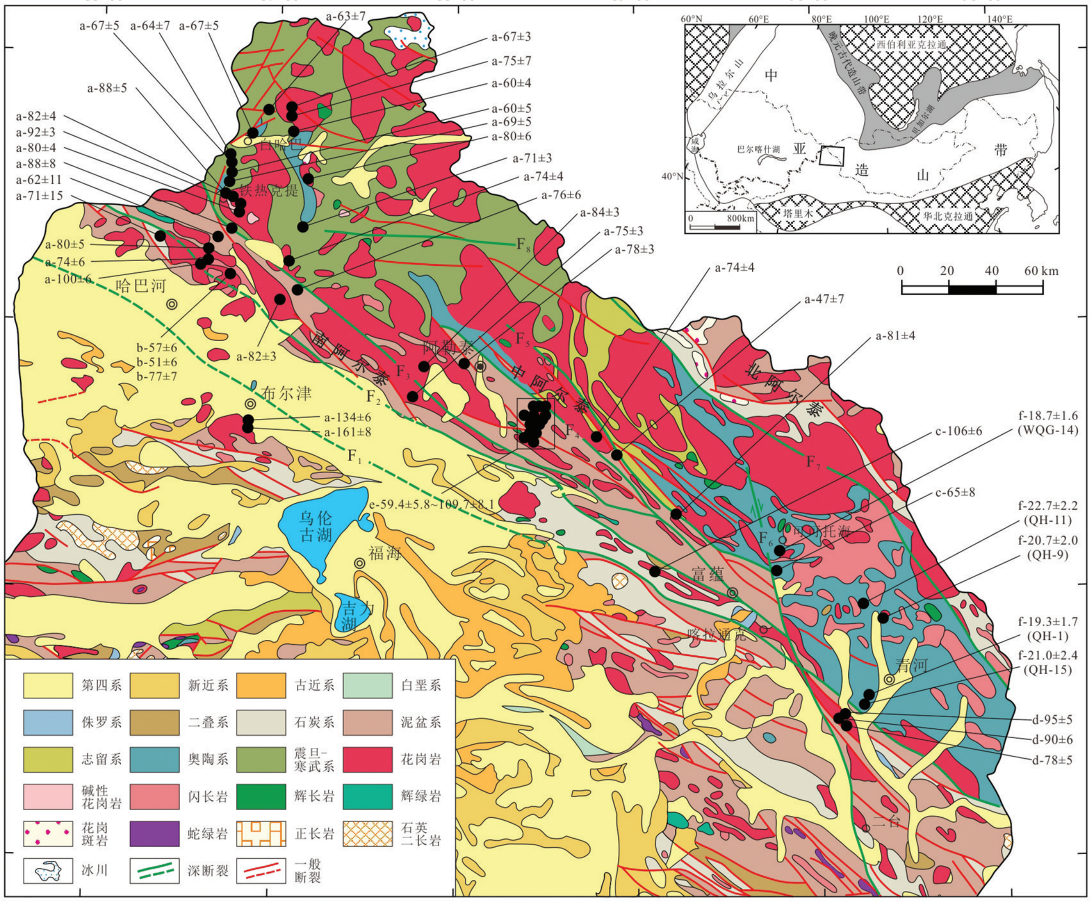

图16 阿尔泰地区地质图及裂变径迹年龄(Ma)统计[162]

F₁—额尔齐斯断裂；F₂—科沙哈拉尔断裂；F₃—库尔特断裂；F₄—康布铁堡(阿巴宫)断裂；F₅—巴寨断裂；F₆—可可托海—二台断裂；F₇—红山咀断裂；F₈—依来克断裂；黑色圆点代表前人磷灰石裂变径迹(AFT)样品点；AFT年龄来源：a—文献[150]；b—文献[149]；c—文献[152]；d—文献[151]；e—文献[161]；f—文献[162]

Fig. 16 Geological map of Altay region[162]

F_1−Irtysh fault ; F_2−Keshahalaer fault; F_3−Kuerte fault; F_4−Kangbutiebao (Abagong fault); F_5−Bazhai fault; F_6−Cocotohai−Ertai fault; F_7−Hongshanzui fault; F_8−Yilaike fault. Black dots represent the previous apatite fission track (AFT) sampling localities. AFT data source: a−Reference [150]; b−Reference [149]; c−Reference [152]; d− Reference [151]; e− Reference [161]; f− Reference [162]

3.4 阿尔金—祁连山隆升过程与热史演化

阿尔金—祁连山位于青藏高原北缘(图1)，新生代以来作为青藏高原北部动力边界经历了挤压、逆冲、走滑和山脉隆升等一系列重大地质事件，因此成为研究青藏高原形成历史的关键地区。

阿尔金山与祁连山的隆升过程记录了高原的变形和向北扩展的历史，对探讨高原隆升动力学具有重要意义，成为长期以来国内外学者研究的焦点[163−201]。

关于阿尔金山的隆升过程，前人已经从 $^{40}Ar/^{39}Ar$ 测年、裂变径迹测年、U−Th/He测年、前陆盆地沉积演化、稳定同位素组成变化、阿尔金断裂走滑变形与山脉隆升的耦合关系等角度进行了探讨，揭示出阿尔金山存在多阶段、多期次的隆升与剥露作用，隆升阶段除了早侏罗世[173−174]与晚白垩世[202]以外，几乎遍布了古新世—中更新世的各个时代[173−174, 176, 178, 180, 182, 189−190, 193, 196−198, 201−204]。尽管如此，10~8 Ma的冷却事件仍被广泛报道[173, 176, 179−180, 182, 189, 195]。

对于祁连山的隆升时间，前人的研究尚存在较大分歧，如早白垩世[199]、晚始新世—渐新世[173, 183, 187−188]、中新世中晚期[172−173, 177, 185, 200]、上新世末[165, 171, 186, 191]和第四纪[163, 166, 168−169, 171, 175, 186, 191]。虽然关于祁连山隆升的

时间说法不一,但是大部分学者认为祁连山主要是晚新生代开始隆升的。

虽然关于阿尔金—祁连山的隆升过程,至今仍存有较大争议,但是前人发表的低温热年代学数据(图17)显示:阿尔金—祁连山及邻区的隆升主要集中在新生代以来,明显的年龄峰值为8.2 Ma、19.7 Ma、28.9 Ma、3.7 Ma、35 Ma、12.8 Ma(图17)。而且,前人揭示的阿尔金—祁连山新生代以来的隆升剥露可以大致划分为4个快速期:48~30 Ma、25~17 Ma、10~7 Ma以及5 Ma以来(图18),其中10~7 Ma是最强的隆升剥露期,在图17中表现出最强的峰值(8.2 Ma)。

徐芹芹等[211]选取了阿尔金山东段以及祁连山西段—河西走廊地区发源于祁连山中部的多条河流,采用岩屑磷灰石裂变径迹测年分析,利用岩屑的统计特征限定了阿尔金—祁连山新生代的隆升-剥露过程。研究显示,阿尔金—祁连山地区存在4个阶段的抬升冷却:21.1~19.4 Ma、13.5~10.5 Ma、9.0~7.3 Ma、4.3~3.8 Ma。其中,4.3~3.8 Ma抬升冷却事件仅体现在祁连山地区,9.0~7.3 Ma抬升冷却事件在区内普遍存在,且9.0~7.3 Ma隆升-剥露造就了现代阿尔金—祁连山的地貌。

3.5 贺兰山、大青山隆升过程与热史演化

3.5.1 贺兰山隆升过程与热史演化

贺兰山位于鄂尔多斯盆地的西北缘,东以银川盆地与鄂尔多斯盆地相邻;西-西北部紧邻巴彦浩特盆地和河套盆地;南接走廊过渡带;总体呈NNE向展布,为一南小北大的楔形体(图7)。

由于紧邻银川盆地和鄂尔多斯盆地,贺兰山的隆升时限对盆地性质以及形成具有重要意义。关于贺兰山的隆升时限以及与鄂尔多斯盆地的关系,目前已有多种不同的认识。部分学者认为,贺兰山在晚三叠世已经隆起作为前隆区,发生逆冲抬升[212-215]。另有部分学者通过对贺兰山沉积、构造现象等认为,鄂尔多斯盆地西北缘在中生代整体上并不是前陆盆地[216-218],晚三叠世贺兰山并未隆起成山,而是处于伸展环境[53-54, 217-222],其隆起时间应为晚侏罗世或之后[216]。赵红格等[223]通过对贺兰山现存地层的分布和岩浆及热液活动等资料分析,认为晚三叠世—中侏罗世贺兰山并未隆升,其隆起时间应在中侏罗世之后,并根据磷灰石和锆石裂变径迹测试结果,提出贺兰山有3次较大的隆升,分别发生在晚白垩世、始新世和上新世。晚白垩世的隆升与鄂尔多斯盆地区域抬升相对应,贺兰山大规模隆起的时间为始新世,快速抬升时期为上新世,与银川地堑的强烈断陷活动相伴生。刘建辉等[224]根据磷灰石裂变径迹测试分析,揭示了贺兰山始于12~10 Ma的快速隆升冷却作用,认为这种快速剥露作用与贺兰山东麓断层具有很好的相关性。

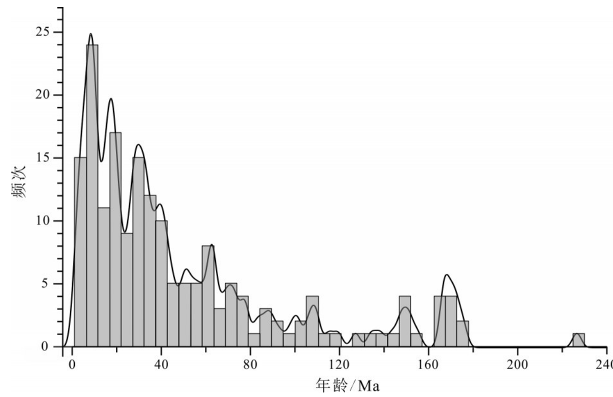

图17 阿尔金—祁连山及邻区基岩磷灰石裂变径迹和(U-Th)/He年龄直方图
数据来源:文献[172-174, 177, 179-182, 198, 200-210]
Fig. 17 Apatite fission track and (U-Th)/He age histogram of bedrock samples from Altun and Qilian Mountains and their adjacent areas
Data source: References [172-174, 177, 179-182, 198, 200-210]

图8是鄂尔多斯盆地西缘贺兰山盆地—银川盆地—铁克苏庙地质剖面。该图显示,银川盆地东界黄河断裂的逆冲走滑运动使得前古生代地层直接覆盖在中生代地层之上,这次断裂活动可能使得西侧贺兰山发生强烈隆升,隆升的时间应该在中生代之后,大约在古新世—早始新世,这一时间与赵红格等[223]所得的磷灰石裂变径迹年龄相当。贺兰山的强烈隆升剥蚀,致使现今贺兰山地区普遍缺失古新世地层沉积,而当时银川盆地并没有形成,也不是现在所处的位置。

图19也显示,NE向贺兰山前断裂为现今银川盆地西边界,该断裂控制了银川盆地内清水营组(E_3)及以后地层的沉积,并且NE向断裂的活动可能使得西侧贺兰山再次发生隆升,可以解释为断块升降运动,山脉上升,盆地下降,逐步形成了现今的构造地貌格局。由于本文没有获得精确的年龄数据,

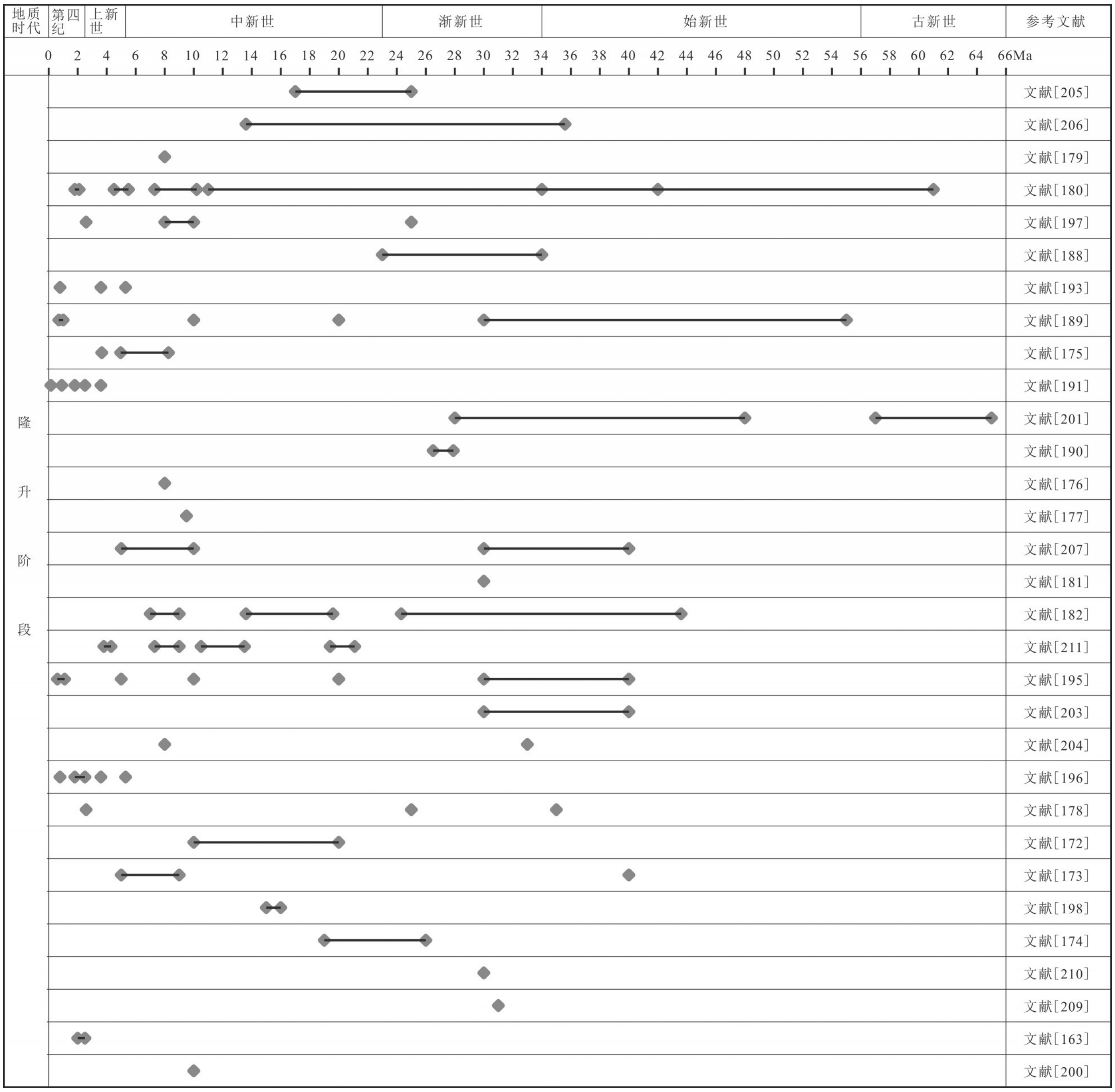

图18 阿尔金—祁连山地区新生代隆升阶段划分（据文献[211]修改）

Fig. 18 Division of Cenozoic uplift stages of the Altun and Qilian Mountains (after reference [211])

这次隆升的具体时间还不能确定，但是根据刘建辉等[224]的研究结果，贺兰山现今地貌的形成可能为12~10 Ma以来。

3.5.2 大青山隆升过程与热史演化

大青山是阴山—燕山板内造山带的重要组成部分[225−227]，其隆升过程对认识板内造山的特点及过程具有重要意义。前人围绕大青山及燕山山脉的隆升做了一系列研究[37, 67, 228−234]。

程绍平等[232]提出地壳均衡隆起是大青山新近纪以来主要的区域变形机制。吴中海和吴珍汉[228]认为大青山发生了两期重要的隆升事件，首先是100~90 Ma间的快速隆升，随后的快速隆升事件发生在50 Ma以来，表明大青山山前正断层开始活动，与河套盆地始新世以来的快速裂陷过程相一致。始新世以来由大青山山前正断层控制的山、盆差异升降运动形成大青山地区现今的盆−山构造地貌格局。

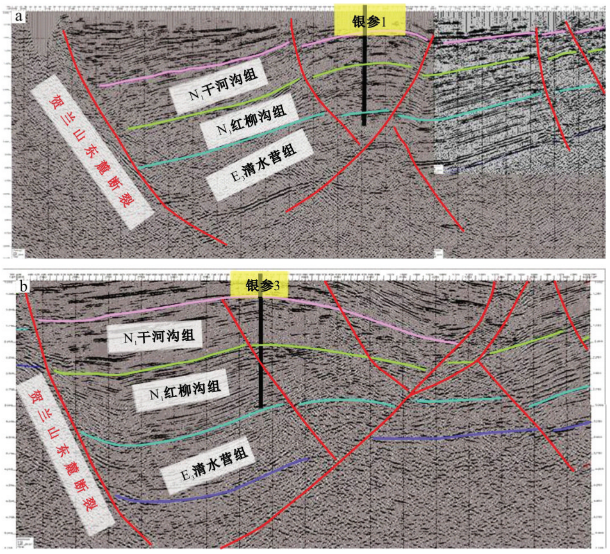

图19 银川盆地EW向地震剖面❶
a—测线YC−2000−608；b—测线YC−2000−580，剖面位置见图7
Fig.19 Seismic profile of Yinchuan basin❶
a−Seismic line YC−2000−608; b− Seismic line YC−2000−580. For seismic lines see Fig.7

Wu and Cui[229]、吴珍汉等[230−231]对燕山中段盘山与雾灵山岩体，西段云蒙山与四合堂岩体以及西南缘八达岭岩体进行了磷灰石及锆石裂变径迹研究，认为燕山山脉的快速隆升事件主要发生在3个不同时期。96 Ma燕山中段的盘山与雾灵山岩体开始快速隆升，96~35 Ma为快速隆升期，形成了盘山与雾灵山等山脉；20~13 Ma以来，西段的云蒙山与四合堂花岗片麻岩体快速隆升，形成云蒙山等山脉；6 Ma以来，燕山西南缘的八达岭岩体开始快速隆升，形成八达岭山脉。马寅生等[233]认为辽宁医巫闾山山脉的隆升历史经历了118~81 Ma期间的第1个快速隆升阶段和14 Ma以来的第2个快速隆升阶段，现今的医巫闾山山脉是14 Ma以来第2个快速隆升阶段的产物。吴中海和吴珍汉[234]根据燕山及邻区的低温热年代学数据，认为燕山及邻区晚白垩世以来经历了6次快速隆升事件，发生时代分别是120~105 Ma、95~85 Ma、60~50 Ma、38 Ma左右、25~20 Ma和10~5 Ma以来。李越等[67]根据磷灰石裂变径迹研究认为，燕山东段响山岩体的隆升时间为白垩纪末—古新世，响山岩体的隆起是由NNE向断裂系活动所致。

徐芹芹等[235]在大青山东段采集了4件基岩样品进行了磷灰石裂变径迹测试，得到的磷灰石裂变径迹中值年龄分布在(57.7±3.8)Ma~(50.4±3.3)Ma，这一年龄结果在大青山及燕山地区都有出现[67, 230−231, 234]。样品的热史模拟结果显示了100~90 Ma以及13.5~7 Ma快速冷却过程。100~90 Ma，大青山发生初次隆升，这与吴中海和吴珍汉[228]研究结果基本一致。而90~13.5 Ma，大青山地区基本处于构造稳定期，13.5 Ma开始了快速冷却的热历史过程，冷却速率加速的转折时间发生在13.5~7 Ma，且13.5~7 Ma快速隆升−剥露最终造就了现代大青山的地貌。

3.6 太行山隆升过程与热史演化

中国的地貌自西向东分成非常明显的三级，其中二三级地貌的分界线为斜贯中国东部的NNE向的大兴安岭—太行山—武陵山构造带，太行山位于该构造带的中段，其隆升历史的研究对中国三级地貌形成时代的确定具有重要意义。前人围绕太行山及其周边山体的隆升做了一系列研究[83, 236−251]。

对太行山隆升时限的研究，部分学者认为其初始隆升在中侏罗世[236, 245, 249]。张家声等[240]对太行山的研究得出太行山与渤海湾盆地之间的伸展滑脱即太行山的隆起有两个快速变动阶段：68~52 Ma和23~18 Ma。吴忱[238]认为太行山的形成时代不超过55 Ma，发育过程与三期夷平面密切联系。徐杰等[239]根据太行山发育的三级夷平面，认为太行山经历了古近纪隆升−稳定、新近纪隆升−稳定和第四纪隆升亦即几次间歇性的形成过程。太行山西侧沁水盆地样品磷灰石裂变径迹证据也显示，太行山在新生代的抬升是不均衡的，前新生代的剥蚀夷平−准平原化后，古近纪初经历了隆升，再到古近纪末的剥蚀夷平，最后到新近纪的快速隆升[251]。

另外，部分学者还针对太行山南、中、北各段的造山过程分别展开了详细的研究[83, 244, 246, 248, 250]。庆建春[83]分别选择太行山中段五台山、北段小五台山、南段临城和内邱3条剖面进行了磷灰石裂变径迹研究，认为太行山晚白垩纪末以来的隆升为分阶段幕式过程，经历了3期快速隆升：74~58 Ma、46~31 Ma

❶李建清. 中卫地区构造演化及圈闭条件研究[R]. 北京大学科技开发部, 2012.

及15 Ma左右，且太行山中部隆升速率大于南北两端。太行山南北两端由于隆升速率偏小，基底年轻年龄还没有剥露出来，只有第一期快速隆升得到体现，其时限为：63~52 Ma。马寅生等[244]认为太行山南缘地区以新生代以来的隆升为特征，分为包括始新世、中新世至上新世中期、早更新世晚期以来的3个快速隆升阶段。龚明权[246]认为太行山南段的隆升成山是在中生代末期至始新世之前整个华北乃至更大范围的北台期夷平面基础上发育起来的。而最新的研究显示，南太行山地区初始隆升始于100 Ma前，50~40 Ma 及10 Ma 左右以来隆升速度加快[250]。李萍萍[248]对太行山北段中生代花岗岩的研究揭示出，这些岩体在早白垩世集中侵位之后，不同部位的隆升历史具有时空差异性，但太行山北段整体经历了晚中新世(8~5 Ma)的快速隆升事件。

新生代太行山的隆升与渤海湾盆地周边山系的构造演化也存在对应关系。李理和钟大赉[98]对鲁西隆起泰山的研究表明，泰山新生代经历两期快速隆升44~37 Ma和23~20 Ma。王振兰等[103]对与泰山同属于一个泰—沂山系的蒙山的磷灰石裂变径迹表明，蒙山分别在距今约42~38Ma和54~50 Ma发生了两次抬升事件。唐智博等[252]研究表明，蒙山自晚白垩世以来经历了70~43Ma和32~20 Ma两个快速抬升阶段。

通过前人的一系列研究可以看出，目前关于太行山的隆升过程，虽然具有很多争议，但是太行山及邻区存在一期早新生代的隆升是毋庸置疑的，这期隆升应该不是偶然的，而可能是区域性构造事件的反映。

3.7 中国北方古新世—早始新世(66~42 Ma)构造地貌特征

磷灰石裂变径迹具有较低的封闭温度(大约110℃)，被广泛应用于造山带剥露和地表剥蚀研究[253−254]，可以揭示岩体冷却−剥露年龄，进而反映区域性构造地貌事件[255]。不同学者对中国北方东部地区的主要山脉进行了大量磷灰石裂变径迹年代学研究[67, 83, 98, 103, 223−224, 229−231, 233−234, 248, 250−252, 256−260]，对各个山脉的构造隆升历史细节进行了有效的约束，积累了大量基础数据。本文不打算对不同山脉区的裂变径迹年龄含义作具体分析，而只试图对裂变径迹年龄数据进行统计分析，揭示统计规律中所蕴含的区域性的强构造事件。

理论上，一次快速构造隆升−冷却事件期或者一次强构造热事件干扰期意味着相对大量的物质冷却通过磷灰石裂变径迹封闭温度等温面，当对一个地区进行磷灰石裂变径迹测年时，在快速抬升冷却阶段或强构造热事件干扰期将形成年龄峰值[261]。因此，一定区域内大量磷灰石裂变径迹年龄分析测试结果的统计峰值将大体对应于该地区的强构造隆升期或强构造热事件干扰期。

本文收集的磷灰石裂变径迹年龄数据主要来源于前人针对燕山山脉、太行山、大青山、贺兰山、吕梁山、蒙山以及泰山开展的研究，共计259个年龄数据。统计分析结果表明(图20)，中国北方东部地区晚中生代以来，不同山体的隆升过程有所差异，但它们都集中体现出(66~42 Ma)抬升冷却阶段。不仅如此，鄂尔多斯盆地中各个构造单元广泛分布59. 7~40. 6 Ma间的磷灰石裂变径迹年龄数据[262]，说明晚白垩世至古新世甚至始新世早中期的抬升运动在鄂尔多斯盆地及其邻区具有整体性[262−263]。因此，区内东部地区可能普遍经历了古新世—早始新世的强隆升−剥露作用。

从更大区域上看，包括中条山、秦岭、大别山、大巴山等在内的整个中国东部地区存在66~42 Ma磷灰石裂变径迹年龄段(图21)。此阶段年龄数据多，区间集中，在东部各山体中均有广泛分布，应为区域重大构造事件的反映，指示了整个中国东部地区可能整体经历了66~42 Ma区域性抬升。与这期抬升剥蚀相对应，东部地区普遍缺失晚白垩世和古新世地层[262−263, 273−276]，环鄂尔多斯盆地、渤海湾盆地甚至整个华北区古近—新近纪沉积地层中发育了第一期区域性不整合面，即始新统与下伏前新生界地层之间的不整合面[273−274, 276−277]。值得注意的是，这期区域性抬升以及不整合面的形成时期大致对应于上述NNE向左行走滑断裂发育的时间。另外，大别造山带裂变径迹年龄数据显示，该带的热隆区以及70~40 Ma AFT等值线主要沿平行郯庐断裂走向(NNE)展布[265, 278]。据此可推知，古新世—早始新世强构造活动应该为中国东部现今构造地貌格局的形成做出了巨大贡献，NNE向大兴安岭—太行山−武陵山重力梯度带的形成可能与该期强构造活动有关。

吴珍汉等[37]认为，中国大陆及邻区西濒太平洋

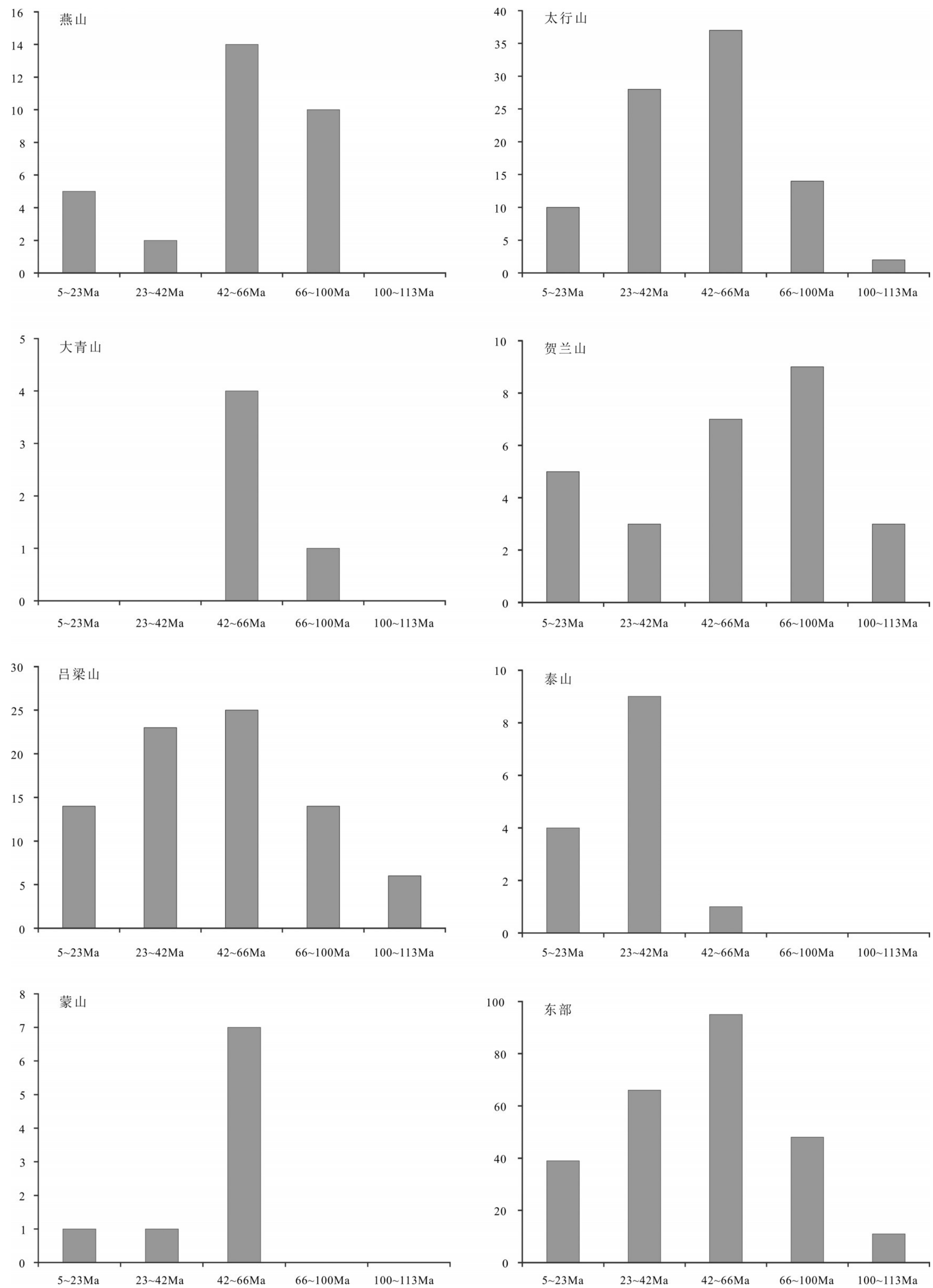

图20研究区东部裂变径迹年龄统计图

数据来源：文献[67, 83, 98, 103, 223−224, 229−231, 233−234, 248, 250−252, 256−260]

Fig. 20 Statistical maps of AFT ages in the east of the study area

Data source: references [67, 83, 98, 103, 223−224, 229−231, 233−234, 248, 250−252, 256−260]

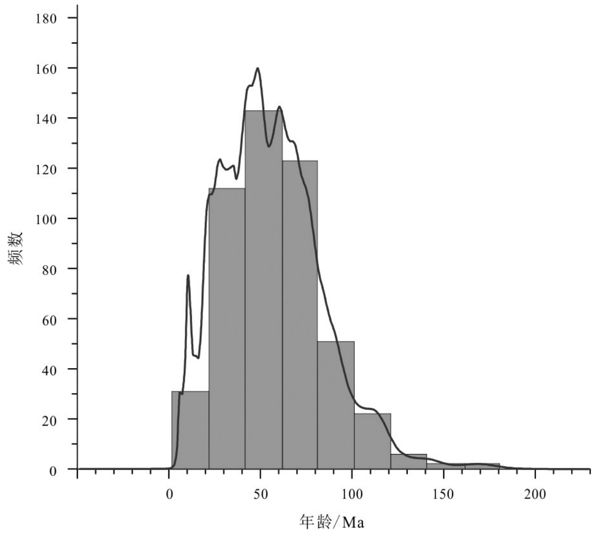

图21 中国东部基岩磷灰石裂变径迹年龄直方图
数据来源：文献[67, 83, 98, 103, 223−224, 229−231, 233−234, 248, 250−252, 256−260, 264−272]
Fig. 21 Apatite fission track age histogram of bedrock samples from eastern China
Data source: References [67, 83, 98, 103, 223−224, 229−231, 233−234, 248, 250−252, 256−260, 264−272]

带，经过侏罗纪—早白垩世强烈的造山运动，地壳逐步挤压增厚，地表海拔不断增高；而中国西部处于古特提斯洋与海陆交互环境，地壳厚度小于或约为30 km，地表海拔高度较小；至晚白垩世，形成东高西低的地势特点。

古新世—早始新世，中国大陆及邻区继承了晚白垩世构造地貌特征，中国东部及邻区主体处于高山和高原环境；西部则处于特提斯洋与海陆交互环境[37]，因此古新世—早始新世中国北方具有东高西低的地势特点。

3.8 晚中新世(8~6 Ma)以来构造地貌特征

晚中新世(8~6 Ma)以来，青藏高原、天山、阿尔泰山、阿尔金—祁连山构造地貌演化进入新的阶段。

现有的关于青藏高原隆升的研究表明，高原的隆升是一个多阶段、不等速、非均变的过程，且大量的低温热年代学、沉积学和构造变形记录揭示出高原的隆升具有大体同时性，集中表现出几个快速的隆升−剥露期：45~38 Ma，25~17 Ma，13~8 Ma，5~3 Ma以来[279−285]，尤其是在8 Ma以及5~3 Ma经历了急剧而强烈的隆升[20, 261, 280, 282, 286−292]。

关于天山隆升和热史演化的研究显示，天山地区普遍存在晚中新世(8~6 Ma)的隆升−剥露过程[118, 122−123, 134, 293−294]，并且8~6 Ma以来的山体隆升是形成现代天山地貌的原因[134]。阿尔泰山青河—富蕴地区磷灰石裂变径迹热史模拟显示，阿尔泰山也经历了8~6 Ma的快速抬升冷却过程[162]。而且，前人揭示的阿尔金—祁连山地区新生代以来的隆升阶段(图18)也同样反映了晚中新世的强隆升−剥露期。从较大区域上看，包括阿尔金山、祁连山在内的整个青藏高原北缘大约在9~7 Ma发生了一次准同时的隆升−剥露事件[175, 177, 185−186, 292, 295−301](图22)。不仅如此，青藏高原东缘也存在这次准同时的强构造活动(图22)，如龙门山地区在10~5 Ma发生了快速的剥蚀冷却事件[302]、鲜水河断裂西侧的贡嘎山在7.0~6.6 Ma发生了一次隆升剥露[281]以及甘孜地区经历了9 Ma的强构造隆升[303]。

综上可以看出，包括青藏高原、天山、阿尔泰山、阿尔金山、祁连山等在内的中国西部地区存在一个晚中新世(8~6 Ma)的等时面，该等时面的存在说明西部地区普遍经历了约8~6 Ma的隆升−剥露事件，8~6 Ma以来山体的抬升是西部地区现今山体高度的主要构成。

4 结 论

在一系列详细野外工作与室内资料整理分析的基础上，本文得出如下结论：

(1)中国北方普遍发育一组NNE向的断裂构造，该组断裂并非全区均匀发育，存在东西差异，东部断裂规模较大，地貌特征明显，向西规模逐渐变小。根据断裂与地层的切割关系、地震反射证据以及磷灰石裂变径迹数据，本文推定NNE向断裂活动的时间为古新世—早始新世，并且根据断裂两侧地层的变形特征，判定NNE向断裂具有左行走滑的运动学特征。

(2)NNE向断裂发育之后，东部渤海湾地区发育了NE向右行、NW向左行共轭走滑断裂。西准噶尔地区发育了NE向左行、NW向右行走滑断裂。东、西部的NE、NW向断裂都叠加在NNE向断裂之上，改造和破坏了早期NNE向断裂。

(3)中国北方NNE向左行走滑断裂大致对应NW−SE向挤压应力场，该期应力场的形成可能与新生代早期太平洋板块NNW向运动有关，即NNE向

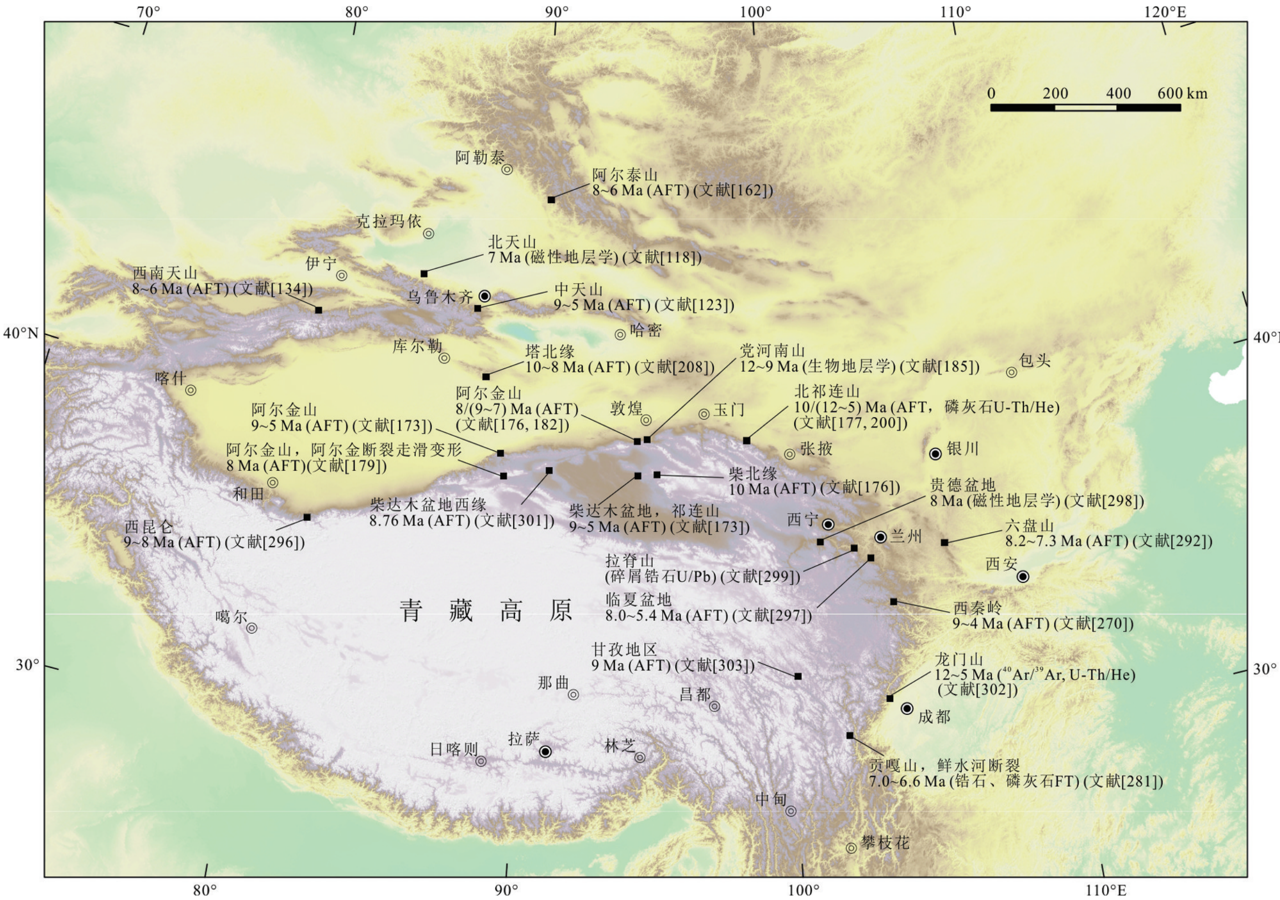

图22 中国西部地区晚中新世隆升–剥露事件[211]
Fig. 22 Late Miocene uplift–exhumation events in western China [211]

左行走滑断裂的发育与太平洋板块西向运动有关。

（4）东部渤海湾地区发育的NE向右行、NW向左行共轭走滑断裂对应了近EW向的挤压应力场，与早期NNE向断裂对应的NW–SE向挤压应力场之间存在一个转变过程，这一转变对应中国东部非常重要的构造事件，转换时限在43~42 Ma，与太平洋板块运动方向由NNW转变为WNW向时间一致。

（5）西部地区NE向左行、NW向右行共轭断裂大致对应了近NS向的挤压应力场，推测可能与印度–欧亚大陆碰撞远程效应有关。

（6）随着印度板块持续向北运动并发生了顺时针的旋转，西部地区一直保持NNE向的挤压应力场，发育了一系列ENE、WNW、NW、NNW向的断裂，体现了应力场的顺时针旋转。而东部渤海湾地区仍然保持近EW向的挤压应力场。

（7）磷灰石裂变径迹年龄显示，中国东部地区可能整体经历了古新世—早始新世（66~42 Ma）区域性抬升，致使东部地区普遍缺失晚白垩世和古新世地层，并形成了始新统与下伏前新生界地层间的区域性不整合面。这期区域性抬升以及不整合面的形成时期与NNE向断裂作用的时间相当，说明这一时期中国东部地区发生了一期重大构造事件，且该期构造事件为现今东部地区构造地貌格局的形成奠定了基础，现今NNE向大兴安岭—太行山—武陵山重力梯度带的形成可能与该期构造事件有关。与东部地区不同，西部地区则存在8~6 Ma的等时面，说明西部地区曾经历过8~6 Ma时的整体隆升–剥露事件，该期隆升与印度–欧亚大陆碰撞有关，并且为西部地区现今构造地貌格局的形成做出了主要的贡献。

（8）由于受到新生代以来各组断裂构造的影响，中国北方山脉和盆地呈现出线状与面状结合的

网格状特征。东部地区受到NNE向断裂控制,山脉和盆地呈NNE向展布,西部地区受到ENE、WNW、NW、NNW断裂的控制,山脉和盆地走向呈近EW向。

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