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# 天山北麓中生代构造特征及其对新生代变形的意义

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**摘 要:** 天山北麓褶皱冲断带经历了多期构造运动,于晚新生代收缩作用下定型,多期叠合作用下,基底构造对后续挤压构造的影响并不明确.基于高精度三维地震和钻井资料,结合野外地质观测,研究天山北麓中生代构造特征和变形机理,以揭示中生代构造对新生代变形和油气运聚的影响和控制因素.研究认为天山北麓中生代发育走滑断层,被白垩系－新生界覆盖.中生代走滑断裂在晚新生代挤压环境下重新激活,其上覆叠加了新生代逆冲断裂和褶皱,中生代构造的重新激活对塑造天山及其天山北麓现今构造发挥了重要作用.依据构造变形期次,将准噶尔盆地南缘的沉积层划分为浅、中、深3个构造层,对应上、中、下3套油气成藏组合;其中,中、深构造层具有较大勘探潜力.揭示天山北麓深部断层与后期挤压构造的关系,明确多期构造叠合演化对油气勘探的影响,为中国西部盆地类似构造研究提供借鉴.

**关键词:** 天山北麓,中生代断层,白垩纪不整合面,新生代褶皱,多期构造变形;石油地质.

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# Mesozoic Structure and Its Impact on Cenozoic Deformation in Northern Piedmont of Tianshan Mountain

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**Abstract:** The fold-thrust belt in the northern piedmont of the Tianshan Mountains underwent polyphase tectonic deformation, acquiring its present configuration during the Late Cenozoic contractional regime. Under multiphase superposition, the influence of basement architecture on subsequent compressive deformation remains constrained. This study investigates the Mesozoic structural characteristics and deformation mechanisms in the northern piedmont of the Tianshan Mountains based on seismic, drilling, and field observation data, aiming to reveal the influence and controlling factors of Mesozoic structures on Cenozoic deformation and hydrocarbon migration-accumulation. Strike-slip faults were developed in the Mesozoic in the northern piedmont of Tianshan Mountain, and were covered by the Cretaceous-Cenozoic strata. Under the Late Cenozoic compression environment, the

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Mesozoic strike-slip fault was reactivated, and the Cenozoic thrust fault and fold superimposed on the Mesozoic fault. The reactivation of Mesozoic structures played an important role in shaping the present structure of the northern piedmont of Tianshan Mountain. According to the deformation sequence, the sedimentary strata in the southern Junggar basin. are divided into three structural layers—shallow, intermediate, and deep. These tiers correspond to upper, middle, and lower hydrocarbon accumulation assemblages, respectively, with the intermediate and deep structural tiers demonstrating particularly significant exploration potential. In this paper it reveals the relationship between deep faults and late compressive structures in the northern piedmont of Tianshan Mountain, explains the influence of multi-stage tectonic evolution on oil and gas exploration, and has reference significance for the study of similar structures in the basins of western China.

**Key words:** northern piedmont of Tianshan Mountain; Mesozoic fault; Cretaceous unconformity; Cenozoic anticline; multi-stage deformation; petroleum geology.

## 0 引言

天山山麓油气资源丰富,南麓的塔里木盆地北缘发现库车超大型天然气田,北麓的准噶尔盆地南缘发现呼图壁油气田、东湾油气田(李本亮等,2011;庞志超等,2023;袁波等,2023).天山南北两麓石油地质条件相似,目前天山北麓的油气勘探成果低于南麓,仍需进一步勘探研究.天山北麓现今的构造格局形成于新生代,发育新生代逆冲褶皱构造(管树巍等,2006;李本亮等,2010;李本亮等,2011;庞志超等,2023;袁波等,2023).出露地表的白垩系与侏罗系间不整合卷入新生代褶皱变形,说明天山北麓经历中生代和新生代两期变形(Guan *et al.*, 2016;Ma *et al.*, 2019).陆内环境下基底构造对后期挤压变形的影响普遍存在,已存在的基底断层是变形薄弱带,遇到后期挤压易于重新活动.例如伊朗扎格罗斯盆地、柴达木盆地、四川盆地,它们都经历了复杂的多旋回演化过程,基底断层的重新活动影响到后期构造变形(Hessami *et al.*, 2001;Soto *et al.*, 2007;Koyi *et al.*, 2016).

由于前期地震反射剖面品质较差,不能满足天山北麓中生代构造研究需求.已有的钻探井深度有限,未能钻遇盆地深层的白垩系-侏罗系地层,因此前人对天山北麓的中生代构造研究比较薄弱.

随着天山北麓近几年采集处理的三维地震品质明显提高,白垩系-侏罗系地震反射信息逐渐清晰.本文基于高精度三维地震和钻井资料,结合野外地质观测,研究天山北麓中生代构造特征和变形机理,揭示中生代构造对新生代变形和油气运聚的影响和控制因素.

## 1 区域地质背景

天山造山带形成始于晚古生代古亚洲洋闭合,大陆块体和岛弧发生碰撞(Windley *et al.*, 1990;Allen *et al.*, 1993;Xiao *et al.*, 2013).研究发现天山、阿尔泰山发育中生代断裂,山体抬升剥蚀,山间盆地堆积厚层砾岩(Hendrix *et al.*, 1992, 1995;Allen *et al.*, 1995;Hendrix, 2000;Yang *et al.*, 2013).中生代,天山隆升的动力来源被认为来自亚洲大陆南部羌塘、拉萨地体的拼贴(Jolivet *et al.*, 2010).早中生代,天山处于构造平静时期,仅存在局部的构造活动,整体处于剥蚀、夷平状态(Allen *et al.*, 1991).晚侏罗世,受块体碰撞拼合的影响,准噶尔盆地与周缘造山带发生构造活动(Yang *et al.*, 2015, 2017;Wang *et al.*, 2022).白垩纪天山至新生代中期,天山长期处于剥蚀状态,古天山再度被夷平(邓启东等,2000).新生代印度板块与欧亚大陆发生碰撞,天山再次隆升(Avouac *et al.*, 1993;Burchfiel *et al.*, 1999),天山北麓现今的地形和构造样式是晚新生代天山隆升挤压的结果.

## 2 天山北麓构造变形特征

天山北麓发育北西-南东向断裂.准噶尔南缘断裂为天山与准噶尔地块的分界断裂,东起乌鲁木齐,向西延伸到托斯台,蜿蜒300~400 km(图1)(邓启东等,2000).断裂西段托斯台、南安集海、南玛纳斯3个菱形断块(凸起)被高陡断层环绕,凸起顶部发育三叠系-侏罗系褶皱,断层和褶皱上覆被白垩系不整合覆盖(图2a~2c).断裂东段北侧斜列清水河背斜、齐古背斜、昌吉背斜、阿克屯背斜、喀拉扎背斜,背斜顶部侏罗系遭受剥蚀,被白垩系角度不整合覆盖(图2d、图3)(邓启东等,2000;He and

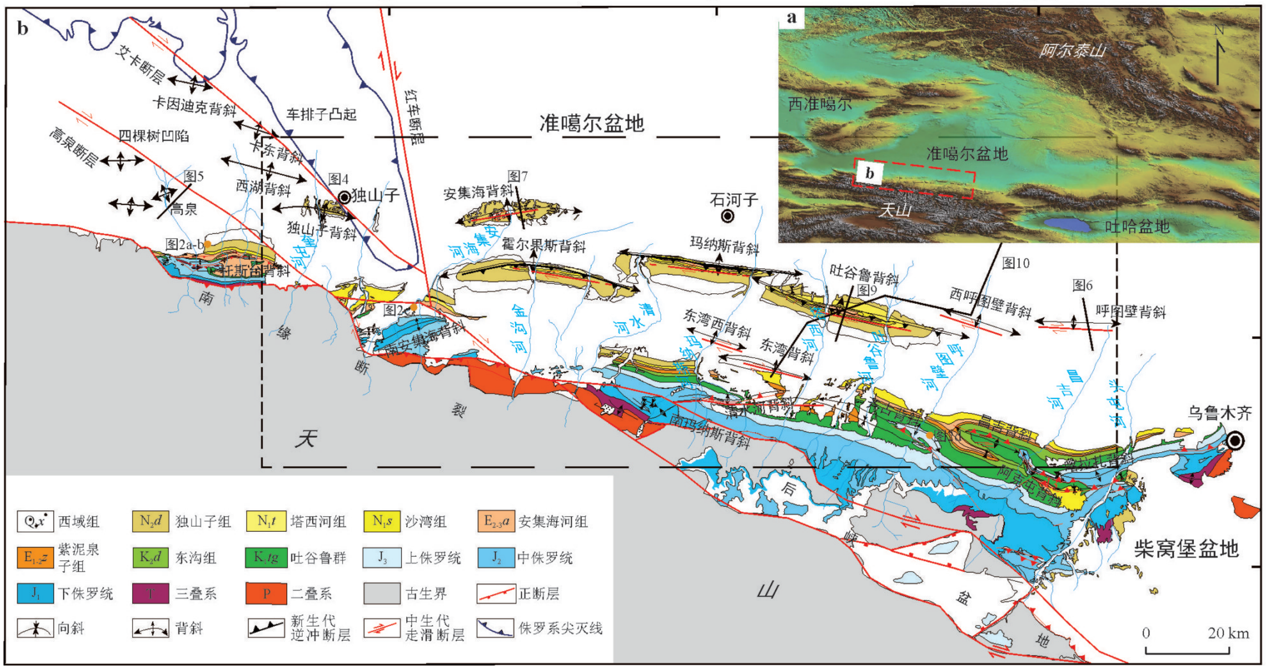


图 1　准噶尔盆地区域位置图(a)和准噶尔盆地南缘地质构造图(标注地震剖面位置)(b)

Fig.1　Regional location map of Junggar basin (a), and geologic map of the south margin of Junggar basin in Xinjiang (blacklines indicate the location of seismic profiles) (b)

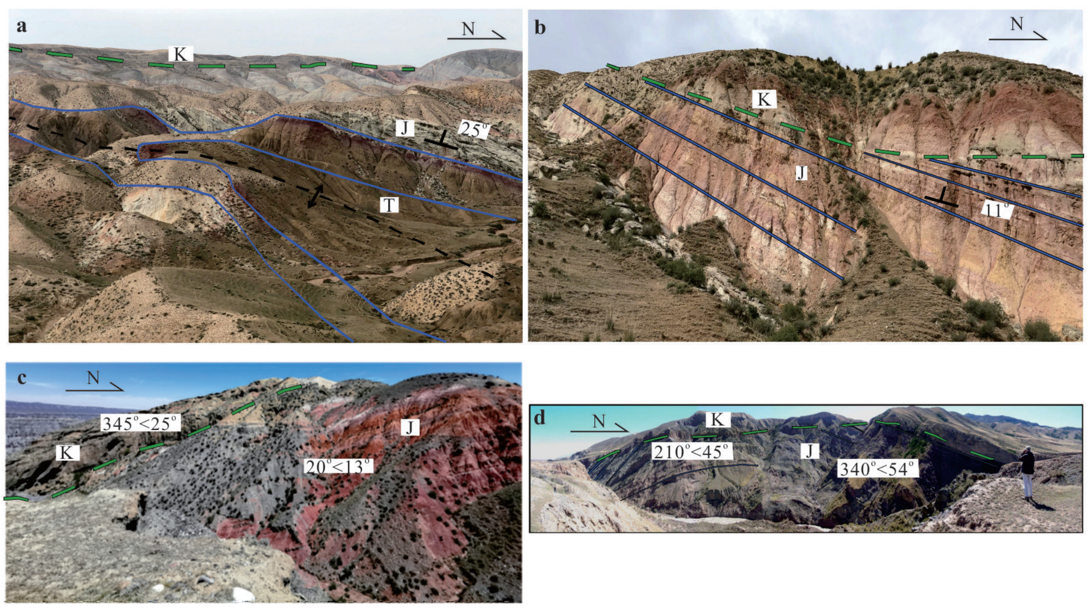


图 2　天山北麓白垩系/侏罗系不整合面野外照片

Fig.2　Field photos of Cretaceous/Jurassic unconformity at the northern piedmont of Tianshan

a,b.托斯台三叠系－侏罗系褶皱被白垩系不整合覆盖(位置见图 1);c.南安集海背斜北翼白垩系/侏罗系不整合面(位置见图 1);d 齐古背斜白垩系/侏罗系不整合面(位置见图 1 引自 He and Suppe,2006)

Suppe,2006).断裂东段南侧后峡盆地堆积 2～3 km 厚侏罗系砂砾岩－砾岩,砾石磨圆度低,分选程度差,属于快速沉积的磨拉石(图 1),后峡盆地边缘发育高陡断层,属于侏罗纪断陷盆地(朱明等,2021).

天山北麓中生代,受西北缘右旋压扭体系影响,发育走滑断裂,造成抬升剥蚀,同时发育断陷盆地(Allen *et al.*,1995;邵雨等,2011).由于白垩系/侏罗系不整合面卷入新生代挤压变形(图 3),天山北麓存

在中生代走滑和新生代挤压两期变形．

天山北麓呈近东－西向展布（图1），被车排子凸起分隔，凸起东侧是霍玛吐冲断带，凸起西侧是四棵树凹陷．

受右旋压扭体系影响，四棵树凹陷中生代发育北西—南东向走滑断裂：艾卡断裂和高泉断裂．受艾卡断裂和高泉断裂控制形成艾卡构造带、高泉构造带2个雁列式背斜带，各构造带背斜平面分布展示右旋压扭特征（图1）．艾卡断裂是车排子凸起与四棵树凹陷的边界断层，断层切过古生界至侏罗系，发育“正花状构造”，构造顶部侏罗系被剥蚀，白垩纪不整合覆盖其上（图4）．高泉断裂表现为高陡直立，石炭系基底卷入，在剖面上发育主干断裂与分支断裂，组成正花状构造样式，为较强的压扭走滑构造，地层相对平缓，为中央洼陷带（图5）（卞保力等，2024）．

霍玛吐冲断带发育雁行式排列断层，断层顶部侏罗系被剥蚀，上覆被白垩系不整合覆盖（图6，7）．

霍玛吐冲断带中生代断层发生走滑位移的证据：（1）断层高陡直立，断层两侧不同构造单元地层并列．呼图壁断层右侧是中－下二叠系断陷，左侧是古生界隆起（图6）．安集海断层两侧并列的侏罗系地层厚度明显不同，左侧侏罗系地层厚度是断层右侧侏罗系地层的两倍（图7）．有人解释断层左侧是断陷盆地，认为这是一条正断层（Windley *et al.*，1990）．但是断层左侧没有出现与断陷相关的楔状沉积，解释为走滑断层比较合理．（2）霍玛吐冲断带走滑断层被白垩系覆盖，属于前白垩纪断层．（3）雁列式断裂模式，例如东湾和东湾西雁列断层、呼图壁、西呼图壁和吐谷鲁雁列断层（图1）．另外，根据中生代天山北麓重力异常特征可以看出霍玛吐冲断带发育多条近南－北向断裂，根据重力异常指示可以

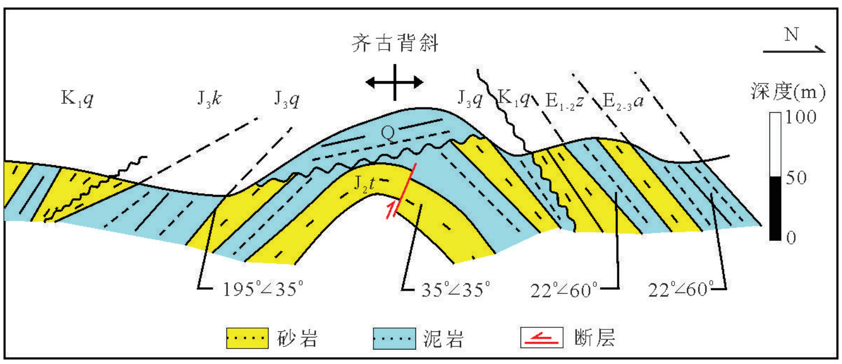


图3　天山北麓野外观测的齐古背斜剖面

Fig.3　Qigu anticline observed in the field at the northern piedmont of Tianshan

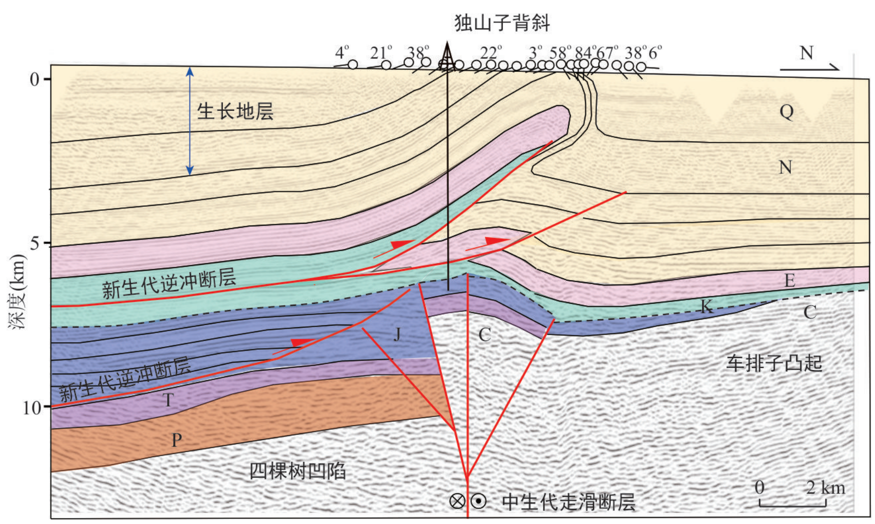


图4　独山子背斜地震剖面解释方案（图例和剖面位置见图1）

Fig.4　The seismic interpretation section across Dushanzi anticline in the southern Junggar basin (see Fig.1 for the legend and location of seismic line)

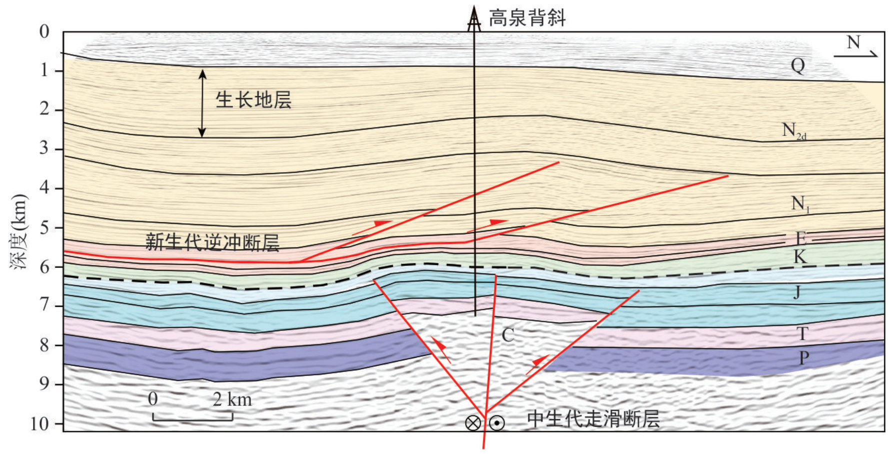


图 5　高泉背斜地震剖面解释方案(图例和剖面位置见图 1)

Fig.5　The seismic interpretation section across Gaoquan anticline in the southern Junggar basin (see Fig.1 for the legend and location of seismic line)

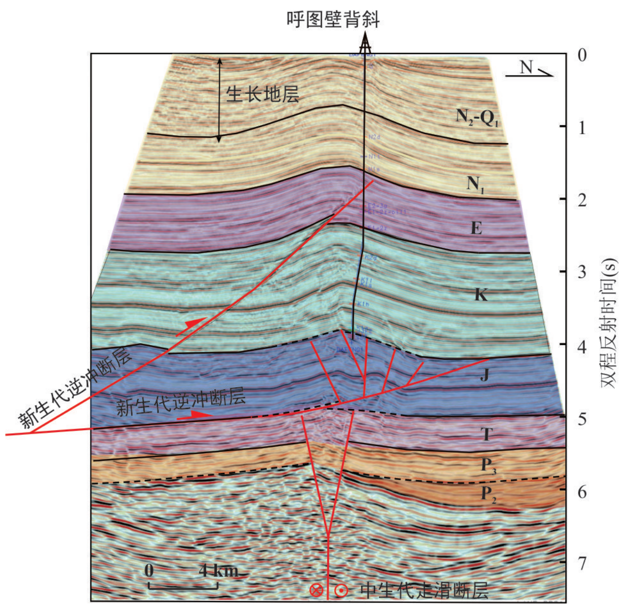


图 6　呼图壁背斜地震剖面解释方案(图例和剖面位置见图 1)

Fig.6　The seismic interpretation section across Hutubi anticline in the southern Junggar basin (see Fig.1 for the legend and location of seismic line)

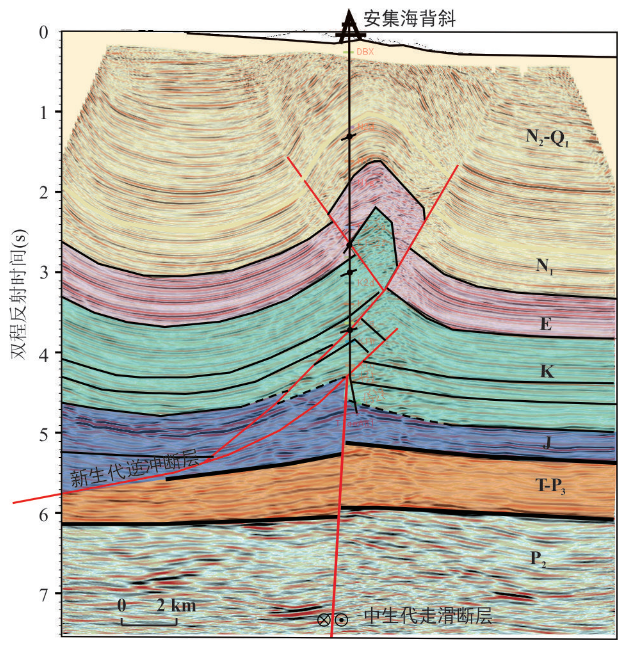


图 7　安集海背斜地震剖面解释方案(图例和剖面位置见图 1)

Fig.7　The seismic interpretation section across Anjihai anticline in the southern Junggar basin (see Fig.1 for the legend and location of seismic line)

看出霍玛吐冲断带近东—西向断裂出现被错动的左旋特征(图 8).近南—北向左旋走滑断裂与南缘右旋走滑断裂的匹配符合 Sylester 剪切模式(Sylvester,1988).因此,我们推断霍玛吐冲断带多条近南—北向走滑断裂之间发育近东—西向走滑断裂.同时,前人研究证明,艾卡断裂和高泉断裂为走滑断裂(杨迪生等,2019;刘刚等,2024;卞保力等,2024).

基于呼图壁背斜地震解释方案(图 6)进行反演恢复分析.呼图壁背斜发育中生代高陡断层和新生代低角度逆冲断层,高陡中生代断层切过古生界和三叠系,平缓逆冲断层位于侏罗系底界,倾斜的逆冲断层突破背斜(图 9a).白垩系不整合面是重要的构造分界,不整合面上覆的白垩系—新生界整合接触(或者假整合接触),作为中生代变形后沉积的地层,经历新生代变形.不整合面下伏地层经历中生代和新生代二期变形.拉平白垩系底界,得到侏罗

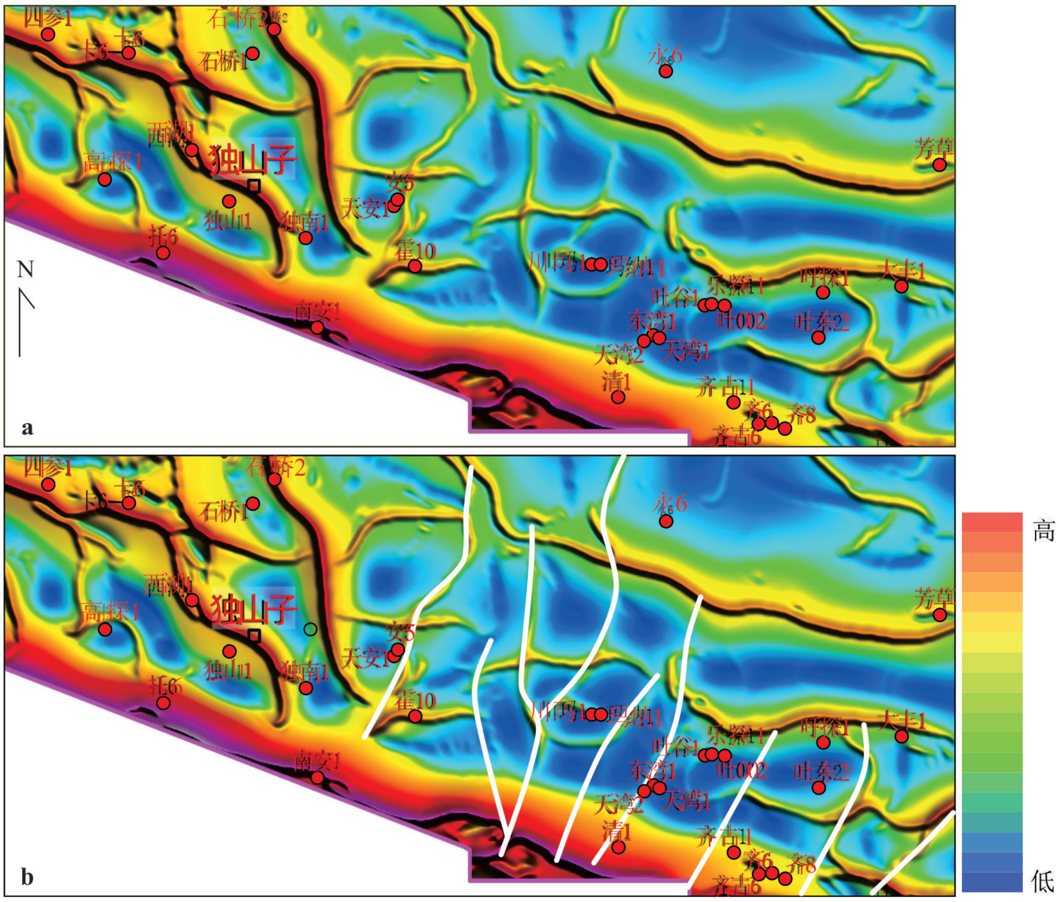


图 8　天山北麓重力异常特征

Fig.8　Gravity anomaly feature of the northern piedmont of Tianshan Mountain

a.不解释断裂，b.解释断裂

纪古构造剖面（图 9b）. 侏罗系－三叠系没有发生褶皱，说明侏罗系地层褶皱发生在白垩纪以后. 基底断层上覆上侏罗统喀拉扎组（$J_3k$）剥蚀，白垩系不整合覆盖侏罗系齐古组（$J_3q$）. 拉平侏罗系底界，得到三叠纪古构造剖面（图 9c）. 三叠系地层发生掀斜抬升，由南向北抬升幅度逐渐减小，被侏罗系不整合覆盖. 二叠系也向南抬升削蚀，发育上二叠统/中二叠统不整合. 这两个不整合面范围明显超越中生代断层位置，属于区域构造不整合.

## 3　讨论

### 3.1　天山北麓构造变形时间与演化序列

根据我们的分析，天山北麓中生代断裂活动发生在晚侏罗世. 断裂导致广泛分布的构造不整合面，例如托斯台背斜、齐古背斜、南安集海背斜观察到的白垩系/侏罗系角度不整合（图 2），盆地隐伏的白垩系/侏罗系角度不整合，车排子凸起、三台凸起、北三台凸起的白垩系不整合. 磷灰石裂变径迹（AFT）热年代数据建议，侏罗纪期间天山发生快速冷却，山体发生强烈隆升事件（Jolivet *et al.*，2010；Yang *et al.*，2013；Jolivet，2017），这与我们观察的结果相吻合. 天山山间盆地堆积侏罗系砾岩（Hendrix *et al.*，1992，1995；Hendrix，2000），准噶尔盆地、塔里木盆地、吐哈盆地的沉积环境由早、中侏罗世的曲流－湖相环境转变为晚侏罗世的冲积扇层序（Hendrix *et al.*，1992，1995；De Grave *et al.*，2007），这与构造抬升事件一致. 侏罗纪变形归因亚洲南部拉萨地块或羌塘地块增生，远距离的挤压作用诱发天山－阿尔泰山发生抬升（Allen *et al.*，1995；De Grave *et al.*，2007；Jolivet，2017），天山、阿尔泰山、扎伊尔山围绕的准噶尔盆地发生逆时针旋转，盆地周缘发育走滑断层（Zhu *et al.*，2023）. 依据构造变形时间和断层类型，我们认为天山北麓中生代构造归属准噶尔盆地周缘中生代走滑断层体系. 白垩纪期间，准噶尔盆地、塔里木盆地、吐哈盆地白垩系沉积于湖相环境，表明处于构造静止期（Hendrix *et al.*，

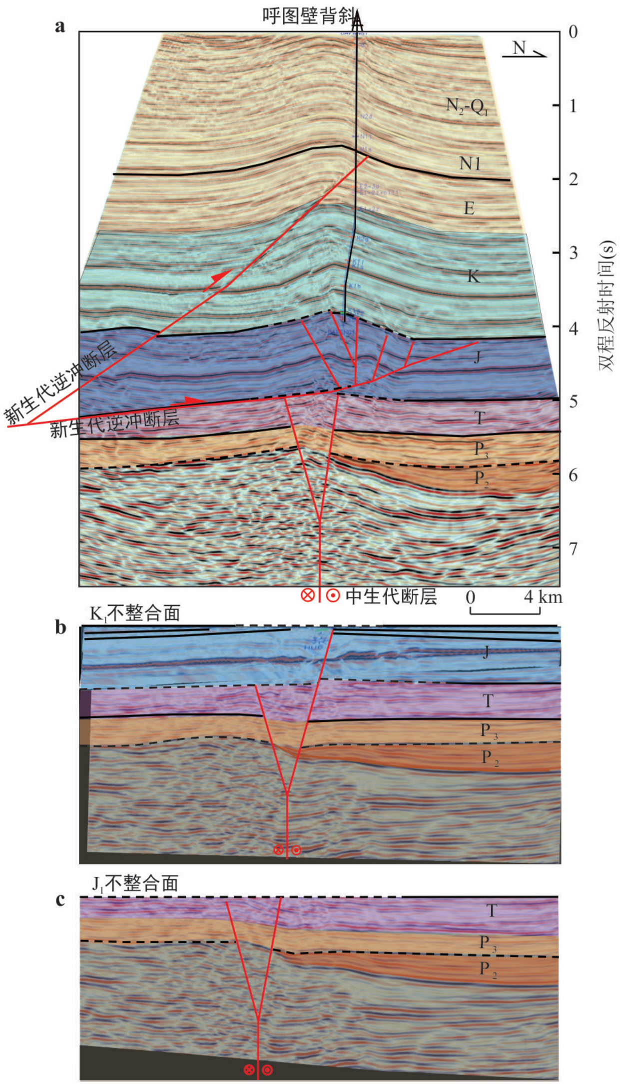


图 9　呼图壁背斜反演恢复剖面

Fig.9　The restoration of the seismic image of Hutubi anticline

1992)，预示中生代变形止于白垩纪．新生代期间，印度板块与欧亚大陆发生碰撞，天山再次隆升，天山北麓发育新生代逆冲褶皱带，白垩系/侏罗系不整合面卷入变形，中生代断层上覆叠加了新生代逆冲断层和褶皱．

依据反演剖面结果(图 9)，我们认为晚侏罗世发育高陡的走滑断层，出现低幅度的隆起，发育白垩系/侏罗系不整合面．新近纪发育逆冲断层，侏罗系及上覆地层发生褶皱，形成呼图壁背斜，同时背斜下伏的中生代断层也重新活动．

### 3.2　天山北麓中生代构造对新生代变形的影响

以往勘探关注中—浅层系，对深层构造缺乏了解．地震和钻井资料证实中生代断层重新激活控制了后续新生代褶皱类型和分布．这种构造继承性表现为：(1)新生代背斜的走向和分布与下伏中生代断裂重合，四棵树凹陷艾卡断层的上覆形成新生代雁行褶皱时，霍玛吐冲断带中生代断层分段排列，新生代褶皱也是分段排列，褶皱的雁行排列是对下伏中生代走滑断层重新活动的响应(图 1)．(2)断层相关褶皱理论认为断层斜坡上盘发育褶皱，断层斜坡决定了褶皱的位置(Suppe，1983)．天山北麓新生代逆冲断层斜坡位于中生代断层上覆，中生代断层重新活动影响新生代逆冲断层斜坡的发育位置．例如，独山子背斜中生代断层重新活动，断层上覆地层隆起，沿隆起的白垩系泥岩新生代逆冲断层上仰，形成逆冲断层斜坡(图 4)．高泉中生代断层重新活动导致挤压脊隆起，挤压脊上覆发育逆冲断层斜坡．同样，呼图壁背斜位于重新活动的中生代断层上覆，断层上覆的侏罗系隆起，新生代逆冲断层沿隆起的侏罗系滑脱面上仰，发育断层斜坡(图 5)．(3)天山北麓中生代走滑断层重新活动，应力以挤压为主，因先存断裂性质影响，走滑断裂的重新活动也伴随着剪切活动的产生，先存断裂的上覆发育剪切型褶皱．独山子背斜前翼地层高陡直立，局部倒转，后翼地层平缓，地层倾角 20°～38°，是三角剪切型断层传播褶皱(陈伟等，2012；Li *et al.*，2020；Peng *et al.*，2024)(图 4)．独山子背斜地表发育剪切破裂，河流阶地发生走滑位移，证实独山子背斜目前依然发生剪切位移(Wei *et al.*，2020)．高泉背斜、呼图壁背斜、安集海背斜后翼地层倾角小于逆冲断层倾角(图 5～图 7)，结合剪切型断弯褶皱特征(Suppe *et al.*，2004)，以及邻区相似的构造特征，我们认为上述背斜属于剪切型断层相关褶皱．天山北麓的中生代走滑断层重新活动影响上覆新生代褶皱变形方式和褶皱类型．

综上所述，基底断层对天山北麓新生代褶皱具有十分重要的影响：重新活动的基底断层造成滑脱面的起伏，控制了逆冲断层斜坡的位置；褶皱雁行排列是对重新活动的基底雁行断层的响应；新生代褶皱的剪切变形预示下伏中生代走滑断层重新活动．天山北麓新生代褶皱上覆沉积新近系生长地层，褶皱隆起和基底断层的重新活动发生在新近纪(袁波等，2023；Peng *et al.*，2024)(图 4～图 6)．

### 3.3　天山北麓多期叠加构造的油气勘探

天山北麓经历中生代—新生代多期构造变形，油气聚集史和圈闭类型复杂．天山北麓沉积侏罗系、二叠系烃源岩，晚侏罗世烃源岩埋藏浅，深度未

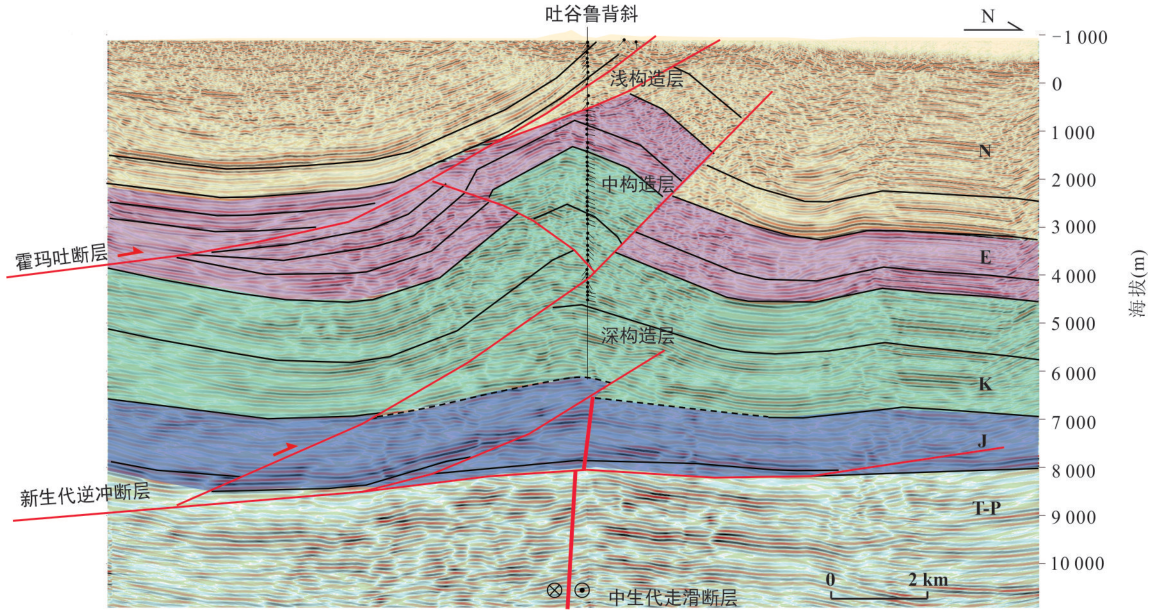


图 10 吐谷鲁背斜地震剖面解释方案(图例和剖面位置见图 1)

Fig.10 The seismic interpretation section across Tugulu anticline in the southern Junggar basin (see Fig.1 for the legend and location of seismic line)

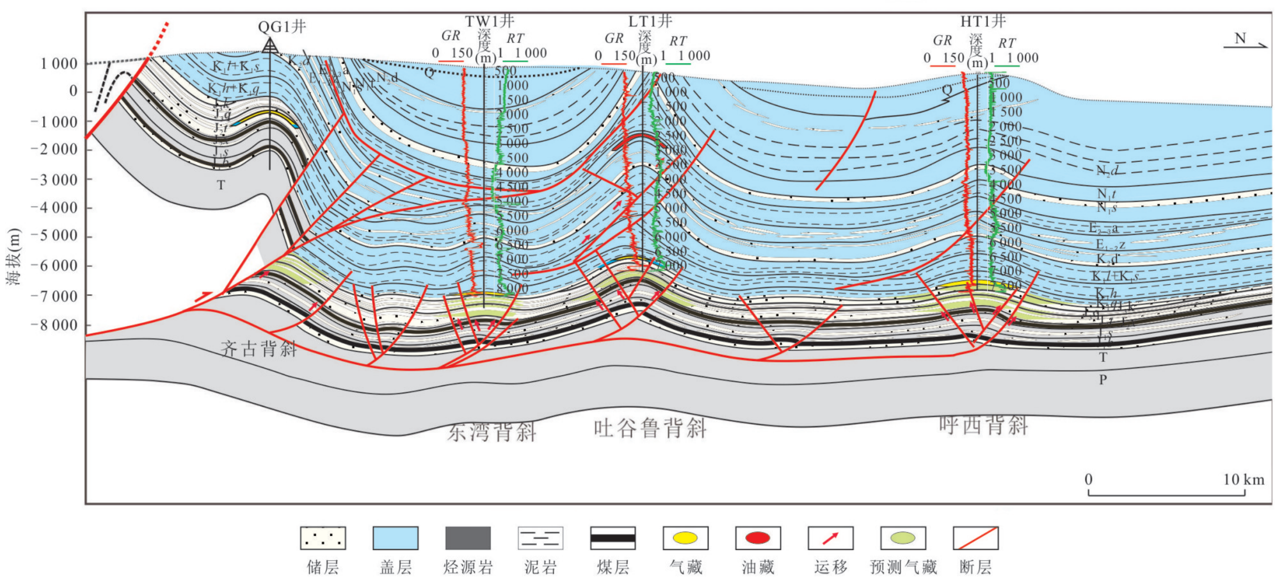


图 11 南缘冲断带油气成藏模式

Fig.11 The hydrocarbon accumulation model of the southern thrust belt

Q.第四系;$N_1t$.新近系塔西河组;$N_1s$.新近系沙湾组;$E_{2\text{-}3}a$.古近系安集海河组;$E_{1\text{-}2}z$.古近系紫泥泉子组;$K_2d$.白垩系东沟组;$K_1l$.白垩系连木沁组;$K_1s$.白垩系胜金口组;$K_1h$.白垩系呼图壁河组;$K_1q$.白垩系清水河组;$J_3k$.侏罗系喀拉扎组;$J_3q$.侏罗系齐古组;$J_2t$.侏罗系头屯河组;$J_2x$.侏罗系西山窑组;$J_1s$.侏罗系三工河组;$J_1b$.侏罗系八道湾组;T.三叠系;P.二叠系

达到成熟门限.晚古近纪(~38 Ma)发育逆冲断层和褶皱,形成三排背斜和大量的构造圈闭,重新激活的中生代断裂沟通深层烃源岩与圈闭的通道,有助于油气聚集(图 9c).中新世晚期(~8 Ma)逆冲断层突破褶皱,例如四棵树凹陷独山子背斜被断层突破(图 4)、霍玛吐冲断带的霍尔果斯、玛纳斯、吐谷鲁背斜被断层突破(图 10)、呼图壁背斜被断层突破(图 6),油气保存条件变差(图 9c、图 10)(袁波等,2023).

依据构造演化序列将天山北麓划分为浅、中、

深3个构造层（图10），对应上、中、下3套油气成藏组合（李学义等，2003）.3个组合是南缘油气勘探的核心与主线，3个成藏组合各有油气聚集特点.浅构造层位于出露地表的逆冲断层上盘，新生界－上白垩统是勘探目的层，上组合的成藏保存条件差，油气聚集困难，处于油气散失状态，油气藏充满度低，勘探价值较低.上组合发现独山子油田，是中国最早的油田之一.中构造层介于浅、深构造层之间，被隐伏的逆冲断层分隔.中构造层并非全区存在，而是局部发育.中组合的区域盖层是古近系安集海河组泥岩，古近系紫泥泉子组、白垩系为主要勘探目的层.中组合构造圈闭以断背斜、断块为主，发育中小型油气藏，例如高产高效的玛河气田，累产天然气120亿方.深构造层位于深层逆冲断层上盘，下组合的区域盖层是白垩系泥岩，下白垩统清水河组和侏罗系是勘探目的层.深构造层经历中生代走滑和新生代挤压二期变形，发育复合型构造宽缓的圈闭，基底断层沟通深层烃源岩与构造圈闭通道，只要构造落实，发现大油气田的可能性极大.目前高泉背斜的GT1井、东湾背斜的TW1井、东湾南断背斜的QB1井以及呼西背斜的HT1井、HU101井和HU102井在下组合均有重大发现（靳军等，2019；庞志超等，2023；宋永等，2025），说明下组合具备大天然气田的勘探潜力（图11）.

## 4　结论

天山北麓发育中生代走滑断层，其上被白垩系底部不整合覆盖.新生代，复活的中生代断层上覆叠加新生代逆冲断层和褶皱，发育"深层高陡走滑断层，浅层低角度逆冲断层和褶皱"叠加型构造.以构造变形期次为依据，将天山北麓分为上、中、下3套油气成藏组合.下组合为下白垩统－侏罗系，经历中生代、新生代二期变形，发育复合型构造圈闭，具有较大勘探潜力.中组合为古近系安集海河组－上白垩统，发育新近纪断背斜和断块，发现中小型油气藏.浅组合为新进系，位于出露地表的逆冲断层上盘，成藏组合保存条件差，勘探价值较低.

## References

Allen, M.B., Engör, A.M.C., Natal'in, B.A., 1995. Junggar, Turfan and Alakol Basins as Late Permian to Early Triassic Extensional Structures in a Sinistral Shear Zone in the Altaid Orogenic Collage, Central Asia. *Journal of the Geological Society*, 152(2): 327－338. https://doi.org/10.1144/gsjgs.152.2.0327

Allen, M.B., Windley, B.F., 1993. Palaeozoic Collisional Tectonics and Magmatism of the Chinese Tien Shan, Central Asia. *Tectonophysics*, 220(1－4): 89－115. https://doi.org/10.1016/0040-1951(93)90225-9

Allen, M.B., Windley, B.F., Zhang, C., et al., 1991. Basin Evolution within and Adjacent to the Tien Shan Range, NW China. *Journal of the Geological Society*, 148(2): 369－378. https://doi.org/10.1144/gsjgs.148.2.0369

Avouac, J. P., Tapponnier, P., Bai, M., et al., 1993. Active Thrusting and Folding along the Northern Tien Shan and Late Cenozoic Rotation of the Tarim Relative to Dzungaria and Kazakhstan. *Journal of Geophysical Research: Solid Earth*, 98(B4): 6755－6804. https://doi.org/10.1029/92JB01963

Bian, B.L., Wu, K.Y., Liu, H.L., et al., 2024. Geological Characteristics, Formation and Evolution of Sikeshu Depression and Its Surrounding in Junggar Basin. *Fault-Block Oil & Gas Field*, 31(4): 570－579 (in Chinese with English abstract).

Burchfiel, B.C., Brown, E.T., Deng, Q.D., et al., 1999. Crustal Shortening on the Margins of the Tien Shan, Xinjiang, China. *International Geology Review*, 41(8): 665－700. https://doi.org/10.1080/00206819909465164

Chen, W., Hao, J.J., Li, S.Q., et al., 2012. The Geometric and Kinematic Numerical Simulation of the Dushanzi Anticline, Southern Junggar Basin. *Chinese Journal of Geology (Scientia Geologica Sinica)*, 47(1): 37－50 (in Chinese with English abstract).

De Grave, J., Buslov, M.M., Van den Haute, P., 2007. Distant Effects of India-Eurasia Convergence and Mesozoic Intracontinental Deformation in Central Asia: Constraints from Apatite Fission-Track Thermochronology. *Journal of Asian Earth Sciences*, 29(2－3): 188－204. https://doi.org/10.1016/j.jseaes.2006.03.001

Deng, Q. D., Feng, X. Y., Zhang, P. Z., et al., 2000. Active Structure of Tianshan Mountains. Seismological Press, Beijing (in Chinese).

Guan, S. W., Zhang, C. J., He, D. F., et al., 2006. Complex Structural Analysis and Modeling: The First Row of Anticlinal Belt on the Southern Margin of the Junggar Basin. *Acta Geologica Sinica*, 80(8): 1131－1140 (in Chinese with English abstract).

Guan, S.W., Stockmeyer, J.M., Shaw, J.H., et al., 2016. Structural Inversion, Imbricate Wedging, and Out-of-Sequence Thrusting in the Southern Junggar Fold-and-Thrust Belt, Northern Tian Shan, China. *AAPG Bulletin*, 100(9): 1443—1468. https://doi. org/10.1306/04041615023

He, D.F., Suppe, J., 2006. Guidebook for Field Trip in South and North Tianshan Foreland Basin, Xinjiang Uygur Autonomous Region, China. Research Institute of Petroleum Exploration and Development (RIPED), PetroChina, Beijing.

Hendrix, M.S., 2000. Evolution of Mesozoic Sandstone Compositions, Southern Junggar, Northern Tarim, and Western Turpan Basins, Northwest China: A Detrital Record of the Ancestral Tian Shan. *Journal of Sedimentary Research*, 70(3): 520—532. https://doi. org/10.1306/2dc40924-0e47-11d7-8643000102c1865d

Hendrix, M.S., Graham, S.A., Carroll, A.R., et al., 1992. Sedimentary Record and Climatic Implications of Recurrent Deformation in the Tian Shan: Evidence from Mesozoic Strata of the North Tarim, South Junggar, and Turpan Basins, Northwest China. *Geological Society of America Bulletin*, 104(1): 53—79. https://doi. org/10.1130/0016-37606(1992)1040053:sracio>2.3.co;2

Hendrix, M.S., Brassell, S.C., Carroll, A.R., et al., 1995. Sedimentology, Organic Geochemistry, and Petroleum Potential of Jurassic Coal Measures: Tarim, Junggar, and Turpan Basins, Northwest China1. *AAPG Bulletin*, 79:929—958. https://doi. org/10.1306/8d2b2187-171e-11d7-8645000102c1865d

Hessami, K., Koyi, H.A., Talbot, C.J., 2001. The Significance of Strike-Slip Faulting in the Basement of the Zagros Fold and Thrust Belt. *Journal of Petroleum Geology*, 24(1): 5—28. https://doi. org/10.1111/j. 1747-5457.2001.tb00659.x

Jin, J., Wang, F.Y., Ren, J.L., et al., 2019. Genesis of High-Yield Oil and Gas in Well Gaotan-1 and Characteristics of Source Rocks in Sikeshu Sag, Junggar Basin. *Xinjiang Petroleum Geology*, 40(2): 145—151(in Chinese with English abstract).

Jolivet, M., Dominguez, S., Charreau, J., et al., 2010. Mesozoic and Cenozoic Tectonic History of the Central Chinese Tian Shan: Reactivated Tectonic Structures and Active Deformation. *Tectonics*, 29(6). https://doi. org/10.1029/2010tc002712

Jolivet, M., 2017. Mesozoic Tectonic and Topographic Evolution of Central Asia and Tibet: A Preliminary Synthesis. *Geological Society, London, Special Publications*, 427(1):19—55. https://doi.org/10.1144/sp427.2

Koyi, H., Nilfouroushan, F., Hessami, K., 2016. Modelling Role of Basement Block Rotation and Strike-Slip Faulting on Structural Pattern in Cover Units of Fold-and-Thrust Belts. *Geological Magazine*, 153(5—6): 827—844. https://doi.org/10.1017/s0016756816000595

Li, B.L., Guan, S.W., Chen, Z.X., et al., 2010. Fault-Related Fold Theory and Application: Case Study on Structural Geology in Southern Junggar Basin. Petroleum Industry Press, Beijing (in Chinese with English abstract).

Li, B.L., Chen, Z.X., Lei, Y.L., et al., 2011. Structural Geology Correlation of Foreland Thrust-Folded Belts between the Southern and Northern Edges of the Tianshan Mountain and Some Suggestions for Hydrocarbon Exploration. *Acta Petrolei Sinica*, 32(3): 395—403(in Chinese with English abstract).

Li, X.Y., Shao, Y., Li, T.M., 2003. Three Oil-Reservoir Combinations in South Marginal of Jungar Basin, Northwest China. *Petroleum Exploration and Development*, 30(6): 32—34(in Chinese with English abstract).

Li, Z.G., Chen, W., Jia, D., et al., 2020. The Effects of Fault Geometry and Kinematic Parameters on 3D Fold Morphology: Insights from 3D Geometric Models and Comparison with the Dushanzi Anticline, China. *Tectonics*, 39(2): e2019TC005713. https://doi. org/10.1029/2019tc005713

Liu, G., Li, J.Z., Zhu, M., et al., 2024. Controlling Factors and Favorable Area Prediction of Cretaceous Qingshuihe Formation in Gaoquan Area of the Southern Junggar Basin. *Earth Science*, 49(10): 3529—3546(in Chinese with English abstract).

Ma, D.L., Koyi, H.A., Yuan, J.Y., et al., 2019. The Role of Deep-Seated Half-Grabens in the Evolution of Huoerguosi-Manasi-Tugulu Fold-and-Thrust Belt, Northern Tian Shan, China. *Journal of Geodynamics*, 131:101647. https://doi.org/10.1016/j.jog.2019.101647

Pang, Z.C., Ji, D.S., Liu, M., et al., 2023. Jurassic-Cretaceous Oil-Gas Accumulation Conditions and Exploration Potential in the Thrust Belt at the Southern Margin of Junggar Basin. *Acta Petrolei Sinica*, 44(8): 1258—1273 (in Chinese with English abstract)

Peng, Z.Y., Wang, X., Graveleau, F., et al., 2024. Structural Interactions between Deep Mesozoic Strike-Slip Faults and Shallow Cenozoic Contractional Folds in the Northern Tianshan Foreland Basin (NW China). *Tectonics*, 43 (2): e2023TC007986. https://doi. org/10.1029/2023TC007986

Shao, Y., Wang, R.F., Zhang, Y.Q., et al., 2011. Strike-Slip Structures and Oil-Gas Exploration in the NW Margin of the Junggar Basin, China. *Acta Petrolei Sinica*, 32(6): 976－984(in Chinese with English abstract).

Song, Y., Pang, Z.C., Li, J., et al., 2025. Genesis and Source of Ultra-Deep Condensate Oil in the Central Part of Southern Margin of Junggar Basin. *Acta Petrolei Sinica*, 46(3):510－531 (in Chinese with English abstract)

Soto, R., Martinod, J., Odonne, F., 2007. Influence of Early Strike-Slip Deformation on Subsequent Perpendicular Shortening: An Experimental Approach. *Journal of Structural Geology*, 29(1): 59－72. https://doi.org/10.1016/j.jsg.2006.08.001

Suppe, J., 1983. Geometry and Kinematics of Fault-Bend Folding. *American Journal of Science*, 283(7):684－721. https://doi.org/10.2475/ajs.283.7.684

Suppe, J., C.D., Zhang, Y.K., 2004. Shear Fault-Bend Folding. In: McClay, K., ed., Thrust Tectonics and Hydrocarbon Systems. *Tulsa, American Association of Petroleum Geologists Memoir*, 82:303－323.

Sylvester, A.G., 1988. Strike-Slip Faults. *Geological Society of America Bulletin*, 100(11): 1666－1703. https://doi.org/10.1130/0016-7606(1988)1001666:ssf>2.3.co;2

Wang, F.J., Luo, M., He, Z.Y., et al., 2022. Late Mesozoic Intracontinental Deformation and Magmatism in the Chinese Tianshan and Adjacent Areas, Central Asia. *GSA Bulletin*, 134(11－12): 3003－3021. https://doi. org/10.1130/b36318.1

Wei, Z. Y., He, H. L., Sun, W., et al., 2020. Investigating Thrust-Fault Growth and Segment Linkage Using Displacement Distribution Analysis in the Active Duzhanzi Thrust Fault Zone, Northern Tian Shan of China. *Journal of Structural Geology*, 133: 103990. https://doi.org/10.1016/j.jsg.2020.103990

Windley, B.F., Allen, M.B., Zhang, C., et al., 1990. Paleozoic Accretion and Cenozoic Redeformation of the Chinese Tien Shan Range, Central Asia. *Geology*, 18(2): 128. https://doi.org/10.1130/0091-7613(1990)0180128:paacro>2.3.co;2

Xiao, W.J., Windley, B.F., Allen, M.B., et al., 2013. Paleozoic Multiple Accretionary and Collisional Tectonics of the Chinese Tianshan Orogenic Collage. *Gondwana Research*, 23(4): 1316－1341. https://doi. org/10.1016/j.gr.2012.01.012

Yang, D. S., Xiao, L. X., Yan, G. H., et al., 2019. Structural Characteristics and Petroleum Exploration in Sikeshu Sag, Southern Margin of Junggar Basin. *Xinjiang Petroleum Geology*, 40(2):138－144 (in Chinese with English abstract)

Yang, Y.T., Guo, Z.X., Luo, Y.J., 2017. Middle-Late Jurassic Tectonostratigraphic Evolution of Central Asia, Implications for the Collision of the Karakoram-Lhasa Block with Asia. *Earth-Science Reviews*, 166:83－110. https://doi.org/10.1016/j.earscirev.2017.01.005

Yang, Y.T., Song, C.C., He, S., 2015. Jurassic Tectonostratigraphic Evolution of the Junggar Basin, NW China: A Record of Mesozoic Intraplate Deformation in Central Asia. *Tectonics*, 34(1): 86－115. https://doi. org/10.1002/2014TC003640

Yang, W., Jolivet, M., Dupont-Nivet, G., et al., 2013. Source to Sink Relations between the Tian Shan and Junggar Basin (Northwest China) from Late Palaeozoic to Quaternary: Evidence from Detrital U-Pb Zircon Geochronology. *Basin Research*, 25(2): 219－240. https://doi. org/10.1111/j.1365-2117.2012.00558.x

Yuan, B., Wang, X., Wang, X.Q., et al., 2023. Characteristics of Structural Stratification and Zoning in Southern Junggar Basin and Its Significance for Oil and Gas Exploration. *Earth Science*, 48(10): 3946－3956(in Chinese with English abstract).

Zhu, M., Liang, Z.L., Wang, X., et al., 2023. Mesozoic Strike-Slip Fault System at the Margin of the Junggar Basin, NW China. *Journal of Structural Geology*, 175: 104950. https://doi.org/10.1016/j.jsg.2023.104950

Zhu, M., Yuan, B., Liang, Z.L., et al., 2021. Fault Properties and Evolution in the Periphery of Junggar Basin. *Acta Petrolei Sinica*, 42(9): 1163－1173(in Chinese with English abstract).

## 中文参考文献

卞保力,吴孔友,刘海磊,等,2024.准噶尔盆地四棵树凹陷及周缘地质特征与形成演化.断块油气田,31(4): 570－579.

陈伟,郝晋进,李世琴,等,2012.独山子背斜的几何学运动学数字模拟.地质科学,47(1):37－50.

邓启东,冯先岳,张培震,等,2000.天山活动构造.北京:地震

出版社.

管树巍,张朝军,何登发,等,2006.前陆冲断带复杂构造解析与建模:以准噶尔盆地南缘第一排背斜带为例.地质学报,80(8):1131−1140.

靳军,王飞宇,任江玲,等,2019.四棵树凹陷高探1井高产油气成因与烃源岩特征.新疆石油地质,40(2):145−151.

李本亮,陈竹新,雷永良,等,2011.天山南缘与北缘前陆冲断带构造地质特征对比及油气勘探建议.石油学报,32(3):395−403.

李本亮,管树巍,陈竹新,等,2010.断层相关褶皱理论与应用:以准噶尔盆地南缘地质构造为例.北京:石油工业出版社.

李学义,邵雨,李天明,2003.准噶尔盆地南缘三个油气成藏组合研究.石油勘探与开发,30(6):32−34.

刘刚,李建忠,朱明,等,2024.准噶尔盆地南缘高泉构造下组合油气成藏主控因素分析及有利区预测.地球科学,49(10):3529−3546.

庞志超,冀冬生,刘敏,等,2023.准噶尔盆地南缘冲断带侏罗系—白垩系油气成藏条件及勘探潜力.石油学报,44(8):1258−1273.

邵雨,汪仁富,张越迁,等,2011.准噶尔盆地西北缘走滑构造与油气勘探.石油学报,32(6):976−984.

宋永,庞志超,李静,等,2025.准噶尔盆地南缘中部超深层凝析油成因与油源.石油学报,46(3):510−531.

杨迪生,肖立新,阎桂华,等,2019.准噶尔盆地南缘四棵树凹陷构造特征与油气勘探.新疆石油地质,40(2):138−144.

袁波,汪新,王心强,等,2023.准噶尔盆地南缘构造分层分带特征及其油气勘探意义.地球科学,48(10):3946−3956.

朱明,袁波,梁则亮,等,2021.准噶尔盆地周缘断裂属性与演化.石油学报,42(9):1163−1173.