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六盘山盆地形成和改造历史及构造应力场演化

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提要:六盘山盆地夹于鄂尔多斯地块、青藏地块和阿拉善地块之间,在中国大地构造体系中处于独特的构造位置。基于野外变形分析与断层滑动矢量构造应力场反演,初步确定了六盘山盆地形成与构造演化历史。结果表明,六盘山盆地主要经历了早白垩世成盆过程和后期改造过程 2 个大的阶段。早白垩世早期,受到区域近 E-W 向引张应力作用而发生断陷,盆内沉积了一套巨厚的河湖相六盘山群;早白垩世晚期在 NW-SE 向挤压下,断陷盆地发生构造反转,局部地区褶皱回返,六盘山群发生不同程度的断裂和褶皱变形,继而盆地开始了长期的隆升剥蚀作用。晚新生代,受到印度—欧亚大陆碰撞产生的远程效应,六盘山盆地先后经历了 NE-SW 向和近 E-W 向挤压应力作用,盆地发生了强烈的褶皱和断裂变形,六盘山快速隆起。六盘山盆地构造应力场演化历史不仅为研究周缘地块的运动学和动力学提供构造地质依据,也对盆地油气勘探具有指导意义。

关　键　词:六盘山盆地;鄂尔多斯地块;早白垩世;构造应力场;断层滑动矢量

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六盘山盆地位于鄂尔多斯地块西南缘,跨越陕甘宁 3 省。盆地总体走向为 NW-SE 向,平面形态表现为向 NE 突出的弧形条带(图 1)。盆地内部发育一系列 NW-SE 向盆岭构造地貌,地势由北东向南西呈波浪状逐渐上升,平均海拔 2 000 m。在大地构造体系中,处于鄂尔多斯、青藏和阿拉善等 3 个地块汇聚部位,即所谓的"似三联点"[1],是鄂尔多斯周缘断裂系和青藏高原东北缘断裂系交汇、复合的地带[3,4]。盆地内发育一系列向东北凸出的弧形活动断裂带。自北东向南西,依次可分为牛首山—罗山断裂带、烟筒山断裂带、香山—天景山断裂带、海原—六盘山断裂带,其中,牛首山—罗山断裂带和海原断裂带是其主要边界断裂。

六盘山盆地无论其地理位置还是其大地构造属性均具有研究的特殊性和重要性,特别是针对与盆地形成和演化历史相关的构造应力场的研究,不仅对鄂尔多斯西缘油气勘探具有指导意义, 同时对探讨相邻地块相互作用具有重要意义。近年来,随着六盘山盆地油气田勘探开发工作的深入,先后有许多学者对盆地的地层、构造特征、演化历史及其动力学等进行了研究,取得了显著的进展[5~14]。但是对六盘山盆地构造应力场演化历史缺乏系统性研究,汤锡元[2]曾指出六盘山盆地形成于早白垩世,古近纪—新近纪复活,但缺乏详细的运动学证据。

1　六盘山盆地沉积充填序列

六盘山盆地基底由中元古界海原群变质岩系及寒武系和奥陶系灰岩、板岩、千枚岩、石英砂岩及石炭系砂砾岩等组成。盆地发育两套沉积盖层,其下为早白垩世六盘山群,其上为古近纪西宁群和新近纪甘肃群,缺失上白垩统和古新统[11~14]。六盘山群是袁复礼 (1925)在六盘山地区建立的,原称"六盘山系",后陕西区域地质调查队(1967)改称为六盘山群。六盘山群为一套巨厚的陆相红色建造,属河流-湖泊相沉积,自下而上划分为三桥组、和尚铺组、李洼峡组、马东山组和乃家河组。上部为河流-湖泊相沉积,岩性由紫灰色砾岩、砂岩和紫红色泥岩组成,发育韵律层理,可见波纹;下部为湖相沉积,岩性主要为紫红色、灰绿色砂质泥岩、砂岩、页岩、砾岩,灰黄色、蓝灰色泥岩、页岩、泥灰岩互层,夹灰岩、鲕粒灰岩、油页岩、石膏。底部主要为紫红色块状砾岩。六盘山群主要含腹足类、双壳类和植物化石等,属于早白垩世早期。该套地层广泛出露于六盘山、马东山和月亮山地区。

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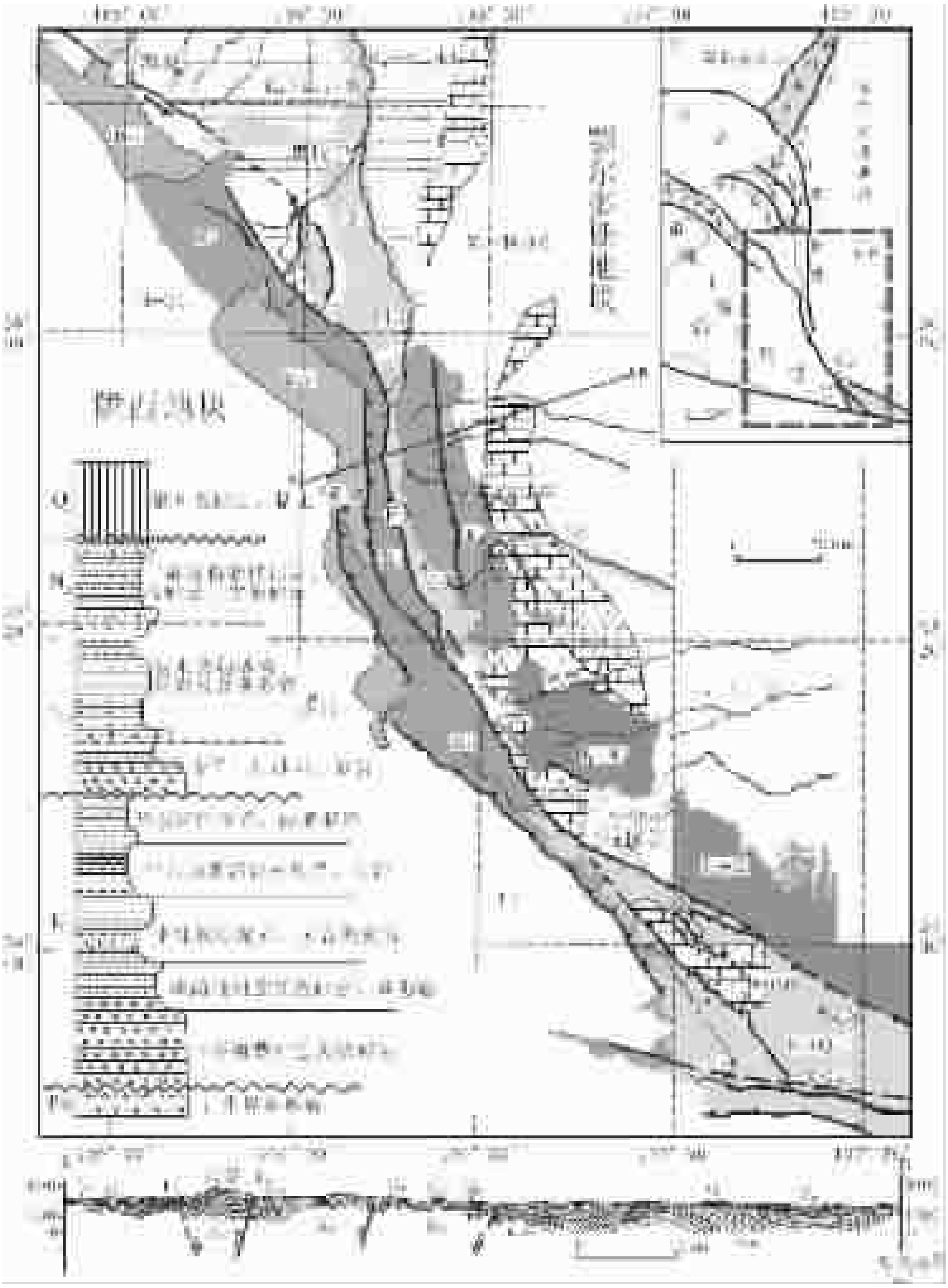

图 1　六盘山盆地地质简图及盆地沉积序列和构造横剖面(盆地沉积序列据 1:20 万海原幅地质图)

F_1—海原断裂；F_2—六盘山东麓断裂；Q_3—晚更新统；Ngn—甘肃群；N_2+Q_{2-3}—上新统和早、中更新统；$N+Q_{2-3}$—新近系、中上更新统；E_{2-3}—始新统、渐新统；K_1+N_2+Q—下白垩统、上新世、第四系；K_1—下白垩统六盘山群；$K_1+E_{2-3}+N$—下白垩统、始新统、渐新统、新近系；K_1l—李洼峡组；K_1zh—志丹群；∈—O—寒武系—奥陶系；Pz+Mz—古生界、中生界

Fig.1　Geological sketch map of the Liupanshan basin, sedimentary sequence and structural cross section (modified from the 1:200 000 Geological Map of Haiyuan)

F_1–Haiyuan fault; F_2–Liupanshan fault; Q_3–Upper Pleistocene; Ngn–Gansu Group; N_2+Q_{2-3}–Pliocene, Middle–Upper Pleistocene; $N+Q_{2-3}$–Neogene, Middle–Upper Pleistocene; E_{2-3}–Eocene and Oligocene; K_1+N_2+Q–Lower Cretaceous, Neogene, Quaternary; K_1–Early Cretaceous Liupanshan Group; $K_1+E_{2-3}+N$–Lower Cretaceous, Eocene, Oligocene, Neogene; K_1l–Liwaxia Formation; K_1zh–Zhidan Group; ∈–O–Cambrian–Ordovician; Pz+Mz–Paleozoic and Mesozoic

始新统、渐新统和新近系遍布盆地[12]。始新统和渐新统在本区分别对应寺子口组和清水营组，为山麓相–湖泊相堆积，岩性主要为砖红色、桔红色粉砂岩、泥岩，含灰白色钙质结核、石膏、灰岩等。新近系在本区称甘肃群，自下而上可划分为咸水河组和临夏组，为河流–湖泊相碎屑沉积，岩性主要为橙黄色、桔红色粉砂质泥岩，富含三趾马化石，底部为砂砾岩、砂岩、砾岩。

2　早白垩世古构造应力场与盆地演化

地壳在某一特定的演化阶段，构造应力场是相对统一的，其主应力方向基本保持不变，因此可以通过多种地质方法反演古构造应力场方向，其中较为常用的方法是通过观测断面上的擦痕滑动矢量来反演古构造应力场[15~17]。笔者主要通过野外对断裂几何学和运动学特征及地层变形特征的观测反演古构造应力场，并利用断层的切割关系及线理的叠加关系，确定断裂活动期次及次序，进而建立构造应力场的演化序列。这种构造解析方法已被成功地应用于中新生代构造应力场研究中[18~19]。反演古构造应力场所用的软件由法国南巴黎大学地质系地球动力学实验室研究开发[15]。

为查明白垩纪以来六盘山盆地构造应力场演化历史，笔者在六盘山盆地南缘对下白垩统六盘山群的地层变形和断裂滑动矢量进行了详细的野外观察和测量，取得了大量第一手野外资料。通过对这些资料进行计算机处理，并结合已有的区域应力场资料和线理叠加分析，反演了六盘山盆地白垩纪以来构造应力场和盆地形成演化历史。

2.1　早白垩世近 E–W 向引张应力场与伸展变形

盆地发育阶段的古构造应力场方向可以通过控制沉积的同沉积生长正断层来确定。通过对这些断层滑动矢量的观测，能够有效地确定盆地形成时期的主应力方向。盆地内部早白垩世六盘山群砂岩中同沉积生长正断层发育(图 2–A)，断层滑动矢量测量和反演结果指示近 E–W 向引张。六盘山群沉积明显受主边界断裂控制。在陇县以南地区，六盘山盆地受后期改造作用较弱，早白垩世断陷盆地没有明显反转。野外观察和测量表明，主边界断裂以正倾滑运动为主，其滑动矢量指示早期近 E–W 向、晚期 NE–SW 向引张(图 3)。这种伸展变形特征与六盘山盆地内沉积序列所记录的构造环境是一致的，六盘山群显示了下白垩统正旋回沉积序列，自下而上为砾岩、含砾砂岩、砂岩和泥岩(图 1)。因此，依据六盘山群同沉积断裂变形特征和古构造应力场反演结果，可以确定早白垩世六盘山盆地是一个受近 E–W 向引张应力场控制的断陷盆地(表 1，图 4~5)。

2.2　早白垩世晚期 NW–SE 向挤压与盆地反转

早白垩世晚期，构造应力体制发生转换，由引张转换为挤压，六盘山断陷盆地发生构造反转，湖盆萎缩。野外大量的断裂变形观测分析结果表明构造反转时期的挤压应力方向为 NW–SE 向(表 1，图 3)。受到斜向构造挤压，与盆地展布方向斜交的断裂表现为以挤压为主，而与盆地走向一致的断裂则具走滑性质(图 3)。位于隆德与泾源之间的六盘山主峰大关山，其两侧出露的六盘山群褶皱构造非常发育，褶皱枢纽轴向指示挤压应力方向为 NW–SE 向，与盆地内断裂滑动矢量反演结果一致(图 3)。该期挤压作用导致六盘山群普遍发生断裂褶皱变形(图 4~5)，盆地反转结束沉积，导致这一地区缺失上白垩统和古新统沉积。

3　晚新生代构造应力场演化与盆地强烈改造

晚白垩世至古新世时期，六盘山盆地与鄂尔多斯盆地一起处于隆升剥蚀状态，缺乏沉积记录。自始新世中晚期以来，

表 1　六盘山盆地南缘断层滑动矢量反演的早白垩世构造应力矢量及参数

Table 1　Early Cretaceous tectonic stress tensors and its parameters computed from fault slip vector measured in the southern Liupanshan Basin

观测点	经度	纬度	地层岩性	擦痕数	σ_1(az/pl)	σ_2(az/pl)	σ_3(az/pl)	R	应力场
H08	106° 25′ 07″	35° 12′ 19″	K_1h 砂岩、泥岩	6	195° /62°	342° /24°	78° /13°	0.248	近 E-W 向引张
H17	106° 39′ 32″	35° 08′ 21″	K_1l 泥岩夹砂岩	5	85° /66°	343° /05°	251° /23°	0.922	
LD04	106° 12′ 49″	35° 28′ 49″	K_1l 泥岩、砂岩	7	357° /71°	194° /18°	102° /05°	0.111	
LD04	106° 12′ 49″	35° 28′ 49″	K_1l 泥岩、砂岩	9	304° /10°	41° /35°	201° /53°	0.729	NW-SE 向挤压
P02	106° 12′ 49″	35° 28′ 49″	K_1s 砾岩	16	133° /02°	42° /03°	257° /87°	0.693	
L01	106° 38′ 45″	35° 04′ 54″	K_1l 砂岩、泥岩	5	122° /23°	319° /66°	214° /07°	0.693	
G04	106° 09′ 02″	35° 59′ 05″	K_1m 泥岩、页岩	4	144° /11°	240° /25°	32° /62°	0.292	
B07	106° 57′ 23″	34° 24′ 00″	K_1d 砂砾岩	7	301° /01°	210° /14°	34° /76°	0.810	
H17	106° 57′ 23″	35° 08′ 20″	K_1l 砂岩、泥岩	4	117° /14°	225° /50°	17° /37°	0.274	
LL46	107° 06′ 21″	34° 35′ 50″	$T_{2\text{-}3}$ 灰岩	8	115° /30°	324° /56°	213° /14°	0.946	

注：σ_1–最大主应力；σ_2–中间主应力；σ_3–最小主应力；az–倾伏向，pl–倾伏角；$R=(\sigma_2-\sigma_1/\sigma_3-\sigma_1)$；$K_1s$、$K_1h$、$K_1l$、$K_1m$ 分别表示下白垩统六盘山群三桥组、和尚铺组、李洼峡组和马东山组；K_1d 为下白垩统东河群；T_{2-3} 为中上三叠统。

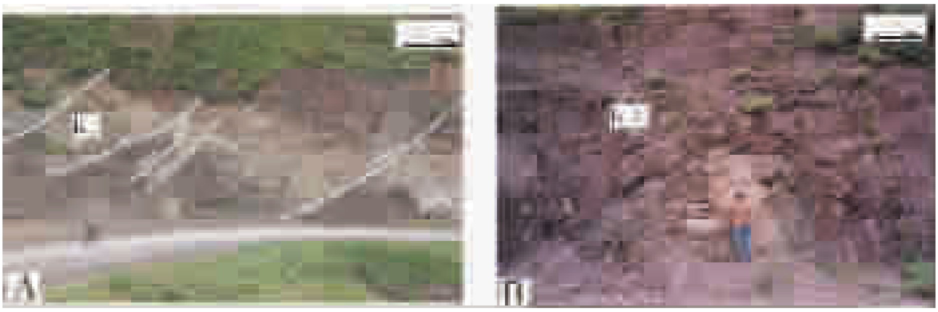

图 2　早白垩世六盘山群同沉积正断层与挤压构造变形
A—泾源县李洼峡组中发育同沉积断层，其上滑动矢量指示近 E-W 向引张；
B—泾源县西（观测点 J02）六盘山内部李洼峡组强烈变形，褶皱发育，其轴面指示 NW-SE 向挤压，K_1l 表示六盘山群李洼峡组

Fig.2　Synsedimentary normal faults (A) and compressive deformation (B) in the Early Cretaceous Liupanshan basin
K_1l– Liwanxia Formation of the Liupanshan Group; A–Synsedimentary normal faults developed in the Liwaxia Formation in Jingyuan County, and the slip vector above it denotes nearly E–W extension; B–Strong deformation and folding of the Liwaxia Formation inside the Liupanshan Group (observational point J02), west of Jingyuan County

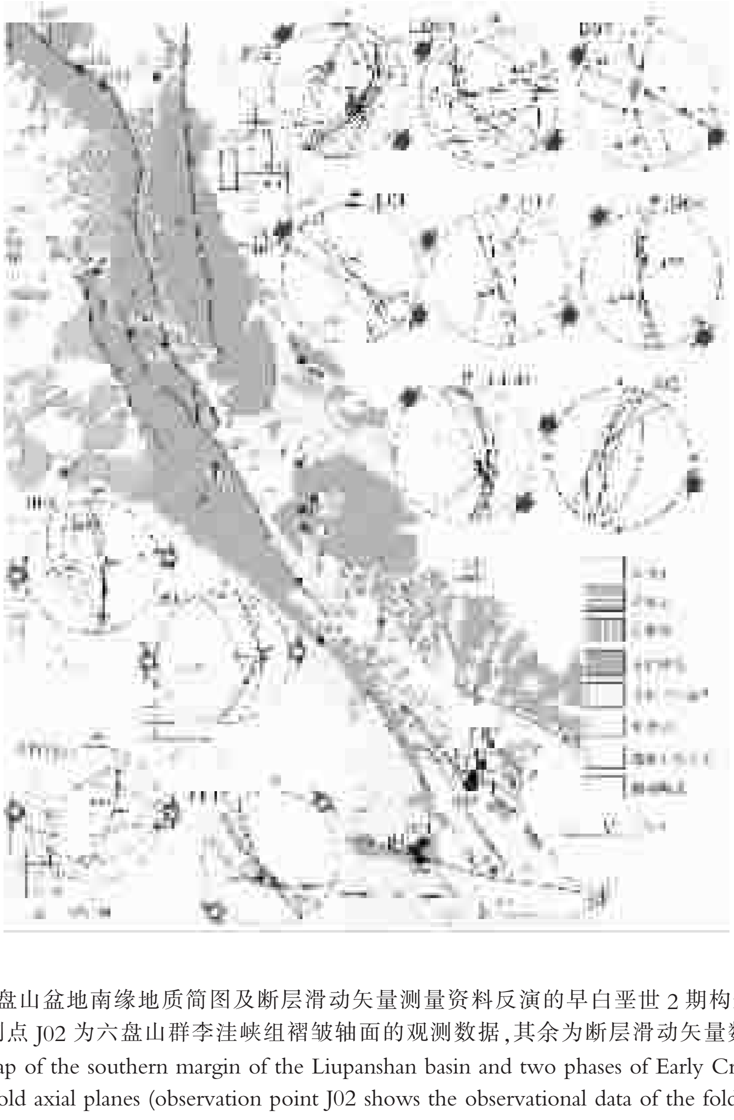

图 3　六盘山盆地南缘地质简图及断层滑动矢量测量资料反演的早白垩世 2 期构造应力场
（观测点 J02 为六盘山群李洼峡组褶皱轴面的观测数据，其余为断层滑动矢量数据）

Fig.3　Simplified geologic map of the southern margin of the Liupanshan basin and two phases of Early Cretaceous stress fields inversed from fault slip vectors and fold axial planes (observation point J02 shows the observational data of the fold axial planes of the Liwaxia Formation of the Liupanshan Group, and other points show the data of fault slip vectors)

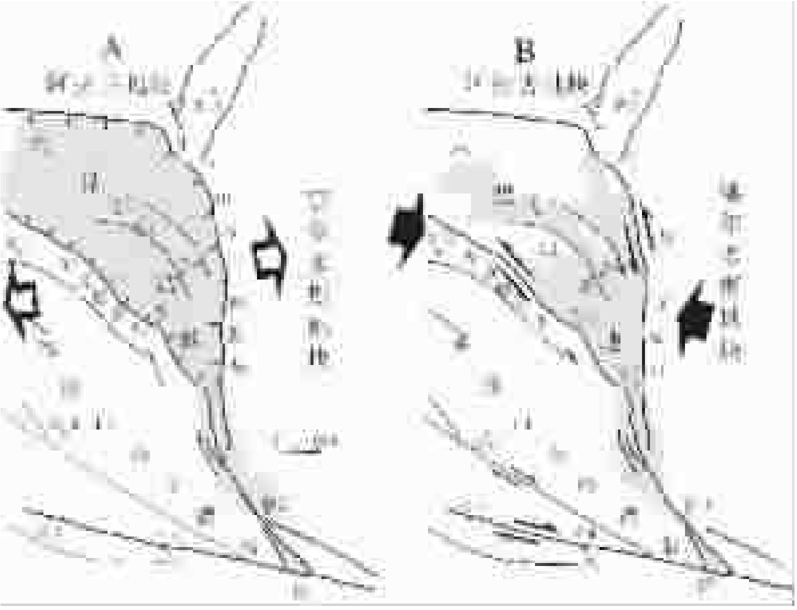

图 4 六盘山盆地早白垩世演化示意图

A—早白垩世早期盆地拉张断陷;B—早白垩世晚期盆地挤压反转

Fig.4 Schematic map showing the Early Cretaceous formation and evolution of the Liupanshan basin

A−Extension and downfaulting of the basin during the early Early Cretaceous; B−Compression and inversion of the Liupanshan basin near the end of the Early Cretaceous

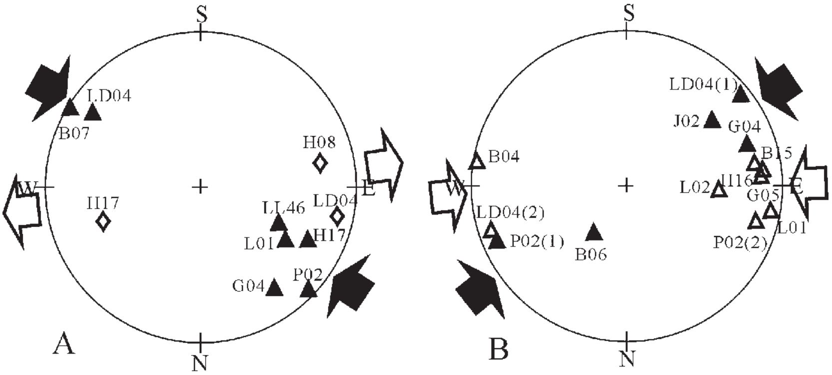

图 5 早白垩世(A)和晚新生代(B)主应力场主应力方向吴氏网投影

Fig.5 Stereonet presentation (Wulf net) of the principal stress directions in the Early Cretaceous (A) and Late Cenozoic (B) principal stress fields

受到喜马拉雅运动的影响,鄂尔多斯地块西北缘发生引张活动[20],六盘山盆地再次发生断陷并接受沉积,开始了始新世—渐新世山麓相–湖泊相和新近系甘肃群河流–湖泊相碎屑沉积。渐新世末期或中新世初期,盆地遭受一次构造挤压抬升,造成渐新统和中新统之间的角度不整合。六盘山盆地强烈的构造变动和构造地貌反转发生在中新世晚期以来的新构造运动时期[21]。

野外断层滑动矢量测量和反演结果,结合线理叠加分析(图 6)及已有区域应力场研究成果[22]表明,晚新生代以来,受印度板块碰撞俯冲作用影响,构造应力场先后以 NE−SW 向挤压及近 E−W 向挤压为主(表 2,图 5,图 7),其中近 E−W 向挤压应力场已被 GPS 观测结果所证实[23,24],应为最新发生的一次构造应力场。早期盆地受 NE−SW 向挤压作用导致盆地强烈变形,主边界断裂以逆冲活动为主,盆地内部发生褶皱变形,六盘山主体开始快速抬升。其后,应力场发生调整,主压应力方向转为近 E−W 向, 盆地主边界断裂发生左旋走

滑活动并兼具逆冲活动[21]，六盘山受挤压发生强烈逆冲活动而急剧隆升。

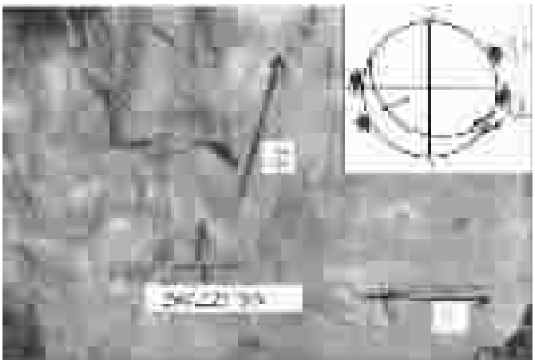

图 6　下白垩统六盘山群发育的 2 组叠加线理（观测点 LD04）

①指示 NE-SW 向挤压；②指示近 E-W 向挤压；NE-SW 向挤压早于近 E-W 向挤压

Fig.6　Two sets of superimposed lineation on a fault plane in the Lower Cretaceous Liupanshan Group (observational point LD04)

① NE-SW compression; ② nearly E-W compression. The NE-SW compression formed earlier than E-W compression

4　初步结论

通过对六盘山群、古近系和新近系变形及其断裂滑动矢量的测量和古应力反演结果表明，六盘山盆地形成与演化大致经历了早白垩世成盆阶段和晚新生代强烈改造阶段。在早白垩世成盆阶段，受到古太平洋板块向亚洲大陆俯冲作用产生的远程效应和对中国东部岩石圈减薄作用的响应，在近 E-W 向引张构造应力场作用下，六盘山断陷盆地沿块体边缘发育，盆内沉积了一套巨厚的河湖相六盘山群。六盘山盆地实际上是中国东部早白垩世断陷盆地的组成部分，它应是岩石圈引张伸展作用的产物[18]。早白垩世晚期构造应力场由近 E-W 向引张转为 NW-SE 向挤压构造应力场，这种转换可能与盆地周缘板块相互作用的调整有关。挤压的结果导致六盘山断陷盆地结束沉积，与鄂尔多斯盆地一起发生整体隆升并处于长期剥蚀状态，缺失了晚白垩世和古新世沉积。在晚新生代的改造阶段，尤其在青藏运动时期，受到印度—欧亚大陆碰撞产生的远程效应影响，六盘山盆地受到青藏高原强烈推挤，构造应力场方向先后发生转换，从早期 NE-SW 向转为晚期近 E-W 向挤压，六盘山盆地内部发生差异隆升，六盘山主体快速隆升，使构造地貌发生强烈的分异。

表 2　六盘山盆地南缘断层滑动矢量反演的晚新生代以来构造应力矢量及参数

Table 2　Late Cenozoic tectonic stress tensors and its parameters computed from fault slip vector measured in the southern Liupanshan Basin

观测点	经度	纬度	地层岩性	擦痕数	σ_1(az/pl)	σ_2(az/pl)	σ_3(az/pl)	R	应力场
LD04	106° 12′ 49″	35° 28′ 49″	K_1h 砂岩、泥岩	15	52° /3°	143° /19°	312° /70°	0.616	近 E-W 向引张
P02	106° 39′ 18″	35° 25′ 07″	K_1s 砾岩	8	247° /5°	153° /43°	343° /47°	0.700	
J02	106° 17′ 06″	35° 29′ 54″	K_1l 泥岩、泥灰岩	9	53° /20°	284° /61°	151° /21°	0.515	
G04	106° 09′ 02″	35° 59′ 05″	E_2 泥岩、页岩	4	72° /11°	183° /62°	337° /25°	0.028	
B06	106° 56′ 48″	34° 26′ 20″	K_1d 砂砾岩	4	214° /56°	328° /16°	67° /29°	0.939	
P02	106° 39′ 18″	35° 25′ 07″	K_1s 砾岩	10	105° /8°	15° /1°	279° /82°	0.786	NW-SE 向挤压
B15	107° 04′ 59″	34° 34′ 56″	K_1s 砂岩	6	81° /10°	351° /2°	247° /80°	0.102	
B04	106° 57′ 21″	34° 26′ 39″	K_1d 砂砾岩	5	279° /1°	12° /72°	189° /18°	0.660	
L01	106° 38′ 45″	35° 04′ 54″	K_1l 砂岩、泥岩	8	100° /2°	195° /64°	9° /26°	0.747	
L02	106° 41′ 56″	34° 51′ 26″	K_1s 砂砾岩	5	93° /29°	324° /49°	199° /27°	0.186	
G05	106° 04′ 59″	36° 01′ 08″	E_2 砂岩、泥岩	11	86° /8°	327° /75°	178° /13°	0.105	
H16	106° 38′ 50″	35° 07′ 07″	K_1l 泥岩、页岩	6	84° /7°	225° /80°	353° /6°	0.414	
LD04	106° 12′ 49″	35° 28′ 49″	K_1l 泥岩、砂岩	4	250° /3°	351° /73°	159° /17°	0.657	
LL46	107° 06′ 21″	34° 35′ 50″	$T_{2\text{-}3}$ 灰岩	4	157° /8°	247° /5°	8° /81°	0.160	

注：σ_1–最大主应力，σ_2–中间主应力，σ_3–最小主应力；az–倾伏向，pl–倾伏角；$R=(\sigma_2-\sigma_1/\sigma_3-\sigma_1)$；$E_2$ 表示始新统寺子口组，其他地层代号同表 1。

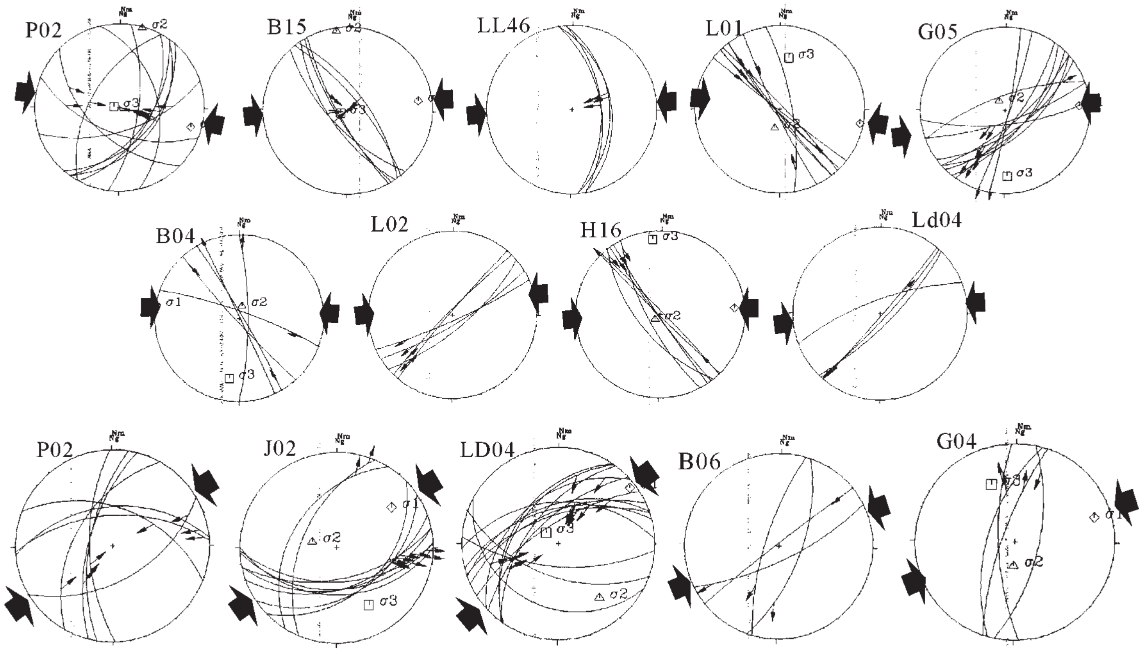

图 7 六盘山盆地南缘断层滑动矢量观测资料反演的晚新生代以来构造应力场

Fig.7 Late Cenozoic tectonic stress fields inversed from fault slip vectors on the southern margin of the Liupanshan basin

总之,六盘山盆地自早白垩世形成以来,经历了多期次的改造,其中在晚新生代构造运动对它的改造最为强烈,使盆地原有面貌发生巨大改变,影响了盆地含油气系统、油气赋存与成藏。因此,六盘山盆地油气勘探不仅要重视原形盆地的恢复,同时更要加强后期改造和油气晚期成藏过程的研究[25]。

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Formation and modification history of the Liupanshan basin on the southwestern margin of the Ordos block and tectonic stress field evolution

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Abstract: Sandwiched between the Ordos block and the Alxa and Qinghai-Tibet blocks, the Liupanshan basin is situated in a special tectonic location in the tectonic system of China. Based on the field analysis of deformation and stress field inversion from fault slip data, the formation and tectonic evolution history of the Liupanshan basin has been preliminarily established. The results show that the basin mainly experienced the stage of basin formation and the stage of modification in the late stage. During the earliest Cretaceous, under the nearly E-W extensional stress, the basin was downfaulted and a very thick fluvial-lacustrine sequence of the Liupanshan Group was deposited in the basin. Near the end of the Early Cretaceous, under the NW-SE compression, the Liupanshan basin was inversed with in fold inversion occurring in some places, and the Liupanshan Group underwent faulting and deformation to different degrees. Then the basin began the long-continued uplift and erosion history. During the late Cenozoic, under the far-field effects caused by India-Eurasia collision, the Liupanshan basin was strongly folded and faulted due to NE-SW compression and then due to E-W compressions and Liupanshan was uplifted rapidly. The evolutionary history of the Liupanshan basin and change in stress regimes during the Early Cretaceous provide constraints on the geodynamics of block interaction in this area and are of importance for oil and gas exploration.

Key words: Liupanshan basin; Ordos block; Early Cretaceous; tectonic stress field; fault slip vector

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