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中中新世中亚构造抬升驱动气候干旱化：以塔里木盆地东南缘江尕勒萨伊剖面为例

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提要:中亚前陆盆地地层中氧同位素和孢粉,以及黄土高原和北太平洋粉尘记录均表明,中中新世(16~12 Ma)中亚地区气候干旱化显著增强。然而,对其驱动机制的认识不一,包括全球降温、中亚地区的构造抬升、高海拔的“原西藏高原”的存在、副特提斯洋的退缩以及上述几者联合作用的结果。不过,全球降温(约14 Ma)、“原西藏高原”的抬升(≥40 Ma)、以及副特提斯洋退缩的时间(＞34 Ma)与中中新世中亚气候干旱化增强的时间(16~12 Ma)不一致。因此,它们可能是导致中中新世中亚干旱化增强的重要边界条件,或者是有利的辅助条件,但没起直接的主导作用。对塔里木盆地东南缘江尕勒萨伊剖面的前期研究结果表明,阿尔金山快速抬升始于16 Ma。在获得了磁性地层年龄的基础上,前人的碳氧同位素数据指示了16 Ma江尕勒萨依地区气候干旱化逐渐增强。鉴于同时发生,笔者把16 Ma气候干旱化增强归因于此时阿尔金山的快速抬升。从更广范围看,中中新世中亚发生了广泛的的地壳缩短变形和造山运动。对中国黄土高原的红粘土以及北太平洋粉尘沉积的多指标分析(磁化率、粒径、粉尘通量以及物源等)表明,中中新世中亚构造抬升及其引起的雨影效应是中亚气候干旱化增强的主因。

关 键 词:构造抬升;气候干旱化;江尕勒萨依;中亚;中中新世
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1 前 言

新近纪以来中亚地区干旱化不断增强,该地区成为气候变化研究的热点区域[1−18]。北太平洋钻孔、中亚干旱区内部及外围的风尘记录均显示, 中亚干旱格局可能从渐新世末就已形成[15,19−20]。中中新世~16 Ma以来,不同气候替代性指标研究表明中亚地区干旱化程度逐渐地或突然地增强。中亚地区许多山间盆地河湖相沉积碳氧稳定同位素研究表明在16~12 Ma期间同位素值发生了逐渐的或突然的正偏,这被解释为反映了气候干旱化的增强,如临夏盆地[2]、循化盆地[6]、柴达木盆地[18]、准噶尔和塔里木盆地[9,21]。来自宁夏固原寺口子剖面、柴达木盆地钻孔、以及准噶尔盆地金沟河剖面的孢粉数据也显示16~12 Ma中亚地区的气候干旱化增强[16,12,22]。北太平洋的粉尘通量在16 Ma左右明显增加[20]。目前,对16~12 Ma中亚气候干旱化增强的驱动机制存在着不同的认识,如中中新世全球降温[7−8,11,22]、中亚地区山脉快速抬升[6,9,16]、高海拔的“原西藏高原”[2]以及后述两者与副特提斯洋从中亚退缩的联合作用结果[18]。因此,针对这一科学问题,有

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必要进一步深入研究。

塔里木盆地东南缘江尕勒萨伊地区连续出露了超过3000 m厚的新近纪河湖相沉积[23−25]。该地区地层中蕴含了区域构造和古气候演变信息，是探究中中新世气候−构造相互作用的理想区域。前人已在江尕勒萨依地层进行了碳氧同位素研究[9]，但由于缺少地层时代，导致未能详细地讨论区域古气候演变情况，也未能深入地探讨气候变化的驱动机制。最近，笔者等对江尕勒萨依剖面开展了详细的磁性地层学和磁化率各向异性研究，获得了该地区新近纪地层时代及构造演变信息[23]。通过结合上述两者，不仅获得了塔里木盆地西南缘构造和古气候演变情况，而且可为探究中中新世中亚气候干旱化加强的驱动机制提供参考。

2　地质背景

江尕勒萨伊位于塔里木盆地东南缘，毗邻阿尔金山，海拔高度为1500~1800 m。构造上，该地区主要受北阿尔金断裂带控制。在卫星图上，北阿尔金断裂带呈现了明显的线性分布特征，北东−南西向延伸了约150 km（图1−A）[25]。北阿尔金断裂带主要由几条近似平行的、且几乎直立的断层组成。这些断层的活动使得位于南部的长英质片麻岩基底上覆于北部的中生代—新生代褶皱变形地层上。其中陡立的老江尕勒萨伊断层向南倾斜，把南部的中生代地层（侏罗系和白垩系）上覆于西北部的新生代地层（图1−B）。侏罗纪地层主要是由砾岩、砂岩、泥岩、以及较厚的煤层组成的河湖相沉积，而白垩纪地层主要为红色泥岩和砂岩的互层[25−26]。新近纪地层主要为河湖相的砂岩、泥岩，以及冲积扇相的砾岩组成（图2~3），岩性总体下细上粗[25]。详细的岩性描述和沉积相划分参见文献[23,25]。沉积学分析表明新近纪地层主要来源于地层南部的前寒武系基岩[25]。江尕勒萨伊新近系地层厚度超过3000 m，实测剖面（图1）厚度为2750 m，地层以70º~85º的倾角向北西倾斜（图1−C, 2）[23]。磁性地层学研究表明实测江尕勒萨伊剖面的时代为22.3~11 Ma，剖面中大套砾岩始现于约16 Ma[23]。

3　数据结果

剖面碳氧同位素数据来自老江尕勒萨依剖面[9]，其向西距离江尕勒萨依剖面约5 km。两剖面岩性一致，尽管不同研究者测量的地层厚度有一定的差别（图3），但通过地层对比，可获取江尕勒萨依剖面的碳氧同位素数据。采集的样品主要是地层中的碳酸盐沉积，包括古土壤、湖相碳酸盐、砂岩中的碳酸盐胶结物等。在排除了后期成岩和碎屑组分后，碳酸盐样品被认为是原生的[9]。

剖面分别包括146个 $\delta^{18}O$ 和 $\delta^{13}C$ 数据（图3）。$\delta^{18}O$ 值介于15.6‰~24.2‰，平均值为19.9‰。$\delta^{13}C$ 值介于−8.9‰~1.5‰，平均值为−2.4‰。从 $\delta^{18}O$ 和 $\delta^{13}C$ 值随深度、或时间演变图可以看出，两者均显示了两阶段变化特征。从22.3 Ma到16 Ma，尽管数值波动较大，但总体上两者基本不变。然而，从16 Ma到11 Ma，$\delta^{18}O$ 从17.7‰逐渐地增至23.1‰，$\delta^{13}C$ 值从−5.3‰逐渐地增至0。

4　讨　论

4.1　中中新世气候干旱化逐渐增强

来自湖相、河流相、冲积扇相、以及古土壤中的碳氧同位素记录已被广泛地用于破译青藏高原北部的古气候和古环境演化历史，而且一般认为 $\delta^{18}O$ 值的正偏反映了气候干旱化的增强[2−3,6,9,18,21,27]。江尕勒萨依剖面的氧同位素记录显示从16 Ma开始其值开始逐渐地增加（图3），可能指示了江尕勒萨依地区此时气候干旱化逐渐增强[9]。

$\delta^{18}O$ 值和 $\delta^{13}C$ 值的相关性分析也支持16 Ma以来此地区气候干旱化逐渐增强的观点。一般认为开放型湖泊碳酸盐的 $\delta^{18}O$ 值和 $\delta^{13}C$ 值的相关性极弱，而封闭湖泊碳酸盐的 $\delta^{18}O$ 值和 $\delta^{13}C$ 值的相关性较强（$\geqslant 0.7$）[28]。对江尕勒萨依剖面而言，从22.3 Ma到16 Ma $\delta^{18}O$ 值和 $\delta^{13}C$ 值的相关性极弱（r=0.11），而从16 Ma到11 Ma两者相关性明显增强（r=0.77）（图4）。然而，沉积相分析表明16 Ma前后沉积环境并不是由开放湖泊突变为封闭湖泊[23,25]。因此，碳氧同位素的相关性分析可能表明16 Ma前江尕勒萨依地区的水体处于开放状态，而后由于周缘山脉的造山运动导致区域水量锐减，使原来开阔的大型湖泊变为数个封闭的山间小湖泊。16 Ma前后沉积相由湖相和河流相突变为冲积扇相，这可能也反映了区域水量的缩减。

此外，中中新世中亚地区广泛地存在干旱化增

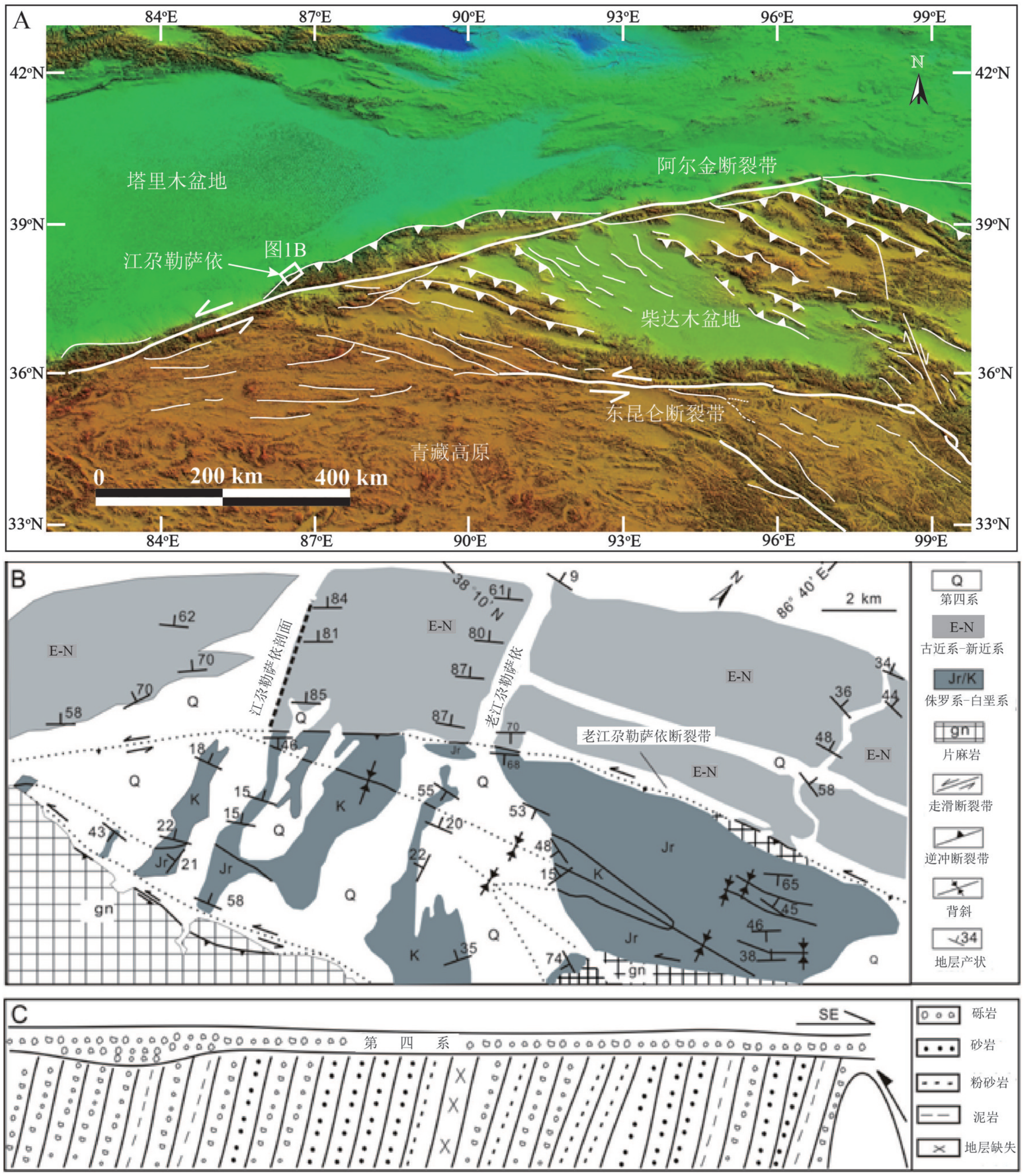

图1 青藏高原北部及天山周围DEM图(A);江尕勒萨依地质图(B);实测江尕勒萨依地层剖面图(C)

Fig.1 A−Digital elevation map of northern Tibet and its surroundings; B−Geological map of the Janggalsay section; C−Cross section of the observed Janggalsay section

强的事件。青藏高原东北缘临夏盆地湖相碳酸盐的 $\delta^{18}O$值在12 Ma前后发生了1.5‰(−10.5‰~−9‰)的正偏[2]。青藏高原东北缘循化盆地的古土壤和湖泊碳酸盐的 $\delta^{18}O$值从16 Ma到11 Ma发生了4.5‰的正偏[6]。柴达木盆地怀头他拉剖面碳酸盐沉积的 $\delta^{18}O$值从12 Ma到10.7 Ma发生了~2.5‰的正偏[18]。Kent−Corson等[9]在中亚地区许多山间盆地沉积剖面的碳氧同位素研究表明,新近纪期间碳氧同位素值均发生了明显的增加。Tang等[16]在天山北部金沟河剖面的孢粉研究表明,16.2 Ma~13.5 Ma藜蒿的

图2 江尕勒萨依剖面远景(A)及江尕勒萨依剖面陡立的河湖相地层(B~D)
Fig.2 Full view of the Janggalsay section(A), Sub−vertical fluvia−lacustrine deposits of the Janggalsay section(B−D)

比例明显增加。Miao等[11]对柴达木盆地西部新近纪河湖相沉积的孢粉研究表明，从约14 Ma开始喜热类和针叶类植被的比例减少，而旱生类植被的比例逐渐增加。青藏高原东北缘寺口子剖面的孢粉研究表明，14.25~11.35 Ma葎草和盐生藜科植被取代了蒿科植被，白刺属和麻黄的含量也明显增加[22]。上述现象均被认为反映了中中新世中亚地区气候干旱化增强。

4.2 中中新世中亚构造抬升驱动了气候干旱化

目前，中中新世气候干旱化增强的驱动机制存在多种可能，包括中中新世全球降温、青藏高原北部快速的抬升、高海拔“原西藏高原”的存在、副特提斯洋的退缩以及上述几者联合作用结果。下面就每种可能展开详细的讨论。

中中新世全球降温发生在约14 Ma [29]。然而，目前中亚地区记录到的干旱化增强的时间是16~12 Ma[2,6,9,11,16,18,21,22]，这个时间或早、或晚于14 Ma。此外，虽然降温通过蒸发富集可导致降水中的氧同位素正偏，但是约14 Ma全球逐渐降温的幅度却不足以解释氧同位素记录中的正偏幅度[2,6,9,18]。因此，虽然中中新世全球降温会增强中中新世中亚干旱化，但不是直接驱动要素。

“原西藏高原”(proto−Tibetan plateau) 由拉萨地块和羌塘地块组成，主要通过古新世—始新世地壳缩短和岩浆作用导致的地壳增厚作用形成[30]。同位素古高度研究表明“原西藏高原”在40 Ma以前已达到或接近现今的海拔高度[31−34]。另外，孢粉古高度研究给出了较低的估算值，但也认为在晚渐新世—早中新世“原西藏高原”的伦坡拉盆地的海拔高度已达到约3200 m[35]。数值模拟研究表明当青藏高原的海拔高度达到2000 m时，季风区的季节性降雨差异和中亚地区的干旱化程度会明显增强[36]。因此，青藏高原南部地区的高海拔是导致中亚干旱化的一个重要边界条件，但由于其抬升的时间大大早于中中新世，所以它也不是中中新世中亚干旱化增强的直接驱动因素。

副特提斯洋的退缩主要从两方面影响中亚地区气候干旱化：一是减少向中亚地区的水汽输送；二是大陆度效应的增强[36−37]。目前虽然对副特提斯洋从塔里木盆地向西退出的最后时间的认识不一致，但一般都认为早于34 Ma[38−40]。这个时间远早于中中新世，因此副特提斯洋的退缩也不是中亚中中新世干旱化增强的直接驱动因素。

对上述三者的分析表明，它们都是导致中亚地

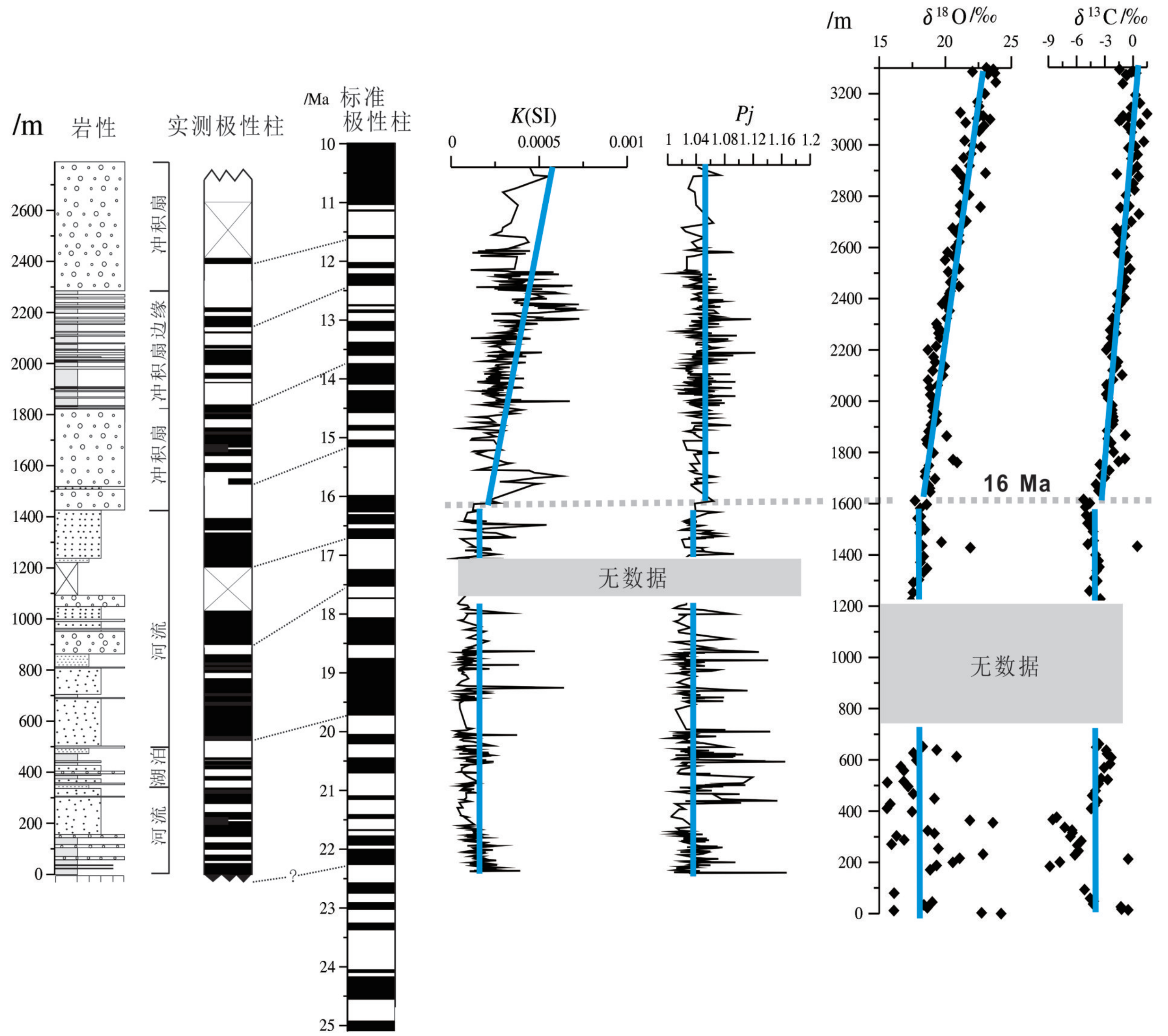

图3 江尕勒萨依剖面岩性柱、实测磁极性柱与标准极性柱对比、磁化率值(*K*)、磁化率各向异性度(*Pj*)以及$\delta^{18}O$和$\delta^{13}C$值
（$\delta^{18}O$和$\delta^{13}C$值源自老江尕勒萨依剖面[9]，其他数据来自笔者前期研究[23]；江尕勒萨依剖面和老江尕勒萨依剖面岩性一致，老江尕勒萨依剖面的16 Ma据岩性对比获得）

Fig.3 Lithology, magnetostratigraphic correlations to the GPTS, and magnetc susceptibility, anisotropy degree of magnetic susceptibility, $\delta^{18}O$ and $\delta^{13}C$ values as a function of depth
（The $\delta^{18}O$ and $\delta^{13}C$ data are derived from Kent−Corson et al. [9] and the other data come from the authors' preliminary studies [23]. The age of 16 Ma is obtained by lithologic correlations based on the knowledge that the Laojanggalsay and Janggalsay sections share the same lithology）

区中中新世干旱化增强的重要边界条件，或者是有利的辅助因素[12]，但没起直接的主导作用。

江尕勒萨依剖面的沉积相分析表明，在16 Ma沉积相由河湖相沉积突变为冲积扇相沉积，剖面中开始出现大套的粗颗粒的砾岩（图3）。磁化率值随时间变化总体上也显示了两阶段的演变特征（图3）。22.3~16 Ma尽管数值波动较大，但总体上基本不变。然而16~11 Ma，磁化率值总体上呈现逐渐增加的趋势。磁化率各向异性度(*Pj*)总体上也分两阶段，16 Ma后其值总体上突然增加（图3）。磁化率值和*Pj*值的突变均发生在16 Ma，被认为指示了阿尔金山的快速抬升[23]。鉴于地层中记录的阿尔金山的快速抬升时间和江尕勒萨依地区气候干旱化增强时间一致，笔者把气候干旱化增强归因于16 Ma阿

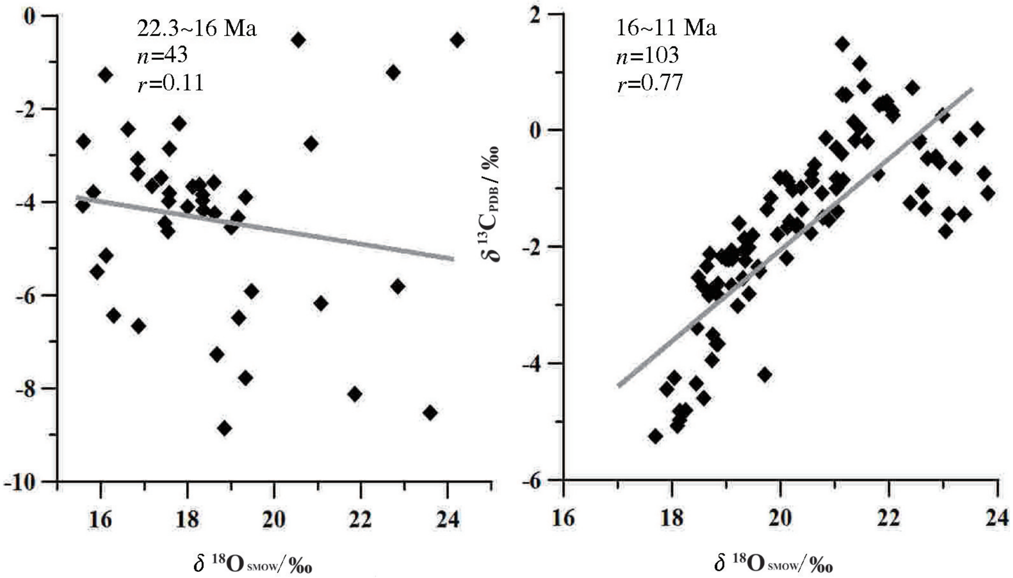

图4 16Ma前后 $\delta^{18}O$ 值和 $\delta^{13}C$ 值的相关性分析(原始数据来自参考文献[9]；n 为样品数量，r 为相关系数)
Fig.4 Correlation between $\delta^{18}O$ and $\delta^{13}C$ values for the intervals between 22.3 and 16 Ma, and between 16 and 11 Ma, espectively. (The data are sourced from Kent-Corson et al. [9]; n and r are number of carbonate samples and regression coefficient, respectively)

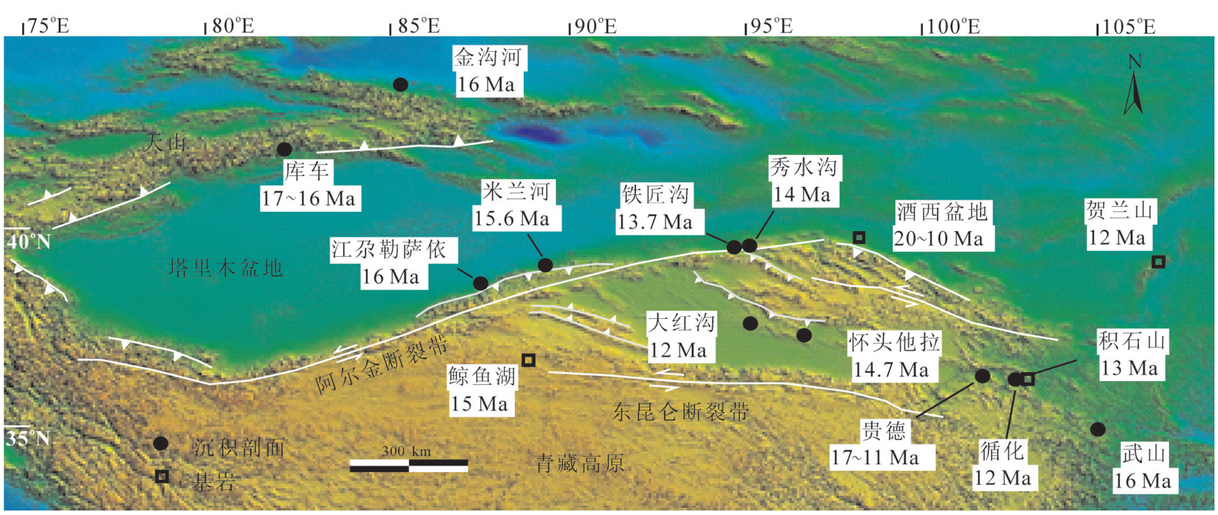

图5 青藏高原北部和天山南北前陆盆地中中新世构造抬升事件
黑点表示磁性地层剖面位置；黑框代表低温热年代学研究位置。磁性地层剖面包括库车[41]、金沟河[42-43]、米兰河[44]、铁匠沟[45]、秀水沟[46]、江尕勒萨依[23]、大红沟[47]、怀头他拉[48]、贵德[49]、循化[6,50]和武山[51]；低温热年代学研究位置包括酒西盆地[52]、鲸鱼湖[53]、贺兰山[54]和积石山[55]
Fig.5 DEM map of Asia, showing places on the northern Tibetan Plateau and its surroundings, where there is evidence of initiation or reactivation of crustal shortening in the middle Miocene
Black dots indicate deformations were registered in sedimentary sections, whereas black boxes suggest that deformations were recorded in bedrocks. The sedimentary sections include Kuche basin[41], Jingou river[42-43], Miran river[44], Tiejianggou[45], Xiushuigou[46], Janggalsay[23], Dahonggou[47], Huaitoutala[48], Guide[49], Xunhua[6,50] and Wushan[51]. The localities of bedrocks, sampled for low-temperature thermochronometry, include Jiuxi basin[52], Jingyu[53], Helan shan[54] and Jishi shan[55]

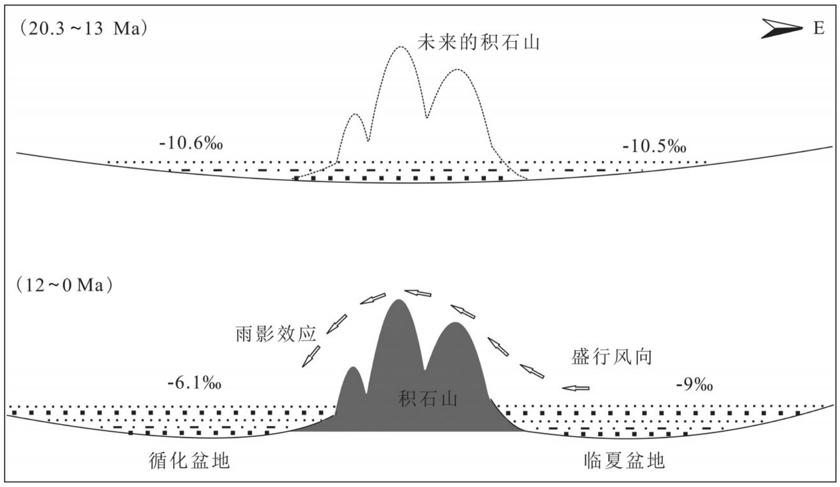

图6 13 Ma积石山的构造抬升引起临夏盆地和循化盆地地层中δ¹⁸O值的差异(也即雨影效应)
(数据来源于Hough et al.[6])
Fig. 6 Rain shadow effect illustrating the discrepancy in average $\delta^{18}O$ values of carbonate samples in the Xunhua and Linxia basins as a result of tectonic uplift of Jishi Shan at 13 Ma
(The data are sourced from Hough et al.[6])

尔金山的快速抬升。

从青藏高原北部和天山南北前陆盆地等更广的范围来看,中中新世中亚发生了广泛的地壳缩短变形和造山运动(图5)。沿着阿尔金断裂带分布的山间盆地中广泛地发育了中中新世同构造粗颗粒砾岩沉积[23,44−46]。低温热年代学(磷灰石U−Th/He和磷灰石裂变径迹)研究表明中中新世青藏高原北部经历了快速剥露事件[52−53,54−55]。青藏高原北部和天山南北前陆盆地开展了大量的综合研究,包括磁性地层学、沉积学、岩石磁学以及物源等分析,结果表明青藏高原北部和天山周围地区在中中新世发生了广泛的地壳缩短和造山运动[6,41−43,47−48,49−51]。少数研究对青藏高原北部的古高度进行了估算,如约15 Ma青藏高原北部和东部地区可能已经上升到1000~1400 m的平均海拔高度[44,56];地层中叶蜡氢同位素研究表明从15 Ma到10.4 Ma柴达木盆地可能抬升了约2100 m[57]。图6显示了由于中中新世(约13 Ma)积石山的快速抬升,引起了雨影效应(rain shadow effect),导致山脉东西两侧的临夏盆地和循化盆地地层中$\delta^{18}O$值的差异[6]。因此,山脉抬升导致的雨影效应可能是造成区域气候干旱化的主要原因。

此外,风尘沉积证据也支持抬升导致了中亚地区气候干旱化的观点。风尘沉积包括中国黄土高原的黄土和红粘土,以及北太平洋中的粉尘沉积,一直被认为是中亚地区气候干旱化的可靠指标[5,20]。来自黄土高原西部的红粘土的磁化率、粒径和粉尘沉积速率,以及北太平洋的粉尘通量在16~14 Ma显著增加(图7)[5,20,58]。对中北太平洋的亚洲粉尘沉积使用钕同位素进行物源分析表明约15 Ma开始来自青藏高原北部的碎屑贡献增大,被认为指示了中中新世青藏高原北部的快速抬升[59]。最近的风蚀模型和物源分析(碎屑锆石U−Pb测年)表明,柴达木盆地和青藏高原北部其他地区可能是黄土高原粉尘的主要源区[60−61]。

5 结论与展望

据笔者的前期研究、文献中已有的碳氧同位素数据以及综述中亚地区的构造−古气候研究,获得以下2点认识:

(1)鉴于地层中记录的阿尔金山的快速抬升时间和江尕勒萨依地区气候干旱化增强时间一致,本文倾向于把中中新世气候干旱化增强归因于16 Ma阿尔金山的快速抬升。

(2)全球降温(约14 Ma)、“原西藏高原”的抬升(≥40 Ma)以及副特提斯洋退缩的时间(>34 Ma)均与中中新世中亚气候干旱化增强的时间(16~12 Ma)不一致,因此前三者均不是后者的直接驱动因素。中中新世中亚地区构造抬升引起的雨影效应可能

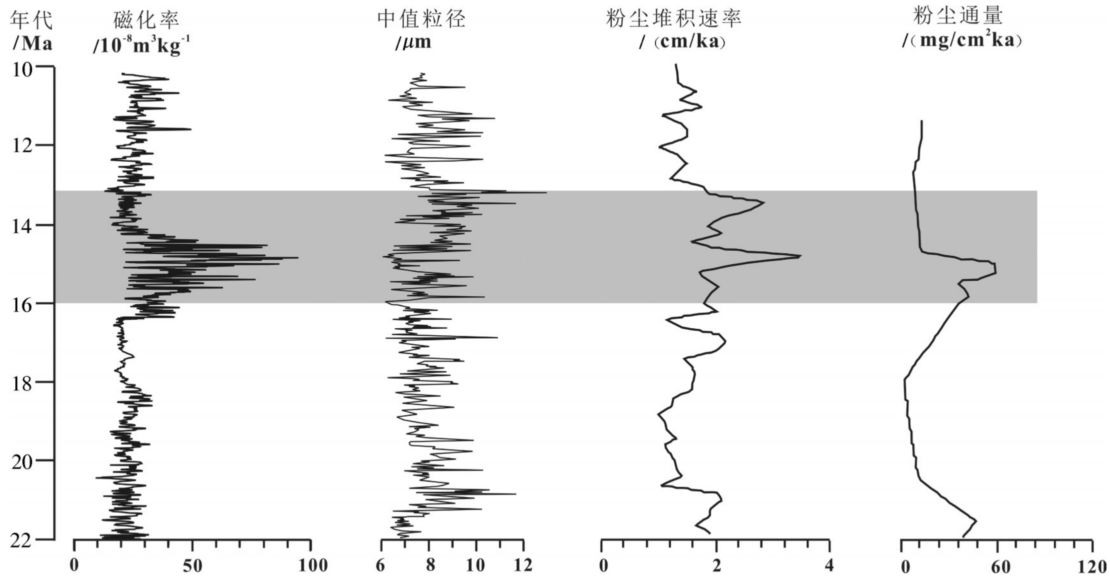

图7 黄土高原秦安剖面磁化率[5]、中值粒径[58]、粉尘堆积速率[58]以及北太平洋的粉尘通量[20]随时间演变情况

Fig.7 Magnetic susceptibility, median grain size, and dust accumulation rate of the Qinan eolian sequences on China's loess plateau [5,58], and the eolian flux deposited in the northern Pacific Ocean from 22 to 10 Ma[20] as a function of age

是中亚气候干旱化增强的主因。

不过，本文更多的是用定性的方法论证"中中新世中亚抬升驱动了气候干旱化"这一观点，因此需要更多的证据来支持这种观点，比如中亚地区，特别是青藏高原北部古高度重建证据。青藏高原北部构造抬升的幅度信息是古气候模拟研究中重要的边界条件。然而相对于高原南部的古高度重建研究，高原北部这方面的研究十分匮乏。因此，将来很有必要加强青藏高原北部的古高度重建研究。

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Uplift−driven climatic aridity during the middle Miocene: A case study of the Janggalsay section, southeast Tarim Basin

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Abstract: Numerous studies suggest an intensification of climatic aridity during the middle Miocene (16−12 Ma) based on oxygen isotopes and pollen records in the foreland basins of the Central Asia, eolian deposits in China's loess plateau and eolian flux from the northern Pacific Ocean. However, controversies remain existent as to the driving mechanisms that have dominated the intensifying aridity, which include global cooling, the rapid uplift of the central Asia, the attainment of a threshold elevation in southern Tibetan Plateau and the retreat of the Paratethys from the central Asia. As the timing of intensification of climatic aridity (16−12 Ma) is inconsistent with the onset age of global cooling (about 14 Ma), that of the attainment of a threshold elevation in the southern Tibetan Plateau (⩾40 Ma), and that of the retreat of the Paratethys from the central Asia (＞34 Ma), the authors hold that these three factors may be only important boundary conditions or favorable auxiliary conditions for the intensification of aridity during the middle Miocene. Previous studies of the Janggalsay strata on the southeast margin of the Tarim Basin indicated that the rapid uplift of the Altun Mountains occurred at ~16 Ma. Combined with new magnetostratigraphic ages, the published carbon and oxygen isotopes data suggest a gradual intensification of climatic aridity since ~16 Ma for the Janggalsay area. Based on the simultaneous relationship, the authors attribute the middle Miocene increasing aridity to the rapid uplift of the Altun Mountains. Viewed from a broader context, the Mid−Miocene crustal shortening deformation is extensively existent within Central Asia. The multi−proxy analysis of red clay in China's loess plateau and eolian dust from the northern Pacific Ocean indicates that the middle Miocene tectonic uplift and accompanying rain shadow effect acted as the major mechanism in driving the increased aridity in Central Asia.

Key words: tectonic uplift; climatic aridity; Janggalsay; Central Asia; middle Miocene

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