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前陆盆地陆源沉积序列的特征与成因机制*

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摘　要: 前陆盆地接受的来自毗邻造山带的陆源碎屑沉积是盆山耦合关系研究的主要对象之一。这套沉积通常具有以下 3 个方面的特征: ①在地层剖面中，前陆盆地陆源沉积序列呈向上变粗的趋势，其成因有多种可能，包括源区构造隆升、侵蚀卸载导致的盆地基底均衡回弹、气候变化、岩性变化等; ②构造抬升导致的粗粒相沉积事件与构造事件之间存在时滞，其大小取决于源区基岩剥露速率、侵蚀与搬运条件、沉积区距造山带构造变形前缘之间的距离等因素; ③粗粒相沉积在前陆盆地内的分布具有穿时性。重视这些方面的研究，有助于得出有关前陆盆地及毗邻造山带演化的合理结论。
关　键　词: 前陆盆地; 构造活动; 气候变化; 时滞; 穿时性
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1　前　言

前陆盆地通常被定义为介于造山带前缘与相邻克拉通之间的沉积盆地[1~3]，一般认为至少包括周缘前陆盆地、弧后前陆盆地以及陆内前陆盆地(或称再生前陆盆地[4]，碰撞后继盆地[5]等)等成因类型[6]。由于富含丰富的油气资源，前陆盆地一直受到石油地质界与构造地质界的普遍关注。特别是在过去的 20 年，关于前陆盆地的分类[7~11]、成因与变形机制[2~18]、沉积充填特征与演化[9~23]等方面的研究已取得了很大进展，这不仅在很大程度上促进了前陆盆地油气资源的开发[6,9]，而且也加深了对相邻造山带演化过程的理解[3,6,24]。

尽管每一类前陆盆地的沉积特征及其演化阶段存在差异[6]，例如，周缘前陆盆地通常发育的深水复理石沉积[25]在陆内前陆盆地中一般不发育，但这些盆地一般都发育一个向上变粗的陆源沉积序列[26~30]。前陆盆地的这套陆源碎屑沉积主要来自与其毗邻的造山带，其记录着造山带的隆升与剥露历史，并受盆地基底沉降机制与沉积分布模式等因素的影响，因此是开展盆山耦合关系研究的主要对象之一。然而，由于前陆盆地向上变粗的陆源沉积的成因具多解性，粗粒相沉积事件与源区构造剥露存在时滞，砾岩沉积在盆地中的分布具有穿时性等，因此，在进行具体的前陆盆地陆源沉积序列研究中，特别是在解读岩相变化与沉积速率变化的地质意义时，需要综合分析相关地质证据，才能得出关于前陆盆地与相邻造山带演化的正确认识。

2　前陆盆地向上变粗的陆源沉积序列

许多前陆盆地发育有厚层的陆源沉积。在纵剖面上，这套沉积常表现为向上变粗的特征[26~30]，地层序列的下部为细粒沉积，向上逐渐变粗至砾岩相沉积; 在横剖面上，则成楔状产出[2]，即沉积中心一般靠近造山带一侧，向克拉通方向沉积厚度逐渐减小。周缘前陆盆地(如喜马拉雅前陆[31]、伊朗的扎

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格罗斯前陆[32])、弧后前陆盆地(如台湾前陆[25]、安第斯前陆[29])、陆内前陆盆地(如祁连山北缘[33~39]、天山南北两麓[40~49])的陆源沉积序列都呈现出向上变粗的特征。天山作为远离大陆边缘的陆内再生造山带,其南北两麓发育典型的陆内前陆盆地(或称再生前陆盆地[6]),所接受的厚达 ~5 km 的新生代沉积总体上表现出向上变粗的特征。在天山北麓,下第三系地层以粉砂岩、泥岩甚至灰岩等细粒沉积为主[50],而上第三系地层岩性明显变粗,特别是上新世以来的地层,为厚层的磨拉石建造(图 1),这一岩相变化指示沉积环境发生了明显改变,由水下环境逐步过渡为气下环境[40,48]。

3 向上变粗的陆源沉积的成因多解性

前陆盆地陆源沉积序列呈向上变粗的趋势,其成因机制主要有以下几种解释。①源区构造隆升与侵蚀[29,34~39,48,51](图 2a)。在构造稳定期,源区相对低的地势导致物理风化较弱,碎屑产率较低,河流搬运作用弱,前陆沉积区主要接受泥岩、粉砂岩等细粒沉积;在构造活跃阶段,随着基岩山地隆升,地势增高,河流搬运动力增大,侵蚀作用随之增强,前陆沉积地层岩性相应变粗(图 2a)。在祁连山北缘的酒西盆地南缘(属陆内前陆盆地[6]),岩相变化与沉积环境演化揭示青藏高原隆升自 13 Ma 以来经历了稳

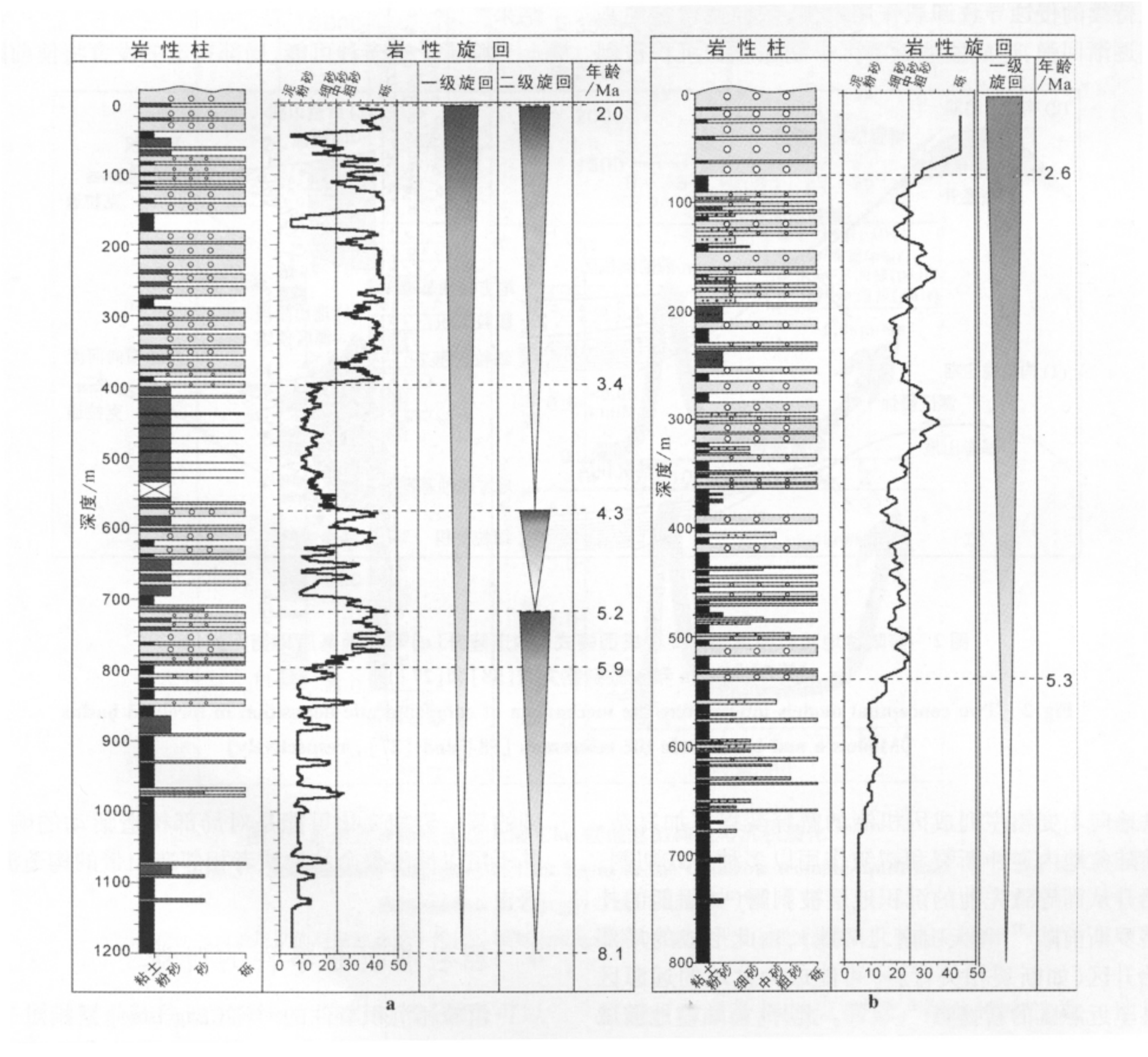

图 1　天山北麓向上变粗的晚新生代陆源沉积

Fig. 1　Late Cenozoic coarsening-upward terrigenous deposits in the northern Tianshan foreland

a: 实测塔西河剖面; b: 实测奎屯河剖面(磁性地层年龄据文献[49])

a: the Taxi He section; b: the Kuitun He section (magnetostratigraphic ages are from the reference [49])

定期(>8.26 Ma)、持续逐步快速隆升期(8.26 ~ <4.96 Ma)和急剧强烈阶段性隆升期(>3.66 ~0 Ma)等 3 个阶段[5]。在祁连山北缘的老君庙,玉门砾岩、酒泉砾岩和戈壁砾石层沉积分别对应于祁连山 3 次阶段性隆升[4,38,39]。②构造平静期源区持续的侵蚀卸载导致盆地基底均衡回弹[7,29,52](图 2b)。在不考虑气候、岩性等因素的前提下,Heller 等[7]运用挠曲模型分析将前陆盆地沉积充填过程划分为 2 个阶段。在造山阶段,构造负载致使盆地基底快速下沉,盆地沉降中心与沉积中心均位于前陆盆地靠造山带一侧,盆地近源区接受粗颗粒沉积,向克拉通方向沉积颗粒快速变细;在后造山阶段,源区持续的侵蚀导致卸载作用发生,从而使得盆地基底逐渐回弹,造成盆地近源区早期粗颗粒沉积被剥蚀、改造,并在盆地远源区再沉积(图 2b)。可见,在造山和后造山 2 个阶段所发育的粗粒相沉积,其构造意义明显不同,前者响应于源区构造活动,而后者则源于构造平静期侵蚀卸载导致的盆地基底均衡回弹。简单地将前陆盆地内单一地点的岩相变化归结为构造成因,可能会得出不合理的结论。③蚀顶过程中岩体抗侵蚀能力的变化或沉积区与造山带活动变形前缘间距离的变化也可能调整砂砾石产率及其在前陆盆地内的分布[2,30,53~54]。④增强的降水或更具侵蚀能力的气候条件也可导致沉积物增粗与沉积速率增大[5~57],2 ~4 Ma 以来全球范围内沉积颗粒变粗、沉积速率增大就被认为是全球气候变化的结果[7]。

除了上述多种可能,局部构造的发育将使前陆盆地向上变粗序列成因机制的解释变得更加复杂。前陆盆地内逆冲断裂和褶皱作用以多种方式切割、抬升从而导致先前的沉积地层被剥露(如伊朗的扎格罗斯前陆[2]和天山南北两麓),由此形成的局部抬升区(如断裂相关背斜)可能成为盆地的远源区甚至近源区的新物源[0,45,59]。此外,前陆盆地前展式的逆断裂作用过程还可能导致发育背驮式盆地(Piggyback basin)[2,45,60]。这些因素会造成前陆盆地沉积演化过程变得更加复杂[9,61],而且也使得正确解读前陆盆地沉积地层的热年代学年龄的地质意义变得更加困难[2]。因此,在盆地内单一地点观察到的某一岩相变化可能是对局部构造活动的响应,并不足以反映整个盆地或者相邻造山带的构造演化历史。

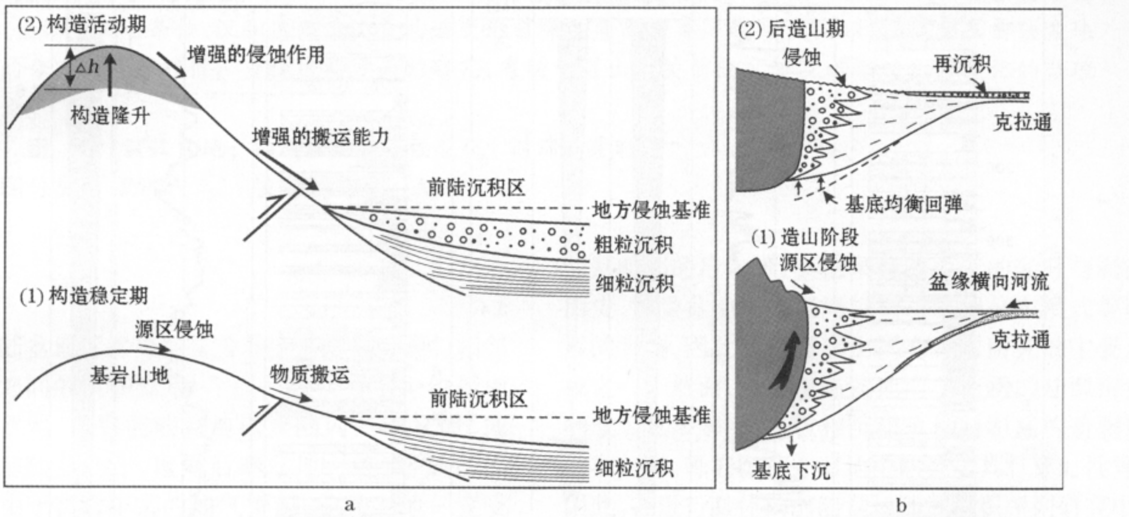

图 2 前陆盆地粗粒相沉积的 2 种成因模式: 构造隆升(a)与盆地基底均衡回弹(b)
(模式 a 和 b 分别据文献[8]和[27])

Fig. 2 Two conceptual models interpreting the mechanism of conglomeratic deposition in foreland basins
(Models a and b are from the references [8] and [27], respectively)

4 粗粒相沉积事件的时滞

粗粒相沉积事件的时滞(Lag time)是相对于源区基岩构造剥露而言的。Zeitler 等[3]、Cerveny 等[4]在研究巴基斯坦北部新第三系西瓦利克群时首先使用了时滞的概念。时滞指的是某一矿物从封闭温度的深度剥露到地表(这里只讨论构造意义上的冷却剥露,即构造剥露),并被搬运到沉积区所需

的时间,也就是矿物的热年龄与其沉积年龄之差[63,64]。因此,由源区构造隆升导致的粗粒相沉积事件与构造剥露之间的时滞[54,63]就包括2部分:基岩剥露到地表的时间与被侵蚀、搬运、沉积所需的时间。与剥露时间相比,侵蚀、搬运所需的时间可以忽略不计[65]。关于吉尔吉斯天山北麓 Chu 盆地盆山耦合关系的研究实例[41,42,66]很好地说明了盆地粗粒相沉积事件与源区构造事件间存在时滞。磁性地层研究(图 3a)显示,Chu 盆地新生代陆源沉积序列中砾石沉积开始于 ~4.0 Ma。裂变径迹(AFT)年龄和(U-Th)/He 年龄与高程的关系(图 3b)、天山剥蚀速率(图 3c)与构造逆冲速率(图 3d)均表明毗邻吉尔吉斯天山新生代构造活动始于 ~11 Ma。这些年龄说明,砾石初始沉积时间与源区构造活动时间相差约 7 Ma,即砾石沉积与源区主要构造事件间的时滞。Heermance 等[45]对中国西南天山喀什前陆盆地进行系统研究后同样发现粗粒相砾石沉积滞后构造事件。

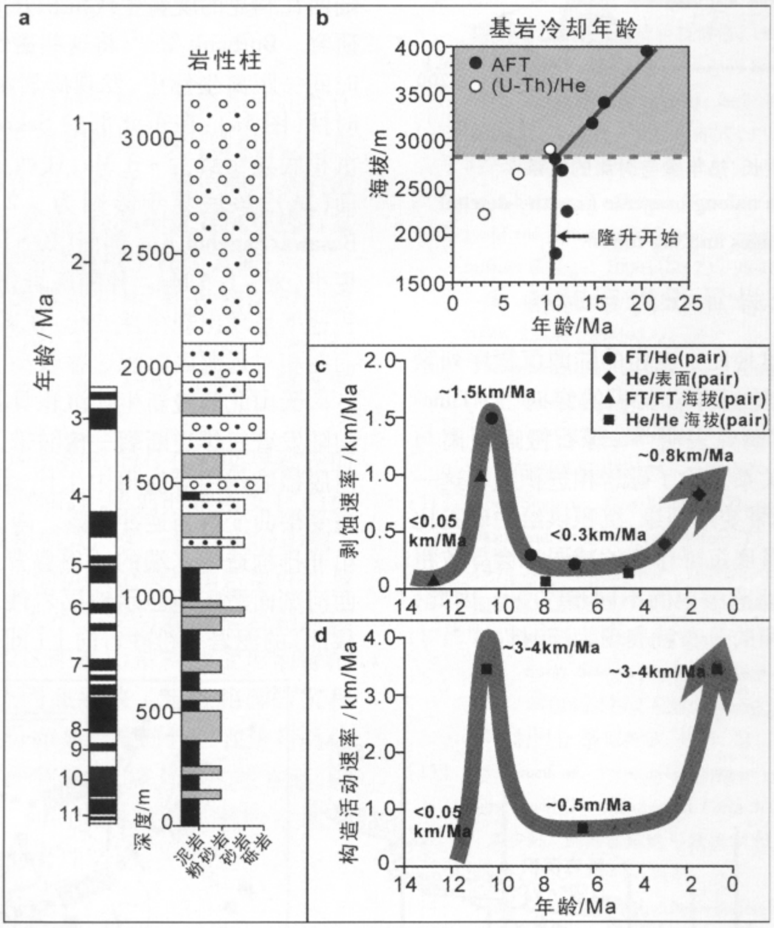

图 3　吉尔吉斯斯坦天山北麓 Chu 盆地盆山构造与沉积演化[41,42,66]

Fig. 3　Sedimentary responses in Chu Basin to the Cenozoic tectonic uplift and exhumation in Kyrgyz Tian Shan[41,42,66]

a. Chu 盆地地层剖面与磁性地层年代; b. 毗邻天山基岩冷却年龄; c. 天山剥蚀速率; d. 构造活动速率

通过对前陆盆地沉积地层进行时滞分析,可以了解相邻造山带的演化状态[67~69]。汇聚型造山带的演化可归结为 3 个阶段[70,71],即生长期(造山带持续隆升,剥蚀量不断增加)、稳态(地形稳定、剥蚀稳定)、衰退期(地形和剥蚀速率均降低)。对于造山带处于哪一个演化阶段,可以通过对盆地沉积地层进行时滞分析加以确定。在盆地中选取一地层柱,从下往上、由老至新对各层位进行裂变径迹定年,如果各层的时滞由下而上减少,则表明造山带仍处于生长期;如果时滞由下而上增加,则表明造山带已处于衰退期;如果时滞恒定不变,则表明造山带已处于剥露稳态和侵蚀稳态(图 4)。

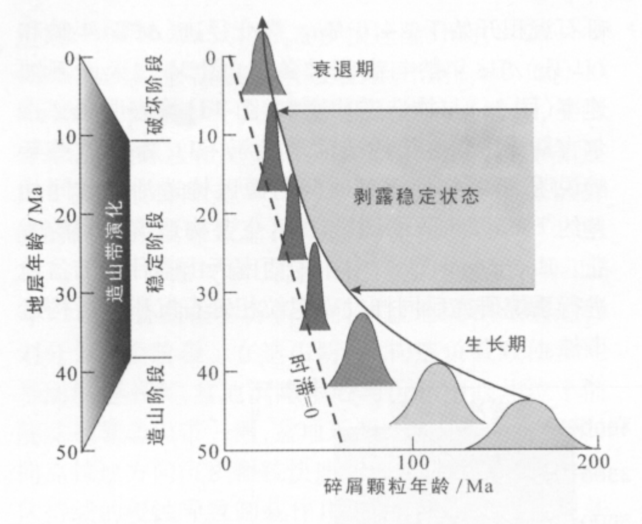

图4 造山带生长、热年龄与时滞的关系[67]

Fig. 4 Relationships among orogenic growth, detrital cooling ages and lag times[67]

5 前陆盆地砾岩沉积的穿时性

另一个与前陆盆地向上变粗的陆源沉积序列紧密相关的问题是粗粒相砾岩沉积的穿时性(Time-transgressive)。已有研究表明[4],砾石搬运距离与所需时间成正相关关系。除了砾岩相进积速率这一因素,随着远离造山带变形前缘,沉积供给中砾石比例的降低以及盆地基底沉降作用的减弱也会导致粗粒相沉积在整个盆地范围内的不同步[10,54]。因此,在整个盆地内砾岩相的分布就表现为穿时性[4,45],并具有与前陆盆地结构相关的复杂的空间几何特征[58,59]。从而,盆地内单一的砾岩年代数据并不能揭示整个盆地的演化历史[5]。如果砾石分布能与特定构造的发育与生长相联系,或者地壳缩短与砾石进积速率相匹配,那么就可以确定这些砾岩沉积代表着一个独立于气候影响的构造耦合[5]。

前陆盆地砾岩沉积具有穿时性的例子来自喜马拉雅前陆盆地。喜马拉雅前陆接受了厚度>10 km的新生代陆源沉积[72]。前人[73,74]曾对喜马拉雅前陆西瓦利克的晚新生代沉积开展了大量的磁性地层研究。Burbank等[72]将这些磁性地层研究剖面点在时间—距离坐标中,发现砾岩沉积表现出明显的穿时性(图5a):在东北部的Sakrana剖面(SK),砾岩沉积底界年龄为~3 Ma,往西南~15 km到Jari剖面(JA),该底界年龄则为~2.0 Ma,而在更南的Basawa/Sanghoi Kas剖面(B/S),砾岩沉积底界年龄更小,为~1.5 Ma。伴随砾岩相向前陆盆地进积,沉积速率呈现出规律性变化:在近源区沉积速率较大,而在相对远源区沉积速率较小[72](图5b)。

天山北麓晚新生代沉积具有相似特征。北天山前陆发育三排逆断裂—褶皱带,断裂扩展褶皱作用、滑脱褶皱作用等使得中生代、新生代沉积地层普遍遭受褶曲变形与逆冲剥露。南北流向的塔西河横切第Ⅱ排构造带东端的吐谷鲁背斜中部,所形成的塔西河剖面清晰地显示地层岩性由剖面底部(即背斜核部)的泥岩与粉砂岩向上(即前陆盆地方向)逐渐

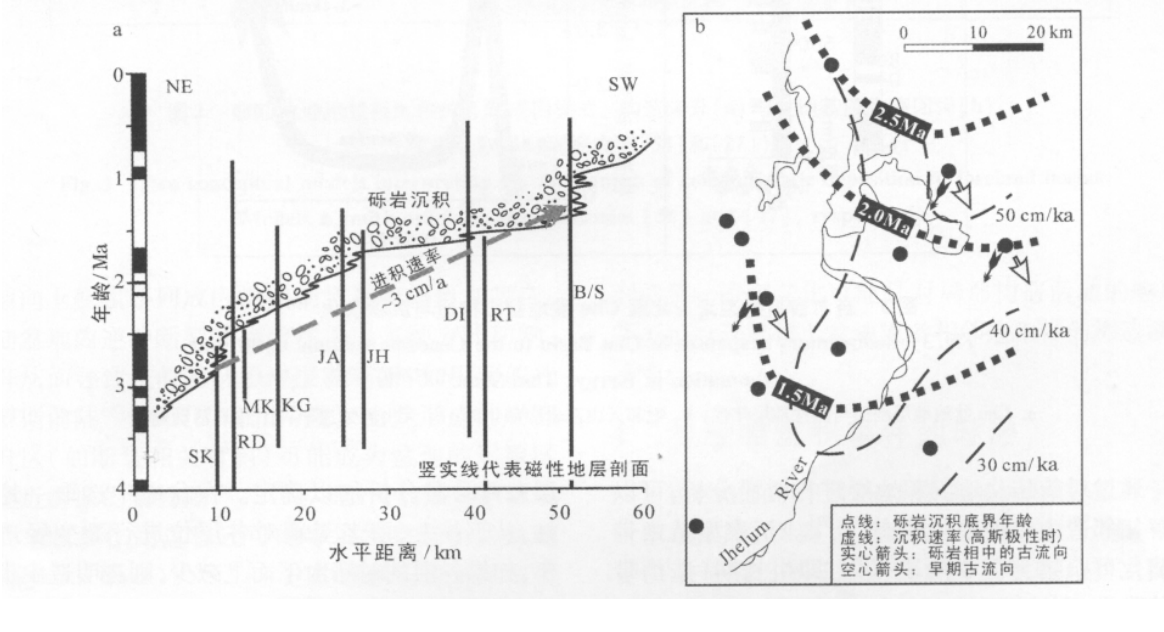

图5 喜马拉雅前陆盆地砾岩相沉积进积过程[72]

Fig. 5 Basinward-progradation of the conglomeratic deposits in the Himalayan foreland basin[72]

变粗为粗砂岩、砾岩(图 1a) 。磁性地层学研究限定塔西河剖面中连续厚层的砾岩沉积出现在 ~5.9 Ma。而在同处第Ⅱ排构造带西端的霍尔果斯背斜,连续、厚层砾岩沉积出现的时间则要早 ~1.6 Ma[75]。在位于更外围的第Ⅲ排构造带的独山子背斜,厚层砾岩沉积出现于 ~5.3 Ma[49]。天山北麓砾岩沉积的不同步可能缘于沉积作用过程在空间上(特别是横向上) 的变化,或者局部构造活动(即背斜生长) 的影响等因素。

6 结 论

前陆盆地陆源沉积是研究构造与沉积间相互作用的良好介质,其岩相、沉积速率、砾石组成成分、重矿物组合等的变化能在相当程度上揭示源区基岩的揭顶、剥露作用过程。然而,在利用这套沉积进行盆山耦合关系研究时,需要注意以下几个方面:

(1) 在前陆盆地陆源沉积中,粗粒相沉积的成因存在多种可能,包括源区构造隆升、构造平静期持续的侵蚀卸载导致的盆地基底均衡回弹、区域气候变化或岩性变化等。

(2) 前陆盆地内局部构造的存在可能导致先前沉积地层的改造,从而对沉积序列的垂向变化趋势(向上变粗) 和平面展布模式产生一定程度的影响。

(3) 源区构造事件的沉积记录与构造事件本身之间存在时滞,时滞的大小主要与源区基岩剥露速率、侵蚀速率以及沉积区距造山带构造变形前缘的距离等因素有关,这也因此导致了粗粒相砾岩沉积在整个前陆盆地中的分布具有穿时性。在进行具体的前陆盆地沉积序列研究时,重视上述这些方面,综合分析多种地质证据,有助于得出关于前陆盆地及相邻造山带演化历史的合理结论。

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Characteristics and Genesis of Terrigenous Depositional Sequences in Foreland Basins

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Abstract: Foreland basins, commonly defined as sedimentary basins lying between the front of the mountain chain and the adjacent craton, represent a well-established model related to tectonics and sedimentation. Many foreland basins are characterized by coarsening-upward terrigenous depositional sequences, within which the occurrence of conglomeratic deposits are commonly considered as indicating tectonic uplift of the source area. The conglomeratic deposition, however, could derive from several totally different scenarios such as hinterland tectonic uplift, isostatic rebound of basement because of erosional unloading, climate change affecting erosion rate, or changes in the lithologic resistance of the source area and so on. As for the tectonic uplift experienced in the source area, its onset timing can not be referred simply from the stratigraphic age of conglomeratic deposits due to the presence of time lag between the tectonic event experienced in the hinterland and the occurrence of conglomeratic deposits in the foreland depositional area. Consequently, the distribution of conglomeratic deposits in the whole basin is time-transgressive, that is, the basal ages of the conglomerate deposits from different locations in a foreland basin may be asynchronous. Given these above possibilities, it is suggested that all the available geological evidences are required to be integrated in the studies of terrigenous depositional successions of foreland basins in order to obtain a better understanding of their relationship between the evolution of the foreland basin and the adjacent orogenic belt.

Key words: Foreland basin; Tectonic events; Climatic change; Time lag; Time-transgressive.