新疆阿克苏地区前寒武纪蓝片岩构造—热演化史*

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Abstract Aksu Precambrian blueschist is located in Kepin uplift of northwestern margin of Tarim basin. In last twenty years, foreign and Chinese geologists have done lots of researches and got lots of new data on isotopic age. However, studies on dating are mostly aimed at determining the metamorphic age, while researches on thermo-tectonic evolution of blueschists are rare. This paper is devoted to discussing the following questions: 1. Whether the quick process of Aksu blueschists' rebound to earth surface has been recorded by fission track? 2. Whether Aksu blueschist has experienced reburial and re-exhumation after its exhumation? If it has, at what depth and when did it happen? 3. How has thermo-tectonic evolution of Aksu blueschist responded to the different tectonic events that have occurred at Tarim continental margins; of blueschist samples collected in Aksu for apatite fission track dating, six are between 107.5 ~ 62.5Ma, far less than blueschist face metamorphic age, and confined fission track lengths are between 10.46 ~ 12.12μm. According to previous researches, regional stratigraphic sequence and results of fission track thermal history modeling, we have basically reconstructed the thermo-tectonic evolution of Aksu blueschist: 1. Aksu blueschist rebounded to surface soon after its formation, and it probably had been under erosion during early Sinian, where there were no sedimentation until later Sinian; 2. Late Sinian strata were continuous. In the whole Paleozoic strata, only mid and upper Silurian, lower and mid carboniferous series were absent. The total thickness of early Sinian and Paleozoic strata were ca. ten thousand meters. Annealing was thorough, so fission track ages were reset; 3. Regional strata largely began to uplift during later Mesozoic, and fission track clock restarted; 4. Deposition began again in Paleocene, Aksu blueschist was heated to partial annealing zone. In Miocene Aksu blueschist was involved in re-exhumation once more, which was assumed to be in response to the result of far-field effects from India-Eurasia collision.

Key words Aksu; Blueschist; Fission track; Thermo-tectonic evolution

摘 要 阿克苏前寒武纪蓝片岩产于塔里木盆地西北缘的柯坪隆起区内。近二十年来,中外科学家对其展开了深入研究,并获得了许多新的同位素年龄资料,但是年龄测定大多偏重于确定蓝片岩的变质年龄,蓝片岩形成后的构造演化方面的研究尚显不足。为了讨论:1. 裂变径迹数据有没有记录到阿克苏蓝片岩形成后快速折返至地表的信息? 2. 阿克苏蓝片岩剥露以后是否经历过再次埋藏和剥露,再次埋藏的深度和剥露的时间? 3. 蓝片岩的构造热演化过程对大陆边缘不同构造事件的响应;采集阿克苏地区前寒武纪蓝片岩带样品进行磷灰石裂变径迹测试,6 个样品的年龄值介于 107.5 ~ 62.5Ma 之间,远小于高压变质年龄,径迹长度介于 10.46 ~ 12.12μm。结合前人研究成果、本区地层序列和裂变径迹热史模拟结果,大致重建了蓝片岩的热史演化:1. 蓝片岩形成(872 ~ 862Ma)后快速折返至地表,可能在整个早震旦世一直遭受剥蚀,到晚震旦世才重新开始接受沉积埋藏;2. 晚震旦世地层基本保持连续,整个古生代也仅缺失中、上志留统,中、下石炭统。至古生代末,早震旦世和整

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个古生代地层厚度已近万米。蓝片岩完全退火,年龄被重置;3. 中生代晚期区内地层普遍开始隆升,裂变径迹时钟重新开始计时;4. 古新世开始有沉积作用发生,样品接受埋藏增温至部分退火带,随后可能由于印度-欧亚板块碰撞的远程效应,中新世地层重新开始隆升剥露。

关键词 阿克苏;蓝片岩;裂变径迹;构造—热演化
中图法分类号 P588.344; P597.3

1 引言

裂变径迹定年是二十世纪60年代开始兴起的一种同位素年代学方法,近二十年来,随着磷灰石裂变径迹实验测试技术的逐步完善,各实验室对磷灰石退火行为研究的深入,各种退火模型的相继提出,计算机热历史模拟技术的实现,研究方法已由原来的定性分析发展到定量模拟,使裂变径迹方法在研究中展示出越来越强的活力(Ketcham *et al.*, 1999, 2000)。在测定火山岩的年龄、研究沉积地层的形成时代、制约断层的活动时间、计算山体的隆升速率等方面得到广泛应用并取得大量成果;除此之外,利用该方法,测定碎屑颗粒的年龄,研究沉积岩的物源,进而恢复可能的山体抬升与剥蚀、沉积物埋藏历史、盆-山耦合也是国际热点。

现今的磷灰石裂变径迹研究不仅提供了样品的年龄,也给出了反映热史的围限径迹长度,根据测得的单颗粒年龄和径迹长度数据,利用计算机结合地质事件进行模拟,可重现该样品的时间-温度演化轨迹,从而提供构造事件发生的年龄,从这点来说,磷灰石裂变径迹是一种不可或缺的热年代学方法,有其独到的发展空间(王瑜,2004;张志诚和王雪松,2004)。

阿克苏蓝片岩产于塔里木盆地西北缘的柯坪隆起区内。近二十年来,中外科学家对其展开了深入研究,并获得了许多新的同位素年龄资料(Nakajima *et al.*, 1990; Liou *et al.*, 1996; Chen *et al.*, 2004),但是年龄测定大多偏重于确定蓝片岩的变质年龄,蓝片岩形成以后构造演化方面的研究尚显不足。

本文首次给出了阿克苏地区前寒武纪蓝片岩裂变径迹的实验数据,目的是为了讨论:1. 裂变径迹数据有没有记录到阿克苏蓝片岩形成后快速折返至地表的信息? 2. 阿克苏蓝片岩剥露以后是否经历过再次埋藏和剥露,再次埋藏的深度和剥露的时间? 以及3. 蓝片岩的构造热演化过程对大陆边缘不同构造事件的响应。

2 地质背景

阿克苏地层单元属于柯坪塔格地层小区,该区位于塔里木盆地西北缘(图1),东起阿克苏、温宿一带,经印干、柯坪,西止于阿图什北,南以柯坪塔格南麓为界,北以皮羌—苏巴什一线以北与阿合奇小区相接。区内地层发育较齐全,唯缺失太古界,下震旦统,中、上志留统,中、下石炭统及中生代地层。下元古界为绿色片岩;上震旦统发育完整,上部为碳酸岩,下部以浅海—滨海相陆源碎屑岩为主,底部含底砾岩(图2);古生界为碳酸岩及陆源碎屑岩;新生界除阿克苏附近见有少量第三纪海相夹层外,一般均为陆相红层及松散的碎屑堆积(新疆维吾尔自治区地层表编写组,1981)。

阿克苏前寒武纪蓝片岩位于新疆阿克苏市西南约20km处,在其南端为震旦系上统苏盖特布拉克组和奇格布拉克组的砂岩不整合覆盖,在震旦系上统底砾岩中有白云母片岩和穿切了蓝片岩而被震旦系地层覆盖的没有经受高压变质的基性岩脉,因此阿克苏蓝片岩是迄今为止世界上所发现的最典型的前寒武纪蓝片岩(图3)。阿克苏蓝片岩为一完整的蓝片岩—绿片岩系列,主要由强烈片理化的绿泥石—黑硬绿泥石石墨片岩、黑硬绿泥石—多硅白云母片岩、绿片岩、蓝片岩及少量石英岩、变铁质岩组成,其峰期变质温度在300~

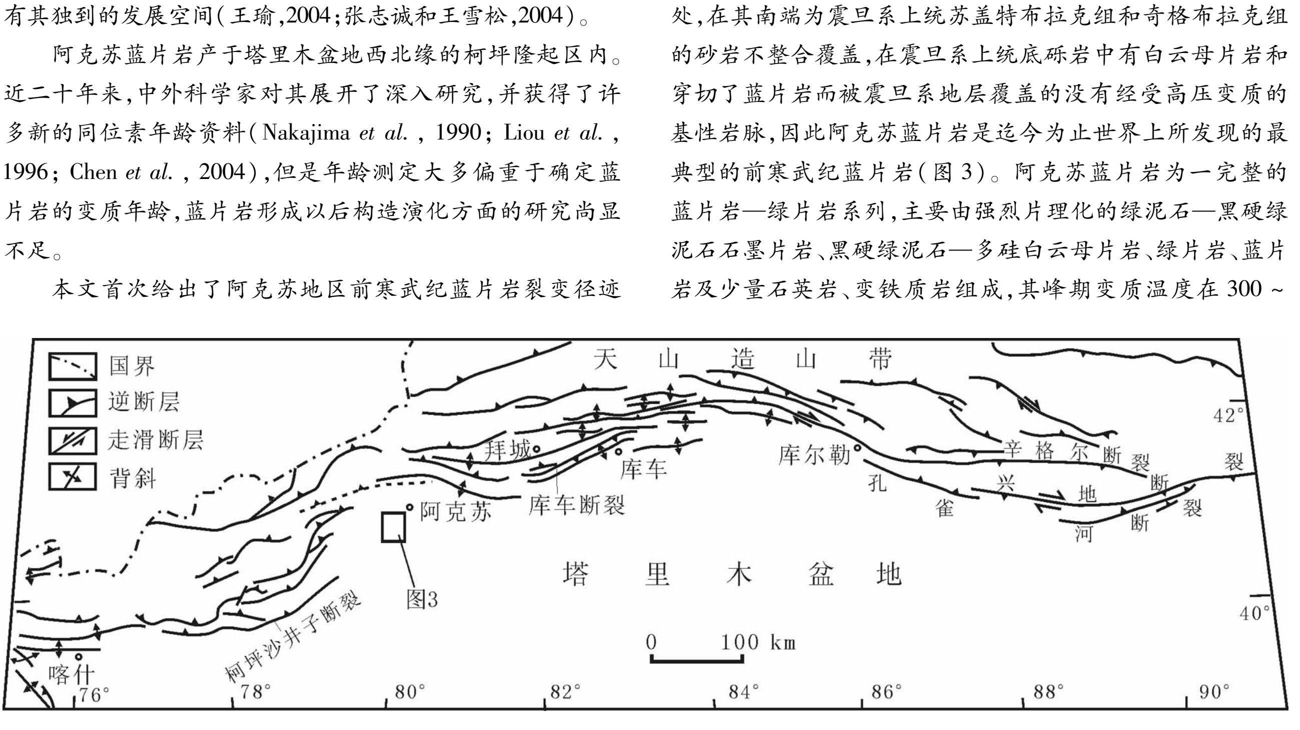

图1 塔里木盆地北缘断裂与褶皱的展布特征(据 Yin *et al.*, 1998 略修改)

Fig. 1 Distributions of faults and folds in northern Tarim (modified after Yin *et al.*, 1998)

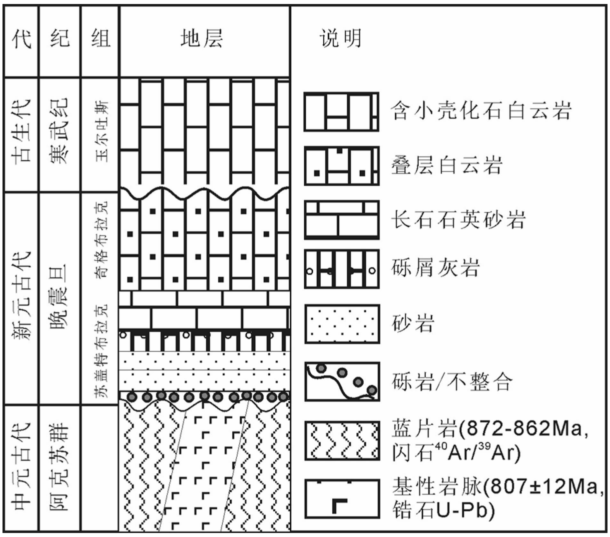

图 2　阿克苏地区地层柱状图(据 Chen *et al.*, 2004 修改)

Fig. 2　Stratigraphic column of the Aksu area (modified after Chen *et al.*, 2004)

400℃,岩层呈北东-南西方向分布,宽约 20km,长约 40km,褶皱变形强烈。阿克苏蓝片岩的变质年龄一直是焦点问题,这不仅关系到阿克苏蓝片岩是不是前寒武纪蓝片岩,更是关系到现今板块机制是否在前寒武纪就已出现。早期基础地质研究已确定阿克苏蓝片岩为前寒武纪蓝片岩(熊纪斌和王务严,1986;董申保,1989;Liou *et al.*, 1989;肖序常等,1990),九十年代发表了 718±22Ma、710±21Ma 的多硅白云母 K-Ar 年龄,698±26Ma、714±24Ma 的 Rb-Sr 等时线年龄和 754Ma 的青铝闪石 $^{40}Ar/^{39}Ar$ 年龄(Nakajima *et al.*, 1990;Liou *et al.*, 1996),这些年龄跟早期基础地质研究推断的 >800Ma 稍有差距。相比之下,最近发表的 872±2Ma 的青铝闪石 $^{40}Ar/^{39}Ar$ 年龄,862±1Ma 的蓝闪石 $^{40}Ar/^{39}Ar$ 年龄显然更为准确(Chen *et al.*, 2004)。

在阿克苏蓝片岩带中没有发现榴辉岩、斜长角闪岩等偏高温的变质岩石,说明蓝片岩不是由这些岩石退变形成的,而是洋壳俯冲变质形成的(姜文波和张立飞,2001)。一般认为高压低温变质作用发生于俯冲板块一侧,作为高压低温变质作用的产物,蓝片岩是洋壳快速俯冲消减的结果,其变质时代代表着板块强烈活动时期。872~862Ma 的闪石 $^{40}Ar/^{39}Ar$ 年龄,代表着蓝闪石片岩的形成年龄,即高压变质作用发生在新元古代早中期,因此阿克苏保存下来的蓝闪石片岩代表新元古代早期末古洋壳快速俯冲消减的产物,也就是说在新元古代早中期塔里木板块内或周围存在过俯冲、碰撞作用。

阿克苏蓝片岩通常被认为是中朝—塔里木板块和哈萨克斯坦板块间俯冲发生高压变质形成的(肖序常等,1992;Liou *et al.*, 1996)。虽然现在越来越多的证据表明新元古代板块构造机制和显生宙以来的板块机制相同,但这主要是

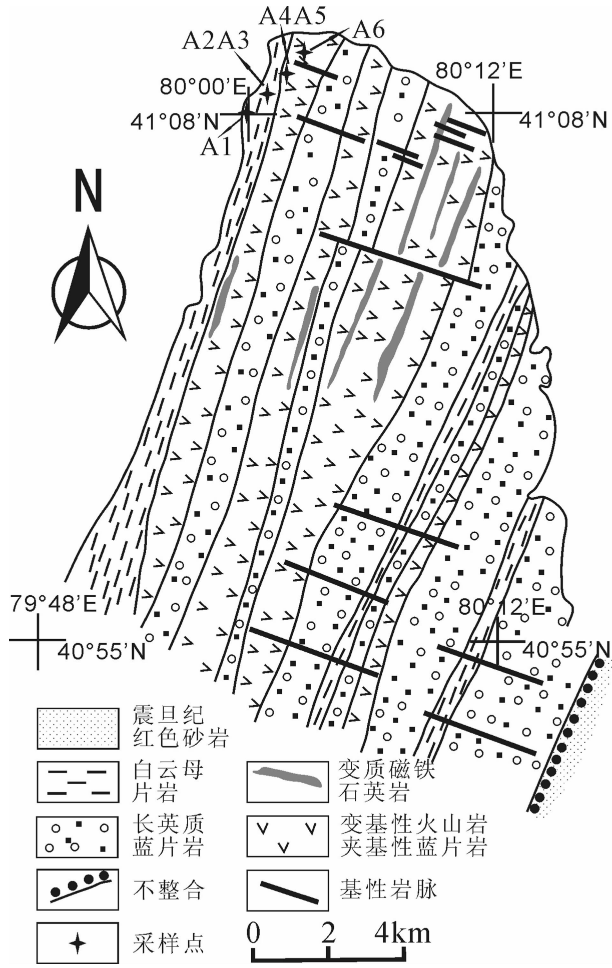

图 3　阿克苏前寒武纪蓝片岩分布地质简图(据张立飞等,1998;Chen *et al.*, 2004 修改)

Fig. 3　Simplified geological sketch map of Aksu Precambrian buleschist (modified after Zhang *et al.*, 1998; Chen *et al.*, 2004)

根据目前所发现的元古代蛇绿岩来确定的,Moores (1993)认为这是由于在新元古代洋壳厚度开始变薄的缘故。阿克苏蓝片岩相变质磁铁石英岩中迪尔闪石的发现进一步证明至少在新元古代,现今的板块构造体制就出现了,板块俯冲发生高压变质,然后快速折返使得高压相系的变质岩石得以保存,所以新元古代可能是地球演化过程中重要的转折阶段(张立飞等,1998)。

阿克苏高压变质带在构造程序上是连续的。北部的镁铁质片岩夹变燧石岩的岩石组合与化学成分均显示出与洋壳顶部类似(熊纪斌和王务严,1986)。而变沉积岩的岩石组合既可以形成稳定大陆边缘,也可以形成洋底,但是由于变质变形破坏了沉积构造,以及露头有限等原因,很难准确恢复它们形成时的古地理环境。迄今为止,尚未发现有混杂岩和蛇绿岩与阿克苏高压变质带共生,因而很难重建该区古构造格局及演化(肖序常等,1992)。

3 裂变径迹实验方法

本次研究的6个裂变径迹样品采集于阿克苏蓝片岩出露区的最北缘(图3)。野外采用便携式GPS逐样定位、标高,样品均采自新鲜露头,单个样品重量>3kg。

裂变径迹测年实验在中国地震局地质研究所地震动力学国家重点实验室进行。样品经破碎、筛选、磁选及重液挑选出纯净的磷灰石,将磷灰石颗粒在薄片上用环氧树脂固化后抛光,用低铀白云母作外探测器进行裂变径迹分析。有关实验条件为:磷灰石自发裂变径迹蚀刻条件为5.5N HNO_3,20℃,20s;白云母诱发裂变径迹蚀刻条件为40% HF,室温,20min。Zeta标定选用国际标准样Fish Canyon Tuff磷灰石(27.8±0.7Ma)及美国国家标准局SRM 612铀标准玻璃,Zeta值为343.4±24。样品热中子辐照送中国原子能科学研究院492#反应堆进行。径迹统计采用Autoscan裂变径迹测试系统,在Zeiss Axioplan 2偏光显微镜放大1000倍条件下完成。本文磷灰石裂变径迹的封闭温度采用110±10℃,部分退火带温度为60~110℃(Green *et al.*, 1985, 1989; Hurford, 1986),年龄误差±1σ。

4 裂变径迹实验结果及热史模拟

6个样品的测试结果见表1和图4。一般而言,当$P(x^2)$>5%,说明样品通过了x^2检验,测试年龄采用池年龄(Pooled age);当$P(x^2)$<5%,说明样品没有通过x^2检验,测试年龄采用中心年龄(Central age)。本文所有样品年龄都通过了x^2检验,并且单颗粒年龄不分散,说明各样品的单颗粒年龄属于同一年龄组分,因此均选用池年龄。6个样品的年龄值介于107.5~62.5Ma之间,远小于其高压变质年龄(872~862Ma),可见蓝片岩的裂变径迹年龄被重置了。晚上震旦世和整个古生代地层厚度近万米(新疆维吾尔自治区地层表编写组,1981),根据地温梯度可推算出蓝片岩被完全退火了,这与测得裂变径迹年龄吻合,磷灰石裂变径迹年龄表明阿克苏蓝片岩在白垩纪隆升剥露。新生代地层总厚度达6千余米(新疆维吾尔自治区地层表编写组,1981),据地温梯度推算,蓝片岩理应再次遭受完全退火,但磷灰石裂变径迹年龄和径迹长度(10.46~12.12μm)说明样品后期仅遭受部分退火。因采样点较集中,可以解释为局部的新生代地层未至6km,当然地层单元内的新生代地层厚度仍需进一步考证。

为进一步了解阿克苏地区蓝片岩带所经历的冷却、埋藏再升温等过程,使用AFTSovle软件(Ketcham *et al.*, 1999, 2000)对样品进行热史模拟,选用Ketcham *et al.* (1999, 2000)的多组分退火模型和Monte Carlo法,根据测得的单颗粒年龄和径迹长度数据,利用计算机结合地质事件进行模拟,重现该样品的时间-温度演化轨迹。Dpar值选取初始值1.5μm,初始径迹长度设为16.3μm,计算模拟10000次以得到最佳拟合曲线。径迹长度测试条数一般要求大于40,以满

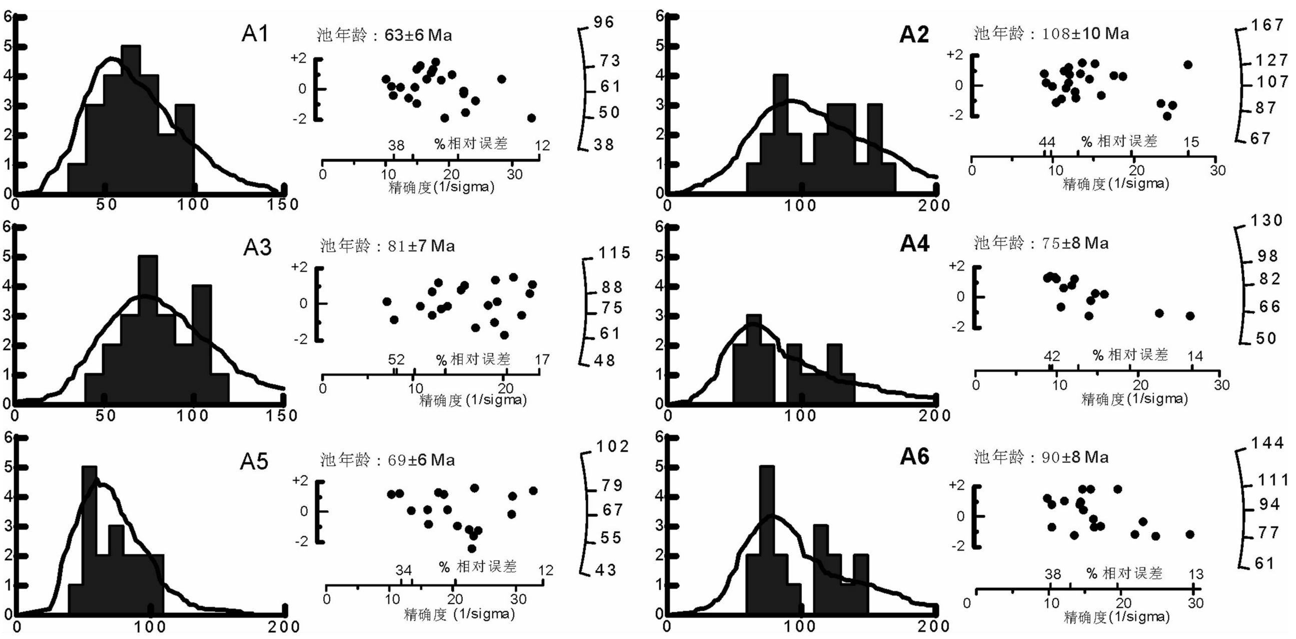

图4 阿克苏蓝片岩地区样品磷灰石裂变径迹年龄直方图和放射图

年龄直方图纵坐标为颗粒数,横坐标为年龄(单位Ma),曲线为拟合中心年龄趋势;放射图左侧坐标为误差范围,右侧坐标为年龄(单位Ma),图中圆点代表测试颗粒,直观标明测试颗粒数

Fig. 4 Apatite fission track dating results from the samples of Aksu blueschist

Ordinate of age histograms is number of grains, abscissa is age (unit Ma), curve is trend of fitting central ages; left coordinate of radial plots is the standardized error, right coordinate is age (unit Ma), round points mean measured grains, obviously indicating number of measured grains

表 1 新疆阿克苏地区磷灰石裂变径迹数据

Table1 Apatite fission track data of the samples from Aksu

样品号/高程(m)	采样位置	岩性	Nc	$\rho_d(N_d)$ ($\times10^5$cm^{-2})	$\rho_s(N_s)$ ($\times10^5$cm^{-2})	$\rho_i(N_i)$ ($\times10^5$cm^{-2})	铀含量 ($\times10^{-6}$)	$P(x^2)$ %	裂变径迹年龄 (Ma±1σ)	平均径迹长度 (μm±1σ)(Nj)	径迹长度标准差 (μm)
A1 1147	N41°07′57.2″ E079°59′21.5″	石英片岩	22	9.880 (2470)	3.44 (527)	9.30 (1423)	11.6	25.2	62.5±5.6	12.12±0.62 (11)	2.044
A2 1148	N41°08′27.8″ E080°00′13.7″	云母石英片岩	23	9.837 (2459)	3.28 (577)	5.11 (899)	6.4	43.2	107.5±9.7	10.46±0.98 (9)	2.946
A3 1148	N41°08′27.8″ E080°00′13.7″	云母片岩	21	9.794 (2448)	3.28 (515)	6.73 (1057)	8.5	61.4	81.4±7.4	12.09±0.30 (45)	1.999
A4 1157	N41°08′58.2″ E080°01′01.6″	基性蓝片岩	14	9.752 (2438)	3.49 (262)	7.77 (583)	9.8	35.5	74.8±7.8	10.88±0.42 (24)	2.063
A5 1157	N41°08′58.2″ E080°01′01.6″	紫红色石英片岩	17	9.709 (2427)	4.78 (640)	11.5 (1538)	14.5	8.6	69.0±6.0	11.38±0.29 (29)	1.555
A6 1144	N41°09′23.0″ E080°01′48.9″	云母石英片岩	18	9.666 (2417)	3.80 (532)	6.96 (974)	8.9	15.2	90.0±8.2	11.50±0.33 (42)	2.106

Nc=样品颗粒数;ρ_d=铀标准玻璃的诱发径迹密度;N_d=铀标准玻璃的诱发径迹数;ρ_s=样品自发径迹密度;N_s=样品自发径迹数;ρ_i=样品诱发径迹密度;N_i=样品诱发径迹数;$P(x^2)$=自由度为(Nc−1)时x^2概率;Nj=所测量的围限径迹长度数。测试人:张志勇

足热模拟的要求,长度测量条数大于100,则热模拟的可信度更高(Rahn and Seward, 2000)。样品A3、A6的径迹长度测量数大于40,其热史模拟结果可供参考。

在热史模拟时,要以研究区的地质背景为基础,充分了解该地区的构造变迁、沉积埋藏和冷却事件年龄,并在此基础上确定模拟的边界条件。本区热模拟的制约条件:所有120~200℃的起始约束都给在150Ma,约束温度范围较大,且高于完全退火带温度;在实测年龄附近给定20~130℃的约束,主要是为了获得样品通过110℃时的裂变径迹年龄;又因研究区内缺失中生代地层,表明此期间以隆升剥蚀为主,而古新世开始有沉积作用发生,故在65.5Ma给出0~40℃的约束,表明此时开始转入埋藏升温阶段;加之观测到围限径迹的缩短信息,表明样品接受埋藏增温至部分退火带,在约20Ma给其40~120℃的约束,计算出的热史曲线自动落入部分退火带,再次证实了样品遭受退火事件。

热史模拟结果见图5。Ketcham *et al.* (2000)的热模拟图一般分为三个部分:可以接受的热史曲线集,高质量的热史曲线集和最佳拟合曲线。从图5中可以看出两个样品的K-S检验>0.90,年龄GOF>0.91,说明模拟结果是高质量的。为避免得到晚期快速冷却的假相(Bruijne and Andriessen, 2002; Kohn *et al.*, 2002),在热模拟时将原设定的初始径迹长度减小,再重新模拟并分析结果(Bruijne and Andriessen, 2002; Kohn *et al.*, 2002,2005;Hu *et al.*, 2006a, b)。考虑到模拟的多解性,笔者曾尝试给出其它的热史模型,但是模拟出的最佳拟合曲线被限定在约束线的端点,且K-S检验和年龄GOF均较小,并且重现的热史曲线跟已有地质资料不符。本文模拟中给定的所有约束温度范围均较大,从模拟结果看,最佳拟合曲线没有被限定在约束温度的端点,模拟重现的时间-温度曲线是可信的。

5 讨论与结论

本文利用裂变径迹测试方法对阿克苏地区进行研究,结合前人研究成果和本区地层序列(图2),大致重建了蓝片岩的热史演化曲线(图6):

(1)上震旦统地层底部底砾岩中含有下伏高压片岩和基性岩脉的小砾石,这强有力的指出了下伏高压片岩和基性岩脉的年龄要比晚震旦世老,从下伏高压片岩的吻合年龄(872±2Ma的青铝闪石^{40}Ar/^{39}Ar年龄,862±1Ma的蓝闪石^{40}Ar/^{39}Ar年龄)和基性岩脉807±12Ma的锆石U-Pb年龄,可推断出上震旦统的底砾岩要比807Ma年轻。蓝片岩形成后应快速折返至地表才能保存其高压低温变质矿物组合,即蓝片岩隆升至地表后可能在整个早震旦世一直遭受剥蚀,到晚震旦世才重新开始接受沉积埋藏;

(2)晚震旦世地层基本保持连续,整个古生代也仅缺失中、上志留统,中、下石炭统,推断在中、上志留世及中、下石炭世地层可能有过短暂隆升,沉积作用暂时停止,随后又转

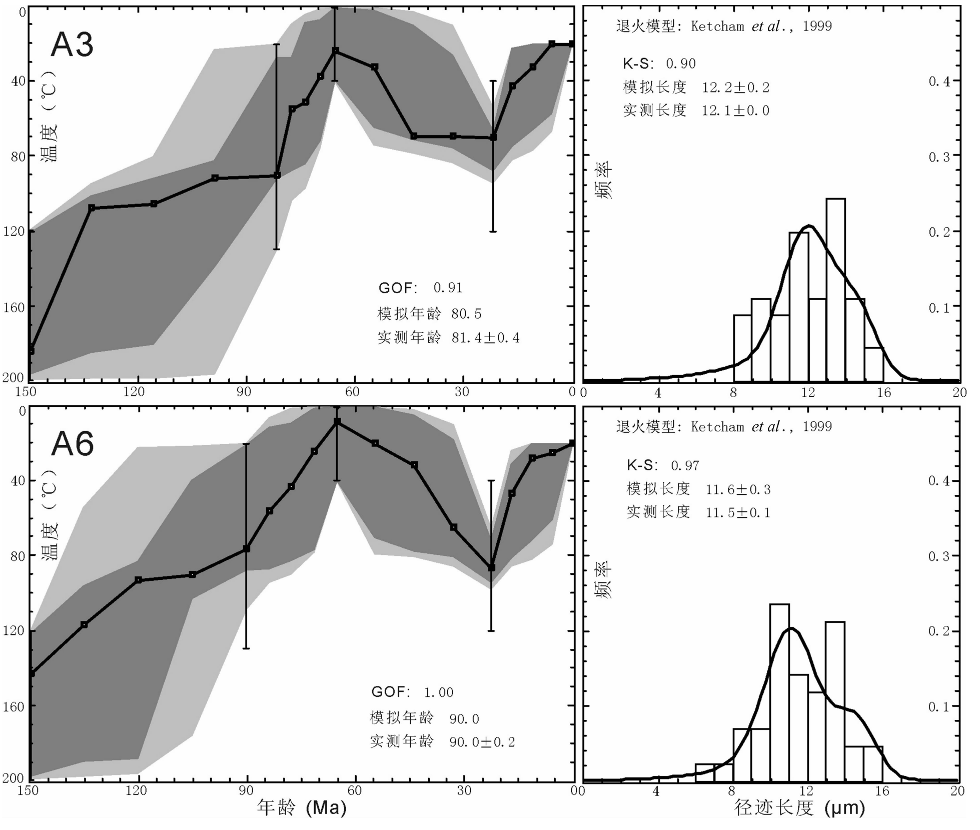

图5 阿克苏蓝片岩地区样品A3、A6的热史模拟图

浅灰区代表“可以接受的”热史拟合曲线集，深灰区为“高质量的”热史曲线集，黑色曲线代表“最佳”热史拟合曲线，竖直线段代表某一时间给定的温度约束范围；“K-S检验”表示径迹长度模拟值与实测值之吻合程度，“年龄GOF”代表径迹年龄模拟值与实测值之吻合程度，若“年龄GOF”，“K-S检验”都大于5%时，表明模拟结果“可以接受”，当它们超过50%时，模拟结果则是高质量的

Fig. 5 Modelled thermal history for the samples of Aksu blueschist

Thick lines show best-fit solutions obtained for these model run, and light-grey and dark-grey colors show general-fit solutions and good-fit solutions obtained for the same model run, respectively. Vertical lines mean temperature restrictions at one time. "K-S test" means inosculated grade of modeled value and measured value for track length. "Age GOF" means inosculated grade of modeled age and measured age. If "K-S test" and "Age GOF" >5%, modeled results are acceptable; if "K-S test" and “Age GOF” >50%, modeled results are of high quality

入沉积埋藏阶段。至古生代末，早震旦世和整个古生代地层厚度已近万米。蓝片岩完全退火，年龄被重置。

(3)因为研究区内缺失中生代地层，加之我们测得的裂变径迹年龄(107.5～62.5Ma)也基本落在白垩纪，本文认为在中生代晚期区内地层普遍开始隆升，裂变径迹时钟重新开始计时。至于何时沉积结束开始隆升，可能是古生代末，也可能中生代早期地层仍在接受沉积，而后的隆升把刚刚沉积的中生代地层剥蚀了。

(4)古新世开始有沉积作用发生，表明开始转入埋藏升温阶段，加之观测到围限径迹的缩短信息，表明样品接受埋藏增温至部分退火带，计算出的热史曲线自动落入部分退火带再次证实了样品遭受退火事件。随后可能由于印度—欧亚板块碰撞的远程效应，地层重新又隆升剥露于地表。

中生代以来天山地区的普遍发育隆升剥露作用(Hendrix *et al.*, 1994; Zhou *et al.*, 1995; Sobel and Dumitru, 1997; 王彦斌等, 2001; 郭召杰等, 2002, 2006; 杨树锋等, 2003; 柳永清等, 2004; 沈传波等, 2005; Zhu *et al.*, 2005a, b; 陈正乐等, 2006; 马前等, 2006; 朱文斌等, 2006, 2007; 张志诚等, 2007)。研究表明，从青藏高原北缘向北，包括塔里木盆地周缘，天山，直至阿尔泰山，隆升剥露作用均具有多期性和阶段性。Hendrix *et al.* (1992)指出，天山中新生代变形作用与不同陆块碰撞增生到亚洲板块南部边缘有关，它们是晚三叠世(230～200Ma)羌塘地块的增生作用；晚侏罗世(140～125Ma)拉萨地块的增生作用；晚白垩世(80～70Ma)Kohistan-Dras岛弧的增生作用以及55Ma以来印度板块与亚洲大陆的碰撞作用。阿克苏蓝片岩的磷灰石裂变径迹年龄与天山及邻区的其他裂变径迹年龄资料基本一致，反映了上述地体与欧亚大陆碰撞对天山地区的远距离影响。

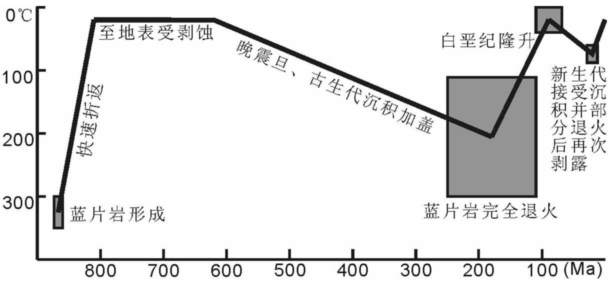

图 6 新疆阿克苏前寒武纪蓝片岩构造-热演化史

灰色矩形代表置信区间,即其中心的曲线拐点可能落在矩形区域中的任意处

Fig. 6 Thermo-tectonic evolution of Precambrian Blueschists in Aksu, Xinjiang

Grey rectangle means confidence interval, inflexion of curve may be in any place of the area

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