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东昆仑野马泉地区磷灰石裂变径迹热年代学及构造意义

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摘要：通过对东昆仑西段野马泉地区所获得的 5 个磷灰石样品的裂变径迹分析，探讨该地区构造演化特征.磷灰石裂变径迹年龄分为 153.8 Ma、106.8～81.0 Ma、48.7～44.4 Ma 3 个年龄组，其中 153.8 Ma 记录了班公湖－怒江洋闭合事件；106.8～81.0 Ma 是拉萨地块与羌塘地块碰撞拼合事件对东昆仑地区的远程效应；48.7～44.4 Ma 是印度－欧亚大陆碰撞之后伸展事件的体现.野马泉地区热历史分为 3 个阶段：第 1 阶段(130～110 Ma)持续隆升，对应班公湖－怒江洋闭合后拉萨地块与羌塘地块拼合事件；第 2 阶段(110～14 Ma)持续隆升，90 Ma 之前隆升速度较快，与阿尔金断裂走滑及西大滩断裂韧性变形有关，90 Ma 之后进入一个时间较长的平稳抬升期；第 3 阶段(14 Ma 至今)受青藏高原新近纪以来强烈构造活动的影响，快速隆升.3 个阶段的隆升速率和隆升量分别 0.021 mm/a 和 0.42 km、0.01 mm/a 和 1.0 km、0.1 mm/a 和 1.43 km，平均隆升速率为 0.028 mm/a，总隆升量为 2.86 km.

关键词：裂变径迹；构造；热历史模拟；岩石隆升；磷灰石；东昆仑.

Apatite Fission Track Thermochronology and Tectonic Significance in Yemaquan Area，East Kunlun

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Abstract：We present the tectonic evolution characteristics of Yemaquan area，which is located in west of the East Kunlun Mountains，according to apatite fission track thermochronology analysis. The results show that apatite fission track ages mainly are divided into three groups，including 153.8 Ma，106.8 to 81.0 Ma，and 48.7 to 44.4 Ma，respectively. The Bangonghu-Nujiang ocean closure event happened in 153.8 Ma，then the collision and combination of Lhasa block and Qiangtang block on the East Kunlun area mainly ranged from 106.8 to 81.0 Ma，and post-orogenic stretching events after the collision between the India-Eurasia occurred during 48.7 Ma and 44.4 Ma. In addition，the analysis results also indicate that three stages of thermal history of Yemaquan area are mainly ranged from 130 to 110 Ma，110 to 14 Ma，and 14 Ma to now，respectively. The first stage，130－110 Ma，corresponds to collision activity between the Lhasa and the Qiangtang block after the closed up of the Bangonghu-Nujiang oceanic basin. The second stage，110－14 Ma，rised continuously，with strike-slip movement of Alkin fault and the ductile deformation of the Xidatan fault occurred during 110－90 Ma. And the last stage，14 Ma to now，uplifted rapid-

ly，and affected by strong tectonic activity of Tibetan plateau since Neogene. Uplift rates and uplift ranges for these three stages are estimated of 0.021 mm/a and 0.42 km，0.01 mm/a and 1.0 km，and 0.1 mm/a and 1.43 km，respectively，with the average uplift rate and the total uplift height of 0.028 mm/a，and 2.86 km，respectively.

Key words：fission track；tectonics；thermal history simulation；uplifting；apatite；East Kunlun.

0　引言

东昆仑山脉是一条巨型岩浆岩带(莫宣学等,2007a),位于青藏高原北部.目前,国内外学者对东昆仑造山带的研究多集中于不同造山旋回各阶段的演化(邓晋福等,1996;郭正府等,1998;罗照华等,1999;袁万明等,2000a)以及对各造山期时限进行厘定的地球化学和同位素年代学(谌宏伟等,2006;刘云华等,2006;Zhu et al.,2006;Chen et al.,2008;过磊等,2010;张炜等,2016;赵菲菲等,2017).相对而言,对中新生代冷却历史的研究较少(袁万明等,2000b,2004,2005;Yuan et al.,2003,2006,2013;Wang et al.,2006;王国灿等,2007;拜永山等,2008;陈宣华等,2011;陈小宁等,2014;Xu et al.,2016).开展东昆仑山脉造山期后冷却、隆升历史研究,对于深入理解东昆仑造山带形成以后的构造演化意义重大.

近年来,磷灰石裂变径迹热年代学研究取得重要进展,已成为揭示造山带地质构造演化的重要手段(Hay et al.,1989;Métivier and Gaudemer,1997;Gleadow et al.,2002;Kohn et al.,2002;Kohn,2005).本文对东昆仑造山带西段野马泉地区的 5 件花岗岩样品进行磷灰石裂变径迹热年代学研究,探讨区内不同阶段构造活动的热年代学制约,定量评价地质热演化历史及隆升特点.

1　地质背景

研究区位于东昆仑造山带西段(图 1),北邻祁漫塔格山北坡岩浆弧带和柴达木陆块,南与东昆中陆块相接(张雪亭,2006;张爱奎,2012).区域地质构造演化经历了 4 个构造旋回,从早到晚依次为:元古宙古陆形成、加里东期裂解及造山、晚华力西－印支期裂解造山和晚中生代－新生代叠复造山(张以弗,

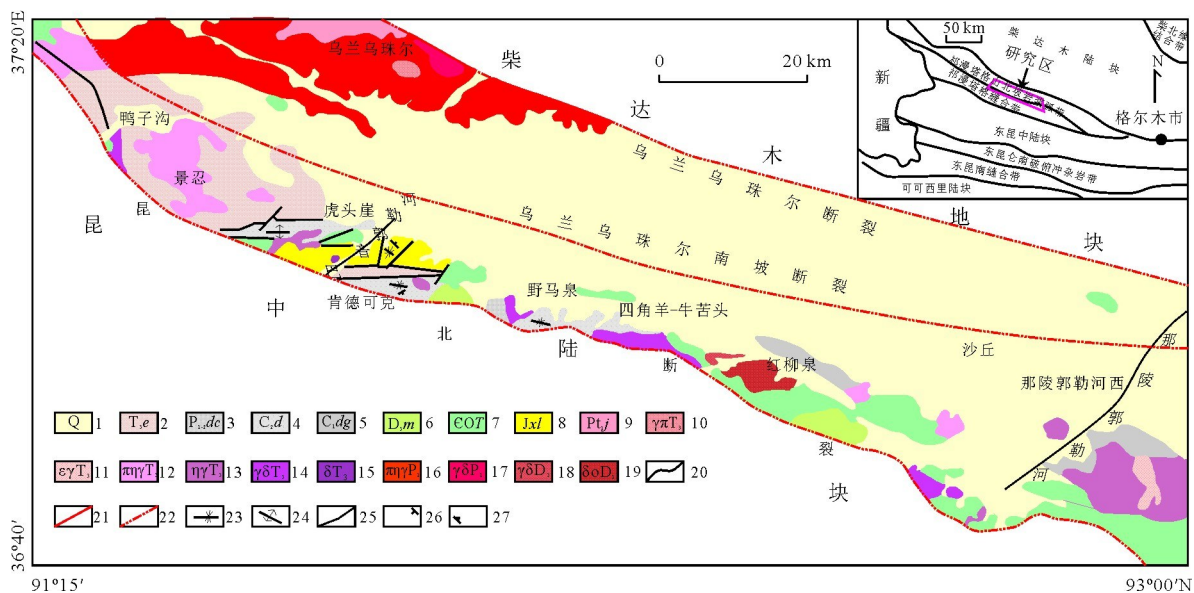图 1　野马泉地区区域地质图

Fig.1　Regional geological map of Yemaquan region in East Kunlun Mountain

1.第四系;2.上三叠统鄂拉山组;3.下－中二叠统打柴沟组;4.上石炭统缔敖苏组;5.下石炭统大干沟组;6.上泥盆统牦牛山组;7.寒武系－奥陶系滩间山群;8.蓟县系狼牙山组;9.下元古界金水口岩群;10.晚三叠系世花岗斑岩;11.晚三叠系世正常花岗岩;12.晚三叠系似斑状二长花岗岩;13.晚三叠世二长花岗岩;14.晚三叠世花岗闪长岩;15.晚三叠世闪长岩;16.早二叠世似斑状二长花岗岩;17.早二叠世花岗闪长岩;18.晚泥盆世花岗闪长岩;19.晚泥盆世石英闪长岩;20.不整合接触地质界线;21.断层;22.大断裂;23.背斜;24.向斜;25.水系;26.地层产状;27.片麻理产状;据张爱奎(2012)修改

1994).区内北西向、近东西向压扭性断裂较发育.

野马泉地区地层主要有下元古代金水口岩群（Pt_1j）、蓟县系狼牙山组（Jxl）、寒武系一奥陶系滩间山群（ϵOT）、上泥盆世牦牛山组（D_3m）、下石炭统大干沟组（C_1dg）、上石炭统缔敖苏组（C_2d）、下一中二叠统打柴沟组（$P_{1-2}dc$）、上三叠统鄂拉山组（T_3e）、新近系油砂山组（N_2y）、第四系（Q）.区内花岗岩浆活动非常发育，主要发育有早古生代和晚古生代一早中生代两个岩浆作用旋回的花岗岩类侵入岩，其中又以后者最为强烈.各个旋回的花岗岩类侵入岩主要受北西向和北西西向两组断裂构造控制.

2　样品采集与分析方法

本次测试样品均为花岗岩类，采集于东昆仑野马泉地区，具体采样位置见图2，样品 K13-1 为花岗闪长岩，K19-1 为二长花岗岩，K21-2 为花岗斑岩，K21-3 为花岗闪长岩，K38-1 为斑状二长花岗岩.

样品粉碎至 60～100 目，应用电磁选、重液选联合双目镜筛选，对磷灰石单矿物进行浓缩.将磷灰石单矿物分布在玻璃上，然后用环氧树脂固定，经研磨、抛光制成薄片.将磷灰石样用 5％ HNO_3 在 25 ℃ 条件下蚀刻 30 s，揭示出自发径迹.采用外探测器法定年，将样品与低铀白云母外探测器同时通过反应堆辐照，在 25 ℃ 条件下，用 40％ HF 蚀刻 20 s，揭示出诱发径迹，使用 CN-5 铀玻璃标定中子注量.在平行于 c 轴的柱面上分别测出诱发径迹密度和自发径迹密度，根据程序（Green，1986）测定水平封闭径迹长度（Gleadow et al.，1986）.通过 IUGS（国际地质科学联合会，International Union of Geological Sciences）推荐的 ξ 常数法，利用标准裂变径迹年龄方程（Hurford and Green，1982）计算磷灰石裂变径迹年龄，获得 Zeta 常数为 $353\pm18(1\sigma)$.

通过 Green（1981）提供的方法计算磷灰石裂变径迹年龄误差，$P(\chi^2)$ 值 $>5\%$ 说明单颗粒属于同一年龄组（Galbraith，1981）.$P(\chi^2)<5\%$ 说明单颗粒年龄分布不均匀.如年龄分散，则以"中心年龄"表示，基于泊松变异的常规分析（Green，1981）无效.
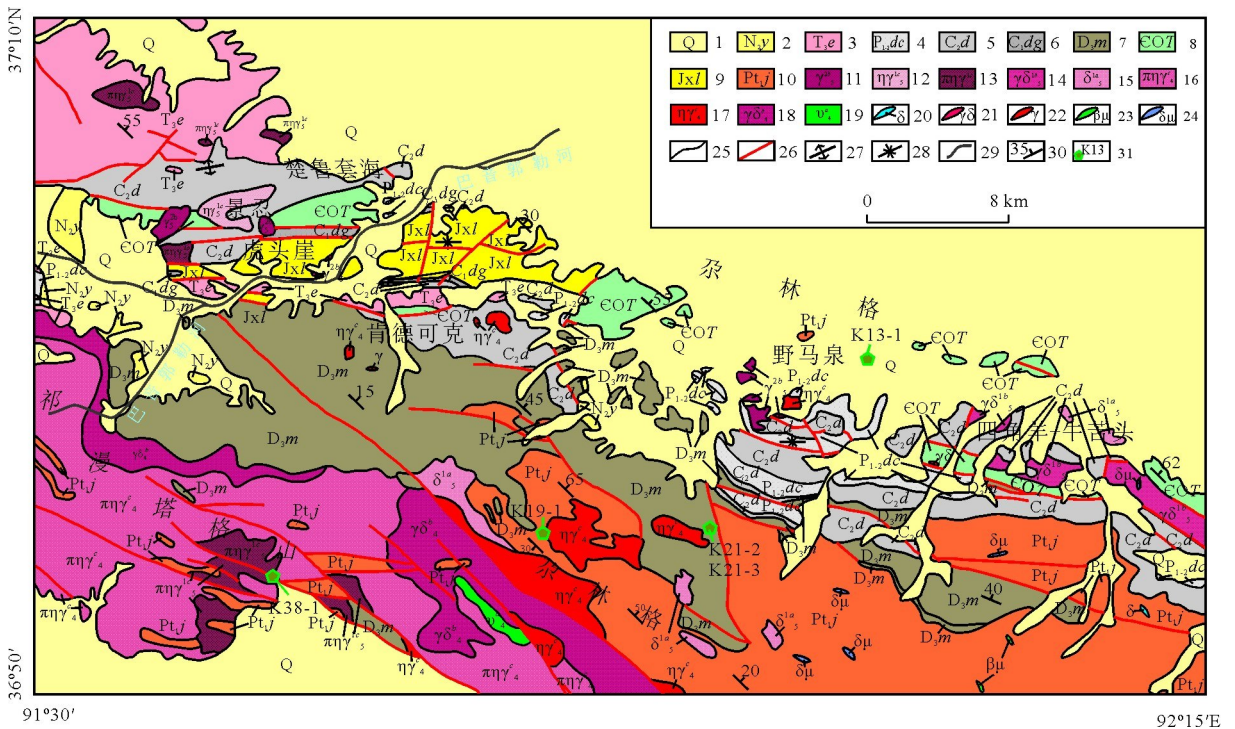

图 2　研究区地质简图与样点位置

Fig.2　Geological map and sample locations in Yemaquan region

1.第四系；2.新近系油砂山组；3.上三叠统鄂拉山组；4.中一下二叠统打柴沟组；5.上石炭统缔敖苏组；6.下石炭统大干沟组；7.上泥盆统牦牛山组；8.寒武系一奥陶系滩涧山群；9.中一古元古界狼牙山组；10.中一古元古界金水口群；11.燕山期钾长花岗岩；12.印支期二长花岗岩；13.印支期斑状二长花岗岩；14.印支期花岗闪长岩；15.印支期闪长岩；16.华力西期斑状二长花岗岩；17.华力西期二长花岗岩；18.华力西期花岗闪长岩；19.华力西期辉长岩；20.闪长岩脉；21.花岗闪长岩脉；22.花岗斑岩脉；23.辉绿岩脉；24.闪长玢岩脉；25.地质界线；26.断层；27.背斜；28.向斜；29.水系；30.地层产状；31.采样点及编号；图改自高永宝等（2014）

3　实验结果与分析

本次试验最终获得 5 个样品的磷灰石裂变径迹分析结果(表 1).

磷灰石裂变径迹年龄在 (66±5)～(143±9) Ma,均远小于岩体时代,表明样品经历热事件的退火作用改造,年龄变小,是 130 Ma 以来陆内造山作用的体现.

样品 K21-2、K21-3 的 $P(\chi^2)$ 检验值大于 5%,单颗粒年龄、径迹长度均呈单峰式分布(图 3 和图 4),显示样品受单一热事件控制,地质意义确切,记录了样品经历的构造热事件.样品 K13-1、K19-1、K38-1 的 $P(\chi^2)$ 检验值小于 5%,长度配分形态、单颗粒年龄均显示出双峰式特征,呈混合型,表明构造演化较为复杂.将裂变径迹年龄应用耶鲁大学 Brandon(2002)开发的 Binom Fit 程序分解,$P(\chi^2)$ 检验值小于 5% 的年龄分解为两组拟合年龄(图 5).

样品的径迹平均长度分布于 (11.0±1.8)～(12.5±1.8) μm(图 4),变化范围较窄,但长度值普遍较小,标准差较大,反映样品经历构造热事件,在退火带时间较长.

统计 $P(\chi^2)$ 检验值大于 5% 和小于 5% 的年龄数据(表 1,图 5),分为 3 个年龄组:153.8 Ma、106.8～81.0 Ma、48.7～44.4 Ma.莫宣学和潘桂棠(2006)通过构造－岩浆事件的约束,提出了特提斯的演化到青藏高原的形成过程,153.8 Ma 记录了晚侏罗世初到早白垩世末班公湖－怒江洋经历的闭合事件,106.8～81.0 Ma 记录了拉萨地块与羌塘地块碰撞拼合在东昆仑地区的响应,阿尔金断裂走滑隆升(李海兵等,2006);48.7～44.4 Ma 是印度－欧亚大陆碰撞之后伸展事件的体现.磷灰石裂变径迹年龄体现出研究区经历了不同阶段构造隆升作用.

$P(\chi^2)$ 检验值大于 5% 的样品 K21-2、K21-3 的年龄、高程数据(表 1)显示,样品高程与样品获得的年龄呈正相关,这与样品脱离退火带的时间有关,与野马泉地区自 130 Ma 以来整体隆升的特征相符.

4　地质热演化历史

根据 Ketcham et al.(1999)的退火模型,运用 Monte Carlo 逼近法进行热历史模拟.依据裂变径迹参数、地质条件确定模拟的初始条件,黑色实线为最佳的热历史路径,红色区域拟合较好,绿色区域为可接受区(图 6).图 6 中 K-S 值、GOF 值均大于 0.5,说明模拟结果较好(Arnaud et al.,2003).

模拟图(图略)显示冷却抬升基本一致,总体上属于 4 阶段演化模式:(1)从 130 Ma 到 110 Ma,温度主体高于 100 ℃,处于磷灰石裂变径迹退火带的底部;(2)从 110 Ma 到 14 Ma,温度从 100 ℃ 降为 65 ℃,温差为 35 ℃,早期相对快速降温与拉萨地块和羌塘地块约 120 Ma 的碰撞活动(莫宣学和潘桂棠,2006)相符,后期进入一个时间较长的平静期;(3)从 14 Ma 至今,温度由 65 ℃ 快速冷却至现今地表温度(约 15 ℃),温差为 50 ℃,为青藏高原的重大隆升期(钟大赉和丁林,1996;张克信等,2008),是印度板块和欧亚板块碰撞(Vincent and Allen,1999;莫宣学等,2007b)的远程效应.

表 1　磷灰石裂变径迹分析结果
Table 1　Apatite fission track analysis results

原样品号	高程(m)	颗粒数(n)	$\rho_s(10^5/cm^2)$ (N_s)	$\rho_i(10^5/cm^2)$ (N_i)	$\rho_d(10^5/cm^2)$ (N_d)	$P(\chi^2)$(%)	中心年龄±1σ (Ma)	$L(\mu m)$ (N)
K13-1	3 002	28	5.144 (1 757)	8.478 (2 896)	13.549 (9 117)	0.9	143±9	12.5±1.8 (101)
K19-1	4 410	28	7.370 (1 194)	27.673 (4 483)	13.727 (9 117)	0	66±5	11.0±1.8 (103)
K21-2	4 330	26	3.693 (506)	9.969 (1 366)	13.904 (9 117)	54.2	90±7	12.3±2.1 (74)
K21-3	4 082	4	5.389 (107)	16.770 (333)	14.349 (9 117)	38.4	81±10	11.8±1.9 (20)
K38-1	4 508	16	2.795 (375)	9.413 (1 263)	15.150 (9 117)	0	71±11	11.7±1.9 (49)

注:ρ_s 为自发径迹密度;ρ_i 为诱发径迹密度;ρ_d 为标准径迹密度;N_s 为自发径迹数;N_i 为诱发径迹数;N_d 为标准径迹数;N 为径迹长度数;$P(\chi^2)$ 为 χ^2 检验值.
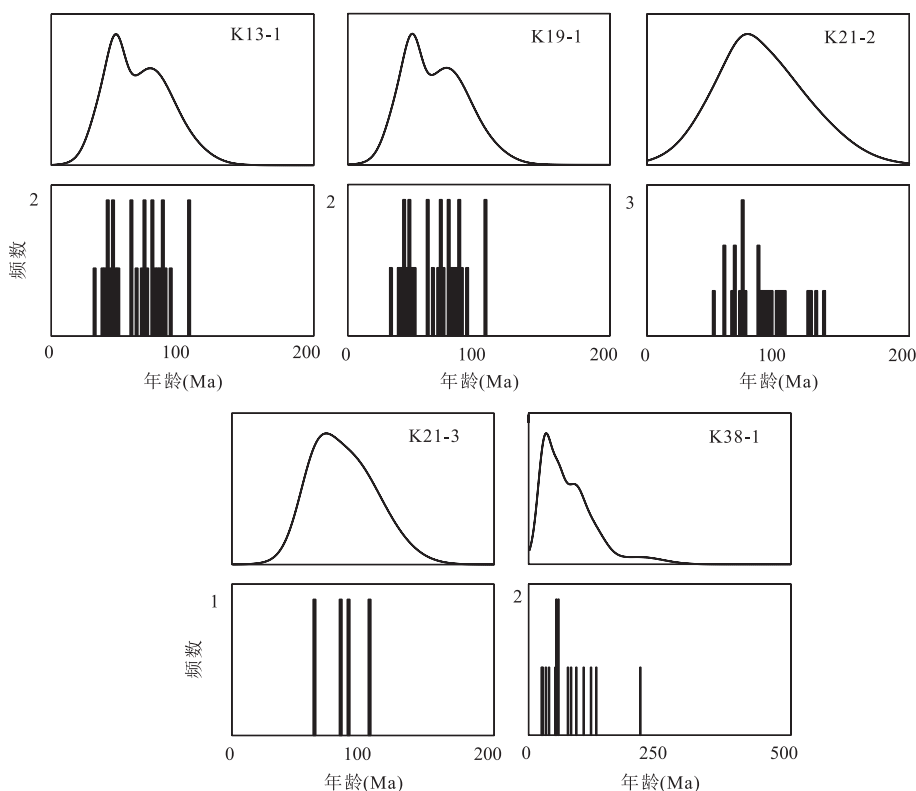
图 3　磷灰石样品裂变径迹单颗粒年龄直方图及其频率曲线

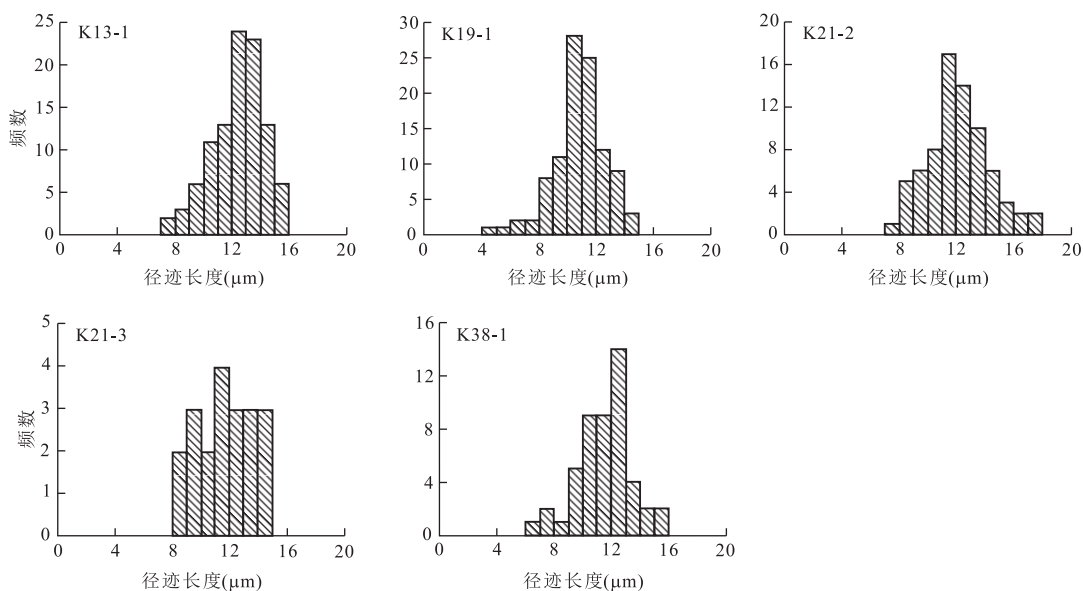Fig.3　Apatite single grain ages histograms and frequency curves

图 4　磷灰石裂变径迹长度分布直方图

Fig.4　Histograms of the apatite fission track lengths

5　岩石隆升

本文应用年龄－封闭温度法、冷却曲线模拟法和年龄－高程法对研究区隆升速率、隆升量进行定量研究.

5.1　年龄－封闭温度法

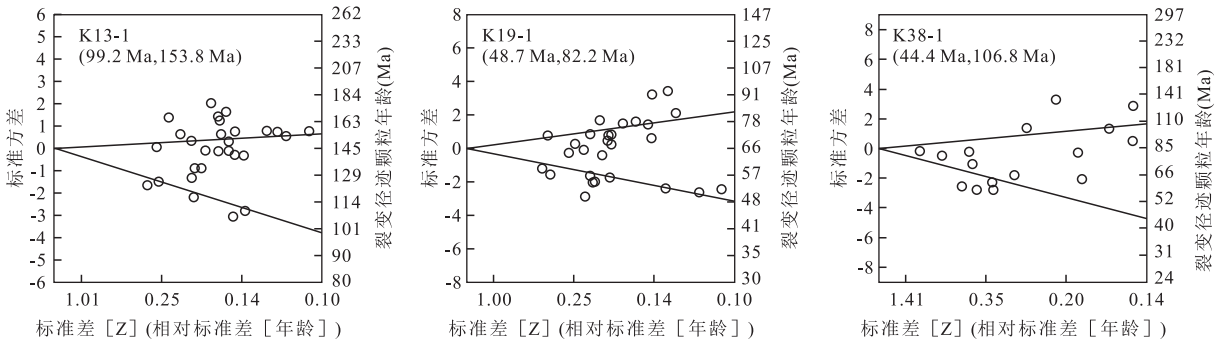年龄－封闭温度法可对研究区的平均隆升状态作出直观评价(Kohn et al.,2002).

图 5 样品 $P(\chi^2)$ 检验值小于 5% 时裂变径迹年龄分组

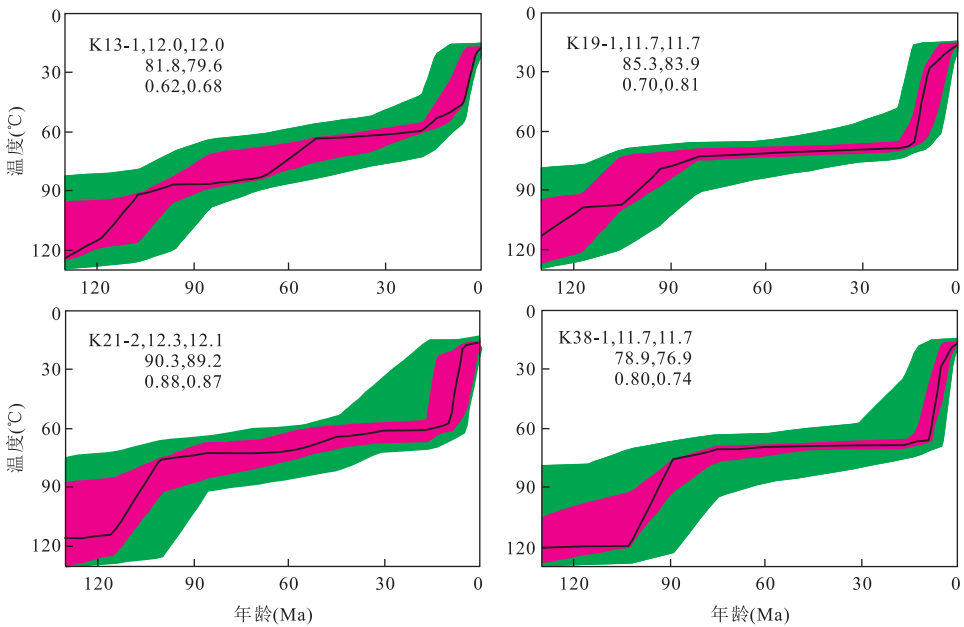Fig.5 Radial plots for AFT age grouping ($P(\chi^2)<5$)

图中左上角分别为样品号及分组得到的年龄

图 6 野马泉地区地质热演化历史模拟结果

Fig.6 Modeling geological thermal evolution histories in Yemaquan region

左上角分别为样品编号,实测、模拟径迹长度(μm),实测、模拟 Pooled 年龄(Ma),K-S 检验值及 GOF 年龄拟合参数

选取 $P(\chi^2)$ 检验值大于 5% 的样品 K21-2、K21-3,封闭温度取 100 ℃,地表温度一般为 15 ℃,造山带平均地温梯度取 35 ℃/km(Pichon et al.,1997).按照公式计算隆升速率:隆升速率×年龄值=(封闭温度-地表温度)/地温梯度.结果显示,样品的平均隆升速率相差不大,分别为 0.027 mm/a、0.03 mm/a,平均为 0.028 mm/a.

5.2 冷却曲线模拟法

不同阶段的隆升速率、隆升程度,可以根据热历史模拟结果计算.第 2 阶段温差和时间差分别为 35 ℃ 和 96 Ma、第 3 阶段温差和时间差分别为 50 ℃ 和 14 Ma,故两阶段的隆升速率和隆升幅度分别为 0.01 mm/a 和 1.0 km、0.1 mm/a 和 1.43 km.由于第

一阶段上限没有其他矿物约束,不能准确计算其隆升速率.假设将第 1 阶段上限定为 130 Ma,根据平均隆升速率 0.028 mm/a 计算,第 1 阶段隆升速率和隆升量分别为 0.021 mm/a 和 0.42 km.3 个阶段累计隆升量为 2.86 km.

5.3 年龄-高程法

通过垂直剖面上两个样品的高差除以同一测年法的年龄获得隆升速率,按公式 $V=\Delta Z/\Delta t$ 计算.本方法不需要古地温梯度值,假定地温梯度保持不变,不受地形影响.适合于垂直采样,可包括钻井、地表垂直剖面采样.笔者在野马泉地区同一钻井中采集了样品 K21-2 和 K21-3,$P(\chi^2)$ 检验值均大于 5%,具有明确的地质热事件意义,采用年龄-高程法计算其隆升

速率为 0.028 mm/a，与年龄－封闭温度法计算的平均隆升速率是一致的，表明本次计算结果可信.

6 讨论

通过热历史演化在磷灰石裂变径迹中的记录，将野马泉地区白垩纪以来构造演化分为 3 个阶段.

第 1 阶段：130～110 Ma，岩石温度下降至 110 ℃进入磷灰石退火带，隆升 0.42 km，隆升速率为 0.021 mm/a，对应拉萨地块与羌塘地块的拼合事件(王璞珺等，2003；莫宣学和潘桂棠，2006).

第 2 阶段：110～14 Ma，温度从 100 ℃降为 65 ℃，温差为 35 ℃，从热历史模拟结果来看，以 90 Ma 为界，早期相对快速降温抬升，后期进入一个时间较长的平静期.110～90 Ma 相对快速抬升事件在区域上得到多处响应，拉萨地块与羌塘地块碰撞拼合后阿尔金断裂发生走滑，形成北东南西向大规模走滑断层；格尔木南侧中生代深成岩体经历了一个重要的挤压事件，同时伴随着西大滩断裂的韧性变形(Mock et al.，1999).90～14 Ma 抬升变缓，但继续抬升冷却.

第 3 阶段：14 Ma 至今，温度从 65 ℃快速降到 15 ℃，温差为 50 ℃.钟大赉和丁林(1996)将青藏高原及周缘 13 Ma 以来划分为 13～8 Ma、3 Ma 至今两阶段构造热事件，张克信等（2008)亦提出 13 Ma 以来属于包括西昆仑和阿尔金在内的青藏高原的重大隆升期.总的来说，该地区受到青藏高原新近纪以来强烈构造活动的影响，快速抬升.

7 结论

对东昆仑野马泉地区 5 个样品进行磷灰石裂变径迹分析，得到磷灰石裂变径迹热年代学及构造事件演化：

(1)东昆仑野马泉地区磷灰石裂变径迹年龄分为 3 组：153.8 Ma 记录了班公湖－怒江洋在晚侏罗世初到早白垩世末闭合事件，106.8～81.0 Ma 记录了拉萨地块与羌塘地块碰撞拼合对东昆仑地区的远程效应，48.7～44.4 Ma 是印度－欧亚大陆碰撞之后伸展事件的体现.

(2)野马泉地区 130 Ma 以来总体上经历了 3 个阶段的演化：第 1 阶段(130～110 Ma)岩石温度处于磷灰石退火带，持续隆升，对应拉萨地块与羌塘地块的拼合事件；第 2 阶段(110～14 Ma)持续隆升，90 Ma 之前隆升速度较快，与阿尔金走滑断裂及西大滩断裂韧性变形有关，90 Ma 之后进入一个时间较长的平静期；第 3 阶段(14 Ma 至今)受青藏高原新近纪以来强烈构造活动的影响，快速隆升.

(3)该地区 3 个阶段的隆升速率和隆升量分别为 0.021 mm/a 和 0.42 km、0.01 mm/a 和 1.0 km、0.1 mm/a 和 1.43 km，平均隆升速率为0.028 mm/a，总隆升量为 2.86 km.

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