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复杂变质带褶皱形态判定新方法
——变斑晶包裹物迹线应用研究

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摘 要:经历了复杂多期变形的片岩和片麻岩地区,褶皱形态及形成时代的判定是变质岩构造地质过程研究的难点之一。变斑晶内包裹物迹线记录了区域变质变形作用历史过程,可为通过野外露头观测难以确定的复杂褶皱形态判定提供新的研究途径。本文以美国科罗拉多州阿肯色河 Texas Creek 地区为例,尝试运用垂直于5期面理弯切轴的定向薄片中叠加面理(变斑晶包裹物迹线)由水平到竖直和由竖直到水平的几何形状变化,确定研究区内一个存在争议的复杂褶皱形态为背形,并推断该褶皱形成于区域内第1期变斑晶生长过程(约为1 500 Ma)中。

关键词:褶皱形态;变斑晶;变斑晶包裹迹线;面理弯切轴

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A new method for ascertaining the shape of isoclinal folds in multiply-deformed metamorphic zone: The application of porphyroblast inclusion trails

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Abstract: It is usually difficult to ascertain the shape of folds in multiply-deformed high-grade metamorphic gneisses and schists. If such rocks contain porphyroblasts, a new approach is possible because of the way through which porphyroblast grew was affected by crenulation versus reactivation of compositional layering. Isoclinally folded rocks in Texas Creek, Arkansas River region of Central Colorado contain relics of fold hinges; nevertheless, it is very difficult to ascertain whether they are antiforms or synforms because of the effects of younger refolding and the locally truncated nature of coarse compositional layering. Using the asymmetry of overprinting foliations relative to the five FIA sets in this region, the authors have revealed that an isoclinal fold, which was previously interpreted as a synform, is actually an antiform, which was developed during the first stage of porphyroblast growth (around 1 500 Ma).

Key words: fold development; porphyroblasts; inclusion trails; foliation intersection/inflection axes (FIAs)

复杂多期变形变质岩区变形期次及岩层关系的厘定是区域变质变形过程研究的关键问题。后期变形作用叠加使得早期变形过程信息通常难以完整记录并保存下来。多期生长变斑晶内包裹物迹线记录了区域变质变形作用过程,并且在经历了后期造山作用后仍能保存下来(游振东,1996;Bell *et al*., 2003

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Aerden *et al*., 2013)。变斑晶面理弯切轴(foliation intersection/inflection axes, FIAs)可以将变斑晶多期生长同区域变质变形作用有效联系起来。如果区域内变斑晶包裹物迹线发育较好,则可为该地区变质变形演化过程研究提供重要研究数据(Hayward, 1990;Bell *et al*., 1995, 1998)。

科罗拉多州中部阿肯色河地区 Texas Creek 以东 Five points gulch-Hindman Gulch 等斜褶皱经历了多期变形作用叠加,难以判断其形态是向形还是背形。此前,Gartner 等(2001)根据其周围堇青石片岩与矽线石英片麻岩的接触关系推断褶皱形态为向形。由于褶皱两翼露头产状近直立,并且轴面两侧变形差异较大,难以根据野外测量露头产状验证褶皱形态的判定正确与否。然而,该褶皱两翼广泛发育的堇青石、斜长石、红柱石等变斑晶内包裹物迹线十分明显,适于面理弯切轴的测定。面理弯切轴对应叠加面理,可根据多期生长变斑晶内包裹物迹线由核部到翼部的变化,将变斑晶多期生长与褶皱形成过程有效联系起来(Bell *et al*., 2003)。运用面理弯切轴对应叠加面理几何形状的不对称性判定褶皱形态及形成时代,可为经历了复杂变质变形过程、通过宏观露头观测难以确定的复杂褶皱形态研究提供新的尝试。

1 区域地质背景

1.1 区域地质概况

美国科罗拉多州中部阿肯色河 Texas Creek 位于 Front Range 南端 Wet Mountains 中部,处于 Yavapai 地体(1 800~1 700 Ma)和 Mazatzal 地体(1 700 ~ 1 600 Ma;Karlstrom and Humphreys, 1998;图1)之间。该地区广泛出露前寒武纪变质沉积岩,岩性主要为黑云母石英片麻岩、矽线石英片麻岩、角闪片麻岩、钙质片麻岩、长英质片麻岩、二云片岩和堇青石片岩。研究区图幅范围内分布有两个较大褶皱,位于北部的 Five Points Gulch-Hindman Gulch 等斜褶皱走向为北西-南东,南部的褶皱走向为近东西向(图2,图中 A 为角闪片麻岩褶皱西端,B 虚线部分为推测地质界线,褶皱东端被 Five Points 剪切带截断)。该地区经历了较强的变质、变形作用事件(1 700~1 400 Ma;Siddoway *et al*., 2000),地表露头面理近直立(图3a)。已查明岩浆侵入活动年龄为1 705、1 663和1 474 Ma(Noblett, 1987;Bickford *et al*., 1989;Siddoway *et al*., 2000;Wobus *et al*., 2001)。广泛发育的斜长石、石榴子石、红柱石和堇青石变斑晶(图3b)为区域构造变形历史过程研究提供了有效数据来源。Siddoway 等(2000)研究认为该地区在1 700 Ma到1 400 Ma期间经历了3期变形和2期变质作用事件。Cao(2009)通过对多期生长堇青石、斜长石和红柱石变斑晶面理弯切轴的研究,揭示该地区堇青石和红柱石等矿物生长过程至少经历了5期变质变形事件。由显微构造分析确定的面理弯切轴数据结合电子探针原位独居石 U-Th-Pb 年代学测定,确定区域内第1期到第5期面理弯切轴年龄为1 506~1 366 Ma。

1.2 地层结构关系

在堇青石片岩与矽线石片麻岩接触部位的等斜褶皱轴面附近测得的面理数据十分复杂(图4)。在图4所示的极点图上可以看出,面理统计数据主要反映晚期北北东到北东走向的变形。Gartner 等(2001)推断 Five Points Gulch-Hindman Gulch 褶皱形态为向形,认为此向形与研究区南部的背形为同期形成的褶皱。然而,南部的褶皱两翼间夹角大约为50°,比北部褶皱明显开阔。此外,Five Points Gulch-Hindman Gulch 褶皱东北部的钙质片麻岩并没有在南部重复出现,由此可推断这两个褶皱不可能是同期形成的。并且,这里可能存在一条平行于成分层的断层,使得堇青石片岩在东南部被截断(图2)。图2中 A、B 所标注的角闪片麻岩也同样被该断层截断。

2 技术方法及数据

2.1 面理弯切轴测量技术

变斑晶内包裹物迹线与变质变形作用之间的联系是近几十年来地质学家所关注的热点问题。变斑晶内包裹物迹线为早期形成的面理,这些包裹物迹线记录并保存了所经历的各期变质变形过程,是早期造山过程变形应力与温压条件研究的重要信息来源(肖龙等, 1993;Bell and Hickey, 1997, 1998;Bell and Welch, 2002;Ali, 2012)。变斑晶面理弯切轴(Foliation Intersection/Inflection Axes, FIAs)测量技术是变斑晶内包裹物迹线排列与区域面理发育过程之间联系研究的重要成果之一(李海兵等, 1997;Bell, 2010;Sanislav and Bell, 2011;Cao, 2012;Aerden

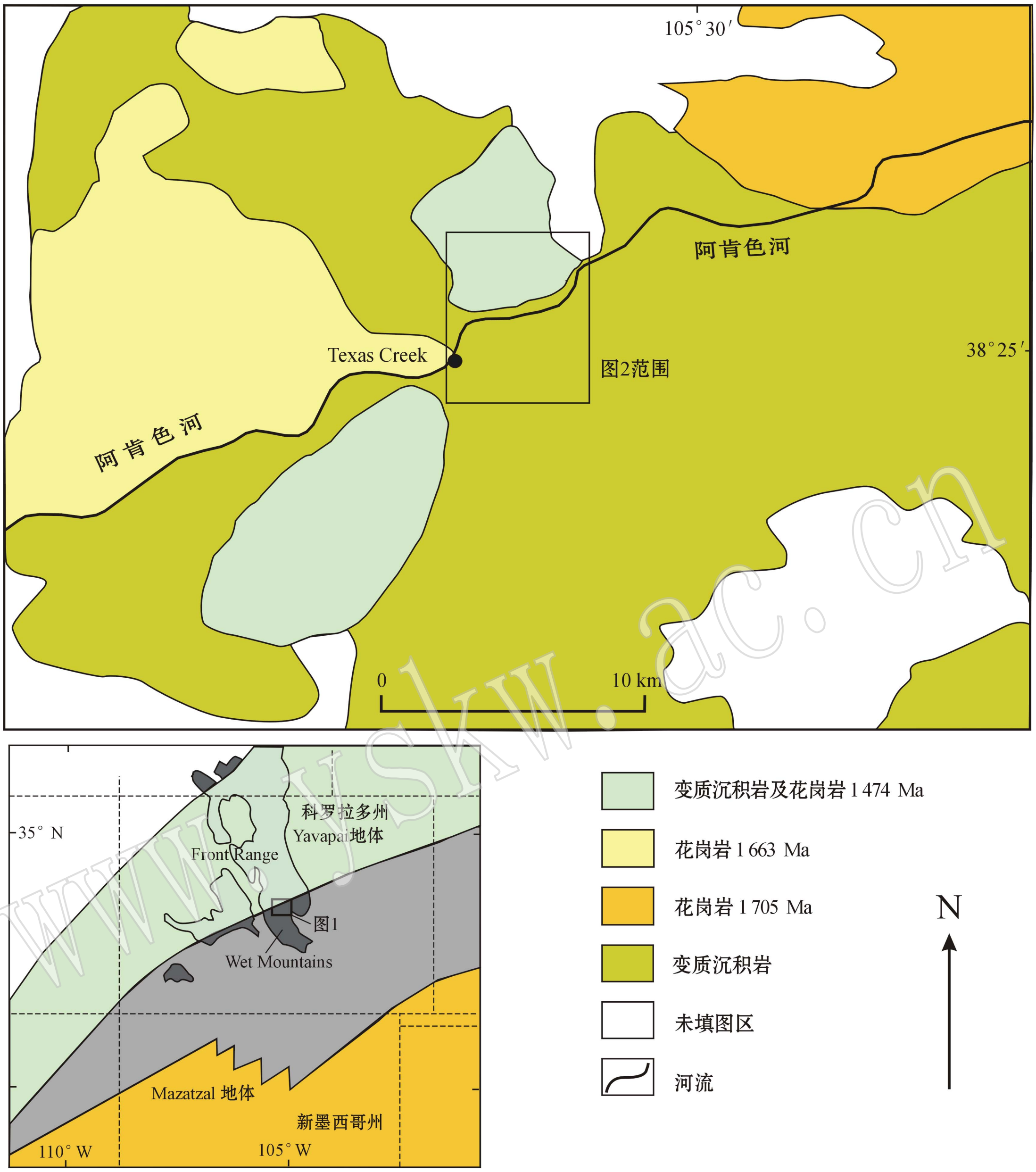

图 1　美国科罗拉多州阿肯色河 Texas Creek 地区地质简图[据 Siddoway 等(2000)和 Wobus 等(2001)修改]

Fig. 1　The location of the area described herein within a regional geological map of the Texas Creek, Arkansas River Canyon and relative to Colorado and New Mexico (modified after Siddoway *et al*., 2000 and Wobus *et al*., 2001)

et al., 2013)。面理弯切轴垂直于岩石变形过程中水平挤压主应力方向,不仅可作为板块相对运动方向的指示工具,也可用于划分区域各期变形事件,重建区域构造历史过程(Bell *et al*., 1995, 1998; Yeh and Bell, 2004; Cao and Fletcher, 2012; Ali, 2012)。

变斑晶面理弯切轴的测定是根据野外采集的同一定向标本中切制的水平面多个方向竖直定向薄片中变斑晶包裹物迹线几何形状(顺时针旋转或逆时针旋转)的变化来判定的。所用定向薄片的切制精度要求较高,首先要在室内将野外采集的定向标本精确复位(误差控制在 1°),然后沿大地坐标正北方向(标为 0°)每间隔 30°依次切制 6 个竖直薄片。在显微镜下观察定向薄片中包裹物迹线形状的变化。在判定发生顺时针与逆时针旋转相互转换的两个相邻 30°竖直定向薄片中间,每间隔 10°再切制两个定向薄片进一步观察,使面理弯切轴数据精确到 5°(图 5; Hayward, 1990; Bell *et al*., 1995, 1998; Shah, 2009, Sanislav and Bell, 2011)。

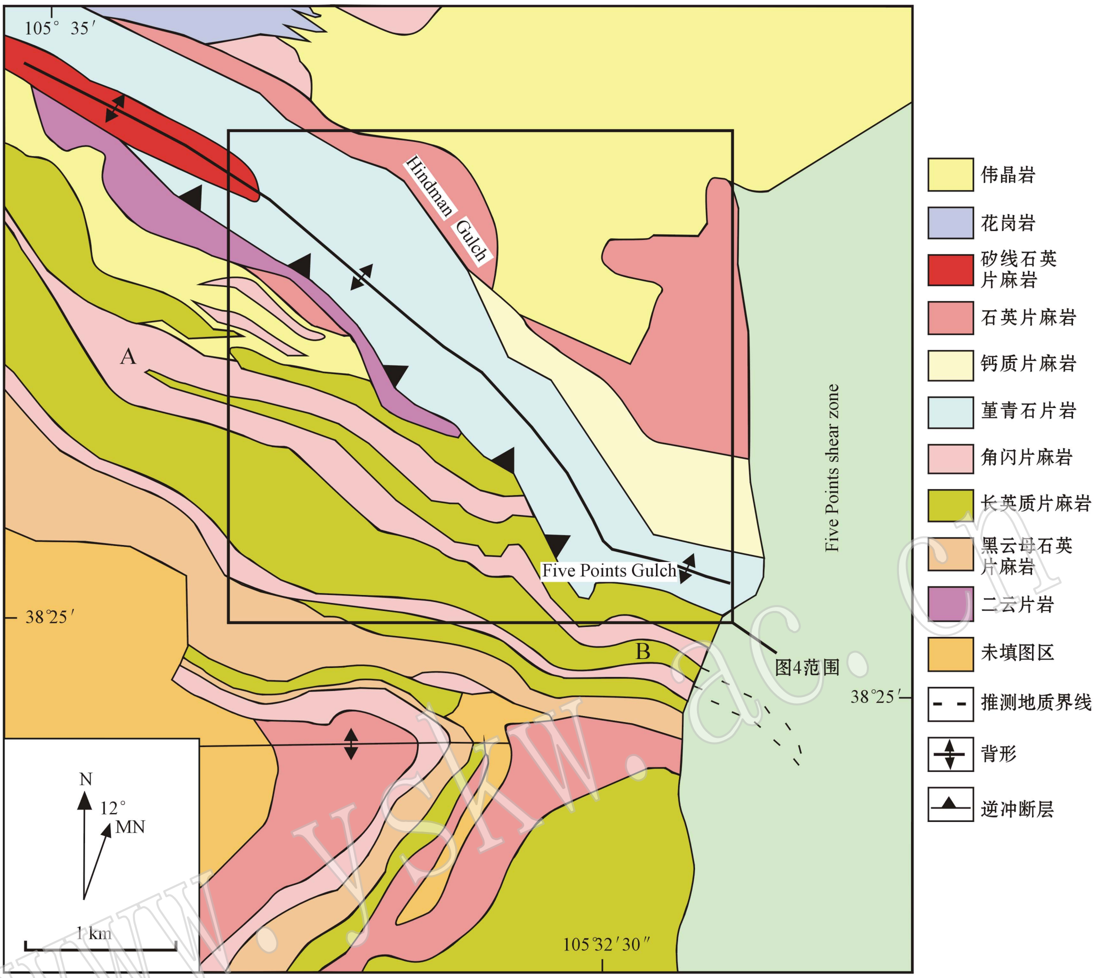

图 2 美国科罗拉多州阿肯色河 Texas Creek 以东地区地质图[根据 Cao 和 Fletcher(2012)修改]

Fig. 2 Geological map of the east Texas Creek, Arkansas River region of Colorado, USA (modified after Cao and Fletcher, 2012)

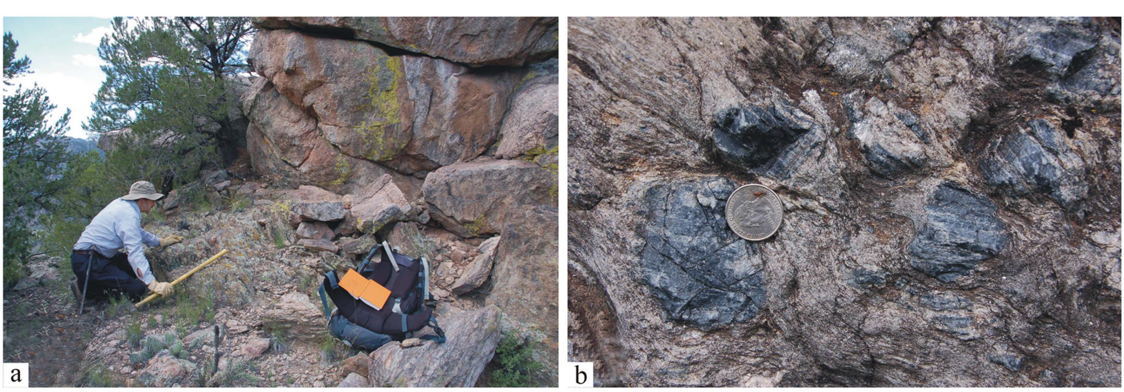

图 3 美国科罗拉多州阿肯色河 Texas Creek 以东地区野外近直立的露头(a)和堇青石变斑晶(b)

Fig. 3 Photo of steeply-dipping outcrop (a) and cordierite porphyroblasts (b) in Texas Creek, Arkansas River Colorado, USA

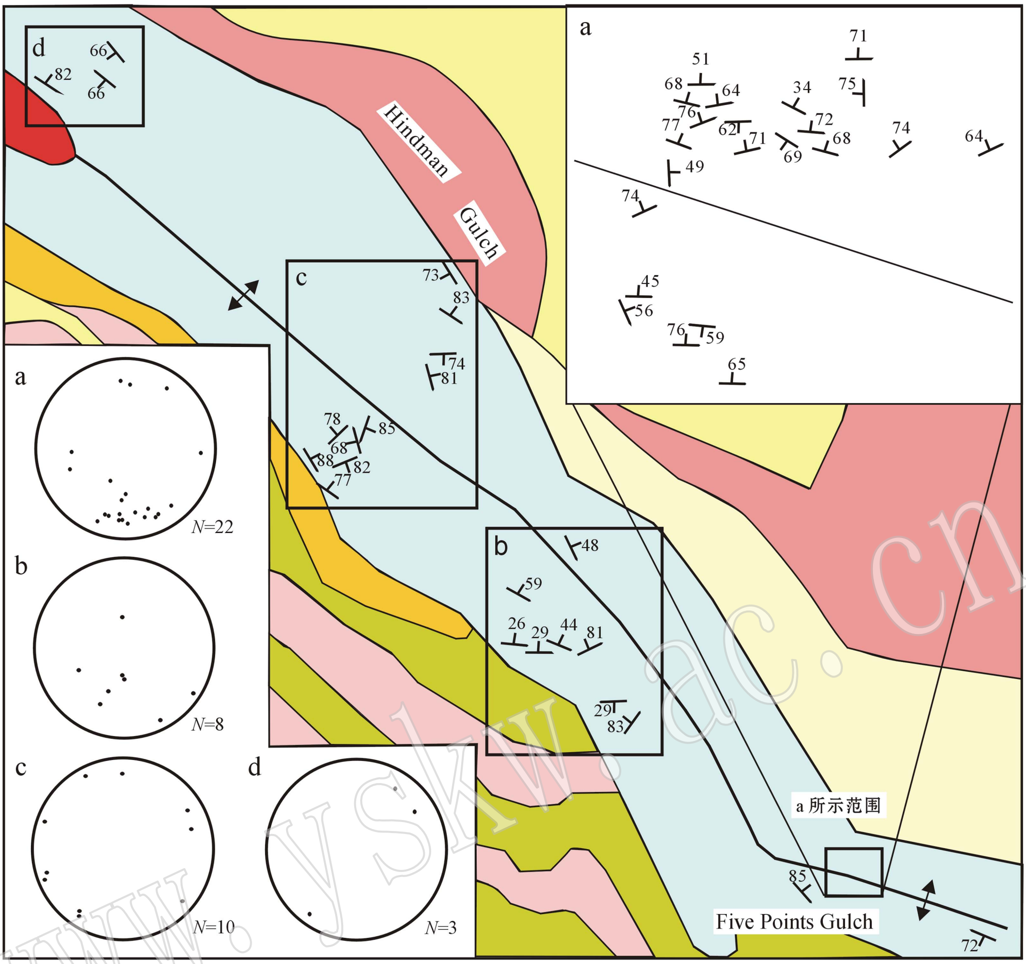

图 4　美国科罗拉多州阿肯色河 Texas Creek 以东研究区采样点图及面理数据赤平投影图(插图 a、b、c 和 d 分别为 4 个区域对应面理数据赤平投影数据)

Fig. 4　Geological map of the area showing the strike and dip of the foliations and stereonets show equal area projections of the poles to foliations for the four areas marked with boxes(the area “a” is shown at a larger scale in the inset in the top RH corner)

多期生长变斑晶包裹物迹线在核部与翼部形状一般会发生变化,也有部分多期生长变斑晶会形成褶劈理(crenulation cleavage 和 crenulated cleavage)(图 6)。根据包裹物迹线由核部到翼部几何形状的变化及褶劈理,可以确定不同期次面理弯切轴形成的先后顺序(Bell, 2010; Cao and Fletcher, 2012)。

2.2　面理弯切轴数据

Cao(2009)由美国科罗拉多州中部阿肯色河 Texas Creek 以东 Hindman Gulch 和 Five Points Gulch 采集的 46 个堇青石片岩样品(采样点见图 4)测得 63 个面理弯切轴数据。通过对变斑晶面理弯切轴的研究,揭示该地区堇青石和红柱石等矿物生长至少经历了 5 期变质变形事件。由多期生长变斑晶内包裹物迹线分析确定区域 5 期面理弯切轴形成的先后顺序如下:第 1 期 FIA 1 为西-东走向,第 2 期 FIA 2 为南西-北东走向,第 3 期 FIA 3 为北北西-南南东走向,第 4 期 FIA 4 为北西-南东走向,第 5 期 FIA 5 为南西-北东走向(图 7)。结合电子探针原位独居石 U-Th-Pb 年代学测定,确定各期面理弯切轴年龄如下:第 1 期 FIA 1 年龄为1 506±15 Ma,第 2 期 FIA 2 年龄为1 467±23 Ma,第 3 期 FIA 3 年龄为1 425±18 Ma,第 5 期 FIA 5 年龄为1 366±20 Ma。用于确定 4 期面理弯切轴的变斑晶内未包含适合年代学测定的独居石颗粒,第 4 期面理弯切轴年龄数据未测得。

2.3　面理弯切轴对应叠加面理数据

面理弯切轴对应叠加面理(变斑晶内包裹物迹线)几何形状的不对称性可以用于判定变斑晶生长

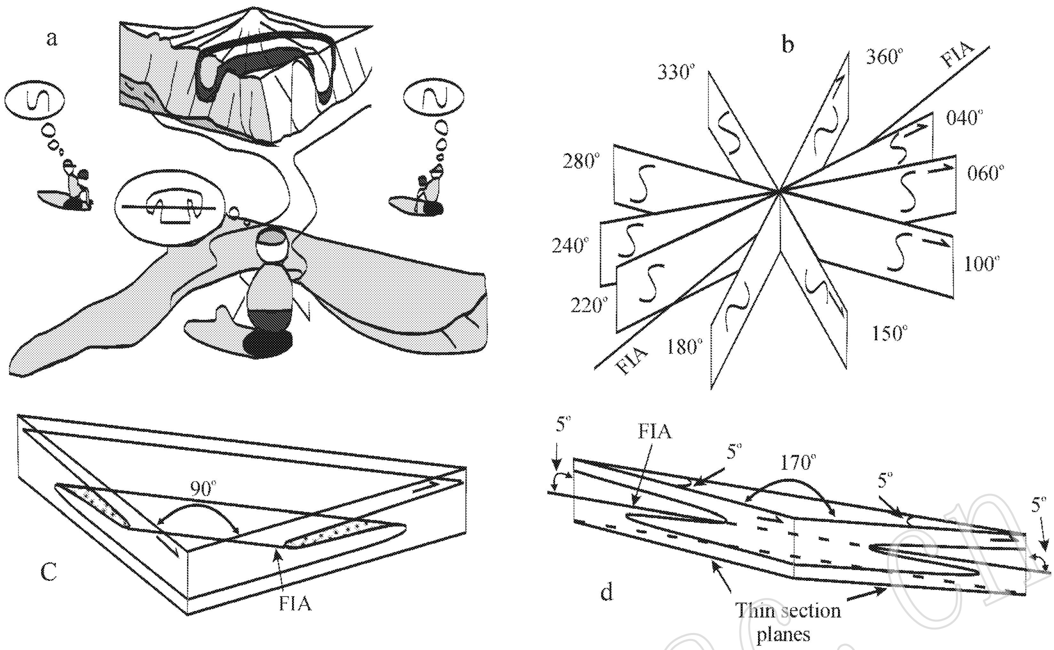

图 5　面理弯切轴(FIA)原理示意图[根据 Bell 等(2004)修改]

Fig. 5　Sketch illustrating the principle behind FIA measurement (after Bell *et al*., 2004)

a—在野外从相互垂直的两个剖面观察同一褶皱可得到几何形状相反的"S"和反"S",仅从一个剖面观测很难推测褶皱形成时挤压应力的方向,只有同时观测到褶皱两个剖面,才能判断褶皱在三维空间的形态; b—FIA 位于从同一方向观察到的变斑晶包裹物迹线几何形状相反(40°时为顺时针旋转"S",360°时为逆时针旋转反"S")的临近两薄片中间; c—两薄片切面夹角为 90°且与 FIA 的交角均为 45°; d—两薄片切面夹角为 170°且与 FIA 的交角均为 5°

a—the geologists on either side see the opposite asymmetry for the same fold in a cliff face, they have no idea of its trend in 3-D, the geologist at the center sees the fold on both cliff faces and knows it must trend from one to the other; b—the asymmetry on a series of differently-striking vertical sections, the asymmetry flips across the compass viewed in the same direction; c—asymmetry of a sigmoid axis in two sections cut 90° apart; d—the sigmoid axis of (c) in two sections cut 10° apart lying on either side of the axis, the switch in asymmetry between them defines the location of the axis within a 10° range

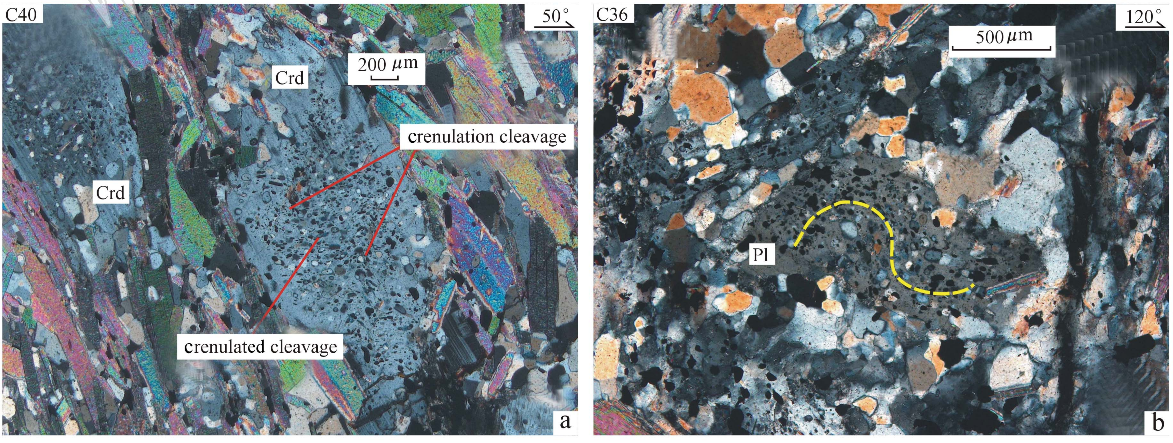

图 6　美国科罗拉多州中部阿肯色河 Texas Creek 地区堇青石变斑晶中细褶皱劈理(crenulated cleavage)与夹皱劈理(crenulation cleavage)(a)及斜长石变斑晶中逆时针旋转包裹物迹线(b)显微照片(正交偏光)

Fig. 6　Crenulation cleavage and crenulated cleavage in cordierite porphyroblast (a) and anticlockwise inclusion trails in plagioclase porphyroblasts (b) from Texas Creek, Arkansas River Canyon, Colorado, USA

过程各期变形事件剪切运动方向和褶皱形成时代的相对顺序(Bell and Bruce, 2007)。各期面理弯切轴对应叠加面理几何形状的不对称性是通过显微镜下目视观察垂直(水平夹角为 90°,由南往北观察)或接近垂直面理弯切轴方向的竖直薄片内变斑晶包裹物迹线的几何形状来判定的。例如:确定 NNE-SSW

方向的研究区内第 2 期面理弯切轴(FIA2)叠加面理的几何形状，需要选择观察 ESE-WNW 方向的竖直薄片(图 7)。叠加面理几何形状的不对称性可划分为 4 种类型：由水平到竖直转变的顺时针旋转，水平到竖直转变的逆时针旋转，竖直到水平转变的顺时针旋转和竖直到水平转变的逆时针旋转。

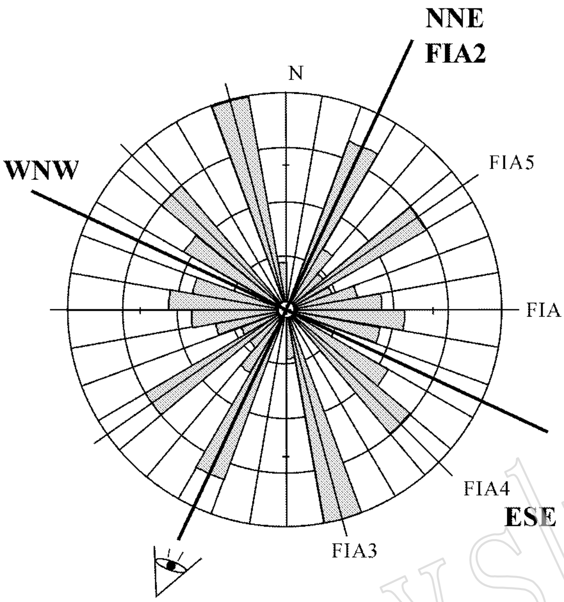

图 7　面理弯切轴对应叠加面理几何形状不对称性的判定示意图［根据 Cao(2009)修改］

Fig. 7　Sketch showing the determination of the asymmetries for samples containing FIA (modified after Cao, 2009)

3　数据解释

3.1　褶皱形成时代

在褶皱形成过程中生长的变斑晶，处于褶皱不同两翼，所包含的包裹物迹线(叠加面理)几何形状是不同的(Bell *et al*., 1986；Bell and Hayward, 1991)。如图 8 所示，在褶皱左翼生长的变斑晶内包裹物迹线为逆时针旋转(ACW)，生长于褶皱右翼的变斑晶内包裹物迹线则为顺时针旋转(CW)。而在褶皱形成后生长的变斑晶则更多是在褶皱不易发生再活化作用的一翼成核生长(Bell *et al*., 2003, 2004)。如果再活化作用从区域变形过程之初就存在，则很少有变斑晶生长在这一翼，因为变斑晶受到再活化作用的影响很难成核生长(图 9)。这一变斑晶成核生长理论可以用于解释图 10 中的统计数据。

3.2　向形还是背形？

图 10 所示为图 2 中 Five Points Gulch-Hindman Gulch 褶皱 SW 和 NE 两翼各期面理弯切轴对应叠加面理几何形状不对称性数据统计图，其中，a 和 b 中下部两个由水平到竖直变化的变斑晶包裹物迹线分别指示了背形和向形形成过程中叠加面理在褶皱两翼的形态；c 和 d 中柱状图分别表示褶皱 SW 和

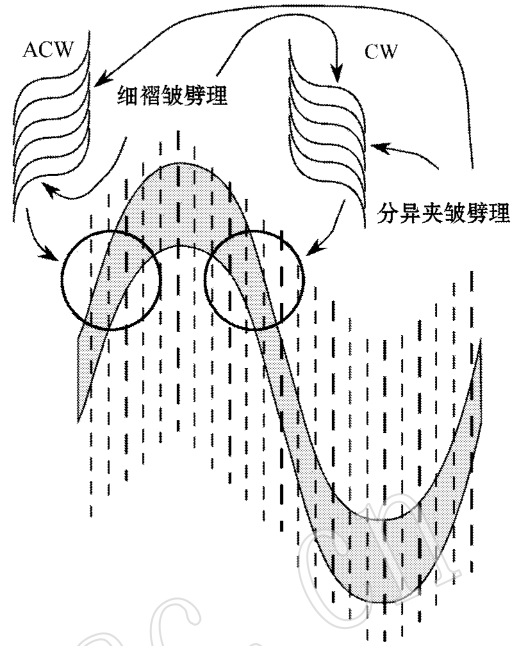

图 8　褶皱形成过程中生长在褶皱两翼的变斑晶内包裹物迹线形状示意图［根据 Bell 等(2003)修改］

Fig. 8　Cross-section showing how the "differentiation" asymmetry of cleavage changes is across a fold hinge for a crenulation cleavage that accompanies fold development (after Bell *et al*., 2003)

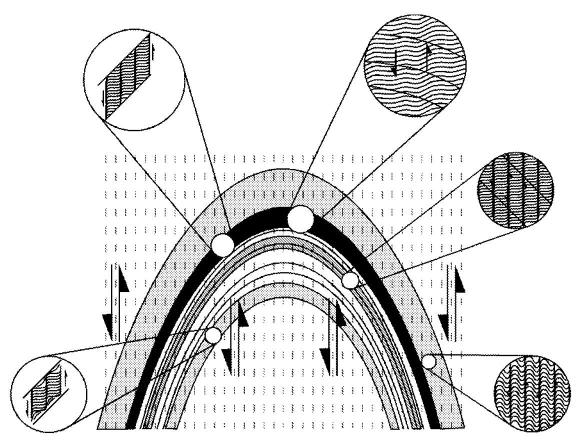

图 9　褶皱形成后变斑晶在褶皱两翼成核、生长过程示意图［根据 Bell 等(2003)修改］

Fig. 9　Sketch showing anticlockwise shear operating on a sub-vertical axial plane cleavage on both limbs of an earlier formed fold that was previously overprinted by a sub-horizontal foliation (after Bell *et al*., 2003)

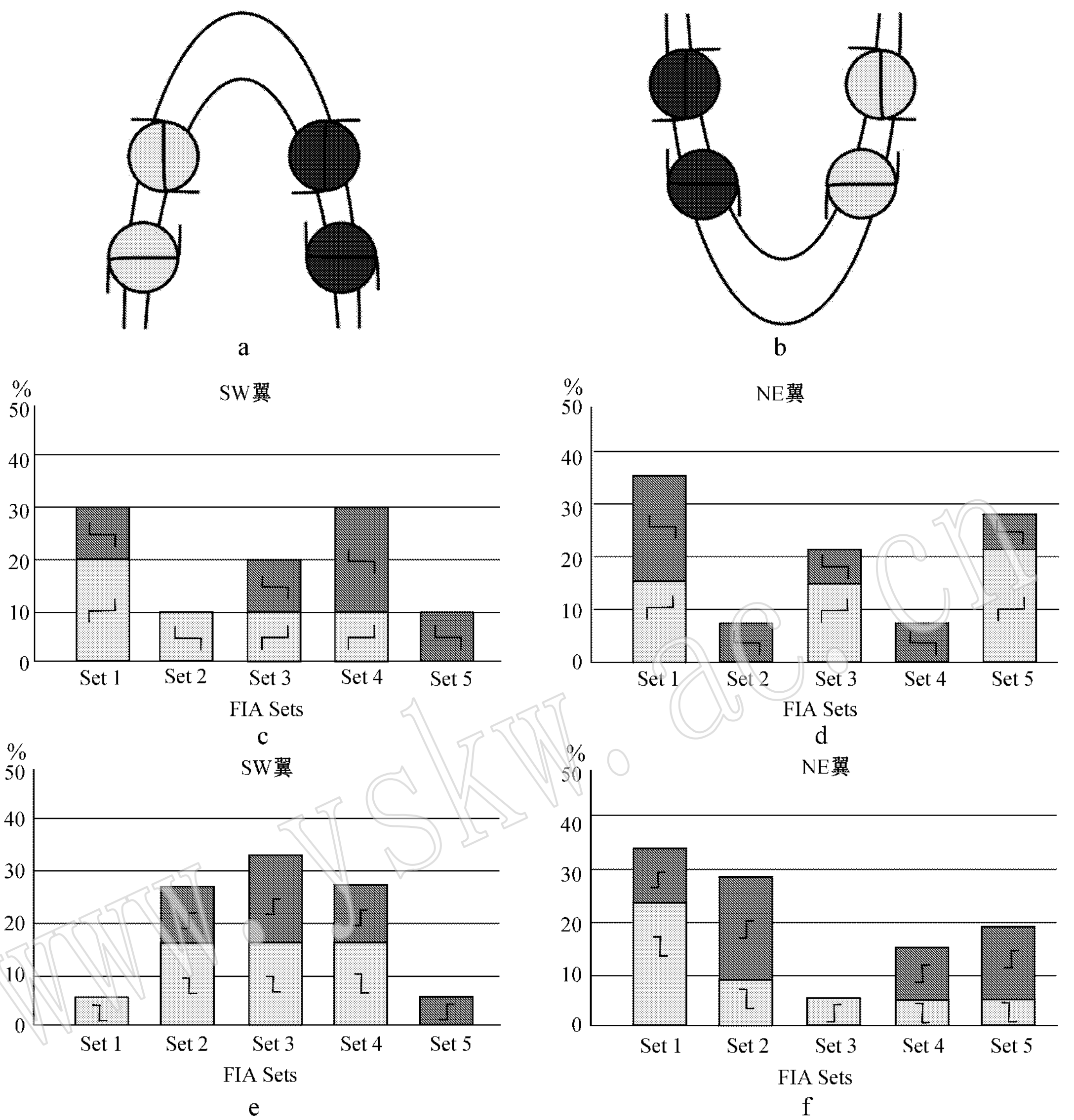

图 10 褶皱南西(SW)和北东(NE)两翼各期面理弯切轴对应叠加面理几何形状不对称性统计图

Fig. 10 Histograms for each limb (SW and NE) of the fold showing the asymmetry of inclusion trails changing from gentle to steep and steep to gentle pitches preserved within porphyroblasts

NE 两翼中保存的各期面理弯切轴由水平到竖直变化的叠加面理数据;e 和 f 中柱状图分别表示褶皱 SW 和 NE 两翼中保存的各期面理弯切轴由竖直到水平变化的叠加面理数据。在由水平到竖直转变的叠加面理几何形状不对称性数据中(图 10c、10d),第 1 期面理弯切轴(FIA1)对应叠加面理在 SW 翼逆时针旋转占多数,而在 NE 翼顺时针旋转占多数。如果变斑晶在褶皱形成过程中生长,则上述统计数据与褶皱为向形的情况截然相反。若该褶皱确定为向形,则由此可推断褶皱形成时间应早于第 1 期面理弯切轴。Ham 和 Bell(2004)、Bell 等(2005)对早于变斑晶生长形成的褶皱中变斑晶包裹物迹线几何形状的不对称性研究证明,它们一旦形成,很难在后期变形事件中发生再活化作用。同样,这种解释也无法说明该褶皱形成于其后几期面理弯切轴形成过程中。第 3 期面理弯切轴(FIA3)在 NE 翼以逆时针旋转为主;第 4 期面理弯切轴(FIA4)在 SW 翼以顺时针旋转为主;而第 5 期面理弯切轴(FIA5)NE 翼上逆时针占多数。如果该褶皱为向形,以上数据很难解释变斑晶生长过程与褶皱形成之间的关系(Bell *et al.*, 2003, 2005;Ham and Bell, 2004;Bell and Newman, 2006)。

若该褶皱为背形，第 1 期面理弯切轴（FIA1）在 SW 翼逆时针旋转叠加面理占多数，在 NE 翼以顺时针旋转叠加面理为主，则可以说明该褶皱形成于第 1 期面理弯切轴形成过程。在褶皱的 SW 翼，第 4 期（FIA4）和第 5 期（FIA5）面理弯切轴数据中以顺时针为主；在褶皱的 NE 翼，第 3 期（FIA3）和第 5 期（FIA5）面理弯切轴数据中以逆时针为主，可以用褶皱形成后变斑晶在褶皱两翼的成核生长理论（图 9，Bell *et al*.，2003）解释。根据以上分析，可推断该褶皱形态为背形，形成于第 1 期面理弯切轴形成过程中。

该褶皱形态为背形而不是向形，可由竖直到水平转变的面理弯切轴对应叠加面理几何形状不对称性统计数据进一步验证（图 10e、10f）。由竖直到水平转变的叠加面理几何形状不对称性数据中，在 SW 翼第 2 期和第 4 期面理弯切轴以逆时针旋转为主，在 NE 翼第 2 期、第 4 期和第 5 期面理弯切轴以顺时针旋转为主。这完全符合褶皱形成后变斑晶在褶皱两翼成核生长理论，进一步说明该褶皱形态为背形。

4　讨论与结论

Gartner 等（2001）认为图 2 中北部 Five Points Gulch-Hindman Gulch 褶皱与南部相对较开阔的背形是同期形成的褶皱，所以推断其形态为向形。通过对研究区南北两个褶皱两翼间夹角的对比分析认为：北部褶皱两翼间夹角较小，且为等斜褶皱，而南部的褶皱两翼夹角明显相对较大，这两个褶皱不可能为同期形成的褶皱。由于研究区褶皱经历了多期变形且变形叠加复杂，根据野外露头观测和面理数据的统计分析很难判断褶皱形态。根据变斑晶在褶皱形成过程中生长于褶皱两翼包裹物迹线（叠加面理）几何形状变化以及变斑晶成核生长与褶皱形成过程理论，由各期面理弯切轴对应叠加面理几何形状不对称性数据统计分析，确定研究区北部 Five Points Gulch-Hindman Gulch 褶皱形态为背形，形成于区域内第 1 期面理弯切轴形成过程（约为 1 500 Ma；Cao，2009）。可见，变斑晶面理弯切轴对应叠加面理几何形状的不对称性数据可有效判定多期变形变质带复杂褶皱形态及形成时代。该方法可广泛应用于包含有变斑晶的类似地区复杂褶皱结构关系的判定，为复杂变质带构造演化过程研究提供新的数据来源。

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