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布容期以来中国黄土沉积地磁极性漂移事件研究进展

Review of the magnetic excursions in Brunhes chron recorded in loess sediments in China

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摘　要　黄土高原风尘沉积序列厚度大、地层连续,是高分辨率古地磁研究和古气候研究的理想材料. 然而,缺少精确年龄控制点制约了黄土古气候信息的区域对比和海陆对比研究. 地磁极性漂移是地球磁场长期变化过程中的基本行为之一,全球同步性使其成为古气候研究可靠的年龄控制点. 布容正极性时记录了多次极性漂移事件,为高分辨率黄土古气候学提供的新的途径. 通过回顾近年来的研究成果可知,黄土沉积物广泛记录了 Laschamp 和 Blake 地磁极性漂移事件,且部分剖面中存在 Mono Lake 事件的报道. 此外尚未明确限定的倾角变负波动不断提出,极大地拓展了黄土沉积物极性漂移事件研究的深度和广度. 然而,部分高沉积速率黄土剖面存在极性事件缺失现象对黄土沉积物可以稳定记录地磁极性漂移事件提出了质疑. 目前对这一现象的解释有剩磁获得机制、Lock-in 效应、沉积间断和气候响应等. 然而,热退磁可有效去除化学剩磁(CRM)的影响,与 CRM 密切相关的剩磁获得机制无法解释相近区域内极性事件记录的差异. 黄土沉积物较浅的 Lock-in 效应否定了其会普遍引起极性事件记录的缺失. 黄土高原内部低沉积速率(小于 10 cm/Ka)地区千年尺度极性事件和地磁场长期变化的记录否定了黄土沉积存在千年尺度的沉积间断. 本文通过分析已有研究成果,认为极性漂移期间地磁场稳定性较差,导致磁性颗粒记录的磁场信息存在差异,可能是极性事件记录缺失的主要原因.

关键词　黄土;布容期;地磁极性漂移

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Abstract　The thick and continuous aeolian loess sequences from Chinese Loess Plateau (CLP) were ideal research materials for paleomagnetic study and paleoclimate research. For the lack of precise age point, uncertainty occurs in regional comparisons and land-ocean comparisons. Magnetic excursion is one of the basic behave in secular variation of the Earth's magnetic field. The global synchronism makes it become the reliable age control tie in the paleoclimate study. The Brunhes chron remarks much times of the magnetic excursions, which provide new way for high resolution loess paleoclimate research. Through the past successes of magnetic excursion research in loess sediments in Brunhes chron, we know that the loess deposition recorded the Laschamp and Blake excursion excellently in different areas in Chinese Loess Plateau (CLP). And the Mono Lake excursion record could be detected in some loess profile. It made the studies of magnetic excursions in loess sediments receives much concern in recent years. However, the absence of excursions in some loess section with high sediment rate caused a suspicion that the Chinese loess could not record the magnetic excursions reliably. To explain this annoyance, much factors like magnetic remanence mechanism, lock-in effect, depositional break and climate response in loess deposition had been discussed. But these could be debated for: 1) Thermal treatment could remove the chimerical remanence efficaciously. 2) The lock-in effect in loess deposition should be shallow (less than 5-10 cm). 3) Chinese loess deposition could record short lived magnetic excursion and millennial secular variation in magnetic field in low sediment rate area in the CLP internal. And we discussed the directional abnormality correlated with low field intensity during the presence of magnetic excursion would be the most important cause for the absence of excursions in some magnetic studies in CLP. The future study of magnetic excursions in loess deposition in CLP would be based on high resolution magnetostratigraphy with high precision timing model.

Keywords　loess; Brunhes chron; magnetic excursion

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0　引　言

地磁漂移(Magnetic Excursion)是指虚磁极(VGP)偏离地磁场长期变化正常范围的现象,也可以定义为虚磁极相对正常值快速摆动大于 45°的行为(Merrill and McFadden, 1994; Laj and Channell, 2007; Roberts, 2008). 大量磁性地层学研究表明,地磁漂移事件并非只发生于局部,而是具有很好的全球性(Guillou *et al.* , 2004; Lund *et al.* , 2005; Laj *et al.* , 2006; Channell, 2006; Cassata *et al.* , 2008). 宇成核素的高通量值多发生于地磁漂移过程中(Wagner *et al.* , 2000),则进一步证明地磁漂移这一地磁场行为具有全球同步性(Laj and Channell, 2007; Roberts, 2008). 由此可见,地磁漂移事件可以作为年代学研究的可靠控制点(Laj and Channell, 2007; Roberts, 2008). 在海洋沉积物的第四纪年代学研究中,GITS 时间标尺已经吸纳了大量极性漂移事件作为精确年龄控制点(Guyodo and Valet, 1999; Laj *et al.* , 2006; Valet *et al.* , 2008; Thouveny *et al.* , 2008; Channell *et al.* , 2009, 2012; Singer, 2014),为高分辨率古气候研究奠定了年代学基础.

黄土沉积物分布广泛、沉积厚度大、且区域地层对比良好,是高分辨率古气候研究的理想材料(刘东生, 1985; 安芷生等, 1998, 2006; Maher and Thompson, 1999; An, 2000). 大量的古地磁学工作已经证明,中国黄土不仅能够记录主要的地磁漂移事件(Heller and Liu, 1982; Zhu *et al.* , 1994, 1999, 2006a,b; Zheng *et al.* , 1995; Fang *et al.* , 1997; Pan *et al.* , 2002; Yang *et al.* , 2004, 2007),而且能够记录地磁漂移过程的精细结构(Zhu *et al.* , 1994; Fang *et al.* , 1997)乃至地磁场的长期变化特征(Heslop *et al.* , 1999; Zhu *et al.* , 2000). 因此,地磁漂移事件的厘定在黄土年代学研究中具有重大的研究价值. 本文将通过分析前人的研究成果,总结目前布容期以来我国黄土沉积地磁极性漂移事件的研究现状和进展,并分析存在的问题.

1　黄土沉积物地磁极性漂移事件的研究意义

广泛分布于中国黄土高原的黄土-古土壤风尘堆积序列具有粒度细、沉积速率高、连续性好、地层层序完整等特征,是蕴含古地磁和古气候信息最为丰富的晚新生代陆相沉积物. 它系统记录了第四纪以来亚洲内陆季风-干旱环境的演化历史和主要的地磁极性倒转过程,在第四纪地质学、古气候学、地层学和古地磁学等研究领域都占有举足轻重的地位(刘东生, 1985; Kukla and An, 1989; An *et al.* , 1990; Evans *et al.* , 1997; 安芷生等, 1998; An, 2000).

在黄土-古土壤序列古环境、古气候研究中,精确定年是最基础、且最核心的工作. 目前应用的主要定年手段有古地磁、光释光(OSL)和^{14}C 放射性同位素定年等手段. ^{14}C 测年技术为重建全新世气候变化,特别对某些极端气候事件精确测年提供了技术支持 (Zhou *et al.* , 1999). 然而,由于残留碳的影响,对于较老沉积物(早于 35 ~ 50 Ka)的年代测定仍存在系统性偏差(Bailey, 2004). 光释光测年为重建 130 Ka 以来的黄土古气候序列提供的良好的时间标尺(Lu *et al.* , 1999),是末次间冰期以来黄土古气候学研究的主要定年手段. 随着理论的发展和技术的更新,Wang 等(2006)尝试通过细颗粒石英回授 OSL 年龄测定,将光释光测年在黄土中的应用延长至 800 Ka,并重新标定了洛川黄土 800 Ka 以来的年代标尺. 然而,该方法的重复性仍然没有得到广泛的认可.

因此,对于早布容期以来,尤其是早于 130 Ka 以来黄土年代学框架的建立,磁性地层学仍然是唯一的手段(Heller and Liu, 1982; Ding *et al.* , 2001; An *et al.* , 2001; Qiang *et al.* , 2001; Guo *et al.* , 2002). 近年来,磁化率时间标尺(Heller and Liu, 1982; Kukla *et al.* , 1988; Heslop *et al.* , 2000)、粒度年代模型(An *et al.* , 1990; Ding *et al.* , 1994, 2002)、以及轨道调谐方法(Ding *et al.* , 1994; Heslop *et al.* , 2000; Sun *et al.* , 2006)在黄土年代学中的应用,使黄土古气候学进入了高分辨率时代.

各种年代模型的建立均离不开精确的年龄控制点,否则就会给黄土古气候的区域对比和海陆对比带来不确定性. 因此,对于布容期以来的黄土高分辨率年代学研究,仅靠布容/松山(B/M)极性界限这一个年龄控制点是远远不够的(Zheng *et al.* , 1995; Fang *et al.* , 1997; Yang *et al.* , 2004, 2007). 地磁漂移是地球磁场在长期变化过程中的基本行为之一,具有全球同步的特点(Roberts and Winklhofer, 2004, Laj and Channell, 2007; Roberts, 2008),可以作为磁性地层学研究中的年龄节点(Champion *et al.* , 1988; Langereis *et al.* , 1997; Lund *et al.* , 2006; Valet *et al.* , 2008). 随着大量时间跨度大、分辨率高的沉积序列(Laj *et al.* , 2006; Laj and Channell, 2007)的系统研究,地磁漂移的发生频率、持续时间及漂移期间地磁场的形态特征逐渐成为地学研究中的一个热点问题(Zhu *et al.* , 1999; Tauxe and Kent, 2004; Laj and Channell, 2007; Roberts, 2008; Valet *et al.* , 2008; Singer, 2014),成为黄土高分辨率年代学研的新途径(Roberts, 2008; Valet *et al.* , 2008; Zhou *et al.* , 2010; Singer, 2014).

2　布容期以来主要的地磁极性漂移事件

目前,关于地磁漂移事件的研究,主要集中于深海沉积物和熔岩流当中,布容期内已经报道的极性漂移事件有十几个之多(Langereis *et al.* , 1997; Worm, 1997; Lund *et al.* , 2001, 2006; Singer *et al.* , 2002; Thouveny *et al.* , 2004; Laj and Channell, 2007; Roberts, 2008; Valet *et al.* , 2008; Kissel *et al.* , 2011; Channell *et al.* , 2012; Singer, 2014). 如表 1 所示,其中确认的极性漂移事件(具有严格的年龄限制,且可以在不同的沉积序列中进行验证)主要有 Mono Lake(32 ka)、Laschamp(41 ka)、Blake(120 ka)、Post-Blake(100 Ka)、Iceland Basin(188 ka)、Pringle Falls(211 ka)、Big Lost(560 ~ 580 ka)、Los Tilos(590 Ka)、Stage 17(670 ka)(Laj and Channell, 2007; Bol'shakov, 2007; Roberts, 2008; Valet *et al.* , 2008; Thouveny *et al.* , 2008; Roberts *et al.* , 2013; Singer, 2014). 其他经报道的极性漂移事件还有 Hilina Pail (17 ka)、Nor-Greenland Sea (70 ka)、CR0 (260 ka)、CR1 (325 ka)、Un-named(400 ka)、CR2 (525 ka)、WE5(528 ka)、WE4(579 ka)、WE2(626 ka)、WE1(722 ka),但或因无法获得准确的时间,或仅为"一孔之见", 发生时间或存在的真实

性还有待进一步确认(Laj and Channell, 2007; Bol'shakov, 2007; Roberts, 2008; Valet *et al.*, 2008; Thouveny *et al.*, 2008; Roberts *et al.*, 2013; Singer, 2014).

表 1　布容期以来主要的地磁极性漂移事件

Table 1　The main magnetic excursions in the Brunhes chron.

Magnetic Excursion	Age(Ka)	Magnetic Excursion	Age(Ka)	Magnetic Excursion	Age(Ka)	Magnetic Excursion	Age(Ka)
Hilina Pali/ Changbaishan	17						
Mono Lake	32	Mono Lake	33	Mono Lake	33		
Laschamp	41	Laschamp	41	Laschamp	40	Laschamp	40 ~ 45
		Norwegian-Greenland Sea	70	Norwegian-Greenland Sea	60	Norwegian-Greenland Sea	70 ~ 80
Post-Blake	100						
Blake	120	Blake	120	Blake	120	Blake	110 ~ 120
						Albuquerque/Fram Strait	155 ~ 165
Iceland Basin	188	Iceland Basin	188	Iceland Basin	188		
Pringle Falls	211 ~ 212	Pringle Falls	211	Pringle Falls	211	Jamaica/Pringle Falls	205 ~ 215
Laguna del	341 ~ 343	Calabrian Ridge 0	260	Calabrian Ridge 0	260	Fram Strait/CRO?	255 ~ 265
				Calabrian Ridge 1	325	Calabrian Ridge 1	315 ~ 325
				Levantine	360 ~ 370		
				Un-named	400	unknown?	400 ~ 420
Sello ?		Calabrian Ridge 2	525	Calabrian Ridge 2	525	Calabrian Ridge 2/WE 1	515 ~ 525
West Eifel 5	528 ~ 531						
		West Eiffel 4	555				
Big Lost/West Eifel 4	555 ~ 559	Big Lost	560 ~ 580	Big Lost	560 ~ 580	Emperor/Big Lost/Cr3	560 ~ 570
Los Tilos	579 ~ 583						
West Eifel 2	626 ~ 630	West Eiffel 2	626 ± 24				
Stage 17	670	Stage 17	670	Stage 17	670		
West Eifel 1	722 ~ 729	West Eiffel 1	722 ± 38				
Singer, 2014		Roberts *et al.*, 2013		Laj and Channell, 2007		Bol'shakov, 2007	

注:表格最下端为主要综述性文章,其中加粗字体表示为全球性的事件,或事件具有良好的时间限定;其余则为没有良好时间限定的事件,或是仅为区域性事件,还有待进一步证实.

3　中国黄土沉积记录的地磁极性漂移事件

自 20 世纪 70-80 年代以来,国内外学者对我国黄土高原黄土-古土壤序列陆续展开了大量磁性地层学研究(王永焱等, 1980; Heller and Liu, 1982; 岳乐平, 1985; Liu *et al.*, 1988;安芷生等, 1989; 丁仲礼和刘东生, 1989; 陈发虎等, 1989; Rolph *et al.*, 1989),为第四纪风成堆积序列年代学框架的建立和黄土地层划分奠定了年代学基础(刘东生, 1985; Heller and Evans, 1995; Evans and Heller, 2001; 邓成龙等, 2007; Liu *et al.*, 2015). 布容正极性时中出现的负极性事件逐渐受到了关注,如兰州九州台剖面中报道了 Blake 和 Biwa 事件(Rolph *et al.*, 1989),靖远曹岘剖面检测出了 Blake 和 Emperor 事件(岳乐平等, 1991),合阳剖面报道了 Blake、吉曼卡(Biwa C)和 Biwa E 事件(王永焱等, 1980),洛川后子头公社腰子村 11-1 孔报道了 Blake 和吉曼卡(Biwa C)事件(王永焱等, 1980),长武丁家沟剖面报道了哥德堡和 Laschamp 事件(王永焱等, 1980),渭南阎村 W7 孔检测出了 Emperor 事件(葛同明等, 1991),陕县剖面 S1 中发现了 Blake 事件(岳乐平等, 1984). 这些早期的工作明确了中国黄土-古土壤序列可以记录地磁极性漂移事件,是潜在的地磁极性漂移事件研究的良好陆上载体,为进一步研究黄土沉积物记录的极性漂移事件提供了理论基础和实践经验. 如岳乐平(1995)通过总结了数十个黄土沉积序列的古地磁结果后认为中国黄土中普遍记录有 Laschamp、Blake 和 Emperor 事件.

然而,这些工作的研究目的并非针对极性漂移事件本身,因此采样分辨率较低,无法获得极性漂移事件的详细过程和确切年代. 导致检出事件的真实性普遍受到质疑,制约了高分辨率黄土古气候学的展开. 为此,20 世纪 90 年代以来,大量高分辨率磁性地层学工作不断展开,并且完成了众

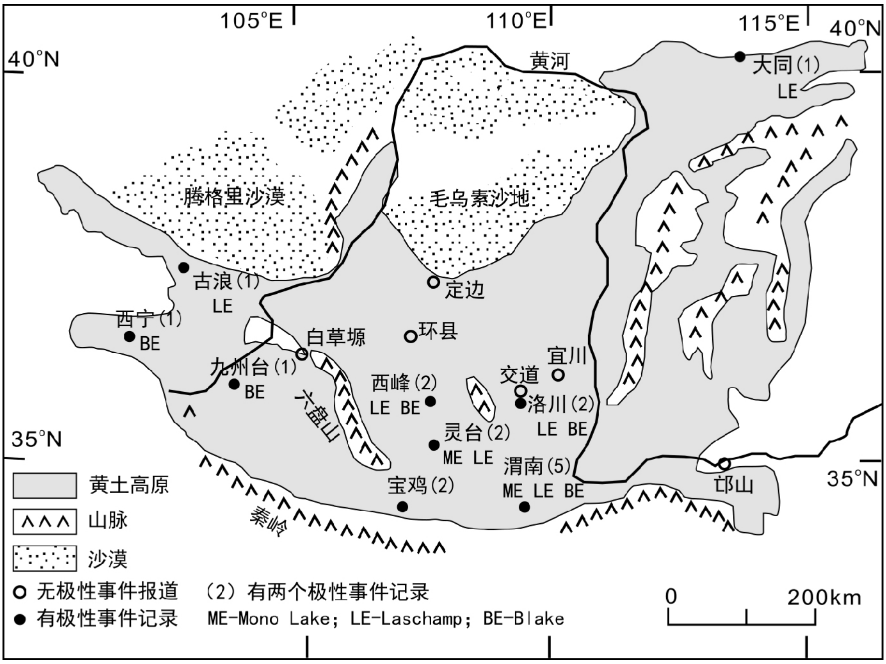

图 1 布容期以来中国黄土沉积记录的极性事件

Fig. 1 The map of magnetic excursions recorded in loess deposits in China in the Brunhes chron

多针对地磁极性漂移事件的高分辨率磁性地层学研究(Zhu *et al.* , 1994, 1999, 2006b；Zheng *et al.* , 1995；Fang *et al.* , 1997；Pan *et al.* , 2002；Yang *et al.* , 2004, 2007；Sun *et al.* , 2013)，并且取得了大量系统性认识.

中国黄土沉积中报道最多，研究最充分的极性漂移事件是 Laschamp 和 Blake 事件. 渭南(Zhu *et al.* , 1999；Pan *et al.* , 2002；Sun *et al.* , 2013)、灵台(Zhu *et al.* , 2000)、西峰(Zhu *et al.* , 2007；Zhou *et al.* , 2010)、古浪(Sun *et al.* , 2013)、大同(Zhu *et al.* , 2006b)、洛川(Zhu *et al.* , 2006a；Zhou *et al.* , 2010；Sun *et al.* , 2013)等剖面的研究中均有 Laschamp 事件报道. Laschamp 事件在黄土沉积中主要记录于黄土层 L1 的中部，年龄为 37.4 ~ 47.5 ka 之间(Zhu *et al.* , 1999, 2006a；Pan *et al.* , 2002；Zhou *et al.* , 2010；Sun *et al.* , 2013). 但在各研究剖面中的具体位置存在差别，古浪(L1LL2 下部, Sun *et al.* , 2013)、灵台(L1LL2, Zhu *et al.* , 2000)、洛川(L1LL2 中部, Zhu *et al.* , 2006a)和大同(Zhu *et al.* , 2006b)剖面主要在次一级黄土层中，而西峰(L1SS1, Zhu *et al.* , 2007；Zhou *et al.* , 2010)、渭南(L1SS2, Pan *et al.* , 2002)剖面则在次一级古土壤中. 此外，Laschamp 事件的 VGP 投影为由亚洲-西太平洋组成南向分支和非洲-西欧构成的北向分支组成的顺时针曲线(Channell. , 2006；Laj *et al.* , 2006). 古浪和渭南的与之相似，但洛川则主要集中于北半球高纬度地区(Sun *et al.* , 2013).

Blake 事件为黄土中另一个广泛报道的极性漂移事件(Fang *et al.* , 1997；Zhu *et al.* , 1999, 2006b；Pan *et al.* , 2002；Zhou *et al.* , 2010；Sun *et al.* , 2013). 早期的研究，如合阳(王永焱等, 1980)、洛川(王永焱等, 1980)、斋堂(安芷生和卢演俦, 1984)、陕县(岳乐平等, 1984)、靖远(岳乐平等, 1991)等剖面均有 Blake 事件的报道，但由于采样分辨率和年龄控制等的约束，真实性有待确认. 完整的 Blake 事件的变化记录首次于西宁剖面检出(朱日祥等, 1993)，随后环县(Zheng *et al.* , 1995)，九州台(Fang *et al.* , 1997)、渭南(Pan *et al.* , 2002)、洛川(Zhou *et al.* , 2010；刘维明等, 2010)、西峰(Zhou *et al.* , 2010)等剖面中均有检出. 主要分布于古土壤 S1 中，西宁(S1-3, Zhu *et al.* , 1994)、西峰(S1SS3, Zhou *et al.* , 2010)、洛川(S1SS3, Zhou *et al.* , 2010)剖面处于次一级古土壤中，九州台剖面处于古土壤和黄土边界处(S1-c 和 L2-2 之间, Fang *et al.* , 1997)，而渭南剖面却处于次一级黄土层中(S1LL3, Pan *et al.* , 2002). 年龄主要为 123 ~ 111 ka，持续为 5.5 ~ 8.5 ka(Zhu *et al.* , 1994；Fang *et al.* , 1997；Zhou *et al.* , 2010). Blake 事件的形态特征也在研究中进行了尝试，九州台剖面由两次倒转组成(Fang *et al.* , 1997)，与海洋沉积物(Laj and Channell, 2007；Rossi *et al.* , 2014)相似，但西宁剖面却更为复杂，由三次倒转组成(Zhu *et al.* , 1994).

Mono Lake 事件在黄土中的报道较少，磁性地层研究有渭南(Zhu *et al.* , 1999；Pan *et al.* , 2002)、灵台(Zhu *et al.* , 2000). 洛川和西峰^{10}Be 研究揭示的磁场强度低值可能为 Mono Lake 事件(Zhou *et al.* , 2010). 其他已经确认的极性漂移事件在黄土中很少检出，葛同明等(1991)认为渭南阎村 W7 孔和武家堡剖面记录了 Emperor 事件(即 Big Lost 事件)，但缺乏严格的年龄限制，准确性存疑. 此外，不同的黄土剖面还在 L3、L5 和 S7 中检出了部分极性事件(Pan *et al.* , 2002；Yang *et al.* , 2007). 渭南剖面 L3 下部检出的极性事件，年龄约 280 ka(Pan *et al.* , 2002)，Pan 等(2002)将其对应于 Langereis 等(1997)提到的 Fram Strait/CR0 事件. 渭南剖

面 L5 检出的极性事件,年龄约 422 ka(Pan *et al.*, 2002),与 Unknown 事件(Langereis *et al.*, 1997)对应较好(Pan *et al.*, 2002).与之类似,宝鸡剖面 L5 中检出了年龄为 413 ~ 433 ka 的极性事件(Yang *et al.*, 2007).宝鸡剖面还报道了 S7 中的极性事件,年龄早于 B/M 界限约 23 ~ 33 ka(Yang *et al.*, 2007).

4　黄土沉积物地磁极性漂移事件缺失的原因分析

经过近 30 年的积累,中国黄土有关极性漂移事件的研究成果不断涌现,涵盖了晚布容期所有已知极性事件(Zhu *et al.*, 1999, 2006a, b, 2007; Pan *et al.*, 2002; Yang *et al.*, 2007; Zhou *et al.*, 2010; Sun *et al.*, 2013),为高分辨率黄土古气候学研究和古气候信息的海陆对比研究提供了年代学基础.然而,部分剖面地磁漂移记录的缺失(鹿化煜等, 2001; 曾庆有等, 2002; Zhu *et al.*, 2007; 邓成龙, 2008)使黄土沉积物对极性漂移事件的记录能力受到质疑.即使已知的极性漂移事件,也并非所有剖面都能检出,白草塬剖面 L1 的沉积速率可达 21.53 cm/ka(Ding *et al.*, 2002),5 cm 间隔古地磁学研究却无法获得地磁漂移记录(邓成龙, 2008).距离相近剖面也并非可以获得相似的极性漂移事件记录,西宁剖面详细记录了 Blake 事件(Zhu *et al.*, 1994),但该地区的土巷道剖面和盘子山探井均无相应记录(鹿化煜等, 2001).Zhu 等(2000)在灵台剖面检出了 Mono Lake 事件,相距不远的西峰剖面却没有磁倾角的显著变负(Zhu *et al.*, 2007).同时,早-中布容期极性漂移事件的检出很少(Pan *et al.*, 2002; Yang *et al.*, 2007),无法证实黄土可以在这一时段内稳定记录极性漂移事件.

究其原因,目前学术界存在多种解释,如所处地理环境不同(Zhu *et al.*, 1998, 2006a),受成壤作用的影响不同(Pan *et al.*, 2002; Zhu *et al.*, 2007; 邓成龙, 2008),锁定深度不同(Spassov *et al.*, 2003; Roberts and Winklhofer, 2004),剩磁获得机制存在差异(Liu *et al.*, 2008; Jin and Liu, 2010; Zhao and Roberts, 2010; Wang and Løvlie, 2010; Zhao *et al.*, 2014),且黄土可能存在局部沉积间断(Stevens *et al.*, 2006; Zhu *et al.*, 2007; 邓成龙, 2008)等.然而现有的研究成果还无法在这一问题上达成一致.

首先,黄土沉积物中天然剩磁的组成十分复杂,包含了沉积剩磁(DRM)、沉积后剩磁(pDRM)、化学剩磁(CRM)及黏滞剩磁(VRM)等.在土壤发育过程中,部分磁赤铁矿颗粒可以载有相对稳定的 CRM(Liu *et al.*, 2005),CRM 是古土壤中天然剩磁的主要贡献者之一(Liu and Zhang, 2013).随着成土作用的加强 CRM 可能会彻底改变 ChRM(Wang *et al.*, 2014).此外,在冬季反复的冻融过程中,粗颗粒磁铁矿在地磁场中会通过物理转动而被重磁化(Wang and Løvlie, 2010).因此,剩磁获得机制的差异,尤其是 CRM 的掩盖效应,导致了不同区域古地磁结果可能出现显著地偏差.然而,现有的岩石磁学研究表明 MB 转换期 ChRM 的载磁矿物主要为 PSD 磁铁矿(Zhu *et al.*, 1994),且通常加热 300 ℃ 就可以有效去除磁赤铁矿载有的 CRM(Liu *et al.*, 2003; Jin and Liu, 2011; Wang *et al.*, 2014).因此,主要基于热退磁建立的黄土磁性地层学可以有效规避 CRM 和 VRM 的影响(Jin and Liu, 2011; Wang *et al.*, 2014; Liu *et al.*, 2008, 2015).

其次,黄土-古土壤序列会受到沉积后的扰动、成壤作用等影响,从而携带 pDRM 或是 CRM,在 pDRM 的锁定过程以及 CRM 的缓慢的获得过程中对地磁的记录发生向下错位(Zhou and Shackleton, 1999; 郭斌等, 2001; 王喜生等, 2007).黄土的重沉积实验(Wang and Løvlie, 2010; Zhao and Roberts, 2010)表明在 ChRM 的获得过程中,普遍存在较浅的 Lock-in 效应.不过,^{10}Be 和古地磁结果在研究 Blake 事件中的相似性(Zhou *et al.*, 2007)对黄土沉积存在显著锁定深度提出了质疑.黄土高原内部沉积速率较低的剖面中 Blake 等极性事件的报道(Zhu *et al.*, 1994; Pan *et al.*, 2002; Yang *et al.*, 2004)表明,Lock-in 效应并不会完全掩盖地磁极性漂移事件在黄土中的记录.Laschamp 事件由黄土高原西北部向东南逐渐增厚的趋势(Sun *et al.*, 2013)指出 Lock-in 效应可能主要影响极性事件的记录位置.

第三,黄土高原不同地区沉积速率往往存在较大的差异,高原内部普遍小于 10 cm/Ka(Zhao *et al.*, 2014),而西北部地区则超过 40 cm/Ka(Rolph *et al.*, 1989).这种差异会引起地磁场信息记录的不同,尤其是较低的沉积速率可能无法有效记录地磁极性漂移事件.同时,黄土高原可能普遍存在着沉积间断(Stevens *et al.*, 2006),可能造成地磁极性漂移事件记录部分甚至全部缺失(Zhu *et al.*, 2007; 邓成龙, 2008).不过,曹县(Heslop *et al.*, 1999)和灵台剖面(Zhu *et al.*, 2000; Spassov *et al.*, 2003)关于地磁场长期变的记录否定了黄土沉积存在明显的沉积间断.即使在接近沙漠边缘,易于发生沉积间断的黄土高原西北部(Stevens *et al.*, 2006),兰州(Fang *et al.*, 1997)和古浪(Sun *et al.*, 2013)剖面也分别检出了 Blake 事件和 Laschamp 事件.

综上所述,Lock-in 效应和沉积间断并不能用来解释所有的地磁极性漂移事件记录缺失现象.极性漂移期间,地磁场的稳定性较差,其信息记录的有效性会降低(朱日祥等, 1993; Sun *et al.*, 1993; Jin and Liu, 2010).如 B/M 转换期内,洛川多套平行样品的古地磁结果差异显著(Jin and Liu, 2010),西峰剖面几乎无法获得稳定的原生剩磁(Sun *et al.*, 1993).极性漂移事件持续时间较短,在地磁场不稳定的情况下,地磁场信息的记录可能不完全(Jin and Liu, 2010; Zhao and Roberts, 2010),造成不同研究中结果存在差异,如环县剖面 Blake 事件的研究中,磁倾角没有明显的变化,但磁偏角却近乎翻转(Zheng *et al.*, 1995).因此,同一区域内不同研究中获得的结果也会存在差异,如洛川剖面 Heller 和 Liu(1982)在布容期内无法检测出任何极性事件,但 Jin 和 Liu(2010),Zhou 等(2010)和刘维明等(2010)则均获得了 Blake 事件的记录.地磁场信息记录的有效性可能是黄土地磁极性漂移事件记录缺失的根本原因.

5　未来展望

经过近 30 多年的研究,黄土-古土壤序列的年代学框架已经建立起来.随着年代学模型的发展,获得了大量高精度磁性地层学结果.地磁极性漂移事件作为磁性地层学研究中的重要组成部分,获得了广泛的重视.随着认识的不断深入,单个样品显示的极性事件缺乏足够的说服力,未来黄土-古

土壤极性事件研究将主要依托高分辨率磁性地层学工作.同时,地磁极性漂移事件的研究离不开精确的年龄控制,高精度年代学模型将成为磁性地层学研究中必不可少的部分.地磁极性漂移事件的记录位置将更加准确,区域差异有望进一步缩小,黄土磁性地层学研究有潜力成为未来地磁极性漂移事件研究领域的核心区域.

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