第 33 卷　第 1 期
2018 年 1 月

地球科学进展
ADVANCES IN EARTH SCIENCE

Vol.33　No.1
Jan., 2018

王蕾彬,魏海涛,贾佳,等.亚洲中部干旱区黄土释光测年研究进展及其问题[J].地球科学进展,2018,33(1):93-102.DOI:10.11867/j.issn.1001-8166.2018.01.0093.[Wang Leibin, Li Guoqiang, Wei Haitao, et al. Advances and issues in luminescence dating of loess deposits in arid Central Asia[J]. Advances in Earth Science, 2018, 33(1):93-102.DOI:10.11867/j.issn.1001-8166.2018.01.0093.]

亚洲中部干旱区黄土释光测年研究进展及其问题*

王蕾彬[1],魏海涛[1],贾　佳[1],李国强[1],陈发虎[1,2]*

(1.兰州大学资源环境学院西部环境教育部重点实验室,甘肃　兰州　730000;
2.中国科学院青藏高原地球科学卓越创新中心, 北京　100101)

摘　要:中亚干旱区广泛分布的黄土沉积为研究这一区域的大气粉尘、环境和气候演化提供了良好载体,而黄土年代学是气候环境研究的基础。近几十年来逐渐发展并日趋成熟的释光测年方法是建立黄土地层序列的重要手段。通过对中亚干旱区的测年进展(主要是释光测年)进行总结梳理,得到如下认识:①释光测年方法与^{14}C测年方法比较,测年范围更广,测年材料易得,在此区域黄土框架的建立中有广泛适用性;②石英光释光单片再生法(SAR)能够用于建立中亚干旱区末次冰期以来黄土沉积的年代框架,但是需要考虑部分地区石英灵敏度偏低、不同粒径结果不一致等问题,这些问题的解决仍然需要更多的方法学的研究;③长石的两步法(pIRIR)与多步法(MET-pIRIR)已经基本克服了传统 IRSL 方法中信号的明显异常衰退现象,在此区域可以建立 MIS 7 以来的年代框架,长石的灵敏度高,可以用来测试石英灵敏度低而无法得出可靠年代的样品,其测年范围比石英更广,在具体的应用中需要根据样品灵敏度高低、年老程度等因素综合考虑来建立年代框架。

关　键　词:中亚干旱区;黄土沉积;石英 OSL 测年;钾长石 pIRIR 和 MET-pIRIR 测年
中图分类号:P597^{+}.3　　**文献标志码**:A　　**文章编号**:1001-8166(2018)01-0093-10

1　引　言

北半球中纬度地带广泛分布的黄土—古土壤沉积是第四纪以来气候变化的良好记录载体[1~4]。其中,中亚干旱区(包括我国新疆、中亚五国和伊朗北部等)的黄土沉积是北半球中纬度黄土沉积区的重要组成部分。与已有大量研究的欧洲黄土和中国黄土高原黄土不同,中亚干旱区黄土沉积所蕴藏的丰富气候和环境记录尚没有得到充分挖掘,其主要原因之一是缺乏足够可靠的高分辨率年龄框架支持。

古地磁测年方法和锆石 U-Pb 测年方法被用于中亚长时间序列粉尘沉积年代序列的建立[5~11]。例如,使用古地磁测年发现,新疆昆仑山北麓黄土形成于 0.95 Ma 前[12,13],伊犁盆地黄土形成于 0.86 Ma 前[14],天山北麓黄土形成于 0.8 Ma 前[7]或者更早[15],塔里木盆地西侧 22 Ma 前可能已有粉尘黄土沉积[16],塔吉克斯坦最早的黄土形成于 2~2.5 Ma 前[5],甚至早至 37 Ma 前[10],中亚五国个别地区黄土在第四纪早期就开始堆积[6,17]等。但古地磁方法适用于长时间尺度框架的黄土年代的建立,时间分辨率低。^{14}C测年方法也被尝试应用于中亚干旱区黄土年代的建立[18],但是,^{14}C测年方法应用于中亚

收稿日期:2017-07-18;**修回日期**:2017-12-13.
*　**基金项目**:中国科学院国际合作局对外合作重点项目“一带一路”国际合作专项(编号:131C11KYSB20160061);中国科学院学部咨询项目“欧亚腹地环境变迁与丝路文明兴衰的战略研究”(编号:2017ZWH006A-018)资助.
作者简介:王蕾彬(1989-),女,山西灵丘人,博士研究生,主要从事释光年代学研究.**E-mail**:wanglb15@lzu.edu.cn
*　**通信作者**:陈发虎(1962-),男,陕西丹凤人,教授,主要从事环境变化与文明演化研究.**E-mail**:fhchen@itpcas.ac.cn

干旱区黄土记录研究过程中,存在可靠的^{14}C测年材料不易获得的问题:①利用蜗牛等软体动物壳体^{14}C测年时由于软体动物可能选择吸收周围环境中缺^{14}C的物质来合成壳体,导致^{14}C年代不准确[19];②干旱区的植物往往产生庞大的根系,土壤中植物残体分泌的腐殖酸也会对^{14}C测年材料产生污染;③^{14}C测年只能用于距今4~5万年以来的样品年龄测定,限制了黄土记录轨道尺度年龄框架的建立。这些均导致了^{14}C测年方法在中亚干旱区黄土测年过程中的局限性[19~21]。

光释光(Optically Stimulated Luminescence, OSL)测年是一种基于矿物发光现象而发展起来的测年方法,可以测量沉积物最后一次见光事件至今的埋藏年龄[22]。其测年材料(石英、长石等矿物)在沉积物中普遍存在,因此该方法在晚第四纪年代学研究中得到了广泛的应用,测年对象包括风成沉积物[23,24]、河湖相沉积物[25,26]、冰川沉积物[27~29]、火山烘烤层[30]、海洋沉积物[31]、构造活动如断层泥[32]和岩石暴露面[33]等。其中,黄土等风成沉积物在沉积前经历了较远距离的搬运,充足的曝光可使得释光信号"回零",满足了光释光测年的前提条件[34]。目前,光释光测年手段在我国黄土高原黄土研究中成果丰硕[24,35~37],同时,这种方法也被学者们探索性地应用于中亚干旱区黄土记录的年龄测定[38~43]。石英OSL测年手段被广泛用于中亚干旱区末次冰期以来黄土沉积年代测定和粉尘沉积模式研究[21,42,44~49]。近年来钾长石红外释光(Infrared Stimulated Luminescence, IRSL)测年技术不断发展,并被用于中亚干旱区黄土记录的测年,取得了一些新的进展[41,43,48,50]。本文通过梳理中亚黄土释光测年的发展历程,总结释光测年已有的研究成果,对目前使用不同释光测年方法获得的测年结果进行阐述,针对测年过程中存在的问题提出可能的解决思路,以期对中亚黄土研究起到借鉴作用。

2 区域概况

狭义的中亚干旱区仅指中亚五国(哈萨克斯坦、吉尔吉斯斯坦、塔吉克斯坦,土库曼斯坦和乌兹别克斯坦)所在的区域,广义的中亚干旱区还包括伊朗北部、我国新疆地区、蒙古高原、阿富汗北部和巴基斯坦北部[51,52],其地理范围为50°~90°E,36°~54°N。中亚干旱区受到西风环流的影响,且远离海洋,气候干旱,为典型温带大陆性气候。这一区域年均降水量随地形海拔差异很大,平原地区为200~400 mm,甚至更少,而部分山区可达600~1 000 mm[53~55];年均温在不同区域差异较小,在伊犁河谷地区约为10 ℃[56,57];帕米尔高原西部的盆地平原为11 ℃,厄尔布士山脉以北地区可达17 ℃[40]。

中亚干旱区的黄土主要分布于沙漠(如克孜勒库姆沙漠、卡拉库姆沙漠、塔克拉玛干沙漠和莫因库姆沙漠等)外围山麓地带和河谷盆地(图1)。在我国新疆地区,黄土主要分布于北天山北麓、伊犁河谷和昆仑山北麓的弧形地带,分布海拔分别在700~2 400,800~2 100和2 000~4 000 m[7,57],沉积厚度大致随海拔高度的升高先变厚后变薄,昆仑山北麓黄土厚度可能超过500 m(据方小敏,私人交流);在中亚五国及以西地区,黄土分布地区与新疆地区类似,主要为河流阶地、高原面以及山麓地带,主要分布在2 500 m以下[58~60],小部分黄土分布在海拔4 000 m以上的高山地区[6,55]。在中亚五国中塔吉克斯坦南部和乌兹别克斯坦的黄土最厚,达100~200 m[5,55]。

3 中亚黄土石英OSL测年进展及其问题

3.1 中亚黄土石英OSL测年进展

石英是黄土沉积物的主要组成矿物,其化学性质稳定不易风化,石英OSL信号在自然条件下容易被晒退,利于释光信号"回零",因此被广泛应用于我国黄土高原的黄土[24,36,37,61,62]、欧洲黄土[63,64]和美洲黄土[65~68]OSL测年研究中,并获得了大量可靠的年龄序列。在中国黄土高原黄土的石英OSL测年中,前人的研究发现,采用不同粒径石英OSL测年方法均能够获得可靠的黄土地层年龄[24,35~37,69,70]。

发展相对成熟的石英OSL测年技术在中亚黄土测年研究中获得了广泛应用,所使用的方法有单片再生法(Single Aliquot Regeneration-dose Protocol, SAR)、标准生长曲线法(Standardised Growth Curve, SGC)以及简单多片再生法(Simplified Multiple Aliquot Regenerative-dose Protocol, SMAR)[21,42,46,49,71]。天山北麓石英SAR方法成功地用于4万年以来可靠年代框架的建立[41,43,48]。同时,石英OSL测年也用于天山中部伊犁河谷末次冰期(约70 ka)以来黄土沉积的年代框架的建立和粉尘沉积研究。Feng等[18]使用石英SMAR测年方法和^{14}C方法对伊犁河谷则克台(ZKT)黄土剖面进行了年代测定,获得的细颗粒(4~11 μm)石英年龄和蜗牛壳体的^{14}C年龄相比差异很大,并认为石英OSL年龄无法用来重建黄土—古土壤序列年龄框架;但是E等[19]使用中颗粒(38~63 μm)石英单片再生剂量法也对则克台黄

土剖面进行了研究,获得了与 Feng 等[18]大体一致的细颗粒石英年龄框架,认为石英 OSL 年龄是可信的。同时, Song 等[20]对比了伊犁河谷昭苏波马(ZSP)剖面细颗粒混合矿物红外后蓝光的石英 OSL 年龄与^{14}C 年龄,也得出区域^{14}C 年龄比实际地层年龄年轻的结论。随后 Song 等[21]对厚度为 20.5 m 的尼勒克(NLK)黄土剖面利用中粒径石英 SAR-SGC 法建立末次冰期 69 ka 以来的黄土年代框架,并对全剖面不同深度发现的蜗牛壳体使用^{14}C 测年进行了年龄测定,获得的蜗牛^{14}C 年龄和石英 OSL 年龄在 25 ka 以来表现出了较好的一致性,他们认为石英 OSL 测年可用于 70 ka 以来黄土样品年龄测定,而^{14}C 测年只能提供 25 ka 以来地层的可靠年代。在古气候的研究方面,Kang 等[42]对厚度 5 m 的塔勒德(TLD)剖面应用细颗粒石英 SAR 方法建立了黄土剖面年龄序列,发现 30 ka 以来黄土连续堆积并且在 MIS 2 黄土沉积速率高,在末次盛冰期(Last Glacial Maximum,LGM)达到最高,相对末次冰期沉积速率慢。Yang 等[46]对喀什河的河流阶地上的尼勒克黄土剖面用石英 SAR 法建立末次冰期以来 45~14 ka 的年龄框架,使用最大年龄模型重建的剖面年龄框架表明在距今 45 ka,35~19 ka 和 14 ka 这 3 个时期区域内粉尘堆积速率较高。

与^{14}C 方法相比,石英的光释光测年上限高,且中亚干旱区黄土沉积的独特性限制了^{14}C 方法的应用,伊犁河谷的尼勒克剖面^{14}C 年代超过 25 ka 就不再增加,则克台剖面则是全剖面蜗牛壳体的^{14}C 年龄整体偏低,反映了干旱区沉积^{14}C 测年的材料的局限性。石英 OSL 测年所用的石英矿物在黄土中广泛存在,能够弥补^{14}C 测年不能测得的年代范围空缺,也为不同研究中讨论末次冰期以来(约 70 ka)气候环境变化提供了可能。

3.2　中亚黄土石英 OSL 测年中存在的一些问题

在中亚黄土已有的石英 OSL 测年研究中也存在一些问题。例如,有些剖面的石英信号较暗,灵敏度不高[43],这种现象应当与石英的物源以及距离物源的远近有关[72,73]。中亚地区的黄土多分布在河谷以及沙漠外围的山麓地区,距离源区较近,且物源多样,容易出现灵敏度低的现象。另外,不同粒径石英 OSL 测年得出的年龄在有些区域一致性很高[18,19](图 2a),但在一些区域差异很大[21,46,49]。Song 等[21]和 Yang 等[46]分别用中粒级和粗粒级石英 SAR 法对尼勒克黄土剖面进行测试,结果如图 2b 所示,部分粗粒径年龄明显小于中粒径年龄。Youn 等[49]对厚 20 m 的位于天山西段山间河流阶地 Bishkek 黄土剖面使用细颗粒、粗颗粒石英 SAR 法开展对比研究(图 2c),发现细粒径石英 OSL 年龄结果整体大于粗粒径石英 OSL 年龄结果,他们认为成壤作用和土壤扰动或者沉积前的部分晒退可能导致细颗粒年龄比粗颗粒偏老,因而选择了粗粒径年代。区域内黄土不同粒径石英测年获得的年龄不一致,可能与样品晒退情况[74]、沉积过程[75]、沉积后的地层稳定性[76~78]和剂量率估算误差[79]等因素有关。中亚干旱区黄土沉积由于物源复杂,搬运距离整体较近,容易导致石英晒退不完全,图 2b 和图 2c 均为粗粒径的年代小于细粒径的年代,而粗粒径的年代误差比细粒径的误差更大,极有可能是晒退情况导致。颗粒越细,在单片测试时测片上就会附着更多的发光颗粒,使得测片间的差异变小,样品的晒退情况难以分辨。若是沉积前晒退完全的样品,对不同粒径测试,均可获得一致的结果(图 2a)。但如果样品埋藏前未得到彻底晒退,则测片上粒径越大(发光颗粒数目越小)越会表现出高的超离散度[46],通常最小的年代模型被采用[80];测片上的粒径越小(发光颗粒数量级增多)则测片间的超离散度越小,样品真实晒退程度被掩盖。因此将石英 SAR 测年应用于中亚干旱区黄土样品时,我们建议先开展详细的方法学研究。

4　钾长石 IRSL 测年及其进展

4.1　钾长石测年进展

长石矿物在黄土中的含量仅次于石英,长石 IRSL 信号也可用于沉积物年龄测定。与石英 OSL 测年相比,长石 IRSL 测年存在很多优点:①灵敏度高,在测试信号弱的年轻样品时具有优势[81,82];②长石释光信号饱和剂量比石英高,可用于更老的样品测试;③长石 IRSL 测年可以应用于含有长石的混合矿物的测试,便于测量一些无法提纯获得足够石英的样品。但是,长石测年过程中也存在一些缺点:①长石信号较石英信号晒退较慢;②长石 IRSL 信号存在异常衰退现象,容易造成样品年代低估[79]。中亚黄土测年研究早期热释光(Thermoluminescence,TL)方法利用细颗粒混合矿物信号建立年代[5,83,84],长石信号比石英亮,在混合矿物 TL 信号中贡献率高。但是有一些学者发现 TL 和放射性碳的年代并不相同[5,85,86]。Zhou 等[38]对乌兹别克斯坦的 Orkutsay 剖面进行了 TL 测年,发现 TL 不能提供老于130ka地层的可靠年代。Frechen等[44]对塔

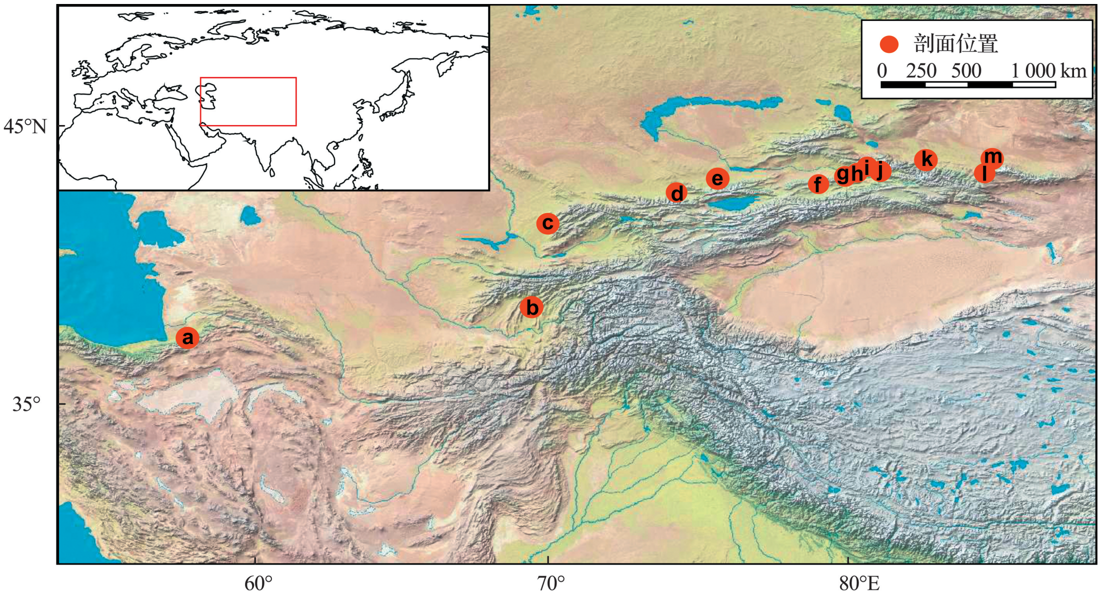

图 1 研究区位置和发表的黄土沉积记录研究点分布图

Fig.1 Location of the study area and published loess record sites in the arid Central Asia

a.Toshan 剖面[50];b.Darai Kalon 剖面[44];c.Orkutsay 剖面[38];d.Bishkek 剖面[49];e.Remsowka 剖面[18];f.昭苏波马(ZSP)剖面[20];g.塔勒德(TLD)剖面[42];h.肖尔布拉克(XEBLK)剖面[47];i.尼勒克(NLK)剖面[21,46];j.则克台(ZKT)剖面[18,19];k.鹿角湾(LJW)/ 鹿角湾 10(LJW10)剖面[43];l.水西沟(SXG)剖面[43];m.柏杨河(BYH)剖面[48]

a:Toshan section[50].b:Darai Kalon section[44].c:Orkutsay section[38].d:Bishkek section[49].e:Remsowka section[18].f:Zhaosuboma(ZSP) section[20].g:Talede (TLD) section[42].h:Xiaoerbulake (XEBLK) section[47].i:Nilka(NLK) section[21,46].j:Zeketai (ZKT) section[18,19].k:Lujiaowan (LJW) / Lujiaowan10 (LJW10) section[43].l:Shuixigou (SXG) section[43].m:Baiyanghe (BYH) section[48]

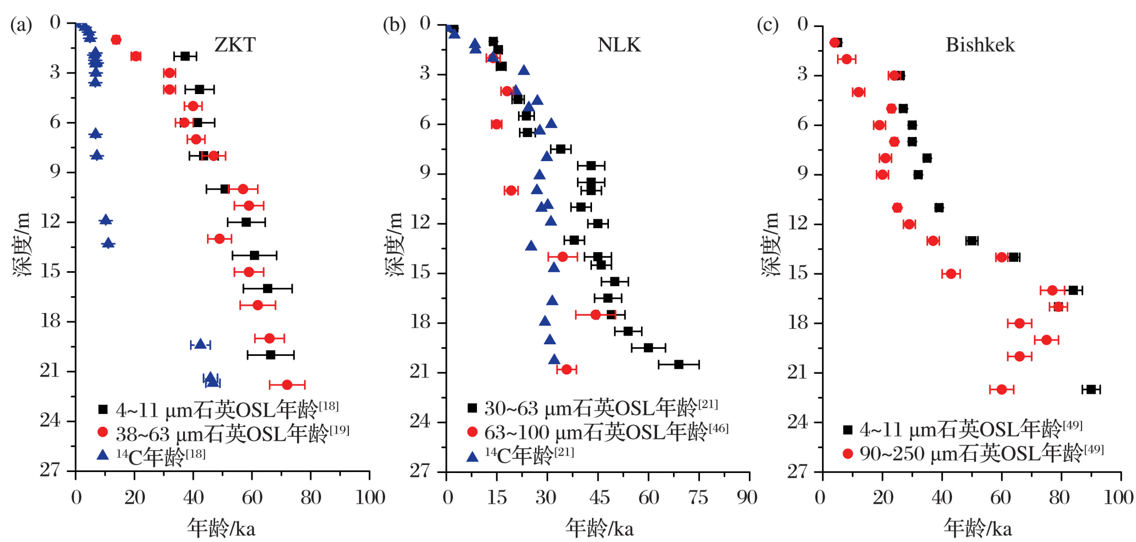

图 2 中亚 3 个黄土剖面石英光释光测年结果以及 ^{14}C 测年结果

Fig.2 The quartz OSL dating results and ^{14}C results from three loess section in the arid central Asia

(a)新疆则克台(ZKT)剖面[18,19];(b)新疆尼勒克(NLK)剖面[21,46];(c)吉尔吉斯斯坦 Bishkek 剖面[49]

(a)Zeketai (ZKT) loess section in Xinjiang Uygur Autonomous Region of China[18,19]. (b) Nilka (NLK) section in Xinjiang Uygur Autonomous Region of China[21,46]. (c) Bishkek loess section in Kyrgyz Republic[49]

吉克斯坦南部的黄土用 TL 和 IRSL 这 2 种方法进行测年也得到了相同的结论,即老于 MIS 5 阶段所测出来的地层年代存在低估。这主要是由于 TL 信号不稳定以及长石 IRSL 信号的异常衰退,使得传统方

法建立的年代框架可靠性不高[79,87~89]。前人尝试了多种方式解决这一问题,如通过测试长石信号的衰退速率 g 值(g-value)对年代进行校正[89~91];此后发展了利用内剂量率及内剂量率产生的等效剂量测年的等时线法对年代进行计算[90,92,93];近年来随着释光测年方法学发展,发现使用钾长石红外激发后红外释光(Post-IR Infrared Stimulated Luminescence, pIRIR,简称两步法)信号可克服 IRSL 信号的异常衰退现象,获得较为可靠的钾长石年龄,这种方法首先由 Thomsen 等[94]基于钾长石在 225 ℃激发的红外后红外释光信号($pIRIR_{(50,225)}$)比在 50 ℃激发的常规红外释光信号衰退速率低这一现象提出,他们认为低温 IRSL 信号主要源于距离较近的电子—空穴对之间通过隧穿效应发生的复合,而在高温激发的红外激发后红外释光信号是由距离较远的电子—空穴对之间的复合所产生,温度越高,则信号越稳定,衰退速率越低。钾长石 pIRIR 法的第一步红外激发去掉易衰退的红外释光信号,第二步在 225 ℃下激发获得不易衰退的稳定信号用于等效剂量计算。此后,Murray 等[95]提出可以将预热温度提高到 320 ℃,使得第二步激发温度可以提高到 290 ℃。基于此,Thiel 等[96]提出了第二步激发温度提高到 290 ℃的钾长石 $pIRIR_{(50,290)}$ 方法。全球范围内,对具有独立年龄的样品应用此方法进行测量对比发现,在 200~300 ka 以内,该方法可得到与独立年龄一致的年代(相应的等效剂量约为 800 Gy,年剂量率为 3~4 Gy/ka)[96,97]。同时,Li 等[98]提出了钾长石多步红外激发测年法(Multi-elevated-temperature post-IR IRSL,MET-pIRIR,简称多步法),该方法通过逐步升高温度激发逐渐去除不稳定信号从而获得稳定的红外释光信号,他们认为基于多步红外激发的 MET-pIRIR 法较之于基于两步红外激发的 pIRIR 法的优势在于,多步法测年过程中可以用等效剂量—温度坪(Equivalent dose-Temperature,De-T)对测试条件进行验证,坪区温度范围内长石红外释光信号不存在异常衰退[98]。

在中亚干旱区黄土沉积钾长石测年研究早期,传统的 IRSL 测年方法只能获得最小年龄[40,44,45]。Machalett 等[45]通过对伊利河谷厚度为 80 m 的 Remisowka 剖面(位置如图 1)开展钾长石多片附加剂量法建立了剖面上部 48 m 的 IRSL 年代框架,获得剖面底部最小年龄约为 94 ka,而该地层的期待年龄应当至少老于 MIS 5。在里海沿岸的伊朗北部黄土分布区,使用钾长石 IRSL 信号测年导致的地层年龄低估的现象同样存在[40,44,60,99]。

随着长石测年方法的发展,钾长石 pIRIR 测年在中亚干旱区黄土测年中得到了尝试性地使用,并取得了一定进展[41,100]。已有研究表明,使用 $pIRIR_{(50,290)}$ 信号(两步激发温度分别为 50 和 290 ℃)钾长石 pIRIR 法能够建立 MIS 7 以来(190~170 ka)黄土沉积物的可靠年代框架,从而为恢复古环境气候变化提供可靠年龄支持[100]。在全新世较年轻的黄土沉积年代学研究方面,Li 等[48]通过对天山北麓鹿角湾 10(LJW10)剖面 2.8 m 厚黄土—古土壤序列开展了粗颗粒石英 OSL 和钾长石 pIRIR 信号稳定性研究,开展了不同激发温度的钾长石 pIRIR 信号稳定性试验、阳光晒退实验、剂量恢复实验以及前置温度实验,提出粗颗粒钾长石 $pIRIR_{(50,170)}$ 信号可以用于末次冰消期以来黄土样品的年龄测定,获得的钾长石 $pIRIR_{(50,170)}$ 年龄与石英 OSL 年龄相比一致性很好,表明测年结果可靠,在此基础上,结合黄土—古土壤序列、年龄框架及古环境代用指标磁化率重建了全新世天山北麓有效湿度变化,发现 5.5 ka 前的早中全新世气候干旱,5.5 ka 以来中亚干旱区气候湿润,有效湿度逐渐增加。Zhao 等[43]对天山北麓鹿角湾(LJW)和水西沟(SXG)剖面开展年代学研究,发现剖面大多数石英信号太暗而难以得到可靠性较高的等效剂量(De),因此以信号灵敏度较高的长石 $MET\text{-}pIRIR_{(110,140,170)}$ 法建立 2 个剖面年代框架,样品在 140 ℃和 170 ℃出现坪区,表明在这 2 个温度下,长石信号异常衰退的影响可以忽略,经过阳光晒退实验和 De 离散度分析等对结果进行可靠性检验,最终以 170 ℃的红外释光信号来建立年代框架。结合粒度测量结果,在 6.7 ka 前的全新世早期,区域环境以干旱为主导;而距今 4~2 ka 时天山北部地区发生了干旱事件。Lauer 等[50]对伊朗北部 Toshan 剖面进行研究,提取细颗粒混合矿物用 $pIRIR_{(50,290)}$ 测年法得到 127~22 ka 以来的年代序列,指出在 MIS 2 时气候可能湿润;Li 等[41]应用石英 OSL 测年和钾长石 $pIRIR_{(50,290)}$ 测年方法对天山北麓 30 m 厚更新世黄土沉积(柏杨河剖面,BYH)进行了测年研究,建立了 150 ka 以来的年代框架,并揭示了天山北麓黄土存在大于 50 ka 的沉积间断,沉积间断主要发生在末次间冰期,黄土主要是在冰期堆积。Lauer 等[100]随后用细颗粒混合矿物中的长石 $pIRIR_{(50,290)}$ 信号,在伊朗北部建立了 MIS 7~MIS 2 较长序列黄土年代框架,并指出在伊朗北部 170~100 ka 间存在由侵蚀导致的沉积间断。

中亚干旱区黄土沉积距离源区较近，对于年轻的黄土沉积，可能因为释光信号信噪比差，在一些区域无法得到可靠的石英释光年代。钾长石灵敏度高，可以弥补这一不足，并已成功应用于全新世年轻黄土样品的测年[41,43]。此外，相比石英信号，长石信号的饱和水平高，在建立老的地层序列时更具潜力。目前中亚干旱区用钾长石建立的最老的可靠地层年代为(206±14)ka[100]。

4.2 钾长石测年需要注意的问题

目前长石测年虽然克服了传统 IRSL 方法带来的显著异常衰退，但是在进行钾长石的 pIRIR 法和 MET-pIRIR 法测试时仍然有以下问题需要注意，如高温下长石会有更多的残余剂量，在测试不同年龄段时 pIRIR 法激发温度的选取，在测试年轻样品时 MET-pIRIR 法需要考虑信号的强弱等。我们建议除了常规的剂量恢复实验和残余剂量测试外，应当通过 g 值测量检验所选温度下钾长石信号的稳定性。对于全新世的年轻样品，选择低温信号(140～170 ℃)可以避免高的残余剂量造成年龄高估。Li 等[101]对钾长石 MET-pIRIR 法和 pIRIR 法进行了比较，发现对于小于 100 ka 的沉积物，pIRIR 法与 MET-pIRIR 法并无多大差异，大于 100 ka，$pIRIR_{(50,290)}$信号的不稳定性增加，建议选取多步法。但是钾长石 pIRIR 法相比 MET-pIRIR 法信号要强，MET-pIRIR 法高温信号很弱，影响了年代的精度，MET-pIRIR 法的测试更具优势[102]。Buylaert 等[103]将 pIRIR 第一步温度提高到 200 ℃，并利用$pIRIR_{(200,290)}$建立了黄土高原靖边剖面 L_2 以来的年代框架，认为当沉积物 De<500 Gy(～150 ka)时，$pIRIR_{(200,290)}$与 MET-pIRIR 可获得一致的结果，提高了 pIRIR 测年的上限。

5 结 论

本文对中亚干旱区黄土释光测年的已有成果进行了梳理，总结了释光测年方法所取得的一些进展。目前此区域的研究成果表明：释光方法比^{14}C 方法测年范围广，测量材料丰富；石英光释光测年主要被应用于末次冰期以来中亚干旱区黄土框架的建立；长石 pIRIR 以及 MET-pIRIR 测年能够用于 MIS 7 阶段以来黄土序列的建立；长石 pIRIR 与 MET-pIRIR 方法克服了传统 IRSL 方法的显著异常衰减问题，较石英信号灵敏度高，在应用中具有优势。但目前长石测年方法在中亚干旱区黄土测年中的应用仍处在初步的应用阶段，需要独立年代去验证。中亚干旱区黄土分布相对离散，多沉积在河谷地区和山麓地带，物源相对复杂，释光性质比物质均一的黄土高原复杂得多，因此我们在采用释光方法建立黄土序列年代时，需进行详细的方法学研究，以得到可靠的黄土—古土壤年代框架。

参考文献(References)：

[1] An Z S, Kutzbach J E, Prell W L, *et al*. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan Plateau since Late Miocene times[J]. *Nature*, 2001, 411(6 833): 62-66.

[2] Dodonov A E, Zhou L P. Loess deposition in Asia: Its initiation and development before and during the Quaternary[J]. *Episodes*, 2008, 31(2): 222-225.

[3] Guo Z T, Ruddiman W F, Hao Q Z, *et al*. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China[J]. *Nature*, 2002, 416(6 877): 159-163.

[4] Licht A, Van Cappelle M, Abels H A, *et al*. Asian monsoons in a late Eocene greenhouse world[J]. *Nature*, 2014, 513(7 519): 501-506.

[5] Dodonov A E, Baiguzina L L. Loess stratigraphy of Central Asia: Palaeoclimatic and palaeoenvironmental aspects[J]. *Quaternary Science Reviews*, 1995, 14(7/8): 707-720.

[6] Dodonov A E. Loess of central Asia[J]. *GeoJournal*, 1991, 24(2): 185-194.

[7] Fang X M, Shi Z T, Yang S L, *et al*. Loess in the Tian Shan and its implications for the development of the Gurbantunggut Desert and drying of northern Xinjiang[J]. *Chinese Science Bulletin*, 2002, 47(16): 1 381-1 387.

[8] Fang X M, Lü L Q, Yan, S L, *et al*. Loess in Kunlun Mountains and its implications on desert development and Tibetan Plateau uplift in west China[J]. *Science in China (Series D)*, 2002, 45(4): 289-299.

[9] Carrapa B, Decelles P G, Wang X, *et al*. Tectono-climatic implications of Eocene Paratethys regression in the Tajik Basin of Central Asia[J]. *Earth and Planetary Science Letters*, 2015, 424: 168-178.

[10] Wang X, Kraatz B, Meng J, *et al*. Central Asian aridification during the late Eocene to early Miocene inferred from preliminary study of shallow marine-eolian sedimentary rocks from northeastern Tajik Basin[J]. *Science in China (Series D)*, 2016, 59(6): 1 242-1 257.

[11] Wang X, Wei H T, Taheri M, *et al*. Early Pleistocene climate in western arid central Asia inferred from loess-palaeosol sequences[J]. *Scientific Reports*, 2016, 6.DOI: 10.1038/srep20560.

[12] Zan Jinbo. Loess on West Kunlun Mountains and Aridification of Asian Inland[D]. Lanzhou: Lanzhou University, 2010.[昝金波. 西昆仑山黄土与亚洲内陆干旱化[D]. 兰州：兰州大学，2010.]

[13] Fang Xiaomin, Lü Lianqing, Yang Shengli, *et al*. Loess in Mt. Kunlun, desert development in the western regions of China, and the uplift of the Qinghai-Xizang Plateau[J]. *Sciences in China*

(*Series D*), 2001, 31(3): 177-184.[方小敏, 吕连清, 杨胜利, 等. 昆仑山黄土与中国西部沙漠发育和高原隆升[J]. 中国科学:D 辑, 2001, 31(3): 177-184.]

[14] Shi Zhengtao. Age of Yili Loess in Xijiang and Its Paleoenvironmental Implications[D]. Xi'an: Institute of Earth Environment, Chinese Academy of Sciences, 2005.[史正涛. 新疆伊犁黄土地层形成时代及环境研究[D]. 西安: 中国科学院地球环境研究所, 2005.]

[15] Sun J M, Ye J, Wu W Y, *et al*. Late Oligocene-Miocene mid-latitude aridification and wind patterns in the Asian interior[J]. *Geology*, 2010, 38(6): 515-518.

[16] Zheng H B, Wei X C, Tada R, *et al*. Late Oligocene-early Miocene birth of the Taklimakan Desert[J]. *Proceedings of the National Academy of Sciences*, 2015, 112(25): 7 662-7 667.

[17] Mavlyanov G A, Kasymov S M, Shermatov M S. The Uzbekistan loess, genesis and distribution[J]. *GeoJournal*, 1987, 15(2): 145-150.

[18] Feng Z D, Ran M, Yang Q L, *et al*. Stratigraphies and chronologies of late quaternary loess-paleosol sequences in the core area of the central Asian arid zone[J]. *Quaternary International*, 2011, 240(1): 156-166.

[19] E C Y, Lai Z P, Sun Y J,*et al*. A luminescence dating study of loess deposits from the Yili River Basin in Western China[J]. *Quaternary Geochronology*, 2012, 10: 50-55. DOI: 10.1016/j.quageo.2012.04.022.

[20] Song Y G, Li C X, Zhao J D, *et al*. A combined luminescence and radiocarbon dating study of the Ili Loess, Central Asia[J]. *Quaternary Geochronology*, 2012, 10(4): 2-7.

[21] Song Y G, Lai Z P, Li Y, *et al*. Comparison between luminescence and radiocarbon dating of late Quaternary loess from the Ili Basin in Central Asia[J]. *Quaternary Geochronology*, 2015, 30: 405-410.DOI:10.1016/j.quageo.2015.01.012.

[22] Huntley D J, Godfrey-Smith D I, Thewalt M L W. Optical dating of sediments[J]. *Nature*, 1985, 313: 105-107.

[23] Lu Huayu, Zhou Yali, Mason J, *et al*. Later Quaternary climatic changes in Northern China—New evidences from sand dune and loess records based on optically stimulated luminescence dating[J]. *Quaternary Sciences*, 2006, 26(6): 888-894.[鹿化煜, 周亚利, Mason J, 等.中国北方晚第四纪气候变化的沙漠与黄土记录——以光释光年代为基础的直接对比[J]. 第四纪研究, 2006, 26(6): 888-894.]

[24] Sun Y B, Clemens S C, Morrill C, *et al*. Influence of Atlantic meridional overturning circulation on the East Asian winter monsoon[J]. *Nature Geoscience*, 2012, 5(1): 46-49.

[25] Zhang J F, Liu C L, Wu X H, *et al*. Optically stimulated luminescence and radiocarbon dating of sediments from Lop Nur (Lop Nor), China[J]. *Quaternary Geochronology*, 2012, 10(15): 150-155.

[26] Long H, Shen J, Wang Y, *et al*. High-resolution OSL dating of a late Quaternary sequence from Xingkai Lake (NE Asia): Chronological challenge of the "MIS 3a Mega-paleolake" hypothesis in China[J]. *Earth and Planetary Science Letters*, 2015, 428(5): 281-292.

[27] Fuchs M, Owen L A. Luminescence dating of glacial and associated sediments: Review, recommendations and future directions [J]. *Boreas*, 2008, 37(4):636-659.

[28] Bateman M D, Swift D A, Piotrowski J A, *et al*. Investigating the effects of glacial shearing of sediment on luminescence[J]. *Quaternary Geochronology*, 2012, 10(7): 230-236.

[29] Duller G A T. Single grain optical dating of glacigenic deposits [J]. *Quaternary Geochronology*, 2006, 1(4): 296-304.

[30] Zhao Hua, Wang Chengmin, Mao Hongliang, *et al*. OSL dating of volcanic baked sediments in Datong area, Shanxi Province of China[J]. *Quaternary Sciences*, 2012, 32(3): 510-515.[赵华, 王成敏, 毛洪亮,等. 大同火山烘烤层的光释光年龄[J]. 第四纪研究, 2012, 32(3): 510-515.]

[31] Yu Tao, Jiang Tao. Research progress and prospect of optical stimulated Luminescence dating for marine sediments[J]. *Geological Science and Technology Information*, 2014,(2): 38-44.[余涛, 姜涛. 光释光测年技术在海洋沉积物研究中的应用现状与展望[J]. 地质科技情报, 2014,(2): 38-44.]

[32] Zhang Jiafu, Zhou Liping. Luminescence dating of sediments[J]. *Nuclear Techniques*, 2007,30(11): 934-939.[张家富,周力平. 释光技术在构造事件定年中的应用[J]. 核技术, 2007, 30(11): 934-939.]

[33] Luo Ming, Chen Jie, Liu Jinfeng. Research progress on luminescence dating of rock surfaces and its application[J]. *Seismology and Geology*, 2017,(1):183-192.[罗明, 陈杰, 刘进峰. 岩石暴露与埋藏面释光测年进展及其应用[J]. 地震地质, 2017,(1): 183-192.]

[34] Roberts H M. The development and application of luminescence dating to loess deposits: A perspective on the past, present and future[J]. *Boreas*, 2008, 37(4): 483-507.

[35] Stevens T, Armitage S J, Lu H Y, *et al*. Sedimentation and diagenesis of Chinese loess: Implications for the preservation of continuous, high-resolution climate records[J]. *Geology*, 2006, 34(10): 849-852.

[36] Lai Z P. Testing the use of an OSL Standardised Growth Curve (SGC) for DE determination on quartz from the Chinese Loess Plateau[J]. *Radiation Measurements*, 2006, 41(1): 9-16.

[37] Lu Y C, Wang X L, Wintle A G. A new OSL chronology for dust accumulation in the last 130,000 yr for the Chinese Loess Plateau [J]. *Quaternary Research*, 2007, 67(1): 152-160.

[38] Zhou L P, Dodonov A E, Shackleton N J. Thermoluminescence dating of the Orkutsay loess section in Tashkent region, Uzbekistan, Central Asia[J]. *Quaternary Science Reviews*, 1995, 14(7): 721-730.

[39] Zhou L P, Fu D P, Zhang J F. An analysis of the components of the luminescence signals of selected polymineral and quartz samples from loess in western China and southern Tajikistan, and their suitability for optical dating[J]. *Quaternary Geochronology*, 2010, 5(2): 149-153.

[40] Frechen M, Kehl M, Rolf C, *et al*. Loess chronology of the Caspian Lowland in Northern Iran[J]. *Quaternary International*,

2009, 198(1): 220-233.

[41] Li G Q, Rao Z G, Duan Y W, *et al.* Paleoenvironmental changes recorded in a luminescence dated loess/paleosol sequence from the Tianshan Mountains, arid Central Asia, since the Penultimate Glaciation[J]. *Earth and Planetary Science Letters*, 2016, 448(15): 1-12.

[42] Kang S G, Wang X L, Lu Y C, *et al.* A high-resolution quartz OSL chronology of the Talede loess over the past ~30 ka and its implications for dust accumulation in the Ili Basin, Central Asia[J]. *Quaternary Geochronology*, 2015, 30: 181-187.

[43] Zhao H, Li S H, Li B, *et al.* Holocene climate changes in westerly-dominated areas of central Asia: Evidence from optical dating of two loess sections in Tianshan Mountain, China[J]. *Quaternary Geochronology*, 2015, 30: 188-193.

[44] Frechen M, Dodonov A E. Loess chronology of the middle and upper Pleistocene in Tadjikistan[J]. *Geologische Rundschau*, 1998, 87(1): 2-20.

[45] Machalett B, Frechen M, Hambach U, *et al*. The loess sequence from Remisowka (northern boundary of the Tien Shan Mountains, Kazakhstan) Part I: Luminescence dating[J]. *Quaternary International*, 2006, 152(3):192-201.

[46] Yang S L, Forman S L, Song Y G, *et al.* Evaluating OSL-SAR protocols for dating quartz grains from the loess in Ili Basin, Central Asia[J]. *Quaternary Geochronology*, 2014, 20(2): 78-88.

[47] Li Y, Song Y G, Lai Z P, *et al.* Rapid and cyclic dust accumulation during MIS 2 in Central Asia inferred from loess OSL dating and grain size analysis[J]. *Scientific Report*, 2016, 6: 32365. DOI: 10.1038/srep32365.

[48] Li G Q, Wen L J, Xia D S, *et al.* Quartz OSL and K-feldspar pIRIR dating of a loess/paleosol sequence from arid central Asia, Tianshan Mountains, NW China[J]. *Quaternary Geochronology*, 2015, 28: 40-53.

[49] Youn J H, Seong Y B, Choi J H, *et al.* Loess deposits in the northern Kyrgyz Tien Shan: Implications for the paleoclimate reconstruction during the Late Quaternary[J]. *Catena*, 2014, 117: 81-93.

[50] Lauer T, Frechen M, Vlaminck S, *et al.* Luminescence-chronology of the loess palaeosol sequence Toshan, Northern Iran—A highly resolved climate archive for the last glacial-interglacial cycle[J]. *Quaternary International*, 2015. DOI: org/10.1016/j.quaint.2015.03.045.

[51] Janos Hormata. Central Asian Civilization History[M]. Beijing: China Translation and Publishing Corporation, 2002.[哈尔马塔. 中亚文明史[M].北京:中国对外翻译出版公司, 2002.]

[52] Hu Zhenhua. Central-Asia and the Central-Asia studies[J]. *Journal of the Central University for Nationalities (Philosophy and Social Sciences Edition)*, 2005, 32(5): 47-53.[胡振华. 中亚与中亚研究[J]. 中央民族大学学报:哲学社会科学版, 2005, 32(5): 47-53.]

[53] Aizen V B, Aizen E M, Melack J M. Precipitation, melt and runoff in the northern Tien Shan[J]. *Journal of Hydrology*, 1996, 186(1): 229-251.

[54] Hu Ruji. Physical Geography of the Tianshan Mountains in China[M]. Beijing: China EnvironmentaI Science Press, 2004.[胡汝骥. 中国天山自然地理[M].北京:中国环境科学出版社, 2004.]

[55] Dodonov A E. Loess records | Central Asia—Encyclopedia of Quaternary Science[J]. *Encyclopedia of Quaternary Science*, 2007, 26: 1 418-1 429.

[56] Ye Wei. Characteristics of physical environment and conditions of loess formation in Yili area, Xinjiang[J]. *Arid Land Geography*, 1999, 22(3): 9-16.[叶玮. 新疆伊犁地区自然环境特点与黄土形成环境[J].干旱区地理, 1999, 22(3): 9-16.]

[57] Ye Wei. The Characteristics and Paleaoclimate of Loess Deposits in Westerly Area[M]. Beijing: Ocean Press, 2001.[叶玮.新疆西风区黄土沉积特征与古气候[M].北京:海洋出版社, 2001.]

[58] Lateef A S A. Distribution, Provenance, Age and Paleoclimatic Record of the Loess in Central North Iran[M]. Eden D N, Furkert R I, eds. Loess-Its Distribution, Geology and Soil. Rotterdam, Balkema, 1988: 93-101. DOI: 10.13140/2.1.3244.834.

[59] Asadi S, Moore F, Keshavarzi B, *et al.* The nature and provenance of Golestan loess deposits in northeast Iran[J]. *Geological Journal*, 2012, 48(6): 646-660.

[60] Kehl M, Sarvati R, Ahmadi H, *et al.* Loess paleosol-sequences along a climatic gradient in Northern Iran[J]. *Eiszeitalter und Gegenwart*, 2005, 55(1): 149-173.

[61] Buylaert J P, Vandenberghe D, Murray A S, *et al.* Luminescence dating of old (>70 ka) Chinese loess: A comparison of single-aliquot OSL and IRSL techniques[J]. *Quaternary Geochronology*, 2007, 2(1): 9-14.

[62] Stevens T, Lu H Y, Thomas D S G, *et al.* Optical dating of abrupt shifts in the late Pleistocene East Asian monsoon[J]. *Geology*, 2008, 36(5): 415-418.

[63] Frechen M. Loess in Europe[J]. *E & G Quaternary Science Journal*, 2011, 60(1): 3-5.

[64] Thiel C, Horváth E, Frechen M. Revisiting the loess/palaeosol sequence in Paks, Hungary: A post-IR IRSL based chronology for the 'Young Loess Series'[J]. *Quaternary International*, 2014, 319(5): 88-98.

[65] Forman S L, Pierson J. Late Pleistocene luminescence chronology of loess deposition in the Missouri and Mississippi River valleys, United States[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2002, 186(1): 25-46.

[66] Berger G W. Luminescence chronology of late pleistocene loess-paleosol and tephra sequences near Fairbanks, Alaska[J]. *Quaternary Research*, 2003, 60(1):70-83.

[67] Miao X D, Hanson P R, Wang H, *et al.* Timing and origin for sand dunes in the Green River Lowland of Illinois, upper Mississippi River Valley, USA[J]. *Quaternary Science Reviews*, 2010, 29(5): 763-773.

[68] Muhs D R, Cattle S R, Crouvi O, *et al.* Loess records[M]// Mineral Dust. Netherlands: Springer, 2014.

[69] Cao G C, Long H, Zhang J R, *et al.* Quartz OSL dating of last glacial sand dunes near Lanzhou on the western Chinese Loess Plateau: A comparison between different granulometric fractions

[J]. *Quaternary Geochronology*, 2012, 10: 32-36.

[70] Kang S G, Wang X L, Lu Y C. Quartz OSL chronology and dust accumulation rate changes since the Last Glacial at Weinan on the southeastern Chinese Loess Plateau[J]. *Boreas*, 2013, 42(4): 815-829.

[71] Li Chuanxiang, Song Yougui, Qian Linbo, *et al*. The history of climate change recorded by the grain size at the Zhaosu loess section in the central Asia since the last glacial period[J]. *Acta Sedimentologica Sinica*, 2011, 29(6): 1 170-1 179.[李传想, 宋友桂, 千琳勃, 等. 中亚昭苏黄土剖面粒度记录的末次冰期以来气候变化历史[J]. 沉积学报, 2011, 29(6): 1 170-1 179.]

[72] Sawakuchi A O, Blair M W, Dewitt R, *et al*. Thermal history versus sedimentary history: OSL sensitivity of quartz grains extracted from rocks and sediments[J]. *Quaternary Geochronology*, 2011, 6(2): 261-272.

[73] Moreno E. An assessment of the luminescence sensitivity of Australian quartz with respect to sediment history[J]. *Geochronometria*, 2011, 38(3): 199-208.

[74] Li S H. Identification of well-bleached grains in the optical dating of quartz [J]. *Quaternary Science Reviews*, 2001, 20 (12): 1 365-1 370.

[75] Fan T L, Fan Y X, Zhao H, *et al*. Investigations on the degree of bleaching of quartz OSL signals using modern aeolian dust from western Loess Plateau, China[J]. *Geochronometria*, 2013, 40 (3): 165-176.

[76] Constantin D, Cameniță A, Panaiotu C, *et al*. Fine and coarse-quartz SAR-OSL dating of Last Glacial loess in Southern Romania [J]. *Quaternary International*, 2015, 357(30): 33-43.

[77] Fan Y X, Zhao H, Chen F H. The equivalent dose of different grain size quartz fractions from lakeshore sediments in the arid region of north China [J]. *Quaternary Geochronology*, 2010, 5 (2): 205-211.

[78] Bateman M D, Boulter C H, Carr A S, *et al*. Detecting post-depositional sediment disturbance in sandy deposits using optical luminescence[J]. *Quaternary Geochronology*, 2007, 2(1/4):57-64.

[79] Aitken M J. Thermoluminescence Dating[M]. London:Academic press, 1985:76-79.

[80] Galbraith R F, Roberts R G. Statistical aspects of equivalent dose and error calculation and display in OSL dating: An overview and some recommendations[J]. *Quaternary Geochronology*, 2012, 11 (8):1-27.

[81] Huntley D J, Lamothe M. Ubiquity of anomalous fading in K-feldspars and the measurement and correction for it in optical dating[J]. *Canadian Journal of Earth Sciences*, 2001, 38(7): 1 093-1 106.

[82] Reimann T, Tsukamoto S. Dating the recent past (<500 years) by post-IR IRSL feldspar-Examples from the North Sea and Baltic Sea coast[J]. *Quaternary Geochronology*, 2012, 10(10): 180-187.

[83] Singhvi A K, Bronger A, Pant R K, *et al*. Thermoluminescence dating and its implications for the chronostratigraphy of loess-paleosol sequences in the Kashmir Valley (India)[J]. *Chemical Geology: Isotope Geoscience Section*, 1987, 65(1): 45-56.

[84] Bronger A, Pant R K, Singhvi A K. Pleistocene climatic changes and landscape evolution in the Kashmir Basin, India: Paleopedologic and chronostratigraphic studies[J]. *Quaternary Research*, 1987, 27(2): 167-181.

[85] Rendell H M. Environmental changes during the Pleistocene in the Potwar Plateau and Peshawar Basin, northern Pakistan[J]. *Proceedings of the Indian National Science Academy, Part A: Physical Sciences*, 1988, 54(3): 390-398.

[86] Agrawal D P, Juyal N, Sharma P, *et al*. Palaeogeography of the loess deposits of Kashmir[J]. *Proceedings of the National Academy of Sciences India*, 1988, 54(3): 385-391.

[87] Wintle A G. Anomalous fading of thermo-luminescence in mineral samples[J]. *Nature*, 1973, 245(5 421): 143-144.

[88] Buylaert J P, Murray A S, Thomsen K J, *et al*. Testing the potential of an elevated temperature IRSL signal from K-feldspar [J]. *Radiation Measurements*, 2009, 44(5): 560-565.

[89] Huntley D J, Lian O B. Some observations on tunneling of trapped electrons in feldspars and their implications for optical dating[J]. *Quaternary Science Reviews*, 2006, 25(19): 2 503-2 512.

[90] Zhao H, Li S H. Luminescence isochron dating: A new approach with different grain sizes [J]. *Radiation Protection Dosimetry*, 2002, 101(1/4): 333-338.

[91] Auclair M, Lamothe M, Huot S. Measurement of anomalous fading for feldspar IRSL using SAR[J]. *Radiation Measurements*, 2003, 37(4): 487-492.

[92] Li B, Li S H, Wintle A G, *et al*. Isochron measurements of naturally irradiated K-feldspar grains [J]. *Radiation Measurements*, 2007, 42(8): 1 315-1 327.

[93] Li B, Li S H, Wintle A G, *et al*. Isochron dating of sediments using luminescence of K-feldspar grains[J]. *Journal of Geophysical Research: Earth Surface*, 2008, 113 (F2). DOI: 10. 1029/2007JF000900.

[94] Thomsen K J, Murray A S, Jain M, *et al*. Laboratory fading rates of various luminescence signals from feldspar-rich sediment extracts[J]. *Radiation Measurements*, 2008, 43(9): 1 474-1 486.

[95] Murray A S, Buylaert J P, Thomsen K J, *et al*. The effect of preheating on the IRSL signal from feldspar[J]. *Radiation Measurements*, 2009, 44(5): 554-559.

[96] Thiel C, Buylaert J P, Murray A, *et al*. Luminescence dating of the Stratzing loess profile (Austria)—Testing the potential of an elevated temperature post-IR IRSL protocol[J]. *Quaternary International*, 2011, 234(1): 23-31.

[97] Buylaert J P, Jain M, Murray A S, *et al*. A robust feldspar luminescence dating method for Middle and Late Pleistocene sediments[J]. *Boreas*, 2012, 41(3): 435-451.

[98] Li B, Li S H. Luminescence dating of K-feldspar from sediments: A protocol without anomalous fading correction[J]. *Quaternary Geochronology*, 2011, 6(5): 468-479.

[99] Karimi A, Frechen M, Khademi H. Chronostratigraphy of loess deposits in northeast Iran[J]. *Quaternary International*, 2011, 234(1): 124-132.

[100] Lauer T, Vlaminck S, Frechen M, *et al*. The Agh Band loess-palaeosolsequence—A terrestrial archive for climatic shifts during the last and penultimate glacial-interglacial cycles in a semi-arid region in northern Iran [J]. *Quaternary International*, 2017, 429(30): 13-30.

[101] Li B, Jacobs Z, Roberts R G, *et al*. Review and assessment of the potential of post-IR IRSL dating methods to circumvent the problem of anomalous fading in feldspar luminescence[J]. *Geochronometria*, 2014, 41(3): 178-201.

[102] Li B, Roberts R G, Brumm A, *et al*. IRSL dating of fast-fading sanidine feldspars from Sulawesi, Indonesia[J]. *Ancient TL*, 2016, 34(2): 1-13.

[103] Buylaert J P, Yeo E Y, Thiel C, *et al*. A detailed post-IR IRSL chronology for the last interglacial soil at the Jingbian loess site (northern China) [J]. *Quaternary Geochronology*, 2015, 30(6):194-199.

Advances and Issues in Luminescence Dating of Loess Deposits in Arid Central Asia*

Wang Leibin[1], Wei Haitao[1], Jia Jia[1], Li Guoqiang[1], Chen Fahu[1,2*]

(1.*Key Laboratory of West China's Environmental System, College of Earth and Environmental Sciences, Lanzhou University*, *Lanzhou* 730000, *China*; 2.*CAS Center for Excellence in Tibetan Plateau Earth Sciences of the Chinese Academy of Sciences*, *Beijing* 100101, *China*)

Abstract: High-resolution loess deposits are widely distributed in Arid Central Asia (ACA) and provide important records associated with dust transportation, paleoenvironmental and paleoclimatic evolution. The chronology is the foundation of the research into loess deposits as an environmental archive. In recent decades, the gradually developed optical dating method has been increasingly matured and become an important approach to establishing the loess-paleosol sequences. Here, we summarized and discussed previous work on loess chronology mainly based on optical dating approach in ACA. The following understandings have been listed: ① In comparison with optical dating method, the suitable material for ^{14}C dating is uncommon in ACA. However, the dating range of luminescence dating is more extensive, and the dating materials are accessible. Thus, the optical dating is widely applicable in the establishment of loess framework in this area. ② Until now, the quartz Single Aliquot Regeneration (SAR) method can be applied to the establishment of loess-paleosol sequence since last glacial period. But several issues remain unaddressed. For example, the Optically Stimulated Luminescence (OSL) signal sensitivity of quartz grains are low in some areas. Furthermore, the results of OSL dating of different grain sizes within a single sample are inconsistent in some areas. The solution of these problems still requires more methodological research. ③ The post-IR IRSL (pIRIR) and multiple elevated temperature stimulation (MET-pIRIR) protoCols of feldspar have basically overcome the anomalous fading issue in the traditional IRSL dating process. In ACA, the framework since MIS 7 can be established with K-feldspar luminescence dating method. Compared with quartz luminescence characteristics, the K-feldspar luminescence signals are more sensitive and exhibit a high saturation level. In specific applications, it is necessary to establish the age frame according to the luminescence sensitivity, the age of samples or other factors.

Key words: Arid central Asia; Loess deposits; Quartz OSL dating; K-feldspar pIRIR and MET-pIRIR dating.

---

* **Foundation item**: Project supported by the International Partnership Program of Chinese Academy of Sciences "CAS Special Project on International Cooperation along the Belt and Road Initiative" (No.131C11KYSB20160061); The Consulting Program of Chinese Academy of Sciences "The strategic research on the environmental changes of Eurasian hinterland and the prosperity and decline of the Silk Road civilization" (No. 2017ZWH006A-018).

First author: Wang Leibin(1989-), female, Lingqiu County, Shanxi Province, Ph. D student. Research areas include optical dating. **E-mail**: wanglb15@lzu.edu.cn

* **Corresponding author**: Chen Fahu (1962-), male, Danfeng County, Shaanxi Province, Professor. Research areas include environmental change and the evolution of human civilization. **E-mail**: fhchen@itpcas.ac.cn