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中国沙漠物源研究:回顾与展望①

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摘 要 沙漠物源研究不仅在风沙地貌学上有重大的理论和实践意义,而且对联结大气粉尘排放、黄土堆积、气候系统和海洋生物地球化学循环也有重要价值。在简要回顾中国沙漠研究的基础上,梳理了中国沙漠物源研究的理论、方法和主要成果,结合国际上沉积物物源分析的趋向,指出目前世界沙漠物源的研究都是基于沉积物组份属性统计的反演模型,这种研究范式在数据获取、处理与解释方面存在缺陷,如沉积物的取样设计与测试分析、未消除"粒级依赖"对沉积物组份影响、数据未进行对数变换、忽视 Dickinson 图解应用的前提条件等。提出今后中国沙漠物源研究的方向:①采用正确统一的取样设计和分析方法对各沙漠的沉积物组份属性进行系统研究,建立中国沙漠沉积物组份的属性数据库;②选择若干典型沙漠,利用其周边山地详尽的地质构造、母岩和气候数据,定量构建沉积物生成的正演模型,模拟源区生成沉积物的数量、成分和结构,并用建成的沉积物组份属性数据验证和校正;③定量评估河流冲积物、冲积—湖积物、洪积—冲积物和基岩风化的残积、坡积物对中国各沙漠物源的贡献率与迁移路径,研究中国各沙漠中细颗粒物质的形成机制,对比中国沙漠与低纬度沙漠物源的形成机制;④定量研究历史和地质时间尺度沙漠—黄土—深海沉积物物源的内在联系及其驱动因素,建立陆地—大气—海洋物质循环的机理模型。

关键词 中国沙漠 沉积物 粒度 地球化学 物源分析

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世界干旱半干旱区约占地球陆地表面的 1/3[1],主要分布于副热带高压带控制下的低纬度地区[2]。中国的干旱半干旱区分布于中纬度的温带内陆,它西与中亚干旱区相接,北与蒙古干旱区毗邻,区域内戈壁、沙漠、黄土呈有规律的空间分异[3],是全球粉尘排放的重要源区之一[4-5]。戈壁、沙漠带的粉尘在大气环流的控制下经风力吹扬,被搬运至下风向处的山前盆地、山麓、河谷、平原等地形区堆积,形成沉积连续的黄土和黄土状沉积物,成为记录陆地环境变迁的良好信息载体[6-9]。冰期时,气候冷干,强劲的风力使被搬运的粉尘颗粒变粗、排放通量增大;间冰期时,气候变得暖湿,风力的减弱使得搬运的粉尘颗粒变细、排放通量减少[10-12]。基于该假说,在过去几十年里,研究人员利用沉积在黄土高原、天山、昆仑山、盆地边缘、河谷等地貌单元内的黄土—古土壤沉积序列,结合年代学和各种物理化学生物指标,反演了中国黄土的形成过程与机制、古大气环流、古全球变化、亚洲内陆干旱化和中国沙漠的形成时间,取得一系列重要的研究进展[6-9,13-30]。然而,相对于成果丰硕的中国黄土研究,作为黄土和亚洲粉尘重要物源地的中国沙漠自身的物源研究则非常有限[3,31-38]。沙漠物源研究不仅在风沙地貌学上有重大理论和实践意义[39-41],而且对认识大气粉尘排放、黄土堆积、气候系统和海洋生物地球化学循环也有重要的理论价值[4,42-47]。

本文的目的是:①总结中国沙漠物源研究的理论、方法和已有成果;②评述目前国际上沉积物物源分析的主要趋向;③指出中国沙漠物源研究存在的问题和未来发展趋势。

1 中国沙漠的自然概况

中国沙漠主要分布于 35°~50° N,75°~125° E 的范围内,它呈一条弧形绵亘于中国的西北、内蒙和东北西部,东西长 4 000 km,南北宽 600 km,面积达 80.89×10^4 km^2,约占整个国土总面积的 8.4%[31,39,41]。中国主要的沙漠有 14 个,其中 5 个分布于沙漠带东部,分别是呼伦贝尔沙地、松嫩沙地、科尔沁沙地、浑善达克沙地和毛乌素沙地,它们的年降水量介于 200~400 mm,干燥度为 1.2~2.0,植被覆盖度较高,以固

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定半固定沙丘为主;其余分布在沙漠带西部,分别是库布齐、乌兰布和、腾格里、巴丹吉林、河西走廊的沙漠、柴达木盆地的沙漠、库姆塔格、古尔班通古特和塔克拉玛干沙漠,它们的年降水量为 100~200 mm,有的甚至不足 50 mm,干燥度为 4.0~60.0,植被覆盖稀疏,除古尔班通古特沙漠外,主要以流动沙丘占优势[31,41]。

2 中国沙漠物源研究的理论、方法与主要成果

2.1 中国沙漠研究的简要回顾

新中国成立初期,根据局部地区营造防风固沙林带的需要,开展了一些小规模的沙漠研究,如毛乌素沙地南缘流动沙丘的研究、科尔沁沙地东南缘章古台和腾格里沙漠东南缘铁路沿线流沙的固定试验[48]。1959 年中国科学院成立了 860 多人的治沙队,采用航空相片判读与野外考察的方法,对中国沙漠和戈壁进行了大规模综合考察,基本摸清了中国沙漠的自然条件与资源、沙丘特征与风沙运动规律[49-51],并建立了 20 多个沙漠试验站,为此后中国沙漠的研究奠定了坚实的基础[51-53]。1966—1976 年间,中国沙漠研究受到影响,转入以治理沙害为中心的专题研究,如沙区的铁路修建、水土资源开发利用等[49,53-54]。1977 年联合国荒漠化会议的召开,引起了全球对土地荒漠化问题的关注,为顺应新形势,中国沙漠研究的重点转入了以土地沙漠化问题为中心的综合研究,开展了干旱半干旱区土地沙漠化与半湿润地带风沙化问题的成因、过程、预测、整治研究[53-55],进行了土壤风蚀的风洞模拟实验,加强了风沙物理与风沙工程的理论与实验研究,同时也开拓了沙漠地区的第四纪研究工作[56]。近 10 多年以来,随着国家经济和科技投入的不断增加,中国沙漠研究开始以沙区长期野外试验站为平台,在不同时空尺度上对沙漠环境与风沙物理、沙漠形成演变与全球变化、沙漠化过程及其防治、沙漠化监测与信息系统等方面进行多学科的交叉集成研究[57-60]。

2.2 中国沙漠物源研究的理论与方法

沙漠地表最基本的特征是堆积了形态各异、大小不同的沙丘,它们是松散沉积物经风力搬运在一定条件下堆积形成的[40,61]。这些沙丘沉积物的粒度、矿物组成、形态、颜色、地球化学、地质年龄等属性特征记录了母岩风化剥蚀、搬运和后期改造过程的信息,受区域地质构造、气候等因素控制。因此,沙漠物源研究的范畴属于地质学,它的理论基础是沉积学理论[62-63]。在中国沙漠物源研究中,传统的方法是沙丘沉积物的粒度分析和重矿物分析,结合野外地貌调查、古地理与地质资料来推断沙漠的物源[31,40]。近 10 多年来,为跟踪国外沉积物物源研究方法,开始尝试地球化学、环境磁学和单颗粒锆石定年的方法来探讨沙漠物源。如石英的氧同位素[32-33]、电子自旋共振信号强度和结晶度[38]、释光灵敏度[3],沉积物的磁化率[64-65]、Pb 同位素[66]、Nd-Sr 同位素和 REE[36,67-68],单颗粒碎屑锆石的形态[69]、U-Pb 年龄和 Hf 同位素[70]的研究。

2.3 中国沙漠物源研究的主要成果

中国沙漠物源研究一直存在“就地起沙”和“外地来沙”的争论。20 世纪 50 年代初,严钦尚[71]和罗来兴[72]对毛乌素沙地南缘陕北榆林、靖边、定边一带流动沙丘的考察和分析,提出了该地区沙源是由于人类不合理使用土地,破坏地表植被,使古沙翻新而成的,属“就地起沙”。20 世纪 60 年代至 80 年代,在对中国沙漠大规模野外调查的基础上,结合地质地貌和古地理资料分析,朱震达等[31]确定中国沙漠物源具有近源性,并按成因将它们的物源归为 4 种类型,即河流冲积物、冲积—湖积物、洪积—冲积物和基岩风化的残积、坡积物,否定了沙漠物源的“外地来沙”。此后,对塔克拉玛干[73-76]、古尔班通古特[77]、库姆塔格[78-79]、柴达木[80]、巴丹吉林[81-82]、腾格里[83-84]、库布齐[85]、乌兰布和沙漠[86-87]、毛乌素[88-89]、浑善达克[90]、科尔沁[91]、松嫩[92]、呼伦贝尔沙地[93]的粒度或重矿物分析也支持这一观点。然而,近年来对中国沙漠带东部 4 大沙地边缘多个地层剖面的光释光(OSL)测年表明:末次冰盛期(LGM)时,这些沙地的东界和南界相对于全新世适宜期(HO)分别向东向南扩张了几百甚至上千公里[94],而中国沙漠带西部的沙漠在 LGM 和 HO 时一直存在活动沙丘[94-96]。考虑到戈壁、沙漠和黄土的同心圆状分布格局,可以推测冰期时中国沙漠带东部沙地有可能是其西部和北部沙漠不断扩展的产物[34],即这些沙地的沙源有可能是“外地来沙”。但随后对浑善达克、科尔沁和呼伦贝尔沙地的重矿物分析[34]、碎屑锆石 U-Pb 年龄和 Hf 同位素[70,97]分析显示,西部沙漠对东部沙地沙源的贡献很小,从而否定了东部沙地“外地来沙”的推断。

近 10 多年来,随着沉积物和单颗粒矿物的元素地球化学、同位素地球化学和定年分析技术的日臻成

熟,同时借鉴国外沉积物物源分析方法,对中国沙漠物源展开了有益的探索。如付旭东等[32-33]利用沙丘沉积物中最常见的轻矿物—石英在表生过程中氧同位素基本保持不变的特性,对中国沙漠 2 个粗粒级的石英研究显示,沙漠石英 $\delta^{18}O$ 值存在“粒级依赖”(Grain-size dependence)且区域差异显著。石英的电子自旋共振(ESR)信号强度和结晶度(CI)也可以用来示踪物源[98-102],Sun 等[38,101]对中国西部沙漠和蒙古戈壁石英的 ESR 信号强度和 CI 研究表明,细颗粒石英比粗颗粒石英更能显示它们的区域差异。基于石英晶体缺陷与其母岩的成岩条件有关[103],石英的释光灵敏度被证明可以示踪物源[104-106]。Lu 等[3]对中国沙漠 3 个粒级的石英研究显示,沙漠石英释光灵敏度也存在“粒级依赖”和显著区域差异,并且沙漠物源与其周围的造山带密切相关。尽管沉积物的磁学特征对戈壁、沙漠的物源有一定的指示意义[64-65],但是对中国沙漠沉积物磁化率的系统报道还很少。Pb 同位素的物源示踪研究主要用于风尘沉积物[107-108],李锋[66]对中国沙漠沉积物的全岩测定显示,它们的 Pb 同位素比值区域差异明显,但值得注意的是 Pb 同位素容易受沉积循环改造和人类排放 Pb 的影响[109]。Nd-Sr 同位素($^{143}Nd/^{144}Nd$ 和 $^{87}Sr/^{86}Sr$ 比值)在风化、搬运、沉积和成岩过程中相对稳定[110],它是近几年沙漠和黄土沉积物物源示踪常用的方法[36,67-68,111-112]。中国沙漠表层沉积物 Nd-Sr 同位素测定显示,它们具有显著的区域差异且受地质构造背景控制,推断其沙源主要来自邻近的山脉和基底岩石[67,111]。尽管稀土元素(REE)也被用于沉积物的物源示踪[36,68,113],但由于 REE 在陆壳中本身的变异不大,加之测试误差较大,使 REE 很难区分地表沉积物之间的细微差别[37]。沉积物物源定量研究是今后主要的发展方向[114-115],重矿物锆石在表生循环中非常稳定且 U-Pb 同位素体系较为封闭[70,97,116],单颗粒锆石 U-Pb 定年技术成为当前定量厘定沉积物源区的热点[35,117-119]。张瀚之等[69]对单颗粒碎屑锆石的形态特征研究显示中国沙漠锆石形态具有明显的区域差异,沙漠物源搬运距离较短,具有近源性。最近对中国几个沙漠单颗粒锆石 U-Pb 年龄的测定显示它们的锆石年龄谱差异明显[35,70,97,118-119],其物源来自周围的造山带。尽管单颗粒锆石 U-Pb 年龄示踪物源有很大优势,但在实用上还存在局限性[37]。

总之,目前对中国沙漠的石英氧同位素、电子自旋共振信号强度和结晶度、释光灵敏度以及沙丘沉积物的磁化率、元素地球化学、同位素地球化学和单颗粒锆石 U-Pb 年龄的研究表明,各个沙漠的物源有显著的区域差异且具有近源性。这与以往传统的粒度分析、重矿物分析结合地质地貌资料推断的中国沙漠物源来自近源的观点基本一致。然而,各种成因的近源物质对各沙漠的供给比例有多大,为大气粉尘、中国黄土和海洋沉积物提供多少物源,仍缺乏定量的数据。此外,中国各沙漠中细颗粒物质的形成机制,是否具有近源性,是否存在“外地来沙”,以及它们对沙漠物源的贡献比例仍是一个尚未解答的问题。

3　沙漠物源定量分析存在的问题及发展趋向

沙丘是沙漠地表最显著的特征,它们是由松散沉积物堆积而成的[40]。这些沉积物与其源区母岩并不是一对一的对应关系[114,120],它们现今的属性特征反映的是母岩岩性及其被风化、再旋回、搬运、混合、沉积、成岩改造的全部历史[114]。沉积物与其源区之间复杂的网络关系很难被完全揭示,因为从“源”到“汇”的过程中,各种各样的因素都会改变母岩碎屑的成分和结构[121-127],造成源区母岩信息的大量丢失,这也是沉积物物源定量分析一直存在的主要障碍[114]。最近 Weltje[115]提出的沉积物生成与物源定量研究的总体结构框架(图 1),代表了当前沉积物物源定量研究的最高水平和今后的发展方向。“源”与“汇”可通过正演模型和反演模型刻画,但正反演模型中的化学(C)、矿物(M)和岩石学(P)数据须通过 CMP toolbox 变换后才能输入模型中,图中的每个箭号代表了一系列的方法和过程。

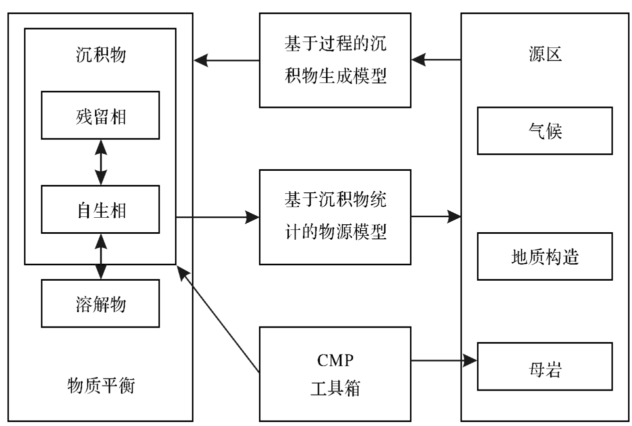

图 1　沉积物生成与物源定量研究的总体结构框架图[115]

Fig.1　Schematic view of the overarching strategy in quantitative sediment-generation and provenance studies[115]

在当前的沉积物物源分析中,绝大多数研究都属于反演模型(Inverse models),即通过三种主要方法(全岩组份的化学、岩矿分析,重矿物的选择性分析,单颗粒矿物的形态、化学和同位素分析)获取沉积物的各种属性数据,然后统计各种指标并制作图表,再依据先验知识推断物源[114]。这种研究范式在世界沙漠物源研究中得到广泛应用,如非洲的Sahara[128-129]、Namib[130-133]、Kalahari desert[134-135],北美洲的Great basin[136-137]、Mojave[138-139]、Sonoran desert[140-141]、Chihuahua desert[142],南美洲的Atacama[143-144]、Patagonia desert[145-146],大洋洲的澳大利亚沙漠[147-149],亚洲的Arabian desert[124]、Thar desert[150-151]和中国沙漠[3,31-38,64-70]。然而,目前这些基于沉积物组份属性统计的反演模型在数据获取与统计分析中,仍然存在几方面明显的问题:①沉积物取样与实验样品的代表性,如沉积物的随机取样是否能代表研究区域的整体水平,用量微少的化学、岩矿和同位素分析测试结果是否能代表每个实验样品的整体,单颗粒矿物的统计与分析需计数多少颗粒才能代表一个沉积物样品的整体[114],仍需要进一步的深入研究;②消除"粒级依赖"对沉积物组份的影响,由于母岩风化后的产物在搬运和沉积过程中的分选作用会造成某些粒级的物质优先富集,沉积物成分与粒级存在一定的函数关系[114]。例如,在细粒物质中SiO_2/Al_2O_3的比值会随着粒级或结构成熟度的减小而减小;中国北方沙漠石英$\delta^{18}O$值随着粒级的减小有增大的趋势[32]。因此,选择恰当的沉积物粒级进行化学、岩矿和同位素分析对沉积物物源研究至关重要。尽管一些学者对沉积物的成分与粒级之间的关系进行了有益的探讨[125-127],但目前仍没有任何方法能消除粒级效应对成分的影响;③组份数据分析中的对数变换,组份数据常用百分比和含量来表示[115],但是为了消除数据间的"假相关"和"负偏置"问题,应该对组份数据进行等度量的对数变换处理[127];④Dickinson图解适用的前提和存在的问题[114-115],目前某些沉积物物源研究只是简单的套用Dickinson图解,并未考虑其正确使用需满足的很多前提条件和问题。

基于沉积物生成过程的正演模型(Forward models)可预测属性明确的源区能生成沉积物的数量、成分和结构,然而这种实用的定量正演模型目前还不存在[115]。构建正演模型的最大障碍是缺乏母岩物理化学风化的机理和速率方面的定量数据,这些问题的解决既需要将母岩定量过程描述和强大的统计技术整合,还需要有充足的高质量数据校正和验证模型。恰当的数值方法和统计方法是未来定量正演模型发展的坚实基础[115]。

目前沉积物物源研究的案例主要集中于沉积物成分属性统计的反演模型,而对基于过程的沉积物生成模型的研究较少。正反演模型都不是完美无缺的,未来沉积物定量物源分析需要改进沉积物数据获取与处理方法,加快构建沉积物生成的正演模型研究。

4 中国沙漠物源研究的问题和未来展望

中国沙漠物源研究基本上都是基于沉积物组份属性统计的反演模型,然而此类模型在属性数据的获取与处理方面仍然存在缺陷:①沙丘沉积物的取样设计并没有严格的统计学意义,沉积物组份的粒度、化学、矿物、同位素测试分析仅仅取用了采样样品的微小部分,这样的测试结果能否代表该样品的整体状况,其可靠性需要评估,用激光粒度仪分析沙丘沉积物的粒度存在很大误差,重矿物分析需要多少样品以及统计多少颗粒才能代表一个样品;②消除"粒级依赖"对沉积物成分的影响,对沉积物组份的化学、矿物、同位素分析时应该选用恰当的粒级,而不是使用全岩分析;③处理组份数据时,应进行对数变换,而不是直接使用含量或百分比。此外,在解释组份数据时,未能整合源区已有的地质构造、母岩、气候、地貌等数据资料,多数研究仍是定性的推断,缺乏定量物源研究的案例。

沉积物物源的研究需要沉积学、岩石学、矿物学、地球化学、构造地质学、地层学、数学地质和地貌学等学科的交叉研究。今后中国沙漠物源研究应做好以下几方面的工作:①采用大面积网格随机取样法对中国各个沙漠的沙丘沉积物进行系统采样;用筛析法分析每个沙漠的粒度组成,然后对不同粒级的沉积物颗粒分别进行矿物组成、地球化学、单颗粒锆石年代学属性的系统测试分析,建立每个沙漠沉积物组份的属性数据库;依据沉积物在搬运、沉积过程中遵守等效沉降原理,使用源岩平均密度指数(SRD)校正不同粒级沉积物组份的粒度、矿物和地球化学数据,消除"粒级依赖"对沉积物成分的影响;基于沉积物组份属性数据的等级结构(岩石→矿物→化学成分),建立化学成分—矿物—岩石之间定量的数学关系(CMP toolbox),将沉积物组份的岩石、矿物、地球化学属性间的关系用数学公式表达,从而定量地反演沙

漠的物源。②选择若干典型沙漠,通过全球的地形、岩性、温度、降水和植被盖度图获取其沉积物源区的属性特征;通过室内实验和野外研究解决母岩和矿物的物理化学风化机制及其速率,建立母岩物理风化形成的矿物颗粒粒度分布模型;用 CMP toolbox 定量表达岩石—矿物—地球化学属性间的关系,定量模拟源区生成沉积物的数量、成分和结构,构建源区沉积物生成的正演模型,并用建成的沉积物组份属性数据库验证和校正模型;具体方法案例可参考文献[152-155]。③研究中国各沙漠中细颗粒物质的形成机制,是否具有近源性以及它们对沙漠物源的贡献比例,对比研究中国沙漠与低纬度沙漠物源的形成机制,定量评估河流冲积物、冲积—湖积物、洪积—冲积物和基岩风化的残积、坡积物对中国各沙漠物源的贡献率以及它们的迁移路径,建立中国沙漠物源区划图,应用到防沙治沙的工程实践中。④基于山地构造抬升—气候—风化剥蚀的相互作用以及沉积物从陆地—大气—海洋迁移的内在联系,定量研究历史和地质时间尺度沙漠—黄土—深海沉积物物源的传输途径及其驱动因素,建立陆地—大气—海洋物质循环的机理模型,为深刻理解地球各圈层间物质交换与地表过程提供依据。

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Provenance Studies of Chinese Deserts: Review and Outlook

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Abstract: Provenance studies of aeolian sand seas not only have great theoretical and practical significance in aeolian geomorphology, but also are essential for understanding the complex linkages between dust emission, loess accumulation, climate system, and ocean biogeochemistry cycles. A brief historical survey of Chinese deserts illustrates the limitations of modern provenance research. The state of the art in basic ideas, techniques, and their applications in provenance analysis of sediments are reviewed across Chinese sand seas. Traditionally sediment provenance studies are deductive approach, which depend on compositional and textural sediment properties based on geochemistry, mineralogy, and petrography, and its main difficulty stems from the fact that sediments are not a one-to-one image of their source, implying that factors other than parent lithology determine their final composition. Combined with the future research trend on quantitative provenance analysis (QPA) of sediments, some problems on data-acquisition and processing methodologies in provenance studies across global sand seas is presented, such as sampling design and physicochemical analysis of sediment, grain-size dependence of sediment composition and environmental bias, compositional data statistically treated with the log-ratio method for avoiding the well-known problems of spurious correlation and negative bias, limitations of typical Dickinson diagrams, and so on. Generally, current more attention has been paid to the inverse approach based on compositional properties, which dominates the field of quantitative provenance analysis, whereas applicable process-based forward model of sediment generation, which could predict simultaneous evolution of the grain-size distribution, as well as the petrographic, mineralogical and chemical composition of weathering products of specific parent rocks under a range of climatic and tectonic conditions, do not yet exist. Unraveling the history of sediments is a complex and challenging task which needs multidisciplinary efforts like sedimentology, petrography, mineralogy, geochemistry, geochronology, structural geology, stratigraphy, mathematical geology, and geomorphology. It is concluded from this review that the QPA of Chinese sand seas over historic and geologic timescale is still in its infancy and future provenance studies is needed to towards a holistic view of sediment routing systems at various temporal and spatial scales and their coupling with uplift, climate and denudation in mountain belts as well as transfer of sediments from the continents to the atmosphere and oceans. These include (i) to build sedimentary compositional data bases using a uniform sampling design and analytical measurements across sand seas of China, to develop and use mathematically rigorous methods of statistical analysis and numerical modeling of sediment composition when dealing with compositional data such as data in percentages, concentrations or proportions, (ii) to construct a process-based sediment generation model (Forward model) capable of predicting the simultaneous evolution of the texture, as well as the petrographic, mineralogical and geochemical composition of weathering products of specific parent rocks under a range of climatic and tectonic conditions, using typical sand deserts of China which have available parent lithology, tectonic setting, regional geography, and climatic-physiographic data sets, to calibrate and validate forward models by sufficient high-quality data bases established at similar temporal and spatial scales, (iii) to assess contribution ratios and transport pathways of four possible proximal sources in Chinese deserts, to reveal mechanism of the formation and production of desert loess and silt quartz grains, to compare aeolian sand sources of Chinese deserts with most of the worldwide low-latitude deserts, (iv) to establish internal connections between deserts, wind-blown dust emission, loess accumulation, and climate system and ocean biogeochemical cycles at historic and geologic scales, and to build a Earth system model coupling with continent, atmosphere and ocean for understanding the Earth surface processes.

Key words: Chinese deserts; sediments; grain-size distribution; geochemistry; provenance analysis