第31卷 第1期
2013年2月

沉 积 学 报
ACTA SEDIMENTOLOGICA SINICA

Vol. 31 No. 1
Feb. 2013

文章编号: 1000-0550(2013) 01-0099-09

陆源沉积岩物源分析研究进展与发展趋势①

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摘 要 陆源沉积岩物源分析对于古地理重建、古环境与古气候恢复、沉积盆地分析、沉积矿产预测、大地构造背景分析及盆山耦合研究等均具有重要意义。在大量文献调研的基础上,本文总结了沉积学方法、岩石学方法、重矿物方法、元素地球化学方法、地质年代学方法、粘土矿物学方法、化石及生标化合物方法及地球物理学方法等传统的物源分析方法及其研究进展; 并介绍了近年来出现的磁性矿物学方法、矿物颗粒微形貌分析等物源分析新方法。由此展望了物源分析的发展趋势: 随着新技术新方法的不断涌现,物源分析将从传统方法向现代测试技术的转化,从单一方法到多方法的综合运用,从单一学科走向多学科联合交叉,从定性分析向定量分析发展。

关键词 陆源沉积 沉积岩 物源分析 研究进展 发展趋势

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中图分类号 P512.2 TE121.3 文献标志码 A

沉积物物源分析包括古侵蚀区的判别、古地貌特征的重塑、古河流体系的再现、物源区母岩的性质的追踪、气候以及沉积盆地构造背景的确定等,是盆地分析的重要内容; 随着地质科学理论的进步和多种现代分析测试手段的提高,物源分析已成为沉积学研究的重点课题之一[1~6]。通过物源分析,既可了解物源区经历的地质演化过程,借助单颗粒矿物同位素测年技术,还可描述遗失的源区年代史[7]。确定物源区的地理位置、母岩性质及其组合特征、沉积物搬运路径与距离,开展物源分析研究,不仅是物源区大地构造背景分析、地壳与大地构造演化恢复、古环境与古气候恢复的重要途径[8~10],而且是沉积区岩相古地理重建、原型盆地恢复、沉积盆地分析、沉积矿床预测的重要依据[11~14]。物源分析还可作为连接沉积盆地与造山带的纽带和盆山耦合研究的切入点[15]; 因此,开展陆源沉积岩物源分析具有重要的科学意义。

1 物源分析方法研究现状

物源分析作为沉积地质学研究的热点问题之一,多种分析方法在应用中得以不断改进和创新。目前国内外常用的物源分析方法主要有以下几种:

1.1 沉积学方法

沉积学法主要依据沉积学原理,对碎屑岩进行物源分析,如根据碎屑岩粒度由物源向盆地方向逐渐变细、地层厚度变大[16]、砂/地比值向盆地中心方向总体呈降低趋势; 古流向测量及玫瑰花状图[17,18]、古地貌分析[19]、结合沉积相分析结果判断物源。根据地层等厚图、沉积相展布图等相关图件,可推断出物源区的相对位置,结合岩性、成分、沉积体形态、粒度及古流向等资料,使物源区分析更可靠。但由于古流向具较大的分散度,故上述标志均具有较大的局限性和不确定性,必须做大量的野外观测和资料统计,方能获取较客观的古水流与物源方向信息。沉积学方法的优点是直接、有效、花费小,但不足之处在于统计工作量较大,且仅能判断物源的大致方向,不能确定物源区的具体位置、母岩性质等具体信息。

1.2 岩石学方法

根据盆地陆源碎屑岩来自母岩的陆源碎屑组合可以推断物源区母岩类型。尤其是砂砾岩中的砾石成分,可反映基底和物源区母岩的成分,也反映磨蚀的程度、气候条件以及构造背景。因此,砾石的各种特征是判断物源区、分析沉积环境的直接标志[20,21]。Dickinson 等依据大量的砂岩碎屑成分统计数据,建立了砂质碎屑矿物成分与物源区之间的系统关系,绘制了多个经验判别三角图解(Q—F—L,Qm—F—Lt,Qp—Lv—Ls,Qm—P—K 等)[22],至今仍然被广泛应用物源区的构造背景分析[23,24],但是该方法未考虑混和物源以及风化、搬运和成岩作用等作用的影响,

①山东省沉积成矿作用与沉积矿产重点实验室开放基金(DMSM200803)、山东省科技发展计划项目(2009GG20001021-07)共同资助
收稿日期: 2012-01-22; 收修改稿日期: 2012-04-18

在应用过程中也曾出现与实际情况不符的情况[15]。

传统的岩石学研究手段在物源分析中仍可发挥重要的作用,如偏光显微镜可直接鉴定沉积物中的岩屑,是物源的直接标志之一。对岩石中主要造岩矿物发光性的研究有助于判别沉积环境和岩石的成因,碎屑颗粒的发光分析可用于物源分析,碎屑岩中常见的石英、长石和岩屑多随物源变化而具有不同的发光特征,故依据碎屑颗粒在阴极光激发下的颜色特征也可分析物源[25,26],但阴极发光对物源的判断受到经验和较多随机因素影响。

1.3 重矿物方法

物源分析可用砂岩的重矿物组合、ATi(磷灰石/电气石)—Rzi(TiO_2矿物/锆石)—MTi(独居石/锆石)—CTj(铬尖晶石/锆石)等重矿物特征指数、以及锆石—电气石—金红石指数(ZTR指数)来指示物源[27,28]。时代较老的沉积物,重矿物自保存至现今,会因温度、埋深等条件的不同而使其种类增多,含量分布较分散,保留源岩的信息减小,对判断物源不利。因此,沉积物时代越新,利用重矿物判断物源的准确性会越高。同时,水动力会影响沉积时重矿物性质,重矿物组合分析法对源区的精确判别仍存在一定缺陷,对于碎屑重矿物组合在物源分析中的应用,应注意不稳定重矿物的组成,因为在某种程度上,不稳定重矿物才具有判别意义[29]。随着电子探针的应用,一些学者利用单矿物(如辉石、角闪石、电气石、锆石、石榴石等)的地球化学分异特征来判别物质来源[30,31],如利用石榴石电子探针分析结果来研究物源有其独到的优越性,可使水动力或成岩作用的影响降低到最小[32]。

1.4 元素地球化学方法

元素地球化学已成为地质构造复杂地区研究的有效手段[33],元素地球化学法已被国内外学者广泛运用,包括常量元素、特征元素及其比值法、微量元素(含稀土元素)法[34~37]。一些元素在母岩风化、剥蚀、搬运、沉积及成岩过程中不易迁移,几乎被等量地转移到碎屑沉积物中,故可被作为沉积物物源的示踪物,如Th、Sc、Al、Co、Zr、Hf、Ti、Ga、Nb及稀土元素(REE)等,尤其是其中的REE因其具有特殊的地球化学性质而在物源示踪中运用很广[38]。

保存在沉积物(岩)中的环境和物源信息,可用多种元素地球化学方法释读,如通过研究元素的组成、组合、相对含量、分布规律、比值关系、多元图解、配分模式,以及元素与同位素的关系等,进行物源示踪。作为古环境分析的替代性指标,研究元素在表生环境下的地球化学行为,可在示踪古气候、沉积物来源、沉积环境和古海洋学事件等领域发挥有效的指示作用[39]。在某种程度上,沉积物成分特征和地球化学特征是物源和沉积盆地大地构造背景的函数[7],通过对砂岩的研究,提出一系列常量、微量元素地球化学端元判别图及稀土元素地球化学模式判别图,用来鉴别不同源区的构造背景,这些方法已被我国学者广泛运用于大地构造背景的判别。

近年来,一些学者还利用电子探针、激光剥蚀等离子体质谱仪(LA—ICP—MS)、激光感生火化电感耦合等离子体质谱(LINA—ICP—MS)、电子顺磁共振(EPR)等成分分析仪器,测得重矿物中的常量元素、石英颗粒微量元素[40,41],根据矿物元素的组成、相对含量、元素的组合,建立多元图解和配分模式,用于物源分析和大地构造背景判别及沉积环境分析[42~44]。大多数特征元素均受成岩作用的影响,导致物源判别结果出现多解性,而选择化学性质相近、相关性强、在沉积成岩过程中富集程度相似的特征元素比值作为物源示踪指标,能够有效地避免成岩作用的影响[45]。

在不发生重结晶的情况下,石英在搬运、沉积和成壤过程中,它的氧同位素比值($\delta^{18}O$)不发生改变,能够保存源岩形成环境等信息[46],因此沉积物中石英的$\delta^{18}O$值可以用来探讨石英的形成环境、追踪物源区和母岩的特征[47]。

元素地球化学分析物源兼具有效、经济、定量等优点,既适用于富含基质的砂岩和页岩,又可确定物源的年龄和地球化学演化历史[11];并可有效的避免水动力因素的影响[38]。元素地球化学分析建立在沉积物对母岩的主元素组合的继承性基础上。但应该注意到主元素的活动性和可迁移性,原则上只是在短距离搬运和化学风化很弱的条件下才具有较好的可比性。化学变异指数(CIA)提供了一种定量硅酸盐矿物风化度的方法[48~51]。同时在进行元素组合分析时,还要考虑到搬运过程中的稀释作用,即应注意相对含量而非绝对含量。

1.5 地质年代学方法

单颗粒碎屑矿物的同位素测年在物源分析中的应用方面,目前应用的方法主要有:碎屑颗粒的(磷灰石、锆石)裂变径迹测年法[52]、含铀微相(锆石、独居石和榍石)U—Pb测年法[53~55]、(碎屑云母和角闪石)$^{40}Ar/^{39}Ar$测年法[56]、Rb—Sr法[57]、Sm—Nd

法[58,59]、Sr—Nd 法[60]、$^{87}Sr/^{86}Sr$ 法[61]、$^{207}Pb/^{206}Pb$[62]法等。

裂变径迹法分析物源区是利用磷灰石、锆石中所含的微量铀杂质裂变时在晶格中产生的辐射损伤，经一系列化学处理后，形成径迹，通过观测径迹的密度、长度等分布，并对其加以统计分析，从中提供与物源区的年龄及构造演化有关的信息。在物源研究方面，不仅可以利用同位素之间的相互关系来判别物源区，如利用绿帘石中的 Nd 和 Sr 同位素比值进行物源判别(幔源或壳源)，更重要的是通过沉积物年龄的测定来判别物源[63]。

1.6　地球物理学方法

地球物理学在物源分析中的应用主要有测井地质学法和地震地层学法[64]。测井地质学法主要利用自然伽马曲线分形维数、地层倾角测井来判断物源方向[65,66]；利用地震地层学确定物源和古水流方向也有成功的案例[18]，如利用地震反射特征勾绘进积方向，详细刻画了北塘凹陷古近系沙三段古物源体系[67]。

1.7　粘土矿物学方法

泥岩的渗透率一般低于砂岩，在成岩过程中不易受到外来流体和物质的影响，故其在确定物源方面可能比砂岩有用。另外，碎屑粘土是泥岩中的独特组分，在确定物源和古气候方面有很大的应用潜力，尤其是在浅层沉积物的物源示踪及第四纪以来的气候变化研究方面应用广泛[68,69]；还可利用 Al/Ca 或高岭石/蒙脱石比值来判断物源方向和预测储层[70]。

1.8　化石及生标化合物方法

借助于沉积物中微体化石的分析，以及泥质区正构烷烃、姥鲛烷、植烷、藿烷和甾烷等生物标志物的特征来判断有无陆源高等植物的输入[71]，通过不同来源和成熟度的生物标志物，来判断沉积有机质与碎屑沉积物的来源。

2　物源分析新技术与新方法

2.1　磁性矿物学方法

磁性矿物学在物质来源鉴别方面发挥着重要作用，通过对环境物质进行磁性测量，分析磁性矿物的类型、组合、含量、粒度和晶畴等特征，可有效揭示物源信息[72]。与传统的研究方法相比，磁学手段具有样品用量少、灵敏度高、简单快速、非破坏性、信息量大等优点[73]，而得以发展和应用。

2.2　矿物颗粒微形貌分析方法

近年来，重矿物颗粒表面结构分析对物源的指示意义也逐渐被重视。重矿物颗粒可以与石英一样进行矿物颗粒表面结构分析，借助扫描电镜可以揭示颗粒表面不同的结构组合，研究重矿物颗粒表面的形态可以确定物源及其运移过程[74]。因此不但可以通过矿物微区探针、化学组成和示踪元素来分析物源，而且可以由矿物表面形态判定沉积物在源区至沉积区搬运过程中的不同阶段并阐明影响矿物颗粒的不同过程。Cardona 等[74]发现重矿物颗粒晶体表面的晶纹和形态不仅可进一步证实通过探针、地球化学和裂变径迹等方法获得的物源信息，而且还可以区分出重矿物的演化阶段并阐明矿物从开始搬运直到最终沉积，影响矿物颗粒的不同过程，并在研究 Guadalete 河流阶地时得到应用。

3　物源分析发展趋势

随着先进分析手段的使用，沉积物所携带的物源信息被大量挖掘，物源区资料的应用前景变得更为广阔，未来的发展呈现如下趋势:

3.1　从传统方法向现代分析测试技术的转化

早期的物源分析主要依靠沉积学、地层学、岩石学、重矿物等方法; 虽然传统的方法依然有效，但现在更多的依赖于扫描电镜、阴极发光、X 衍射、电子探针、能谱分析、电子探针及激光剥蚀等离子体质谱仪(LA—ICP—MS)、激光感生火化电感耦合等离子体质谱(LINA—ICP—MS)、电子自旋共振(ESR)测年、电子顺磁共振(EPR)等现代分析测试技术的综合运用[75~80]。

3.2　从单一方法到多方法的综合运用

物源分析正从早期单一方法到多方法的综合运用、从单一学科走向多学科联合交叉转变，如岩石特征—重矿物—全岩主量元素—微量元素—稀土元素组合[81]，岩石学数据—古水流数据—岩石化学[82]组合、重矿物—元素地球化学—同位素年代地质学组合[83~86]、同位素地球化学—粘土矿物学的组合[58]、重矿物—石榴石地球化学—古流向的综合运用等[87]。在地质工作者不懈的努力和探索中，随着现代测试技术的不断提高，物源分析方法将会更加完善和丰富. 由定性分析走向定量分析，由单一方法走向多学科多方法的综合运用，这将是物源体系分析的未来发展方向[88]。

3.3　从定性判断到定量分析

定量物源分析(QPA: quantitative provenance analysis)是定量地评价从可识别的物源区到盆地充填过程中的碎屑物质类型、数量及供给速率[89]。随着先进分析手段，如电子探针、离子探针、等离子质谱技术以及同位素测年等的应用，从定性到定量是物源分析的必然趋势。现代分析测试技术、数学定量模型[90]和计算机技术的提高[91]为定量物源分析提供了发展机遇[92~93]。沉积物(特别是单颗粒矿物)所携带的物源信息的大量挖掘变得可行，物源区资料的应用前景也更为广泛。

在定量研究方面，已发展出两个分支：一是模式识别，如判别分析、模糊聚类、神经网络识别[94]；另一分支则基于"质量守衡"原理，通过数理统计方法实现物源的定量识别[89]，提出了物源定量识别的非线性规划数学模型，并利用模型计算了东海陆架北部表层沉积物细粒级部分之长江、黄河物源的贡献量。

3.4 新技术新方法不断涌现

在国内外广大学者的不断探索和实践中，有关物源分析的新技术新方法层出不穷。如最新的研究结果显示，Hf同位素[2,3]与斑脱土化学特征[95]被作为物源变化的标志首次应用于物源分析；磁性矿物包裹体及磁学手段被不断发展和应用[72,73]；近年来，石英颗粒[96]及重矿物[74,97]的显微晶面形貌特征对物源的指示意义也被成功应用。

4 影响因素与问题讨论

构造运动对物源位置、物质成分及结构、搬运路径、甚至最终的沉积位置等方面有明显影响，构造抬升可以使物源区发生变化，可造成地层岩石碎屑组分及年龄分布范围加大；走滑断层可使某一时期沉积物与源岩发生长距离侧向位移，造成沉积体系的不连续及其与源区的分离；逆冲推覆作用可使源岩消失殆尽或仅留残片[7]，都会增加物源分析的难度，故物源分析必须结合其构造背景、构造运动的特点。

虽然物源分析在上述各个方面取得了重要的进展，但目前仍然存在一些问题尚待解决，如：哪种沉积物或元素对环境的变化最为灵敏？如何确定再旋回石英颗粒的物源？搬运路径中的沉积体系构型较少涉及；机械沉积分异作用和化学沉积分异作用对母岩和沉积岩(物)造成的成分差异未被评估；在每个沉积阶段，母岩在被风化侵蚀过程中，矿物种类、组分的改变或溶解对物源分析所造成的影响需要评估；这些因素对物源分析结果均会产生一定影响，如何量化这些因素，目前的研究基础较薄弱。物源区分析往往是基于碎屑组分、化学成分或年龄等与可能物源区的对比，往往仅具有统计意义。因此，深入了解区域地质背景，把握物源区与沉积区的构造活动和演化历程，大量收集可能的物源区的地质信息，在此基础上，结合一定数量的样品测试，进行数据统计分析，才能得出理想的物源分析结果。

5 结 语

作为沉积盆地分析的重要内容之一，陆源沉积岩物源分析不仅是古地貌的重塑、岩相古地理重建、原型盆地恢复、沉积盆地演化再现、盆地沉积格局与沉积体系分析、沉积矿产预测、油气储层预测、母岩性质追踪的重要依据，而且是物源区大地构造背景分析、地壳与大地构造演化恢复、古环境与古气候恢复的重要途径，还可作为连接沉积盆地与造山带的纽带和盆山耦合研究的切入点。陆源沉积岩物源分析将在未来的地质研究、沉积矿产预测和勘探中发挥重要的作用，并倍受大地质工作者关注。在科学理论不断进步、科学仪器日新月异、新技术方法层出不穷的新时代，陆源沉积岩物源分析也必将迈入快速发展的新纪元。

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Research Progress and Development Tendency of Provenance Analysis on Terrigenous Sedimentary Rocks

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Abstract: Provenance analysis on terrigenous sedimentary rocks is significant for all of palaeogeomorphology remolding, palaeogeography reconstruction, palaeoenvironment and palaeoclimate recovering, original basin resuming, sedimentary basin reappearing, depositional system analysis, sedimentary deposits forecasting, petroleum reservoir predicting, parent rock property tracing, geotectonics settings analysis, crust and geotectonics evolvement resume, and study on coupling of basin and moutains. We summarized traditional provenance analysis methods and research progress of sedimentological method, petrographic method, heavy mineral method, element geochemistry method, geochronology method, clay mineral method, fossil and biomarker method, and geophysics method. We also introduced new methods on provenance analysis of magnetic mineralogy method, mineral micro-texture method upraise in recent years. Herewith, we prospect development tendency of provenance analysis: with constantly upraising of new technique and new method, provenance analysis transferring from traditional methods to modern testing technics, from single technique to colligation of multiple methods, from one subject to alliance and overlap of multiple disciplines, from qualitative analysis to quantitative analysis.

Key words: terrigenous deposit; sedimentary rock; provenance analysis; research progress; development tendency