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Paleoclimatic Significance of Grain-size from Lacustrine Sediments in China

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Abstract

In the research of using lacustrine sediments to recovery regional paleoclimate and paleoenvironment, the indicative significance of grain-size often has multiple interpretations. By summarizing the research results of 50 lacustrine sediments in China and combining the grain-size data of Gahai Lake and Langbapu Lake, we discuss the reason that the grain-size has multiple interpretations and the regular pattern of grain-size in different kinds of lakes. No matter in the short-time-scale and high-resolution research or in the long-time-scale and low-resolution research, the interpretations of grain-size for paleoclimate and paleoenvironment all have multiplicities. However the coarse sediments in the former indicates humid climate, the interpretation of the later one needs to consider many influence factors such as lake types and characteristics, the position of sampling points, the source of sediments and so on. If the sampling point is located in the deep-water area of the lakes, which are big and deep enough, the coarse sediment is probably dominated by high precipitation or strong wind. The three rings model of Grain size can affect the central area in the small and shallow lakes, meanwhile, the coarse grain content can also represent the strong precipitation, therefore, and the indicative significance of grain-size often has multiple interpretations in these kinds of lakes. Generally, coarse grain which lasts for a long period can represent the dry climate, which increase abruptly indicates high precipitation.Sampling points also have obvious influence on grain-size. Hydrodynamic force in the central of lakes and sediments source is simple relatively. Sediments are problely affected by runoff of entering into lake, aeolian and other factors. So it is more complex to explain.

Keywords: Grain size; Lakes; Paleoclimate; Paleoenvironment; Langpapu Lake; Gahai Lake

中国湖泊沉积物中的粒度变化及其古气候和古环境指示意义*

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摘　要：利用湖泊沉积物恢复区域内古气候和古环境的研究中，粒度的指示意义往往具有多种不同的解释。本文通过总结我国近 50 个湖泊的粒度研究成果，结合柴达木盆地尕海湖和元谋盆地浪巴铺古湖的研究数据，探讨粒度具有多解性的原因，以发现粒度在不同类型湖泊中的变化规律。无论是在短时间尺度、高分辨率，还是在长时间尺度、低分辨率研究中，粒度对于古气候和古环境的解释都具有多解性，但前者粒度的变粗主要指示了降水增多的湿润气候，后者粒度参数的解读要综合考虑湖泊类型与特点、采样点位置、沉积物来源等多重因素的影响；面积和水深均较大的湖泊，如采样点

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位于湖心深水区，其沉积物粒径变大应首先考虑流域地表侵蚀增强或者“尘暴”爆发导致沉积物来源的变粗，而非干旱气候下的湖泊萎缩事件；面积小而且水深较浅的湖泊，粒度分布的环带状模式影响可延至湖心，但同时必须注意到，降水增多时，地表侵蚀加剧，同样能够把更多粗颗粒带入湖泊甚至湖心，因此这类湖泊粒度的解释存在不确定性，一般可理解为较长时间跨度的粒度变粗和变细分别对应湖泊收缩和扩张，而粒度的突然变粗则指示短时间内的降水增多；采样点的选择对粒度的影响也是显著的，相比来说，湖心水动力和沉积物来源单一，解释也相应单一，而湖滨沉积物则可能受到入湖径流、风成等多重因素影响，解释起来更加复杂。

关键词：粒度；湖泊；古气候；古环境；浪巴铺古湖；尕海

引言

粒度是利用湖泊沉积物重建古气候和古环境的常用代用指标之一，因其具有样品需求量小，测试简单、迅速、经济，结果重复性好，对气候变化敏感，响应迅速等特点，在古气候和古环境研究中得到广泛应用[1-81]。前人研究发现，受时间分辨率[1, 2]，沉积物来源[3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]，湖泊特征[17, 18]，流域植被类型[14, 19, 20]，采样点位置[21, 22]等多重因素影响，粒度参数对古气候和古环境的解释具有不确定性，因而需借助其它指标对其指示意义进行约束。本文分析了我国近 50 个湖泊（古湖泊）[1-81]的粒度研究结果，结合本人的一些研究工作，探讨不同条件下控制粒度参数（主要是中值粒径，粘土和砂含量）发生变化的主导因素及其内在机制，总结粒度在时空二维度中的变化规律，力图解决粒度在解释古气候和古环境中存在的问题，为今后的研究提供参考。

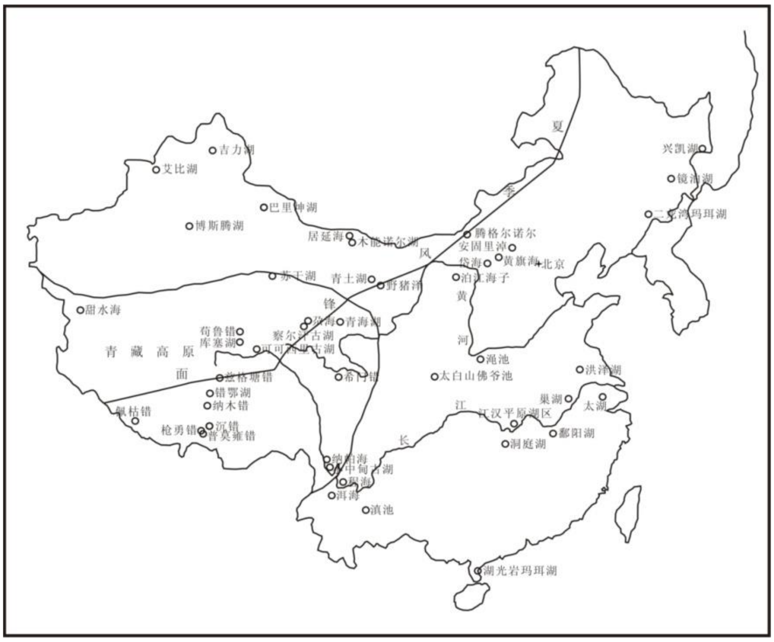

图 1 本文分析的中国主要湖泊分布图

1　不同时间尺度下的湖泊沉积物粒度记录

1.1 短时间尺度

有学者研究洱海[1, 23]、程海[1]、滇池[2]近现代以来湖泊沉积物中的高分辨率粒度变化，对比气象观测数据发现，沉积物粒径与流域降雨量变化具有较好的正相关关系，两者的波峰和波谷能够分别一一对应， 说明粗颗粒组分的增加指示降雨量较大的湿润年份，细颗粒组分的增加指示降雨量相对较小的干旱年份。因此得出结论，在短时间尺度、高分辨率（年际、10a）研究中，粗粒沉积物指示降雨量较大的湿润年份；细粒沉积物指示降雨量相对较小的干旱年份。在最近几十年甚至是几百年内，降水量的多寡不足以使湿润区湖泊发

生较大幅度的扩张和收缩[1，18，23]，再加上有些湖泊本身具有出流口，限制了湖面的高度[18，23]。由此我们可以理解，在较短时间尺度内，相当一部分湖泊的湖面高度是比较稳定的，采样点相对于湖岸的距离没有发生太大变化，水动力条件也基本恒定。按照理想的湖泊沉积作用模式，从湖岸到湖心，随着水深的不断加大，其水动力条件由强变弱，湖泊沉积物具有从湖岸到湖心大致依次出现砾－砂－粉砂－粘土的环带状分布规律[24，25]。在湖面保持基本稳定的时期内，粒度的同心圆式分布也基本不会发生扩展或收缩，因此流域内地表径流和地下渗流强度成为控制采样点粒度发生变化的最主要因素[1，2，17，18，23]。湖泊汇水区内降雨量大时，地表径流发育，较强的机械搬运作用可将较粗的陆源颗粒输入湖盆并沉降，从而导致沉积物颗粒变粗；降水量小时湖泊流域内地表径流不发育，携带能力减弱，只有少量陆源细颗粒能够到达采样点，沉积物粒径较小[1，2，17，23]。

即便在短时间尺度和高分辨率下，有学者研究安固里淖[26]400 年来和青藏高原苟鲁错[27]最近半个世纪以来的沉积物粒度变化后发现，粗粒物质增多对应低湖面时的干旱期，与洱海[1]、滇池[2]、程海[1]的研究结果正好相反。这种差异可能是由湖泊所处气候区以及自身特点的不同导致的。

1.2 长时间尺度

长时间尺度中湖泊沉积物粒度对古气候的反馈具有多种表现形式[21，28，29，30，31，32]，有些甚至截然相反[33，34]，这是由于在较长的时间跨度中，影响粒度变化的湖面高度[35]，温度[15，36]，降水[37]，风尘[3，4，5，6，7，8，9，10，11，12，13]，植被[38]，冰川[15，16，39]等因素都可能发生较大的变化，而且研究者选取的钻孔位置，也会对其产生影响[21，40]。目前多数学者研究认为，气候干旱期，湖水位下降，采样点更靠近湖岸，水深变浅，水动力增强，因而沉积物颗粒较粗。相反，在气候湿润期，湖泊面积扩大，采样点距离岸边的距离较远，粗颗粒物质难以到达，因而沉积颗粒较细[26]。即：细粒沉积物指示降水较多的湿润气候，粗粒沉积物标志降水较少的干旱气候[18，25，26，27，28，29，34，35，36，38，39，40，41，42，43，44，45，46，47，48，49，50，51，52，53，54，55，56，57，58，59，60，61，62，63]。

但在新疆吉力湖[64]、博斯腾湖[30，37，65]，东北二龙湾玛珥湖[14]、镜泊湖[17]，内蒙古木能诺尔湖[66]，青藏高原普莫雍错[67]，云南点苍山冰川湖[33]的研究中发现，粗粒沉积物增多时，反映流域内降水增多，地表径流水动力增强，有更多相对较粗的颗粒从流域地表被带到采样点沉降下来。当沉积物中细颗粒组分增多时，反映湖泊流域内气候干旱，降水稀少，地表水动力减弱，带入湖泊的颗粒以细颗粒为主[14，17，23，30，31，33，37，64，65，66，67，68]。

青海湖[21]和兴凯湖[32]的研究结果表明，粒度对古气候和古环境可能存在一种更为复杂的反馈关系。冷干和暖湿气候条件下，青海湖 QH-2000 钻孔中粗颗粒组分均表现为明显的增多。冷干气候条件下植被的减少，湖区水土保持能力的减弱，以及相对湖水水位的降低是造成入湖粗颗粒物质明显增多的主要原因；暖湿气候条件下冰融水的大量补给或降水量的增加，导致湖区地表径流的相对发育，是造成入湖粗颗粒物质明显增多的主要原因；介于二者之间的气候条件下，沉积物的粒径变化相对平缓。兴凯湖 XK-1 钻孔沉积物粒度揭示，粗粉砂和砂增多对应降水减少的低湖面时期，细粉砂增多对应于降水增加的高湖面时期，粘土增加对应气候干燥的静水沉积环境。

长时间尺度的湖泊沉积物中，粗粒沉积物的增多指示湖面收缩的干旱时期还是地表径流加强的湿润时期，需要结合不同对象的具体情况来具体分析，同时还需要参考其它古气候指标。一方面，当气候湿润，湖面升高，同一沉积位置由于距湖岸变远，湖水能量降低使得物质较细[56]。另一方面，由于气候湿润条件下，降雨量大，地表径流增大，侵蚀能力增强，湖泊流体水动力增大，较粗颗粒也可以被带到离湖岸更远的地方，甚至湖心[67]；反之，气候干旱时，可以是因湖面降低而沉积粗颗粒[29]，而较弱的地表径流搬运粗颗粒物质的能力也会下降[37]。通过分析前人研究成果，结合本人的一些工作，我们总结，粒度对古气候反馈形式的不同，主要与湖泊类型[17，28，35，37，62，67]、湖泊面积与水深[30，32，39，49，67]、采样点位置[21，40，67]等因素有关。

2 不同类型湖泊中的沉积物粒度记录

2.1 封闭与开口湖泊

无论是粗粒还是细粒沉积物的增多指示高湖面时期，其前提条件之一是湖盆必须在一个相对较大的空间内是封闭的，这样才可能出现历史时期的高湖面。但在开口湖中，粒度的记录则恰好相反。侯新花等[17]研究了镜泊湖（开口湖）全新世以来的粒度变化后发现，湖泊沉积物主要由入湖河流和降水冲刷携带而来，在水动力较强时，细颗粒来不及沉积下来就随着出湖水流流走了，只有粗颗粒沉积下来，而在水动力较弱时，大部分细粒颗粒物质沉淀在湖中。因此开口湖中粗颗粒的增多反映流域降雨量较大，湖水水动力较强，细粒物质的增多对应降雨量较小的干旱时期，与封闭湖泊中的记录恰好相反[63]。

2.2 不同面积和水深

湖泊面积和水深决定了其面对气候变化时的稳定性，进而决定了湖心沉积物粒度受湖泊扩大和收缩影响的大小。同处我国内陆干旱区的博斯腾湖[65]和巴里坤湖[41]，相同的粒度特征却指示完全相反的古气候状况，可能是由两者不同的特征决定的。博斯腾湖湖水面积约 1000 km^2，平均水深 8 m，最大水深 16.2 m，采样点位于湖心最大水深处，至今没有发现高湖面的湖岸堤或湖岸阶地，表明湖面波动不大，湖泊中心沉积物的粗细主要取决于入湖水动力和流量的大小。巴里坤湖湖面面积不足 100 km^2（2005 年），平均水深 0.6 m，最大水深约 1 m，古湖岸线显示巴里坤湖面积曾达到约 800 km^2，1984 年湖水面积萎缩至 112 km^2，研究表明粗颗粒指示了较低的湖水位，气候较为干旱，物理风化强盛，植被覆盖度下降；细粒沉积物增多指示了较高的湖水位，气候较为湿润，地表化学风化相对增强，植被盖度增加。

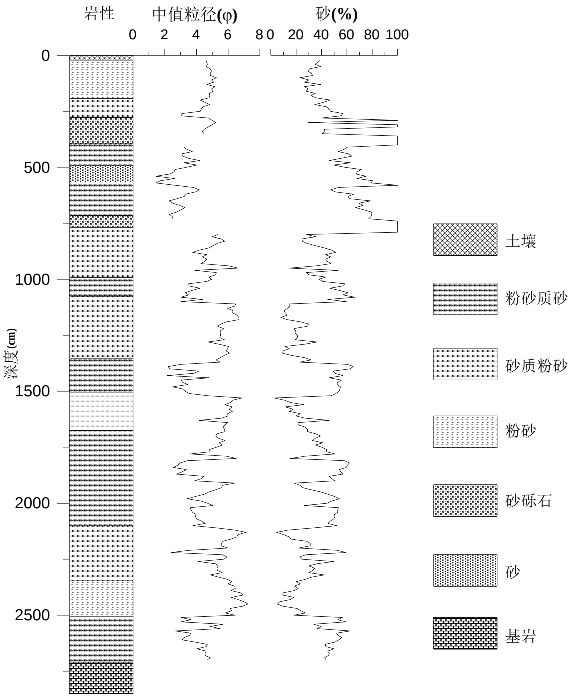

图 2 浪巴铺剖面粒度曲线

有学者提出，对于面积和水深均较大的湖泊，很难出现湖心水深浅到能够受到表层水流扰动的条件[67]。因此对于这类湖泊，其湖心沉积物粒度的变粗主要因为流域降水增加，地表侵蚀能力加强，相对较粗的颗粒被带入湖盆[31，65，66，67，68]。而对于面积和水深均较小的湖泊[41，55，62]，湖面容易发生明显的扩张和收缩，湖心离岸较近时，沉积物颗粒变粗，湖心离岸较远时，沉积物颗粒变细。

2.3 古湖泊——元谋盆地浪巴铺古湖粒度特征及气候意义

浪巴铺古湖位于云南元谋县城以西 20km 的浪巴铺村附近，地理坐标 25°41′5" N，101°42′2" E，海拔 1630m。古湖面积约 1km^2，从周围地貌来看，湖泊深度和汇水面积都十分有限，因此湖泊水位易受降水影响，发生较

大幅度变化。2.8～4.0 m、5.5～6.0 m、7.3～8.1 m 等 3 处为砂砾石层，分布连续，磨圆度高，最大粒径 2 cm，为典型的湖滨相沉积。由此可判断浪巴铺古湖曾收缩到剖面位置，因此浪巴铺古湖沉积物中细颗粒沉积物增加指示湖面上升的湿润时期，粗颗粒沉积物增加指示水位下降的干旱时期。浪巴铺剖面沉积物中值粒径(φ)变化范围为 1.45～7.24，中值粒径为 4.67。砂含量 2.58％～100.00％，平均含量 42.86％。黏土含量 0.00％~17.80％，平均含量 7.82％。从图 2 可发现，浪巴铺古湖经历了至少 7 次较大幅度的湖面涨落[88]。

3 同一湖泊的不同采样点位置对粒度测试结果的影响

同一湖泊的不同部位，其粒度变化规律可能截然不同，这在一些面积较大的湖泊中表现尤其明显[21，40，69]。总结前人研究不难发现，在湖岸阶地[56，62]、古湖相沉积物[29，46，50，54]、离岸较近[55]、湖滨陆地[35，41，42，57]取样，得出的结论多是粗粒沉积物的增加指示低湖面时的干旱时期，细颗粒的增加对应高湖面时的湿润期。因为湖岸线附近，是湖面扩张和收缩影响最直接的区域，而且古湖岸阶地[55，56，62]和古湖岸线[41，62]，也留下了确凿的湖面涨落证据。湿润期湖面升高，采样点远离湖岸，沉积物粒度变细，反之沉积物粒度变粗。

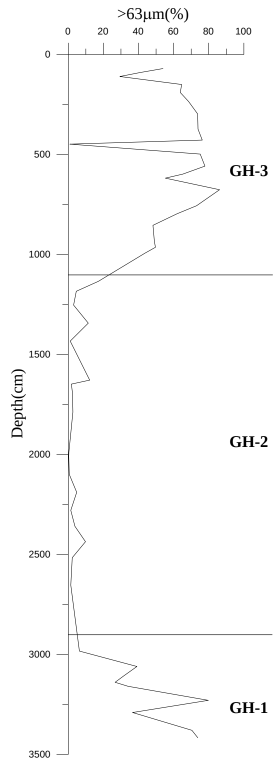

图 3 尕海 GH-2 孔砂含量变化曲线

2003 年 5 月，中科院青海盐湖所用汽车钻在尕海湖西岸钻取 DG02 和 DG03 岩芯，地理坐标为 DG02 钻孔 37°10′ N，97°33′ E，DG03 钻孔 37°08′N，97°33′E。DG02 钻岩芯长 34.57 m，在不同层段选取 48 个样品进行粒度分析，结果见图 3。岩芯按粒度特征分为三段，GH-1 阶段沉积物粒度组成以砂和粉砂为主，孢粉资料[35]和相邻 DG03 钻孔的数据[42,82-87]表明，这段时期气候干旱但不稳定，钻孔点水位较低，沉积物粒径为整段岩芯中较粗的一段。GH-2 阶段粗粒组分含量非常低，主要以粘土和粉砂为主，为全剖面最细的一段。其他代用指标[82-87]也表明，这段时期是全新世气候最为湿润的一段时期，气候进一步湿润，湖面上升，钻孔位置水深较大，距离湖岸位置较远，沉积物以细粒物质为主。GH-3 阶段沉积物组成以砂和粉砂为主，砂含量是全剖面最高的一段，孢粉分析显示该段代表干旱半干旱生境的藜科花粉含量显著增加[35]，表明该段气候明显变冷，降水也大为衰减，湖泊强烈收缩，湖面下降，钻孔位置水深剧烈减小甚至出露在湖面以上，沉积物以粗粒物质为主。

钻孔地点选在湖心[64, 65]或者靠近湖心的深水区[14, 67]，如果其湖泊面积和水深足够大，则湖面的扩张和收缩一般不能对中心部位的沉积物粒度产生直接影响，因此湖中心粒度的变化主要受区域内降水量和降水强度的影响。殷志强等[24]分析我国北方内陆湖泊安固里淖湖泊沉积物粒度特征，将其划分为湖滨带，湖滨－湖心过渡带，湖心带，见图 4。安固里淖是河北坝上地区最大的内陆封闭湖泊，面积 47.6 km^2，最大水深 4.0 m，平均水深 2.5m，湖盆呈浅碟状，湖底平坦。根据殷志强等的研究结果和图 3 可知，从湖岸到湖心，粗颗粒物质逐渐减少，细粒物质增多，湖心区所占面积最大，粒度呈现以 40 μm 为峰值的单峰模式。粒度的这种环带状分布规律在中国多数湖泊中都是存在的[25]。我们注意到，湖滨的砂带和湖滨－湖心过渡的粉砂带，宽度十分有限，湖盆以湖心粘土带为主，如果钻孔地点选在湖泊中心深水区，那么较小规模的湖泊收缩和扩张，不能对其粒度特征产生影响，而一次较强的降雨[14, 30, 31, 33]或者风沙过程[71, 72]，则可以将相对较粗的颗粒带至湖心并沉积下来。此时沉积物粒度的变粗指示了降水较多的湿润气候或者沙尘较多的恶劣气候。这种结论在中国不少湖泊研究中得到了印证[14, 64, 65, 66, 67, 68]。

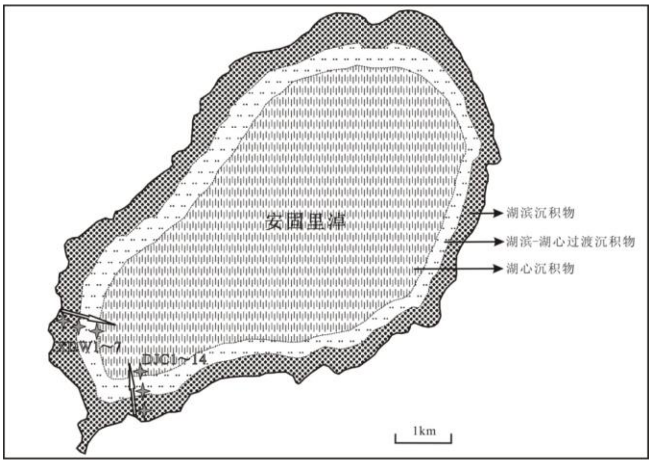

图 4 安固里淖湖泊沉积物环带状分布规律（据殷志强等，有修改）

4　结论

(1) 无论是在短时间尺度、高分辨率研究，还是在长时间尺度、低分辨率研究中，粒度对于古气候和古环境的解释都具有多解性。但前者粒度的变粗主要指示了降水增多的湿润气候，后者粒度参数的解读要综合考虑湖泊类型与特点、采样点位置、沉积物来源等多重因素的影响。

(2) 对于面积和水深均较大的湖泊，如采样点位于湖心深水区，其沉积物粒径变大应首先考虑流域地表侵蚀增强或者“尘暴”爆发导致沉积物来源的变粗，而非干旱气候下的湖泊萎缩事件。

(3) 面积小而且水深较浅的湖泊，粒度的环带状分布模式影响可大至湖心，但同时必须注意到，降水增多时，地表侵蚀加剧，同样能够把更多粗颗粒带入湖泊甚至湖心，因此这类湖泊粒度的解释存在不确定性。一般可理解为较长时间跨度的粒度变粗和变细分别对应湖泊收缩和扩张，而粒度的突然变粗则指示短时间内的降水增多。

(4) 我国西北地区有很多已经消亡和正在逐步消亡的湖泊，事实证明该地区古湖曾广泛发育，并发生巨大的湖面涨落。该区域湖相和古湖相沉积物的变粗反映了湖面下降，湖泊萎缩事件，但需要甄别沉积物中水成和风成组分。

(5) 采样点的选择对粒度的影响也是显著的，相比来说，湖心水动力和沉积物来源单一，解释也相应单一，而湖滨沉积物则可能受到河流三角洲、风沙活动、浊流等多种因素影响，解释起来更加复杂。

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REFERENCES

[1] Jingan Chen, Guojing Wan, Feng Zhang et al. Environmental records of lacustrine sediments in different time scales: Sediment grain as an example [J]. Science in China: Series D, 2003, 33(6):563-568.

[2] Xiaolei Wang, Hao Yang, Qiguo Zhao et al. Modern sedimentation rates and dry-humid change inferred from grain size records in Dianchi Lake, Yunnan Province [J]. Geographical Research, 2011, 30(1): 161-171.

[3] Zhangdong Jin, Sumin, Wang, Ji Shen et al. Dust-storm Events in Daihai Lake Area, Inner Mongolia During the Past 400 Years: Evidence from Grain-Size Analysis of Lake Sediments [J]. Journal of Lake Sciences, 2000, 12(30: 193-198.

[4] Jibin Xue, Wei Zhong. Variations in Dust Event Reflected by Grain-size Component of Lacustrine Records in Droughty Area: a case study on Barkol Lake, Xinjiang, China [J]. Acta Sedimentologica Sinica, 2008, 26(4): 647-654.

[5] Ruijie Lu, Hong Xia, Mingrui Qiang et al. Environmental Evolution in Past 130 Tears Recorded by Bojianghaizi Lake Sediments in North Mu Us Desert, China [J]. Journal of Desert Research, 2008, 28(1): 44-49.

[6] Hao Long, Naiang Wang, Yu Li et al. Partical Size Characteristics of Deposits from PJHZ Section in Northern Edge of Mu Us Desert and Their Environmental Significance [J]. Journal of Desert Research, 2007(2): 187-193.

[7] Qiumin Zhai, Weili Qiu, Rongquan Li et al. The Middle and Late Holocene Lacustrine Sediments and its Climate Significance of Angulinao-Bojianghaizi Lakes, Inner Mongolia [J]. Journal of Palaeogeography, 2000, 2(2): 84-91.

[8] Hongyuan Shen, Yulian Jia, Hongmei Zhang et al. Environmental change inferred from granular size character of lacustrine sediment in Inner Mongolia Huangqihai, during 8.0-2.2 Ka BP [J]. Arid Land Geography, 2006(4): 457-462.

[9] Yongbo Wang, Xingqi Liu, Enlou Zhang et al. Dust-storm Events in Kekexili Area, Northern Tibetan Plateau During the past 4000 Years: Evidence from Grain-size Analysis of Lacustrine Sediments in Kusai Lake [J]. Acta Sedimentologica Sinica, 2009, 27(4): 691-696.

[10] Qiang Zhao, Naiang Wang, Hongyi Cheng et al. Grain-size Characteristics of Qingtu Lake Sediments and its Paleaoenvironment Explaination [J]. Arid Land Geography, 2003(1): 1-5.

[11] Mingrui Qiang, Fahu Chen, Aifeng Zhou et al. Prelim nary study on Dust Storm events Documented by Grain Size Component of Sugan Lake Sediments, North Qaidam Basin [J]. Quaternary Sciences, 2006(6): 915-922.

[12] Hao Long, Naiang Wang, Haizhou Ma et al. Eolian Activity and Environment History Recorded by the Qingtu Lake, NW Tengger Desert [J]. Acta Sedimentologica Sinica, 2007, 25(4):626-631.

[13] Zhangdong Jin, Chengjuan Zou, Nanhua Gao et al. Paleoenvironmental Change and Dust Storm Event at Daihai Area Since the Little Ice Age [J]. Journal of Xian Engineering University, 2001, 23(4): 6-10.

[14] Qiang Wei, Jingtai Han, Dong Li. Grain-size characteristics and its Paleoenvironmental Significance of Erlongwan Marr Lake [J]. Quaternary Sciences, 2008, 28(5): 957-958.

[15] Junbo Wang, Liping Zhu. Grain-size Characteristics and Their Paleo-environmental Significance of Chen Co Lake in Southern Tibet [J]. Progress in Geography, 2002, 21(5): 459-467.

[16] Jiule Li, Baiqing Xu, Shubiao Lin et al. Glacier and Climate Changes over the Past Millennium Recorded by Proglacial Sediment Sequence from Qiangyong Lake, Southern Tibetan Plateau [J]. Journal of Earth Sciences and Environment, 2011, 33(4): 402-411.

[17] Xinhua Hou, Yanhong Wu, Liyuan Yang, The paleo-precipition history recorded by the characteristics of grain-size of Lake Jingpo during Holocene [J]. Journal of Lake Sciences, 2006, 18(6): 605-614.

[18] Jingan Chen, Guojiang Wan, Jingyi Xu. Sediment particle sizes and the dry-humid transformation of the regional in Erhai Lake [J]. Acta Sedimentologica Sinica, 2000, 18(3): 341-345.

[19] Yanbin Lv, Jiaju Zhao, Wei Huang et al. Decomposition of the Grain-size Component and Its Climate Implication from Lake Barkol, Xinjiang [J]. Acta Sedimentologica Sinica, 2011, 29(1): 134-142.

[20] Rongyan Chen, Xueliang Song, Shitao Zhang et al. Dianchi Lake Sediment Records of Climate Changes and Humane Activitiesin the Past 700Years [J]. Journal of Salt Lake Research, 2008, 16(2): 7-12.

[21] Xingqi Liu, Sumin Wang, Ji Shen. The Grainsize of the Core QH-2000 in Qinghai Lake and Its Implication for Paleoclimate and Paleoenvironment [J]. Journal of Lake Sciences, 2003, 15(2): 112-117.

[22] Liping Zhu, Jianting Ju, Junbo Wang et al. Environmental Changes Recorded in Core Sediments from the Pumoyum Co Lake of the Tibetan Plateau during the Initial stage of the Last Deglacial Period [J]. Quaternary Sciences, 2006, 26(5): 772-780.

[23] Jingan Chen, Guojiang Wan, Degui Tang et al. Modern Climate change Inferred from Grain-size and Isotope records in Erhai Lake [J]. Progress in Natural Science, 2000, 10(3): 63-69.

[24] Zhiqiang Yin, Xiaoguang Qin, Jinshui Wu et al. Multimodal Grain-size Distribution Characteristics and Formation Mechanism of Lake Sediments [J]. Quaternary Sciences, 2008, 28(2): 345-353.

[25] Qianli Sun, Jie Zhou, Jule Xiao. Grain-size Characteristics of Lake Daihai Sediments and its Paleaoenvironment Significance [J]. Marine Geology & Quaternary Geology, 2001, 21(1): 93-95.

[26] Jiaming Jiang, Jinglu Wu, Ji Shen. Lake Sediment Records of Climatic and Environmental Change in Angulinao Lake [J]. Scientia Geographica Sinica, 2004, 24(3): 346-351.

[27] Xiaotian Wang, Shijie Li. Environmental Changes Revealed by Modern Lake Sediment in Goulu Co, Tibetan Plateau [J]. Journal of Lake Sciences, 2002, 14(3): 217-222.

[28] Hao Long, Naiang Wang, Yu Li et al. Mid-Holocene Climate Variations from Lake Records of the East Asian Monsoon Margin: A Multi-Proxy and Geomorphological Study [J]. Quaternary Sciences, 2007, 27(3): 371-381.

[29] Qingzhong Ming, Huai Su, Zhengtao Shi et al. Last Five Heinrich Events Revealed by Lacustrine Sediments from Xiaozhoudian Basin in Yunnan Province [J]. Acta Geographica Sinica, 2011, 66(1): 123-130.

[30] Fahu Chen, Xiaozhong Huang, Meilin Yang et al. Westerly Dominated Holocene Climate Model in Arid Central Asia--Case study on Bosten Lake, Xinjiang, China [J]. Quaternary Sciences, 2011, 26(6): 881-887.

[31] Qiuliang Wang, Changan Li, Yuanyun Li et al. Grain-size characteristics of sediments in the Jiangling section and their paleoclimatic significance [J]. Geology in China, 2006, 33(6): 1406-1410.

[32] Jian Wu, Ji Shen. Paleoclimate evolution since 27.7kaBP reflected by grain size variation of a sediment core from Lake Xingkai, northeastern Asia [J]. Journal of Lake Sciences , 2010, 22(1): 110-118.

[33] Jianqiang Yang, Zhijiu Cui, Chaolu Yi et al. Glacial Lacustrine Sediment’s Response to Climate Change since Holocene in Diancang Mountain [J]. Acta Geographica Sinica , 2004, 59(4): 525-533.

[34] Gengnian Liu, Hairong Fu, Zhijiu Cui et al. An 8000 Years Environmental Change Record of Lacustrine Deposits of Foyechi Lake at Taibai Mountains [J]. Research of Soil and Water Conservation, 2005, 12(4): 1-4.

[35] Bishan Chen, Anding Pan, Yuanfang Zhang. Grain-size Characteristic and their Environmental Significance of Gahai Lake Sediments in Qaidam Basin [J]. Marine Geology & Quaternary Geology, 2007, 27(4): 588-597.

[36] Liping Zhu, Junbo Wang, Xiao Lin et al. Environmental changes reflected by core sediments since 8.4 Ka in Nam Co, Central Tibet of China [J]. Quaternary Sciences. 2007, 27(4): 588-597.

[37] Xiao Zhong, Fahu Chen, Shun Xiao et al. Primary study on the environmental significances of grain-size changes of the Lake Bosten sediments [J]. Journal of Lake Sciences, 2008, 20(3): 291-297.

[38] Jun Li, Shuyun Wang, Duowen Mo. Environmental changes and Relationships with Human Activities of Dongtinghu Plain Since 6000 kaBP [J]. Acta Scintiarum Naturalium Uniwersities Pekinensis, 2011, 47(6): 1041-1048.

[39] Yanbin Lei, Chengjun Zhang, Huaming Shang et al. The Grain Size Characteristic of Ximencuo Lake Core in the Northeast Tibet Plateau and its Environmental Significance [J]. Marine Geology & Quaternary Geology, 2006, 26(3): 31-38.

[40] Xuelian Guo, Qi Wang, Jian Shi et al. Characters of the Total Organic Carbon and Organic Carbon Isotope and Grain Size and Paleoclimate Significance in Qinghai Lake Sediments [J]. Marine Geology & Quaternary Geology , 2002, 22(3): 99-103.

[41] Jibin Xue, Wei Zhong, Yinjuan Zhao et al. Holonece Climatic Instability Recorded by a Lake Section in Northeast Xinjiang, China [J]. Journal of Desert Research, 2008,28 (24): 648-656.

[42] Guangchao Cao, Haizhou Ma, Hao Long et al. Particle Size Characteristics of Deposits from DG03 Core of Gahai Lake in East of Qaidam Basin and Their Environmental Significance [J]. Journal of Desert Research, 2008, 28(6): 1073-1077.

[43] Yong Yin, Nianqiao Fang, Qian Wang, et al. Magnetic Susceptibility of Lacustrine Sediments and Its Environmental Significance:Evidence from Napahai Lake, Northwestern Yunnan,China [J]. Scientia Geographica Sinica, 2002,22 (4): 413-419.

[44] Jingan Chen, Guojiang Wan. Sediment Particle Size Distribution and Its Environmental Significance in Lake Erhai, Yunnan Province [J]. Acta Mineralogica Sinica, 1999, 19 (2): 175-182.

[45] Jingan Chen, Guojiang Wan, Ronggui Huang. Study of sediment particle sizes in lake Chenhai, Yunnan province[J]. Advances in environmental science, 1999,7 (4): 77-83.

[46] Zhili Zhao, Yong Wang, Peiyi Yao, et al. Environmental Changes Recorded by Lacustrine Sediments since Lake Holocene in central Inner Mongolia [J]. Geological Bulletin of China, 2011,30 (8): 1251-1255.

[47] Shuxin Zhang, Taibao Yang, Qingchun Tian et al. Keke Xili BDQ drilling core's Granularity characteristics and total organic carbon content reflect paleo-climate and environment [J]. Northern Environmental, 2011, 23(1-2): 103-105.

[48] Yongbo WANG, Xingqi LIU, Xiangdong Yang et al. A 4000-year moisture evolution recorded by sediments of Lake Kusai in the Hoh XiL aera, northern Tibetan Plateau [J]. Journal of Lake Sciences, 2008, 20 (5): 605-612.

[49] Xinyuan WANG, Li Wu, Guangsheng Zhang et al. Characteristics and Environmental Significance of Magnetic Susceptibility and Grain Size of Lake Sedinents since Holocene in Chaohu Lake, Anhui Province [J]. Scientia Geographica Sinica, 2008, 28(4): 548-553.

[50] Guoliang LEI, Hucai Zhang, Wenxiang Zhang et al. Characteristics of Grain-size and Sedimentation of Shell Bar Section in Salt Lake Qarhan, Qaidam Basin [J]. Acta Sedimentologica Sinica, 2007, 25(2): 274-282.

[51] Yuanyun Xie, Changan Li, Qiuliang Wang et al. Grain-size Characteristics and Their Environmental Significance of Jiangling Lake Sediments in Jianghan Plain [J]. Journal of Jilin University(Earth Science Edition), 2007, 37(3): 570-577.

[52] Huachun He, Haiyan Ding, Zhenke Zhang et al. Grain-size Characteristics and Their Environmental Significance of Hongze Lake Sediments [J]. Scientia Geographica Sinica, 2005, 25(5): 80-86.

[53] Xiaocui Wang, Cheng Zhu, Li Wu et al. Grain-size characteristics and Sedimentary Environment Change of JZ-2010 section in Jianghan Plain, Hubei Province [J]. Journal of Lake Sciences, 2012, 24(3): 480-486.

[54] Heling Jin, Honglang Xiao, Hong Zhang et al. Evolution and Climate Changes of the Juyan Lake Revealed from Grain Size and Geochemistry Element Since 1500 a BP [J]. Journal of Glaciology and Geocryology, 2005, 27(2): 233-240.

[55] Zhuang Miao, Guijin Mu, Shun Yan et al. Environmental Evolution of Aiby Lake Indicated by Ash core Sediment's Information[J]. Arid Land Geography, 2003, 26(4): 367-371.

[56] Liping Zhu, Junbo Wang, Ling Chen et al. 20,000-year Environmental Change Reflected by Multidisciplinary Lake Sediments in Chen Co, Southern Tibet [J]. Acta Geographica Sinica, 2004, 59(4): 514-524.

[57] Shiyue Chen, Sumin Wang, Yanhong Wu. Sedimentary Cycles and Paleoenvironmental Evolution of the Co Ngoin Lake in Tibetan Plateau since Late Cenozoic [J]. Acta Geoscientica Sinica, 2006, 27(4): 315-322.

[58] Qiumin Zhai, Zhiyong Guo, Juan Shen. Grain-size Characteristics of Sediment Profile and Their Environmental Significance in Mianchi Basin, Western Henan Province [J]. Journal of Henan University(Natural Science), 2011, 41(3): 272-278.

[59] Qiumin Zhai, Zhiyong Guo, Juan Shen. Sedimentary Characteristics of Lacustrine Sediment Profile and Paleoenvironment in Mianchi Basin, Western Henan Province [J]. Scientia Geographica Sinica, 2011, 31(8): 922-928.

[60] Wenyu Shi, Tiefei Jia, Weiguo Zhang. Holocene environment changes recorded by the lacustrine sediment in three large lakes in the lower yangtze River [J]. Journal of Shanghai Normal University(Natural Sciences), 2010, 39(4): 432-440.

[61] Huiyan Shen, Shijie Li, Shoubing Yu et al. Grain-size Characteristics of Sedments from the Zigetang Co Lake, Tibetan Plateau and Their Environmental Implication [J]. Quaternary Sciences, 2007, 27(4): 613-619.

[62] Shijie Li, Hongliang Zhang, Yafeng Shi et al. A high Resolution MIS3 Environmental Change Record Derived from Lacustrine Deposit of Tianshuihai Lake, Qinghai-Tibet Plateau [J]. Quaternary Sciences, 2007, 2008, 28(1): 122-131.

[63] Jiajia Xu, Yulian Jia, Zhongping Lai et al. Climate Variations During Early TO Mid-Holocene in Huangqihai Lake in Northern China Based on the Lake Deposit Analysis [J]. Acta Sedimentologica Sinica, 2012, 30(4): 731-738.

[64] Qingfeng Jiang, Ji Shen, Xingqi Liu et al. Environmental changes recorded by lake sediments from Lake Jili, Xinjiang during the

past 2500years [J]. Journal of Lake Sciences, 2010, 22(1): 119-126.
[65] Fahu Chen, Xiaozhong Huang, Jiawu Zhang et al. Humid Little Ice Age in the Central Asia documented by Bosten Lake, Xinjiang, China [J]. Science in China, Series D, 2006, 49(12): 1280-1290.
[66] Xiangmin Zheng, Hui Wang, Limin Zhou et al. Information of Environmental Evolution Recorded by Munengnuor Lake Sediment in the Lower Reaches of Heihe River [J]. Chinese Journal of Soil Science, 2009, 40(5): 1189-1192.
[67] Liping Zhu, Jianting Ju, Junbo Wang et al. Environmental Changes Record in Core Sediments from the Pumoyum Co Lake of the Tibbetan Plateau during the Initial Stage of the last Deglacial Period [J]. Quaternary Sciences, 2006, 26(5): 772-780.
[68] Yuanyun Xie, Qiuliang Wang, Changan Li et al. Climatic Implication of Grain Size from Lacustrine Sediments: Acasr studt of Jiangling Section, Jianghan Plain, China [J]. Geological Science and Technology Information, 2004, 23(4): 41-43.
[69] Jibo Dong, Zhisheng An, Fengyan Lu. Quantitively Partition of Eolian and Hydromorphic Components in Lacustrine Sediments:an example from Lake Qinghai [J]. Journal of Geomechanics, 2010, 16(4): 402-411.
[70] Yongbo Wang, Xingqi Liu, Enlou Zhang et al. Dust-storm Events in Kekexili Area, Northern Tibetan Plateau During the Past 4000 Years: Evidence from Grain-Size Analysis of Lacustrine Sediments in Kusai Lake [J]. Acta Sedimentologica Sinica, 2009, 27(4): 691-696.
[71] Shun Xiao, Fahu Chen, Mingrui Qiang et al. Distribution Pattern of Grain Size in Surface Sediments from Sugan Lake and Its Potential in Recording Aeolian Dust in Arid China [J]. Acta Geographica Sinica, 2007, 62(11): 1153-1164.
[72] Yulin Han, Xiaodong Tan, Zhong Chen et al. Magnetic granulometry of recent sediments from the Huguang Maar and its implication for provenience [J]. Chinese Sci Bull, 2010, 55, doi: 10.1007/s11434-009-0585-5
[73] Jianen Han, Rongping Lv, Jia Yu et al. Variation characteristics of the depositional environment in the Peiku Co Basin, Tibet [J]. Geology in China, 2009, 36(4): 800-808.
[74] Tiefei Jia, Xuerong Dai, Weiguo Zhang et al. Sediment Records in Chaohu Lake and Its Significance on Environmental Change in Holocene [J]. Scientia Geographica Sinica, 2006(6): 706-711.
[75] Xingqi Liu, Yongbo Wang, Ji Shen et al. Evolution of Chaka Salt Lake during the last 16 000 years and its response to climate change [J]. Acta Geologica Sinica, 2007, 81(6): 843-849.
[76] Jinliang Feng, Liping Zhu, Yuxiang Li. Sedimentary environments and facies about Chen Co lacustrine delta, South Tibetan Plateau [J]. Geographical Research, 2004(5): 649-656.
[77] Guoliang Lei, Hucai Zhang, Wenxiang Zhang et al. Characteristics of Grain-size and Sedimentation of Shell Bar Section in Salt Lake Qarhan, Qaidam Basin [J]. Acta Sedimentologica Sinica, 2007(2): 274-282.
[78] Jibin Xue, Wei Zhong. Variations in Dust Event Reflected by Grain-size Component of Lacustrine Records in Droughty Area: Acase study on Barkol Lake, Xinjiang, China [J]. Acta Sedimentologica Sinica, 2008(4): 647-654.
[79] Xueliang Song, Jiesen Li, Zixiong Zhang et al. The Discovery of an Arid Climate Period 200 Years before Present in Kunming Region [J]. Yunnan Geographic Environment Research, 1998(1): 20-25.
[80] Xingqi Liu, Sumin Wang, Ji Shen. The Grainsize of the Core QH-2000 in Qinghai Lake and Its implication for Paleoclimate and Paleoenvironment [J]. Journal of Lake Sciences, 2003(2): 112-117.
[81] Zhiqiang Yin, Xiaoguang Qin, Jinshui Wu et al. The Multimodal Grain-Size Distribution Characteristics of Loess, Desert, Lake and River Sediments in Some Areas of Northern China [J]. Acta Sedimentologica Sinica, 2009, 27(2): 343-351.
[82] Guangchao Cao, Haizhou Ma, Pu Zhang et al. Geochemical composition of sediment in Gahai Lake since 11.5 ka BP and its environmental implication [J]. Acta Sedimentologica Sinica, 2009, 27 (2): 360-366.
[83] Zhong Chen, Haizhou Ma, Guangchao Cao et al. Climate-environmental evolution in Gahai Lake area of Qaidam Basin since Late Last Deglacial Period [J]. Geochimaca, 2007, 36(6):578-584.
[84] Zhong Chen, Haizhou Ma, Guangchao Cao et al. Climate-environmental evolution in Gahai Lake area since the Lake Glacila Period from Loss-ON-Ignition [J]. Marine Geology & Quaternary Geology, 2007, 27(1):131-138.
[85] Xiying Zhang, Haizhou Ma, Fengqing Han et al. Mineral assemblages and palaeoenvironmental changes of Core DG03 of GahaiLake in Delingha Basin [J]. Acta Sedimentologica Sinica, 2007, 25(5):767-773.

[86] Guangchao Cao, Haizhou Ma, Zhong Chen et al. Geo-chemical characteristic of the elements of Gahai DG03 Core and its environmental significance [J]. Journal of Salt Lake Research, 2008, 16 (2): 13-18.
[87] Zhong Chen, Haizhou Ma, Guangchao Cao et al. Carbonate content in the Core DG03 of Lake Gahai and its paleoenvironmental significance [J]. Journal of Salt Lake Research, 2007, 15 (2): 6-11.
[88] Huayong Li, Qingzhong Ming, Hucai Zhang et al. Dry- hot Climate changes from 210 to 120 KaBP by Lacustrine Sediments in Yuanmou Basin, Yunnan [J]. Journal of Geomechanics, 2013, 19 (1): 14-25.

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