云南星云湖现代盘星藻与湖泊水深关系及其化石记录的探讨

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摘要 盘星藻化石在我国第四纪湖相地层中频繁出现, 但其在第四纪古环境研究中的指示意义存在较大的争议. 一些研究认为盘星藻大量的出现代表了湖泊变浅, 一些研究则认为盘星藻主要集中在湖泊水深较大的区域. 本文对位于云南中部的星云湖现代水样和湖床表层沉积物样品中盘星藻的分布状态进行调查, 结果显示湖面水体中盘星藻浓度在水平方向上随水深基本没有变化, 在垂直方向上盘星藻在湖水底部浓度最大, 推测可能与盘星藻重力沉降及波浪扰动底泥产生的再沉积作用有关; 湖床表层沉积物中盘星藻含量与水深无明显关系. 初步认为, 在一些较大湖泊的沉积物中, 盘星藻的分布与水深的关系可能是沉积过程造成的, 较大湖泊中风浪的作用使得盘星藻趋中沉积非常明显; 而湖水中是否有大量盘星藻生长可能与河流输入、水体营养化状态、水温、pH、盐度等水环境状态有关. 不同区域、不同类型的湖泊可能机制并不一样, 没有统一的规律. 因此, 在第四纪古环境研究中将盘星藻含量作为水深的指标需结合其他指标综合分析. 星云湖过去3000年化石盘星藻含量的变化与沉积物粒度和磁化率指示的区域人类活动强度变化趋势一致, 且更敏感地响应了人类活动导致的湖泊水体富营养化过程.

关键词 盘星藻, 水环境指标, 水位变化, 营养变化, 星云湖

孢粉分析作为一种古生态古环境代用指标, 在第四纪研究中起着不可替代的作用. 湖相沉积孢粉分析时经常会出现一些陆生植物花粉以外的微体古生物化石, 如藻类、枝角类等残体. 藻类植物绝大多数生活在水体中, 与陆生植物相比, 藻类等水生生物能更快地响应水体环境变化^[1]. 因此, 在孢粉分析中, 藻类植物能够提供水生生态环境变化的信息, 这有助于提高基于孢粉分析重建第四纪环境的可靠性. 在沉积物中, 盘星藻是出现频率最高的众多藻类之一, 隶属于绿藻门绿藻纲绿球藻目水网藻科. 盘星藻

在世界范围内广泛分布, 通常生长在天然的淡水环境中, 如湖泊、池塘和水库等. 由于其细胞壁的外层由孢粉素和氧化硅组成, 具有很强的耐腐蚀性, 因而其化石能很好地被保留在沉积物中^[2-7]. 研究发现, 盘星藻化石最早出现在早白垩纪地层中^[8]. 此外, 盘星藻易于鉴定, 并且通常都能鉴定到种或亚种. 因此盘星藻应该是研究古生态古环境潜在的生物指标. 在已有的古生态古环境研究中, 盘星藻一直受到研究者的关注. 例如, 关于盘星藻常见种及其变种的形态、分布及其可能的生态指示意义, 国际上开展了较

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Chen X M, Huang X Z, Tang L Y, et al. A preliminary investigation of relationship between modern *Pediastrum* and the level of Xingyun Lake, central Yunnan, and its implications for the interpretation of the fossil record (in Chinese). *Chin Sci Bull*, 2016, 61: 2395–2408, doi: 10.1360/N972016-00127

多系统的研究^[2-6,9-12], 这些研究为应用盘星藻化石重建古生态古环境奠定了良好的基础, 并取得了一定的进展. 研究认为, 在特定的第四纪孢粉组合中, 盘星藻的出现及丰度变化能够指示盐度、水位/水深的变化, 进而间接反映当时的气候变化^[7,13-19], 也可以指示温度状况^[5,16,18,20-23], 还可以用于推导湖泊的营养水平及人类活动^[16,20,22,24-29]. 也有研究认为盘星藻化石含量的变化能够反映湖泊初级生产力, 进而揭示其与区域气候变化的关系^[1,30-33].

在我国, 盘星藻也一直受到研究者的关注. 水域面积很大的滇池和博斯腾湖表层沉积物盘星藻分布的研究表明, 在湖泊水深较大的地方, 盘星藻的浓度显著增加^[34,35]. 而在诸多关于盘星藻化石环境意义的研究中, 具有争议的就是盘星藻化石含量变化与湖泊水位的关系(表1). 具体而言, 前人的研究可以归纳为两类观点: 一种认为湖泊沉积物中盘星藻化石含量的升高可以反映湖泊水位升高或水深增加^[13,36-46]; 另一种认为盘星藻含量的升高指示湖泊

水位降低或水深变浅^[47-55]. 然而, 盘星藻化石频繁地出现在第四纪沉积物的孢粉组合中, 上述两种相互矛盾的观点使得地层盘星藻化石在古环境研究中的应用变得很有争议, 理清盘星藻含量与湖泊水深关系, 明确盘星藻的环境意义, 对于提高利用孢粉组合重建第四纪环境的可靠性很有必要. 而现代盘星藻的研究是化石盘星藻研究的基础. 鉴于此, 论文通过对云南中部星云湖现代盘星藻的调查, 探讨湖水及湖泊表层沉积物盘星藻含量变化与湖泊水位/水深的关系, 并对过去3000年以来地层中化石盘星藻含量的变化及湖泊状况进行讨论.

1 研究区概况

星云湖位于滇中高原南部江川盆地东侧(图1(a), (b)), 地理坐标24°17'~24°24'N, 102°45'~102°49'E, 属于珠江流域南盘江水系的源头湖泊, 为高原断陷型浅水湖泊. 该湖呈南北向不规则椭圆形, 南北长约10.5 km, 东西宽约3.8 km, 水位在海拔1722.5 m时,

表1 过去对盘星藻化石与水位变化的研究

Table 1 Summary of the previously published studies on fossil *Pediastrum* and water depth variation

盘星藻类型	研究点	年代(cal ka BP)	指示意义	参考文献
盘星藻	滇池	16~0	含量升高指示水深增加; 湖泊富营养化	[37]
盘星藻	滇池	13~0	含量升高指示水深增加	[40]
盘星藻	洱海	10~0	含量升高指示湖泊水体扩大	[41]
单角, 短棘等	东海	晚更新世	高含量指示水域大, 水体较深	[36]
盘星藻	察尔汗剖面	36~18	在一定范围内指示水位和盐度变化	[56]
盘星藻	察尔汗盐湖	94~10	含量升高反映湖泊水深增加, 盐度降低	[46]
盘星藻	扎布耶盐湖	36~0	浅水(水深不超过15 m): 高含量指示水深增加	[38]
盘星藻	克鲁克湖	11.9~0	含量增加反映水深增加	[43]
盘星藻	巴彦查干	11.1~5.1	含量增加指示湖泊水深增加, 季风增强	[42]
盘星藻	科尔沁沙地巴克窑地区	0.15~0	含量增加指示湖泊水位上升	[39]
盘星藻	许果错	8.2~0	相对丰度变化可以作为指示相对湖面变化的指标: 含量降低指示湖面下降	[44, 45]
盘星藻	湖光岩玛珥湖	11.6~7.8	含量升高指示湖面水位变浅	[51]
盘星藻	湖光岩玛珥湖	42.5~0	高含量指示浅水湖(5~6 m)	[47]
盘星藻	双池玛珥湖	7.2~0	周期性变化反映湖水深度变化	[48]
单角, 二角, 短棘	双池玛珥湖	2.5~0	大量出现反映水面变浅, 含量增加反映 气温升高, 降水量增加	[49]
盘星藻	安徽巢湖	4.8~0	含量降低指示湖泊水位回升	[52]
盘星藻	乌伦古湖	10~0	含量指示温度和湖泊水位: 含量增加 指示湖泊水位低, 温度升高, 有效湿度降低	[50,53]
盘星藻	赛里木湖	11~10	含量增加指示湖泊水位下降到一定深度, 温度升高	[54]
短棘和单角	星云湖	36.4~13.6	高含量指示湖泊水位降低	[55]

图1 星云湖地理位置及采样点分布图. (a), (b) 星云湖的地理位置; (c) 星云湖流域和等深线及盘星藻采样点分布图

Figure 1 Location of Xingyun Lake and sampling sites. (a), (b) Location of Xingyun Lake in Yunnan Province; (c) catchment and bathymetry of Xingyun Lake, and the location of sampling sites for *Pediastrum* analysis

湖面面积34.7 km²; 湖泊平均水深7 m, 最大水深11 m. 星云湖湖盆两侧不对称, 东侧较陡, 西侧湖底较平坦(图1(c)). 星云湖主要的入湖河流有东西大河、螺蛳铺河等14条季节性河流, 河流及湖泊积水主要靠降水补给. 2007年前, 湖水由隔河经抚仙湖流入南盘江. 2007年以后, 随着星云湖-抚仙湖出流改道工程的竣工, 星云湖湖水改迁流向, 抚仙湖湖水倒灌流入星云湖.

星云湖湖水在垂向上没有水温变化, 冬季为13.3℃, 夏季为22.3℃, 湖水无温跃层出现. 湖浪和湖流是星云湖湖水的主要运动形式. 湖浪能引起湖水混合, 在风力和湖流的作用下, 滨岸带较粗的沉积物被搬运和改造, 细颗粒物质被搬向敞水区, 特大的风浪还把较多的贝壳碎片推进滨线附近, 形成风浪贝壳层. 星云湖流域盛行西南风, 风向与湖泊延长方向基本一致, 在风力的摩擦作用下, 星云湖的湖流形

式为表层湖水向北流动而下层湖水则向南流动^[57].

星云湖是江川盆地的母亲湖和生命湖^[58], 其担负着饮用水源等多种功能. 随着本地经济的发展, 大量工业、农业及生活污水排入湖泊, 再加上过量的湖泊垦殖, 导致湖泊水质急剧恶化. 据玉溪市环境保护局历史监测资料, 星云湖水水质偏碱性. 自20世纪80年代中期至今, 星云湖水水质类别从IV类下降为V类, 仅适用于一般工业用水^[59]. 资料显示, 2001~2012年星云湖湖水总氮平均浓度 1.38 mg L^{-1} ($0.91\sim 2.1\text{ mg L}^{-1}$); 高锰酸盐指数平均浓度为 7.6 mg L^{-1} ($5.5\sim 10.2\text{ mg L}^{-1}$); 总磷平均浓度为 0.252 mg L^{-1} ($0.079\sim 0.546\text{ mg L}^{-1}$)^[58]. 星云湖的14条入湖河流的水质也均劣于V类水质^[58,60,61]. 水体营养状态由20世纪80年代中期的中营养状态上升到2000年早期的中-富营养状态^[58,61,62]. 湖水透明度在1987年为 2.4 m , 到2000年为 1.13 m , 而在2009年仅为 0.33 m ^[63]. 星云湖水生生物丰富, 据调查, 1980年以前湖内有水生高等植物17种, 浮游植物8属72种, 浮游动物59种, 鱼类20种^[64]. 随着湖泊水体水质和营养状况的变化, 湖内生物多样性降低、

生物种类减少、耐污种群数量及生物量增加: 水生植物退化严重, 由20世纪80年代的苦草为优势种的群落转变为红线草为优势种、狐尾藻为次优势种的耐污性种群; 浮游植物种类减少而生物量则增加, 同时优势种由硅藻门转化为蓝藻和绿藻^[59,64]. 对星云湖湖水的水质化学参数测量结果见表2.

2 资料和方法

2013年5月, 沿西南-东北线在星云湖不同水深处采集10个湖床表层沉积物样品, 分别在水深4, 4.5, 5.2和6.5 m处采集4个湖面水体表层样品, 同时在湖泊水深8 m处按照0.5 m间隔在不同水深处采集水样16个(图1(c)). 湖床表层沉积物样品的采集用德国制造的Grab表层湖泊沉积物采样器, 水样采集用自制的水样采集器, 并同时测量了水体的水质化学参数(表2). 样品带回实验室后, 湖床表层沉积物样品经过冷冻干燥后进行盘星藻提取, 这与孢粉提取同步进行, 详细方法见参考文献[65,66]; 水样则先在其中加入石松孢子片剂, 离心, 加9:1混合液处理, 之后

表 2 星云湖水样水质参数测量结果

Table 2 Basic water chemistry and limnological variables of water samples from Xingyun Lake

样品号	水深(m)	pH	盐度(g L ⁻¹)	溶解氧(%)	电导率(ms cm ⁻¹)
表样1	4	8.47	0.36	60	0.546
表样2	4.5	8.44	0.36	61.9	0.547
表样3	5.2	8.4	0.37	67.8	0.549
表样4	6.5	8.45	0.36	80.3	0.54
水柱样1	0.5	8.48	0.36	59.1	0.506
水柱样2	1.0	8.5	0.36	65.2	0.497
水柱样3	1.5	8.51	0.36	58.1	0.486
水柱样4	2.0	8.5	0.36	48.8	0.495
水柱样5	2.5	8.47	0.36	50.8	0.493
水柱样6	3.0	8.48	0.36	27.9	0.48
水柱样7	3.5	8.48	0.36	40.9	0.485
水柱样8	4.0	8.45	0.37	41.3	0.489
水柱样9	4.5	8.35	0.37	73.7	0.489
水柱样10	5.0	8.51	0.36	53.3	0.476
水柱样11	5.5	8.48	0.37	59.5	0.477
水柱样12	6.0	8.48	0.37	50	0.476
水柱样13	6.5	8.51	0.37	47.6	0.476
水柱样14	7.0	8.52	0.36	57.1	0.473
水柱样15	7.5	8.48	0.37	42.5	0.509
水柱样16	8.0	8.54	0.37	42.6	0.643

小试管净化,最后制半活动片鉴定统计.盘星藻浓度的计算与孢粉浓度计算方法类似,即统计到的该类型盘星藻的数目除以样品的干重(或水样体积)得到;百分比含量则以陆生植物花粉及盘星藻总和为基数进行计算.对星云湖沉积岩芯XY08A (24°20'11"N, 102°46'56"E)沉积物进行化石盘星藻分析,具体钻孔和年代框架见文献[65],同时计算了化石盘星藻的百分含量和浓度.

3 结果

3.1 星云湖现代盘星藻分析结果

星云湖水体和表层沉积物样品中共鉴定出2个盘

星藻种,即短棘盘星藻(*Pediastrum boryanum*)和单角盘星藻(*Pediastrum simplex*)(图2).水样中盘星藻浓度较低,在2~6粒 mL^{-1} 之间变化.其中不同水深处表层水体中的盘星藻浓度随水深基本没有变化(图3(a));敞水区水柱不同层位水样中盘星藻的浓度在底层相对最高(图3(b)).湖床表层沉积物中盘星藻浓度较水体高,在60700~104000粒 g^{-1} 之间变化(平均浓度为81000粒 g^{-1}).其百分含量在66%~80%之间变化,平均含量为76%.表层沉积物中盘星藻浓度和百分含量变化随湖泊水深增加无明显规律(图4).

3.2 过去3000年化石盘星藻分析结果

星云湖XY08A孔的化石盘星藻含量非常丰富,

图2 星云湖水样及沉积物中的盘星藻照片. (a)~(d) 单角盘星藻; (e)~(i) 短棘盘星藻

Figure 2 Photos of *Pediastrum* types from water and lake sediments of Xingyun Lake. (a)~(d) Photos of *Pediastrum simplex*; (e)~(i) photos of *Pediastrum boryanum*

类型与现代样品中的一致,为单角盘星藻和短棘盘星藻.盘星藻百分含量在3.4%~68%之间变化,平均含量为36.5%(图5(a)).其浓度波动较大,最高浓度为233630粒 g^{-1} ,最低为6680粒 g^{-1} ,平均浓度为45230粒 g^{-1} (图5(b)).2000 cal a BP前,盘星藻百分含量和浓度都较低,分别为5.7%和19470粒 g^{-1} .2000 cal a BP以来,其百分含量和浓度逐渐增加,其中盘星藻百分含量在1500 cal a BP以来急剧升高,并于1000 cal a BP以后达到最高值,此时平均百分含量为56.1%.而盘星藻浓度逐渐增加并在700 cal a BP时达到最高值233630粒 g^{-1} ,之后略有下降并在过去300年逐渐升高.

4 讨论与结论

4.1 盘星藻含量与湖泊水深关系

已有的研究,大多将地层沉积物中盘星藻化石含量的变化与湖泊水位/水深联系.然而,无论国际上还是我国的研究,关于两者的关系都有争论.有的研究认为较高含量的盘星藻指示深水环境^[67],有的研究则认为高含量的盘星藻反映的是浅水环境^[68,69].基于此,大量研究认为盘星藻化石含量的变化可以揭示湖泊水位的变化:一些研究认为盘星藻化石含量升高表明湖泊水位升高;一些研究则认为盘星藻化石含量升高反映湖泊水位降低.关于前一种解释的研究大部分都是基于现代盘星藻研究的结果.例如,南半球Titicaca湖现代盘星藻与湖泊水深的研究^[70]发现,在湖泊0~2 m之间葡萄藻属和盘星藻较少见(<20%);在水深2~4 m之间其含量从20%增加到70%;4~200 m时其含量达到90%^[70].基于该结果,Sylvestre^[15]和Gosling等人^[17]对该湖泊沉积物中化石盘星藻进行分析,并分别结合沉积物中硅藻及孢粉组合揭示了末次盛冰期和末次冰期-间冰期的湖泊水位变化.在我国,孙湘君和吴玉书^[34]对滇池不同水深部位表层沉积物中盘星藻分布的研究发现,水深4.5 m以浅的表层沉积物中盘星藻数量少,从4.5 m起随水深增加,盘星藻数量急剧增加,在湖盆最深处数量最高;新疆博斯腾湖在水深较浅处的表层沉积物中盘星藻偶见,而当水深大于10 m以上,表层沉积物中盘星藻浓度快速上升^[35];又如青海柴达木盆地克鲁克湖的研究,发现从水深0.6~8.6 m表层沉积物的盘星藻百分含量逐渐增多^[43].这些结果都显示盘星

藻含量随着湖泊水深增加而升高.因此,大部分研究基于此结果将化石盘星藻含量的升高(降低)解释为湖泊水位的升高(降低)或湖泊水深增加(变浅)^[19,37,39,43~46,56].然而,对星云湖不同水深处湖面表层水体、表层沉积物盘星藻浓度变化进行分析,也在湖泊水深最深处沿垂直方向对不同水位处水体中盘星藻浓度变化进行分析.结果发现,在水平方向上,星云湖不同水深处湖面表层水体中盘星藻浓度从湖岸到水深最深处随水深增加基本没有变化(图3(a));而在垂直方向上,即湖泊水深最深处不同水位水体中盘星藻浓度在水体底部最高(图3(b)).对于湖床表层沉积物中的盘星藻,其浓度和百分含量变化随湖泊水深增加无明显变化规律,不同水深处湖床表层沉积物中盘星藻浓度和百分含量相差不大(图4).Edwards等人^[71]对阿拉斯加州的Birch湖不同水深处表层沉积物中盘星藻含量的变化进行研究,发现盘星藻随水深变化均匀分布;同时还对该区域的24个不同水深湖泊中表层沉积物中的盘星藻含量进行对比,结果发现盘星藻在深水 and 浅水湖泊中都有分布,盘星藻含量与湖泊水深无规律可循,认为湖泊水深与盘星藻含量变化没有相关关系.湖泊水体中盘星藻的分布及其沉降过程极为复杂.首先,湖泊水体中的盘星藻不仅是湖泊本身生长的,还可能源于入湖河流的外源输入.而盘星藻能够在湖泊水体中生长则还与湖泊水体的营养状态、水体温度、pH及盐度等水环境状态有关.例如,Weckström等人^[5]对芬兰拉普兰地区的16个亚北极湖泊现代盘星藻组合的研究发现,湖泊水体的pH和溶解有机碳是影响盘星藻分布的主要环境因素.此外,湖泊水体中的盘星藻,一方面在水平方向上受到风力、入湖水流等因素的影响;另一方面,在垂直方向上还会受到外界的物理因素(如风浪、湖流、底泥的再悬浮和再沉降等)和自身的生理调节机制(盘星藻的原位生长,盘星藻附着湖泊底泥表面越冬休眠等)的综合作用^[72,73].即使盘星藻已经沉降于湖床底泥表面,在其他诸多复杂因素(如流入流出湖泊的河流、湖泊水动力、风力等)的影响下,盘星藻可能还会随着湖泊底泥被搬运、再悬浮、再沉降等.此外,湖床表层沉积物中盘星藻的分布也受到很多因素的影响,所以当湖床表层沉积物中的盘星藻含量随湖泊水深有规律变化时,并不能简单地认为盘星藻含量的变化代表了湖泊水深的变化.在滇池^[34]、博斯腾湖^[35]及克鲁克湖^[43]研究中

图3 星云湖水样盘星藻浓度图. (a) 湖泊不同水深表层水体盘星藻浓度图; (b) 湖泊水深最深处水柱不同层位水样盘星藻浓度曲线

Figure 3 *Pediatrum* concentration diagrams of water samples from Xingyun Lake. (a) *Pediatrum* concentration diagram of surface water samples from different water-depth of the lake; (b) *Pediatrum* concentration diagram of water samples from the water column in the deepest part of the lake

盘星藻在湖泊水深较深处的湖床表层沉积物中含量显著增加的现象,一方面可能是湖盆结构影响的结果,另一方面与盘星藻沉积的过程有关,而不是盘星藻在湖泊水体中生长分布的必然趋势.对于星云湖而言,因其湖盆相对平坦(图1(c)),湖床表层沉积物中盘星藻在不同水深处几乎均匀分布(图4).因此,湖泊水深最深处湖床表层沉积物中的盘星藻含量并不一定最高,同样,湖床表层沉积物中盘星藻含量的最高值并不一定出现在湖泊水深最深处.

另外,关于盘星藻含量的升高(降低)指示湖泊水位升高(降低)或水深增加(变浅)的其他研究则认为,由于盘星藻分布在淡水环境中,盘星藻含量增加说明水体盐度降低,盐度降低则湖泊水位升高^[38,46,56].然而,湖泊沉积物中盘星藻化石含量的增加是否能够指示湖泊盐度的降低,需要根据湖泊的具体情况来判断.就已有的研究来看,盘星藻生长需要的最适宜盐度范围和受限盐度范围尚无具体数据.当然,若盘星藻化石出现在盐湖中,其含量的升高可能指示当时湖泊盐度降低,但也有可能是外源河流输入导

致少量盘星藻化石出现.而对于微咸水湖泊而言,盘星藻化石含量变化有可能指示湖泊盐度变化.

盘星藻含量与湖泊水深关系的另一种相反的解释就是,盘星藻含量升高(降低)反映了湖泊水位降低(升高)或水深变浅(增加).关于这种解释,主要是由于已有的研究认为盘星藻一般分布在水深不超过15 m的浅水湖泊中^[49,74].而现代盘星藻的调查资料则显示,在一些深水湖泊,如抚仙湖(最大水深158 m,平均95 m)^[75]、泸沽湖(最大水深105 m,平均38 m)^[76]、程海(最大水深35 m,平均水深26.5 m)^[77]中都有盘星藻出现.此外,唐领余等人^[45]在西藏一些高山深水湖(如公珠错、玛朋错、崩错和普莫雍错等,水深在20~90 m之间)的湖床表层沉积物中也发现了大量盘星藻.可见,盘星藻分布在水深不超过15 m的浅水湖泊这一结论值得商榷.此外,也有研究认为,盘星藻的生长受到温度的控制,其生长最适宜的温度在23℃左右,并且大多数盘星藻的种在每年3~10月生长^[13],因此盘星藻含量升高表明温度升高,相应地,温度升高,蒸发量增大,湖泊水位下降^[50,53,54].然而,盘星藻是广温

图4 星云湖不同水深湖泊表层沉积物样品盘星藻浓度及百分含量图

Figure 4 Diagram of *Pediastrum* concentration and percentages of surface lake sediments from different water-depth of Xingyun Lake

性的藻类, 其对温度的适应性较大, 通常在4~36℃范围内都能出现^[13,36]. 盘星藻的大多数种对温度的耐性较广, 而个别对温度较敏感的盘星藻种则有的为暖水种(如*Pediastrum simplex*), 有的为冷水种(如*Pediastrum kawraiskyi*)^[3]. 因此, 湖泊沉积物中盘星藻化石含量的增加是否能够指示温度的升高, 需要看具体的盘星藻种类同时结合湖泊沉积物的孢粉组合及其他指标.

综上所述, 湖床表层沉积物中盘星藻的分布与湖泊水位/水深无明显共性规律. 星云湖现代盘星藻的结果以及与其他大湖的对比表明, 第四纪湖泊沉积物孢粉组合中化石盘星藻含量的变化不能简单用于反映湖泊水位/水深的变化. 当然, 湖泊水位/水深的变化可能会导致水体环境的变化, 如水位降低引起湖泊底泥侵蚀导致水体富营养化、水位升降引起盐度变化等, 这些因素也可能引起盘星藻含量的变化. 另外, 不同的盘星藻种可能分布的水深范围不同. 例如, 最近Whitney和Mayle^[7]对南美一开阔浅水湖表层沉积物中不同盘星藻种的含量变化与水深的关系进行探讨, 结果发现并非所有盘星藻种都与湖泊水位关系显著. 因此, 用盘星藻重建湖泊水位变化需要具体湖泊具体讨论, 且需要结合其他证据综合

分析.

4.2 星云湖过去3000年盘星藻化石与湖泊环境变化

星云湖过去3000年沉积物中化石盘星藻在2000 cal a BP以前百分含量和浓度都较低, 而在2000 cal a BP以来呈显著增加趋势, 并在1500 cal a BP后开始急剧升高(图5(a), (b)). 粒度和磁化率结果(图5(c), (d))显示, 在~1100 cal a BP以前, 沉积物平均粒径变化相对稳定, 而磁化率值较低且变化稳定; 在1100 cal a BP以来, 沉积物平均粒径表现出大幅度变化, 磁化率呈现异常高值并伴随有波动. 根据Wu等人^[78]对星云湖沉积物粒度和其他磁学参数及历史文献资料的分析, 星云湖沉积物粒度的高频率波动和磁化率值的突变都反映的是流域内人类活动对区域环境的影响: 较强的人类活动导致土壤侵蚀加剧, 水土流失携带大量侵蚀的物质进入湖泊. 盘星藻化石含量和浓度的变化与沉积物粒度和磁化率的变化相似, 只是时间有差异: 盘星藻的增加略领先于磁化率的增加. 星云湖沉积物中出现的化石盘星藻类型是短棘盘星藻和单角盘星藻, 其世界很多地方广泛分布. 已有的研究表明, 短棘盘星藻生态幅较广^[1,3], 单角盘星

图5 星云湖过去3000年化石盘星藻含量与粒度和磁化率的对比

Figure 5 Comparison of the fossil *Pediastrum* content with mean grain size and magnetic susceptibility from Xingyun Lake during the past 3000 years

藻可能生活在相对温暖的地区^[3]。然而,对位于亚热带地区的星云湖而言,温度应不是盘星藻生长的限制因子,因而沉积物中盘星藻化石含量的变化可能对温度的细微变化不敏感。又如前文所述,星云湖湖床表层沉积物中的盘星藻与湖泊水深没有必然关系,而短棘盘星藻和单角盘星藻主要分布在中营养或富营养的水体中^[3,4],可见星云湖沉积物中的盘星藻可能代表的是湖泊水质或湖泊水体营养状况。因此,结合沉积物粒度和磁化率指标,推断星云湖过去3000年沉积物中化石盘星藻含量的变化可能与人类活动引起的湖泊水体营养状况的变化有关。星云湖流域有很长的人类活动历史,Wu等人^[78]通过对磁学参数及区域历史资料的研究,发现在1450~900 cal a BP人类活动开始逐渐增强,900 cal a BP以来人类活动急剧增强,导致区域出现严重的水土流失、土壤侵蚀等问题。最近Hillman等人^[79]通过对星云湖过去3500年沉积物有机质和碳酸盐同位素及Pb, P, Al等元素的测量,发现星云湖流域在1450 cal a BP就开始受到人类

活动影响,~1150 cal a BP以后人类活动急剧增强,在人类活动的影响下土壤侵蚀严重,加上生活污水等营养盐随之进入湖泊,导致湖泊水质下降,出现明显的富营养化。由此可见,在2000 cal a BP星云湖沉积物中化石盘星藻含量开始增加并在~1500 cal a BP急剧升高是在人类活动影响下湖泊污染、水体富营养化所致。另外,需要指出的是,尽管星云湖沉积物粒度、磁化率和盘星藻在过去3000年的变化中都出现了突变,反映了人类活动的变化,但粒度和磁化率的突变时间略滞后于盘星藻的变化(图5)。Hillman等人^[79]的研究中有机质和碳酸盐同位素及Pb, P, Al等元素的突变也开始于~1150 cal a BP。这可能说明相对于其他物理化学指标,盘星藻能更敏感地响应湖泊水环境的轻微变化。最后,需要说明的是,星云湖沉积物中盘星藻浓度的变化与百分含量的变化趋势在1100 cal a BP以来明显不同,这是由于盘星藻浓度受到沉积速率的影响。如前所述,区域受到剧烈人类活动影响,土壤侵蚀加剧,导致沉积速率增加(1.5 mm

a^{-1}), 此时沉积物粒度的变化亦可以佐证. 并且生物对于环境的响应与物理、化学过程不一样, 是一个非线性的过程^[80]. 研究表明, 较快的沉积速率会导致孢粉浓度降低^[81]. 因此, 盘星藻浓度的变化仍然能够揭示区域较强烈的人类活动.

本文关于盘星藻与湖泊水位/水深的关系的结论

主要基于星云湖单个湖泊的调查结果, 缺乏对多个湖泊、更大空间范围内的对比讨论. 因此, 今后将开展更多空间分辨率更高, 多因素(环境和水质等参数资料)的现代过程调查, 并结合数量统计学方法, 能够更好地理解和明确盘星藻的生态指示意义, 从而更好解释第四纪孢粉学记录, 更准确重建湖泊古环境变化.

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A preliminary investigation of relationship between modern *Pediastrum* and the level of Xingyun Lake, central Yunnan, and its implications for the interpretation of the fossil record

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Fossil *Pediastrum* is frequently found in Quaternary lacustrine deposits and has attracted much attention because it can be well preserved and easily identified. However its palaeoenvironmental significance is unclear. Several studies suggest that the occurrence of a large amount of *Pediastrum* indicates a gradually decreasing lake-level, while others point out that *Pediastrum* mainly occurs in the deep areas of lakes. Thus clarifying the relationship between *Pediastrum* and lake levels is of great importance for improving the reliability of palaeoenvironmental reconstruction. In this study, we investigated the occurrence of *Pediastrum* in Xingyun Lake, a semi-enclosed shallow fault and eutrophic lake located in central Yunnan Province, southwest China. We obtained 4 lake surface water samples at water depths of 4, 4.5, 5.2 and 6.5 m; 16 water samples collected at various depths within the water column at the deepest part of the lake; and 10 lake surface sediment samples taken at different water depths from the lake shore to the deepest part using a Grab sampler. We present the results of *Pediastrum* analysis of samples of both the lake water and surface sediments of Xingyun Lake and discuss the relationship between the *Pediastrum* distribution and the lake-level/water depth. The variation of the fossil records during the past 3000 years is also reported. The results show that two types of *Pediastrum* were identified in the water and lake sediment samples, including *Pediastrum boryanum* and *Pediastrum simplex*. The concentration of *Pediastrum* in the water samples is extremely low, varying from 2 to 6 grains mL⁻¹. Spatially, the concentrations of *Pediastrum* in the surface lake water samples exhibit little change with increasing water depth. In terms of the depth variation within the water column in the deepest part of the lake, the *Pediastrum* concentration of the bottom sample is the highest, which may be related to the effects of resuspension and redeposition of lake sediments caused by wind-induced turbulence in shallow water. With respect to the lake surface sediment samples, the *Pediastrum* content is relatively high. The concentration of *Pediastrum* varies from 60700 to 104000 grains g⁻¹, with an average of 81000 grains g⁻¹; and the relative percentage abundance ranges from 66%–80%, averaging around 76%. Interestingly, both the concentration and percentage content of *Pediastrum* in these samples exhibit no significant relationship with water depth. Based on comparison of the results from Xingyun Lake with those of other workers, we conclude that the relationship between the *Pediastrum* distribution and water depth inferred from the lake sediments of several relatively larger lakes mentioned in previous studies may be caused by depositional processes: turbulence resulting from wave activity in these larger lakes could result in the resuspension of *Pediastrum* in shallow water and its focusing into deeper areas. However, whether or not there is a large quantity of *Pediastrum* living in the lake water may be related to the physicochemical status of the lake water, determined by factors such as the river input, nutrient level, temperature, pH and salinity. In addition, these factors may vary between different lakes in different regions. Therefore, the variation of *Pediastrum* content cannot be used as an indicator of water depth or lake-level without careful consideration of these factors. In addition, it needs to be used in the context of multi-proxy studies. Both the percentage and the concentration of fossil *Pediastrum* in the sediments of Xingyun Lake exhibit distinct features over the last 3000 years: very low values before 2000 cal a BP followed by a rising trend, and then an abrupt increase after 1500 cal a BP. This is consistent with variations in the intensity of human activity revealed by frequent high-amplitude fluctuations in mean grain-size and by an abrupt increase in magnetic susceptibility. In addition, the abrupt changes in fossil *Pediastrum* in Xingyun Lake precede those of mean grain-size and magnetic susceptibility, suggesting that the *Pediastrum* from the Xingyun Lake sediments may be a sensitive indicator of the process of lake water eutrophication caused by human activities.

***Pediastrum*, water environment indicator, lake levels, nutritional change, Xingyun Lake**

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