A RE-EVALUATION OF MOUNTAIN LAKE, GILES COUNTY, VIRGINIA: LAKE ORIGINS, HISTORY AND ENVIRONMENTAL SYSTEMS

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Dissertation submitted to the Graduate Faculty of
Virginia Polytechnic Institute and State University
In partial fulfillment of the degree of

Doctor of Philosophy

In

Biology

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December 3, 1999
Blacksburg, Virginia

Keywords: Mountain-Lake, Virginia, Paleolimnology, Diatoms, Sediment-cores, Coring-device

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ABSTRACT

This project included the following goals: 1. To review and assess the geomorphology and lake morphometry of Mountain Lake, Giles County, Virginia with regard to its age and origin. This included production of an updated bathymetric map of Mountain Lake using Sonar imaging of the lake bottom. 2. To evaluate present trophic conditions in the lake waters. This analysis included the first-reported nutrient conditions for input streams to the lake and rainwater. 3. To collect representative “modern” bottom sediment samples and to analyze these sediment samples for sedimentological characteristics, diatoms , and terrestrial pollen. This analysis focussed on present environmental conditions in the lake, and the determination of modern diatom thanatocommunities. 4. To collect complete bottom sediment cores from the lake. Coring was done using a diver-assisted manual coring device designed specifically for this project. 5. To analyze Mountain Lake sediment cores for sedimentology, age determination, and temporal differences in sediment characteristics, diatoms and pollen. This analysis focussed on interpretation and documentation of environmental changes through the lake’s history.

Primary discharge from the lake presently occurs through a leaky subterranean pathway associated with the deepest, crevice-like portion of the lake. This discharge results in the crevice drain not filling shut with sediment despite its location within the lowest portion of the lake. The lake structure, crevice, and subterranean drain are associated with a regional lineation feature represented in part by the path of Salt Pond Drain and a small input stream (“I-4”) to the lake. Initial damming was caused by downdrop of overlying rock. The damming is not complete, and the rate of discharge through time is controlled, in part, by regional tectonic events and by a balance of hydrologic conditions and sedimentation factors. The present lake is generally oligotrophic in nature, with phosphorus representing the major limiting nutrient. Rainfall presently represents the largest source of nutrient to the lake.

Present diatom flora in Mountain Lake includes 66 individual taxa, representing 25 genera. Of these, 12 forms or species have not been reported in Virginia inland waters prior to this project. The diatoms reflect the oligotrophic and circumneutral nature of the lake. At least seven diatom thanatocommunities can be defined in the lake, based on taxa, delineated by depth and nutrient conditions. The ratio metric of planktonic to littoral diatoms can be used to estimate past water depths in the lake from bottom sediment.

An orange clay layer at 5 cm from the modern sediment/water interface represents human intervention in lake history, namely the hotel and road building in the early 20th Century. The age of the lake is greater than 6000 years. Specific ^{14}C from sediment produced dates of 1860 ±100, 4220 ±50 and 6160 ±70 bp. Within this interval, at least 6 extended periods of low or empty lake level occurred (at approximately 100, 400, 900, 1200, 1800, and 4200 yrs bp). Several of these low intervals are likely to correspond with cool dry conditions co-incident with solar minima events. When the lake has been low or empty, it has tended to develop *Sphagnum* bog conditions with the low lake surrounded by open or wooded meadows. Terrestrial flora surrounding the lake appears to have remained relatively similar through 6100 years, although red spruce originally accompanied hemlock.

“Now within the green ravine of middle years I stood…”

Ray Bradbury. *Remembrance*, 1972

ACKNOWLEDGEMENTS

I would like to thank my graduate committee with whom I have shared this project during the last three years of the 20th Century. I have very much valued your input and guidance. I especially acknowledge and appreciate my major professor, Dr. Bruce Parker for his patience and moral support, and for putting up with important things being left for him on his desk at 3 a.m. I will also thank Christine Parker for adopting me at various points along the way. I have enjoyed the chance to study and teach with my committee members, especially with Dr. George Simmons, and Dr. Stephen Scheckler, both of whom I greatly respect. I have likewise enjoyed input, advice and interaction from Dr. Kenneth Stein and Dr. Terry Hufford, particularly on technical issues.

I especially thank Mary Schaeffer for moral support. I thank the Biology and Geology Department secretaries for always saving my tail. And I thank Dr. Joe Cowles both for his mentorship and for running a world-class Department precisely the way it should be run.

I thank those who financially supported my project, the Wilderness Conservancy at Mountain Lake, Mountain Lake Hotel, and the Miles Horton Foundation. I thank Conservancy Director Jeff Slack, and Ed Protz of Mountain Lake Hotel. And I personally thank Miles and Ruth Horton for their hospitality and friendship. I thank CQS, Inc. of Harrisburg, Pennsylvania, and Lois and David Graham (my big sister and brother-in-law) who are invaluable and irreplaceable.

I thank Mary Ng (my little sister who got her doctorate first). And I especially would like to thank my parents, Caroline Crain-Ludwig, Francis E. Ludwig and Terence J. Cawley, as they have been most supportive of all (and have put up with my eccentricities longer than anyone else). I thank Anne Kottman, who has also been very patient.

I thank my earliest teachers, my best friends, my peers and especially my students, as they have had far more input than they realize. I admire those of you who have come before me, and I envy you who will follow with new ideas and neat adventures.

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INTRODUCTION

Mountain Lake is located near the summit of Salt Pond Mountain (elevation 1177 m / 3860 feet), Giles County, Virginia, in the Ridge and Valley Province of the Southern Appalachians (37° 21' 56" N, 80° 32' 00" W). It is underlain by Ordovician and Silurian (noncarbonate) shale and sandstone of the Martinsburg, Juniata and Clinch Formations. While relatively small, Mountain Lake is the only natural lake in the highlands of the Southern Appalachians. Mountain Lake has a maximum depth of approximately 33 m at the north end of the lake; this deep portion consists only of a narrow crack or crevice feature in the bottom of the lake. Most of the deep end of the lake is approximately 24 m deep, shallowing to the south. The lake is also the centerpiece of the Mountain Lake Hotel and Resort, and the Wilderness Conservancy at Mountain Lake. As such, the relatively pristine lake is increasingly subject to human use and potential human impacts. Mountain Lake is positioned such that it receives rainfall from points west and is potentially susceptible to damage from acid rains or rain-carried nutrients.

From the beginning, Mountain Lake has been an enigma. At nearly 4000’ elevation, it exists where no lake is likely. It is as surprising a sight to come upon today as it must have been to Christopher Gist, the European surveyor who was first led to the lake in 1751. Most lakes in eastern North America have a glacial origin; however the glacial ice sheets never ranged as far south as Virginia.

G.E. Hutchinson and Grace Pickford considered the lake in 1932 and decided that a landslide formed it; yet there is no evidence of a landslide at the site. Historical records have suggested that the size of the lake has varied periodically through time, yet it has long been contested whether the lake has actually been ‘empty’ at various times in the past. It has been a matter of local folklore whether the Porterfield family really salted cattle on the lake-bottom meadows (around “Salt Pond”) in the late 1800s, and whether the lake filled rapidly after a local earthquake toward the end of the 1890s.

Today's Mountain Lake is an oligotrophic, high altitude, subalpine lake. As such, it and its surrounding ecosystem, represents an epitome of the diverse "Southern Appalachian Highlands Ecoregion" (as defined by the Sierra Club Critical Ecoregions Program, http//www.sierraclub.org/ecoregions/southapp.asp). The ecosystem surrounding the lake is recognized for its endemic taxa, particularly plants, birds and amphibians. Due to its high elevation, lack of carbonate buffering, specific location, and relatively pristine condition, the lake represents a potential "early warning system" for ecosystem impacts to the entire Southern Appalachian region. This potential has been underlined by the establishment of the Wilderness Conservancy at Mountain Lake in 1992, and that it is presently targeted as a unique status area by the United Nations Southern Appalachian Man-in-the-Biosphere group. Lake stewardship and management of potentially human nutrient flows into the lake are now considered vital to its preservation (see Chapter 1).

Since the 1930s, numerous workers have considered the origin, geology, phytoplankton community, and physical and chemical limnology of Mountain Lake. (e.g., Hutchinson and Pickford 1932, Roth and Neff 1964, Marland 1967, Obeng-Asamoa and Parker 1972, Parker *et al*. 1975, Dubay and Simmons 1981, Parson and Parker 1989a,b, Beaty and Parker 1994, Beaty 1995). Deevey, in 1957, produced the first bathymetric map of the lake, using lake soundings and (War Department) aerial photographs (Deevey *et al*. unpublished 1957; Beaty and Parker 1994). This lake bathymetry has been updated using Sonar by the present author in 1997-1998, and, with this study, the lake origin is now recognized (Chapter 1) as being related to a regional fracture feature.

In 1997-1998 the present author undertook a re-evaluation of the water quality and present trophic state of the lake (Chapter 2), and the extant and historical diatom and pollen taxa of Mountain Lake (Chapter 3). Sediment coring of Mountain Lake has proved important for interpretation and analysis of the lake's paleoenvironments. Because of the undisturbed nature of the sediments, the lack of permanent stream inputs, and the very low sedimentation rates (we estimate these to be presently at about 1mm/yr) Mountain Lake affords a good, albeit challenging subject for coring. A special diver-assisted coring device was designed and built specifically for use in this study (Chapter 4).

Analysis of diatoms and other organisms, sediments, and pollen from lake-bottom cores has been an increasingly important tool to paleolimnology and paleoenvironmental interpretation ever since Deevey's "pre-Mountain Lake" work at Linsley Pond, Connecticut (1942). In more recent years, knowledge of the environmental preferences of diatoms (i.e., Cairns, 1964, Patrick and Reimer, 1966, 1975; Lowe, 1974) and of pollen and sedimentary features (i.e., Traverse 1983, 1994) has increased, allowing for more complete interpretation of paleoenvironments from lake sediments. At Mountain Lake, Marland (1967) followed Deevey's lead, studying cladocerans from Mountain Lake sediments. Marland concluded that the lake could have been 2000 years old, but suggested that it may have had previous 'incarnations' before that time.

This study (Chapter 5) specifically examines the diatom, pollen, and sedimentary content of ^{14}C dated cores from the deepest portion of Mountain Lake. Water depth and potential changes in the lake through the past 6100 years are documented, as evidenced by changes in diatom and pollen content, sedimentary erosion features, and the presence of wood fragments, plant fiber, and *Sphagnum* spores. Diatom thanatocommunity contents are identified for selected time periods in the lake. These findings provide the first detailed diatom, pollen, and sedimentology-based paleolimnology of the lake. The 5 chapters of this study have been submitted separately to professional journals. As per Virginia Tech Biology Department Standards, the individual chapters/papers are formatted (i.e. reference citation formats) to be consistent with the requirements of the individual journals to which they have been submitted.

The original goal of this project was primarily to explore only Mountain Lake's paleolimnology using diatoms and pollen from sediment cores, as presented in Chapter 5. An initial review of lake geology and morphometry, however, showed the previous geological work to be inadequate, and earlier lake origin hypotheses to be wrong. With our subsequent discovery of the lake-bottom fracture feature in late 1996, we added the geology and morphometry portion of this study, presented as Chapter 1. This phase included the production of the Sonar-based bathymetric map, as well as imaging the fracture trace using geophysical resistivity techniques. The resulting information was presented in a poster at Geological Society of America, Southeastern Section (Athens, Georgia) in March 1999, and the material was submitted to *The British Journal of Landforms and Geomorphology* for journal publication.

In 1997-98, we were commissioned by the Miles Horton Foundation and The Wilderness Conservancy at Mountain Lake to consider the present lake water quality and trophic state. We submitted proposals for this additional phase of the study, which provided us with adequate financial support, and the water quality data were added as Chapter 2 of the dissertation. The information was presented in poster form at the Phycological Society of America (Saint Louis, Missouri) in August of 1999 and was subsequently submitted to the *Journal of Freshwater Ecology* for publication.

In order to interpret sediment cores from the lake, we judged that analysis of modern diatoms and pollen from near-surface time-averaged sediments was important, especially in light of the water quality and trophic work available. The subsequent discovery of diatom taxa not previously described from the lake, as well as diatom thanatocommunity structure, and the development of a depth metric for the lake, produced Chapter 3. Initial information from this phase of the project was presented as an oral paper at the Phycological Society of America (Flagstaff, Arizona) in August 1998, and was submitted to *Diatom Research* for journal publication.

Because previous lake coring attempts had not been particularly successful, we next became interested in the logistics of actually coring Mountain Lake. This led to the design of our diver-assisted coring device, using available off-the-shelf hardware. When the coring device proved successful, both inexpensive and functional, its design was submitted as a short methods paper in the *Journal of Sedimentary Research*. This also became dissertation Chapter 4.

The final dissertation chapter (5) represents the sediment core analysis around which the project was initially developed. Resolution of the core was adequate for paleolimnological interpretation using diatoms, pollen, and sedimentary structures. This work was subsequently submitted to *Quaternary Research* for journal publication. A poster session on this portion of the project will be presented at Geological Society of America, Southeastern Section (Charleston, South Carolina) in April, 2000.

CHAPTER 1:
NEW OBSERVATIONS ON THE GEOMORPHOLOGY AND ORIGINS OF MOUNTAIN LAKE, VIRGINIA

(Submitted To: British Journal of Landforms and Geomorphology)

ABSTRACT

Mountain Lake is the only natural lake in the unglaciated Southern Appalachian Highlands. It is located near the summit of Salt Pond Mountain, Giles County, Virginia, at an elevation of 1177 meters (3860 feet). It is underlain by Ordovician and Silurian (noncarbonate) shale and sandstone of the Martinsburg, Juniata and Clinch Formations. Historical and sediment records suggest that the size of the lake has varied periodically through time. Hutchinson and Pickford (1932) proposed the lake origin as valley damming by a landslide. Parker *et al.* (1975) modified the landslide hypothesis to the primarily vertical collapse of a proposed canyon feature in the Clinch. Fracture trace analysis now reveals a regional lineation feature associated with the lake. This is present surficially both down-gradient from the lake to the northwest, and up-gradient to the southeast. Sonar bathymetry and diver reconnaissance show it expressed as a (relatively sediment-free) narrow open crevice in the deepest (33-meter) portion of the lake. Hydrologic observation and resistivity suggest preferential water movement along this fracture, as well as leakage directly from the lake. The present study suggests conduit erosion within this feature and periodic downsettling of overlying Clinch material as the primary mechanism of lake origin and water level control through time.

INTRODUCTION

Mountain Lake is the only natural lake in the unglaciated Southern Appalachians. It is located in Giles County, in southwest Virginia, about 15 miles from Blacksburg and the Virginia Polytechnic Institute and State University. It lies near the top of Salt Pond Mountain (37° 21' 56" N, 80° 32' 00" W), at an elevation of 1177 m. The lake is approximately 900 m long by approximately 250 m wide, forming an elongate club-shaped body oriented from south to northwest (Figure 1-1). Mountain Lake has a maximum depth of approximately 33 m at the north end of the lake; this deep portion consists only of a narrow crack or crevice feature in the bottom of the lake. Most of the deep end of the lake is approximately 24 m deep, shallowing to the south.

Christopher Gist (1751), a British surveyor, was the first European to discover Mountain Lake. Gist described the relatively small lake as surrounded by an extensive wide meadow in which he found a line of six strong springs. From this description and his published sketch, it appears clear that Gist found the lake at a time when the water level was considerably lower than at present. A row of lake-bottom springs does exist along the contact between the Martinsburg shale and overlying Juniata sandstone; these springs are presently at about 8 meters depth in the full lake and have been located by Scuba divers in the course of this project .

Since 1751, the lake water level is known to have fluctuated periodically. Indeed, numerous in-place tree stumps have been collected from the lake. Most graphically, a stump of yellow pine (*Pinus pungens* Lamb) was recovered from growth position at a depth of 10 meters in the lake (Parker *et al*., 1975). ^{14}C dating of this wood produced an age of 1655±80 AD. Tree ring analysis revealed that the tree had grown for at least 30 years along the shore of a much smaller Mountain Lake.

More recent fluctuations include a period of relatively low lake levels in the mid and late 1950s when the lake became once again low enough that the lake-bottom springs were temporarily exposed. The lake returned to normal full levels after a local earthquake in April 1959 (Hopper and Bollinger, 1971). This earthquake registered as 6 or greater on the Richter scale; it sprung door hinges and cracked a large stone fireplace mantle at the Mountain Lake Hotel (Parker *et al.*, 1975). Lake levels have remained relatively full since that time, although the level drops seasonally at an unusually rapid rate during dry portions of the late summer. The lake has been low in 1997 and 1998, largely due to drought conditions throughout the summer, dropping nearly three meters from full level, with no surface outflow into Pond Drain. Such a drop is more than three times the water loss expected from evapo-transpiration alone.

REVIEW OF MOUNTAIN LAKE ORIGIN HYPOTHESES

G. E. Hutchinson and Grace Pickford (1932) first scientifically described the lake. They suggested that Mountain Lake was the result of landslide damming of the valley (see Hutchinson's lake type 20a, (1957)), and described the lake as a pristine oligotrophic system. Others have subsequently suggested other less likely origins, including a glacial cirque, volcanic caldera, and karst sinkholes. These were reviewed and rejected by Parker *et al*. (1975), who returned to a variation of the landslide hypothesis.

Based on preliminary geologic analysis, Parker *et al.* (1975) suggested that a small narrow valley was eroded headward by Salt Pond Drain through the relatively resistant Clinch sandstone. Subsequent to this surface erosion feature, wall collapse occurred, with primarily vertical movement of the infilling material. This hypothesis is reasonable, so far as it goes, but does not fully explain either the structural reasons for Mountain Lake's existence, or why a partial canyon feature does not remain today in the upper portion of the Salt Pond Drain valley.

GEOLOGIC AND PHYSIOGRAPHIC SETTING OF MOUNTAIN LAKE

Mountain Lake is situated within the top of a shallowly dipping antiformal feature associated with the regional Ridge and Valley topography of the Southern Appalachians (Figure 1-1). Rocks surrounding the lake tend to dip shallowly away from the lake to the west, and east at about 10 degrees, and plunge similarly toward the north (Schultz *et al.,* 1986). These rocks belong structurally to the Narrows thrust sheet, a large ramping structure associated with this portion of the Valley and Ridge Province in Virginia (Perry, 1977).

Mountain Lake is unusual in that it is underlain by three different geological formations. These are the Ordovician-age Martinsburg Shale to the south end of the lake, the Ordovician-age Juniata red quartz sandstone which underlies the middle portion of the lake, and the Silurian-age Clinch white quartz sandstone which forms the northern end "dam" structure of the lake. These formations contain little or no potential for carbonate buffering and are primarily responsible for low alkalinity and relatively moderate pH (6.5 to 7.2) conditions within the lake (see Beaty and Parker, 1994). Very large angular Clinch boulders are present surrounding the northern end of the lake.

The Martinsburg shale is locally a fine-grained to sandy gray shale, which weathers to gray-yellow. In the area around Mountain Lake the Martinsburg is entirely non-calcareous. Lesure estimated that at least 550 meters of Martinsburg underlie Mountain Lake (Lesure *et al.* 1982).

The Juniata Formation is a reddish-brown, iron-rich quartzite sandstone. The rock is relatively fine-grained, and locally shows crossbedding and occasional trace fossils. The Juniata is relatively thin-bedded, and breaks into thin flattish blocks. The rock is cemented with a combination of silica and iron minerals. According to Lesure *et al.* (1982), the Juniata contains minor amounts of feldspar, zircon, and other opaque minerals in addition to the more common quartz. In the area around Mountain Lake, the Juniata is estimated to be about 60 m thick.

The Clinch Formation is a white to light gray, fine to coarse-grained quartzite sandstone. The Clinch is often conglomeratic (with rounded white quartz pebbles), although the rock texture tends to become finer grained toward the top of the formation (Folk, 1960). The Clinch is cemented with silica, and is thus hard, somewhat brittle, and very resistant to weathering. Near Mountain Lake, the Clinch is noticeably crossbedded, and contains *Skolithos*-type trace fossils. A thin mantle of the overlying Rose Hill sandstone often covers the Clinch, although in the region of the lake this primarily occurs as broken float. The thickness of the Clinch in this area has been measured as variable from 15 to 40 m.

The recharge area of Mountain Lake is delineated topographically, and the lake remains relatively isolated physically and hydrologically. The lake is more than 670 m (2200 ft) above the nearby New River channel and less than 137 m (450 ft) below the peaks that surround it. The region surrounding the lake is largely wooded and presently comprises lands of The Wilderness Conservancy at Mountain Lake, established in 1992.

Water input to the lake is nearly or entirely derived from the local recharge area. Surface runoff enters the lake from at least five small, primarily ephemeral streams. Of these streams, only one is perennial (Stream "I-4" located toward the north end of the lake). This stream flows northwest (from approximately 140°) into the lake (Figure 1-2). In addition, there are lake-bottom springs associated with the Martinsburg/Juniata contact, and this study also suggests that there is spring water movement at depth associated with the I-4 stream as well.

Drainage from the lake is provided from the northwest end of the lake by means of Salt Pond Drain. This is a small bouldery headwater stream with multiple channels, which flows to the northwest (from approximately 140°). It flows in a relatively flat-floored valley filled with sandstone float, and wooded with hemlock, rhododendron, and hardwoods. The stream is very small where it presently leaves the lake. Parker *et al*. (1975) suggested that only about one-half of the water leaving the lake could be accounted for by flow from this surface location.

APPROACH AND METHODOLOGY

Examination of the regional and local geology of the drainage basin is necessary in order to understand the origin of Mountain Lake in light of previous hypotheses. As stated previously, the lake is situated on Ordovician and Silurian aged Martinsburg, Juniata, and Clinch Formations, and is dammed primarily by rock material of the Clinch. Initial field reconnaissance and comparison with previous work was initiated in the fall of 1996. Rock type collections, observation of bedding features, and strike and dip measurements were taken. The perimeter of the lake was examined in both dry and wet intervals, and photographs were taken of wet-weather inputs, local vegetation, and geologic features. Particular attention was paid to sediment load and periodicity of input sources.

Initial reconnaissance and photography of Pond Drain were carried out in November 1996, after undergrowth had died back. Attention was paid to possible periglacial geomorphology and colluvium (McDonald and Bird, 1986), stream channel forms, qualitative water volume, and disappearance/reappearance of minor channels. Sonar bathymetry of the lake was done in fall of 1996.

Field reconnaissance was followed with structural analysis of the immediate region. Interpretation of regional folding links the local Mountain Lake anticline with the Narrows thrust sheet and more directly with a large-scale fault to the northeast of the lake (Figure 1-1).

Initial fracture trace analysis has been carried out using geologic and topographic map techniques. Additional aerial photography was done in early April 1997 (before deciduous foliation) using both color and infrared photography. Temperature measurements were made along Salt Pond Drain in late summer in an attempt to locate subterranean water output from the (cold) lake bottom into the stream.

In summer 1997, resistivity profiles were made at the North end of the lake and across Pond Drain. Additional resistivity transects (Figure 1-1) were made during the summer of 1998, both along input stream I-4 (MLLINE-1 and MLLINE-2), and along Pond drain (MLLINE-3 MLLINE-4). These transects were acquired using a CAMPUS Geopulse and a 250m cable with connections every 10 meters. The Wenner array configuration, with ***a*** -spacings of 3, 4 and 5 meters was used for the surveys.

Additional sonar measurements as well as diver reconnaissance of the lake's "deep hole" were done in summer and fall of 1998.

FRACTURE TRACE ANALYSIS

The floor of Mountain Lake is composed of the Martinsburg, Juniata, and Clinch Formations. Toward the head of the lake (south), the Martinsburg shale has produced a shallowly dipping lake floor (Figure 1-2), which in places is covered with flattened boulders of Clinch quartzite float. The Juniata Formation overlies the Martinsburg; this unit is discernible in cores from the middle of the lake where it forms the foundation to a more sloping lake floor. A thin tongue of Juniata extends northwestward from the northwest end of the lake, paralleling Pond Drain. The location of this tongue suggests that most of the northern portion of the lake bottom is underlain by Juniata. This interpretation is supported in part by the sloping bathymetry of the northwest portion of the lake (Figure 1-2). Overlying the Juniata at the north and northeast end of the lake is the much more resistant coarse-grained Clinch quartzite. Where the Clinch is present around the lake, the surface contours are often steeper; the presence of the lake-bottom Clinch is supported in part by much steeper bathymetric contours along the northeast edge of the lake (Figure 1-2).

Zones of structural weakness in the bedrock, which provide additional permeability, largely control the physiography of Mountain Lake. Overprinted on the geological units is a local lineation feature (Figures 1-1 and 1-2) that intersects the deepest, northern portion of the lake, trending approximately NW by N (striking/trending from approximately 140°). This feature is oriented parallel to the direction of primary compressive stress during the Alleghenian Orogeny. The lineation is perpendicular to both of the major tectonic features in the area, the Saltville Thrust Fault to the Southeast and the Narrows Thrust Fault to the Northwest. The lineation feature also is perpendicular to an unnamed regional fault on Salt Pond Mountain (Figure 1-1). We suggest that this lineation feature may have initially been produced when tectonic stresses perpendicular to the original compression were expressed, and the rock fractured with little lateral displacement.

The proposed fracture feature is traced northwest of Mountain Lake by Pond Drain, which continues northwestward until it reaches flatter land near the center of the adjacent syncline (and then diverts northward over colluvium). The lineation appears to continue across the syncline, where it may be expressed by drainage on the opposite side of the valley. The same lineation feature is discernible on the eastern side of the lake as well, and is indicated by the I-4 stream channel, and by the twin-peak topography of Salt Pond Mountain.

The deepest point in Mountain Lake is a small depression in the northeast corner where depths of 33 m (106 ft) were measured by us with sonar equipment. This is an anomaly in the deep end of the lake, where there are generally uniform depths of 23-24 m (75-80 ft). The hole begins at the projected contact between the Juniata red sandstone and the Clinch. The feature is elongate in the northwest-southeast direction, and oriented parallel to (and superimposed upon) the regional lineation. This is a crevice with very steep walls on either side but slopes more gradually upward toward its southeastern end. Scuba divers reported that the walls of the depression were composed mostly of red Juniata sandstone. The feature has remained unfilled despite sediment influxes since at least 1957, and probably much earlier.

The valley of Pond Drain is a flat-floored valley, with multiple stream channels, covered by angular Clinch boulders and cobbles. Much of the water appears to travel just below the surface of the valley through channels in the Clinch float. The orientation of this stream valley is controlled by the lineation feature, upon which it is superimposed. This process alone would normally produce a straight V-shaped valley, but periglacial activity (such as frost wedging, hydration, hydrolysis, and exudation) and mass wasting has modified it to its present profile.

RESISTIVITY DATA

Direct current resistivity techniques measure the apparent resistivity of the sediments and rocks below the survey line. Resistivity is the inverse of conductivity. Porosity changes affect the conductivity and resistivity of sediments and rocks by filling open space with (non-conductive) air or with (very conductive) water. This makes direct current resistivity techniques very effective for imaging zones of contrasting porosity. Fractures in rocks increase the porosity in the vicinity of the fractures; fractures that are filled with air increase the apparent resistivity, while fractures that are filled with water decrease the apparent resistivity. See Telford (1990) for a review of resistivity techniques, effects of porosity/water content and resistivity ranges of wet and dry sediments and rock.

Resistivity techniques were chosen over other seismic techniques in part due to equipment and access restrictions of the Wilderness Conservancy at Mountain Lake.

In summer 1997, two initial resistivity surveys were collected across Pond Drain to determine if the apparent resistivity structure obtained would be consistent with the expected resistivity structure for a fracture zone. The data sets were acquired using a CAMPUS Geopulse and a 250-meter cable. The Wenner array configuration, with an ***a*** -spacing of 4 meters, was used for the surveys. The apparent resistivities of these initial surveys showed pronounced low values near the proposed fracture trace and much higher values away from the fracture. This relationship is consistent with the resistivity structure expected in a water-filled fracture zone.

In summer 1998, additional resistivity transects (MLLINE-1, MLLINE-2 and MLLINE-3 MLLINE-4) were completed (Figure 1-1). These surveys were collected using the Wenner array configuration at a variety of different ***a*** -spacings (closer *a*-spacings produce data sets of greater resolutions).

Transects MLLINE-1 and MLLINE-2 were collected perpendicular to stream I-4 on the southeast side, upgradient of the lake (see Figure 1-1), at ***a*** -spacings of 4 and 5 m, respectively. Stream I-4 is coincident with the proposed fracture trace at these locations. MLLINE-3 and MLLINE-4 were collected perpendicular to pond drain on the northwest (downgradient) side of the lake, with ***a***-spacings of 3 and 5 m, respectively. The surveys (Figures 1-3, 1-4,1-5 and 1-6) were collected in a southwest-to-northeast orientation.

The apparent resistivity data sets were then imported into Res2dinv ©, a resistivity inversion program written by Geoelectrical Imaging (Austin, Texas). This program uses the least squares inversion technique with damping factor optimization. This inversion program generates three images for each apparent resistivity survey. The models generated by the inversion program show unfractured sandstone bedrock (Juniata and/or Clinch) as having resistivity values ranging from 4000-10000 Ohm-m, with an average value of approximately 5500 Ohm-m. The dry fractured bedrock shows resistivity values ranging from 6000-12000 Ohm-m, with an average value of approximately 6500 Ohm-m. Wet fractured bedrock shows resistivity values ranging from 500-2500 Ohm-m, with an average value of approximately 1500 Ohm-m. The dry weathered layer, composed of sediments and cobbles, shows resistivity values ranging from 6000-10000 Ohm-m, with an average value of approximately of 6500 Ohm-m. The wet weathered layer shows resistivity values ranging from 500-2500 Ohm-m, with an average of 1500 Ohm-m.

Survey MLLINE-1 was collected farthest upgradient (southeast) along the course of the I-4 input stream. The transect was made at more than 10 m elevation above the first expression of flowing surface water and perpendicular to the I-4 channel trace where there were expressions of previous surface water flow. Figure 1-3 shows a resulting resistivity model with a pronounced resistivity high of 6000-10000 Ohm-m (between 26-36 meters along the transect). At depth, the data changes to a pronounced resistivity low, 2500-3500 Ohm-m. This pattern is consistent with air-filled fractured bedrock at shallow depths, with a fairly sudden change to water filled fractured bedrock at a depth of about 10 m.

MLLINE-2 was collected downhill from MLLINE-1 in the region of input stream I-4 where surface waters were currently flowing. Figure 1-4 shows a resistivity model with two pronounced lows, 400-1000 Ohm-m (at 35-45 m and at 70-80 m across the transect) that continue as resistivity lows at depth. These lows are separated by a resistivity high, 1500-4500 Ohm-m, between 50-65 m. This pattern is consistent with two water-filled fractured zones of bedrock separated by unfractured bedrock. Note that the high values are considerably lower than would be expected for air-filled fractures.

MLLINE-3 was collected downgradient of the lake, with the southwest end of the profile over the proposed fracture and the northeast end continuing across Pond Drain valley. Figure 1-5 shows a resistivity model with a pronounced resistivity low, 1500-2500 Ohm-m between 16-28 m along the transect, that continues to depths of at least 6 m. The rest of the model shows median resistivity values averaging about 6000 Ohm-m. This pattern is consistent with water filled fractured bedrock to the southwest and unfractured bedrock to the northeast.

MLLINE-4 was collected several hundred meters farther downgradient from the lake, across the Pond Drain valley. The valley in this region is broad and flat and contains a greater volume of boulders and float than previous survey areas. This very porous terrain made for difficult ground coupling and therefore produced shallow signal penetration depths. Figure 1-6 shows a model with a pronounced resistivity low, 300-1100 Ohm-m (55-65 m along the transect) that continues at depth and resistivity highs, 3500-12000 Ohm-m, on either side. This pattern is consistent with water-filled fractured bedrock surrounded by unfractured bedrock.

The pronounced resistivity lows and highs in all of these models have similar value ranges across the sections and are consistent with a water-filled fracture zone and unfractured bedrock, respectively. There seems to be a probable sense of dip to the fracture zone that is also consistent across the sections; this dip sense appears to be to the southwest. The low resistivities at depth in all of these models most likely represent an expression of the water table.

WATER BUDGET

The watershed feeding Mountain Lake extends less than a kilometer to the ridge of Salt Pond Mountain. The total area of this watershed is about 1.3 km^2. The average annual rainfall of 113 cm (Dr. David Smith, Virginia Tech School of Forestry, pers. comm.) gives the watershed a yearly total precipitation input of 1.47×10^6 m^3 of water per year. Of this amount, loss to evapotranspiration accounts for approximately 58 $cm.yr^{-1}$, or a total of 0.754×10^6 m^3 per year. In addition, Mountain Lake Hotel and Resort activities (wastewater from the resort is removed outside the Mountain Lake drainage basin) consume approximately 0.03×10^6 m^3 per year (Mr. Jeff Slack, The Wilderness Conservancy at Mountain Lake, pers. comm.).

The remaining surface runoff and groundwater flow to the lake therefore amounts to 0.686×10^6 $m^3.yr^{-1}$. Given an overall volume of the lake estimated at 1.0925×10^6 m^3, this indicates a lake water residence/replacement time of approximately 1.59 yr. All of this remaining water must exit through the northern end of the lake, as the Martinsburg shale serves as an effective aquiclude, restricting any significant groundwater flow at the southern end.

We note, however, that far less of this water is exiting through the surface stream at the mouth of the lake. We estimate that approximately half of the total liquid outflow leaves the lake on the surface, and this agrees with calculations by Parker *et al.* (1975). The remainder must be conducted through a permeable aquifer or through subterranean channels. The outflow from these appears to be a hidden spring line beneath the float-covered surface of Pond Drain valley, in an area of the stream where water flow increases substantially with no surface tributary. This is most likely where the remainder of Mountain Lake's water budget is expelled. Due to the concerns of The Wilderness Conservancy at Mountain Lake, we have been unable to use dye tracers to determine the exact locations of these springs, but qualitatively one can see a region of dramatically increased flow some hundreds of meters downstream from and northwest of the lake. The location elevation is only a few meters below the maximum depth of the lake.

Scuba diver reconnaissance of the deepest portions of the lake occurred in October of 1998, shortly after a period of relatively heavy rainfall to the lake basin. Divers reported a cloudy region at the bottom of the lake hypolimnion below about 24 m, and associated with the proposed fracture feature. In addition, when the divers disturbed silt near the fracture (at bottom depths between 27 and 30 m), it moved with water flow, parallel to the fracture, and toward the northwest. This suggests significant bottom water flow associated with the fracture feature.

INTERPRETATION OF LAKE ORIGIN

Mountain Lake is a meta-stable result of the prevailing structure and geomorphology of this particular area. The most important factors are the composition of the underlying formations and the presence of the fracture lineation described earlier. The difference between iron and silica cementing agents between the Juniata and Clinch is likely causal to the preferential weathering of the Juniata, while Clinch bedrock (and the omnipresent quartzite float) tends to remain coherent.

We propose that the linear fracture feature has significantly influenced valley formation along the length of Pond Drain. As downcutting in the stream headwaters reached the resistant Clinch in the vicinity of the lake, surface water found a subterranean short path in the form of secondary permeability along the fracture trace. Additional erosion centered primarily on this pathway, removing fine sediments (derived largely from the Juniata and Martinsburg) to create the present lake basin. Subsequent downdrop of the overlying resistant rock (primarily the Clinch) at the north end of the lake in turn constricted the subterranean pathway, causing the lake to be formed.

As continued leakage along the fracture slowly re-opens the pathway, the equilibrium is increasingly disturbed, and the lake water level eventually begins to drop. A resulting, much smaller “Salt Pond” with no surface outlet is the result during such times. Subsequent collapse of the overlying resistant rock may occur naturally with time and continued erosion, or be affected by local tectonic adjustments (such as the local 1959 earthquake). The periodic sequence of erosion followed by progressive vertical collapse is the primary cause of Mountain Lake’s variable size through time.

In addition to geologic factors, the lake water budget suggests that the water level equilibrium of Mountain Lake is precarious. A lake water residence time of only 1.59 yr suggests that the lake size can quickly be affected by even relatively small changes in local precipitation levels. Evidence of this has come during recent drought conditions at the lake in 1997 and 1998; a rapid lake level drop of only three meters produced a noticeable change in the lake’s areal extent, particularly in the shallow, southern portion of the lake. Such climatic changes, as well as related changes in groundwater (lakebottom spring) flow and bottom sedimentation, are likely factors determining the variability of the lake depth.

CONCLUSIONS

1. Primary discharge from the lake is presently through a leaky subterranean pathway associated with the deepest, crevice-like portion of the lake. This discharge results in the crevice drain not filling shut with sediment despite its location within the lowest portion of the lake.

2. The lake structure, crevice, and subterranean drain are associated with a regional lineation feature represented in part by the path of Salt Pond Drain and input stream I-4. This lineation is interpreted as a fracture feature and probable fault associated with regional Appalachian fold and thrust tectonics.

3. The pronounced resistivity lows expressed across this lineation feature are consistent with a water-filled fracture zone.

4. Erosion of and drainage from this portion of the valley prior to lake formation was related to a partially subterranean outlet. This outlet path was associated with physical and compositional differences of the Clinch and Juniata sandstone (including possibly the formational contact or an unconformity) and with the zone of weakness related to the linear fracture feature.

5. Damming has been caused primarily by progressive downdrop of overlying rock. The damming is not complete, and the rate of discharge through time is controlled in part by regional tectonic events and by a balance of hydrologic conditions and sedimentation factors.

6. Thus the precise origin of Mountain Lake was not the result of landslide damming of a valley (as per Hutchinson and Pickford, 1932), nor by the collapse of Clinch sandstone cliffs (as per Parker *et al.*, 1975). Instead, the origin as described above seems to be unique for lakes worldwide, and is not included in Hutchinson's (1957) long list of lake origins.

ACKNOWLEGEMENTS

Our particular appreciation goes to the Miles C. Horton Foundation for funding this project in 1997-99 and to the Wilderness Conservancy at Mountain Lake for their financial support in 1998-99. We also thank CQS Inc. of Harrisburg, Pennsylvania, and Manzo, Inc. of New Jersey which provided additional funding and support. We thank the officers and members of the dive club at Virginia Tech for their help and service during the 1998 season and Ross Irwin III for field support and commentary in 1996-97. We thank the Geophysics program at Virginia Tech for access to their resistivity equipment, and for their continued interest in the project. Lastly, we thank Jeff Slack and the staff of the Wilderness Conservancy at Mountain Lake, as well as the Mountain Lake Hotel for their help and cooperation in our field studies during both 1997 and 1998.

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CHAPTER 2:

A RE-EVALUATION OF THE TROPHIC STATE OF MOUNTAIN LAKE, GILES COUNTY, VIRGINIA

(1999. Journal of Freshwater Ecology, 14(4): 535-544.)

ABSTRACT

Limnological studies of Mountain Lake, Giles County, Virginia were conducted from June to October of 1997 and April to October of 1998 to evaluate the lake's trophic state, which was considered to be in an early stage of eutrophication from the late 1980s to early 1990s. Orthophosphate-P levels averaged 1.5µg/L in 1997 and 2.2µg/L in1998, much lower than the 27.0µg/L in 1990 and even higher levels of the 1980s. Ammonium-N also dropped, but nitrate-N increased in 1997-98 compared to 1990. The N:P ratio of 143:1 in 1997 and 244:1 in 1998 compared to 9.4:1 in 1990 clearly indicated P as the major limiting nutrient. Dissolved silica, hardness, alkalinity, and pH in the lake were similar to earlier studies. Phytoplankton taxa and cell densities were similar to those of the mid-1980s. Mountain Lake is thus oligotrophic and presently shows no signs of eutrophication. Input streams feeding the lake were also low in key nutrients, but precipitation constituted a major source of P, N, and acidity to the lake.

INTRODUCTION

Mountain Lake, Virginia is located in the Ridge and Valley Province of the unglaciated southern Appalachians (37° 21' 56" N, 80° 32' 00" W) near the summit of Salt Pond Mountain (elevation 1180 m) in Giles County, and is the only natural lake in the unglaciated southern Appalacian highlands. The lake has a replenishment time of about 1.6 years, being recharged continuously by groundwater and runoff from a mixed conifer and hardwood forest, which overlies sandstones and noncalcareous shales.

Numerous studies of this lake have been conducted since the 1930s addressing its origin, geology, phytoplankton community, and physical and chemical limnology (e.g., Hutchinson and Pickford 1932, Roth and Neff 1964, Obeng-Asamoa and Parker 1972, Parker *et al*. 1975, Parson and Parker 1989a,b, Beaty and Parker 1994, Beaty 1995).

Parson and Parker (1989a) first suggested that this oligotrophic subalpine lake was undergoing increasing stress due to human perturbations primarily associated with a nearby resort. Beaty and Parker (1994) and Beaty (1995) suggested that Mountain Lake had reached an oligo-mesotrophic state, manifesting early stages of eutrophication. These conclusions were based largely on the increases in lake mean nitrate nitrogen (NO_3-N) and orthophosphate phosphorus (PO_4-P) concentrations, as well as increased summer hypolimnetic oxygen deficit, and change in phytoplankton cell numbers. Beaty and Parker (1996a,b) also reported on possible impacts or shifts in phytoplankton community structure in Mountain Lake with increases in N and P inputs and changes in N:P ratios.

With the creation of the Wilderness Conservancy at Mountain Lake in 1992, concern over human use and impacts to the relatively pristine condition of this lake increased. Lake stewardship and management of nutrient inputs to the lake assumed greater importance for preserving this relatively unspoiled ecosystem.

In the present study, we reassessed the current (1997-1998) trophic state of Mountain Lake, addressing potential nutrient concentrations (PO_4-P, NH_4-N, NO_3-N, and SiO_2) as well as alkalinity, hardness, pH, dissolved oxygen, temperature, Secchi disc transparency, and phytoplankton taxa and counts. We also evaluated nutrient inputs from streams and rainwater.

METHODS AND MATERIALS

Lake water samples were collected monthly from June to October 1997, and April to October 1998 from the north end, deepest portion of the lake (Figure 2-1). Samples for chemical analyses were taken from 0.1, 1.0. 6.0, 10.0, and 16.0 meters with a Kemmerer water bottle, placed in acid-washed 1-liter polypropylene bottles, and transported on ice to the laboratory where any turbidity was removed by filtration through sterile Whatman GF/C filters. Filtered samples were then frozen for later analysis; preliminary tests confirmed that our chemical measurements were unaffected by storage at -10°C for up to three months.

All frozen water samples were thawed and analyzed for orthophosphate-phosphorus (PO_4-P), ammonia-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), and in 1998 dissolved silica (SiO_2), using wet colorimetry and spectrophotometry as described by Beaty and Parker (1994, 1996b). Dye indicator was used to determine pH, while alkalinity and hardness were evaluated titrimetrically (APHA *et al*. 1995).

Samples for measuring dissolved oxygen were collected from 14, 17, and 20 meter depths with a Kemmerer water bottle, transferred to 250 ml screw capped glass bottles, fixed, and then analyzed by the azide modification of the Winkler method (APHA *et al*. 1995). Hypolimnetic oxygen deficit calculations were made as described by Hutchinson (1957) and outlined for Mountain Lake by Roth and Neff (1964). For these calculations, the hypolimnion was assumed to begin at 14 meters depth, and Roth and Neff's areal value of this stratum (60,000 square meters) was used.

Monthly samples for phytoplankton cell counts were collected with a Kemmerer water bottle at 0.1 and 6.0 meters in 1997 and also at 10.0 and 17.0 meters in 1998. These were fixed with acid-Lugol's solution for later identification and enumeration using the Utermohl settling technique and an inverted microscope as described by Beaty and Parker (1994).

Lake water transparency was determined with a standard Secchi disk. Water temperature was determined at 1-meter intervals using a Yellow Springs Instrument Company Model 33 S-C-T meter.

Water samples from five input streams were collected monthly for chemical analysis. Samples were collected in acid-washed 1-liter polyethylene bottles and treated similarly to the lake samples.

Rainwater was collected daily when rain events occurred using rain gauges located on a roof of the hotel and, in 1998, also on the boat dock roof at the southern end of the lake. The collectors consisted of 25 cm diameter Nalgene collection funnels and 2-liter Nalgene reservoirs. Samples were decanted into acid-washed polypropylene bottles and frozen for later analysis as described above.

RESULTS AND DISCUSSION

Orthophosphate-Phosphorus (PO_4-P)

Lake annual mean PO_4-P levels in 1997 and 1998 were 1.5 and 2.2 µg/L, respectively (Table 2-1). These values were similar to those observed by Parson and Parker (1989a), lower than those reported by Beaty and Parker (1996a), and are characteristic of oligotrophic lakes. The slight increase in 1998 over 1997 may have come from increased precipitation in the winter, spring, and early summer along with input through runoff.

Beaty and Parker (1994) discussed specific human perturbations during the late 1980s and early 1990s, which probably affected PO_4-P levels in the lake (e.g., the removal and flushing of old septic tanks in 1989, and the razing of old, and constructing of new buildings and cottages). The return of the mean lake water phosphate level to those observed prior to the late 1980s suggests that these human disturbances had only a temporary impact on lake PO_4-P increases and eutrophication.

Input streams in 1997-98 contained 3-4 times the PO_4-P concentration of the lake, and rainwater contained 14-50 times the PO_4-P concentration of the lake (Table 2-1). These additions of PO_4-P were not detectable in the lake perhaps because of rapid uptake and conversion of this limiting nutrient into organic phosphate within the lake (Parson and Parker 1993, Beaty and Parker 1996a).

Ammonium-Nitrogen (NH_4-N)

NH_4-N has been identified as the most important nitrogen nutrient in Mountain Lake (Parson and Parker 1993, Beaty and Parker 1996a). Mean NH_4-N levels have not changed appreciably in annual values since the mid 1980s, with the exception of 1989, the year of the removal of the old septic tanks (Beaty and Parker 1994, 1996a).

During our two-year study, NH_4-N ranged from 1.7 to 92.0 µg N/L (Table 2-1). The highest values generally occurred at depths in the lake where phytoplankton counts were lower than at the surface (data not shown). As with PO_4-P, the input streams contributed some additional NH_4-N, and rainwater contained high concentrations of NH_4-N. In fact, rainwater means were 270 (1997) and 503 µg/L (1998) or 19 and 31 times the mean concentration in the water column. As with the PO_4-P, NH_4-N in the lake most likely was rapidly assimilated by biological activity (Parson and Parker 1993, Beaty and Parker 1996a).

Nitrate-Nitrogen (NO_3-N)

Lake NO_3-N concentrations ranged from undetectable to 3,200 µg/L, with mean values of 200 and 500 µg/L in 1997 and 1998, respectively (Table 2-1). These values are far greater than those observed previously by Parson (1988) and reported by Beaty and Parker (1994); they are primarily due to increased NO_3-N measured in the hypolimnion in the 16 and 17 meter depths samples (data not shown).

Epilimnetic NO_3-N levels in Mountain Lake usually decrease during summer thermal stratification, which Beaty and Parker (1996a,b) suggested may be due to uptake and assimilation by the abundant microphytoplankton (20-200 µm organism size) mainly consisting of green algae. The expected near-surface depletion occurred in summer1998 but not during the severe drought of summer 1997 when algal densities were low and rainwater inputs were lacking. (data not shown). Nitrate levels in input streams were variable, but nitrates in the rainwater samples were high.

Nitrogen:Phosphorus Ratios

The large body of literature from Redfield (1958) to Hillebrand and Sommer (1999) suggests that N:P ratios of 16:1 to 17:1 are in balance (or that both N and P are about equally limiting at these ratios). Ratios of inorganic N:P for 1997 (143:1) and 1998 (244:1) show that phosphorus, and not nitrogen, is likely the limiting nutrient in Mountain Lake. These ratios on a lake mean basis are much higher than those of 2.9:1 to 34.0:1 reported previously (Parson 1988, Beaty and Parker 1994).

Even if samples high in NO_3-N from the hypolimnion are omitted from the calculation, the N:P ratio in the epilimnion of Mountain Lake during 1997 and 1998 both approximate 84:1. This value is still much higher than the ratios reported by Beaty and Parker (1994). Thus, the ratios for Mountain Lake indicate that PO_4-P is presently severely limiting in the epilimnion, and that P is the chief variable responsible for controlling productivity and the oligotrophic state in Mountain Lake.

Dissolved Silica (SiO_2)

The 1998 mean values for dissolved silica (as SiO_2) in Mountain Lake (0.395 mg/L), input streams (0.44 mg/L), and rainwater (0.38 mg/L) (Table 2-2) were quite low and probably limited growth of some silicious diatoms. Earlier studies suggested that <1.0 mg/L of SiO_2 probably explained the low numbers of planktonic diatoms, but algae with smaller silica requirements, such as the silicious scaled *Synura sp.* or the silicious spined *Mallomonas sp.* which sometimes occur in the lake, probably were not limited by this nutrient (Parson 1988, Beaty and Parker 1994). However, the attached diatoms in the lake are often abundant and may be less limited by SiO_2 because of the higher volumes of water continuously flowing past their attached cells. Most other phytoplankton including the bluegreen and green algae have little or no silica requirement and will not be affected except indirectly as it may preclude competition from diatoms.

Alkalinity, Hardness, pH, and Temperature

Alkalinity, hardness, pH, and temperature of Mountain Lake showed essentially no change since the earlier investigations of Roth and Neff (1964) and later reports (Table 2-2). The lake is dimictic, completely mixing in the spring and fall, with thermal stratification developing in late April and lasting through October. Surface temperatures approached a maximum of ~25°C in August with a thermocline region developing and remaining between 6 and 10 meters throughout the summer.

Alkalinity of 2.9-10 mg/L, hardness of 12.4-34.0 mg/L, and pH ranges of 5.8-6.8 approximate the ranges previously reported (Roth and Neff 1964, Obeng-Asamoa and Parker 1972, Parson and Parker 1989a, Beaty and Parker 1994). Temperatures, not reported here, also were similar.

The conditions of low alkalinity, low hardness, and circumneutral pH all indicate a poor buffering capacity for the lake water, and signal the lake's sensitivity to acid precipitation or increases in alkaline inputs, both of which have occurred at Mountain Lake (Parson and Parker 1989a, Beaty and Parker 1994). If acid or alkaline inputs are severe enough, drastic changes in pH will occur and most likely will cause shifts in the phytoplankton community structure.

Parson and Parker (1989a), for example, reported a dramatic increase in pH and hardness in June of 1985, just after the addition of crushed limestone to construct paths at the south end of the lake. The change in pH and hardness in surface runoff was almost immediately accompanied by a shift in the algal community structure in the lake, which became dominated by *Scenedesmus bijuga*. This event generated a decrease in Shannon-Weiner diversity values lasting through July of that year. Although this perturbation was short lived, the potential for drastic change in phytoplankton community structure and primary productivity was underscored.

Limestone has again been introduced in large amounts into the lake drainage basin in 1998 and 1999. Input streams at the south end of the lake reflected this change with subsequent increases in alkalinity, hardness, and pH. This surface water however now flows into a man-made wetland created in 1996-1997, which presently appears to decrease the impact of the limestone on the lake.

Alkalinity, hardness, and pH of input streams and rainwater at Mountain Lake are reported in Table 2-2. Input streams may slightly increase, while rainwater may decrease these three variables in Mountain Lake. The acid rain events (pH <5.6) are consistent with reports throughout much of the southern Appalachians (Bulger *et al*. 1998).

Dissolved Oxygen

Beaty and Parker (1996a) noted that the calculated hypolimnetic oxygen deficit during summer thermal stratification had increased over the past 30 years and that bottom anoxia events had occurred in the lake since 1994. Such anoxia events were taken as a primary indicator of increased lake eutrophication. During the summer of 1998 an average hypolimnetic oxygen deficit (0.0089 mgO_2/cm^2/day), similar to those reported by Beaty and Parker (1994, 1996a), was calculated, while in 1997 more variable hypolimnetic oxygen deficit values were noted. Bottom anoxia, however, was not observed in the lake during 1997 or 1998. Since the lake was 1-3 meters below full capacity during both falls, light penetration probably was deeper and may have slowed development of anoxic conditions. In addition, there is dissolved oxygen evidence from bottom-waters suggesting that significant oxygenated groundwater may reach the lake bottom directly in the form of springs.

Trophic State Indices

Trophic state indices based on Secchi depth transparencies and hypolimnetic oxygen deficits were compared with values obtained by Parson (1988) and Beaty and Parker (1994). The values for hypolimnetic oxygen deficit closely approximated the values observed by Parson (1988), while the Secchi depth transparencies were slightly lower in mid-autumn than those reported by either Parson (1988) or Beaty (1995). Secchi depth transparency values continue to place Mountain Lake within the oligotrophic category based on Carlson's (1977) index and mesotrophic category using Walker's (1979) index. Thus, the average long-term trophic status of Mountain Lake based on these few indices appears not to have changed significantly since 1985 (Parson 1988, Beaty and Parker 1994).

Phytoplankton

Phytoplankton numbers and composition at Mountain Lake for 1997 and 1998 are similar to those reported earlier (Parson 1988, Beaty 1995; Tables 2-3 and 2-4). The phytoplankton community is still dominated by chlorophycean algae in the summer months, with microplankton making up the largest fraction of the community. During this study a lower number of phytoplankton was observed in 1997 than in 1998, a condition likely due to the lower rainfall and therefore a decreased amount of nutrient input (especially phosphate) into the water column. The dominant algal taxa in the lake were essentially the same as those reported by Parson (1988) and Beaty and Parker, 1994). *Dinobryon* spp. occurred in the phytoplankton during cooler months of both 1997 and 1998; these were absent during 1989-91. This genus is a biological indicator of low PO_4-P (Hutchinson 1967).

In addition, the non-native invasive weed *Ceratophyllum demersum*, which had been increasingly abundant in the lake in recent years, was undetected in 1998. Apparently this macrophyte has been replaced by the native, lower nutrient macrophytes, *Nitella megacarpa* and *Elodea canadensis.*

The present study of lake water quality was carried out as one portion of a comprehensive re-evaluation of the lake system (i.e., in conjunction with geomorphology and lake origin, diatoms and pollen in lake sediment cores, and delineation of specific water/nutrient sources to the lake). Because of the wider scope of the present study objectives, some variables considered in the earlier evaluations of the trophic state of the lake (extractable chlorophyll and primary productivity) were omitted in favor of first-time nutrient data on rain and stream inputs to the lake instead. Nevertheless, much of the body of data obtained during 1997 and 1998 enables us to conclude that the trophic state of Mountain Lake has apparently returned from an oligo-mesotrophic state reported by Beaty and Parker (1994) to an improved oligotrophic condition similar to that observed by Parson (1988) and earlier workers.

Mountain Lake continues to be a delicate ecosystem that is easily affected by human or natural environmental changes. Its trophic state may shift dramatically with only slight increases in nutrient inputs, particularly phosphates. The current high N:P ratio is evidence of the severe P limitation. The preferred N source in Mountain Lake has been shown to be NH_4-N (Parson and Parker 1993, Beaty and Parker 1996a), and this nutrient has dropped from 1989 to values measured in 1985 and earlier. However, lake mean NO_3-N concentrations apparently have increased.

The return of Mountain Lake to an oligotrophic condition probably is aided by the rapid flushing rate of the lake (~1.6 years). In addition, input streams and springs feeding the lake are presently relatively free of nutrients. Precipitation, however, appears to be a major source of important nutrients (PO_4-P, NH_4-N, NO_3-N) as well as the major source of acidity.

ACKNOWLEDGEMENTS

We thank the Miles Horton Foundation of Virginia Tech for research funding in 1997-98 and the Wilderness Conservancy at Mountain Lake (WCML) for funding in 1998. WCML also provided boats and personnel to collect the rainwater samples.

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CHAPTER 3:

SEDIMENT DIATOM ASSOCIATIONS AND POLLEN OF MOUNTAIN LAKE, A SUBALPINE ECOSYSTEM, GILES COUNTY, VIRGINIA

(Submitted to: Diatom Research)

ABSTRACT

Mountain Lake, Virginia is a small, unique, oligotrophic subalpine ecosystem in the Southern Appalachians. Traditionally, its diatom fauna, determined from plankton tows and settling chambers, has been considered sparse and of low diversity. We present 66 diatom taxa (representing 25 genera) present from sediment in Mountain Lake. Twelve of these taxa are new records for the inland waters of Virginia. Hierarchical cluster analysis suggests seven diatom thanatocommunities in the lake, divided between shallow (primarily pennate) and deep-water (primarily centric) assemblages. Shallow diatom groups are further defined by differences in epiphytic, and possibly nutrient-sensitive forms. The ratio of planktonic to littoral forms may be used as a metric to estimate past water depths from sediment. Pollen in the sediments matches typical regional flora, and appears distributed in sediment by plant proximity, current and settling characteristics. These findings provide the first comprehensive diatom / pollen training set for limnology / paleolimnology in Mountain Lake.

INTRODUCTION

Comparative studies of diatom assemblages along with bottom sediment variations have proven useful for evaluating lake environmental and nutrient conditions (e.g. Brugham 1983, Engstrom *et al*. 1985, Anderson 1990a, 1990b). Diatom analysis of sediments also enables delineation of individual thanatocommunities (or "death-assemblages") within lakes (e.g., Anderson 1986, 1990a, 1990b, Cameron 1995). Distribution of thanatocommunities depends on nutrient, depth/light conditions, and often substrate (Anderson 1990a). Similarly, pollen sampling and analysis reflects directly or indirectly the present floras surrounding a lake. Pollen is deposited within lakes as a sedimentary particle, and distributed according to currents, watermass, and settling regimes (Traverse 1994), independent of light and nutrient conditions.

Diatom assemblage "training sets" (Hakansson *et al*. 1998) and metrics (Wolin & Duthie, 1999), when compared with lake sediment core samples, can be used to infer past environmental and depth conditions within lakes. Similarly, pollen from the same modern sediment samples can be compared to historic palynomorphs from lake cores.

This study assesses the diatoms, pollen and sedimentology in time-averaged, modern-age (Eckman dredge) sediment samples from Mountain Lake, a natural, oligotrophic subalpine lake located in the Appalachian fold belt of Southwestern Virginia.

SITE DESCRIPTION

Mountain Lake is the only natural lake in the unglaciated Southern Appalachians. In addition to its unique origin associated with a fault or fracture feature (Cawley *et al*. in review b), the lake has exhibited significant depth fluctuations through time. Historically it has been called either "Mountain Lake" or "Salt Pond" according to its level at the time. With depth changes, environmental conditions within the lake also have changed significantly through time. Mountain Lake has been considered relatively pristine and oligotrophic since it was first studied by Hutchinson & Pickford (1932).

Mountain Lake lies near the top of Salt Pond Mountain (37° 21’ 56” N, 80° 32’ 00” W), in Giles County, Virginia, at an elevation of 1170 m. When full, the lake is approximately 900 m long, by 250 m wide, forming an elongate club-shaped body oriented from south to northwest (Fig. 3-1). The lake is approximately 33 m deep at its deepest point at the north end of the lake, although this deep portion consists only of a narrow crack or crevice feature on the lake bottom. More generally, the deep end of the lake is approximately 24 m deep, shallowing to the south.

Topography delineates the recharge area of Mountain Lake, which remains relatively isolated both physically and hydrologically. Five small individual streams enter the lake, all of these are ephemeral except one (stream I-4, Fig. 3-1). Because of the largely undisturbed nature of the sediments, and the lack of permanent stream inputs, Mountain Lake provides a good sedimentary record for analysis.

Mountain Lake has traditionally (in the 20th Century) exhibited an oligotrophic algal flora including attached macroalgae (Table 3-1) (Dubay 1976, Dubay & Simmons 1981, Cawley *et al*. 1999), as well as pico- nano- and microplankton (Beaty & Parker 1996a). Previous workers have reported relatively low numbers of diatoms from the lake plankton, representing relatively low diversity. The benthic, periphytic, or Aufwuchs diatoms have not been examined previously.

Beaty & Parker (1994) presented evidence suggesting that Mountain Lake had entered early stages of eutrophication by the late 1980s. N:P ratios during this time were trending downward from 34:1 to 2.9:1. Beaty & Parker (1996b) also demonstrated that additions of phosphate, ammonium, and sometimes nitrate salts stimulated phytoplankton photosynthesis. More recently, Cawley *et al*. (1999) showed that the lake has returned to more oligotrophic conditions in the 1990s, largely due to phosphate limitation, with N:P ratios of 143:1 in 1997 (mean NH_4-N = 14.0 µg/l, NO_3-N = 200.0 µg/l, PO_4- P= 1.5 µg/l), and 244:1 in 1998 (mean NH_4-N = 16.0 µg/l, NO_3-N = 500.0 µg/l, PO_4- P= 2.2 µg/l).

Additional water quality data from 1997-98 includes lake pH of 6.0 to 6.8, relatively low calcium and magnesium hardness values averaging 20.84 mg/L, and low average lake alkalinity of 6.41 mg/L (Cawley *et al*. 1999).

Silica may also limit diatoms in Mountain Lake (Paasche 1975, Beaty & Parker 1994), with a lake average for silica in 1997-98 of 0.385 mg/L (Cawley *et al*. in review a). Planktonic diatoms within the lake may be more silica limited than epiphytic ones, due to increased water flow around the more stationary forms (see also Schelske 1975).

METHODS AND MATERIALS

Field Description, Sampling, and Storage Protocol

Sediment grab samples (Fig. 3-1) were taken from 16 sites in the lake along four east-west transects (4 sample locations in each transect). The samples were taken using a standard Eckman dredge (model # 196 BIO, Wildco, Wildlife Supply Company, Ohio). For a complete description of the Eckman sampler and its operation, see Mudroch & Azcue (1995).

Once each sample was collected, field descriptions, including Muncel color determinations, were made while the sample remained in the dredge. A 25 mm diam. glass tube was inserted vertically into the sample, and the resulting “mini-core” was examined for textural or color differences from top to bottom.

The top 5 cm of undisturbed sediment was sampled from the top of each Eckman grab, and stored as a time-averaged sample in clean, labeled (transect / sample #, depth, and location) 1 liter plastic sampling bags. Samples were transported on ice to Virginia Tech and refrigerated. Three subsamples were taken for each location: one for wet/dry analysis and dry sieve analysis, one for diatom analysis, and a third for pollen analysis.

Physical Evaluation of Grab Samples

Physical evaluation of 150 g (wet) samples included particle size distribution by dry sieving (modified ASTM procedure # D 421), as well as by soil hydrometer (modified ASTM procedure #D 422). Wet versus oven-dried weights were determined, and petrographic analysis of coarse fractions (>Parsing # 10 standard sieve) were included.

Diatom Extraction Procedure

Subsamples for diatom extraction consisted of approximately 10 g of lake sediment. The methodologies for diatom extraction are derived largely from Barss & Williams (1973), Brasier (1980), and Baron (1987). Further notes on diatom recovery may be found in Pakorny (1963).

Diatoms were treated initially with 3% hydrogen peroxide (H_2O_2) for 24 hr, then decanted and rinsed. After further rinsing and decanting, samples were subjected to hypochlorite (5.25% Na ClO) bleach for 24 hr, decanted and rinsed. Remaining large sand particles were removed by settling.

Multiple strews of each sample were mounted in Histoclad refractive mounting media (1.4 - 1.7 refractive index). Residues were preserved in distilled water and ethyl alcohol within labeled glass vials, as suggested by Pakorny (1963).

Diatom counts were carried out via optical and video microscope. Statistical counts of relative abundance were made; initially, counts of 300 were made. Once the similarity of results for samples was established, then counts of 100 were made with random recounts for comparison.

Sporomorph Extraction Procedure

Maceration methodology for palynomorphs was modified from Iverson (1975), Traverse (1988), and McLean (personal communication). Maceration included: 1. removal of carbonates by concentrated hydrochloric acid, 2. removal of silicates by concentrated hydrofluoric acid, 3. oxidation by sodium hypochlorite bleach, and 4. acetolation with acetic anhydride.

Statistical relative counts were made using the video microscope. Once again, counts of 300 were made until consistency of sample contents was verified, after which subsequent counts of 100 were made, with blind recounts.

Analysis of Data Sets

Numerical data from these analyses were entered into Microsoft Excel (Office 98) spreadsheets for data manipulation. Count percentages were calculated, as were various metrics, including planktonic versus littoral ratios for diatoms and arboreal versus herbaceous forms for pollen. Cluster analyses were carried out using hierarchical clustering (SAS). The metric of planktonic to littoral diatoms was selected as representing water-depth change, which could be useful in later core analysis for past lake water levels (Wolin & Duthie, 1999). Results of the cluster analyses were graphically plotted on a base map of (GPS) lake location and sonar bathymetry (Cawley *et al*. in review b) using Adobe PhotoShop version 6.

RESULTS AND DISCUSSION

Sedimentology

Mountain Lake sediment was primarily unconsolidated, and composed of sand-sized organic particles, quartz sand and clay balls (Table 3- 2), The larger sand fraction mostly consisted of white and reddish quartz sand and larger wood and leaf fragments. The fine sand and silt size fraction was comprised of decayed plant material, pollen, occasional chitin fragments, clay balls, diatoms and fine silicates. Clays in the sediment were largely contained in larger size-fraction clay lumps and balls (fecal pellets?) and were, therefore, under-represented in the sieve analysis by weight. The clay fraction included very fine organic material and siliceous diatom sediment ranging to less than 22 µm.

The average weight loss by drying of the samples was 78%, with sediment containing a large percentage of water overall. Samples taken near the southern (shallow) end of the lake contained slightly more large sized (>2 mm) sand, both natural and introduced “beach” sand associated with the Mountain Lake Hotel. Deeper, undisturbed samples from the northern regions of the lake contained primarily smaller sized material. Nearly all deeper samples exhibited a well-defined red-orange, relatively inorganic, silty layer at approximately 5 to 7 cm depth containing relatively few diatoms and pollen. This layer had thicker consistency than sediments above and below. We suggest that this inorganic-rich layer may represent increased erosion into the lake at the time the Mountain Lake Hotel and the road skirting two sides of the lake were constructed in the early 1930s. We did not include material from this layer in our analyses of “modern” sediments.

Diatom Analysis

Past studies of diatoms in Mountain Lake (Parson & Parker 1989a, 1989b) have included almost exclusively identifications of diatom genera in living plankton. Diatoms in the lake plankton, both in plankton tows and from settling chambers, were inevitably sparse. During this study we compared plankton tow and settling chamber results with those collected earlier, obtaining very similar results. We suggest that diatoms in the water column may be slow-growing, slow developing, and nutrient- and silica-limited. Although cell division rates and standing crop appear to be consistently low in Mountain Lake, diatoms still represent significant biomass in the lake through time.

In this study we also placed glass slide diatometers at different depths in the lake, to compare diatometer communities with those from sediment. In all cases, the diatometer glass slides were virtually devoid of diatoms after 1 and 2-wk intervals. The very few diatoms encountered on the diatometer slides were small *Navicula* spp. associated only with diatometers placed at the surface (0.1 m).

Our diatom data suggest that relatively few diatoms occur in the water column of Mountain Lake at any given time, the diatoms in the water column consist largely of planktonic forms which are not likely to colonize glass slides, and epiphytic and littoral diatoms (which more likely might colonize glass slide diatometers) remain primarily physically associated with the lake bottom. Additionally, glass slides have smooth surfaces, lacking crevices, and thus may not provide an optimum substrate for diatom colonization in lake waters (see Bergey 1999).

Diatoms from the sediment surface/water interface (time-averaged sample representing the past 50 years) provided a far more complete list of diatom species. Diatoms from Mountain Lake identified during the course of this study are shown in Table 3-4. At least 66 individual species and varieties, representing 25 genera have been presently identified. In this paper, we have presented individual diatom taxa according to their traditionally-accepted names and citations (Hufford 1987; Trumbull & Hufford 1989) for consistency with pre-existing taxa lists for Mountain Lake and other waters; we have however tried to indicate revised generic names of groups where appropriate (after Fourtanier & Kociolek 1999). Such revisions are presented in parentheses within Table 3-3.

We report here that 12 of the identified diatom taxa extant in Mountain Lake are recognized to be new records for Virginia inland waters (Hufford 1987; Trumbull & Hufford 1989). These taxa include *Cymbella delicatula* Kutz. var. *delicatula, Eunotia pectinalis* var. *undulata* (Ralfs) Rabh., *Fragilaria bicapitata* A. Mayer var. *bicapitata, Fragilaria brevistriata* var. *inflata* (Pant.) Hust., *Gomphonema acuminatum* var. *elongatum* (W. Sm.) Carr., *Gomphonema affine* Kutz. var. *affine, Gomphonema intricatum* Kutz. var. *intricatum, Gomphonema truncatulum* var. *turgidum* (Her.) Patr., *Navicula scutelloides* W. Sm. ex Greg. var. *scutelloides, Nitzschia sinuata* (W.Sm.) Grun. var. *tabellaria* Grun., *Pinnularia abaujensis* var. *rostrata* (Patr.) Patr. and *Stephanodiscus alpinus.* Hust.

Several additional points regarding the present list deserve comment. First, earlier identification lists have described *Cyclotella meneghiniana* as the dominant centric diatom present in the lake (Parson & Parker 1989a). We have not identified *C. meneghiniana* in any of our samples. We now conclude that the primary *Cyclotella* species present are *C. bodanica* and *C. stellegera.*

Second, the centric *Stephanodiscus alpinus* is relatively common to the lake as well. *Stephanodiscus alpinus* in Mountain Lake is, as noted above, a new record for the inland waters of Virginia.

Third, the Intraspecific Resource Curves produced by Tilman *et al*. (1982) for nutrient resources of silica and phosphorus predict that *Stephanodiscus* and not *Asterionella* should be abundant in this lake based on the silicon and phosphorus levels in 1997 and 1998.

In fact, we suggest that diatoms identified as *Asterionella formosa* by previous workers in Mountain Lake are, in fact *Synedra ulna* and *Synedra ulna* var. *longissima* which frequently associate in *Asterionella*-like colonies.

It was noted that *Tabellaria fenestrata* (Lyngb.) Kutz. var. *fenestrata* within Mountain Lake exhibited a range of discernible forms, from a heavy ribbed form through the nominate morphology. In a similar way, a small distinctive notched teratological form of *Cymbella affinis* Kutz. var. *affinis* was present in the shallow south end of the lake. The regular form of *affinis* was also present.

Mountain Lake diatom count data is presented in Table 3-4. When this data was subjected to hierarchical cluster analysis, seven individual cluster groups or thanatocommunities stood out, two of which were subgroupings of a larger group.

These groupings are shown projected geographically onto the lake map in Fig. 3-2. The cluster groups show primary divisions apparent between shallow, intermediate, and deep-water diatom groups.

Beginning at the shallow south end of the lake, it was clear that most of the samples were relatively similar, dominated by pennate forms. In this portion of the lake the water is less than 12 m deep, shallow enough for the bottom to remain well within the photic zone.

The shallow group (samples 1,2,3,4 and 8) was delineated by larger numbers of epiphytic and littoral diatoms. This thanatocommunity group overall included count numbers of *Gomphonema*, *Pinnularia*, *Eunotia*, and *Cymbella* species. The shallow group was further subdivided into two smaller groups.

The first group (samples 1 and 2) corresponded to shallow (< 9 m) relatively sandy bottom conditions with little bottom vegetation present. The diatom thanatocommunity in this region appeared delineated by the presence of *Stephanodiscus alpinus*, *Tabellaria fenestrata*, *Cocconeis placentula*, *Caloneis ventricosa*, *Eunotia pectinalis pectinalis* , and *E. pectinalis* *undulata*, *Synedra ulna*, as well as *Pinnularia* , *Navicula, Gomphonema*, and *Nitzschia* species. The average ratio of planktonic to littoral diatom types for these two samples was 0.56:1.

The second group (samples 3 and 4) was delineated largely by epiphytic diatoms closely associated with beds of *Nitella* and *Elodea* within the shallow (< 9 m) portion of Mountain Lake. *Nitella megacarpa* has historically been the primary macrophyte within the lake (Jervis *et al*. 1988; Dubay & Simmons 1981). *Nitella* is associated with noncarbonate, low phosphate oligotrophic waters. These vegetation beds appear to be associated with higher nutrient waters from input stream I-1 and I-2 via a small man-made wetland near the Mountain Lake Hotel. The diatoms present in this grouping may also result from somewhat higher nitrogen and phosphorus levels, by plant-associated nutrients, or by slightly increased access to dissolved silicon from moving water.

This group included larger numbers of *T.fenestrata*, and smaller numbers of *S. alpinus*, as well as (epiphytic) *Cymbella* species, including *C. lunata,C. cuspidata, C. naviculaformis* and *C. affinis*. Also included were numbers of (epiphytic) *Gomphonema*, including *G. acuminatum (coronata)*. Compared to the initial shallow-water group there were different *Navicula* species represented. And there were significant numbers of *Melosira italica* not present in the less vegetated region. The average ratio of planktonic to littoral diatom types for these two samples was 0.47:1.

Since the mid-1980s, *Nitella* beds within Mountain Lake had been declining, replaced in part by *Ceratophyllum demersum*, a vascular freshwater weed species associated with more eutrophic conditions (Beaty & Parker 1994). At the time of our sampling, *Ceratophyllum* had become well-established in the region of the lake near our sampling point “7”. Our sediment sample “7” consisted almost entirely of living and decayed *Ceratophyllum* material. The sample was associated with a low diversity, near monoculture of *Cocconeis placentula*, an epiphyte on *Ceratophyllum.* In 1997 and 1998, *Ceratophyllum* appears to have decreased in the lake, as the waters became increasingly oligotrophic (Cawley *et al*. 1999).

Samples 5, 6, 7, and 8, although not grouped by the cluster analysis, all occurred at mid-depths between 6 and 13 m. An average of planktonic to littoral diatoms for these samples was 5.6:1, in general, an order of magnitude higher than the average ratios of the shallower samples.

The two intermediate deep groups (6, 9, 10, and 12) and (14 and 15) appeared relatively similar to each other, both representing relatively steeper rock (geologically lying on sandstone rather than shale) and fine organic sand to silt-covered bottom conditions between 10 and 21 m. These groups were primarily represented by *C. stellegeria, Nitzschia sinuata, S. alpinus,* and *T. fenestrata.* In addition, a number of various *Fragillaria* species were present, and an occasional shallower water form. The average ratio of planktonic to littoral forms in this region was 15:1, again, approximately a tenfold increase over the mid-depth sample ratios.

The deepest-water diatom association represented the silt-covered bottom plateau region of the lake primarily deeper than 21 m, below the active photic zone for the lake. Sediment forming diatoms here were also almost exclusively planktonic forms from the surface. In Mountain Lake, fairly consistent numbers of *C. stellegeria, N. sinuata, S. alpinus* and *T. fenestrata* represented this thanatocommunity. The primary apparent difference between this group and the intermediate ones was an apparent dearth of *Fragillaria.* The ratio of planktonic to littoral forms in this region was also about 15:1.

Pollen Analysis

The region surrounding Mountain Lake is largely wooded and comprises lands of the Mountain Lake Wilderness Conservancy, established in 1992. The lake is presently surrounded on three sides by a fringe of virgin eastern hemlock (*Tsuga canadensis* (L.) Carr) undergrown by *Rhododendron maximum* L. and *Rhododendron canadense* (L.) BSP. thickets. Higher on the hillsides above the lake are mixed hardwoods, including beech, birch, maple, occasional cherry, oak, and other species associated with higher elevations of the Southern Appalachians (Thorn & Cooperider, 1960). To the southern, shallow end of the lake, land surrounding the Mountain Lake Hotel has long been cleared. This area is planted in grass near the hotel and lake and grows to open herbaceous fields on the southwest end (south to east-facing) slope.

In Mountain Lake, the size and relative isolation of the drainage basin is expected to encourage the abundance of locally-derived pollen. Within Mountain Lake, sediment mixing and pollen input from surface streams was expected to be small, as was bottom mixing due to waves or bottom fauna. The list of identified and counted pollen from Mountain Lake from this study, and their relative percentages in our samples are presented in Table 3-5.

Pollen types found in individual samples appears visually to be quite consistent; pine, birch, oak/maple, grass and flowers, as expected, are the largest pollen components of the samples, and these appear to be homogeneously distributed across the lake. However, cluster analysis of the pollen breaks the samples into six apparent assemblage groups (Fig 3-3). The group consisting of samples 3, 9 and 12 represents pollen washed into the lake via surface input streams.

In general, it is much less useful in this context to further discuss the individual components of the individual pollen groups. It is interesting to note, however, that once again, the shallow portion of the lake appears to be delineated separately from the deeper end of the lake. In the same way, the shallow region of the lake is again separated into two apparent groups, potentially delineating two individual water masses in the shallow region, this time not by nutrient, but primarily by current and particle-settling characteristics of individual grains, as well as locality of flora and pollen (see Traverse 1994).

CONCLUSIONS

1) At least 66 taxa of diatoms, from 25 genera are now known to be extant in Mountain Lake, Virginia. Twelve of the individual taxa identified and reported in this paper are recognized to be new records for Virginia inland waters.

2) Diatoms in the water column of Mountain Lake are sparse, and consist primarily of planktonic forms. Littoral and epiphytic diatoms are not well represented within the water column. Smooth glass-slide diatometers do not successfully record diatoms present in the lake.

3) Cluster analysis of diatom counts from Mountain Lake sediments suggests seven individually delineated regions or thanatocommunities within the lake based on sediment diatom assemblages. The lake assemblages are basically divided between shallow (primarily pennate) and deep-water (primarily centric) assemblages, while the shallow groups may be defined by difference in epiphytic, and possibly nutrient-sensitive forms.

4) Diatom species extant in Mountain Lake reflect in general the oligotrophic, mineral-poor, and circumneutral to very slightly acidic water conditions known to be present. The separation of diatom thanatocommunities within the lake sediments suggests that it is prone to relatively little internal turbulence or mixing of sediments.

5) If a metric using the ratio between planktonic and littoral diatom taxa is applied to Mountain Lake sediment samples, shallow samples from less than 9 m produce a diatom ratio signature of less than 1.0. Ratios for intermediate depth samples, between depths of 6 and 13 m produce a signature value averaging between 1.0 and 10.0. And ratios for deep-water samples, from depths below 12 m produce an average metric signature > 10.0.

6) Pollen analysis of the same sediments matches typical regional flora; cluster analysis of pollen data delineates six individual assemblages. One of these cluster groups represents pollen washed in by input streams. Two further cluster groups delineate differing water masses within the shallow portion of the lake, presumably by sedimentary factors and individual location of pollen sources.

7) The findings outlined here add significantly to the increasing evidence showing Mountain Lake as a unique and singular ecosystem within the Southern Appalachians. These findings provide an important training set and indicators for present depth and environmental conditions across the lake; the same training set may now be used to interpret sediment cores from Mountain Lake, providing insight and understanding on the lake’s past depth changes and environmental history.

ACKNOWLEDGMENTS

Our appreciation goes to the Miles C. Horton Foundation for funding in 1997-98, and to the Wilderness Conservancy at Mountain Lake for financial support in 1998. We thank the staff of the Wilderness Conservancy at Mountain Lake, and the Mountain Lake Hotel for their cooperation in 1997 and 1998. Finally we thank our lab and field assistants, Ross Irwin, Steve Ruzila, Amanda Cordes, Jim Broyhill, Chris Nessel, John Amos and Victor Baranauskas.

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CHAPTER 4:

REPORT OF AN INEXPENSIVE LAKE SEDIMENT CORING DEVICE DEVELOPED TO SAMPLE MOUNTAIN LAKE, GILES COUNTY, VIRGINIA

(Submitted to: Sedimentary Research)

ABSTRACT

Because of the undisturbed nature of the sediments, and the lack of permanent stream inputs, Mountain Lake, Giles County, Virginia affords a good, albeit challenging subject for sediment coring. This short paper reports on a new, inexpensive coring device developed for collecting sediment cores in Mountain Lake. The new device may prove useful for core collection within Scuba diver depth ranges in lakes and reservoirs when typical gravity corers and split spoon corers fail or perform ineffectively. We estimate the overall cost of the coring device itself to be about $50.00, and the assembly time at about 4 hours. A parts list with estimated prices is provided.

INTRODUCTION

In 1997-1998 we undertook a re-evaluation of the water quality (Cawley *et al*. 1999), lake history and origins (Cawley *et al*. in review b), and the extant and historical diatom and pollen taxa (Cawley *et al*., in review c, d) of Mountain Lake in Giles County, Virginia. Sediment coring of Mountain Lake has proved important for interpretation and analysis of the lake's paleo-environment through time. Because of the undisturbed nature of the sediments and the lack of permanent stream inputs, Mountain Lake affords a good, albeit challenging subject for coring. Apart from Marland's (1967) unpublished work on lake copepods, no sediment work had been done previously at Mountain Lake. The single earlier attempt at coring Mountain Lake was only partially successful. In that attempt, gravity coring of the lake bottom had been used with little success, proving to be logistically difficult.

Mountain Lake is located near the summit of Salt Pond Mountain (elevation 1177 m), Giles County, Virginia, in the Ridge and Valley Province of the Southern Appalachians (37° 21' 56" N, 80° 32' 00" W). While relatively small (0.9 km maximum length, 0.25 km width, 189,000 m^2 surface area), Mountain Lake remains the only natural lake in the highlands of the unglaciated Southern Appalachians. Mountain Lake has a maximum depth of approximately 33 m at the north end of the lake; this deep portion consists only of a narrow crack or crevice feature in the bottom of the lake. Most of the deep end of the lake is approximately 24 m deep, shallowing to the south.

G. E. Hutchinson and Grace Pickford (1932) first scientifically described the lake. They suggested that Mountain Lake was the result of landslide damming of the valley (see Hutchinson's lake type 20a, (1957)), and described the lake as a pristine oligotrophic system.

Numerous studies of this lake have been conducted since the 1930s addressing its origin, geology, phytoplankton community, and physical and chemical limnology (e.g. Hutchinson and Pickford 1932; Roth and Neff 1964; Obeng-Asamoa and Parker 1972; Parker *et al*. 1975; Parson and Parker 1989a,b, 1993; Beaty and Parker 1994; Beaty 1995). Deevy, in 1957, produced the first bathymetric map of the lake, using lake soundings (Deevy, unpublished 1957; Beaty and

Parker 1994). This lake bathymetry has been updated using Sonar by the present authors in 1997-1998, and the lake origin has been re-evaluated as being related to a regional fracture feature (Cawley *et al*. in review b).

Because of low terrestrial sediment input to the lake and traditionally low lake productivity (Beaty and Parker 1994), the amount of Mountain Lake bottom sediment is small. Estimates by Marland (1967) had suggested that the lake sediments might be no more than one meter thick in the central region of the lake. From the low accumulation rates of the lake sediments, we estimate sediment build-up in the lake at rates of about 1.0mm per year. Eckman dredge sampling of the sediments had shown that they were composed of quartz sand, sand-sized organic particles, organic silt, and a small amount of clay, primarily in the form of (fecal pellet?) clay balls(Cawley *et al*. in review c). The sediments contained a high water content (average of 78%) and were of a relatively unconsolidated nature, making coherent core sampling difficult. In addition, the lake depth, temperature, and bottom conditions limited the time that divers could operate in the deeper portions of the lake. Gravity coring had already proven relatively ineffective, while split spoon and core-barrel samplers proved to be beyond our budget on this project. For further discussion of coring devices, see Mudroch and Azcue (1994).

In response, we developed our own coring device for use in these sediment and lake conditions. It was successful and inexpensive. The particulars of the device are reported here as being potentially useful in other lakes and sediment coring situations.

DESCRIPTION OF THE CORING DEVICE

This project included recovery of 7 full-depth sediment cores from the lake. Sediment cores were taken from a transect near the north-south center line of the lake. Coring focussed on both the shallow (southern) end lake bottom, as well as coring the deeper plateau-like portions of the lake. In all cases, coring was made to refusal.

The cores were lifted from the lake bed, and capped underwater. Individual cores were labeled as to top and bottom. They were transported to Virginia Tech, and stored in (-10° C) chest freezers in the Biology Department.

The process of coring Mountain Lake included Scuba assistance and reconnaissance of the lake bottom. This included visual descriptions of bottom landmarks and textures, as well as operation of the coring device at depth. A physical description of the coring device follows.

Stem and Foot Valve

The upper portion of the coring device, shown as Figure 4-1 and captioned separately, consists of a central 1.5 cm (0.5 in) metal pipe (A) of approximately 1.5 meter length. The lower end of this stem was threaded on a lathe with approximately (22cm) of straight parallel threads. This threaded portion extends through the drive head and anvil mid-portion of the corer. Below this it is affixed (via threading with a 0.5” to 0.75” adaptor) to a foot-valve (B) internal to the device. As the corer is driven into the sediment, the foot valve allows water to escape from the core barrel into the interior of the pipe stem. When the corer is withdrawn, however, the foot-valve closes. This provides a firm vacuum grip on the sediments within the barrel. In our operation we had no difficulties with sediment fouling the foot valve. However, should foot valve fouling pose a problem in some situations, a piece of cheesecloth placed within the top of the barrel should prevent such fouling.

The central pipe extends upward from the anvil and terminates in a “T” fitting (C). This fitting serves as the primary cable attachment point for the coring device as well as an escape route for water from within the coring barrel. The center of gravity of the corer lies well below this point, resulting in vertical orientation of the corer.

Anvil

At the bottom of the corer stem, a drive head and anvil (D) is positioned. The body of this anvil (E) consists of a 5 cm (2 in) PVC coupling joint. The piece as purchased consists of a PVC body threaded on each end. Two threaded end caps (F) are intended to fit tightly over 5 cm (2 in) -diam PVC pipe lengths, and a rubber O-ring inside (G) produces a tight seal between the pipe sections. In this application, the upper portion of the coupling is affixed to the metal pipe stem instead—This is done by modifying two PVC plate bushings (H), which are then threaded onto the iron pipe. The PVC adaptor plates actually have a tapered female pipe thread; we extended the pipe through the taper by applying PVC solvent to the internal threads, and then forcing it to thread. The upper plate is threaded all the way onto the corer stem. The lower plate is made slightly smaller around its diameter using an electric grinder, and is then positioned approximately halfway inside the PVC coupling, and affixed with PVC cement.

The threaded portion of the metal stem is then screwed into the interior plate. The threaded end must extend about 2.5 cm beyond the plate, giving room to thread on the foot valve. The upper portion of the anvil coupling is then carefully filled with concrete (I) , and the upper plate forced tight down upon it. Once this is in place, then the upper end-cap (F) is threaded tightly down over the plate. In our prototype, the body was drilled at this stage, and 2.5 cm metal screws threaded through it into the wet concrete for additional structural integrity, and to hold the end cap in place. A metal striking plate (J) was affixed to the top of the ring by screws to prevent the PVC from the possibility of cracking in use.

Barrel

The coring device Barrel (Figure 4-1) consists of a 1 to 3 meter length of standard 5 cm (2 in) diameter PVC casing pipe (K). This PVC casing serves as the sediment sampling sleeve, providing support for the relatively unconsolidated sediment during collection and transfer.

The lower tip of the coring barrel has been edge-sharpened on a grinding wheel. The sharpened PVC seems to cut well through both sandy and silty sediments. Only once did we have the sharpened edge of the barrel chip or crack, in a case where a buried sandstone cobble lodged tightly in the end of the core barrel.

The coring barrel is affixed to the coring device anvil by means of the black rubber O-ring and threaded collar (Figure 4-1 and caption). This ring and collar mechanism holds the barrel tightly in place, and also provides a tight seal around the top of the core. In our use of this corer, we had no problems with the barrel becoming disconnected from the unit when the core was being removed from the lake bottom.

Drive Weights

A series of drive weights (L) are placed over the central portion of the pipe, and above the anvil. These doughnut-shaped (athletic) weights may be raised and dropped in combination by the supporting diver. Approximately 20 to 40 pounds of drive weights (depending on the specific nature of the sediments at the location) provide mass and inertia to the coring device, as well as add vertical orientation.

OPERATION AND DISCUSSION

We estimate that the assembly time for this coring device is about 4 hours, once the basic parts are on hand, although the concrete fill in the anvil portion should dry and cure at least overnight before use. A parts list, with estimated prices, for this coring device is shown in the caption of Figure 4-1. We estimate an overall cost of the coring device itself to be about $50.00, depending on the number of athletic weights used.

Once a clean core barrel is connected to the corer, then the device is lowered via metal cable from the surface. In use, the coring device rights itself vertically in the water. Air within the core barrel escapes through the internal foot valve. In our prototype, the air escaped with a long low musical tone. When dropped to the bottom, the core barrel tends to enter the sediment cleanly to a depth of several centimeters. For our coring, we enlisted the help of a team of two Scuba divers, one who operated the coring device, and one who assisted. The diver operator makes sure that the device is vertical, and then lifts and drops the drive weights, hammering the core barrel cleanly into the sediment.

As the coring device sinks into the sediment, it is most efficient for the diver to operate it from a kneeling position, with one knee on either side of the barrel. When the core barrel is at refusal, the sound of the hammer strokes changes significantly. The change can be heard from the boat above as well as by the divers. At this point, the diver pulls the cable as a signal to the boat. The boat crew begins pulling up the cable, while the divers rock the core device gently. This combination lifts the coring device effectively. When the lower end of the barrel comes free of the sediment, the assistant diver places a PVC cap over the lower end to seal in the sample. The core is then brought to the surface, separated from the coring device, capped, and labeled.

Coring of the lake took place in the summer and fall field season 0f 1998, with good success. Coring began experimentally in shallow conditions in sandy sediments, and progressed to deeper, finer sediments. The deepest cores from the lake were taken from depths of between 18 to 24 m. Sediment depth was approximately 1 m, although within the individual cores the organic sediments showed compression of about 20%. Details of the core sedimentology and palynology will be published elsewhere.

CONCLUSIONS

This type of inexpensive coring device may prove useful for collecting lake sediment cores within Scuba diver depth ranges when typical gravity corers and split spoon corers fail or perform ineffectively.

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CHAPTER 5:

INTERPRETATION OF LAKE HISTORY BASED ON DIATOMS AND POLLEN FROM SEDIMENT CORES, MOUNTAIN LAKE, VIRGINIA

(Submitted to: Quaternary Research)

ABSTRACT

Mountain Lake, Virginia is a small, unique, oligotrophic subalpine ecosystem in the Southern Appalachians. Its structurally-based and climatological origins and history have had significant impact on its depth, and therefore its sedimentology and algal flora through time. ^{14}C dates establish specific Mountain Lake sediment ages at 1860, 4220, and 6160 years B.P.. Sediment core analysis suggests at least 6 extended periods in these intervals when Mountain Lake has been dry or very small in size. These individual periods (at approximately 100, 400, 900, 1200, 1800 and 4200 years B.P.) are evidenced by changes in diatom and pollen content, sedimentary erosion features, and the presence of wood fragments, plant fiber, and *Sphagnum* spores. The ratio of planktonic to littoral diatoms is used as a metric to estimate past water depths from sediment. Past low water intervals may correspond to dry periods co-incident with solar minima. The lake shows progressive (albeit slow) eutrophication through time, as well as anthropogenic impacts (including increased sedimentation, eutrophication and diatom diversity) during the 20th Century. These findings provide the first published diatom, pollen and sedimentology-based paleolimnology of the lake.

INTRODUCTION

Mountain Lake is located near the summit of Salt Pond Mountain (elevation 1170 m / 3860 feet), Giles County, Virginia, in the Ridge and Valley Province of the Southern Appalachians (37° 21' 56" N, 80° 32' 00" W). Although small, Mountain Lake is the only natural lake in the unglaciated highlands of the Southern Appalachians. Mountain Lake has a maximum depth of 33 m at the north end of the lake; this deep portion consists only of a narrow crack or crevice feature in the bottom of the lake. Most of the deep end of the lake is approximately 24 m deep, shallowing to the south.

Since the 1930s, numerous workers have considered the origin, geology, phytoplankton community, and physical limnology of Mountain Lake. (e.g., Hutchinson and Pickford 1932, Roth and Neff 1964, Marland 1967, Obeng-Asamoa and Parker 1972, Parker *et al*. 1975, Dubay & Simmons 1981, Parson and Parker 1989a,b, Beaty and Parker 1994). Deevey, in 1957, produced the first bathymetric map of the lake, using lake soundings and (War Department) aerial photographs (Deevey *et al*. unpublished 1957, Beaty and Parker 1994). This lake bathymetry has been updated using Sonar by the authors in 1997-1998, and the lake origin is now recognized as related to a regional fracture feature (Cawley *et al*. in review b). Historical records suggest that the size of the lake has varied periodically through time.

In 1997-1998 the authors undertook a re-evaluation of the water quality (Cawley *et al*. 1999), lake history and origins (Cawley *et al*. in review b), and the extant and historical diatom and pollen taxa (Cawley *et al*., in review c, d) of Mountain Lake. Sediment coring of Mountain Lake has proved important for interpretation and analysis of the lake’s paleoenvironments. Because of the undisturbed nature of the sediments, the lack of permanent stream inputs, and the very low sedimentation rates (presently estimated at about 0.5 to 1mm/yr), Mountain Lake affords a good, albeit challenging subject for coring.

Analysis of diatoms and other organisms, sediments and pollen from lake-bottom cores has been an increasingly important tool to paleoenvironmental interpretation ever since Deevey’s “pre-Mountain Lake” work at Linsley Pond, Connecticut (1942). In more recent years, knowledge of the environmental preferences of diatoms (i.e., Cairns 1964, Patrick and Reimer 1966, 1975, Lowe 1974. Batterbee *et al*. 1999, Wolin and Duthie, 1999) and of pollen and sedimentary features (i.e., Traverse 1988, 1994, Cameron 1995) has continued to increase, allowing for better interpretation of paleoenvironments from lake sediments. Workers such as Bradbury (1975), Hakansan *et al*. (1993, 1998), and Cooper (1995) have applied diatom analysis to historic land use and anthropogenic impacts in Minnesota, around the Chesapeake Bay, in European lakes, and other areas. Blinn and Helvey (1994) applied diatom community analysis to stratigraphy at Montezuma's Well in Arizona.

This study examines the diatom, pollen and sedimentary content of ^{14}C dated cores from the deepest portion of Mountain Lake. Water depth and changes in the lake through the past 6100 years are documented, as evidenced by changes in diatom and pollen content, sedimentary erosion features, and the presence of wood fragments, plant fiber, and *Sphagnum* spores. Diatom thanatocommunity contents are identified for selected time periods. These findings provide the first published diatom, pollen and sedimentology-based paleolimnology of the lake.

METHODOLOGY

Apart from Marland's (1967) unpublished work on copepods, no sediment work had been done previously at Mountain Lake. Marland's attempt at coring Mountain Lake in 1965-66 was only partially successful. In that attempt, gravity coring was used, proving to be logistically difficult. In response, we developed our own (diver-assisted) coring device for use in Mountain Lake (Cawley & Parker in review d).

Our recovery included 7 complete cores from the lake. Sediment cores were taken from a transect near the north-south center-line of the lake (Figure 5-1). Of these, results from the three best deep cores (D, F, and G) are presented here. Frozen cores from the lake were described and correlated; the correlation strategies of Anderson (1986, 1990a, 1990b) were used, where applicable.

Subsamples for diatom and palynomorph extraction consisted of 10 g of lake sediment, selected at intervals of 3-5 cm. The spacing of the subsamples depended on the physical features of the material.

Diatoms were oxidized from each sample with hydrogen peroxide (3% H_2O_2) followed by hypochlorite bleach (5.25% NaClO). The methodologies used are derived from Barss and Williams (1973), Brasier (1980), and Baron (1987). Multiple strews of each sample were mounted in Histoclad refractive mounting media (1.4 - 1.7 refractive index). Residues were preserved in distilled water and ethyl alcohol within glass vials, as suggested by Pakorny (1963). Diatoms were counted via video microscope. Statistical counts of relative abundance were made; initially, counts of 300 were made (where possible). Once the similarity of results for samples was established, then counts of 100 were made (where possible) with random recounts for comparison.

Maceration methodology for palynomorphs was modified from Iverson (1975), and Traverse (1988), including 1) removal of carbonates by concentrated hydrochloric acid, 2) removal of silicates by concentrated hydrofluoric acid, 3) oxidation by sodium hypochlorite bleach, and 4) acetolation with acetic anhydride. Statistical relative counts of pollen were made via video microscope. Again, counts of 300 were made (where possible) until consistency of sample contents was verified, after which subsequent counts of 100 were made (where possible), with blind recounts.

Two samples for ^{14}C were taken from organic-rich layers in core (G) at 27 and 45 cm. One ^{14}C sample was taken from an organic-rich layer near the bottom of core D, at 53 cm. Samples were submitted to Beta Analytical of Miami FL. One sample (D 53 cm) contained sufficient carbon to be processed by standard radiometric analysis with extended counts. The other two (G 27 and G45 cm)were analyzed by accelerator mass spectrometry (AMS).

RESULTS

Older diatoms and pollen within shallower lake cores (A, B, and C) were found to be in poor condition. This was not unexpected because these materials have been exposed to repeated subareal exposure during low lake levels.

In contrast, preservation of both diatoms and pollen from the deeper cores was generally good. Broken and abraded materials in the deep cores coincided with past periods of low water levels, and proved to be diagnostic. As suggested by Wolin and Duthie (1999), a ratio metric of planktonic to littoral diatoms developed from modern Mountain Lake sediments (Cawley *et al.* in review c) was used to estimate past lake water levels. Resolution of sediment structures was excellent in cores D, F, and G. (Core E, which was taken from a sloping portion of the lake bottom, showed evidences of turbidity flow.)

Core F correlates directly to core D (Fig 5-2 and 5-3). Core D was collected from a shallower region of the lake bottom than core F, and shows consistently shallower sedimentary and diatom thanatocommunity structure. ^{14}C dates establish sediment at 53 cm in core D at 1860 ± 100 B.P. (D 53). The top 15 cm of core G also correlates with D and F. Below 15 cm, however, time and sediment is missing. This is likely due to its location near the lake bottom outflow in the deepest portion of the lake (see Cawley *et al*. in review b). Older material however, is preserved in core G below this sediment unconformity. ^{14}C dating at 27 cm in core G results in an age of 4220 ± 50 B.P.(G 27), while the core bottom dates at 6160 ±70 years B.P.(G 45).

Diatoms, pollen, and erosional features in these cores (Tables 5-1 and 5-2) suggest at least 6 prolonged periods when Mountain Lake has been dry or small in size. These periods occurred at approximately 100, 400, 900, 1200, 1800 and 4200 years B.P.. The lake shows progressive (albeit slow) eutrophication through time, as well as anthropogenic impacts during the 20th Century.

DISCUSSION

0 to 1800 yrs B.P.:

We have documented the present state of the lake and diatom thanatocommunities elsewhere (Cawley *et al*. 1999). We have identified 66 taxa of diatoms presently in the lake representing 25 genera (see also Trumbull and Hufford, 1989). These flora reflect the circumneutral pH and relatively low (oligotrophic to meso-oligotrophic) nutrient conditions of modern Mountain Lake. In the deep portions of the present lake, the planktonic to littoral ratio of diatoms is greater than 10.0 (specifically 12.0 and 15.0 in regions near our core samples.) The present deep-water flora of the lake is dominated by *Stephanodiscus alpinus*, *Cyclotella stellegera*, *Tabellaria fenestrata*, *Nitzschia sinuata* and *Fragilaria* species, together with species of *Eunotia*, *Anomoeneis*, *Navicula*, *Amphora*, *Cymbella*, and *Pinnularia.*

The complete cores (as well as Eckman samples) exhibited a well-defined red-orange inorganic silty layer at 5 to 7 cm depth. This layer had thicker consistency than sediments above and below. We suggest that this inorganic-rich layer represents erosion into the lake at the time the Mountain Lake Hotel and the road skirting the lake were constructed in the early 1930s. At estimates of 1 mm/year of sedimentation, an age of approximately 50-70 years B.P. appears reasonable. This estimate is also supported by the qualitative observation that somewhat more *Castanea* (American chestnut) pollen occurs below this layer than above it. The American chestnut blight swept through the southern Appalachians in the 1930s, bringing with it a functional demise of the chestnut forests.

Diatoms at this 5 cm level closely resemble the modern flora, although the density and diversity of diatoms appears generally less. The planktonic to littoral ratio (see Table 5-2) is less than at present; at no time in the past did we see a ratio as high as the ratio of 10 to 15. Tappan (1980) suggested that, if water depth is held constant, an increase in the ratio of centric to pennate diatoms indicates increased eutrophication. We suggest, in light of meso-eutrophic symptomology in the lake (Beaty & Parker 1994), that Mountain Lake has eutrophically "aged" significantly in the 20th Century, primarily due to human activity. We also note that *Stephanodiscus alpinus* is a recent addition to the lake flora likely associated with eutrophication.

At 10 cm (~100 yrs B.P.) in core F, we find a decrease in diatom density and diversity (at 10 species, down from 23 species in samples below). In addition, *Sphagnum* spores are present at 10 cm in core G (these are comparable with extant *Sphagnum* spores from Spruce Bog, a relict peat bog in Giles County, Virginia). We suggest that the change in diatom community, as well as the presence of *Sphagnum* indicates a relatively short period when the lake was very low or dry. This time-period in the late 1800s corresponds to historical reports that the lake ("Salt Pond") was a small pond used for salting cattle, which then filled after a local earthquake toward the end of the 1890s (Hilda Roberts, pers. comm.). This event underscores the apparent structural role of the regional fault / fracture feature in the lake's periodic loss and reformation through time (Cawley *et al.* in press b). In fact, Parker *et al*. (1975) documented historic evidence of at least 4 brief periods of very low lake levels in the past 400 years.

At 17 cm (approximately 400 years before present), we find wood particles and shale fragments associated with a period of lake-bottom erosion. The 20 cm portion contains virtually no diatoms of any sort. These data suggest an extended period of low water and subareal exposure, during which the area around the lake/pond was at least partially wooded. This interpretation is supported by historical record, as well as a well-preserved portion of yellow pine (*Pinus pungens* Lamb) recovered from growth position at a depth of 10 meters in the lake (Parker *et al*. 1975). ^{14}C dating of this wood produced an age of 1655±80 AD. Tree ring analysis revealed that the tree had grown for 30 years along the shore of a much smaller Mountain Lake. We now suggest that this extended low water period at Mountain Lake may correspond to a dry period co-incident with the Maunder Solar Minimum (Eddy 1977; Parker *et al*. 1982).

A more noticeable layer of shale fragments and wood particles occurs (primarily in core D) at 31 cm, or about 900 years B.P.. Here, diatoms are diverse (with 40 species present), suggesting relatively high lake productivity during this time. The planktonic to littoral ratio for core D is 1.2, suggesting shallow conditions. We also find *Sphagnum* spores at this level, suggesting that the lake was again fairly low or empty at this time, and was associated with a peat bog. We note that this time, about 1100 AD, corresponds with yet another solar minimum, the Wolf Minimum (Eddy 1977; Parker *et al*. 1982), when history suggests that agriculture failed in both Europe and the American southwest due to cold and dry conditions. We also note that at approximately 28 cm in core D there is a sizeable fragment (+1 cm) of wood material that appears to be charcoal, suggesting possible fires during this time period.

Sphagnum continues to be present in the cores downward from 900 years before present to 42 cm, or approximately 1200 B.P. This suggests well-developed peat in the lake basin during this interval. At 1200 B.P., we again see an erosion surface present in the core with shale chips, suggesting exposure. The planktonic to littoral diatom ratio, at 0.7 in core D, supports this interpretation.

The layer at 53 cm in core D consists of a mat of plant fiber, which corresponds to abundant *Sphagnum* spores in the samples. This layer produced a ^{14}C age of 1860± 100 years B.P.(sample D 53). Diatoms here include a reduced fauna (see Table 5-3), and we find approximately 20% of the *Tabellaria* and *Pinnularia* present to be aberrant morphologic forms. We suggest that these aberrant forms may be associated with bog formation; prolonged low lake levels should accompany higher allochthonous to autochthonous organic matter input, raising humic, fulvic acid, and tannin levels as well as lowering pH (Kirschner *et al*. 1999). Wolin and Duthie (1999) refer to numerous examples where lower lake levels correspond with increased humification and lower diatom-inferred pH conditions.

Both cores D and F end at refusal at this point, apparently at an erosional surface; the lowest portion of core F consists of greenish shale chips and a sandy layer. The ratio of planktonic to littoral diatoms, however was between 3.4 and 6.6, suggesting that a period of deeper water had likely preceded the low water interval and bog formation.

1800 to 6100 yrs B.P. (core G):

A sediment unconformity occurs in core G at approximately 15 cm depth. The underlying 35 cm of core G predates both core D and F. Less organic material is apparent in this older interval. There is only one prolonged low water event specifically discernible within this section. It seems likely, however that the periodic short term filling and emptying of Mountain Lake was occurring throughout the interval.

At 27 cm in G, a plant fiber layer provided a ^{14}C age of 4220± 50 yrs B.P. Diatom flora at this level is reduced; five species are present, being fragmentary remains of a few large individuals that may be *Cymatopleura* or *Surirella*. These forms may be mud- or soil-dwellers, and may represent a mud-surface thanatocommunity. *Sphagnum* spores are present although wood particles are lacking, suggesting a less-wooded situation around the lake. At 25 cm, trilete (fern and/or moss) spores are abundant, suggesting an open fern meadow. Pollen counts contain abundant grass pollen, as well as occasional hemlock.

This low lake interval corresponds well with the "First Dark Age in Egyptian History", (see Bell, 1971, 1975.) approximately 4180 to 4135 years B.P. (2180 to 2135 B.C.), when severe drought lasting several decades appears to have occurred across the entire Eastern Mediterranean and adjacent lands. Bell suggests that this early Egyptian "Dark Age" was precipitated by climatic conditions, which, again, may have been associated with a solar minimum event.

At 37 cm in core G, approximately 10 diatom species occur. The planktonic to littoral ratio is 1.8, suggesting shallow waters, and some diatoms are abraded. The thanatocommunity at this level is sparse, with low population density, including *Fragilaria* species, a few *C. kutzingiana*, and occasional *Pinnularia*.

Core G below 37 cm consists primarily of finely-banded silty clays. We suggest that individual bands represent fine-scale records of short-period lake level changes. Individual layers are thin and numerous, and would present a challenge to resolve.

At 45 cm the bottom clay of the core carbon dates at 6160± 70 yr. B.P. (G 45). The interval below 40cm contains a thanatocommunity dominated by *Tabellaria*, including ridged forms of *T. fenestrata*, as well as *T. quadrisepta* not seen elsewhere. Battarbee *et al.* (1999) cite *T. quadrisepta* as a marker species for acidic water conditions. At 45 cm (Table 5-4), the thanato-community contains *Cyclotella meneghiana*, the only samples in our study where this species was found. At t 45cm the diversity is high, with 21 species; this thanatocommunity does not resemble a pioneering community early in the lake's history. Rather, it appears that by 6100 years B.P., Mountain Lake was long established, with productive rather than “hungry” waters. The planktonic to littoral diatom ratio suggests deep and open waters. Pine, hemlock, hardwood and grass pollen suggest that the local flora were not greatly different than at present. The deepest samples of G contain occasional grains of hemlock and spruce pollen (compared with extant red spruce pollen from the Spruce Bog), suggesting that, although hemlock was present in the local flora by 6100 years ago, spruce had not yet entirely vanished from around the lake.

CONCLUSIONS

1. The clay / inorganic silt layer at 5 to 6 cm in the lake core reflects human-related sediment from the building of the present hotel and the cutting of 2 roads around the lake in the early 1930s. This is supported qualitatively by a drop in chestnut pollen above this layer.

2. The core record shows Mountain Lake to be aging via eutrophication. Early sediments show few organics and small rates of sedimentation. More recent sediments contain more organic materials and more diverse diatom thanatocommunities. This eutrophication has accelerated in the past 100 years.

3. A drop in diatom diversity at 10 cm corresponds to the late 1800s when the lake was temporarily low (“Salt Pond”) during which the surrounding unforested meadow was used as pasture. This low period is supported by the historical record.

4. Mountain Lake was low or dry for at least 30 years in the mid 1600s. The lake was also low or empty for more extended periods at about 900, 1200, and 1800 years before present. The lake basin tended to develop a peat bog during these periods. Some low water periods may correspond to dry periods associated with solar minima, specifically including the Maunder and Wolf minima.

5. Low water and a peat bog and fern meadow situation was present in the lake basin at 4200 years B.P. Diatoms at this time likely represent mud- or soil-colonizing forms. This time period corresponds with historical records of great and prolonged droughts in the Mediterranean region,

which were likely the main cause of Egypt’s “First Dark Age”, and may have been associated with a solar minimum event.

6. Layered clays and silts in the oldest portions of the core probably represent smaller scale lake water level changes.

7. At 6100 years B.P., deep, open waters occurred in Mountain Lake; diatoms were already diverse, productive, and well-established. The lake at that time was surrounded by a terrestrial flora not greatly different from the modern, although red spruce and hemlock coexisted around the lake.

ACKNOWLEDGMENTS

Our appreciation goes to the Miles C. Horton Foundation for funding in 1997-98, and to the Wilderness Conservancy at Mountain Lake for financial support in 1998.. We thank CQS Inc. of Harrisburg Pennsylvania which provided additional funding and support. We thank the dive club at Virginia Tech for their help and service, especially Blair Russel, Sebastian Wolter, and Ian Norfolk. We thank the staff of the Wilderness Conservancy at Mountain Lake, and the Mountain Lake Hotel for their cooperation in 1997 and 1998. Finally we thank our much-valued friends Ross Irwin, Steve Ruzila, Amanda Cordes, Jim Broyhill, Chris Nessel, John Amos and Victor Baranauskas for their unending help and moral support.

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DISSERTATION CONCLUSIONS

The following conclusions have been drawn from this project:

1. Primary discharge from the lake is presently through a leaky subterranean pathway associated with the deepest, crevice-like portion of the lake. This discharge results in the crevice drain not filling shut with sediment despite its location within the lowest portion of the lake.

2. The lake structure, crevice, and subterranean drain are associated with a regional lineation feature represented in part by the path of Salt Pond Drain and input stream I-4. This lineation is interpreted as a fracture feature and probable fault associated with regional Appalachian fold and thrust tectonics.

3. The pronounced resistivity lows expressed across this lineation feature are consistent with a water-filled fracture zone.

4. Erosion of and drainage from this portion of the valley prior to lake formation was related to a partially subterranean outlet. This outlet path was associated with physical and compositional differences of the Clinch and Juniata sandstone (including possibly the formational contact or an unconformity) and with the zone of weakness related to the linear fracture feature.

5. Damming has been caused primarily by progressive downdrop of overlying rock. The damming is not complete, and the rate of discharge through time is controlled in part by regional tectonic events and by a balance of hydrologic conditions and sedimentation factors.

6. Thus the precise origin of Mountain Lake was not the result of landslide damming of a valley (as per Hutchinson and Pickford, 1932), nor by the collapse of Clinch sandstone cliffs (as per Parker *et al.*, 1975). Instead, the origin as described above seems to be unique for lakes worldwide, and is not included in Hutchinson's (1957) long list of lake origins.

7. The trophic state of Mountain Lake has apparently returned from an oligo-mesotrophic state reported by Beaty and Parker (1994) to an improved oligotrophic condition similar to that observed by Parson (1988) and earlier workers.

8. Mountain Lake continues to be a delicate ecosystem that is easily affected by human or natural environmental changes. Its trophic state may shift dramatically with only slight increases in nutrient inputs, particularly phosphates. The current high N:P ratio is evidence of severe P limitation.

9. The return of Mountain Lake to an oligotrophic condition probably is aided by the rapid flushing rate of the lake (~1.6 years). In addition, input streams and springs feeding the lake are presently relatively free of nutrients. Precipitation, however, appears to be a major source of important nutrients (PO_4-P, NH_4-N, NO_3-N) as well as the major source of acidity.

10. At least 66 taxa of diatoms, from 25 genera are now known to be extant in Mountain Lake, Virginia. Twelve of the individual taxa identified and reported in this paper are recognized to be new records for Virginia inland waters.

11. Diatoms in the water column of Mountain Lake are sparse, and consist primarily of planktonic forms. Littoral and epiphytic diatoms are not well represented within the water column. Smooth glass-slide diatometers do not successfully record diatoms present in the lake.

12. Cluster analysis of diatom counts from Mountain Lake sediments suggests seven individually delineated regions or thanatocommunities within the lake based on sediment diatom assemblages. The lake assemblages are basically divided between shallow (primarily pennate) and deep-water (primarily centric) assemblages, while the shallow groups may be defined by difference in epiphytic, and possibly nutrient-sensitive forms.

13. Diatom species extant in Mountain Lake reflect in general the oligotrophic, mineral-poor, and circumneutral to very slightly acidic water conditions known to be present. The separation

of diatom thanatocommunities within the lake sediments suggests that it is prone to relatively little internal turbulence or mixing of sediments.

14. If a metric using the ratio between planktonic and littoral diatom taxa is applied to Mountain Lake sediment samples, shallow samples from less than 9 m produce a diatom ratio signature of less than 1.0. Ratios for intermediate depth samples, between depths of 6 and 13 m produce a signature value averaging between 1.0 and 10.0. And ratios for deep-water samples, from depths below 12 m produce an average metric signature > 10.0.

15. Pollen analysis of the same sediments matches typical regional flora; cluster analysis of pollen data delineates six individual assemblages. One of these cluster groups represents pollen washed in by input streams. Two further cluster groups delineate differing water masses within the shallow portion of the lake, presumably by sedimentary factors and individual location of pollen sources.

16. The findings outlined here add significantly to the increasing evidence showing Mountain Lake as a unique and singular ecosystem within the Southern Appalachians. These findings provide an important training set and indicators for present depth and environmental conditions across the lake; the same training set may now be used to interpret sediment cores from Mountain Lake, providing insight and understanding on the lake’s past depth changes and environmental history.

17. The type of inexpensive coring device described herein may prove useful for collecting lake sediment cores within Scuba diver depth ranges when typical gravity corers and split spoon corers fail or perform ineffectively.

18. The clay / inorganic silt layer at 5 to 6 cm in Mountain Lake core reflects human-related sedimentfrom the building of the present hotel and the cutting of 2 roads around the lake in the early 1930s. This is supported qualitatively by a drop in chestnut pollen above this layer.

19. The core record shows Mountain Lake to be aging via eutrophication. Early sediments show few organics and small rates of sedimentation. More recent sediments contain more organic materials and more diverse diatom thanatocommunities. This eutrophication has accelerated in the past 100 years.

20. A drop in diatom diversity at 10 cm corresponds to the late 1800s when the lake was temporarily low ("Salt Pond") during which the surrounding unforested meadow was used as pasture. This low period is supported by the historical record.

21. Mountain Lake was low or dry for at least 30 years in the mid 1600s. The lake was also low or empty for more extended periods at about 900, 1200, and 1800 years before present. The lake basin tended to develop a peat bog during these periods. Some low water periods may correspond to dry periods associated with solar minima, specifically the Maunder and Wolf events.

22. Low water and a peat bog and fern meadow situation was present in the lake basin at 4200 years B.P. Diatoms at this time likely represent mud- or soil-colonizing forms. This time period corresponds with historical records of great and prolonged droughts in the Mediterranean region, likely the main cause of Egypt's "First Dark Age", and possibly caused by a solar minimum event.

23. Layered clays and silts in the oldest portions of the core probably represent smaller scale lake water level changes.

24. At 6100 years B.P., deep, open waters occurred in Mountain Lake; diatoms were already diverse, productive, and well-established. The lake at that time was surrounded by a terrestrial flora not greatly different from the modern, although red spruce and hemlock coexisted around the lake.

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EDUCATION:

1996-Present
Virginia Polytechnic Institute and State University, Blacksburg, VA
Doctorate in Biology. , Defended November 8, 1999.
*Major Advisor: B. C. Parker
*Topic: *A Re-Evaluation Of Mountain Lake, Giles County, Virginia: Lake Origins, History, And Environmental Systems*

1994-1996
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Masters of Science in Geology, Defended July 29, 1996.
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*Topic: *Dynamic Systems Analysis of Dinoflagellate Assemblages from the Atlantic Coastal Plain, USA.*

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South Dakota School of Mines and Technology/New Jersey State Museum
Summer Field Course: Field Paleontology and Biostratigraphy; Environmental Analysis
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1981-1986
The Pennsylvania State University, State College, PA
Bachelor of Science *Major: Earth Science (Geology) Minor: Writing
Penn State Earth and Mineral Sciences Interest House (*Residential Community)*

EXPERIENCE:

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1999 Virginia Tech (All-university) Graduate Teaching Award.
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May, 1996
1996 Tillman Excellence-in-Teaching Award.

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Pennsylvania Registered Professional Geologist # PG-001529-G

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Citation in *National Who's Who of American Business Leaders*

1993
NICET Certification in Engineering Technology, Level 1 Certification number: 084120

1989-1996
CQS Inc., Harrisburg, PA
Development and Technical Partner; Co-owner; Co-founder

1989-1994
Temple University Geology Department, Philadelphia, PA
Department Manager

1986-1989
Tethys Consultants Inc./ Mid-Atlantic Testing, Harrisburg, PA
Staff Geologist

Teaching Philosophy—*Jon C. Cawley*

If I were asked to choose or expound a particular teaching philosophy, it would likely be that of the 12th Century Chan scholar, Gaoan, who stressed the finding and shaping of Potential in the individual student. Encouraging self-worth and a sense of Awe in the individual student is as important as providing timely skills and information.

> *Gaoan said:*
>
> *"There are no wise or foolish students--it is just a matter of the teacher refining them to bring out virtuous actions in them, testing them to discover their potential abilities, bringing them out and encouraging them, to give weight to their words, taking care of them to make their practice complete. Over long months and years, the name and the reality will both grow rich.*
>
> *All people have the spirit--it is just a matter of careful guidance. It is just like jade in the matrix--if you throw it away, it is a rock, but if you cut and polish it, it is a gem. It is also like water issuing from a spring; block it up and it makes a bog, open a deep channel for it and it becomes a river."*
>
> *Letter to Commander Li*