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ASSESSMENT OF CHANGING LAND-USE PRACTICES ON BASIN SEDIMENT YIELDS AND PROVENANCE IN WESTERN NORTH CAROLINA USING MULTIVARIATE FINGER PRINTING TECHNIQUES

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ABSTRACT

Fairfield Lake, located approximately 16 km east of Cashier, NC, was constructed in 1890, and contains a 111-year record of upland erosion and reservoir sedimentation. During this investigation, multivariate fingerprinting techniques were used in conjunction with sediment mixing models to determine the proportion of lake bed sediment derived from the major bedrock formations and the predominant land-use types within the Fairfield Lake Watershed. Data collected from a total of 19 cores demonstrate that sedimentation within the Lake has been limited since dam closure. However, lacustrine deposits dated using ^{210}Pb, combined with cartographic information from aerial photographs obtained in 1963, 1975, 1988, and 2000, indicate that sedimentation rates have increased several fold during the past two decades in response to local development. The statistical treatment of geochemical data collected from delineated land-use categories, and the two underlying bedrock formations, suggest that the soils associated with these sediment sources can be geochemically fingerprinted. Moreover, the developed mixing models show a change in sediment source coincident with the documented increase in sedimentation rates associated with development. Nonetheless, the utilized approach will require modification before it can be effectively applied on a large scale in western North Carolina.

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SUMMARY AND CONCLUSIONS

Stratigraphic data collected from 19 cores indicate that sedimentation within Fairfield Lake has been limited since dam closure in 1890. Most of the sediment that enters the lake is deposited near the mouth of tributaries creating deposits on the order of 50 to 100 cm in thickness. Deep-water areas located along the axis of the reservoir, and which are removed from the direct influx of tributary sediment, have received only a limited amount of debris.

Cores dated using ^{210}Pb clearly indicate that sedimentation rates have significantly increased during the past few decades. The most significant increases occur in the mid-1980s and the late 1990s, both of which correspond to periods of development documented by the comparison of aerial photographs obtained in 1963, 1975, 1988, and 2000. The more recent sedimentation rates are several fold greater than the rates observed during the first half of the 1900s. If the current rates of sedimentation continue into the future, sediment accumulation will likely lead to ecological impacts within the lacustrine system and cause problems for those utilizing the lake for recreational activities.

The Fairfield Lake Watershed is underlain by two bedrock formations: the Whiteside Granite and the Tallulah Falls Formation. The statistical treatment of geochemical data from sediments overlying the rock units suggest that the soils derived from these lithologies can be delineated on the bases of Cu, Mn, Sn, U, and Zn. That is, the bedrock units exhibit a unique geochemical fingerprint defined by these five parameters. Similarly, materials from differing sediment sources within the Whiteside Granite, including forests, roads, lawns, and alluvial deposits along upland streams, can be defined on the basis of Ag, Bi, Cr, Mn, Mo, Ni, Sb, Sn, and Zn. Thus, the results from the linear discriminant analysis suggest that it is possible to use sediment mixing models to determine the quantity of material derived from differing lithologies or land-cover types.

In light of the above, a separate sediment mixing model was developed using the parameters defined in the discriminant analysis to (1) assess the relative contributions of sediment derived from the different bedrock units that underlie the watershed, and (2) define the contributions of materials to the lake from four different upland sediment sources. With respect to differentiating between bedrock sources, the model worked reasonably well. However, it appears to have been unable to distinguish between sediment derived from the Tallulah Falls Formation and sediment from a micaeous, more mafic-rich unit of the Whiteside Granite. These two units apparently have a similar geochemical fingerprint. The modeling of the relative contributions of sediment from forests, lawns, roads, and upland alluvium also shows promise in that the model was able to define systematic changes in core geochemistry that are related to changing sediment sources. In addition, the estimated influx of sediment from roads and lawns generally coincides with the onset of land-use alterations as defined by cartographic information obtained from aerial photographs. However, the model appears to have overstated the contributions of sediment from lawns during periods of sediment influx from rocks with a Tallulah Falls type fingerprint. Moreover, it appears that the geochemical signal of lawns, roads, and forests may be muted by geochemical processes as the sediments are transported through upland streams to depositional sites within the lake.

RECOMMENDATIONS

(1) Our initial study design treated the Tallulah Falls Formation and the Whiteside Granite as homogenous units. However, application of sediment mixing models to the collected data suggests that the contributions of material from the Tallulah Falls Formation could not be differentiated from a micaeous, more mafic rich unit of the Whiteside Granite. This problem may be addressed using one of two different approaches. First, the micaeous unit of the Whiteside Granite can be treated as a separate sediment source. Thus, in this study, the mixing models would examine the contributions of material from three lithologic units. For small watersheds, such as the Fairfield Lake Basin, this approach may work well. However, for larger watersheds, the approach may lead to an unmanageable number of different sediment sources. A second approach is to define sediment sources according to the gross mineralogical composition of the rocks. In this case, sediments from the Tallulah Falls Formation and the micaeous unit of the Whiteside Granite would be treated as a single source type. There is some merit to this approach in that previous studies have shown that rock units of similar composition also function similarly in terms of their erodibility. Model output may then lead to a conclusion that sediment from particular lithologic (mineralogic) group tends to produce most of the sediment in an area and, therefore, these rock units should be treated differently (perhaps more stringently) in terms of management practices. The downside of this approach is that it requires a detailed understanding of the lithology and distribution of the bedrock units prior to the sampling of the upland soils.

(2) The discrimination of the upland sediment sources yielded semi-unique geochemical fingerprints in which about 90 % or more of the samples from a given source area could be correctly classified. However, the fingerprint was not perfectly unique. Thus, a large suite of elements (more than the 20 some parameters initially used in this study) should be examined to define a more specific geochemical fingerprint for each source type. This may require the analysis of as many as 40 different elements, at least until a list of the best discriminating parameters are defined for a region. The analyses should include elements that exhibit different geochemical behaviors including trace metals (Fe, Mn, Al), heavy metals (Cu, Zn, Pb, Cr. Ni, Co), base metals (Na, Mg, Ca, K) and, perhaps, elemental isotopes.

(3) The use of sediment mixing models assumes that elemental mass is conserved during transport from upland areas to the depositional sites within the lake. This was not the case for several of the parameters which defined the geochemical fingerprint for the upland sediment sources. Concentrations for these elements were substantially lower in the lake bed deposits than in the uplands. Investigations should be undertaken to determine if weighting factors based on the ratios of the elements to "insoluble" constituents (e.g., Ti) can be used to reduce the effects of elemental loss on the mixing model results.

INTRODUCTION

The impacts of sediment on streams and rivers of the southern Appalachians has become a significant issue in the past decade. Much of the attention given to the "sediment problem" is the direct result of its potential ecological impacts and the costs involved in dredging many of the area's reservoirs. In 1993, for example, the Southeast United Methodist Assembly paid over $0.5 M to dredge portions of Lake Junaluska, NC (Gibson 1998), and it is once again being dredged at a cost that may exceed expenditures put forth in 1993. Similarly, Lake Lure, NC, was dredged in 1997 at a cost of $1.4 M.

It is generally assumed that most of the sediment found in the region's streams and reservoirs is the result of land-use alterations, particularly those associated with development activities. In fact, many federal, state, and local agencies have stated that anthropogenically derived sediment (i.e., sediment resulting from human activities) is the most serious non-point source pollutant in the mountainous terrain of western North Carolina (see, for example, Gibson 1998). This logically stems from a number of observations including, to mention a few, the occurrence of intensively gullied roads and hillslopes in zones of new construction, silt fencing that is sediment laden or has been overridden by debris downslope of construction operations, and the obvious movement of sediment to streams from cleared terrain during runoff events.

While there is no reason to believe that the majority of the sediment found within the region's streams and reservoirs is not the result of human activities, there have been few attempts to quantify the impacts of land-use alterations on upland erosion in the southern Appalachians. Particularly lacking is a coherent, quantitative understanding of (1) the *natural* rates of sediment production associated with "pristine" conditions, and (2) a quantitative assessment of the relative contributions of sediment to the region's water bodies from differing forms of land-use practices and rock types.

Early studies to calculate basin sediment yields in other areas have relied heavily on the analysis of lake and reservoir sedimentation (Dearing and Foster 1993). While providing highly valuable data on basin sediment yields, these methods are plagued by an inability to identify the predominant areas contributing sediment to the rivers and streams that feed the lacustrine systems. Numerous approaches have been used to circumvent this problem including (1) the delineation and mapping of barren lands, or regions of obvious sheet, rill, gully, and bank erosion, and (2) the use of direct monitoring techniques including suspended sediment sampling, erosion pins, cross-channel surveys, and runoff troughs (Imeson 1974; Peart and Walling 1986). These methods are plagued by operational (sampling) difficulties and generally provide a data set that is both temporally and spatially limited (Peart and Walling 1986). Some studies have relied on the use of soil loss equations to determine provenance by estimating relative sediment yields from subbasins of a watershed. This approach, however, raises questions as to the reliability of the utilized equations, and the uncertainties associated with calculating the sediment delivery ratios required to convert estimates of upland erosion to one of downstream sediment yield (Peart and Walling 1986).

As a result of the problems outlined above, many investigators have abandoned these traditional approaches and turned to physical and geochemical fingerprinting techniques to determine sediment provenance. A variety of parameters has been utilized to fingerprint sediment sources including grain size (Knox 1987; Sutherland 1991), mineralogy (Fan 1976), mineral magnetics (Oldfield et al. 1979; Walling et al. 1979), radionuclides, (Peart and Walling 1986), and heavy metal pollutants (Lewin and Wolfenden 1978; Macklin 1985; Knox 1987, 1989 Passmore and Macklin 1994). Perhaps one of the more significant conclusions reached by these earlier investigations is that erroneous sediment-source area associations may occur when only a single fingerprinting parameter is used. As a result, more recent investigations have relied on multiple parameters and the utilization of multivariate statistical techniques to manipulate the data (e.g., Passmore and Macklin 1994; Collins et al. 1997a, 1997b). The application of more rigorous statistical methods has been paralleled by the development of sediment mixing models which allow a more accurate assessment of the relative contribution of material derived from each of the delineated source areas (Peart and Walling 1986; Yu and Oldfield 1989; Collins et al. 1997a, 1997b, 1998). In light of the above, it is now generally accepted that fingerprinting techniques represent a reliable means of assessing sediment-source area relations over historic time frames in some environments. When combined with studies of reservoir sedimentation, these methods can be extremely useful in determining the impact of land-use alterations on both sediment provenance and basin sediment yields.

This investigation examines the use geochemical fingerprinting techniques and sediment mixing models within the Fairfield Lake Basin to determine if they can be effectively utilized in the steep terrain of western North Carolina. More specifically, the study attempts to determine the relative contributions of sediment, at any given time, to Fairfield Lake from specific geologic units and delineated land-cover types (e.g., forests, roads, lawns, etc.). To our knowledge, this is the first attempt to apply these procedures in the southern Appalachians.

GEOGRAPHIC AND GEOLOGIC SETTING OF THE STUDY AREA

Bedrock Geology of the Fairfield Lake Basin

Fairfield Lake is located in Jackson County adjacent to U.S. Route 64 about 16 km east of the high growth area of Cashiers (Fig. 1). The Fairfield Lake Watershed is underlain by crystalline rocks of the Blue Ridge Geological Province (Brown 1985). The geology of the area, like much of the Blue Ridge Province of western North Carolina, is dominated by high-grade metamorphic rocks (the Tallulah Falls Formation) that have been intruded by igneous plutons (the Whiteside Granite) during multiple episodes of mountain building (McKniff 1967; Hadley and Nelson 1971; Witherspoon 1982). Radiometric dating of the Whiteside Granite using $^{206}Pb/^{238}U$ isotopic methods by Miller et. al. (1998) estimate that the pluton is 466 Ma. Field observations show that the Whiteside Granite is a light-colored, meta-igneous rock that, mineralogically, contains plagioclase, quartz, microcline, biotite, and muscovite (in decreasing order of abundance). The amount of plagioclase exceeds microcline making these rocks more calcium-rich than granites. They are best classified as granodiorites, tonalites, or monzodiorites. Foliation of the micas is absent in many exposures but pronounced in others. Near the contact with the Tallulah Falls Formation, the Whiteside Granite is well foliated and is cut by coarse pegmatites. Grain size is variable ranging from less than 1 mm to 5 mm with the average size falling between 0.5 and 1 mm. Weathering produces a gray to light brownish gray friable and sandy material. This weathering is typical of the soils from the rock unit (Sherrill 1997).

Hatcher (1971) describes the Tallulah Falls Formation as a metamorphosed Precambrian pelite-quartzofeldspathic sandstone – basalt assemblage. Within the Fairfield Lake Watershed the Tallulah Falls Formation appears as a series of interbedded and discontinuous schists and gneisses that Witherspoon (1982) has subdivided into three subunits: Hornblende Gneiss, Mica Garnet Gneiss, and Mica Schist and Gneiss. The Hornblende Gneiss is dominated by hornblende and plagioclase, possesses some compositional banding, and is dark green to black in color. Soils generated from these rocks are red. The Mica – Garnet schists are very distinct. They have high concentrations of muscovite and biotite and possess a well-defined schistosity and compositional banding. The presence of garnets within these units makes them even more distinct. Oxidation of the garnets produces a reddish-brown stained schist that lacks strength and therefore decomposes readily. The soils are also red. The Mica Schist and Gneiss is the most abundant unit and has well defined schistosity and compositional banding. These rocks contain plagioclase, quartz, microcline, biotite, and muscovite, mineralogy similar to the Whiteside Granite. However, the amount of biotite and muscovite is much higher than in the Whiteside Granite. Witherspoon (1982) indicates that saprolites produced from these rocks are gray to yellow and are difficult to distinguish from Whiteside Granite saprolites. All of the units are thinly bedded and the metasedimentary units often grade into each other.

On site field review of the region around Fairfield Lake by one of the present investigators (Yurkovich) indicates that the map (scale 1:24,000) produced by Witherspoon (1982) is an accurate representation of the existing geology. Therefore, the Witherspoon (1982) map, with minor adjustments, is used as the base map for the geology (Fig. 2). Over three-quarters of the

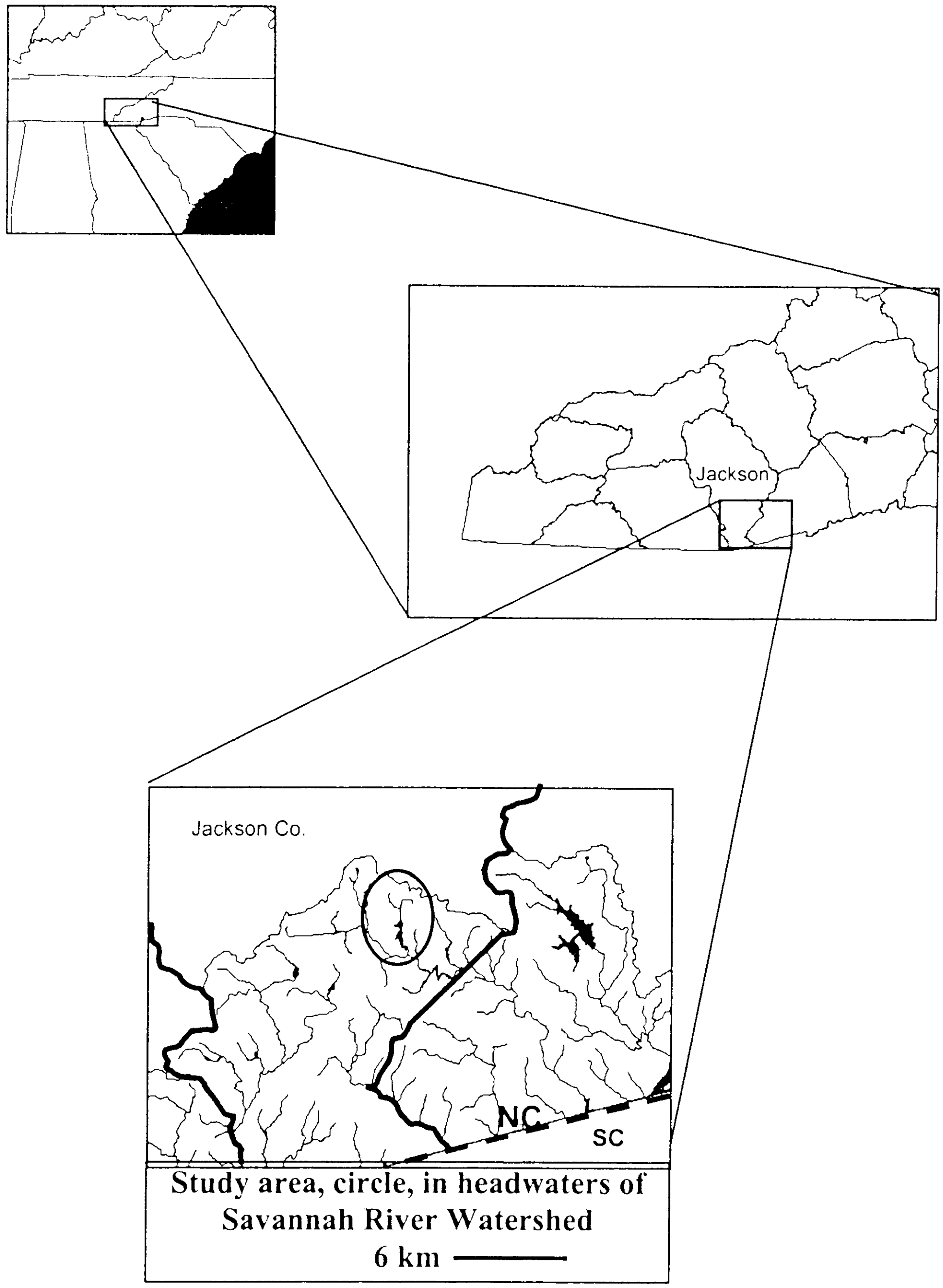

Figure 1. Maps showing the location of the Fairfield Lake Watershed in western North Carolina.

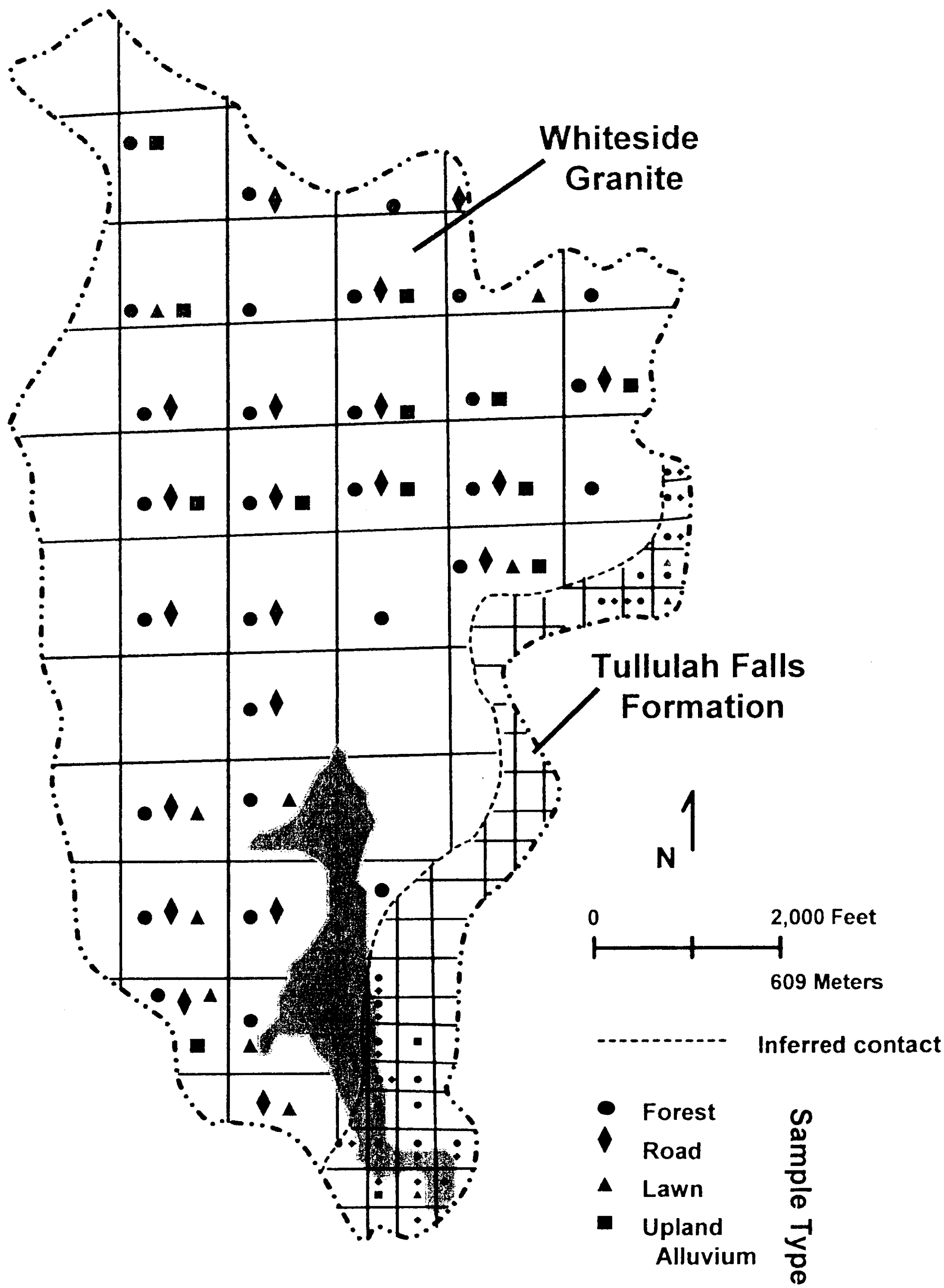

Figure 2. Bedrock geology and upland soil sampling locations within the Fairfield Lake Watershed. The grid used to randomly select sampling sites is overlain on the watershed. A smaller grid size was applied to the Tallulah Falls Formation to compensate for the limited exposure of these rock types within the basin.

underlying area is composed of Whiteside Granite (also referred to in the geological literature as the Whiteside Granite Gneiss and the Whiteside Gneiss); the remainder the rocks are composed of the Tallulah Falls Formation (Fig. 2).

Geomorphology of the Fairfield Lake Basin

Fairfield Lake sits in the northern headwaters of the Savannah River system, an area characterized by high relief, extensive bare rock cliff faces (or exfoliation surfaces) and widespread colluvial deposits located along toe slopes of the rock cliffs. The Lake is 0.3 km^2 in areal extent, and has a drainage area of 7.27 km^2. Treys Island Creek and its tributary, Long Branch, enter the north end of the Lake and provide the bulk of its inflow (Fig. 3). The basin slope is 100 m/km. The climate of the study region is humid subtropical, with mild summers and cold winters. The average annual rainfall is about 230 cm based upon 50 years of record at Lake Toxaway, which is about 9 km from the study area. The region commonly receives very intense rainfall. Since 1950, there have been 93 days with over 10 cm of rain and 6 days with over 20 cm of rain.

The base level of the Fairfield Lake Watershed sits at 957 m. To the east lie the bare rock faces of Little Bald Rock and Bald Rock Mountains (Fig. 4) that rise to 1,289 m and mark the eastern edge of the drainage basin. These exfoliation surfaces produce a maximum relief of 330 m within a 0.6 km distance thus giving this side of the basin a very steep slope. With the exception of the bare rock cliffs the eastern side of the basin is predominantly forested and has limited development. The headwaters of Treys Island Creek and Long Branch flow off a high elevation plateau. Because of the low relief on the plateau it is undergoing rapid residential development. To the northwest the relief approaches 425 m with more exfoliation surfaces exposed. In the west and southwest sections the watershed topography moderates yet the slopes remain steep. It is in these portions (northwest, west, and southwest) of the watershed that extensive residential development has taken place.

The Lake was impounded in 1890 and contains a continuous sediment record of nearly 111 years. In 1999 the owners of Camp Merrie Woode (located on the northern shore of the Lake) used heavy equipment to remove sediment from the Lake at the base of the waterfalls where Treys Island Creek enters the lake. Otherwise the remainder of the Lake sediment has not, to our knowledge, been disturbed by dredging activity.

Fairfield Lake is not a homogeneous body, but can be subdivided into 3 distinct sections which will be referred to as the upper-, middle-, and lower-lake segments. The uppermost segment exhibits water depths ranging from 0 to 4 m (Fig. 5), and primarily receives drainage from two catchment areas. Flow from one of these catchments (Treys Island Creek) enters the upper lake segment from the north and possesses a basin area of 4.91 km^2. The inflowing water traverses a large waterfall before entering the reservoir. The second unnamed drainage, encompassing an area of 1.03 km^2, enters an embayment located on the west side of the lake. Additional input of water and sediment is derived from a series of small, ephemeral tributaries that drain the exfoliation surfaces and steep terrain along the northeast side of the lake basin.

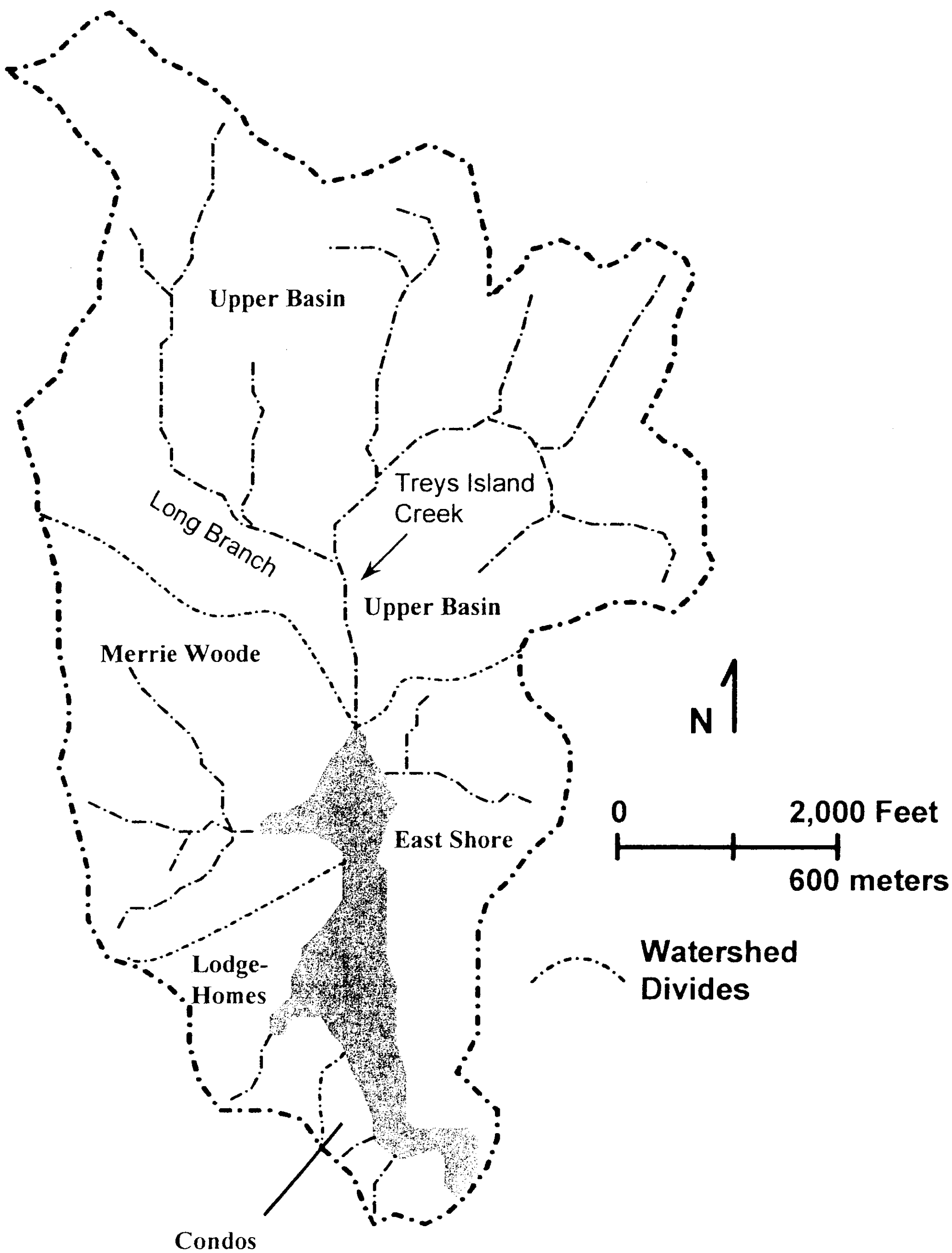

Figure 3. Subbasins within the Fairfield Lake Watershed used to examine changes in land-use alterations.

Figure 4. Exfoliation surfaces located along northeast side of the Fairfield Lake Basin.

The mid-segment of the lake is dominated by an embayment located on the west-side of the reservoir. Water depths increase abruptly within the "neck" that separates the upstream from the middle segments of the lake so that the reservoir is generally on the order of 5 m deep in its mid-section. Most of the water and sediment in this segment is derived from a stream that enters the embayment from the west (Fig. 3), although runoff also comes from small, ephemeral tributaries that drain the steep hillslopes along the east side of the reservoir. The lower-segment of the lake is generally characterized by narrow valley widths and predominately receives inflow from two small tributaries that drain an area of development to the southwest (Fig. 3). Water depths in the lower-segment are generally greater than those in the upstream areas, exceeding 8 m in depth (Fig. 5).

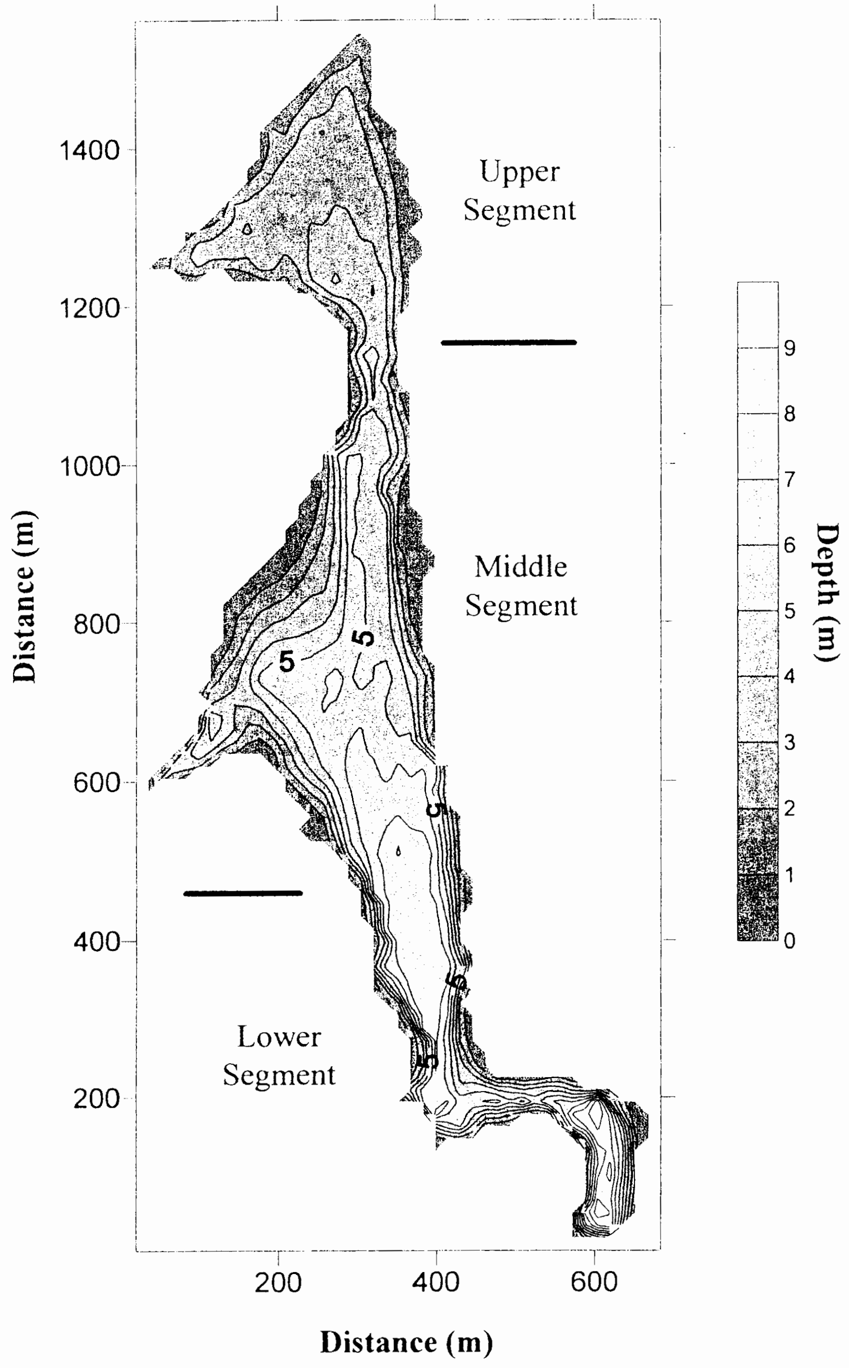

Figure 5. Bathymetry of Fairfield Lake. Map based on the 457 data points contoured using Surfer 7®.

PROCEDURES

Use of the multivariate fingerprinting technique requires the collection of sediment samples from upland areas as well as the lacustrine sediments within Fairfield Lake. In order to minimize sampling biases, the upland sampling sites were selected by overlaying a numbered grid on a base map of the Fairfield Lake Basin. The size of the grid was adjusted to insure the collection of a similar number of samples of the soils overlying the Whiteside Granite and the Tallulah Falls Formation. The grid sizes used were 366 m per side in the Whiteside Granite and 122 m per side in the Tallulah Falls Formation (Fig. 2). Soils samples were collected over the two rock units in both undeveloped (predominantly forested lands) and developed areas. Fewer samples were collected from the portion of the basin underlain by the Tallulah Falls Formation because of the small area, abundant cliffs, and the general lack of streams and development. A summary of the samples collected from each rock type and land-use category is listed in Table 1.

The procedure used for sample collection in the field is similar for undeveloped and developed areas. First, the organic layer (O-Horizon) was gently removed using a trowel or pocketknife. A gardener's bulb planter (tube diameter of 6 cm) was inserted 5 cm into the A-Horizon of the soil and the soil was transferred to a labeled ziplock bag. Three other samples, taken within a 10-meter circle of the first, were collected in the same fashion. All four samples are placed in the same ziplock bag generating a composite sample from within the circle. Slight variations in this sampling procedure occurred in certain sites. For example, along roads, trails, and gullies the samples were taken within ditches when present, and all four samples were collected within a 10-meter distance. Samples adjacent to streams were collected in the upper 5 cm of the bank sediment.

The samples were split in the Sediment/Soils Laboratory at Western Carolina University, and half of the material from each sample was shipped to the Nevada Bureau of Mines and Geology for geochemical analysis, whereas the remaining material remained at WCU for mineralogical and physical characterization.

TABLE 1
Distribution of Collected Upland Soil Samples

	Number of Samples Collected		
Sediment Source	***Whiteside Granite***	***Tallulah Falls Formation***	***Total No. of Samples***
Forested Areas	30	16	46
Roads	20	16	36
Lawns	9	4	13
Upland Alluvium	12	1	13
Total Number of Samples	71	37	108

In addition to sample collection, information was obtained at each site on a variety of other parameters including slope angle, slope aspect, vegetative cover (type), canopy percent, geomorphic setting, evidence of erosion, and land use.

It was critical to collect cores of the lake bed sediments from depositional zones that were representative of sediment flux to the lake as a whole. In order to establish a detailed plan for collecting the cores, the bathymetry of the lake was determined and spot samples of the lake bed sediment were collected using a grab sampler. The bathymetry of the lake was determined by using a Hondex® portable depth sounder (accurate to within 15 cm). Depth measurements were collected from 457 locations positioned along 22 transects oriented perpendicular to the lake basin. A bathymetric map was subsequently produced from these data using Surfer 7® (Golden Software, Inc.).

Core samples were collected to determine the stratigraphy of the lake bed, and to provide materials for geochemical analysis. Core locations were chosen on the basis of bathymetry, as well as the bedrock geology, geomorphology, land use patterns, and drainage network of the lake basin. The highest core densities were collected in the vicinity of two major embayments on the west side of Lake Fairfield; a lower density of cores was collected along the north-south axis of the lake and a small embayment in the southwestern portion of the lake. Cores were collected using a Wright-Livingston coring device from 16 locations in water depths ranging from 1.4 m to 6.6 m; most cores were collected for a water depth between 2 and 3 m. Immediately after collection, sediments were extruded from the coring device into clear, plastic tubes and labeled for identification.

The sedimentology of each of the cores obtained from Fairfield Lake was described in the Soils and Sedimentology Laboratory at WCU. The descriptions are based on the nomenclature used for the field analysis of soils as presented by the USDA Soil Survey Staff (1999) and Birkeland (1999). While this classification system was never intended to be applied to lake bed sediments, it provides a convenient method of defining the nature of the materials observed within the cores.

Once described, the data were used to identify spatial variations in depositional patterns within the lake and the total thickness of the lake bed sediments. These interpretations ultimately led to the selection of three cores (3A, 4A/B, and 11A) for further study including the analysis of the deposits for ^{210}Pb and ^{137}Cs (for age dating purposes) and a suite of elements for the purpose of multivariate fingerprinting. The sampling interval for ^{210}Pb and ^{137}Cs analysis was adjusted to obtain approximately 20 samples that extended through the lacustrine sequence. These sediments were sent to Flett Research Ltd. located in Winnipeg, Canada for analysis.

Sampling of the cores for geochemical analysis was adjusted to obtain approximately 30 samples from each core. This resulted in sampling increments of 3 cm, 4 cm, and 3 cm for Cores 3A, 4A/B, and 11A, respectively. In some cases, the sampling interval was shortened or expanded to avoid the collection of materials from more than one stratigraphic unit because it is possible that the sediments in each unit is derived from a different sediment source within the watershed.

Except for the analysis of the materials for age dating purposes, all of the geochemical analyses were performed under the direction of Dr. Paul Lechler at the Nevada Bureau of Mines and

Geology in Reno, Nevada. Elemental concentrations were determined using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Quality of the data were assured through analysis and monitoring of blanks, replicates, controls, and standard reference materials (e.g., USGS, NIST, and in-house and international SRMs).

In addition to the geochemical analyses, both the upland samples and the lake bed cores were analyzed for grain-size distribution and organic matter content. The grain-size distribution of each of the sediment samples was determined in the Sedimentology/Soils Laboratory using both wet-sieving and hydrometer techniques following the procedures of Sheldrick and Wang (1993). The organic matter content of the samples was estimated by loss-on-ignition (550° C, 4 hrs).

All statistical analyses were performed using SYSTAT® v. 9.0. The sediment mixing model(s) were developed using Microsoft Excel®.

RESULTS

A Brief History of Land-Use Alterations within the Fairfield Lake Basin

Fairfield Lake was created by the construction of a dam in 1890. The property around the lake was owned by the Toxaway Company which built the Fairfield Inn along the southwestern margin of the lake in 1897. Camp Merrie Woode was built on the northern end of the Lake in 1919 and has been used as a girl's summer camp since that date. Initial construction of condominiums and homes began near the Fairfield Inn subsequent to 1971 when the property was acquired by Realtec, Inc. Fairfield Communities, Inc. has continued the development on the west side of the lake since 1980 and razed the original Fairfield Inn building in 1986. The company has since replaced it with a new structure (Williams 1987). Summer home development in the northern portion of the watershed began in 1995 by the Westmark Corporation and continues to the present time.

In order to more quantitatively examine the changes in land-use outlined above, alterations in land cover categories within the Fairfield Lake Watershed were determined from large scale (1:26,000 to 1:23,000) aerial photographs acquired on 4 different dates. The United States Forest Service produced the 1963 and 1975 photographs as part of their continuous forest inventory program. The 1988 photographs were flown for Jackson County, NC, tax mapping purposes. The 2000 information was determined from on-the-ground updating of 1997 aerial photographs flown for Jackson County tax mapping purposes.

Presentation of the data have been subdivided into 5 subbasins to permit discrimination of sediment accumulations in the lake bottom with building and road construction occurring in a particular sub-drainage. This was thought necessary because the sedimentary patterns suggest that sediment entering the reservoir is not uniformly distributed across the lake bed (as will be discussed in more detail below). The sub-drainage areas are shown in Figure 3 and the respective areas are listed in Table 2. The number of buildings and the lengths of roads constructed were determined for the time periods between each set of aerial photographs and are also presented in Table 2. Road lengths were measured from the aerial photographs using a Sokki Digitizing Line-Area Meter.

The data show that each subbasin has a somewhat different history of land-use alteration. However, in general, significant development post-dates 1975, and the most important periods of land-use change occurred in the mid- to late-1980s and, within the upper drainage, during the past 6 years.

Petrographic Analyses of the Bedrock Units

An understanding of the mineralogical composition of the underlying bedrock is required to effectively interpret the geochemical data collected from both the Lake bed and the soils of the upland areas. Thus, a representative suite of rock samples from the Whiteside Granite and Tallulah Falls Formation were collected and subjected to standard thin section analyses. More

TABLE 2
Summary of Land-Use Alterations in the Fairfield Lake Basin
(see Figure 3 for Location of Subbasins)

Subwatershed- Land-use Category	Merre Woode	Lodge-Homes	Condos	East Shore	Upper Basin	Total Area
Basin Area (ha)	103	47	12	74	491	727
1963 Data						
Road Length (km)	1.45	3.25	0.21	1.31	5.15	11.37
# of Buildings	25	7	0	0	0	32
Building Density (#/ha)	0.24	.015	0	0	0	0.044
Road Density (km/ha)	0.014	0.069	0.01	0.02	0.01	0.016
1975 Data						
Road Length (km)	2.09	3.7	1.46	1.31	7.24	15.8
# of Buildings	29	9	34	0	0	72
Building Density (#/ha)	0.28	0.19	2.83	0	0	0.099
Road Density (km/ha)	0.02	0.08	0.12	0.02	0.015	0.021
1988 Data						
Road Length (km)	3.2	3.7	1.46	1.31	7.72	17.39
# of Buildings	45	24	65	0	2	136
Building Density (#/ha)	0.44	.051	5.42	0	0.004	0.187
Road Density (km/ha)	0.03	0.08	0.12	0.02	0.015	0.023
2000 Data						
Road Length (km)	6.64	3.7	1.46	1.31	20.74	33.85
# of Buildings	60	32	65	0	16	173
Building Density (#/ha)	0.58	0.68	5.42	0	0.032	0.238
Road Density (km/ha)	0.064	0.08	0.12	0.02	0.042	0.326

specifically, petrographic analysis involving the examination of at least 1000 points on each thin section was used to determine the modal mineralogy (volume percent of minerals) comprising the two rock types. In addition, data were gathered on grain size, mineral fabric, and other textural features in order to characterize the rocks. Table 3, which includes data from both this study and Witherspoon (1982), summarizes the diverse mineralogy of the units. Witherspoon's (1982) data were obtained primarily outside the Fairfield Lake Basin but provide additional insights into the mineral diversity within the rock units. The documented variation in mineralogy reflects the composition of the parent material from which these rocks were derived.

The Whiteside Granite, which comprises most of the watershed, and has a mineralogy that is distinct from the Tallulah Falls Formation. Weathering of the Whiteside Granite produces sediment that is dominantly feldspar (plagioclase and microcline) and quartz with minor amounts of the micas (biotite and muscovite). However, in some samples of the Whiteside Granite the volume percent of mica can approach the amounts found in the Tallulah Falls Formation. Decomposition of the Tallulah Falls Formation produces sediment characterized by a more diverse suite of minerals than that of the Whiteside Granite. As mentioned above, units with

TABLE 3
Variation in Mineralogy of Rock Units
(Numbers are Volume Percent)

Whiteside Gneiss

Plagioclase	32.8 – 66.7
Quartz	8.2 – 40.6
Microcline	0.0 – 25.6
Biotite	4.8 – 28.9
Muscovite	0.3 – 9.7
Accessory Minerals – epidote, allanite, sphene, apatite, zircon, opaque minerals	0.0 – 16.5 (most contain <1.0)

Tallulah Falls Formation

Mica Schists and Gneisses

Plagioclase	11.7 – 63.1
Quartz	11.3 – 39.0
Muscovite	0.5 – 44.0
Biotite	2.3 – 34.1
Microcline	0.8 – 60.3
Accessory Minerals – apatite, zircon, allanite, opaque minerals	0.0 – 0.8

Mica – Garnet Schists

Muscovite	3.8 – 73.5
Biotite	5.0 – 29.4
Quartz	3.0 – 50.2
Plagioclase	2.0 – 41.1
Garnet	0.8 – 9.2
Accessory Minerals – staurolite, kyanite, zircon, opaque minerals	0.0 – 1.1

Hornblende Gneisses

Hornblende	56.8 – 78.9
Plagioclase	12.2 – 32.5
Quartz	1.3 – 7.9
Epidote	0.2 – 6.5
Sphene	0.2 – 3.9
Accessory Minerals – garnet, biotite, opaque minerals	0.0 – 1.0

Tallulah Falls Formation are not continuous but often grade into each other thus allowing mixing of sediments with differing mineralogies during erosion, transport, and deposition. The mineralogy of the sediment from these units includes high concentrations of hornblende and micas in addition to the feldspars and quartz. The rocks of the Tallulah Falls Formation also possess the accessory minerals sphene and epidote, both of which produce a characteristic signature within their sediment.

Geochemical Fingerprints of the Bedrock Units

A total 108 sediment samples were collected (as described in the procedures section) from the drainage basins surrounding Fairfield Lake. Each sample was analyzed for a suite of 16 elements as well as 2 isotopes of Se and 4 isotopes of lead using an ICP-MS (Table 4). These elements are primarily trace and heavy metals which were believed to possess a high potential for differentiating between the various sediment sources. The mean and standard deviations of the elemental concentrations found in each of the delineated sediment sources are presented in Table 4.

The statistical summaries suggest that the sediments overlying the two rock types differ in their geochemical composition (Table 4). Thus, a stepwise, linear discriminant analysis was used to determine if the sediments from the two bedrock units could be separated on the basis of their geochemistry and to determine which elements are best suited for differentiating materials from the two rock types.

Although the method is fairly robust, linear discriminant analysis assumes that the data exhibit a normal distribution. To determine if this assumption was met for the samples from the Fairfield Lake Basin, normal probability plots were created for each element using both the total data set and the data stratified by rock type. These graphs plot elemental concentrations determined for the sample against the corresponding values of a mathematical normal distribution. A perfectly normal distribution should produce a straight line. However, this was not the case for our geochemical data. Thus, the values were transformed using both a square root and logarithmic (base 10) function and then reanalyzed using normal probability plots. The logarithmic transformation was most effective in producing a normal distribution. Thus, the log-transformed data were used in further statistical treatments.

The stepwise procedure revealed that the rock type from which the sediment was collected could be statistically determined on the basis of sediment geochemistry. Of the 101 samples collected, the analysis classified 93 % of the samples correctly (Table 5). However, classification of the data used in creating discriminant functions can lead to overly optimistic results. A better method to check the success of the analysis is to create discriminant functions using half the data and subsequently test the analysis using the remainder of the data set. In our case, the limited number of samples collected from the Tallulah Falls Formation prohibited this approach. However, SYSTAT allows for the formation of a Jackknifed classification matrix. This matrix is calculated by creating functions using all of the data except for one observation and then determining if that particular observation is correctly classified (SYSTAT, 1996). It is, in

TABLE 4

Descriptive Statistics of Geochemical Data Stratified by Rock Type and Land-Use Category

	Ag	As	Bi	Cd	Cu	Cr	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	U	Zn
Whiteside Granite																
Number of samples	72	72	72	72	71	72	70	72	72	72	72	72	71	72	72	72
Mean (µg/g)	0.029	1.404	0.099	0.074	2.793	12.124	42.606	113.995	0.209	4.722	10.884	0.102	0.493	0.722	1.555	24.435
Standard Deviation	0.059	1.456	0.107	0.064	3.047	7.928	31.319	76.777	0.113	3.143	5.918	0.079	0.267	0.315	2.158	17.110
Tallulah Falls Fm.																
Number of Samples	37	37	37	37	37	37	37	37	37	37	37	37	37	37	37	37
Mean (µg/g)	0.038	2.259	0.110	0.086	17.271	38.779	54.821	232.885	0.648	14.497	15.388	0.149	0.952	1.212	0.794	42.813
Standard Deviation	0.024	1.101	0.114	0.042	10.425	25.947	30.400	129.986	0.641	6.440	20.302	0.072	0.378	0.344	0.508	15.251
Forests																
Number of Samples	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31
Mean (µg/g)	0.034	1.433	0.094	0.088	2.121	8.515	55.405	77.685	0.236	3.349	10.020	0.137	0.503	0.702	1.447	17.169
Standard Deviation	0.018	0.605	0.123	0.034	0.849	4.764	24.391	60.267	0.113	1.870	5.517	0.047	0.239	0.186	0.682	7.275
Roads																
Number of Samples	20	20	20	20	19	20	18	20	20	20	20	20	19	20	20	20
Mean (µg/g)	0.013	1.140	0.092	0.042	2.571	14.849	26.761	167.242	0.197	6.061	10.823	0.050	0.490	0.790	1.402	28.700
Standard Deviation	0.008	0.542	0.063	0.021	1.972	6.133	19.127	65.125	0.091	2.792	4.527	0.025	.246	0.198	0.794	9.649
Lawns																
Number of Samples	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Mean (µg/g)	0.024	3.059	0.133	0.101	7.359	23.901	66.599	171.075	0.256	8.976	13.152	0.140	0.784	1.020	3.146	50.429
Standard Deviation	0.012	3.496	0.173	0.040	6.402	9.555	47.677	92.780	0.087	3.922	9.758	0.070	0.230	0.612	5.850	29.535
Alluvium																
Number of Samples	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Mean (µg/g)	0.047	0.529	0.097	0.073	1.457	8.072	15.317	76.242	0.124	2.845	11.520	0.069	0.256	0.436	0.898	16.603
Standard Deviation	0.143	0.305	0.056	0.136	0.753	5.553	12.479	38.276	0.128	1.539	5.624	0.136	0.172	0.176	0.454	12.181

* Note: Isotopic data for Pb and Se are not shown because they were not utilized in statistical analyses.

TABLE 5
Summary of Discriminant Analysis Applied
To Bedrock Formations within the Fairfield Lake Basin.

Classification Matrix			
Rock Type	*Whiteside Granite*	*Tallulah Falls Formation*	*Percent Correctly Classified*
Whiteside Granite	63	4	94
Tallulah Falls Formation	3	31	91
Number of Samples	66	35	93

Jackknifed Classification Matrix			
Rock Type	*Whiteside Granite*	*Tallulah Falls Formation*	*Percent Correctly Classified*
Whiteside Granite	63	4	94
Tallulah Falls Formation	3	31	91
Number of Samples	66	35	93

Model Summary	*Factor 1*
Eigenvalues	2.180
Canonical Correlations	0.828
Standarized Constants for Discriminant Functions	
Cu	1.17
Mn	0.70
Sn	0.26
U	-0.7
Zn	-1.13

essence, a form of cross-validation. The Jackknifed classification matrix (Table 5) also suggests that greater than 90% of the samples can be correctly labeled. The elements included in the discriminant function by the stepwise procedure, and that are therefore most suited for delineating the source rocks, are Mn, Cu, Zn, Sn, and U.

Geochemical Fingerprints of Specific Land-Use Categories

The above analysis revealed that bedrock lithologies had a significant influence on upland sediment geochemistry. This suggests, then, that land-cover types can be distinguished most effectively by multivariate methods when they are underlain by a single (relatively homogeneous) rock unit. Thus, it was decided to focus on the sediments from three land-use categories in addition to alluvial deposits along upland streams within the area underlain by the Whiteside Granite. The Whiteside Granite was selected for study for two reasons: (1) it encompasses a majority of the terrain surrounding Fairfield Lake (Fig. 2), and (2) the abundance, access to, and topography of the various sediment sources underlain by the Whiteside Granite allowed for the collection of a greater number of samples, and thus, a more spatially complete data set than could be developed for the Tallulah Falls Formation.

Differentiation of the land-use categories on the basis of sediment geochemistry relied on linear discriminant analysis and is similar to that which was used to delineate sediments collected from the two bedrock formations. In this case, however, only samples from the Whiteside Granite were utilized, and the samples were stratified into four categories including those collected from forests, roads, lawns, and alluvium of selected upland creeks. Table 4 summarizes the mean and standard deviations of the geochemical data used in the analysis.

The stepwise procedure was able to effectively separate the samples from the four source area categories. In fact, the Jackknifed classification matrix presented in Table 6 shows that 86 % of the samples were correctly classified. Materials collected from forested terrains (31 samples) and lawns (9 samples) were most effectively delineated, whereas the materials obtained from roads (19 samples) and alluvium (11 samples) were more difficult to separate. The difficulties in separating sediments from roads and alluvium comes as no surprise as the materials from the roads were generally collected from the adjacent drainage ditch, and their physical characteristics appear similar to that found within stream banks.

A total of 9 elements were incorporated into the discriminant model to effectively separate the four sediment source areas. They include Ag, Bi, Cr, Mo, Mn, Ni, Sb, Sn, and Zn. Based on the F-to-remove statistics, the most useful elements in the model are Sb and Zn, followed by Sn, Ni, Mn, and Cr. Ag and Bi appear to be the least useful variables. SYSTAT calculates Wilks' lambda, a multivariate statistic that tests the equality of group means between the elements included in the discriminant functions, and converts it into an approximate F statistic. Comparison of this statistic with the F distribution generates an associated probability of <0.0001, suggesting that there is a highly significant difference between the groups.

TABLE 6
Summary of Discriminant Analysis
Applied to Sediment Sources within the Whiteside Granite

Classification Matrix					
Land-Use	*Forests*	*Roads*	*Lawns*	*Alluvium*	*Percent Correctly Classified*
Forests	31	0	0	0	100
Roads	0	16	1	3	80
Lawns	0	0	9	0	100
Alluvium	0	1	1	9	82
Number of Samples	31	17	11	12	92

Jackknifed Classification Matrix					
Land-Use	*Forests*	*Roads*	*Lawns*	*Alluvium*	*Percent Correctly Classified*
Forests	29	1	1	0	94
Roads	1	15	1	3	75
Lawns	0	0	9	0	100
Alluvium	0	2	1	8	73
Number of Samples	30	18	12	11	86

Model Summary	*Factor 1*	*Factor 2*	*Factor 3*
Eigenvalues	3.608	1.152	0.821
Canonical Correlations	0.885	0.732	0.671
Standarized Constants for Discriminant Functions			
Ag	0.57	0.173	-0.67
Bi	-0.16	0.45	-0.12
Cr	2.00	0.01	1.25
Mn	0.20	1.16	-0.93
Mo	-0.51	-0.08	-0.36
Ni	-0.48	-0.76	-0.50
Sb	0.95	-0.29	1.01
Sn	0.14	0.30	-1.37
Zn	-0.60	-1.38	1.06

While the groups can be separated on the basis of the elements used, some investigators have argued that the elements included in sediment mixing models should be able to delineate the different sediment sources 100 % of the time (Collins et al. 1997a). Our data falls short of such a high degree of accuracy. However, the collected samples are currently being analyzed for an additional suite of elements including the major cations and Al, Si, and Ti at the time of this writing. Once these analyses are complete, the discriminant procedure will be re-applied to determine if a more effective delineation can be obtained by a different suite of parameters.

Depositional Patterns within Fairfield Lake

A total of 19 cores were obtained from Fairfield Lake to determine the general depositional patterns that have occurred within the reservoir during the past 111 years (Fig. 6). The cores ranged from 0.3 to 2 m in length (Table 7). In most cases, the length of the core recovered exceeded 85 % of the total coring depth (Table 7). The difference in these two measures is generally attributed to sediment compaction. However, Wright (1991) argues that in many cases, the reduction in core length (i.e., the recovery) is not related to compaction, but to the formation of a "plug" within the piston coring device. Once it has formed, further penetration of the device forces sediment beneath the piston to the sides where it passes along the outside of the tube. In our case, the reduction in core length, in comparison to coring depth, is thought to be primarily related to compaction and not the formation of a "plug" within the tube. In Fairfield Lake, many of the fine-grained lake bed sediments are highly saturated and organic rich, particularly in the upper segment of the reservoir where recovery tended to be the worst. Such sediments are known to be easily compacted upon disturbance. In addition, loss due to plug formation is generally associated with continued motion after a sediment plug has developed within the tube. This most often occurs when the coring device is pushed into the sediment to a certain depth, and then after coming to rest, is pushed farther. This practice was avoided in areas where recovery was a concern. In fact, in many cases, several attempts were made at the same site to recover the most complete cores possible by shoving the piston coring device into the sediments in a single, continuous motion.

In order to accurately determine sedimentation rates within the reservoir it is essential to be able to delineate the contact between the lake bed sediment and the underlying geologic materials. In several cores, the contact was delineated by a buried soil and could therefore be identified with a reasonable degree of certainty on the basis of sediment color, soil structure, and/or the presence of clay films on soil grains and ped faces. In a majority of the cores, however, delineation of the contact between lake bed materials and underlying alluvial deposits proved to be much more difficult than anticipated because the general sedimentology of the deposits were similar. Sediments associated with both lacustrine and fluvial depositional processes were characterized by interbedded fine- and coarse-grained materials, many of which were of similar composition. Ultimately, the boundary between lacustrine and alluvial sediments was interpreted on two parameters. First, some of the lacustrine sediments contained an abundance of partially decomposed plant debris, were black in color, and exhibited a low bulk density. Although these units were commonly separated by loose, loamy sand beds, and therefore did not necessarily reveal the base of the lake deposits, they could be used to determine the minimum depth (thickness) of the lacustrine sequence. Second, nearly all of the cores contained layers of

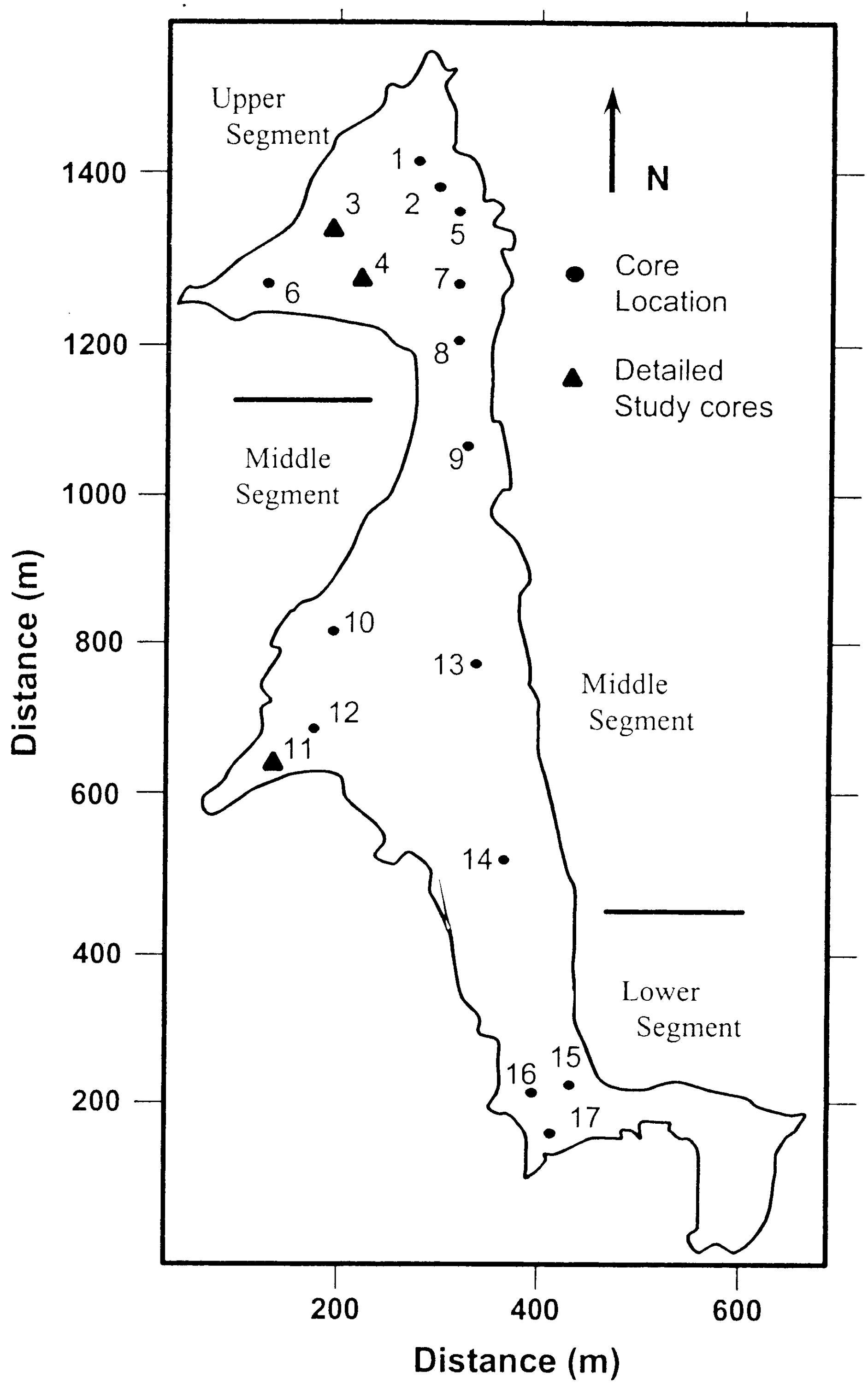

Figure 6. Location of coring sites within Fairfield Lake.

TABLE 7
Summary of Core Data and Estimated Sedimentation Rates

Sample Number	Total Depth (cm)	Average Percent Recovered	Thickness of Lacustrine Deposits (cm)		Sedimentation Rates[2] (cm/yr)	
			Uncorrected	Corrected[1]	Uncorrected	Corrected[1]
Core 1A/B	115	83	79	97	0.71	0.87
Core 2A/B	150	55	34	63	0.31	0.57
Core 2C	100	80	>80	>100	0.72[4]	0.90[4]
Core 3A/B	164	89[3]	53	59	0.48	0.53
Core 4A/B	140	96	106	130	0.95	1.17
Core 4C	93	95	>87	>93	0.78[4]	0.83[4]
Core 5A/B	200	86	10	13	0.09	0.12
Core 6A/B	124	90	78	84	0.70	0.76
Core 7A/B	143	97	2	2	0.02	0.02
Core 8A	35	91	>30	>35	0.27[4]	0.32[4]
Core 10A/B/C	177	100	9	9	0.08	0.08
Core 11A	80	91	60	65	0.54	0.59
Core 12A	98	94	>92	>98	0.83[4]	0.89[4]
Core 12B/C	172	87	88	98	0.79	0.88
Core 13A	100	78	0	0	0.00	0.00
Core 14A	30	100	10.5	10.5	0.09	0.09
Core 15A	50	90	>45	>50	0.41[4]	0.45[4]
Core 16A	49	73	>67	>49	0.32[4]	0.44[4]
Core 17A/B	113	95	6	6	0.05	0.05

1 – reported data have been corrected for compaction.
2 – sedimentation rates based on dam closure of 1890 (111 yrs).
3 - 92 % recovered in Core 3A.
4 – Represents minimum possible sedimentation rates based on corrected and uncorrected deposit thicknesses.

subangular quartz and feldspar clasts that ranged from 1 to 2 cm in diameter. In many instances, these beds were part of a fining upward sequence ranging from gravel to fine sand, and were on the order of 40 to 50 cm in thickness. These deposits were not only located close to the margins of the lake, but throughout its axis. Given the low gradient of the lake bed, it seems highly unlikely that such thick deposits of coarse material could be carried into the center of the reservoir to produce the fining upward sequences that are observed. Thus, these layers have been interpreted to represent alluvial materials deposited prior to lake/dam construction. This interpretation is supported by ^{210}Pb data (presented below) that suggest that the sediment immediately overlying a coarse unit dates to approximately 1885.

Based on the above interpretations, sedimentation within the lake has been limited. Most cores reveal that less than 1 m of lake bed deposition has occurred since dam closure in 1890 (Table 7) and it seems improbable that deposits greater than 1.5 m exist anywhere within the reservoir. Assuming uniform deposition through time, calculated sedimentation rates are well below 1 cm/yr for most of the coring locations (Table 7). Examination of the lacustrine deposits shows, however, that they are composed of alternating sequences of fine and coarse (sand-sized) sediments. In addition, the contacts between these beds are commonly abrupt. These stratigraphic relations indicate that sedimentation rates have not been uniform during the past century. Rather, lacustrine deposition appears to have been characterized by periods of relative slow, uniform deposition of silts and clays that are separated by periods of rapid deposition of loose, well-sorted sands.

The thickest lacustrine deposits occur in the upper segment of the lake (Cores 1A/B, 2A/B, 2C, 3A, 4A/B, 4C, 6A/B). Deposition in this area may be promoted by (1) inflow of water and sediment from two significant tributaries (Fig. 3); (2) relatively shallow water (Fig. 5), and (3) a larger abundance of aquatic vegetation than is found in other regions of the lake. The latter factor has led to lake bed deposits that are characterized by an abundance of partially decomposed plant debris. Thick lacustrine deposits are also found along the axis of the embayment in the middle segment of the lake (Cores 11A, 12A, 12B/C; Table 7; Fig. 6), whereas cores located along the margins of the lake (e.g., Core 10A/B/C, and farther downvalley, Core 17A/B) encountered buried soils at shallow depths and exhibit rather low sedimentation rates.

Lake bed sediments appear to be very thin along the axis of the lake. The lacustrine sequence in Cores 5A/B, 7A/B, and 14A are less than 15 cm thick, whereas coarse alluvial gravels are at the lake bed surface at coring site 13A (Fig. 6; Table 7). Similarly, coarse gravels were encountered at coring site 9 near the surface prohibiting the collection of the lake bed sediments (Fig. 6). The thickness of the lacustrine deposits increases to approximately 50 cm or more at coring sites 15A and 16A located near the sharp bend in the lower reaches of the lake. These sediments could be associated with the inflow of debris from two tributaries that enter the lake from the southwest (Fig. 3). The observed depositional patterns suggest that a majority of the sediment that enters the lake from the surrounding streams is rapidly deposited near their mouths, limiting the accumulation of debris within the deeper water areas of the reservoir.

Temporal Variations in Sedimentation Rates

The general sedimentologic and stratigraphic characteristics of the cores investigated in detail (Cores 3A, 4A/B, and 11A) are illustrated in Figures 7-9. The cores were selected on the basis that (1) the lacustrine sediments were relatively thick and well-preserved, allowing for a greater sampling interval and a reduction in sampling error, (2) the cores extended through all of the lacustrine materials, insuring that the entire record of deposition within the lake could be examined (assuming there were no significant erosional events), and (3) sediment recovery was better than 90 % for the sections of the core that were geochemically analyzed. In addition, the selection of cores from both the upper and middle segments of the lake allows for a comparison of the influx of sediment from different subbasins of the Fairfield Lake drainage system. Water depths and the coarse grained nature of the sediment within the lower segment of the lake prohibit the collection of cores that extended through the entire thickness of the lacustrine deposits. Thus, cores from this area were not selected for detailed study.

The use of ^{137}Cs and ^{210}Pb to estimate the rates of sediment accumulation in lakes and reservoirs has become a well-established procedure (Ritchie et al. 1973; Robbins and Edgington 1975; Krishnaswami and Lal 1978; Walling and He 1993; Dickin 1997). Approximately 20 samples were collected from all three cores and analyzed for ^{137}Cs and ^{210}Pb by Dr. Robert Flett (Flett Research Ltd.) located in Winnepeg, Canada. Levels of ^{137}Cs within the samples were below the

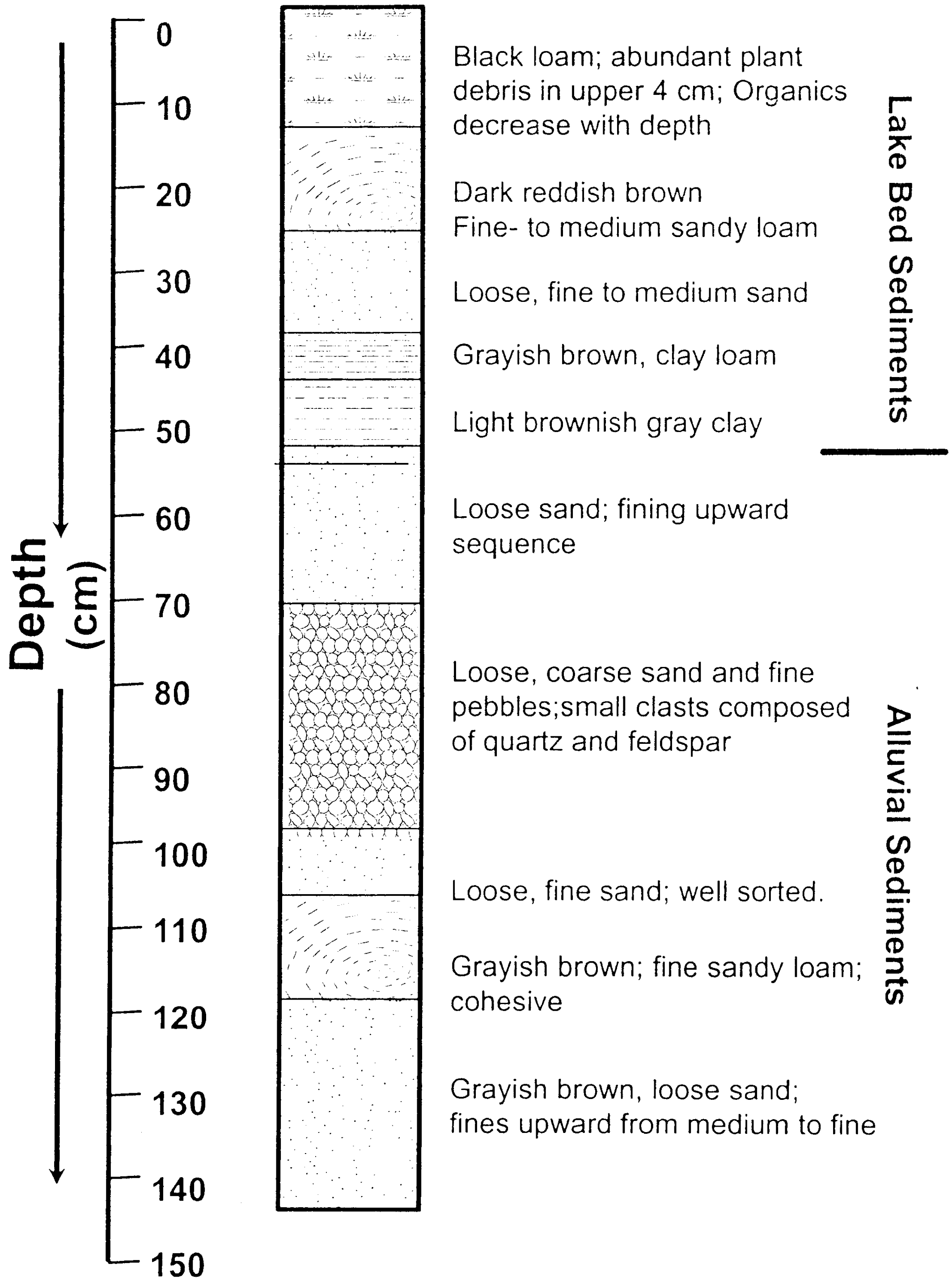

Figure 7. General stratigraphy of Core 3A.

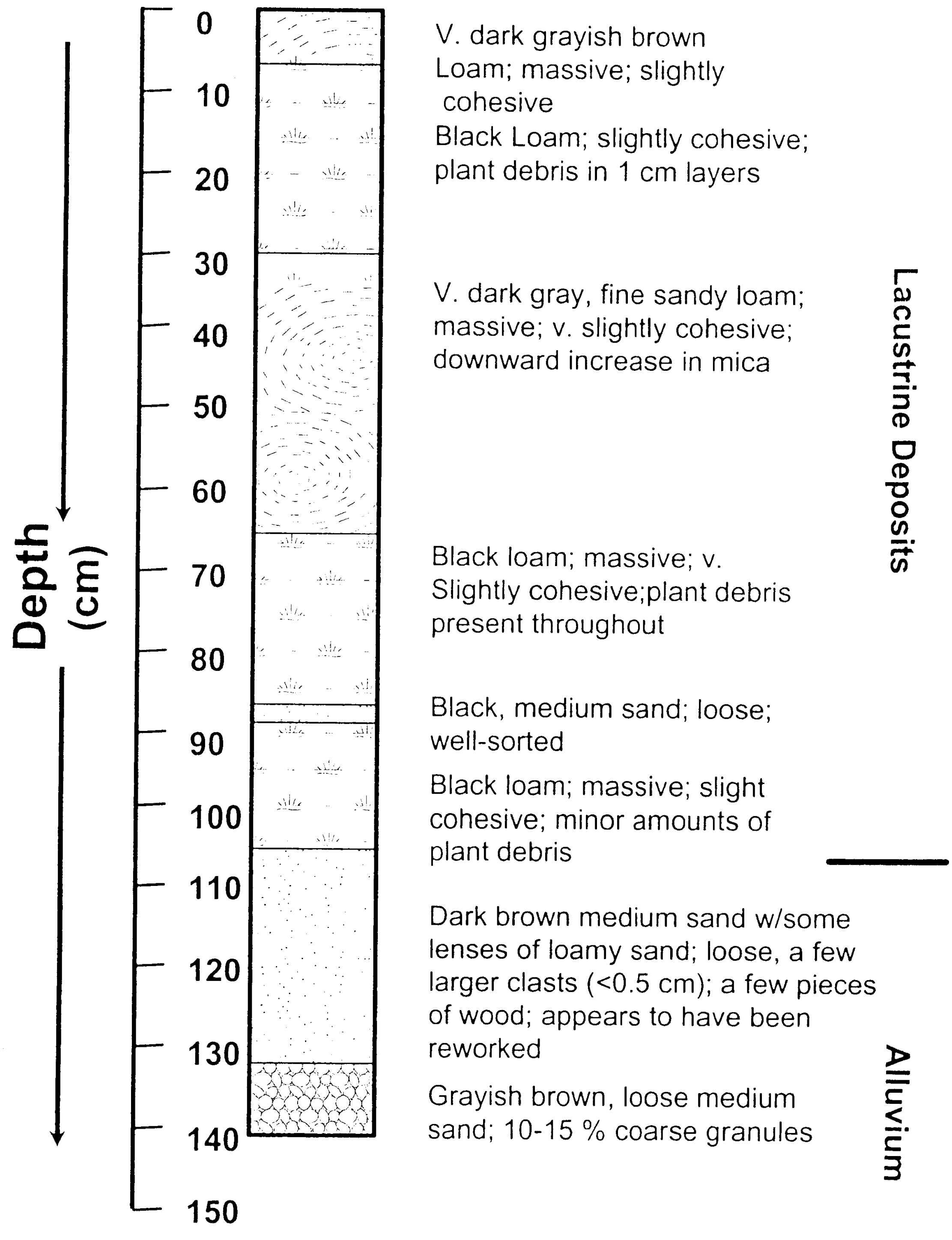

Figure 8. General stratigraphy of Core 4A/B.

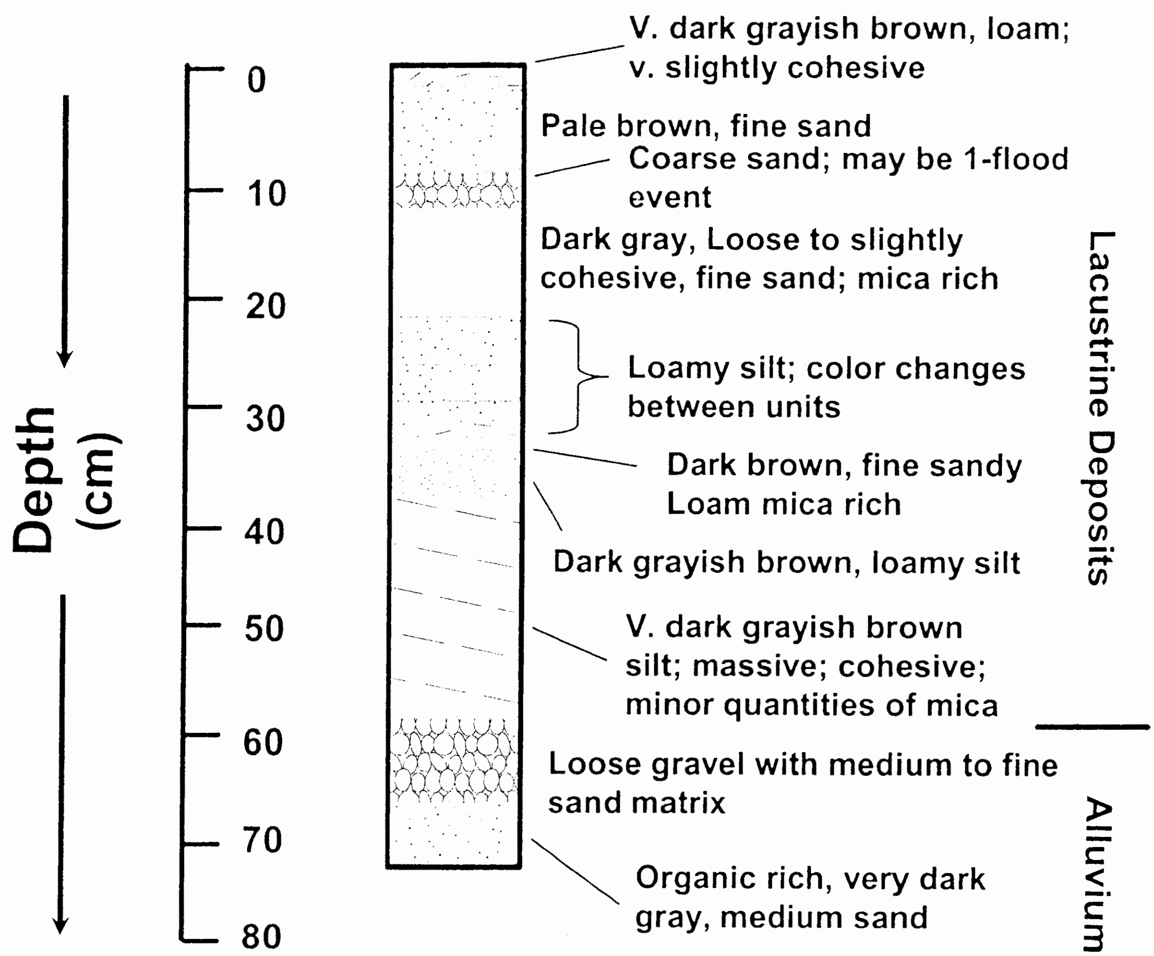

Figure 9. General Stratigraphy of Core 11A.

limits of detection. The levels of ^{210}Pb were also low, but could be accurately determined. The raw data suggest that the coring sites experienced varying rates of lacustrine deposition. Therefore, deposit age was estimated using the CRS model which allows for variable sedimentation rates. However, the model assumes that the input of ^{210}Pb is constant over time. The episodic influx of ^{210}Pb to the system will invalidate this assumption and, therefore, the dates supplied by the model need to be used with some degree of caution.

One method to check the obtained age estimates is to use the age-depth curves presented in Figure 10 to determine the age of the materials at the base of the lacustrine sequence. These materials should have begun to accumulate shortly after dam closure in 1890. The lower most unit of the lacustrine materials in Core 4A/B is characterized by a medium sand that contains small, irregular-shaped lenses of loamy sand. It also contains a few pieces of woody debris. This unit has been interpreted to represent the reworking of the alluvial materials during the onset of lacustrine deposition. Projection of the age-depth curve in Figure 10 to the base of these lacustrine sediments generates an age of approximately 1885, a date close to, but shortly before dam closure in 1890. The basal lacustrine materials in Cores 3A and 11A were more difficult to define, but appear to date to approximately 1932 and 1917, respectively. Thus, ^{210}Pb underpredicts the age of the deposits. However, it is important to recognize that minor changes in the depth at which the alluvial-lacustrine contact is defined leads to rather large changes in unit age because the sedimentation rates at this period in time are relatively low. For example, a decrease of approximately 2.5 cm in depth of the lacustrine-alluvial contact in Core 11A would provide an age of 1890, the assumed date of dam closure. The point is that minor changes in either the depth-age curve produced by the CRS model or the depth of the contact measured during the sampling process could account for the difference observed between the age of the basal reservoir materials and the date of reservoir construction. At this time, the dates provided by ^{210}Pb need to be used with particular caution for cores 3A and 11A. However, the future collection of ^{137}Cs data (using a more sensitive detector) may allow us to better constrain the age of the sediments within the cores.

While the actual age of the sediments may vary slightly from those estimated here, the relative increases or decreases in accumulation rates through time are likely to be accurately portrayed by the data. All three cores show recent, several fold increases in sedimentation rates during the past few decades (Fig. 10; Table 8). Sedimentation rates during the first half of the 20th century appear to be on the order of 0.20 to 0.50 cm/yr. In contrast, accumulation rates during the past two decades reached a maximum of 3.05 and 3.75 cm/yr for Cores 3A and 4A/B, respectively. The maximum sedimentation rate observed in Core 11A is 10 cm/year. This rate corresponds to the deposition of a 12 cm layer of sediment near the top of the core. ^{210}Pb data suggest that these materials were deposited in about 2.5 months. Examination of the unit shows, however, that it consists of a fining-upward sequence of fine to coarse sand that is likely to have been deposited in a single runoff event. Thus, a sedimentation rate on the order of, or slightly greater than, 2.42 cm/yr, determined from the period of 1996 to 2000, is probably more representative of the long-term deposition at this coring location. Nonetheless, it illustrates how large "slugs" of sediment can be introduced to the lake in a short period of time if it is available for transport within the basin.

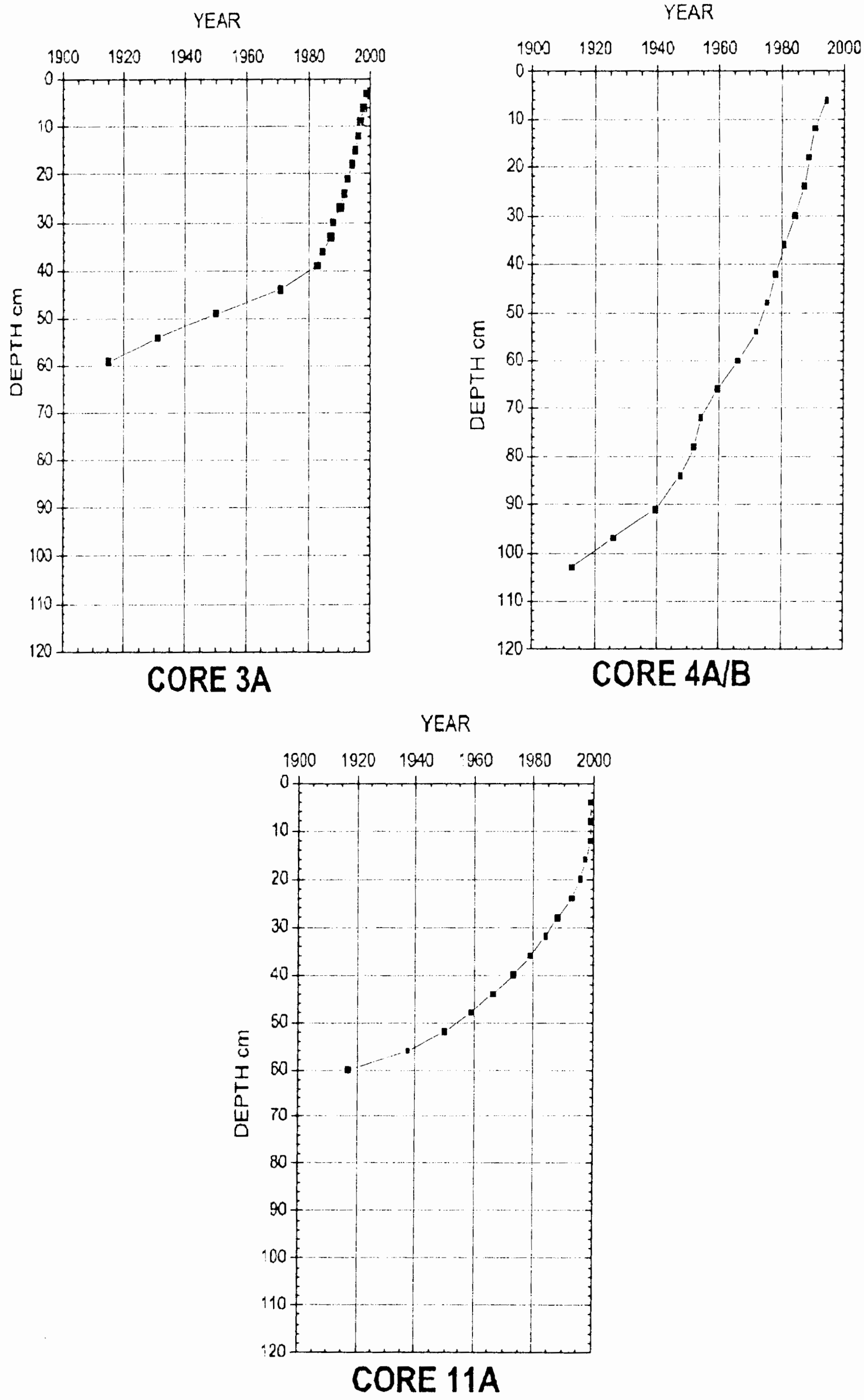

Figure 10. Depth-age curves for Cores 3A, 4AB, and 11A based on ^{210}Pb data.

Cores 3A and 11A both suggest that sedimentation rates increased substantially in the mid- to late 1980s, and have increased even more dramatically within the past five years (Table 8). Core 4A/B suggests that the influx of large amounts of sediment may have begun before the 1980s, and that sedimentation has recently decreased slightly from a maximum that occurred in the late 1980s. The difference in the timing, and rate, of sedimentation portrayed by Core 4A/B and the other two cores is not completely understood. However, the spatial patterns of sedimentation within the lake vary significantly, as shown above, and these patterns are likely to play a significant factor in controlling the observed variations in sediment accumulation rates. In particular, Cores 3A and 11A are both located within the confines of embayments along the west side of the reservoir, whereas Core 4A/B is located in more open water near the mouth of an embayment (Fig. 6).

Modeling Sediment Source Area Contributions

Nature and Development of the Sediment Mixing Models

The complex processes involved in the erosion, transport, and deposition of sediment ultimately result in a deposit that represents a mixture of material derived from multiple source areas within the watershed. If the physical and geochemical properties of the source area sediments are conserved during the transportational and depositional process, then it is possible to determine the relative contributions that each source contributed to the resulting mixture. Total conservation of parameter values is rarely achieved in nature. Nonetheless, some properties are generally conserved. This prompted Yu and Oldfield (1989) to develop an empirically based, sediment mixing model that was capable of determining the relative contributions of material

TABLE 8

Summary of Sedimentation Rates Calculated on the Bases of ^{210}Pb Dating

Core Number	Depth Range (cm)	Age Range (YBP)	Calendar Years	Sedimentation Rate (cm/yr)
Core 3A	0-18	0-5.9	1995-2001	3.05
	18-39	5.9-17.2	1983-1995	1.86
	39-44	17.2-29.2	1971-1983	0.42
	44-54	29.2-69.1	1931-1971	0.25
Core 4A/B	0-18	0-11.2	1989-2001	1.61
	18-24	11.2-12.8	1988-1989	3.75
	24-54	12.8-27.9	1973-1988	1.99
	54-91	27.9-60.6	1940-1973	1.13
	91-103	60.6-87.5	1913-1940	0.45
Core 11A	0-12	0-1.2	2000-2001	10.00[1]
	12-20	1.2-4.5	1996-2000	2.42
	20-32	4.5-15.8	1985-1996	1.06
	24-56	15.8.-62.5	1938-1985	0.55
	56-60	62.5-83.1	1917-1938	0.19

[1] – Deposition is likely to have occurred during one flood event.

from different source areas to the Rhode River Estuary on the western shore of Chesapeake Bay. The model proposed by Yu and Oldfield (1989) has since been modified and improved to determine the provenance of suspended sediments (Collins et al. 1997a, 1998), floodplain deposits (Collins et al. 1997a), and reservoir bed materials (Yu and Oldfield 1993). We modify and used the basic sediment mixing model first proposed by Yu and Oldfield (1989) and later modified by Collins et al. (1997a). Constraints on the mixing model require that (1) each source type contributes some sediment to the mixture, and thus the proportions derived from *n* individual source areas (x_j, j=1,2,...*n*) must be positive ($0 < x_j \leq 1$), and (2) the contributions from all of the source areas must equal unity, i.e.:

$$\sum_{j=1}^{n} x_j = 1 .$$

In addition, some differences (error) between the values of the measured parameters in the source area and the mixture must be allowed. For any individual parameter, the error can be determined as follows:

$$\varepsilon_i = b_i - \sum_{j=1}^{n} a_{ij} x_j$$

for i=1,2,...m, where b_i (i = 1, 2, 3.....m) are the measurements on "m" independent parameters within the sediment mixture, a_{ij} (i = 1, 2, 3....m, j=1,2,...*n*) are the measurement on the corresponding i^{th} parameter within the j^{th} source area, x_j is the proportion of the j^{th} source component in the sediment mixture, and ε_i is the residual error corresponding to the i^{th} parameter. When the number of measured parameters is greater than the number of source areas ($m \geq n$), the system of equations is over-determined, and a "solution" must be obtained using an iterative computational method that minimizes an objective function, thereby obtaining a best fit solution to the entire data set (Yu and Oldfield 1989). There are several ways to obtain a best fit, but in previous studies, the objective function, f, has taken the form of the sum of the relative errors where $f(x_1,\ldots,x_m) = \sum_{i=1}^{m} \left|\varepsilon_i / b_i\right|$ (Yu and Oldfield 1989) or

$f(x_1,\ldots,x_m) = \sum_{i=1}^{m} \left(\varepsilon_i / b_i\right)^2$ (Collins et al. 1997a). We use the later form for f, as it is consistent with the least squares problem.

In essence, these sediment mixing models require that the parameters that most effectively separate the land-cover types are measured in both the source area sediments and the mixture (deposits). Subsequently, the relative contributions from each sediment source are adjusted using an iterative process until the differences (error) between the measured parameter values in the source materials and the deposits are minimized for all of the utilized properties. The iteration scheme used for this non-linear constrained optimization problem is the generalized reduced gradient method (Lasden et al. 1978).

Recent studies by Collins and his colleagues have argued that various correction factors need to be incorporated into the mixing models to account for difference in parameter values that are likely to result during erosion, transport and deposition. Perhaps of most importance is the inclusion of a particle size correction factor. Particle size has a significant influence on sediment geochemistry (Whitney 1975; Ackermann 1980; Forstner 1982; Salomons and Forstner 1984; Horowitz and Elrick 1988). Thus, small differences in particle size distribution that occur by hydraulic sorting or selective deposition may result in large differences in parameter concentrations. As a result, many geochemical and mineralogical properties cannot be directly compared unless a correction factor is utilized in the sediment mixing models (Collins et al 1997a), Correction factors were developed for our models following the procedures of Collins et al. (1997b).

In this study, sediment mixing models were developed and applied to each sample contained within the three cores selected for detailed investigation. One model was constructed to define the relative contributions from differing rock types and a second to define contributions from 4 different sediment sources within the Whiteside Granite.

A significant problem with the use of sediment mixing models is that a verification of the results is difficult to perform. Nevertheless, the utilization of the models requires some form of verification to insure that the results are credible. In this investigation, two approaches were utilized. First, we examined how well the modeling results fit the data (i.e., the goodness-of-fit) by comparing the measured parameter values in the mixture with the predicted values. The assessment of these relative errors provided insights into whether the mixing model resulted in an acceptable prediction of the fingerprinting properties. The mathematical expression used to estimate relative error is given by:

The relative error: $$\%error = \sqrt{\frac{\left(\sum_{i=1}^{m}\left(b_i - \sum_{j=1}^{n} a_{ij}x_j\right)\right)^2}{\sum_{i=1}^{m}(b_i)^2}} * 100\%$$

Second, temporal changes in the relative contributions of sediment from the identified source areas as defined by the model were compared to changes in land-use practices as determined from sequential aerial photographic mapping. In essence, this process assesses whether the model results are intuitively correct.

Selection of Multivariate Fingerprinting Parameters and Modeling Results

Once the basic form of the model had been developed, an initial run was conducted using all of the elements that had been included in the discriminant analysis to differentiate between the two predominant bedrock sources, and within the Whiteside Granite, the three land-use categories plus upland alluvium. These initial runs exhibited extremely large relative errors. Inspection of the data revealed that the error was primarily related to concentrations of some elements within the cores that were lower than the concentrations measured within the upland soils. As mentioned earlier, it is generally accepted that differences in concentration between the upland soils and the lake can result from changes in organic matter content or grain-size; materials with more organic carbon and/or a higher percentage of fine sediment exhibit higher elemental values (Horowitz and Elrick 1988). Thus, changes in these two parameters could be responsible for the observed differences in the geochemistry between the lacustrine sediment and hillslope materials. However, in this case, the lake bed sediments tend to be finer-grained and possess more organic matter than the upland sediments. As a result, when the effects of these two parameters were removed (by normalization) the differences actually increased. In fact, for some core samples, relative error exceeded 125 %. In addition, correlation analysis found that the relations between organic carbon content (which ranged from 0.5 to 6.3 %) and element concentrations were not statistically significant (Table 9). The relations between the percent silt and clay in the sample did correlate with the concentrations of some elements, but these correlations were relatively weak (Table 9). Thus, there was no evidence to suggest that organic matter and grain size weighting factors should be included in the models used here.

An assumption inherent in the application of mixing models to the determination of source area contributions is that the elements are conserved during the transport of sediment from the uplands to the depositional sites. This is clearly not the case for the Fairfield Lake Basin. At this time, the processes responsible for the loss of elemental mass are not fully understood. However, it is probably related, in part, to the intense weathering of the material during transport through the upland streams and the loss of the mass from the drainage system in solution.

Regardless of the processes responsible for reduced concentrations within the cores, the use of parameters which exhibit large differences in concentration between the uplands and the lake inhibits the effective modeling of the source area contributions. Thus, the elements that exhibited the largest differences were removed. For the case of modeling the contribution from the two rock types, Mn was extracted from the model. Mn and Cr were removed from the mixing models used to determine source area contributions for the various land-use categories.

Previous studies have also shown that mixing models tend to be more effective if number of parameters included in the model are equal to the number of potential source areas. Thus, Bi was removed from the land-use model because it was the least significant parameter in differentiating between the various land-use categories.

In order to determine if the reduced suite of elements could be effectively distinguished between rock type and land-use sediment sources, the remaining parameters were reexamined using linear discriminant analysis as used earlier. In the case of differentiating between rock types, the remaining elements could adequately separate the groups with only a minor loss of classifying power (Table 10). The reduction in parameters for the separation of four source areas within the Whiteside Granite was more significant, resulting in about a 10 % loss in classifying power (Table 11). It is hoped that the inclusion of additional elements, which are currently being analyzed for, will increase our ability to separate these groups, but at this point in our analysis, Ag, Mo, Ni, Sb, Sn, and Zn were used to model source area contributions.

The results obtained from the models are shown on Figures 11-12. The results generally exhibit less than 10 % relative error.

TABLE 9

Pearson Correlation Coefficients for Selected Elements,
Percent Silt and Clay (<63 μm), and Percent Organic Carbon (Loss-on-Ignition)

	Carbon	Mud	Ag	Bi	Cr	Cu	Mn	Mo	Ni	Sn	Sb	U	Zn
Carbon	1.00												
Mud	0.17	1.00											
Ag	0.12	0.02	1.00										
Bi	-0.02	0.05	0.00	1.00									
Cr	-0.07	0.07	0.01	0.14	1.00								
Cu	-0.04	0.05	0.11	0.12		1.00							
Mn	-0.05	-0.02	0.04	0.26	0.57	0.57	1.00						
Mo	0.12	0.10	0.30	0.18	0.44	0.66	0.31	1.00					
Ni	0.01	0.23	0.05	-0.15	0.76	0.62	0.70	0.40	1.00				
Sn	-0.01	0.21	0.13	0.26	0.74	0.72	0.67	0.58	0.58	1.00			
Sb	0.19	0.11	0.66	0.24	0.25	0.40	0.24	0.52	0.52	0.28	1.00		
U	0.16	0.34	-0.01	0.09	-0.15	-0.30	-0.11	-0.12	-0.12	-0.15	-0.10	1.00	
Zn	-0.09	0.14	-0.02	0.26	0.58	0.62	0.63	0.34	0.34	0.73	0.55	-0.01	1.00

TABLE 10

Summary of Revised Discriminant Analysis
Applied to Bedrock Formations within the Fairfield Lake Basin

Classification Matrix			
Rock Type	*Whiteside Granite*	*Tallulah Falls Formation*	*Percent Correctly Classified*
Whiteside Granite	67	4	94
Tallulah Falls Formation	4	32	89
Number of Samples	71	36	93
Jackknifed Classification Matrix			
Rock Type	*Whiteside Granite*	*Tallulah Falls Formation*	*Percent Correctly Classified*
Whiteside Granite	67	4	94
Tallulah Falls Formation	4	32	89
Number of Samples	71	36	93

Model Summary	*Factor 1*
Eigenvalues	2.008
Canonical Correlations	0.817
Standarized Constants for Discriminant Functions	
Cu	1.113
Sn	0.157
U	-0.243
Zn	-0.442

Note: Mn has been removed from original discriminant analysis.

TABLE 11
Summary of Revised Discriminant Analysis
Applied to Land-Use Categories within the Whiteside Granite

Classification Matrix					
Land-Use	*Forests*	*Roads*	*Lawns*	*Alluvium*	*Percent Correctly Classified*
Forests	24	2	5	0	77
Roads	0	17	1	2	85
Lawns	0	1	8	0	89
Alluvium	0	3	0	8	73
Number of Samples	24	23	14	10	80

Jackknifed Classification Matrix					
Land-Use	*Forests*	*Roads*	*Lawns*	*Alluviums*	*Percent Correctly Classified*
Forests	24	2	5	0	77
Roads	0	16	2	2	80
Lawns	0	1	8	0	89
Alluvium	0	3	0	8	73
Number of Samples	24	22	15	10	79

Model Summary	*Factor 1*	*Factor 2*	*Factor 3*
Eigenvalues	3.405	0.755	0.448
Canonical Correlations	0.879	0.656	0.556
Standarized Constants for Discriminant Functions			
Ag	-0.647	0.125	-0.604
Mo	-0479	0.230	-0.156
Ni	0.344	0.533	-0.017
Sb	-0.772	-0.015	1.055
Sn	-0.243	0.185	-1.252
Zn	0.454	0.228	1.003

Note: Mn, Cr, and Bi have been removed from original discriminant analysis.

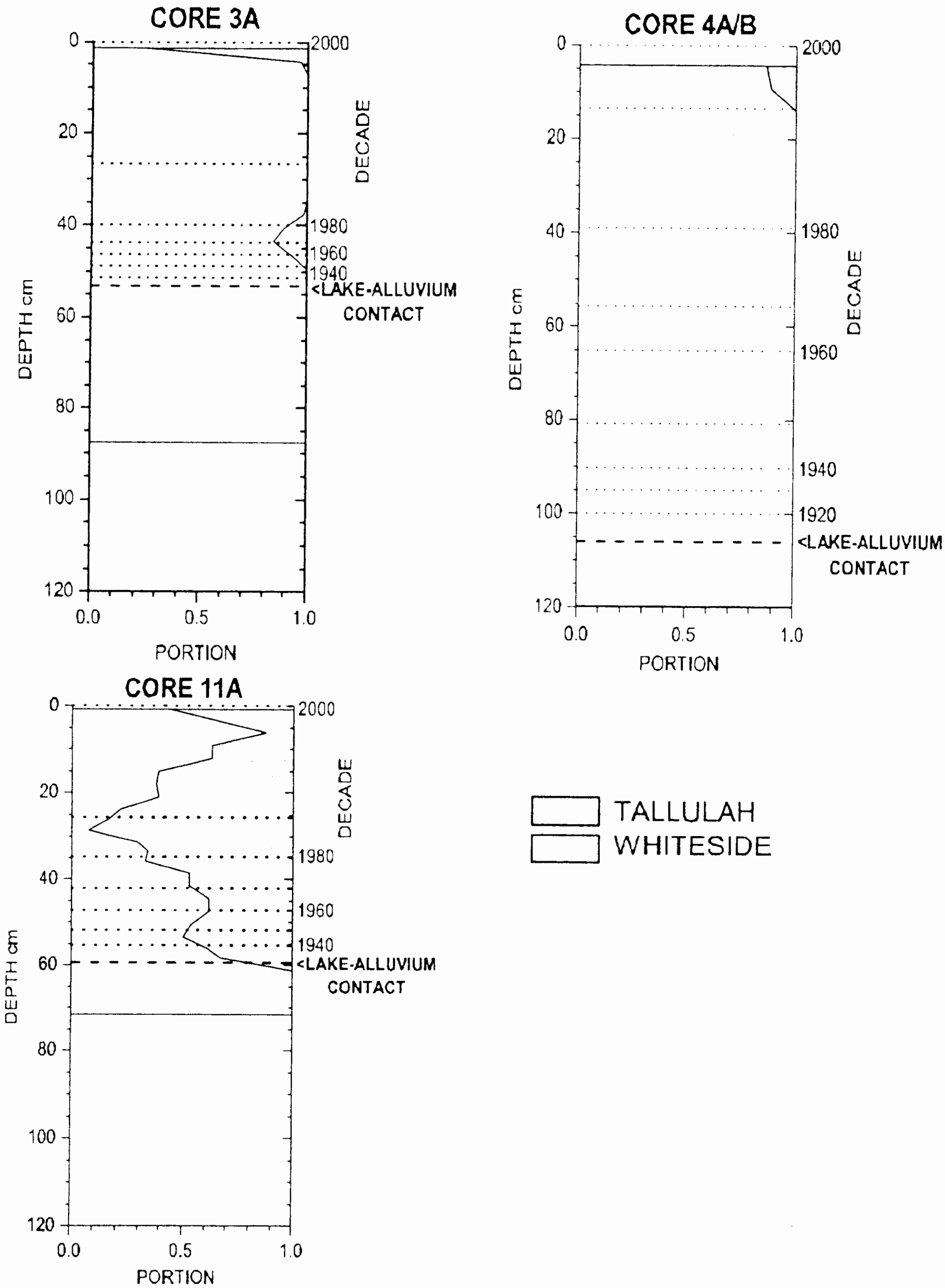

Figure 11. Estimated contributions of sediment from bedrock sediment sources.

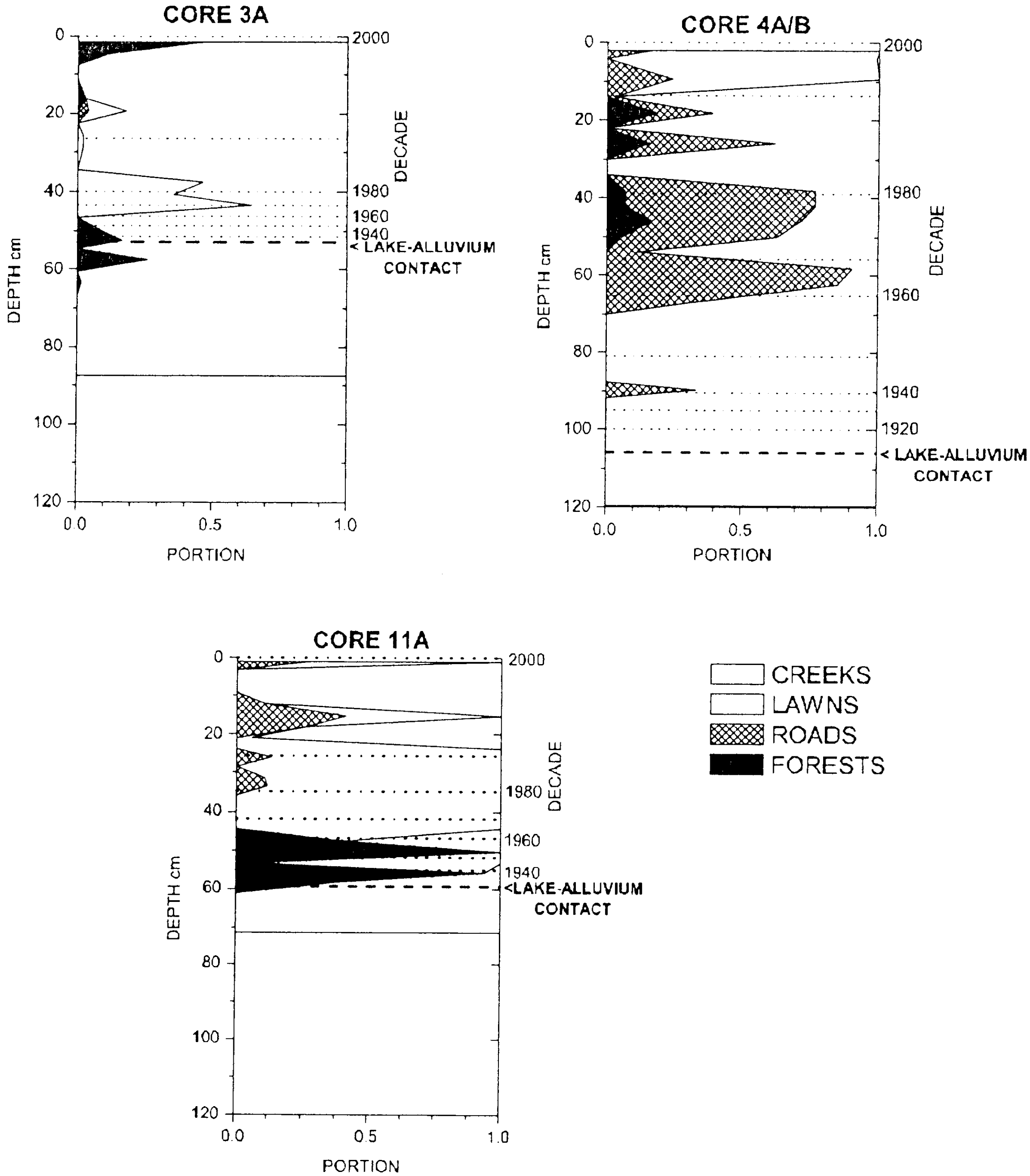

Figure 12. Estimated contributions of sediment from land-cover types located within the Whiteside Granite.

DISCUSSION

Defining Source Area Contributions from Differing Rock Types

The Whiteside Granite underlies approximately 75 % of the Fairfield Lake basin and nearly all of the subbasins that contribute sediment to the upper and middle segments of the lake. It could be reasonable argued, then, that most of the sediment found within the lake, and particularly within Cores 3A and 4A/B which were obtained from the upper lake segment, should be derived from the Whiteside Granite. This hypothesis is supported by the fact that spatial depositional patterns within the lake suggest that there is very little transport of silt- and sand-sized particles between lake segments. Rather, most of the sediment appears to enter the lake from tributary channels and remain close to the tributary mouths. Having said the above, it has been recognized in other environments that more easily eroded lithologies may contribute substantially larger proportions of sediment to lakes and reservoirs even when their areal distribution is limited.

The mixing model estimates that the Whiteside Granite supplies nearly all of the sediment to the lake at coring sites 3A and 4A/B (Fig. 11). While these are encouraging results, there are some minor exceptions. In Core 3A the model suggests that 7 to 15 % of the sediment between 42 and 48 cm in depth is derived from the Tallulah Falls Formation. Sedimentologically, this interval corresponds to a clay-rich unit that contains a relatively large amount of charcoal fragments. The ^{210}Pb data indicate that it was deposited over a period of about 2 decades (~1955-1977) and that sedimentation rates were relatively slow, being similar to those observed at the onset of dam closure. Given the lengthy settling times for clay-sized particles, and that clay comprises a significant proportion of the sample, it is possible that some of the material could have been transported from the lower segment of the reservoir to this site.

Not all of the data, however, support the contention that the sediment in Core 3A is derived from the Tallulah Falls Formation. For example, the modeling results for the lower 90 % of Core 4A/B do not indicate any significant contribution of sediment from the Tallulah Falls Formation. Given that Core 3A and 4A/B are in close proximity, and therefore should be composed of sediment from similar sources, the lack of sediments from the Tallulah Falls Formation in Core 4A/B is problematic.

Geological mapping and field observations in the area have revealed that the Whiteside Granite contains zones of more micaeous, mafic-rich rocks. Thus, an alternative explanation is that these micaeous rocks exhibit a geochemical fingerprint that is similar to the Tallulah Falls Formation. If this is the case, the modeling results illustrate variations in the contributions of sediment from two lithologies, both of which are associated with the Whiteside Granite. There are some mineralogical data to support this hypothesis. Table 3 shows, for example, that some samples of the Whiteside Granite can have nearly 30 % biotite; add to that muscovite and the rocks are very rich in mica (as is the case for rocks of the Tallulah Falls Formation). Micas are known collectors of a variety of cations. Therefore, it would not be unreasonable to see chemical signatures similar to the Tallulah Falls Formation where the two rocks types are in contact.

The mixing model estimates that the lower most section of Core 11A consists almost exclusively of the Whiteside Granite (Fig. 11). These sediments have been interpreted on the bases of core stratigraphy as alluvial deposits. Given that upvalley exposures of the Tallulah Falls Formation are extremely limited, the modeling results are reasonable. In contrast, the lacustrine sequence is portrayed to be a mixture of both the Whiteside Granite and the Tallulah Falls Formation (Fig. 11). However, the subbasin feeding the embayment is underlain exclusively by the Whiteside Granite and site 11A is located very close to the mouth of the tributaries that deliver most of the water and sediment to the middle segment of the lake. Thus, while it is possible that fine-grained sediment derived from exposures of the Tallulah Falls Formation surrounding the lower segment of the lake are deposited in the area of Core 11A, it seems improbable that more than 60 % of the sediment in the core could consistently be derived from the Tallulah Falls Formation. As suggested for Core 3A, a more plausible explanation is that the sediment designated as coming from the Tallulah Falls Formation is actually from the micaeous units within the Whiteside Granite.

Given the results derived from both Cores 3A and 11A, we are conducting a more in-depth assessment of the similarities and differences between the more mica-rich units within the Whiteside Granite and other sediment sources within the basin. This examination includes a comparison of the unit's geochemistry and mineralogy to that of the Tallulah Falls Formation and the lake bed sediments. Ultimately, the problem of differentiating between sediments of the Tallulah Falls Formation and other micaeous units within the watershed may be addressed using one of two approaches. First, the micaeous unit of the Whiteside Granite may be treated as a separate sediment source. Thus, the mixing models would examine the contributions of material from three lithologic units. For small watersheds, such as the Fairfield Lake Basin, this approach may work well. However, for larger watersheds, the approach may lead to an unmanageable number of different sediment sources. A second approach is to define sediment sources according to the gross mineralogical composition of the rocks. In this case, sediments from the Tallulah Falls Formation and the micaeous unit of the Whiteside Granite would be treated as a single source type. There is some merit to this approach in that previous studies have shown that rock units of similar composition also function similarly in terms of their erodibility. Model output may then lead to a conclusion that sediment from a particular lithologic (mineralogic) group tends to produce most of the sediment in an area and, therefore, these rock units should be treated differently (perhaps more stringently) in terms of management practices. The downside of this approach is that it requires a sound understanding of the lithology and distribution of the bedrock units prior to the sampling of the upland soils.

Defining Source Area Contributions from Differing Land-Use Categories

The modeling results obtained for Cores 3A and 4A/B suggest that the lacustrine sequence within the embayments of the upper lake segment are dominated by sediments from the Whiteside Granite. It should be possible to determine the contribution of sediment from each of the three land-use categories and the upland alluvium underlain by this particular rock type.

The developed model estimates that the material underlying the lacustrine sequence in Core 3A, which have been interpreted on the basis of core sedimentology to be alluvial deposits, are derived almost exclusively of floodplain sediments (alluvium) from the upland areas (Fig. 5). As land-use records suggest contributions from roads and lawns are minimal. The amount of sediment derived from forested areas is also trivial. The limited input of material from this source is consistent with local field observations of erosion following major runoff events that suggest that very little sediment is derived from this land-cover type. The lower most section of the lacustrine sequence (dating from ~1917 to 1955) is depicted by the model to be composed primarily of sediment from upland creeks and, to a much lesser degree, forested terrains. Sedimentation rates during this interval are very low, while development within the region was minimal.

The modeling results for the lower sections of Core 4A/B are similar to those of Core 3A. Alluvial materials are shown to be dominated by sediments from upland floodplains, and with the exception of one sample, the lower section of the lacustrine sequence is shown to be composed of upland alluvium. The influx of debris from roads and lawns, which were generally not present at the time that these sediments were deposited, is shown to have been limited.

The data presented above suggest that the model output related to the pre-lake deposits and the early lacustrine sequence is reasonable. However, the question arises as to why the model has reported that a majority of the sediment is derived from upland alluvial deposits while contributions from forested terrains (as well as roads and lawns for more recent deposits) is minimal (Fig. 12). In response to this question, it is important to recognize that most sediment eroded from forests, roads, and lawns is transported to stream channels that subsequently carry the materials to Fairfield Lake. Examination of the geochemical data (Table 4) shows that the geochemistry of the alluvial deposits within the uplands is very distinct from the other sediment sources. In particular, the concentration of most of the elements is lower in the alluvial deposits than it is within the other groups. It follows, then, that once entering the stream channels, the sediments are altered, producing materials of a similar composition (the composition of the alluvial deposits). Thus, it appears that the geochemical signal of the sediment from forests, roads, and lawns may be muted during transport through the upland streams, unless the influx of debris from the forests, roads, and lawns is significant or the rates of transport from the uplands to the lake are rapid. It may be possible to alleviate this problem by selecting parameters that are not significantly modified during transport by fluvial processes. Alternatively, the ratio of the concentration of more-soluble to less-soluble elements has been extensively used in regional studies of rock weathering to quantify solute transport. It may be possible to include weighting factors that are based on such ratios into the mixing models to correct for the loss of elemental mass during transport through the upland streams.

Interestingly, the contributions of sediment from roads and lawns increases within the upper parts of the cores and which post-date the mid-1900s (Fig. 12). Given the systematic changes in the nature of the predicted source area contributions (and in measured sediment geochemistry) within the cores, it appears that changes in sediment source have, in fact, occurred during these depositional intervals. It is more difficult to determine, however, where the material is coming from. For example, between a depth of 36 to 48 cm (1955-1985) in Core 3A, lawns are estimated to provide about half of the sediment to the lake bed. Lawns associated with Camp Merrie Woode and other areas did exist within the upland drainage system at the time that these sediments were deposited. However, it does not seem reasonable to suggest that the limited area of these sites could have provided such a significant contribution of material to the lake. In addition, aerial photographs show that new development was limited within the upper drainage system prior to 1983 and that the primary change was in the length of roads in the area, rather than home sites. Thus, the model does not appear to correctly analyze the sediment sources for this particular interval.

The contributions of sediment depicted by the model from roads seem more realistic. For instance, the upper section of the Core 4A/B (above 70 cm) is shown to be comprised of a mixture of materials, a primary component of which is the sediment from roads. The ^{210}Pb data suggest that the influx of road debris began in about 1960. Roads were present in the area prior to 1963 (Table 11) and sedimentation rates did, in fact, begin to increase slightly after about 1940 (Table 7). The modeling results suggest that roads continue to be a significant source to the present time.

Core 11A is more difficult to interpret because the earlier analysis suggested that the sediment is derived from differing lithologies. Both the underlying alluvial deposits, and the lower section of the lacustrine sequence are estimated to be composed primarily of upland floodplain sediments. After about 1975 (above a depth of 70 cm) roads begin to provide a significant amount of sediment to the lake. During this interval, sedimentation rates, road development, and buildings increased in number. Thus, the model agrees with other data suggesting that sediment source areas change in response to land-use alterations. As was the case for Core 3A, the most significant errors in the model appear to be associated in zones of the core where sediments are erroneously depicted as coming from the Tallulah Falls Formation. Such zones are consistently estimated by the land-use mixing model to contain significant amounts of sediment from lawns, which again, there seems to be little physical evidence for. In summary, then, the model identifies changes in sediment source associated with human activities, but it does not adequately define the nature of these changes using the parameters that are currently available for inclusion in the model.

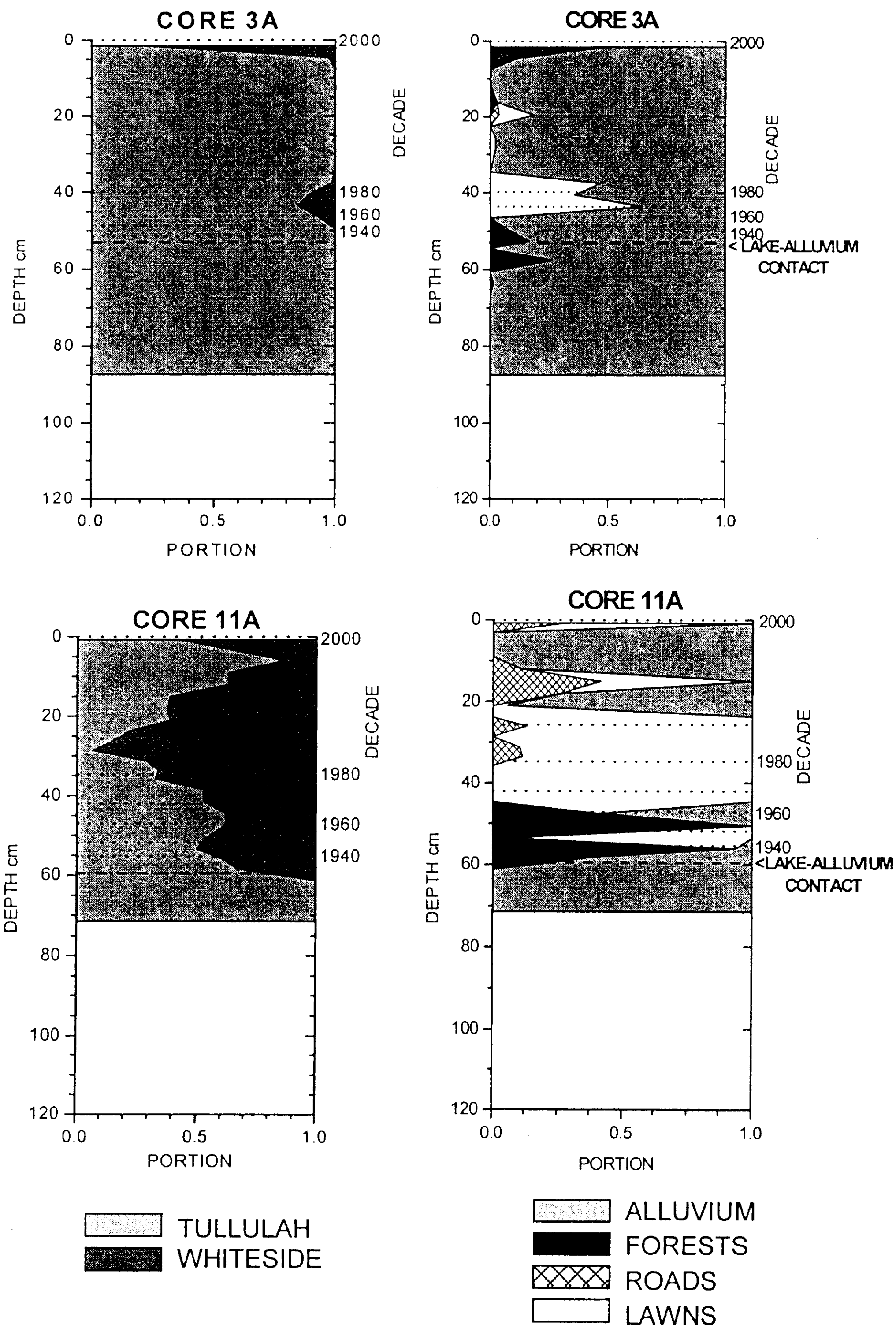

Figure 13. Comparison of model results for land cover type and rock type sources for Cores 3A and 11A.

SUMMARY AND CONCLUSIONS

Sedimentation within Fairfield Lake has been limited since dam closure in 1890. Most of the sediment that enters the lake is deposited near the mouth of tributaries, creating deposits on the order of 50 to 100 cm in thickness. Deep-water areas located along the axis of the reservoir, and which are removed from the direct influx of tributary sediment, have received only a limited amount of debris. Lacustrine deposits in these areas are generally less than 40 cm thick.

Dating of the lacustrine sequence is plagued by low ^{137}Cs concentrations and varying rates of sediment influx. However, ^{210}Pb data clearly indicate that sedimentation rates have significantly increased during the past few decades. The most significant increases occurred in the mid-1980s and the late 1990s, both of which correspond to periods of development documented by the comparison of aerial photographs. The more recent sedimentation rates are 5 to 6 time greater than the rates observed during the first half of the 1900s. If these sedimentation rates continue into the future, sediment accumulation will have a significant impact on the lake. For example, a sedimentation rate of 3.0 cm/yr (which is similar to those observed during the past 5 to 10 years) would result in the infilling during the next century of most of the upper lake segment as well as the embayment within the middle segment. Problems associated with decreases in water-depth immediately adjacent to the tributary mouths can be expected over the next few decades.

The statistical analysis of geochemical data collected from the Whiteside Granite and the Tallulah Falls Formation within upland areas suggest that the sediments associated with these lithologies can be delineated on the basis of Cu, Mn, Sn, U, and Zn. Similarly, sediments from differing sources within the Whiteside Granite, including forests, roads, lawns, and alluvial deposits along streams can be defined on the basis of Ag, Bi, Cr, Mn, Mo, Ni, Sb, Sn, and Zn. Thus, the results from the linear discriminant analysis suggest that it is possible to use sediment mixing models to determine the quantity of material derived from differing lithologies or land-cover types. However, the fingerprint for each source type was not perfectly unique in that the samples could not be correctly classified 100 % of the time. Thus, a larger suite of elements should be examined to define a more specific geochemical fingerprint for each source area.

Application of mixing models to samples from Cores 3A and 4A/B suggests that most of the sediment is derived from the Whiteside Granite. The results are consistent with expectations given that these two cores were obtained from the upper segment of the lake which receives inflow from tributaries underlain almost exclusively by the Whiteside Granite. However, a few samples in Core 3A and a majority of samples from Core 11A are estimated to have received significant contributions from the Tallulah Falls Formation. While it is possible that fine-grained sediment from the Tullalah Falls Formation could have been transported by the lacustrine processes from the lower lake segment to coring sites 3A and 11A, the general sedimentation patterns observed in the lake suggest that this is highly unlikely. A more plausible explanation is that the sediment is derived from a micaeous unit contained within the Whiteside Granite and which exhibits a geochemical fingerprint similar to the Tallulah Falls Formation.

The use of geochemical fingerprints and mixing models to determine the relative contributions of sediment from varying land-use types appears to hold a significant amount of promise in this particular area. As expected, pre-lake alluvial deposits are estimated to be composed of upland floodplain materials, and to a much lesser degree, sediments from forested areas. In addition, contributions from forests are minimal, and sediments from anthropogenic sources (roads and lawns) generally correspond to periods of basin development. However, the application of the models is not without problems. Of utmost significance is a loss of elemental mass between the upland sediments and the lake basin. This loss is most likely due to intense weathering and the transport of material out of the watershed in solution. Examination of group means, which shows that elemental concentrations are substantially lower in upland alluvial deposits than within forests, roads, or lawns, suggests that the process of element loss is initiated rapidly within the upland streams. If this is the case, the geochemical fingerprints of the sediments from forests, roads and lawns may be muted during transport and may only show up in the lake when the sediment flux from these sources is significant. At all other times, the fingerprint would predominantly correspond to the upland alluvium. To overcome this difficulty, it may be possible to include correction factors for the loss of elemental mass that are based on changes in the ratios of more soluble to less soluble (e.g., Ti, Al) constituents.

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