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

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Mountain Lake, Giles County Virginia--Clinch Boulders at North end of Lake.

ABSTRACT

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

INTRODUCTION

Mountain Lake is the only natural lake in the unglaciated southern Appalachians. It is located in Giles County, in southwest Virginia, about 15 miles from Blacksburg and the Virginia Polytechnic Institute and State University. It lies near the top of Salt Pond Mountain (37° 21' 56" N, 80° 31' 39" W), at an elevation of 1177 meters. The lake is approximately 900 meters in length, by approximately 250 meters in width, forming an elongate club-shaped body oriented from south to northwest (figure 1). Mountain Lake is approximately 33 meters deep at its maximum depth, at the north end of the lake; this deep portion consists only of a narrow crack or crevice feature in the bottom of the lake. More generally the deep end of the lake is approximately 24 meters deep, shallowing to the south.

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

Since that time, the lake water level is known to have fluctuated periodically. Most graphically, a stump of yellow pine wood was recovered from growth position at a depth of 10 meters in the lake (Parker *et. al*., 1975). ^{14}C dating of this wood produced an age from the mid 1600s. Tree ring analysis revealed that the tree had grown for at least 30 years along the shore of a much smaller Mountain Lake.

More recent fluctuations include a period of relatively low lake levels in the mid and late 1950s when the lake became once again low enough that the lake-bottom springs were temporarily exposed. The lake returned to normal full levels after a local earthquake in April 1959 (Hopper and Bollinger, 1971). This earthquake registered as 6 or greater on the Richter scale; it sprung door hinges and cracked a large stone fireplace mantle at the Mountain Lake Hotel (Marland, unpublished, 1967). Lake levels have remained relatively full since that time, although the level drops seasonally at an unusually rapid rate during dry portions of the late summer. The lake has been low in 1997 and 1998, largely to drought conditions throughout the summer, dropping nearly three meters from full level, with no surface outflow into Pond Drain. Such a drop is more than three times the water loss expected from evapo-transpiration alone.

REVIEW OF MOUNTAIN LAKE ORIGIN HYPOTHESES

G. E. Hutchinson and Grace Pickford first scientifically described the lake (Hutchinson and Pickford, 1932). They suggested that Mountain Lake was the result of landslide damming of the valley (see Hutchinson's lake type 20a (1967)), and described the lake as a pristine oligotrophic system. Others have subsequently suggested other less likely origins, including a glacial cirque, volcanic caldera, and karst sinkholes. These were reviewed and rejected by Parker *et al*. (1975), who returned to a variation of the landslide hypothesis. Based on preliminary geologic analysis, Parker *et al*. (1975) suggested that a small narrow valley was eroded headward by Salt Pond Drain through the relatively resistant Clinch sandstone. Subsequent to this surface erosion feature, wall collapse occurred, with primarily vertical movement of the infilling material. This hypothesis is reasonable, so far as it goes, but does not fully explain either the structural reasons for Mountain Lake's existence, or why a partial canyon feature does not remain in the upper portion of the Salt Pond Drain valley.

Figure 1. Regional geology of Mountain Lake, showing fracture trace and resistivity transects. Modified after Shultz (1986).

GEOLOGIC AND PHYSIOGRAPHIC SETTING OF MOUNTAIN LAKE

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

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

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

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

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

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

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

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

Figure 2. Sonar bathymetric map of Mountain lake in 1997 showing fracture trace.

APPROACH AND METHODOLOGY

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

Initial reconnaissance and photography of Pond Drain was carried out in November 1996, after undergrowth had died back. Attention was paid to possible periglacial geomorphology and colluvium (McDonald and Bird, 1986), stream channel forms, qualitative water volume, and disappearance/reappearance of minor channels. Sonar bathymetry of the lake was done in fall of 1996 and spring of 1997.

Field reconnaissance was followed with structural analysis of the immediate region. Interpretation of regional folding links the local Mountain Lake anticline with the Narrows thrust sheet and more directly with a large-scale fault to the northeast of the lake (figure 2).

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

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

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

FRACTURE TRACE ANALYSIS

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

Zones of structural weakness in the bedrock, which provide additional permeability, largely control the physiography of Mountain Lake. Overprinted on the geological units is a local lineation feature (figure 1, figure 2) that intersects the deepest, northern portion of the lake, striking / trending N 40 W (from approximately 140°). This feature is oriented parallel to the direction of primary compressive stress during the Appalachian Orogeny. The lineation is perpendicular to both of the major tectonic features in the area, the Saltville Thrust Fault to the Southeast and the Narrows Thrust Fault to the Northwest. We suggest that this lineation feature may have initially been produced when tectonic stresses perpendicular to the original compression were expressed, and the rock fractured with little lateral displacement.

The proposed fracture feature is traced northwest of Mountain Lake by Pond Drain, which continues northwestward until it reaches flatter land near the center of the adjacent syncline (and then diverts northward over colluvium). The lineation appears to continue across the syncline, where it is possibly expressed by drainage on the opposite side of the valley.

The same lineation feature is discernible on the eastern side of the lake as well, where it is indicated by the I-4 stream channel, and by the twin-peak topography of Salt Pond Mountain.

Figure 3. Resistivity transect MLLINE-1 collected upgradient of the lake along input stream I-4, shown NE to SW.

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

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

RESISTIVITY DATA

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

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

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

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

The apparent resistivity data sets were then imported into Res2dinv, a resistivity inversion program written by M.H. Loke. This program uses a smoothness-constrained least squares inversion technique. The data sets were inverted with the damping factor optimized. (For a review of inversion techniques see Parker, R. (1994).) This inversion program generates three images for each apparent resistivity survey. The models generated by the inversion program show unfractured sandstone bedrock (Juniata and/or Clinch) as having resistivity values ranging from 4000-10000 Ohm-m, with an average value of approximately 5500 Ohm-m. The dry fractured bedrock shows resistivity values ranging from 6000-12000 Ohm-m, with an average value of approximately 6500 Ohm-m. Wet fractured bedrock shows resistivity values ranging from 500-2500 Ohm-m, with an average value of approximately 1500 Ohm-m. The dry weathered layer, composed of sediments and cobbles, shows resistivity values ranging from 6000-10000 Ohm-m, with an average value of approximately 6500 Ohm-m. The wet weathered layer shows resistivity values ranging from 500-2500 Ohm-m, with an average of 1500 Ohm-m.

Figure 5. Resistivity transect MLLINE-3 collected downgradient of the lake along Pond Drain, shown SW to NE.

Survey MLLINE-1 was collected furthest upgradient (southeast) along the course of the I-4 input stream. The transect was made at more than 5 meters elevation above the first expression of flowing surface water and perpendicular to the I-4 channel trace (where there were expressions of previous surface water flow). Figure 3 shows a resulting resistivity model with a pronounced resistivity high of 6000-10000 Ohm-m (between 26-36 meters along the transect). At depth, the data changes to a pronounced resistivity low, 2500-3500 Ohm-m. This pattern is consistent with air filled fractured bedrock at shallow depths, with a fairly sudden change to water filled fractured bedrock at a depth of about 6 meters.

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

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

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

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

WATER BUDGET

The watershed feeding Mountain Lake extends less than a kilometer to the ridge of Salt Pond Mountain. The total area of this watershed is about 1.3 square kilometers. The average rainfall of 113 cm per year (David Smith, Virginia Tech Forestry Department, pers. comm.) gives the watershed a yearly total precipitation input of 1.47×10^6 cubic meters of water per year. Of this amount, loss to evapotranspiration accounts for approximately 58 cm/year, or a total of 0.754×10^6 cubic meters. In addition, Mountain Lake Hotel and Resort activities (wastewater from the resort is removed outside the Mountain Lake drainage basin) consume approximately 0.03×10^6 cubic meters per year (Jeff Slack, The Wilderness Conservancy at Mountain Lake, pers. comm.).

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

We note, however, that not anywhere near all of this water is exiting through the surface stream at the mouth of the lake. It is our present estimate that approximately half of the total liquid outflow leaves the lake on the surface. The remainder must be conducted through a permeable aquifer or through subterranean channels. The outflow from these appears to be a hidden spring line beneath the float-covered surface of Pond Drain valley, in an area of the stream where water flow increases substantially with no surface tributary. This is almost certainly where the remainder of Mountain Lake's water budget is expelled. Due to the concerns of The Wilderness Conservancy at Mountain Lake, we have been unable to use dye tracers to determine the exact locations of these springs, but qualitatively one can see a region of dramatically increased flow some hundreds of meters downstream from the lake.

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

INTERPRETATION OF LAKE ORIGIN

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

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

Figure 4. Resistivity transect MLLINE-2 collected upgradient of lake along input stream I-4, shown NE to SW.

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

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

CONCLUSIONS

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

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

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

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

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

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Figure 6. Resistivity transect MLLINE-4 collected downgradient of the lake along Pond Drain, shown SW to NE.