TRACKING SLUDGE DISPOSAL USING ELECTRICAL CONDUCTIVITY MAPPING[1]

Michele M. Coleman, Karl E. Butler, Anthony Mersich and Tom A. Al[2]

Abstract. Disposing of lime neutralization sludge from an acid mine water neutralization facility back into the acid generating waste rock could provide several benefits for reclamation of abandoned coal mines. These include: a low cost final disposal area for the sludge; reduced diffusion of oxygen into the waste rock; reduced personal liability by eliminating sludge ponds, and less disturbance of land for sludge disposal purposes. NB Coal had been depositing lime neutralization sludge from its acid mine water treatment plant back onto the waste rock at the backfilled Fire Road strip mine since 1992. Chemical investigations have identified a decrease in the mine water acidity and iron and aluminum concentrations, which may be in part due to the application of the sludge.

Electromagnetic (EM) surveys were first used over parts of the Fire Road mine in 2000 to identify subsurface accumulations of acid mine drainage (AMD). One unexpected result was the observation of anomalous electrical conductivities in an area that had previously been used for the disposal of sludge. The possibility of using electrical conductivity as a tracer to track sludge migration within the waste rock motivated NB Coal to sponsor the acquisition of an EM apparent conductivity survey over the entire backfilled pit. Results of that survey, conducted in 2004, show that distribution of electrical conductivity over the mine is highly variable. A long, linear conductivity high, located along the high wall of the mine, is attributed to pooling of mine water and higher porosities (higher water contents) in that zone. Other conductivity highs, however, are clearly associated with historical patterns of sludge application and its subsurface migration. The presence of moist, conductive sludge filling a portion (or all) of the void space in the waste rock above the water table may explain this association. If so, then apparent conductivity maps may be useful as a management tool to decide which parts of the mine site would benefit most from the application of sludge for purposes of reducing the infiltration of oxygen and production of AMD.

Additional Key Words: acid mine drainage, surface coal mining, coal mine reclamation, lime neutralization sludge, electromagnetic, resistivity, geophysics

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[2] Michele M. Coleman is the Environmental Coordinator, NB Coal Limited, Minto NB E4B 3V1 Canada. Karl E. Butler and Tom A. Al are Associate Professors in the Dept of Geology, University of New Brunswick, Fredericton NB E3B 5A3 Canada. Anthony Mersich is completing his final year in the undergraduate Geophysics Program at the University of Alberta, Edmonton, AB, Canada.

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Introduction

The Fire Road Mine was operated as a surface coal mine for NB Coal Limited between 1982 and 1985 in Minto New Brunswick, Canada (Fig. 1). The coal seam in this central New Brunswick mine is confined to the Pennsylvanian Sunbury Creek Formation, which consists of nearly horizontal bedded, quartz rich, brown to gray colored sandstone (Ball, 1984). This medium to coarse grained formation contains abundant interbedded conglomerate, minor shale units and common dissemination of woody origin coal partially altered by pyrite replacement. The coal was extracted from depths of 15 to 20 meters. Approximately 100 hectares were disturbed during the operation of this strip mine.

Figure 1. Location of the Fire Road Mine in New Brunswick, Canada.

In 1984, the presence of acid mine drainage was identified. Mining was halted in 1985. With the exception of a mine water holding pond, the entire mine site was backfilled and graded. A temporary lime neutralization system and several sedimentation ponds were constructed on the site. Because the mining operation had been a cut and fill operation, the porosity of the backfilled mine was higher than the surrounding undisturbed bedrock. While the treatment plant was pumping water from the site, the depressed groundwater table in the backfilled area was a sink, not only for precipitation on the site, but also for groundwater and runoff from an adjacent drain and adjacent undisturbed land. The site continued to treat approximately 2.4 million cubic meters of acid mine water each year. By 1992, the expanse of sedimentation ponds covered a staggering ten hectares, most of them off of the mined site, and the annual addition of 1.5 hectares of sedimentation ponds was quickly approaching adjacent wetlands and streams, as illustrated in Fig. 2. Several reviews of alternatives to dealing with the acid mine water were conducted and it was determined that 'pump and treat' using hydrated lime was the most effective option.

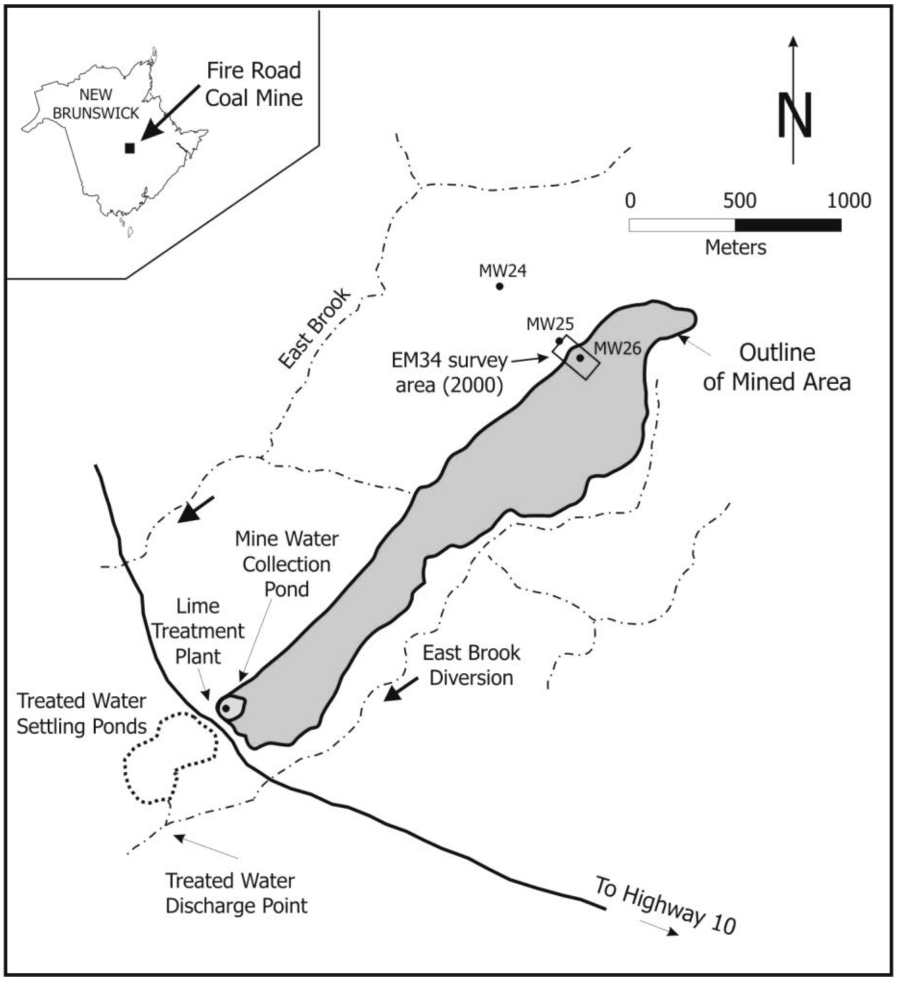

Figure 2. Map of Fire Road mine and some of its sedimentation ponds.

Discussions then focused on minimizing the environmental impact on the surrounding undisturbed lands, minimizing the economic impact for future land use in the area and reducing the extent of the long term liability for the sludge ponds. Several recommendations had been made about the potential to "store" or place the sludge back into the waste rock. The concept raised many eye brows for its approach, but when considered in light of Fire Road's unique hydrological design, it was deemed worthy of further investigation. If the worse case scenario occurred during the trials, the contaminated water would still be within the confines of the mined site and within the influence of the mine water treatment plant.

Relocation of the sludge has been continuous since 1992. Recently, geophysical methods have been applied on site – originally to determine the distribution of AMD, and most recently, to assist in the mapping of the distribution of sludge within the waste rock backfill.

Hydrogeological Characteristics of the Site

After mining ceased, the entire site was graded to mimic the approximate relatively level topography of the original site. The back end, however, remained slightly elevated due to the incomplete compaction of the backfill. Backfilling resulted in the mined area having a higher porosity than the surrounding undisturbed bedrock.

The original topography of the site contained a minor stream of bog drainage which bisected the mine. The contour of the stream bed was reinstated during the backfilling of the site and, although many attempts were made in the late 80's and early 90's to construct a perched artificial stream bed back across the site, the blocky sandstone backfill eventually perforated each clay and fabric liner, thus effectively directing the stream flow back into the mine water table. Hence, the stream was kept diverted around the southern edge of the mine in the south diversion drain. The locations of both of these channels are evident on Fig. 2.

The stream bed hollow, however, is the lowest elevation on the entire the site, which made it the overflow point for high levels of mine water on the site. In order to capture and treat all acid mine water, the operation of the treatment facility depresses the water table in the cut to an elevation which prevents an overflow at the old stream bed. NB Coal has attempted to monitor if mine water was leaving the site as groundwater through the placement of additional wells along the north east - south west trending highwall. This technique proved to be a hit or miss method for identifying acidic plumes.

Early in the evaluation of the scope of this situation, a hydrogeological investigation was conducted to determine the flow of mine / ground water onto the site (Gemtec 1988). It was determined that 45% of mine water was from precipitation, 19% was from the adjacent ground water table being depressed and 27% was from leakage from the south diversion drain. The balance of 9% was captured in the area between the mine and the diversion drain. Monitoring wells were installed to track the in-situ chemistry of the mine water. It was not identified at the time whether these wells would provide information on the chemistry of nearly static water or of the mine water flowing through the waste rock.

Sludge Relocation Trials

Relocation Trials

The first sludge relocation trials were conducted in 1992. Additional trials were conducted between 1993 and 1999. Since 2000, a maintenance program has relocated approximately 27,000 m^3 of sludge onto the waste rock annually, 260,000 cubic meters in total. Because of the thixotropic behavior of the sludge, it was best moved with a floating dredge equipped with a horizontal auger for a continuous summer relocation operation. It was soon determined that the dredging operation had to be conducted using a concentration of sludge in the water slurry that would allow the sludge to flow but would not result in an excess of water being re-circulated back onto the mine site and into the mine water system, only to have to be pumped and treated by the lime neutralization plant. This was controlled by requiring a 22-28 % by volume freeze-thawed saturated solids concentration in the dredge output.

Bench Leaching Trials

The initial concerns for relocating the sludge back onto the waste rock consisted of the potential for the metals in the sludge to dissolve when put back into acidic conditions. A series of investigations conducted in 1997 (NB Coal Limited) concluded that the metal hydroxides did not dissolve when placed in an aggressive leaching regime. The trials did identify that excess unrelated lime in the sludge would temporarily bolster the pH of the local mine water, providing another benefit to the placement of sludge onto the waste rock.

Field Trials

A major benefit of placing the sludge back onto the waste rock was the possibility that it would plug pores in the waste rock, thereby minimizing the transport of oxygen and /or water to the surface of the pyrite and reducing or inhibiting the production of acid mine drainage. In Coleman et al. (1997), field trials performed to determine where the sludge was settling after it was deposited onto the waste rock confirmed that it was plugging voids below the surface. In excavations below the frost line, the sludge was still retaining moisture and remained gelatinous. Sludge deposits above the frost line still plugged voids in the waste rock but had been dried out either by heat/ wind dessication or by the freeze/thawing action. Geotechnical research was conducted on the potential for the sludge to be used as a capping material on the surface of the waste rock. The investigation summarized that although there were many reasons to continue to relocate the sludge onto/into the waste rock, the physical and chemical properties of the sludge were transformed after the sludge became dessicated either by heat, wind, or freeze thawing and that the original moist gelatinous or compacted condition could not be replicated.

Effect on Minewater Chemistry

Sludge continues to be relocated onto the waste rock each summer. The chemistry in the ground water wells is tested every other year. The chemistry in the mine water is monitored weekly. It has been interesting to note that the chemistry in the ground water wells has not varied noticeably since the late 1980's. The chemistry of the mine water, however, improved in both lower acidity concentrations and lower metal concentrations. This has resulted in a decrease in the consumption of hydrated lime by 75%. During years of major sludge relocation projects or when too much treated water was recirculated during the dredging process, the chemistry of the mine water had a marked decrease in acidity. Table 1 presents the decrease in the metal concentrations since 1992. It is interesting to note that aluminum, as a result of chlorite dissolution, is the metal in highest concentration. It has been postulated that acid generation in abandoned coal mines tends to peak approximately 15 years after the onset of acid generation (Ziemkiewicz et al., 1991). It has not been determined if the ‘improvement’ in the mine water quality was due to the weathering of the waste rock or the addition of sludge into the waste rock.

Hydrological Affects

It is also important to identify that, after one very aggressive dredging program whereby approximately 150,000 m^3 of sludge was relocated back onto the waste rock in the area between the old stream bed and the current mine water pond, mine water started to pool on the surface of the reclaimed mine at the old stream bed location. This was a major cause for concern because the water in the mine water pond had been drawn down significantly below the overflow elevation by the treatment plant. Having no tools to evaluate the issue below the surface, it was assumed that the sludge applied the previous year had settled in such a manner so as to interfere with the flow path of mine water from the back end of the mine towards the mine water pond. The flow path had to be re-established by trenching from the stream bed to the mine water pond along the high wall .

Table 1. Comparison of mine water quality since the initiation of sludge relocation.

Year	Lime (tonnes)	Precipitation (mm)	Lime/Precip. ratio	Acidity (mg/l)	Aluminum (mg/l)	Iron (mg/l)
1992	2417	1039	2.33	869 to pH 7	118	n/a
1993	2113	1201	1.76	1099 to pH 7, 8.3	149	43
1994	1785	1140	1.57	778 to pH 8.3	122	40
1995	1492	1246	1.2	732 to pH 8.3	110	33
1996	1662	1306	1.27	716 to pH 8.3	98	17
1997	1009	996	1.01	891 to pH 8.3	84	19
1998	1197	1238	.97	806 to pH 8.3	91	23
1999	700	1150	.61	536 to pH 8.3	59	13
2000	623	1166	.53	500 to pH 8.3	55	15
2001	534	802	.67	576 to pH 8.3	54	22
2002	736	1276	.58	602 to pH 8.3	59	15
2003	685	1172	.58	543 to pH 8.3	61	14

The variation in the mine water chemistry between the wells and the mine water pond, and this blockage indicate that the sludge was impacting both the mine water chemistry and the flow path. The lack of variation in the chemistry in the wells indicates that there are multiple flow regimes occurring within the confines of the waste rock.

Field Trials of Geophysical Methods

Since 1997, Fire Road Mine has been used as a field camp study site for a third year Environmental Geology course offered by the University of New Brunswick, Department of Geology. The course and content was designed by Drs. Tom Al and Karl Butler from UNB. The first few years focused on the geology of the site, the factors contributing to the generation of acid mine drainage, and the geochemistry of the mine water.

In 2000, geophysical applications were introduced into the curriculum. Geophysical methods sensitive to electrical conductivity are commonly used in groundwater investigations; they may be used to define stratigraphy and structures that control groundwater flow, or for direct detection, delineation and monitoring of conductive plumes caused by AMD or other sources of contamination (e.g., McNeill, 1990; Patterson et al, 1994; Hammack et al., 2004; Butler et al., 2004). AMD is readily identified by its high electrical conductivity compared to natural surficial groundwaters. Given that Fire Road geology includes only minor conductive clays, which are interspersed throughout the overburden column as a result of the mining process, subsurface electrical conductivities were expected to vary primarily with the porosity and water saturation of the backfill and to be dependent on the water's conductivity. Water conductivity is proportional to the sum of (concentration x valence x mobility) for all ion species present. AMD tends to be particularly conductive because of the abundance of H^+ and SO_4^- ions, which have high ionic mobilities.

Initial Field School Investigation

Initially, in May of 2000, field school students collected electromagnetic terrain conductivity data in two areas (Butler, 2000). NB Coal was interested in an area where it was thought the highwall might be fractured, allowing for the possibility of AMD leakage. Several monitoring wells had been drilled in a hit or miss pattern over the area in the past, but no definite plume had been found. This initial geophysical reconnaissance did not identify any obvious conductive plume.

Results of surveys at the second site, spanning a small section of the highwall near the northern end of the mine (Fig. 2) proved to be far more interesting. The study site encompassed undisturbed till-covered sandstone bedrock, the highwall, and part of the cut that had been up to approximately 14 m deep prior to being backfilled with waste rock. It included two groundwater monitoring wells, and a berm that separated an area where mine water neutralization sludge had been applied to the waste rock, from an area where no sludge had been deposited.

Apparent conductivity surveys acquired at this site using Geonics EM31 and EM34 terrain conductivity meters with varying depths of investigation (approximately 3 to 30 m) yielded three main results. First, as expected, electrical conductivities were much higher within the waste rock backfill than in the natural bedrock outside the pit. More surprising was the observation that conductivities within the backfilled cut were markedly higher in a zone immediately adjacent to the highwall than they were elsewhere in the waste rock. Finally, the most interesting observation was that apparent conductivities within the backfill appeared to be subtlely dependent on whether it had been treated with sludge. A subsequent field school held in the spring of 2001 used resistivity imaging surveys for a detailed investigation of how conductivity varied with depth (Al and Butler, 2001). Most recently, in the spring of 2004, a mine-wide apparent conductivity survey was initiated to determine if the conditions in the small 100 m by 200 m study area were representative of the mine site as a whole. This mine-wide survey and an interpretation of its results with emphasis on the implications for mapping sludge distribution in the waste rock are the focus for the remainder of this paper.

Apparent Conductivity Survey of Fire Road Mine

Data Acquisition and Instrumentation

A mine-wide apparent conductivity survey, employing an EM31 terrain conductivity meter

(Fig. 3) was initiated by field school students in early May, 2004. It was resumed and completed 7.5 weeks later in late June. A small area in the middle section of the mine was resurveyed in June to determine how greatly apparent conductivities had changed as a result of the seasonal decline in water table and soil moisture levels during that period. As shown in Fig. 4, most data were acquired along a series of sub-parallel lines oriented perpendicular to the trend of the cut. The nominal distance between lines was 40 m, although line spacings as small as 10 m were used in some areas of special interest. Several tie lines parallel to the trend of the pit were also surveyed. Station spacing along each line was determined by the walking speed of the operator and by the data logging rate of 1 reading per second and was typically 0.6 to 0.8 m.

Figure 3. Student carrying the EM31, the backpack-mounted DGPS and their respective data loggers during UNB field school in May 2004.

Like all terrain conductivity meters, the EM31 utilizes a sinusoidally oscillating primary magnetic field to induce eddy currents in the earth; it measures the secondary magnetic field produced by those eddy currents to infer the apparent conductivity of the ground using a low induction number approximation (McNeill, 1980). If the ground in the vicinity of the instrument is homogeneous and of moderate to low conductivity (less than ~100 mS/m), then the measured value is equal to the true conductivity of the ground. In a more realistic case, where the shallow subsurface might be approximated by two or more horizontal layers of low to moderate conductivity, the apparent conductivity measurement is approximately equal to a weighted average of the true layer conductivities, to a depth that is proportional to the transmitter-receiver coil separation. For the EM31, with it's coplanar transmitter and receiver coils separated by3.66 m at opposite ends of a rigid boom, the effective depth of exploration is about 6 m when operated in the vertical dipole mode employed for this survey. However, the decline in sensitivity with depth is gradual and material located below 6 m depth can still influence the apparent conductivity reading, particularly if it is much more conductive than the material above.

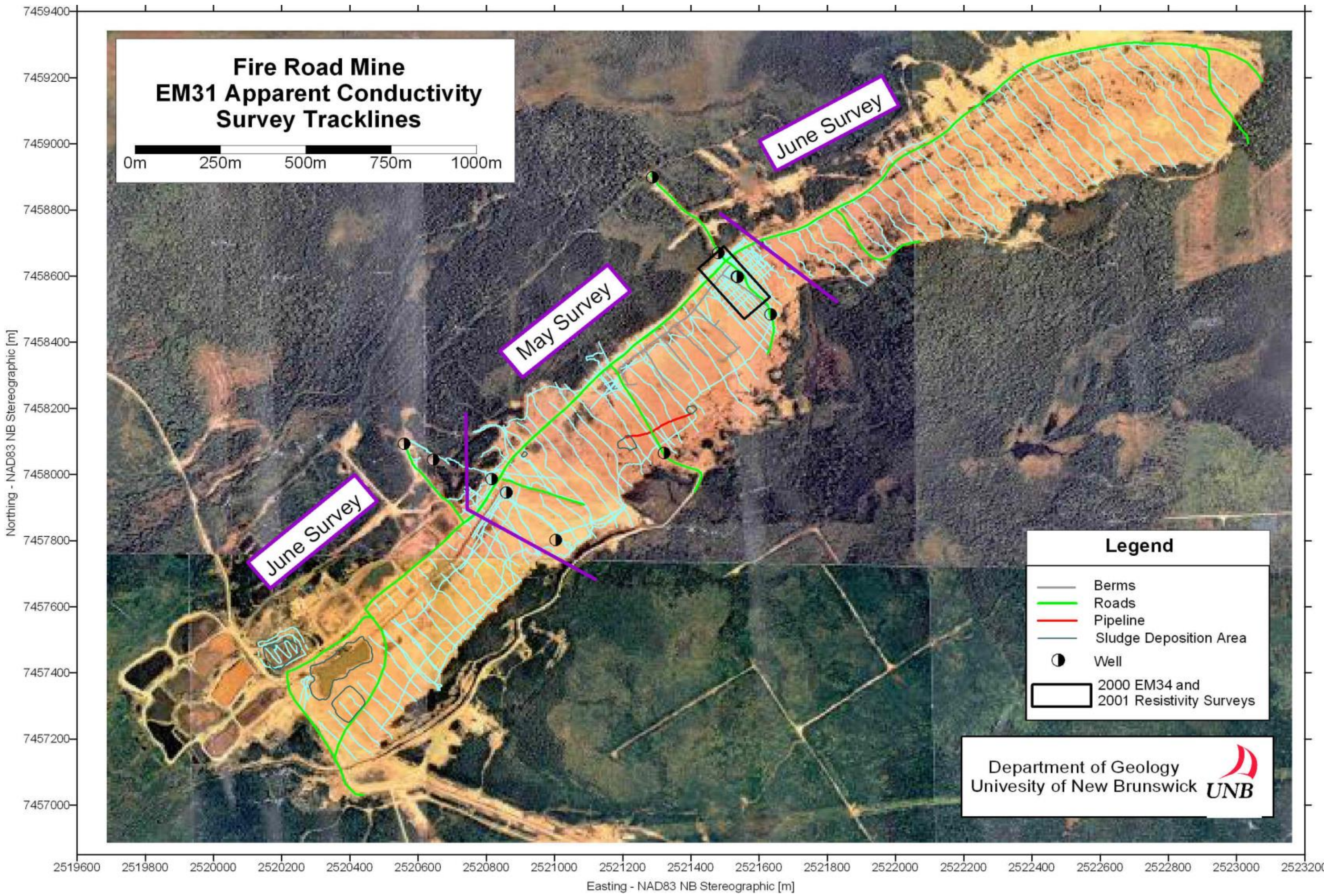

Figure 4. Apparent conductivity survey tracklines superimposed on an air photo of the mine. The middle part of the mine was surveyed May 1 – 3 while the ends were surveyed between June 23 and 29. Note the settling ponds at the southwest end of the mine.

The EM31 and a backpack-mounted differential GPS (Trimble Pathfinder Pro XR DGPS) were carried by a single operator as shown in Fig. 3. A data logger automatically collected apparent conductivity measurements and corresponding DGPS positions while the operator walked. The DGPS used real time differential corrections from a Canadian Coast Guard beacon signal to provide horizontal positions with estimated sub-meter precision. Elevation uncertainties, typically about 3 times greater than horizontal, are estimated to have been approximately +/- 2 m. The DGPS was controlled by Trimble Terrasync software running on a handheld computer. This software allowed the operator to navigate along lines displayed on an electronic map of the mine site, eliminating the need to physically mark lines in the field.

EM31 Data Editing and Processing.

The merged EM31 and DGPS data stored in the data logger were downloaded to a computer for editing and basic processing prior to production of a map. The first step was to "level" the data by removing any day-to-day variations in apparent conductivity readings that could be attributed solely to drift in the instrument calibration and/or slight changes in soil moisture content. This was accomplished by comparing apparent conductivity profiles collected on a common line on consecutive days and determining the bulk shift that would make them match as closely as possible. The differences from day to day were quite small – typically 0.5mS/m to 0.75mS/m or less. Corresponding bulk shifts were applied to each day's data to make them consistent with readings acquired on the first day of the survey in each month.

The next step was to remove any erratic apparent conductivity values related to the presence of metallic debris. This was accomplished by searching the data set for stations exhibiting any highly anomalous in-phase responses which are (along with erratic apparent conductivities) indicative of proximity to metal. Stations exhibiting in-phase values greater than 1 ppt or less than -1 ppt were eliminated from the apparent conductivity data set.

Spatial averaging or smoothing of the apparent conductivity values was conducted next to remove the low amplitude (~1mS/m) fluctuations that occurred from data point to data point along each survey line. This short wavelength variability is not an accurate portrayal of the conductivity of the rock below the EM31, but a result the jostling of the instrument as it is carried over the terrain of the mine. Smoothed data points were calculated as the symmetrical tapered average of five consecutive readings typically acquired over a distance of 2.4 – 3.5m, which is well within the radius of approximately 6 m sampled by the instrument.

Finally, the total data set of approximately ~ 37,000 smoothed readings was interpolated (to make it suitable for contouring) to a 10 by 10 m grid using an inverse-distance-to-first-power algorithm, and presented as a color shaded map of shallow apparent conductivity. Elevation data acquired by the DGPS were gridded in the same way to produce a color shaded map of the mine site topography.

Apparent Conductivity Survey Results and Discussion

The topographic map in Fig. 5 shows that elevation generally increases towards the northeast along the axis of the mine and towards the southeast across the width of the mine. A topographic low where a stream once flowed across the site is also evident 1/3 of the way up the axis of the mine.

A comparison of the topography to the apparent conductivity map in Fig. 6 shows that there is a tendency for apparent conductivity to drop with elevation. This is at least partly a consequence of the fact that water table depth tends to increase with elevation inside the highly permeable waste rock backfill. For example, in May, 2004, the water table depths at monitoring wells 27 and 22, located in topographically high areas, were 7.8 and 7.5 m whereas the water table depths at wells 19 and 17, located in lower areas, were only 3.1 and 1.8 m respectively. The very low conductivities at the northeast end of the mine are also likely a consequence of the facts that (i) sludge has never been deposited there and (ii) the bottom of the mined area rises to the northeast along the mine axis so that the thickness of porous backfill saturated with conductive mine water decreases in that direction.

The most striking conductive feature in Fig. 6 is the narrow, linear conductivity high that lies immediately adjacent to the highwall along the whole length of the mined area. Note that conductivity drops abruptly to the northwest of this anomaly as one moves across the highwall and into the natural surroundings where the relatively low porosity glacial till and sandstone bedrock are intact and where groundwater conductivities are much lower. This prominent linear anomaly is thought to be associated with the presence of highly conductive AMD mine water in a zone of unusually high porosity next to the highwall where the backfill is poorly compacted. Additional factors contributing to elevated conductivity along the highwall include the fact that surface elevation (and hence water table depth) tend to decrease towards the highwall and the fact that the bottom of the mined area also gets deeper in that direction (yielding a greater thickness of porous backfill saturated with conductive mine water). It is also possible that conductivities are enhanced along this linear trend because sludge was preferentially deposited along the highwall (for ease of access with limited lengths of pipe) and because sludge would have preferentially migrated towards the highwall as a result of the topographic slope. The reduced amplitude of the highwall anomaly to the north of well #26 offers some support for this idea as sludge has never been deposited in that north-western part of the mine.

Several other discrete conductivity highs are labelled A – H on the apparent conductivity map. The conductivity highs at B and C are coincident with areas (outlined in grey) where sludge was pumped from a pipeline into the waste rock during the summers of 2003 and 2002 respectively. Conductivity plumes extending towards the northeast and northwest from those areas probably represent the migration of sludge beneath the surface. The plume extending northeast from C may also be a consequence of leaks from the temporary sludge pipeline, a section of which was lying on the ground during the EM31 survey.

Anomaly A is a rectangular conductivity high, confined by a berm of waste rock on its south-western side. It lies in a region where sludge relocation trials (including the use of tractors to compact sludge spread on the surface) were conducted in 1996 (Coleman et al., 1997), and where the first field trials of apparent conductivity mapping were carried out by UNB field school students in 2000. Curiously, the conductivity high in this area (anomaly A) is located on the north side of the berm, whereas NB Coal personnel, including the first author, recall that sludge had been applied on the south side of the berm only. This seems to be at odds with the positive correlation between conductivity and sludge deposition observed at point B and C, and we are not sure how to explain it. One possibility is that the sludge deposited south of the berm eight years ago has dried out substantially and become much less conductive. At the same time, it may have penetrated sufficiently deeply into the waste rock to restrict the flow of groundwater down the axis of the cut, thereby causing an up-gradient pooling of conductive groundwater that is the source of anomaly A.

The large and very high apparent conductivity anomalies at D and E both lie in topographically low areas where conductive mine water is likely close to the surface. However, a shallow water table alone seems to be an inadequate explanation because the apparent conductivity in an equally low drainage canal, indicated by a pink line running across the mine from point D, is not nearly so high. It is interesting to note that these two large anomalies are located in the area where so much sludge was deposited in 1995 that it blocked the flow of minewater down the axis of the mine, necessitating the construction of a drainage ditch running to the mine water collection pond. Perhaps the sludge preferentially enhanced the conductivity at D and E because it migrated towards those areas from the higher ground in between, or because sludge present in the near surface remains moister and hence more conductive in the low-lying areas.

Anomaly F is unusual in that it is a relatively high conductivity zone located outside the confines of the mined area. It is likely indicative of a high water table and a local thickening of the unconsolidated sediment overlying bedrock in this topographically low area. It may also be related to the presence of lime neutralization sludge that has occasionally leaked from the pipeline that passes through this area on its way from the settling ponds at the southwest end of the mine.

The area labelled G at the southwest end of the mine lies outside the mined area but includes measurements made over an old dry, sludge settling pond (encircled by a grey line) situated on top of glacial till. The conductivity of the old pond is slightly elevated compared to the background conductivities immediately to the northwest of it. The highest conductivities in this area are found on the southern side of the pond. This may be indicative of an increase in sludge thickness or moisture content along the southern boundary but readings in this area, close to the mine office and treatment plant may also be elevated by proximity to metallic debris.

Finally, the grey line encircling a *low* conductivity area labelled H marks the boundary of a topographically low area on the waste rock that was prepared as a possible settling pond but never used.

<u>Seasonal Variations in Apparent Conductivity</u> Figure 6 also shows how the apparent conductivity structure of a 300 by 300 m section of the mine changed between early May and late June, 2004. While the gross conductivity patterns remained similar, there was clearly a substantial drop in conductivity overall, likely as a result of declining moisture levels in the vadose zone and a lowering of the water table with the onset of summer. Differences in the sensitivity of the color scale to variability in the two different conductivity ranges make it difficult to be sure whether one time of year is better than the other for purposes of identifying spatial variability; this is a point on which we intend to follow-up. The seasonal difference should also be kept in mind when interpreting the mine-wide map in Fig. 6 which is a composite of measurements made in early May (central area) and late June (both ends of the mine).

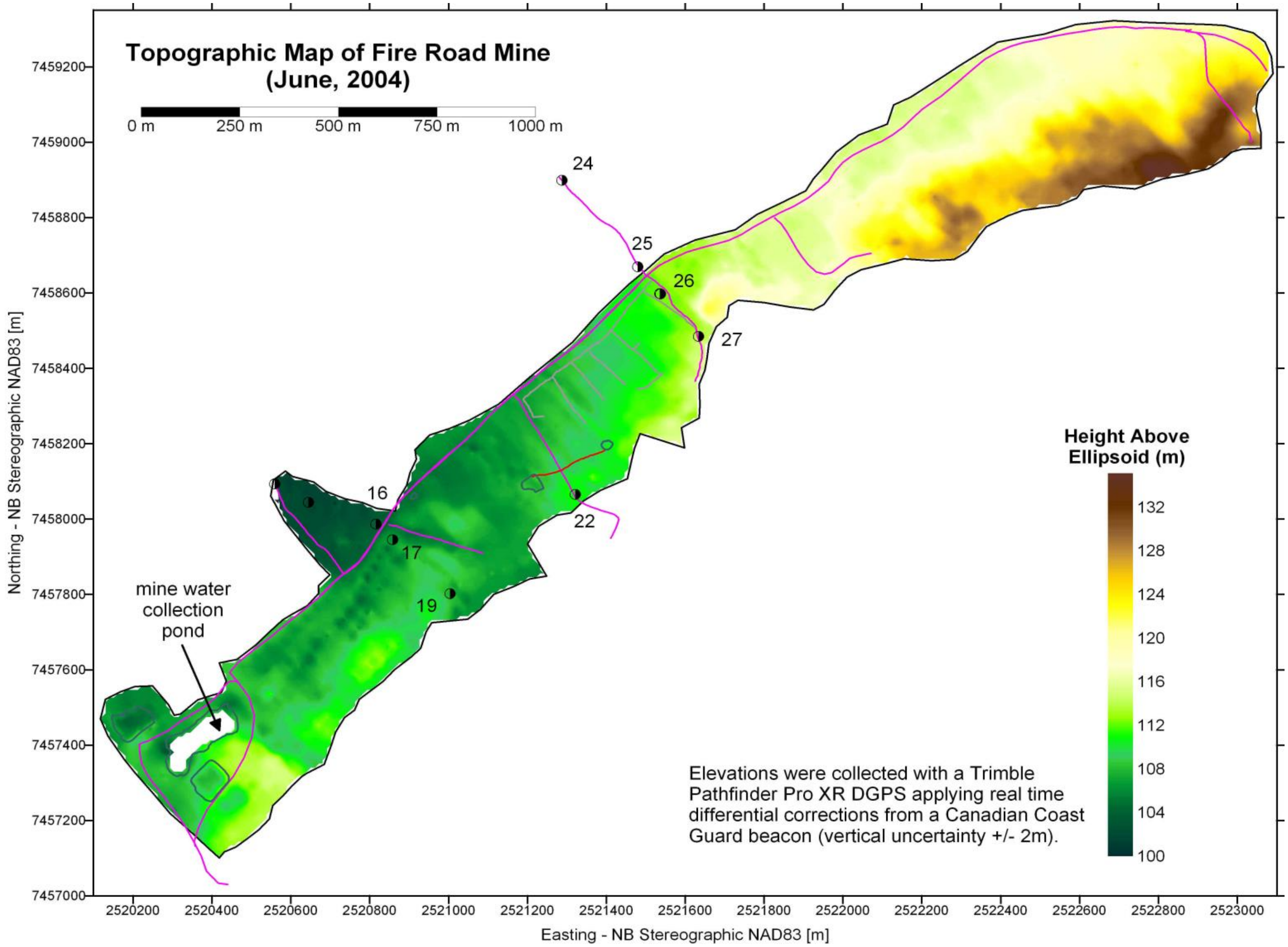

Figure 5. Topographic map of the backfilled Fire Road mine, based on DGPS elevations with uncertainties of approximately +/- 2 m). The elevations are given as ellipsoidal heights (i.e. not reduced to elevations above mean sea level).

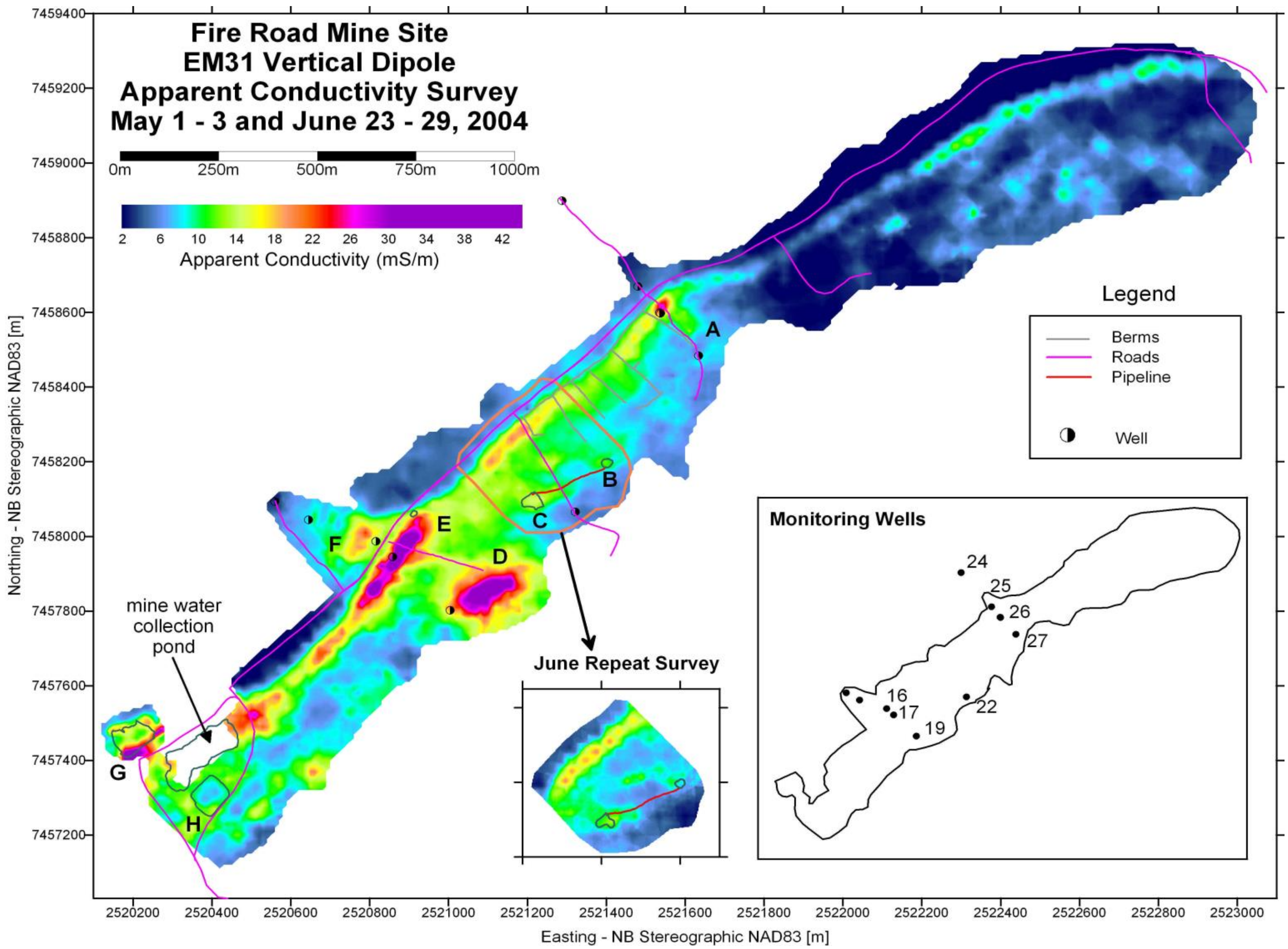

Figure 6. EM31 Apparent conductivity map of the backfilled Fire Road Mine and adjacent natural ground north of its highwall. Note that the colour scale is non-uniform, saturating at 30 mS/m. See Fig. 4 for the distribution of survey lines acquired in May vs. June.

A Model for Sludge-Enhanced Apparent Conductivity

We speculate that the elevated conductivities seen in areas of past sludge deposition are likely the result of sludge infilling void space in the waste rock above the water table. A vadose zone filled with moist sludge having high concentrations of current-carrying ions would be expected to be much more conductive than one filled mostly with air. The fact that sludge does indeed fill void space and retain moisture (below the frost line) was confirmed by previously mentioned trenching studies (Coleman et al., 1997). The prospect of being able to use conductivity to map sludge in the vadose zone is very appealing in that it might be used to help manage remediation efforts aimed at reducing the diffusion of oxygen into the waste rock.

It is also possible that sludge may infiltrate into void space below the water table and thereby displace conductive mine water. This would explain why a drainage ditch had to be constructed through an area that seemed to block the flow of groundwater down the mine after great volumes of sludge were deposited there in 1995. However, the plugging of void space below the water table would not be expected to affect shallow apparent conductivity measurements as much as infilling of the vadose zone for two reasons. First, the vadose zone is closer to the surface and hence has more effect on apparent conductivities measured with the EM31. Secondly, the conductivity contrast between wet sludge and AMD mine water is unlikely to be as great as the contrast between moist sludge and air. Lab experiments are currently underway to measure sludge conductivity as it dries in order to be able to compare it to mine water conductivities measured in the monitoring wells.

The question of how sludge is distributed *vertically* through the waste rock cannot be answered with a single map of apparent conductivity. A comparison of two or more maps acquired with terrain conductivity meters having different depths of exploration would help, but better vertical resolution can be obtained by the use of resistivity imaging techniques, such as those applied by UNB field school students in May, 2001 (Al and Butler, 2001). Resistivity methods involve the direct injection of current into the earth through a pair of electrodes known as the current dipole and measurement of the resulting electric potential differences across other pairs of electrodes known as potential dipoles. Information on how electrical resistivity (or its reciprocal, conductivity) varies with depth is obtained by increasing the separation between current and potential dipoles, while information on lateral changes in resistivity is obtained by moving the whole electrode array along a line or over an area.

Resistivity data were collected in the vicinity of monitoring wells 25 and 26 along two 200 m profiles located to the north and south of the berm that lies along the southern edge of anomaly A. The data were acquired in dipole-dipole mode using dipoles 10 m long and five potential measurements for every current dipole location (i.e. a = 10 m, and 'n-spacings' of 1 through 5). They were subsequently processed using the two-dimensional, minimum structure inversion code DCIP2D (Oldenburg and Li, 1994) to obtain estimates of how true conductivity varied laterally and with depth along the two lines, as shown in Fig. 7 (Al and Butler, 2001). For purposes of comparison, the sections in Fig. 7 also include the depth to the water table, and the depth to bedrock interpolated from the nearby monitoring wells 25, 26 and 27. The sections show that conductivities in the undisturbed sandstone outside the cut and below the mine floor, at 10 -14 m depth, were vastly lower than those inside the backfilled cut. In addition, the section for

Line 20, located south of the berm in the area where sludge had been deposited, shows those conductivities above the water table at 5.5 m depth were just as high as conductivities below the water table. This lends support to our idea that moist conductive sludge is likely present in the vadose zone.

As a final comment, we note that the peak conductivities in the section for Line 80, located north of the berm where sludge was *not* deposited, were three to four times higher than those found beneath Line 20. This is consistent with the fact that elevated apparent conductivities are seen to the north of the berm in maps created using both the EM31 and the deeper-penetrating EM34 terrain conductivity meters (Fig. 6 and 7 respectively). Our speculative explanation, already offered above in the discussion of Anomaly A, is that conductive mine water may be pooled in the area, its flow impeded by the presence of sludge that has infiltrated deeply and plugged void space within the waste rock immediately south of the berm.

Conclusions

Apparent conductivity mapping at Fire Road Mine, using an electromagnetic terrain conductivity meter sensitive to electrical conductivities in the upper 6 – 10 m of the subsurface shows promise as a tool for inferring the lateral distribution of lime neutralization sludge that has been deposited over the past 13 years into various parts of the backfilled cut. The use of a data logger and an integrated DGPS for navigation allowed data to be collected efficiently by a single operator on foot. The density of data was sufficient to produce a map of the entire mined area that reveals several well-defined apparent conductivity highs in areas where the shallow subsurface is thought to contain either high mine water content or conductive sludge.

Our model for the origin of conductivity anomalies associated with the sludge envisages the presence of moist, conductive sludge filling a portion (or all) of the void space in the waste rock above the water table. This idea is supported by trenching studies and by a resistivity imaging survey, which found the vadose zone conductivity in one sludge deposition areas to be significantly higher than one would expect if the void space was mostly air-filled.

Seasonal variations in shallow apparent conductivities are to be expected in response to changes in water table depth and vadose zone moisture content. At Fire Road, maps from a portion of the pit that was surveyed twice, in early May and late June, exhibit very similar conductivity patterns but conductivities were lower overall in June. It would be worth investigating whether there is an optimal time of year when the conductivity of sludge-bearing zones contrasts most sharply with the surroundings.

Challenges involved in interpreting the apparent conductivity structure at Fire Road Mine include inferring the depth (e.g. above or below water table) of conductive zones and which anomalies may be explained by the presence of conductive mine water versus conductive sludge. Site-specific knowledge and a topographic map of the mine site, based on GPS data collected at the time of the EM survey, are helpful in assessing which anomalies are most likely sludge-related. Moreover, the 2004 map now provides a benchmark to which repeat surveys may be compared to assess the impact of future sludge applications.

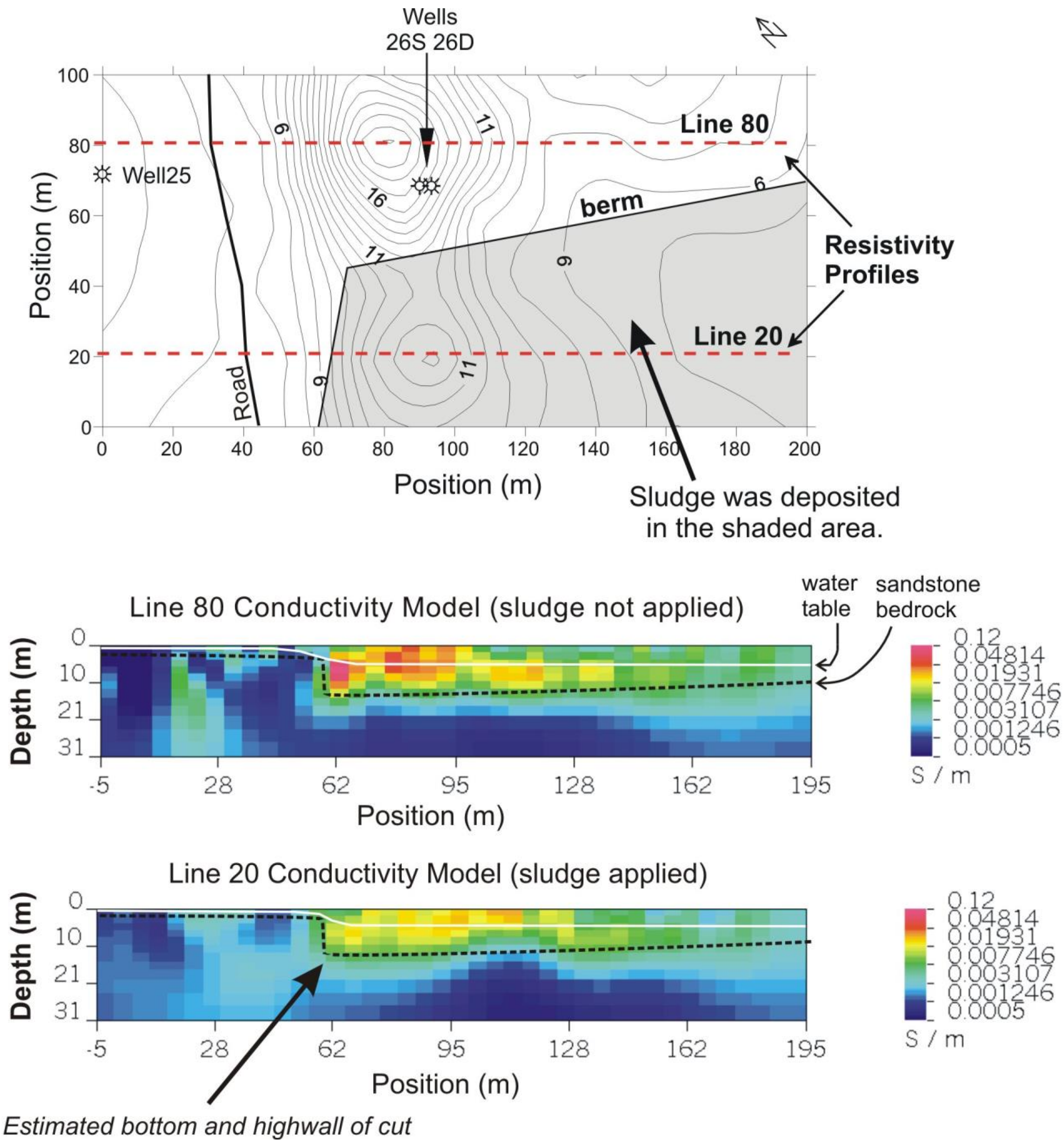

Figure 7. *Upper Panel:* EM34 apparent conductivity map for the 100 by 200 m portion of the mine site originally surveyed in 2000. (The EM34 was operated in horizontal dipole mode with a coil separation of 10 m, giving an effective depth of penetration of about 7.5 m.) *Lower Panels:* Estimates of the true conductivity structure as a function of depth obtained by inverting resistivity imaging data acquired along two profiles that crossed over the highwall and onto the backfilled mine as shown in the map above. The bottom profile passes over waste rock that has been treated by the application of sludge.

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