

STANDARD OPERATING PROCEDURE NO. 23

GEOPHYSICAL SURVEYS WITH ELECTROMAGNETIC INDUCTION AND GROUND PENETRATING RADAR EQUIPMENT

REVISION LOG		
Revision Number	Description	Date
23.0	Original SOP	11/24/03
23.1	Grammar and content	12/1/03
23.2	Measured vs. inferred properties and references	2/4/04
23.3	Add GPR method	2/17/04
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1.0 PURPOSE AND SCOPE

This Standard Operating Procedure (SOP) serves as a supplement to the Quality Assurance Project Plan (QAPP) and provides technical guidance and methods that will be used for geophysical surveying using electromagnetic induction and ground penetrating radar equipment that may be performed during field activities at the Molycorp Site.

Electromagnetic induction (EMI) is a well established surface geophysical method for measurement of the apparent electrical conductivity of soils and geological formations as well as ground water (Hendrickx, J.M.H. and R.G. Kachanoski, 2002). Indirectly it may provide information on soil moisture (Kachanoski et al., 2002; Sheets and Hendrickx, 1995), texture, salt content (Hendrickx et al., 1992; Sheets et al., 1994), and bulk density. At mine sites, electromagnetic induction can be used to locate seepages of acidified groundwater containing sulfides and chlorides (Hendrickx et al., 1994; Hendrickx and Kachanoski, 2002). EMI measurements provide a weighted average of the apparent electrical conductivity of a soil profile to a depth of 1.5 m (Geonics EM38), 6 m (Geonics EM31), or 60 m (Geonics EM34). It is also possible to use the EM38 and EM31 to obtain

information on the vertical distribution of apparent electrical conductivities at a site (Borchers et al., 1997; Hendrickx et al., 2002).

Ground-penetrating radar (GPR) is a well-established technique to study the shallow subsurface. The GPR technique is based on propagation and reflection of electromagnetic waves in the subsurface. Fundamental properties that control the behavior of electromagnetic waves are dielectric permittivity (ϵ), electrical conductivity (σ), and magnetic permeability (μ) (Von Hippel, 1954). A range of electromagnetic properties for common geologic materials can be found in Davis and Annan (1989) and in Van Heteren et al. (1998). When a propagating electromagnetic wave encounters an electromagnetic contrast, part of the energy, proportional to the magnitude of change, is reflected.

For most natural sediments, variations in μ are insignificant (Van Dam et al., 2002). However, the relative permittivity ($\epsilon_r = \epsilon/\epsilon_0$, where ϵ_0 is the permittivity of free space) plays an important role in both propagation and reflection of electromagnetic waves. Water has a relative permittivity of around 80, compared with air and quartz that have values of 1 and around 4.3, respectively. Therefore, the relative permittivity of bulk sediment is governed by its water content.

The propagation velocity of electromagnetic waves is essentially frequency independent between 100 and 1000 MHz, assuming $\sigma < 0.1$ S/m (Davis and Annan, 1989). The propagation velocity is then found by $v = c_0/\epsilon_r^{1/2}$ where c_0 is the electromagnetic wave velocity in vacuum. Below 100 MHz, the EM wave velocity decreases with increasing water content. Attenuation of the electromagnetic signal is governed by σ and ϵ_r . Fine-grained sediments such as silts and clays, have high conductivities and cause a high signal attenuation. Therefore, GPR is limited to environments of low conductivity.

Each measurement shows the reflection strength versus two-way-traveltime. By performing multiple measurements along a transect GPR can be used to obtain a two-dimensional image of the shallow subsurface. Common mid point measurements allow for a conversion of two-way-traveltime into depth. By varying the antenna frequency one can make trade-offs between resolution and signal penetration.

2.0 RESPONSIBILITIES AND QUALIFICATIONS

The RI Project Manager or Field Manager has the overall responsibility for implementing this SOP. They will be responsible for assigning appropriate environmental staff to implement this SOP and for ensuring that the procedures are followed by all personnel.

All personnel performing these procedures are required to have the appropriate health and safety training. In addition, all personnel are required to have a complete understanding of the procedures described within this SOP and receive specific training regarding these procedures, if necessary.

All environmental staff and assay laboratory staff are responsible for reporting deviations from this SOP to the RI Project Manager or Field Manager.

3.0 RELATED STANDARD OPERATING PROCEDURES

Related SOPs include:

- SOP 1 Data management (including verification and validation)
- SOP 3 Surveying (GPS)
- SOP 37 Routine site visits
- SOP 22 Analytical data validation

4.0 EQUIPMENT LIST

The following materials and equipment listed will be needed for EMI or GPR geophysical logging:

- geophysical instruments
- waterproof pens
- manufacturer's operating manuals
- field map
- GPS
- field book or voice recorder
- field sample forms
- non-metallic tape measure(s)
- cart (GPR)

Other materials and equipment may be needed based on field conditions.

5.0 PROCEDURES: EM INDUCTION

Exploratory surveys consist of three passes along a transect, one pass with each of three Geonics, Inc. instruments: EM31, EM34, and EM38.

1. Set the ground conductivity meter to zero according to the manufacturer's instructions before use.
2. The person carrying the instrument must take off all metallic objects such as jewelry, belts with metal parts, and metal framed glasses. Steel support shoes/boots cannot be worn, which means the surveyor must use fiberglass-reinforced protective foot ware. Persons with metal pins or plates as a result of an injury should not carry the machine. Check for interference from other metal objects. When the EM38 is used with the data logger, check for interference with

the data logger by comparing a few readings with and without the data logger. The data logger should be carried opposite of the EM38.

3. Use a GPS to determine the exact locations of all measurements or run measurements in straight transects with the end points located. Other points along the transect can be interpolated if run at regular distance intervals, but flagging each station location guarantees that measurements from each instrument are co-located. Station intervals along transect should be determined by the survey's goals, but a 5 to 10 m interval is good for exploratory surveying.
4. For each transect and at each station, collect measurements in both vertical and horizontal dipole mode, recording them in a field notebook or on a voice recorder.
5. Repeat each transect with a different instrument, beginning with the instrument measuring the shallowest depth of exploration. This ensures a series of depth measurements. The EM 31 has an effective depth of exploration of 6 m. For the EM 34, this increases to 60 m. For the EM 38, it ranges from 0.75 to 1.5 m.
6. The results from each survey should include instrument model, vertical orientation measurement, and horizontal orientation measurement for each station location (use UTM coordinates).

GROUND PENETRATING RADAR (GPR)

Exploratory surveys consist of one or more transects made with the appropriate GPR instrument.

1. Set up the GPR instrument according to the manufacturer's instructions before use.
2. The people operating the instrument should minimize the use of metallic objects such as jewelry and belts with metal parts. Steel support shoes/boots cannot be worn, which means the surveyor must use fiberglass-reinforced protective foot ware. Be aware of possible interference from other metal objects such as vehicles, fences and powerlines in the immediate area. Cell phones should not be used.
3. Lay out (preferably) straight transects using tape measures. Use a GPS to determine the exact locations of all start and end points of all the measurement lines. If possible mark the start and end locations of each transect with stakes.
4. Station intervals along the transects should be determined by using the manufacturer's instruction on how to avoid "aliasing". Depending on the frequency that is used, the station spacing is commonly 0.2m to 0.05m.
5. After completing the transect measurement in "common offset" mode (i.e., the distance between both antennas remains the same), perform "common mid point" (CMP) measurements in order to estimate the electromagnetic wave velocity. During CMP measurements the antennas are moved away from each other (at increments half that of the common offset step size), while keeping the midpoint the same (see manual for further details). CMP measurements ideally are performed twice for each line (not for each measurement point): one parallel with

- the common offset transect (i.e., on the same line as on the common offset line), one perpendicular to it (i.e., for this a tape measure has to be placed perpendicular to the common offset transect; the mid point has to be on the common offset transect). The start position for CMP measurements can be chosen anywhere on the transect, but the best is to select a location where horizontal reflectors are present in the common offset radargram; if this is not possible select a point in the middle of the transect.
6. During the exploratory surveys repeat each transect with different frequencies to find out which frequencies perform best. We begin with the 100 MHz antennae (pulseEKKO 100 system). The 100 MHz usually gives a good overall picture of the subsurface structures. After the 100 MHz measurements, repeat the measurements with 50 MHz antennae (pulseEKKO 100 system) for a possible deeper penetration and with 200 MHz antennae (pulseEKKO 100 system) or 225 MHz antennae (pulseEKKO 1000 system) for a higher resolution. In later stages of the project we will choose one or two frequencies at which we do all data collection.

6.0 DOCUMENTATION

Documentation of observations and data acquired in the field will provide information on the activities concluded and also provide a permanent record of field activities. The observations and data will be recorded with waterproof ink in a permanently bound weatherproof field logbook with consecutively numbered pages, and on field data sheets.

Project and subcontractor staff are responsible for documenting logging activities. Field notes will be kept during logging activities. The following information will be recorded in a bound field log book:

- Names of personnel
- Weather conditions
- Date, time and location of logging
- Description of survey set-up and data collection
- Times that procedures and measurements are completed
- Summary of data reduction and preliminary interpretations
- Documentation of all problems encountered
- Calibration information
- Other applicable information

7.0 FIELD NOTES

Note the distance to any large metal items, telephone and electrical wires, or structures, if present, from each station.

8.0 REFERENCES

- Borchers, B., T. Uram, and J.M.H. Hendrickx. 1997. Tikhonov regularization for determination of depth profiles of electrical conductivity using non-invasive electromagnetic induction measurements. *Soil Science Society of America Journal* 61:1004-1009.
- Davis, J.L. and Annan, A.P., 1989, Ground-penetrating radar for high resolution mapping of soil and rock stratigraphy. *Geophysical Prospecting*, 37, 531-551.
- Hendrickx, J.M.H., B. Baerends, Z.I. Raza, M. Sadiq, and M. Akram Chaudhry. 1992. Soil salinity assessment by electromagnetic induction on irrigated land. *Soil Sci. Soc. Am. J.* 56:1933-1941.
- Hendrickx, J.M.H., C.D. Grande, B.A. Buchanan, and R.E. Bretz. 1994. Electromagnetic induction for restoration of saline environments in New Mexico. Chapter 13 *in*: ECM Series on Environmental Management & Intelligent Manufacturing. *Editors* Rohinton K. Bhada, Abbas Ghassemi, Timothy J. Ward, Mohammad Jamshidi, and Mohsen Shahinpoor. Volume No. 1 "Waste-management: From Risk to Remediation" ECM Press, Albuquerque, New Mexico. pp. 247-265.
- Hendrickx, J.M.H., B. Borchers, D.L. Corwin, S.M. Lesch, A.C. Hilgendorf, and J. Schlue. 2002. Inversion of soil conductivity profiles from electromagnetic induction measurements: theory and experimental verification. *Soil Science Society of America Journal* 66:673-685.
- Hendrickx, J.M.H., and R.G. Kachanoski, 2002. Nonintrusive electromagnetic induction. In: J.H. Dane and G.C. Topp (eds.) *Methods of soil analysis. Part 4. Physical Methods*. Soil Science Society of America, Madison, Wisconsin. pp. 1297-1306.
- Huisman, J.A., S.S. Hubbard, J.D. Redman, and A.P. Annan, Measuring Soil Water Content with Ground Penetrating Radar: A Review, *Vadose Zone Journal*, 2, 476–491, 2003.
- Kachanoski, R.G., E. de Jong, and J.M.H. Hendrickx. 2002. Nonintrusive water content measurement in the field. Section 3.1.3.2 *In*: J.H. Dane and G.C. Topp (eds.) *Methods of soil analysis. Part 4. Physical Methods*. Soil Science Society of America, Madison, Wisconsin. pp. 497-501.
- Sheets, K.R., J.P. Taylor, and J.M.H. Hendrickx. 1994. Rapid salinity mapping by electromagnetic induction for determining riparian restoration potential. *Restoration Ecology* 2:242-246.
- Sheets, K.R., and J.M.H. Hendrickx. 1995. Non-invasive soil water content measurement using electromagnetic induction. *Water Resources Research* 31:2401-2409.

- Van Dam, R.L., Schlager, W., Dekkers, M.J. and Huisman, J.A., 2002, Iron oxides as a cause of GPR reflections. *Geophysics*, 67, 536-545.
- Van Heteren, S., FitzGerald, D.M., McKinlay, P.A. and Buynevich, I.V., 1998, Radar facies of paraglacial barrier systems: coastal New England, USA. *Sedimentology*, 45, 181-200.
- Von Hippel, A.R., 1954, *Dielectric Materials and Applications*, (New York: John Wiley and Sons).