Review and Summary of EM Concepts from *Geophysics for the Mineral Exploration Geoscientist*

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1 A Brief Introduction to EM Geophysics

Electromagnetic (EM) surveys are predominantly active geophysical methods that employ artificially generated electromagnetic fields, with applications spanning airborne, surface, and downhole settings. While traditionally used for mineral exploration, EM techniques are increasingly applied in mining to improve orebody delineation and reduce drilling costs. The principal objective is to characterize spatial variations in electrical conductivity, represented through maps, cross-sections, or 3D models, to identify discrete conductive targets.

The key properties relevant to EM surveys are electrical conductivity and magnetic permeability. Electrical conductivity (σ) describes how easily electric charges move under an applied electric field and is expressed by Ohm's law ($\mathbf{J} = \sigma\mathbf{E}$). Its reciprocal is resistivity. Magnetic permeability (μ) defines the extent to which a material becomes magnetized in response to an external magnetic field, given as the ratio of magnetic flux density (B) to field intensity (H). Magnetic viscosity refers to a time-dependent, dispersive form of magnetic permeability.

EM methods operate by transmitting a time-varying current through a transmitter to generate a primary magnetic field, which, upon interaction with conductive materials, induces eddy currents in accordance with Faraday's Law. These eddy currents produce a secondary magnetic field that is measured by a receiver, providing diagnostic information about subsurface conductors.

2 Differences between Time-Domain and Frequency-Domain Electromagnetic Methods

Time-domain electromagnetics (TDEM) and frequency-domain electromagnetics (FDEM) differ in how the primary magnetic field is generated and how subsurface responses are measured. In TDEM, the field is created by abruptly turning on or off a steady current, inducing eddy currents in the ground that decay over time; measuring this decay provides information on subsurface conductivity and geometry. Because measurements are taken after the primary field is switched off, TDEM systems are highly sensitive to weak secondary fields, less affected by transmitter–receiver orientation, and capable of deeper penetration, making them the preferred method for mineral exploration.

In contrast, FDEM uses a continuous alternating current to generate a sinusoidally varying primary field that induces continuous eddy currents in the ground; their strength and phase are measured relative to the primary field. However, because the receiver detects both the strong primary and weak secondary fields simultaneously, FDEM is less sensitive to small conductivity variations and more prone to noise. As a result, FDEM is mainly used for shallow applications such as engineering, archaeology, and groundwater studies, while TDEM dominates mineral exploration.

3 Generation of the Primary Magnetic Field

In electromagnetic surveys, the primary magnetic field is typically generated using a large loop, whose strength is defined by the magnetic dipole moment ($m = nIA$), where I is the current, n the number of turns, and A the loop area. A larger dipole moment enhances the strength of the primary field, producing stronger eddy currents and improving the signal-to-noise ratio of the secondary field measurement.

Large loops distribute the magnetic field over a wider volume, enabling detection of deeper targets; unlike small coils, whose field strength decreases with distance as $1/r^3$, large loops decrease more gradually as $1/r^2$. Transmitter currents can reach several hundred amperes but are limited by the back electromotive force (emf) generated during current turn-off, which depends on the loop's inductance. Large multi-turn loops generate higher back emf, requiring slower ramp times for current switching, which reduces the rate of magnetic field change and diminishes the quality of the EM response.

4 The Concept of Coupling

Coupling in electromagnetic surveys refers to how effectively the transmitter's primary magnetic field induces currents in a conductor, and this depends entirely on geometry. If the magnetic field cuts across the conductor at right angles (perpendicular to its plane), strong eddy currents are generated, giving a well-coupled response. If the field runs parallel to the conductor's plane, little or no current flows, and the response is null coupled. In practice, this means a vertical conductor may respond strongly when the transmitter loop is beside it but show no response when the loop is directly above, while a flat-lying conductor gives the opposite behavior.

5 The Eddy Current

Eddy currents are circular electrical currents induced in subsurface conductors whenever the primary magnetic field changes and intersects them perpendicularly, with their strength increasing when the field varies more rapidly, according to Faraday's Law. In simple homogeneous bodies, these currents flow in closed loops perpendicular to the field, but their exact patterns depend on the conductor's size, shape, and electrical uniformity. Immediately after the primary field is switched off, currents flow near the conductor's surface, then gradually diffuse inward as they lose energy, with slower decay in more conductive bodies. Early-time currents mainly reflect the conductor's geometry, while later-time currents reveal internal conductivity, making the time-varying eddy current patterns a key tool for interpreting subsurface structures in EM surveys.

6 Receiver Sensors and Magnetic Field Components in EM Surveys

In EM surveys, the decay of eddy currents is measured by detecting the secondary magnetic field using different types of sensors. A B-field sensor directly measures the field strength, while a coil (dB/dt sensor) measures the rate of change of the field. Airborne systems can convert dB/dt measurements into B-field data. Both sensor types measure the field along specific directions, called components: Z (vertical), X (horizontal along the survey line), and Y (horizontal across the line). Because the orientation of the secondary field changes with position and time as eddy currents migrate, measuring all three components gives a complete picture of the field. Comparing these components helps determine the location, shape, and orientation of subsurface conductors, making three-component measurements essential for accurate interpretation.

7 On-Time and Off-Time Measurements

In time-domain electromagnetic surveys, the subsurface response is measured as a function of delay time following the abrupt turn-on or turn-off of the primary field. Each delay corresponds to a measurement channel, forming a time series that records the decay of the secondary magnetic field. Most systems use off-time measurements, taken after the primary field is switched off, as they are less affected by transmitter–receiver geometry and noise. Some systems also collect on-time measurements, while the primary field is active, though these are more sensitive to positional variations. To improve data quality, thousands of decay repetitions are recorded, and equivalent measurements are stacked to suppress noise, which is particularly critical at late times when signals are weak. These stacked results are grouped into receiver windows (channels) that widen with delay time and are spaced approximately logarithmically, providing higher resolution at early times when decay is rapid and lower resolution at later times when decay is slower.

8 Step and Impulse Responses

In time-domain EM surveys, the ground's response to a changing primary magnetic field can be recorded as either a step or impulse response. Using a B-field sensor, a step change in the primary field produces the step response, while an extremely short pulse (impulse) produces the impulse response. A coil sensor, which measures the time derivative of the magnetic field (dB/dt), records the slope of the step response—effectively giving the impulse response—or can be used to measure the step response by transmitting a long triangular pulse. In practice, ideal step or impulse waveforms are not possible, so finite-width pulses are used; the measured signals approximate the ideal responses and are distorted by the ground, carrying information about subsurface conductivity. Modern TDEM systems often record both B-field and dB/dt data, and although the specific responses depend on the transmitted waveform, they retain the essential characteristics of step and impulse responses, which form the basis for interpreting conductor properties.

9 Diffusion in a Homogeneous Half-Space

In a time-domain electromagnetic survey over a homogeneous half-space, the ground is electrically uniform except at the air–earth boundary, making it the simplest case to study electromagnetic diffusion. When the transmitter loop is turned off, eddy currents form in the ground to oppose the loss of the primary field; these currents initially resemble an image of the loop. Immediately after their creation, they expand outward and downward, forming a doughnut-shaped flow called a "smoke ring." As time progresses, the smoke ring blurs, loses energy, and continues to migrate downward at roughly a 30° angle, with its strength and velocity strongly influenced by the ground's conductivity. Because the half-space has no subsurface boundaries, the only limit on current expansion is the ground–air interface, making it an unconfined conductor where the eddy currents can freely diffuse in all directions. The diffusion depth is the depth of maximum current density at a given delay time, increasing with the square root of time and more rapidly in resistive ground than in conductive ground. In resistive media, signals decay quickly and must be measured early, while in conductive ground diffusion is slower and shallower.

10 Diffusion in a Thin Layer (Conductive Overburden)

A thin, conductive, flat-lying layer—often occurring as conductive overburden near the surface—produces a strong EM response because it couples closely with the transmitter loop. Eddy currents form at the top of the layer and diffuse laterally within it, making the layer act as an unconfined conductor with a power-law decay that is faster than that of a half-space. The response depends on the conductance (conductivity × thickness) rather than conductivity or thickness alone. If the layer is thicker, diffusion also extends downward and the response starts resembling that of a half-space. In multilayer settings, each conductive layer contributes to the overall decay, with stronger and slower-decaying conductive layers dominating over thin resistive ones. In practice, early-time measurements capture the quickly decaying response of the conductive overburden, while late-time measurements reveal the deeper, slower-decaying signal from the underlying half-space

11 Diffusion in Confined Conductors

A confined conductor is a localized body of contrasting conductivity within a homogeneous host, such as mineralization. When the primary field is turned off, eddy currents are induced both in the background and within the conductor, but inside the conductor their diffusion is confined by its boundaries. The response depends strongly on the conductor's shape, size, and conductivity. At late times, the decay is exponential rather than a power law, characterized by a time constant (τ), which reflects the conductor's quality: large τ values indicate good conductors (high conductivity or large size) that sustain currents longer (late-time conductors), while small τ values correspond to poor conductors that decay quickly (early-time conductors). Although the initial amplitude is determined by geometry and depth, not conductivity, the rate of decay reveals the conductor's quality. In conductive environments with overburden or conductive host rocks, their strong, fast-decaying power-law responses dominate at early times, so the confined conductor's exponential response becomes visible only at late times. This makes late-time measurements crucial for detecting good conductors in noisy, conductive settings, while weak or poor conductors may remain hidden.

12 Current Channelling in Conductive Environments

In conductive settings, target conductors often connect electrically with surrounding rocks or overburden, enabling interaction between their eddy current systems. Here, conductors are energized not only by the collapsing primary field but also by slow-moving half-space eddy currents and by direct current flow through the conductor, a process known as current channelling. This effect depends on background conductivity, conductor connectivity, and distance from the source loop. In resistive environments, channelling appears briefly at early times, while in conductive environments it persists longer and may dominate the response. Current channelling amplifies surface signals and broadens anomalies, but it also causes faster decay and can obscure distinctions between good and poor conductors, sometimes erasing diagnostic information apart from conductor location. Additionally, conductive overburden or resistive inclusions can distort half-space currents, further complicating interpretation.

13 Acquisition of EM Data

The way EM data are acquired depends on target type, depth, geometry, host rock conductivity, and survey objective—whether detecting discrete conductors (e.g., orebodies) or mapping broader conductivity variations (e.g., regolith profiles). No single EM system is optimal for all cases, which is why multiple designs exist. Step and impulse responses each provide different advantages, requiring secondary fields to be measured over different time intervals. Key acquisition parameters include transmitter waveform, base frequency, system geometry, and data normalization, all of which determine resolution, depth of investigation, and ability to characterize conductor geometry. The transmitter waveform, shaped by loop inductance, controls early- versus late-time resolution, with triangular or ramped pulses commonly used. Base frequency tuning is critical: lower frequencies increase penetration depth and late-time resolution for good conductors, while higher frequencies improve near-surface and poor-conductor resolution, as well as lateral resolution in airborne systems. System geometry—the orientation, size, and arrangement of transmitter and receiver coils—further influences lateral resolution and coupling. Horizontal loops are most common, coupling well with layered media and a variety of dips, while survey modes may use moving-loop or fixed-loop setups. Measuring multiple components (Z, X, and sometimes Y) enhances conductor characterization. Together, these acquisition choices define the system's sensitivity, resolution, and depth performance.

14 Moving- vs Fixed-Loop EM Survey Modes

In moving-loop mode, both transmitter and receiver are moved together, with the in-loop configuration (receiver at the center of the loop) being most common. This mode provides excellent resolution and is especially useful in reconnaissance surveys where conductor dip and orientation are unknown, as new eddy current systems are induced at each station. Variants such as the separated-loop configuration improve sensitivity to steeply dipping conductors, though responses may vary depending on survey direction. Moving-loop setups typically use 50–500 m loops with portable generators, achieving strong dipole moments but producing complex anomaly shapes, and requiring significant across-line access. In contrast, fixed-loop mode keeps the transmitter loop stationary—often very large and oriented parallel to the conductor strike—while the receiver is moved along traverses or in boreholes. This method requires prior knowledge of conductor orientation but allows deep penetration with strong transmitter currents, producing simpler anomaly forms. Although fixed-loop mode has lower resolution, three-component measurements and multiple loop locations can improve diagnostic capability. It also offers simpler logistics in rugged terrains since only the receiver is moved, though setting up large loops can be challenging.

15 Transmitter Loop Size and EM Survey Design Considerations

The size of the transmitter loop strongly affects the strength and depth of EM investigations. Larger loops produce stronger fields and increase signal-to-noise ratios at later delay times, enabling deeper penetration, but they also enhance responses from conductive host rocks and near-surface layers, which can mask target responses. Thus, there is a trade-off: larger loops provide greater depth but lower spatial resolution, especially in moving-loop mode. Typically, a loop-to-depth ratio of about 1:3 is effective in resistive environments, while more conductive settings may require a ratio closer to 1:2. Optimal loop size depends on environmental conductivity, target depth, and survey type, and often benefits from computer modelling. In broader EM survey design, detectability and resolution depend on target characteristics (conductivity, geometry, orientation, depth) and host environment. For example, horizontally oriented conductors may be detectable at greater depths than vertical ones, depending on field orientation and receiver placement. Because explorers usually have limited prior knowledge, survey parameters are best optimized using modelling to predict depth of investigation, resolution, and detectability under specific conditions.

16 Common Pitfalls in EM Data Interpretation

Interpretation of EM data is prone to pitfalls that can lead to misclassification of conductors unless carefully recognized and corrected. Ambiguities arise from non-uniqueness in inversion, and conductive environments are particularly problematic, as overburden can obscure or distort deeper signals, channel currents, and broaden anomalies, often masking weaker conductors. Interactions between nearby conductors further complicate resolution by shielding or distorting responses, while cultural features (fences, powerlines) and topography can generate misleading anomalies unless cross-checked with maps and survey geometry. Additional complications include induced polarization, which alters decay rates and polarity at later times, and superparamagnetism, where fine magnetic grains produce spurious long-lived decays that mimic higher conductivity. Finally, electrical anisotropy modifies the orientation and strength of eddy current systems, creating apparent conductivity variations linked to rock fabric