Noninvasive monitoring of CO_2 sequestration sites using airborne EM technology

- The objective of this study is to show effectiveness of potential field EM airborne technology in monitoring quality and saturation level of CO_2 reservoirs

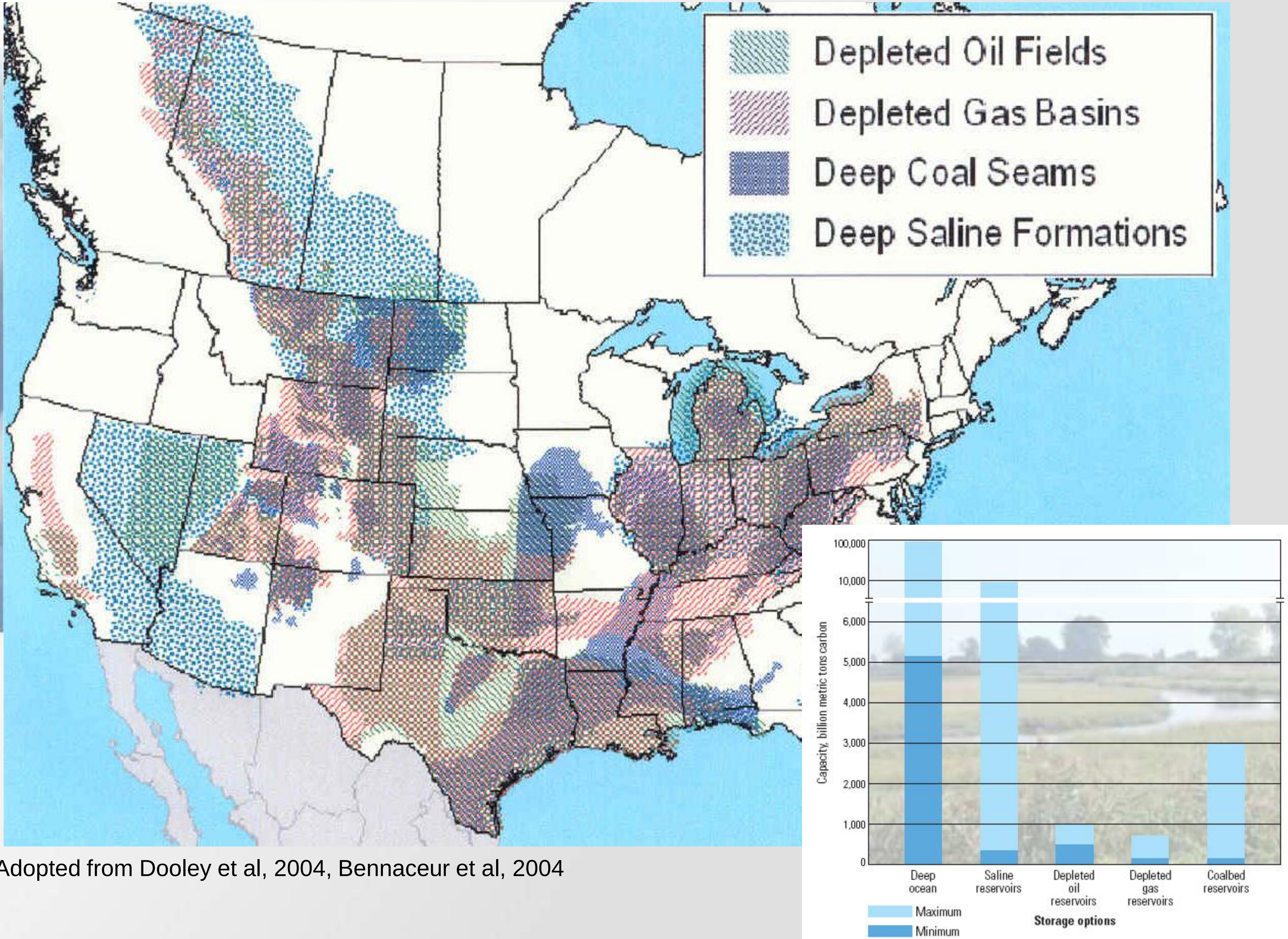
- To discuss potential advantages of airborne technology as alternative to Electrical Resistance Tomography (ERT) and Controlled Source Audio frequency Magneto-telluric Surveys (CSAMT) and benefits of integrating EM data with seismic data

- To investigate potential for recovery of such parameters as porosity, gas saturation and estimates of gas volume, which could not be determined using any of these technologies alone

- To show possibility of mapping the changes in electrical properties due to CO_2 injection as a function of time

- To show cost-effectiveness of the airborne technology and its potential application for CO_2 sequestration in the future

Potential CO_2 sequestration sites in North America



Adopted from Dooley et al, 2004, Bennaceur et al, 2004

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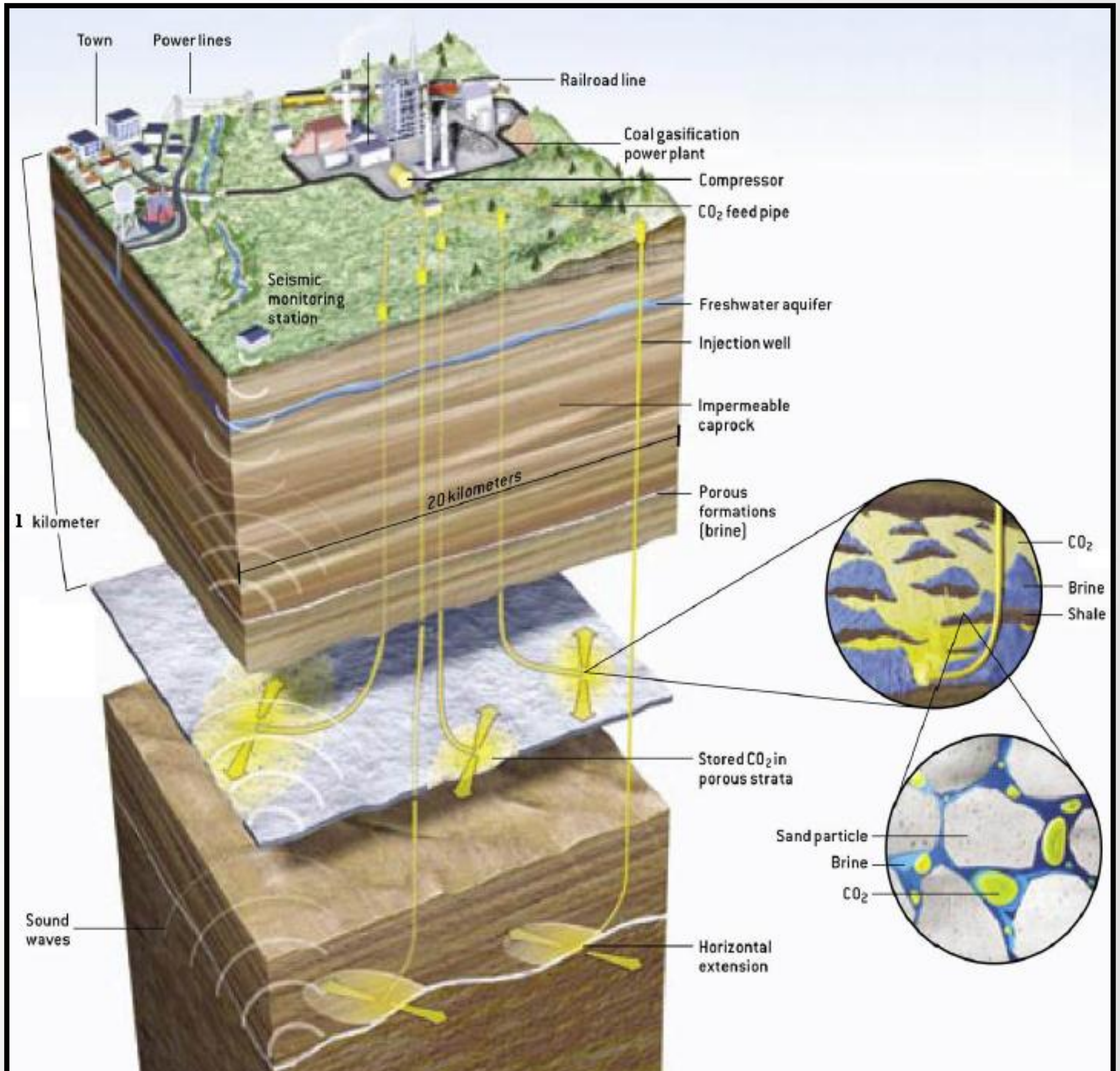
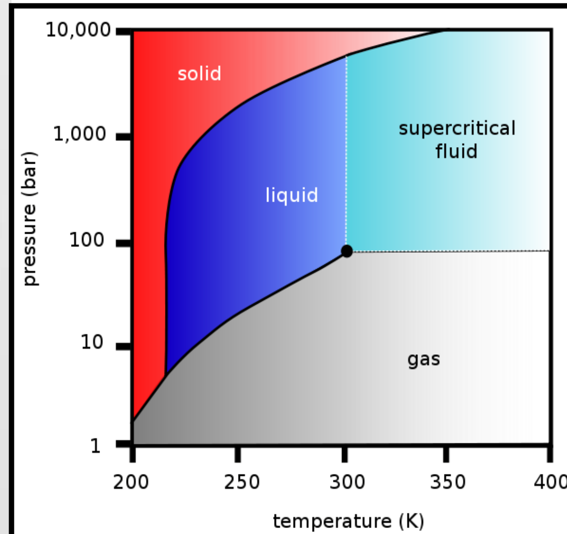
Brief introduction t CO_2 sequestration in deep saline aquifers



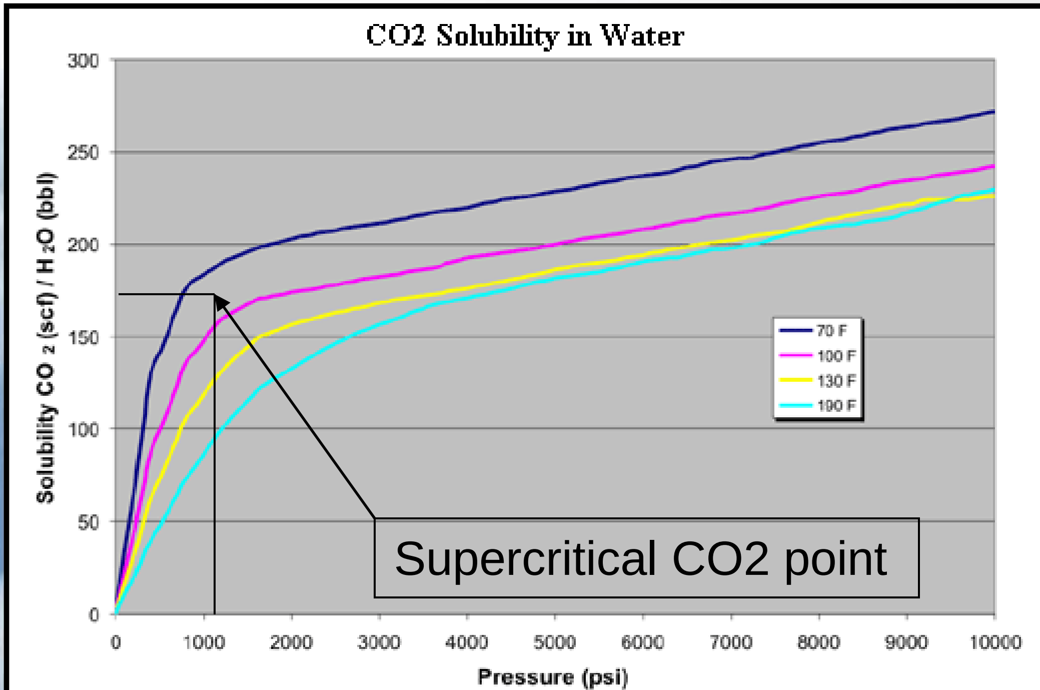
Adopted from Friedmann, 2005



Adopted from Jacobs, 2005

- CO_2 capture reservoirs can be located at depths of 800 meters and more
- Reservoir thickness may vary from several to hundreds of meters
- Reservoir CO_2 storage capacity may reach thousands of MT (Megatons)

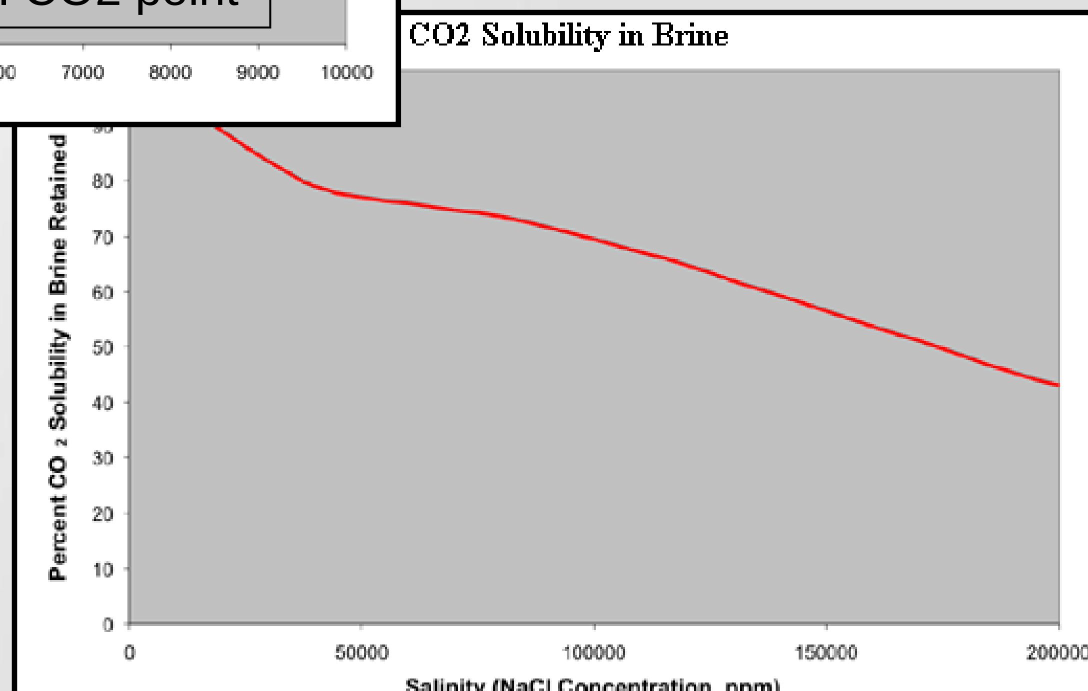
Solubility of CO_2 in H_2O



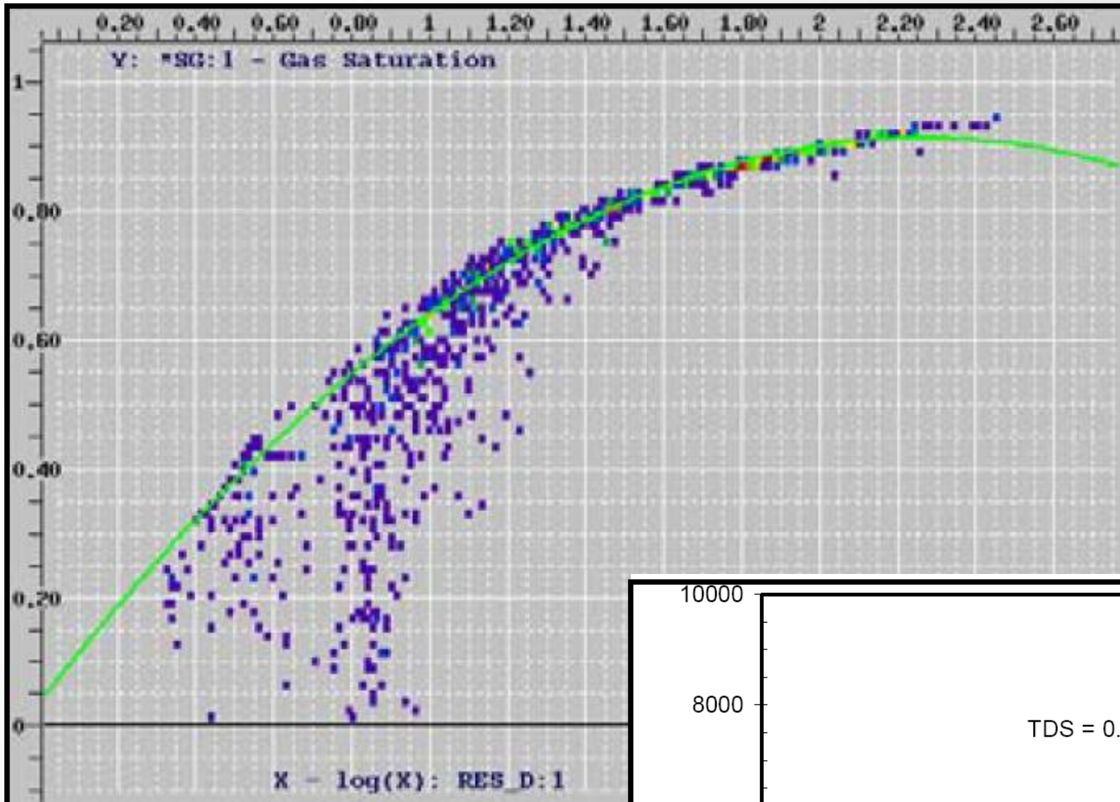
About 15% of injected CO_2 dissolves in brine. The rest of the carbon dioxide occupies the pore space

At $2*10^5$ mg/L TDS concentration brine can accommodate roughly 45% of CO_2 volume dissolvable in pure H_2O

Under conditions suitable for CO_2 sequestration deep saline formations in supercritical phase the CO_2 solubility in fresh water is 170 sci/bbl (or 82g/L) and more



Electrical resistivity as a function of gas saturation and of TDS content



Adopted from Harris et al, 2009

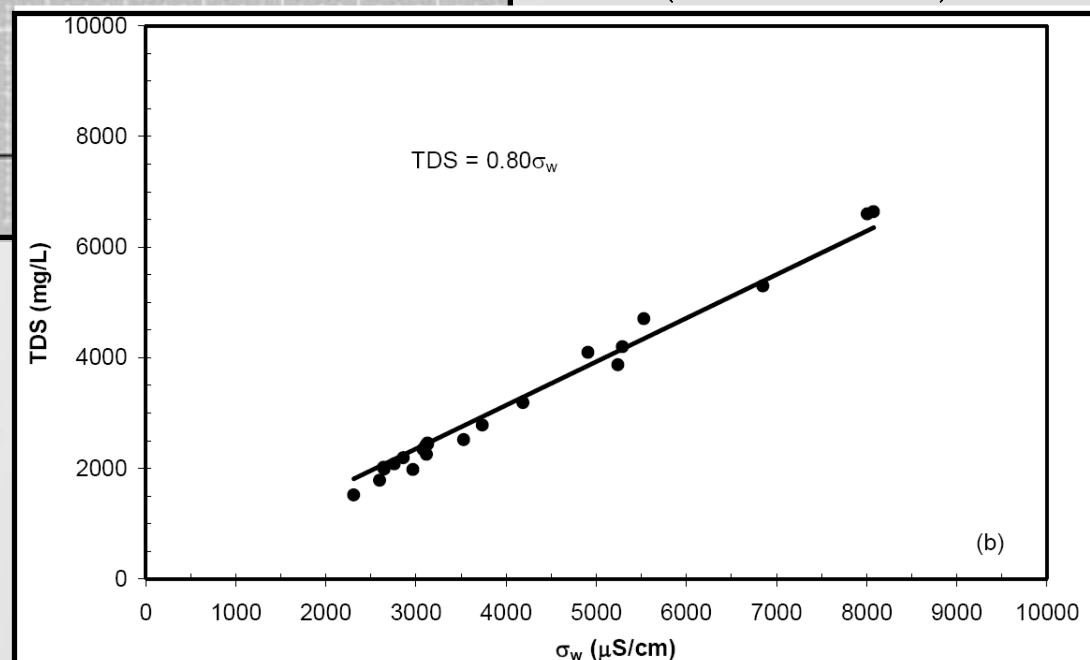
Saline water in deep sequestration reservoirs can be up to 6 times richer in TDS content than seawater and reach up to $2*10^5$ mg/L. With effective porosity at 30% this would results in formation conductivity up to 4.5 S/m (0.22 Ohm*m)

Saturation range: 0 to 95%

Electrical resistivity range:

5 Ohm*m to 400 Ohm*m

(almost a 100-fold increase in electrical resistivity)



Adopted from Lipinski, 2007

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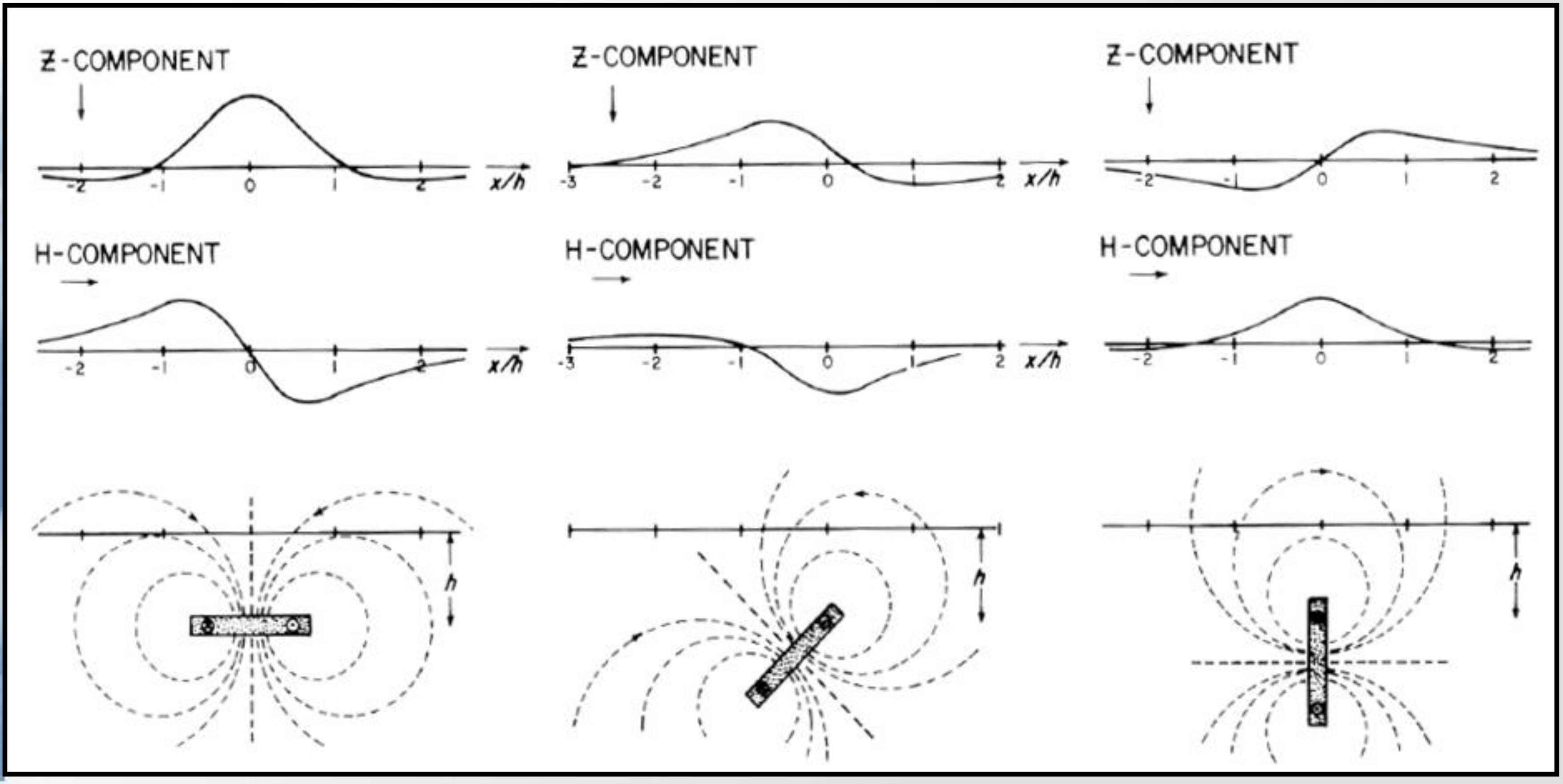
Importance of measuring all components



Deep saline formation can be approximated with a thick horizontal layer. A significant part of target response is derived from the X component of the secondary magnetic field. AirMt system seems to be more sensitive to such horizontal component anomaly than ZTEM, which only measures the vertical component.

Furthermore in perfectly horizontally homogeneous media Tx = Ty = 0, therefore we can not use the tipper data for interpretation within layered geological model (Berdichevsky et al, 2003)

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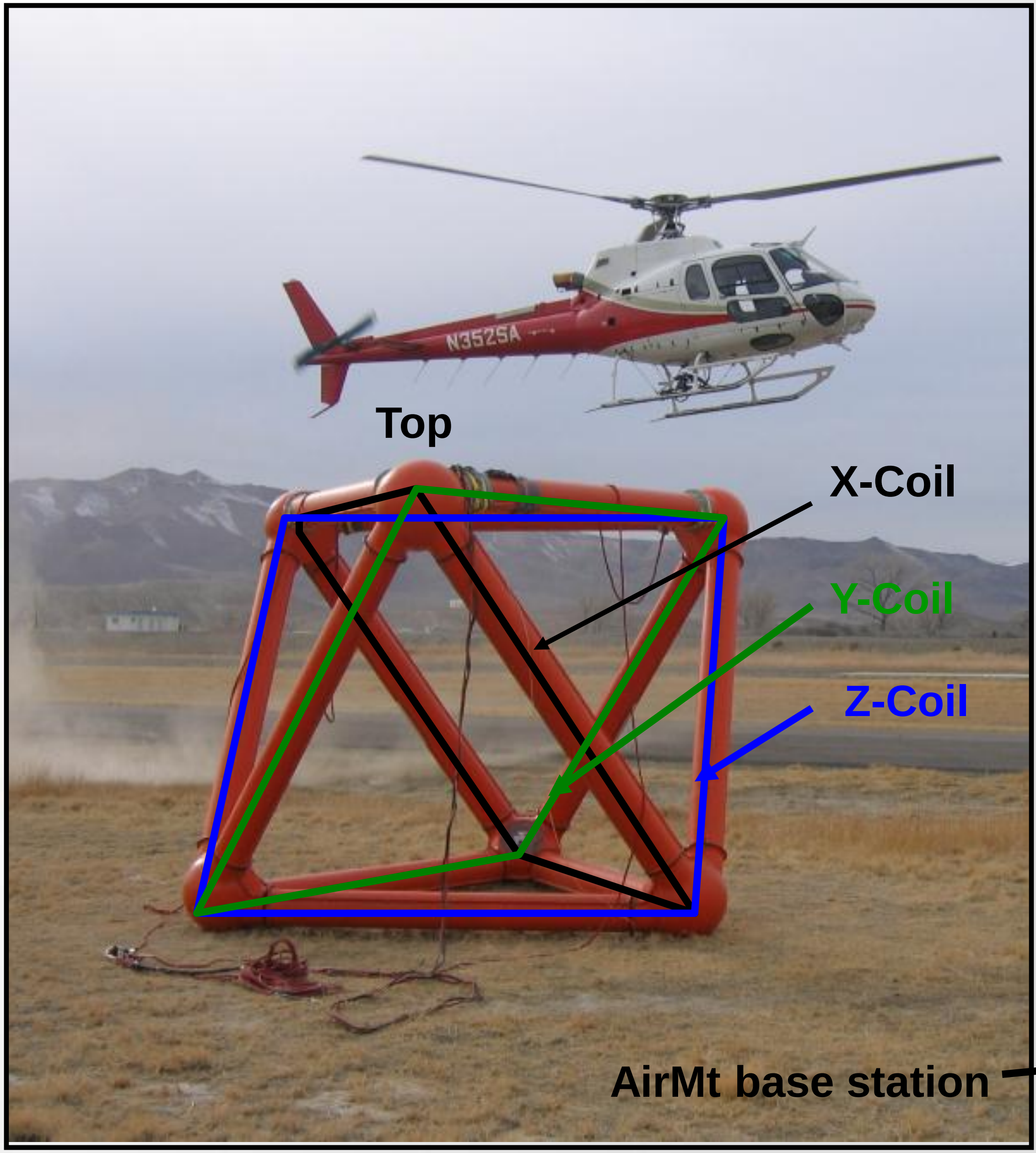
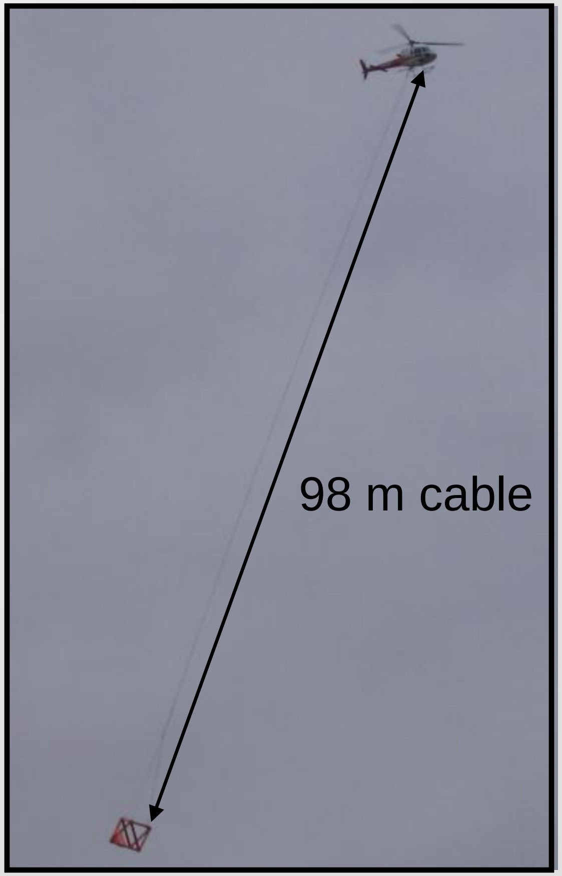
AirMt system





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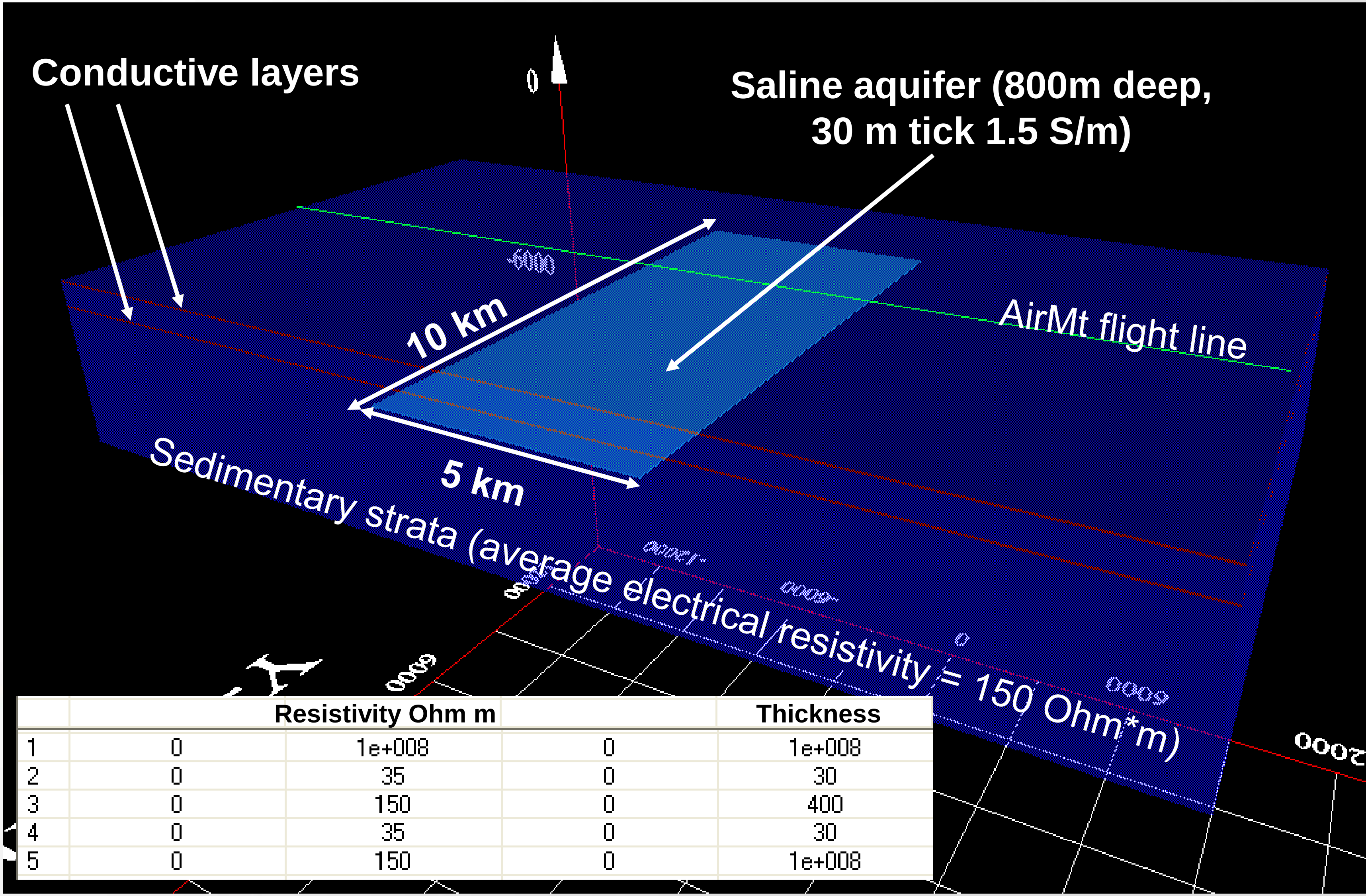
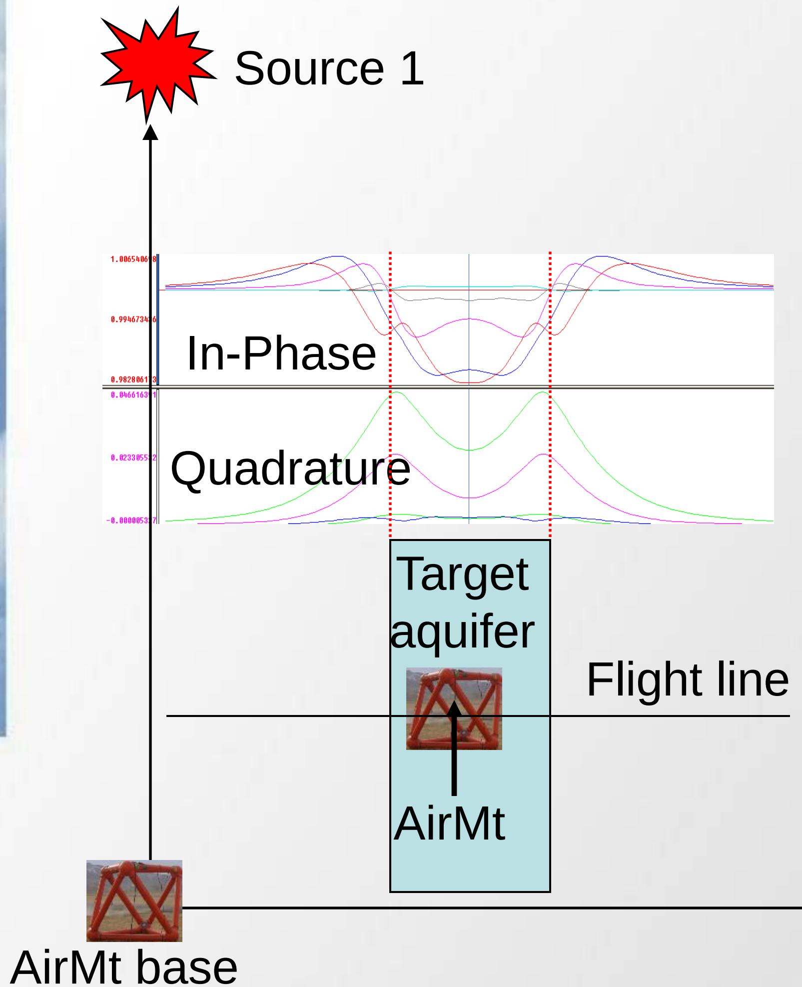
Deep saline aquifer model



	Resistivity Ohm m			Thickness
1	0	1e+008	0	1e+008
2	0	35	0	30
3	0	150	0	400
4	0	35	0	30
5	0	150	0	1e+008

Saline aquifer electrical resistivity was initially set at 1.5 S/m and gradually decreased simulating the sequestration process

Modeling AirMt data



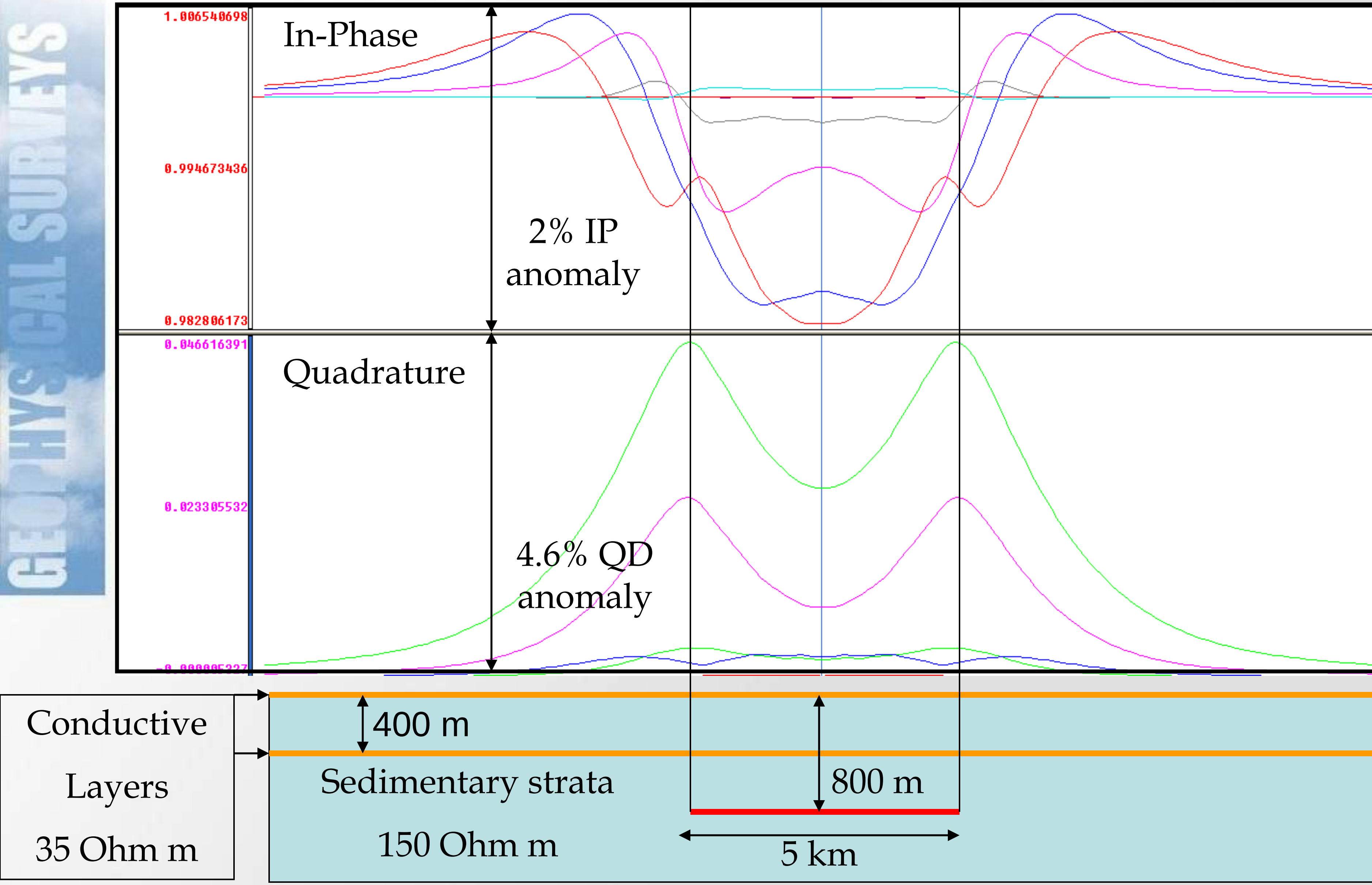
In Emigma software each magnetic field component is modeled individually, therefore they are sensitive to which way primary field is propagating from

In order to equally excite all 3 magnetic field components (Hx, Hy and Hz), two sources of natural plane wave were assumed coming from two orthogonal directions.

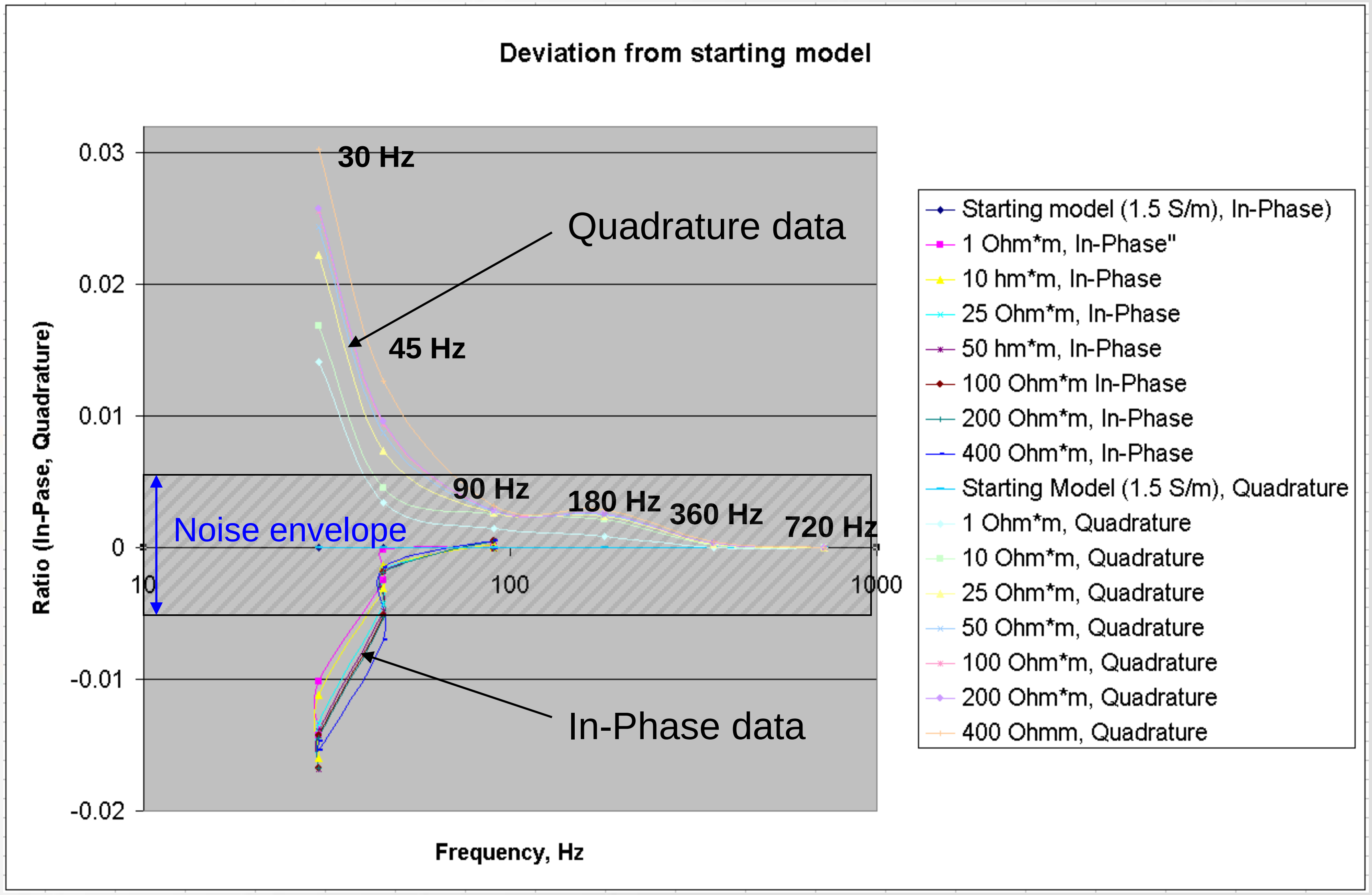
Total field (In-Phase and Quadrature) is calculated from averaged individual magnetic field components according to the formula:

$$Ht = \sqrt{Hx^2 + Hy^2 + Hz^2}$$

Predicted shape of AirMt anomaly over 1.5 S/m 800 m deep saline aquifer

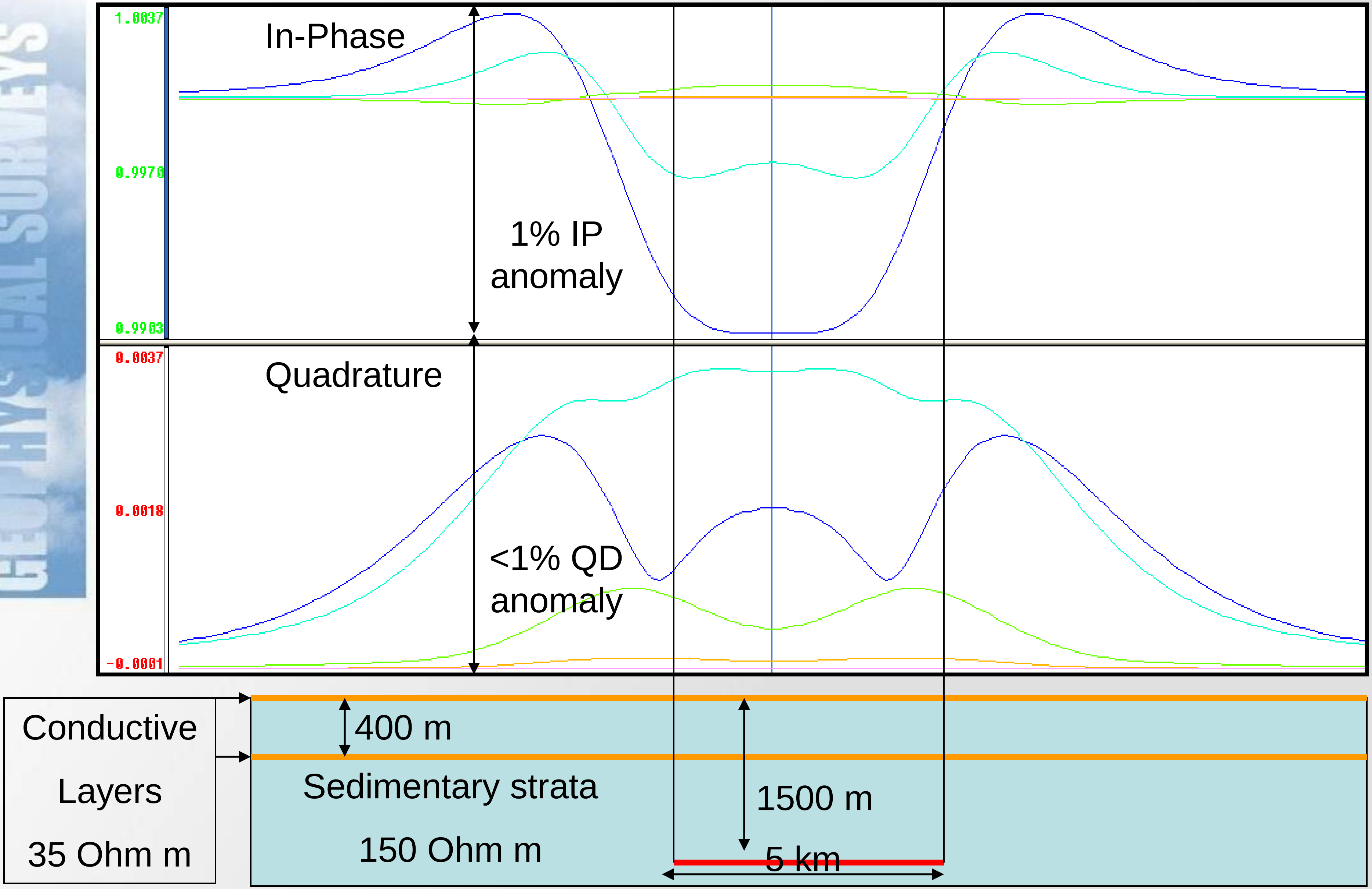


Difference caused by introduction of CO2 to a saline water aquifer based on AirMt modeling



These curves were acquired from modeling of 800m deep saline aquifer at different stages of sequestration process

Predicted shape and amplitude of AirMt anomaly over 1.5 S/m 1.5 km deep saline aquifer



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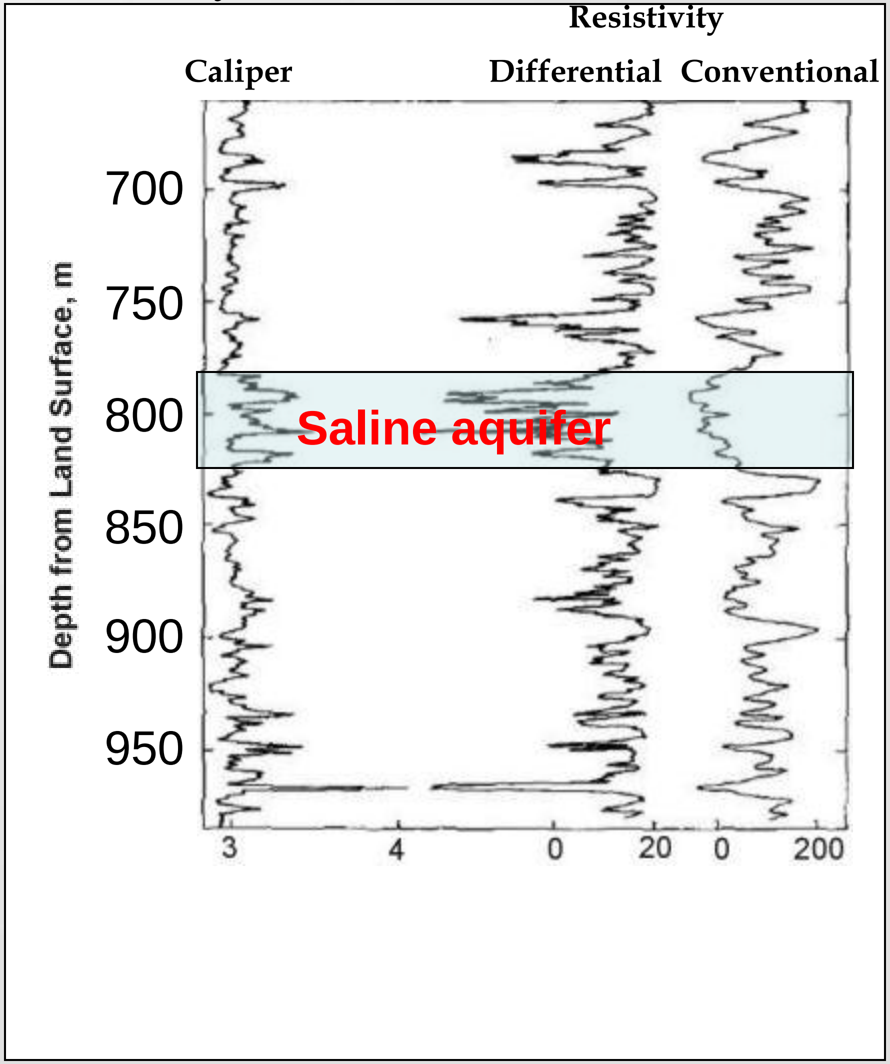
Quantitive AirMt data interpretation and combining EM data with seismic data

Use existing well data to construct a generalized layered Earth model and then assign electrical properties to each generalized layer

Study deviations from beginning model with introduction of CO_2

Before any survey is flown, forward modeling should be used to simulate AirMt response based on known geology and well log resistivity values

Use geologically constrained inversion upon survey completion in order to convert measured data into units of apparent resistivity and/or gas saturation values



Conclusions

AirMt can be a cost-effective tool for monitoring CO_2 deep saline and depleted Oil and Gas fields sequestration reservoirs under favourable conditions:

- Initial conductivity of the reservoir has to be high enough for AirMt to distinguish it from the bulk resistivity of the surrounding strata
- The depth to reservoir must not exceed 1.5 km
- The thickness of reservoir must be sufficient to expect reasonable amplitude of Hx and Hy components of the secondary magnetic field
- For shallower reservoirs (under 1 km) it may be possible to give evaluation and some quantitive analysis such as saturation level of aquifer based on low frequency AirMt data interpretation
- There must be pre-existing well-log data (calibration sites) in order to numerically interpret AirMt
- Comparing AirMt technology to CSAMT technology AirMt has advantages of being more cost-effective and providing much better sampling rate (approximately 1 reading per every 10 meters)
- Magnetovariational soundings (such as AirMt technology) are not sensitive to nearsurface disturbances of electrical field (as in case with CSAMT soundings)

Suggested approach

1. Fly AirMt survey before the sequestration, including at least a 30% buffer zone around the sequestration site
2. Use line spacing roughly ½ of the estimated depth to the top of sequestration formation
3. Include as many monitoring wells to fall on the flight path as possible in order to further accurately calibrate the AirMt data
4. Calibrate AirMt data using well logs for numerical solution
5. Present the measured data in units of electrical resistivity plotted as a function of frequency using synthetic electrical field components for impedance (Z) calculation
6. Perform numerical interpretation of variation in electrical properties of sequestration reservoir and convert these data into gas saturation estimates to evaluate losses/gains in sequestered CO_2
7. Derive additional reservoir properties from combining AirMt data with seismic data (if available)
8. Repeat AirMt survey as needed (depending on storage capacity and injection rate): in the middle of the sequestration and after, in order to study the variation in sequestration aquifer.

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