Use of Seismic and EM Data for Exploration, Appraisal and Reservoir Characterization

Anton Ziolkowski and Folke Engelmark

Petroleum Geo-Services

CSEG, Calgary, 6 May 2009

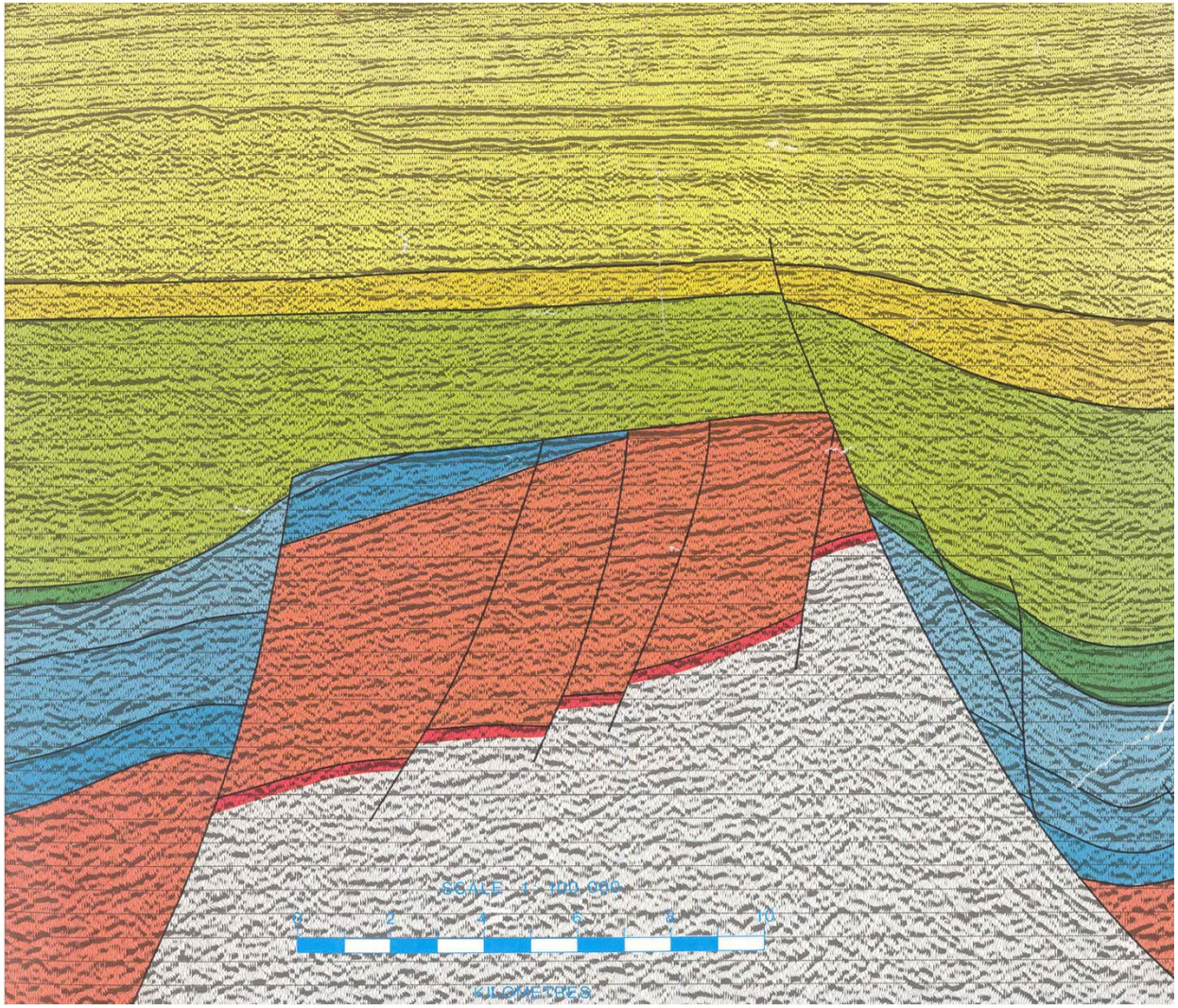
Outline

- Exploration, appraisal, reservoir characterization
- Physical properties and geophysical methods
- Relationships among geophysical methods
- Inputs and outputs
- Modelling, inversion, and uncertainty
- Seismic and EM together: carbonate example
- Time-lapse methods and reservoir characterization
- Conclusions

Exploration, appraisal and reservoir characterization

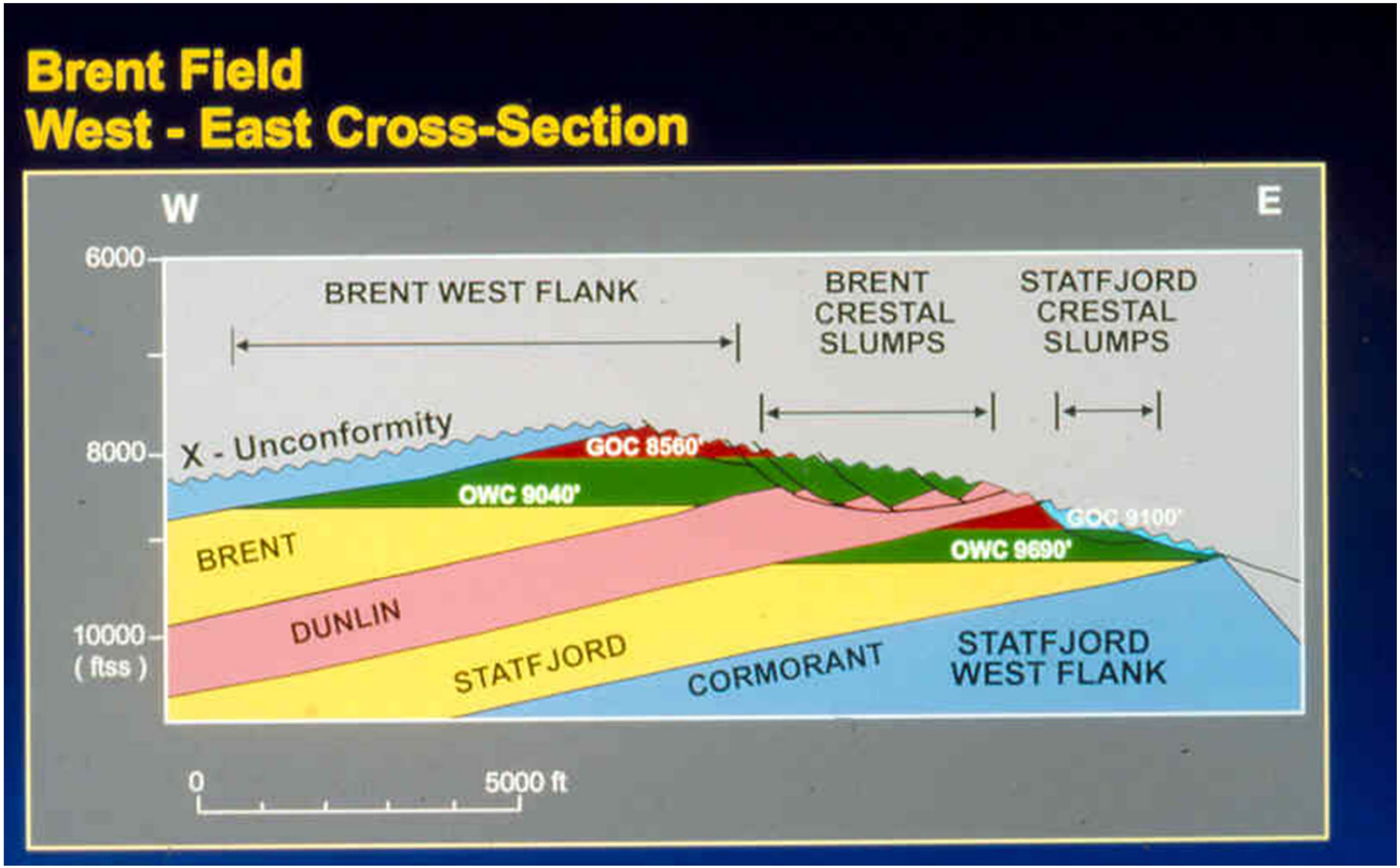
- Exploration: Is there any oil or gas?
- Appraisal: How much oil or gas?
- Reservoir characterization: What are the reservoir parameters in space at a given time?
  - Porosity
  - Permeability
  - Saturation

SNORRE FIELD



Shown with permission of John Underhill

Brent Cross Section: Interpretation after drilling



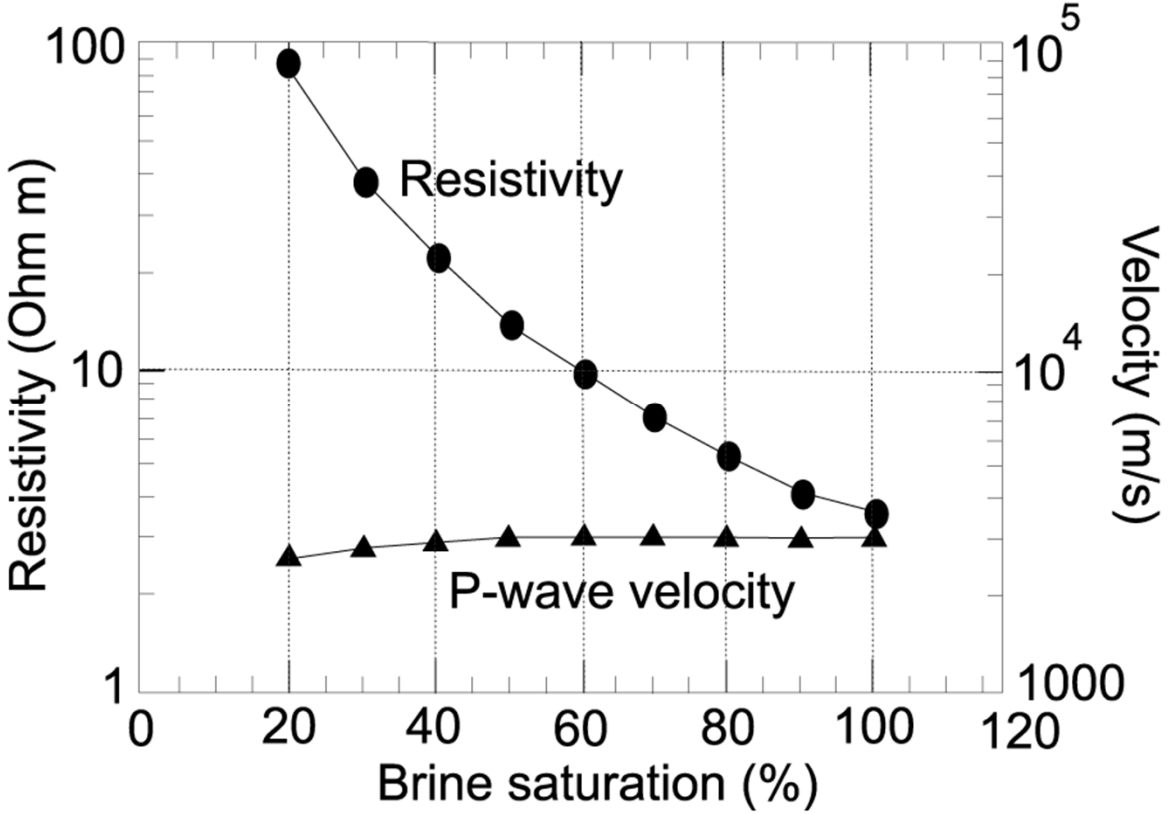
Shown with permission of John Underhill

Exploration: Is there any oil?

- It would be great if we could answer this question without drilling.
- ExxonMobil and Shell have had considerable success in reducing drilling risk in deep water plays by using conventional controlled source electromagnetic (EM) exploration in conjunction with seismic data.
- So it can be done: there is synergy between seismic and EM data for exploration.

Why we should be interested in EM

Fluid saturation and rock properties



P-wave velocity is affected only slightly by hydrocarbon saturation in a porous rock.

Resistivity can vary by more than an order of magnitude.

Picture redrawn from Wilt M. and Alumbaugh D. 1998, The Leading Edge 17, 487-492.

How do we combine seismic and EM data?

- Seismic data provides structure
- EM data provides fluid content
- Right?

Outline

- Exploration, appraisal, reservoir characterization
- Physical properties and geophysical methods
- Relationships among geophysical methods
- Inputs and outputs
- Modelling, inversion, and uncertainty
- Seismic and EM together: carbonate example
- Time-lapse methods and reservoir characterization
- Conclusions

Physical properties and geophysical methods

Technique	Equations	Physical Properties
Gravity and gravity gradiometry	Newton's law of gravitation; Laplace's equation	Density ρ
Seismic reflection and refraction	Wave equation (Hooke's law and Newton's laws of mechanics)	P-wave velocity V_p S-wave velocity V_S Density ρ
Electromagnetics	Maxwell's equations	Magnetic permeability μ_m Electrical conductivity σ Electrical permittivity ε

Outline

- Exploration, appraisal, reservoir characterization
- Physical properties and geophysical methods
- Relationships among geophysical methods
- Inputs and outputs
- Modelling, inversion, and uncertainty
- Seismic and EM together: carbonate example
- Time-lapse methods and reservoir characterization
- Conclusions

Relationships among geophysical methods

- Seismic data and gravity data share density as a parameter.
- Reflection coefficient is angle-dependent so AVO effects can be used in principle to determine velocity and density contrasts.
- There is a one-to-one mapping of seismic reflections with density contrasts.
- So seismic data and gravity data can be combined very easily.

- There is no such mapping for velocity contrasts and electromagnetic parameters.

Outline

- Exploration, appraisal, reservoir characterization
- Physical properties and geophysical methods
- Relationships among geophysical methods
- Inputs and outputs
- Modelling, inversion, and uncertainty
- Seismic and EM together: carbonate example
- Time-lapse methods and reservoir characterization
- Conclusions

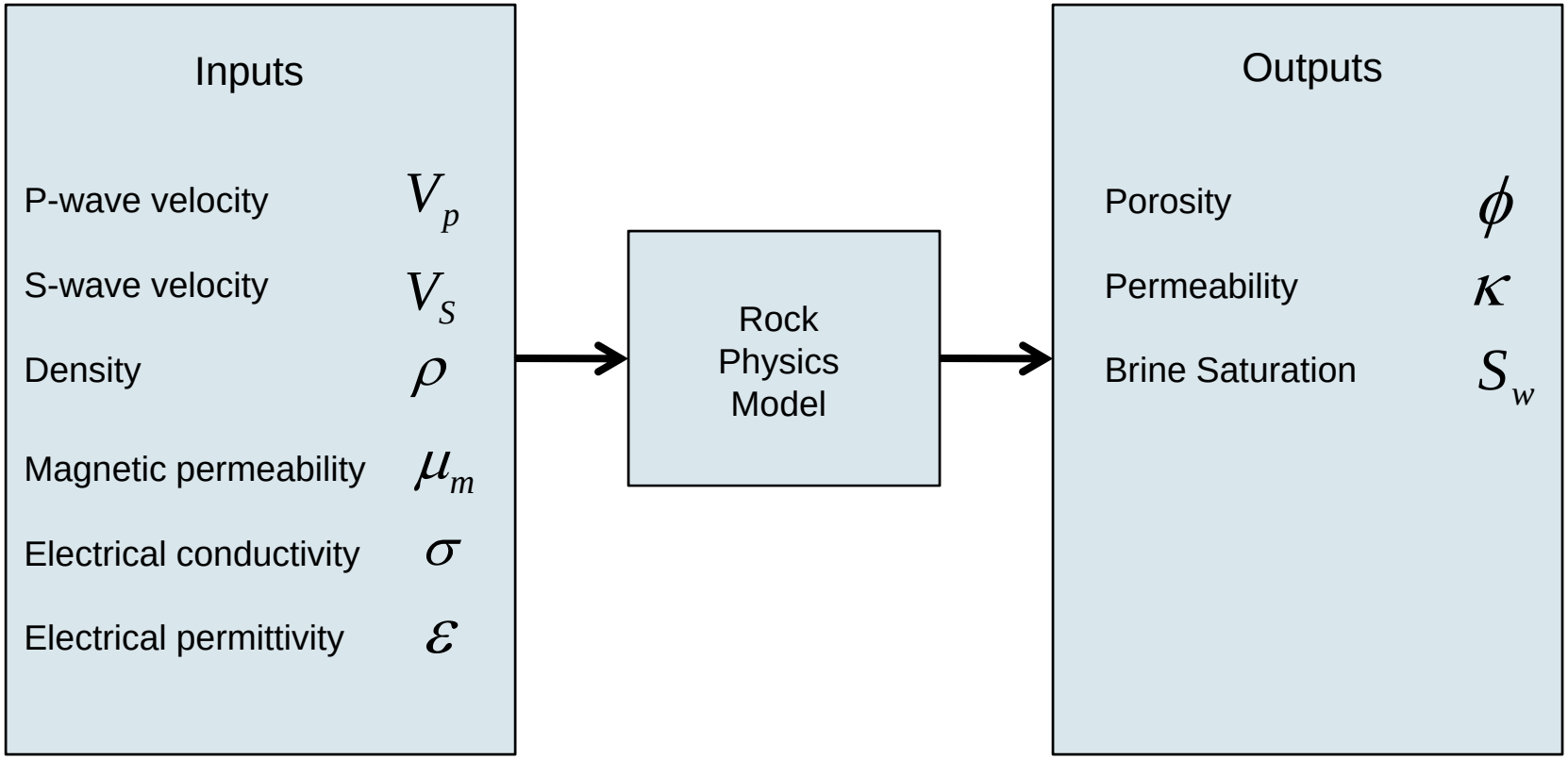
Geophysical inputs and outputs

What can we get out of the geophysical data?

Input	Output	
Gravity and gravity gradiometry data	Density	ρ
Seismic reflection and refraction data	P-wave velocity	V_p
	S-wave velocity	V_S
	Density	ρ
Electromagnetic data	Magnetic permeability	μ_m
	Electrical conductivity	σ
	Electrical permittivity	ε

Reservoir properties from physical properties

How can we get reservoir properties out of the data?



More rock physics in the wave propagation?

- Since Biot in the 1950's many people have struggled to develop a model for wave propagation in a fluid-saturated permeable rock which generates synthetic data that matches measurements, including the slow P-wave predicted by Biot.
- This model does not yet exist.
- There is therefore no rigorous theory to determine reservoir parameters from seismic data.
- A rock physics model must be assumed.

Outline

- Exploration, appraisal, reservoir characterization
- Physical properties and geophysical methods
- Relationships among geophysical methods
- Inputs and outputs
- Modelling, inversion, and uncertainty
- Seismic and EM together: carbonate example
- Time-lapse methods and reservoir characterization
- Conclusions

Connecting seismic and EM data

- Assume the structural model from seismic data.
- Assume a relation between Vp, say, and electrical conductivity σ.
  - This might be supported by a well-log
  - Or there might be a more complicated relation involving porosity
- Perform one-to-one mapping of conductivity to the structure.
- This gives a starting resistivity model for inversion of EM data.
- Allow the resistivity in each layer to vary within bounds.
- In the reservoir layer the resistivity may be free to vary much more.
- It may be difficult to pick top and bottom of the reservoir from the seismic data; different combinations of layer thickness, porosity and saturation can give the same resistivity.

Connecting seismic and EM data – a comment

- This is only one way to do it.
- There are other ways, but the principle is the same:
  - Assumptions about the Earth (prior knowledge) are made to find out about the Earth.
- This principle is well-established, and great care is often taken to define the uncertainty in the assumptions.

- Can we avoid doing this?

Migration of EM data

- We have developed confidence in our ability to find geological structure from seismic data, using depth migration and full waveform inversion.
- Our algorithms are tested on synthetic data and we know what happens when, for example, the data do not have enough low-frequency content.

- A similar approach needs to be developed for EM data, with resistivity corresponding to velocity.
- Obviously, bandwidth and sampling are critical, just as they are for seismic data.
- If this can be developed, the output from EM data processing would be resistivity as a function of subsurface position.
- EM and seismic data can then be used together to look for hydrocarbons.

Uncertainty

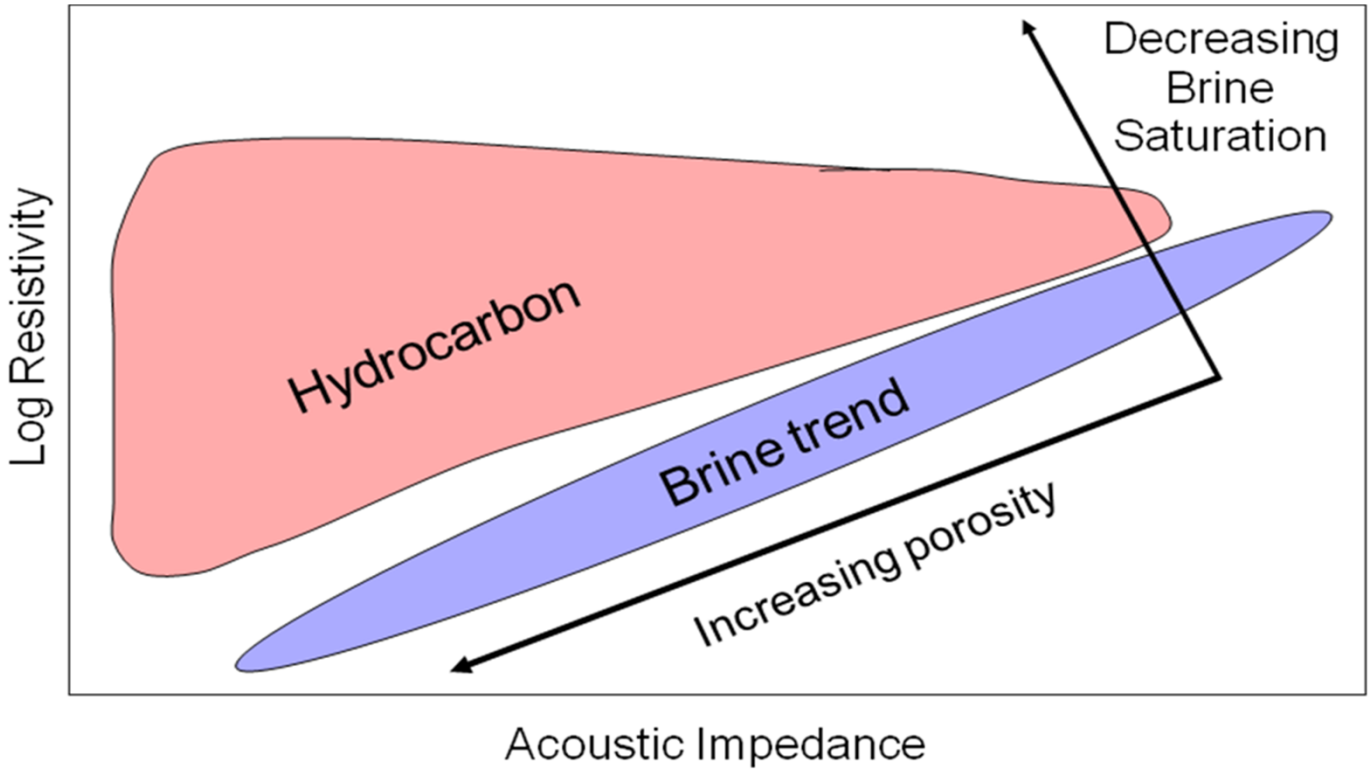
- We should certainly quantify the uncertainty in our results including structure derived from seismic data.
- Ideally this should be done by comparing the forward-modelled data with the real data and measuring the error.
- The same should be done with the EM data.

Outline

- Exploration, appraisal, reservoir characterization
- Physical properties and geophysical methods
- Relationships among geophysical methods
- Inputs and outputs
- Modelling, inversion, and uncertainty
- Seismic and EM together: carbonate example
- Time-lapse methods and reservoir characterization
- Conclusions

Use of Seismic and EM data together

Resistivity versus acoustic impedance for carbonate reservoirs



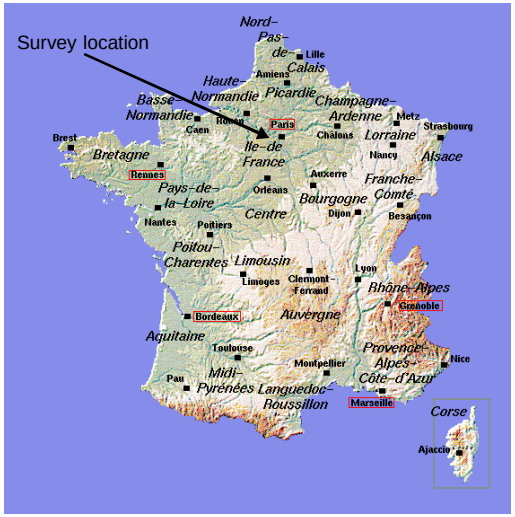
Outline

- Exploration, appraisal, reservoir characterization
- Physical properties and geophysical methods
- Relationships among geophysical methods
- Inputs and outputs
- Modelling, inversion, and uncertainty
- Seismic and EM together: carbonate example
- Time-lapse methods and reservoir characterization
- Conclusions

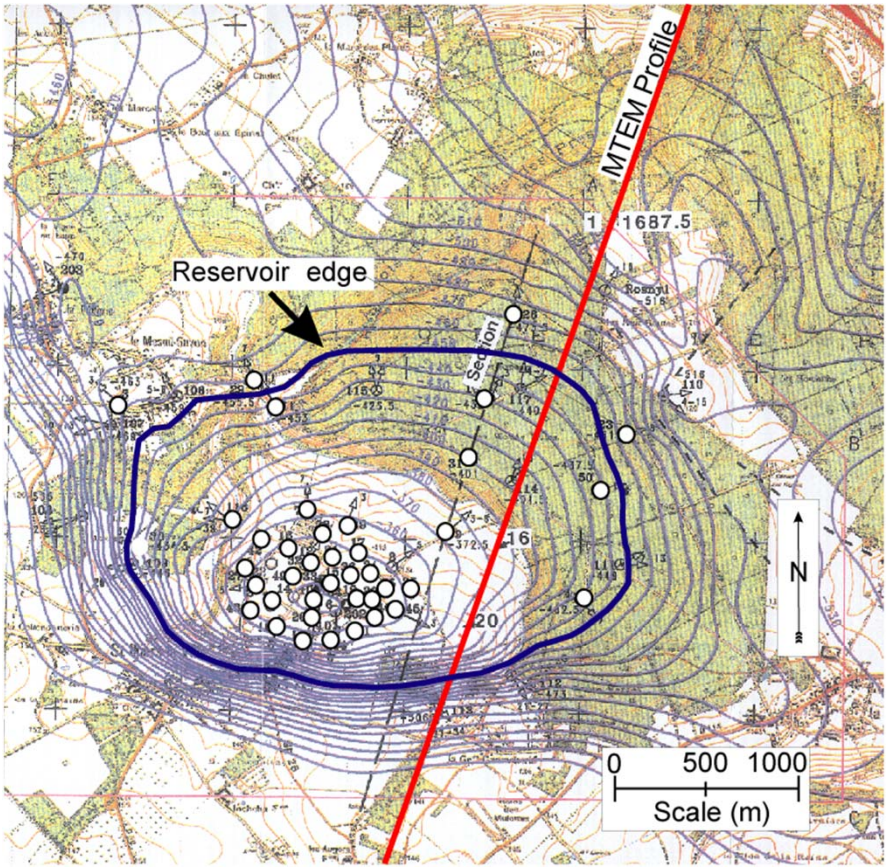
Reservoir characterization

- Time-lapse geophysical data sets enable changes to be observed.
- For seismic data stress has a big effect and affects the response outside the reservoir as well as inside.
- For EM data, stress has no known impact. Resistivity variations should be confined to the reservoir.
- Furthermore, resistivity is much more sensitive to variations in hydrocarbon saturation (at high saturations) than seismic parameters.

St. Illiers la Ville Gas Storage Reservoir

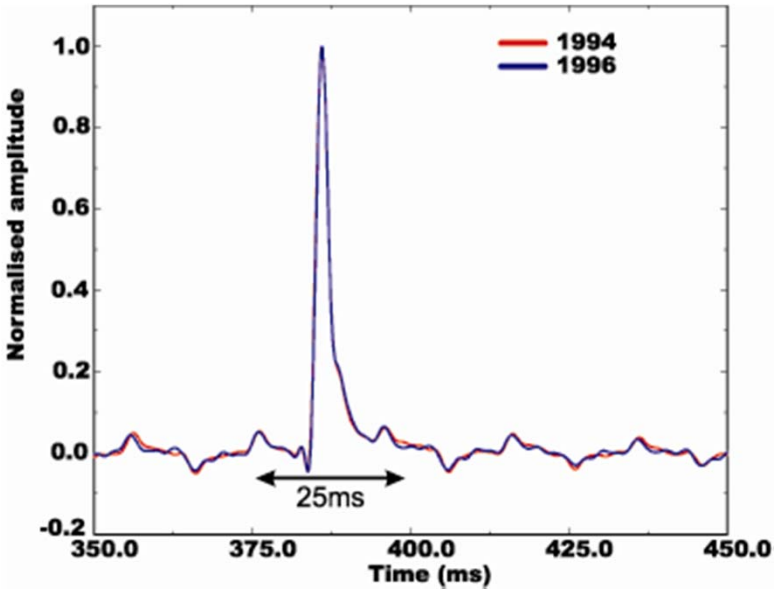


The surveys took place over an underground gas storage reservoir 30km west of Paris in 1994 and 1996.

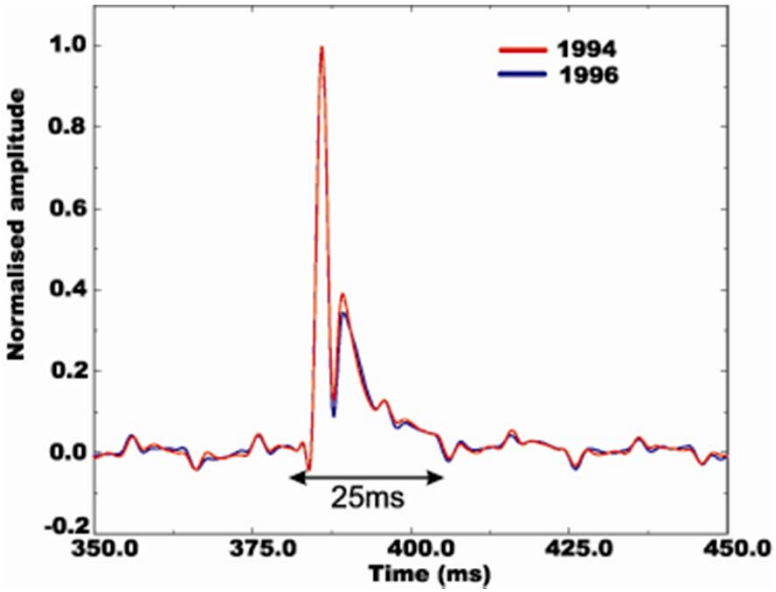


White circles denote monitoring wells. Contours are the depth to the top of the reservoir.

Impulse Responses St Illiers la Ville

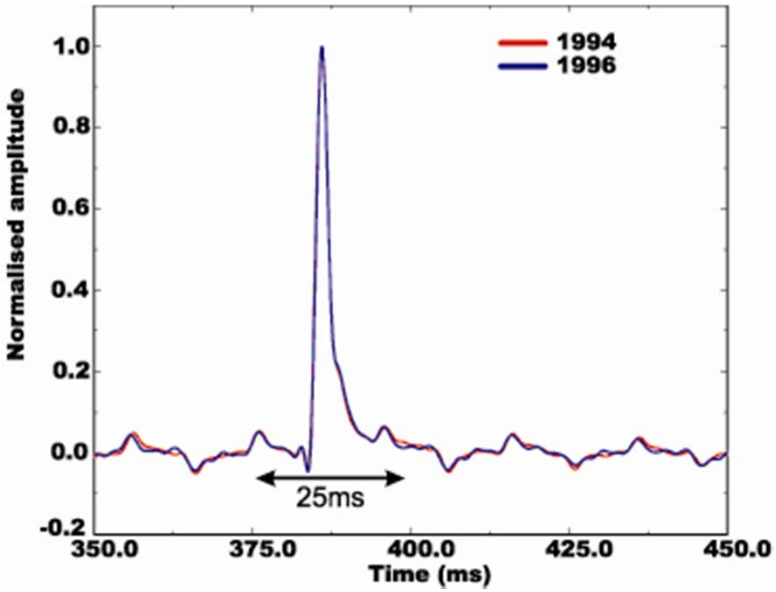


North of the reservoir

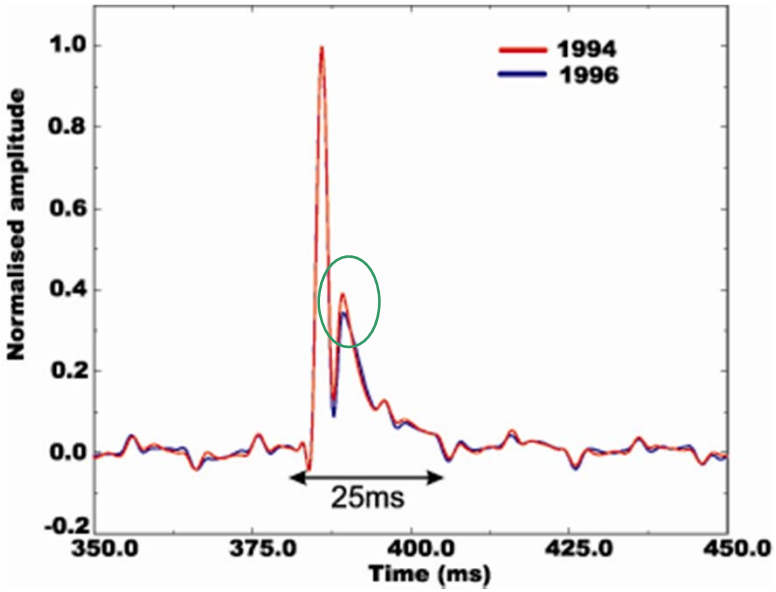


Over the reservoir:
a second peak

Impulse Responses St Illiers la Ville

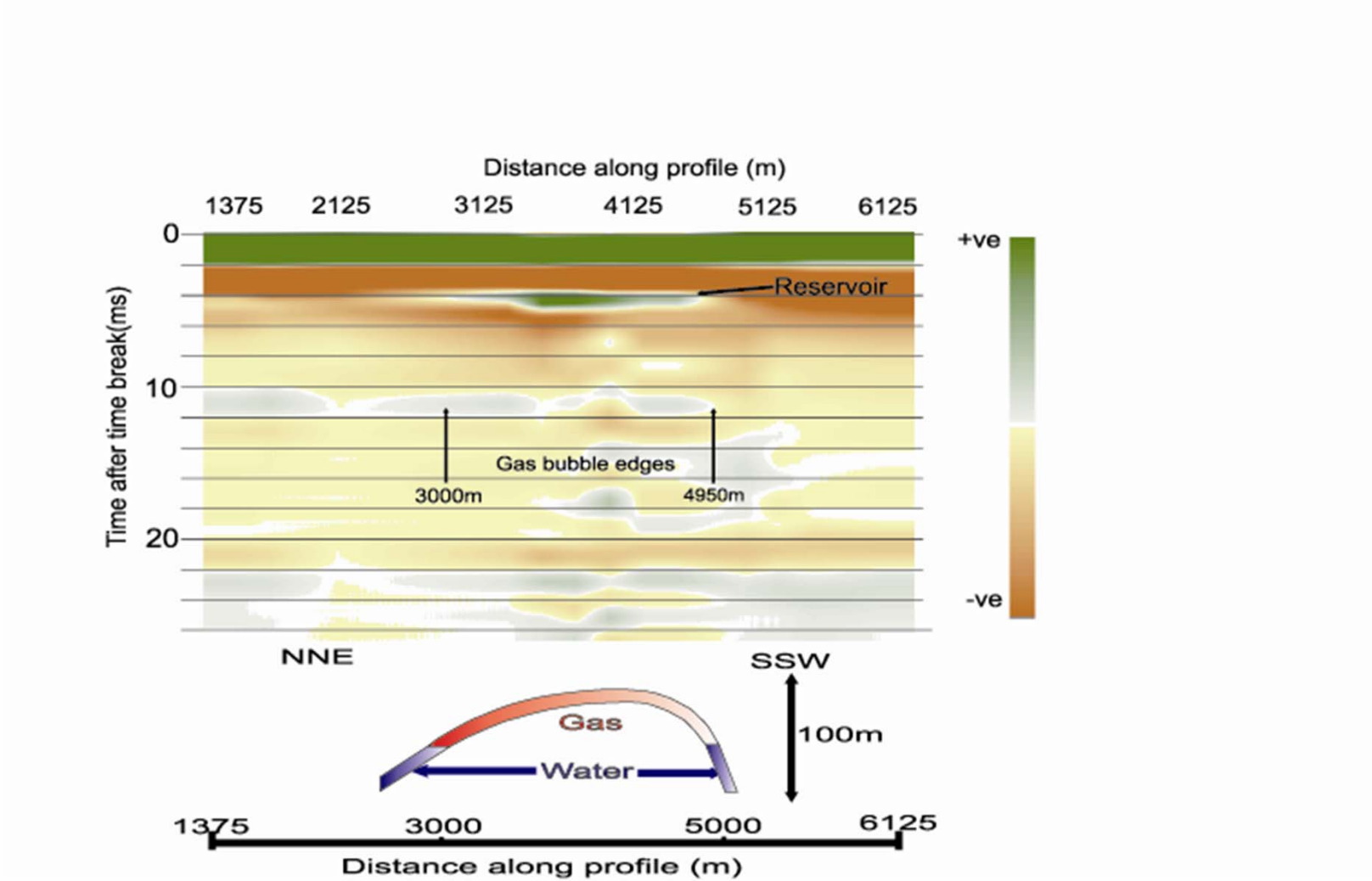


North of the reservoir



Over the reservoir:
a second peak

Section across St Illiers la Ville Reservoir



Conclusions

- There is no rigorous way to find a resistivity model from seismic data.
- If EM data can be depth migrated *independent* of seismic data, there is then synergy between seismic and EM that allows hydrocarbons to be identified even in carbonates.
- 4D EM can be a very useful addition to 4D seismic in reservoir monitoring and characterisation, especially where the hydrocarbon saturation is high – in early production.
- By extension of the same idea, EM can be used to monitor CO_2 sequestration after the initial seismic anomaly has been observed.

Acknowledgements

- We thank Gaz de France for permission to show the MTEM data.