Monitoring and Characterization Based Upon Geophysical Onset Times*

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Abstract

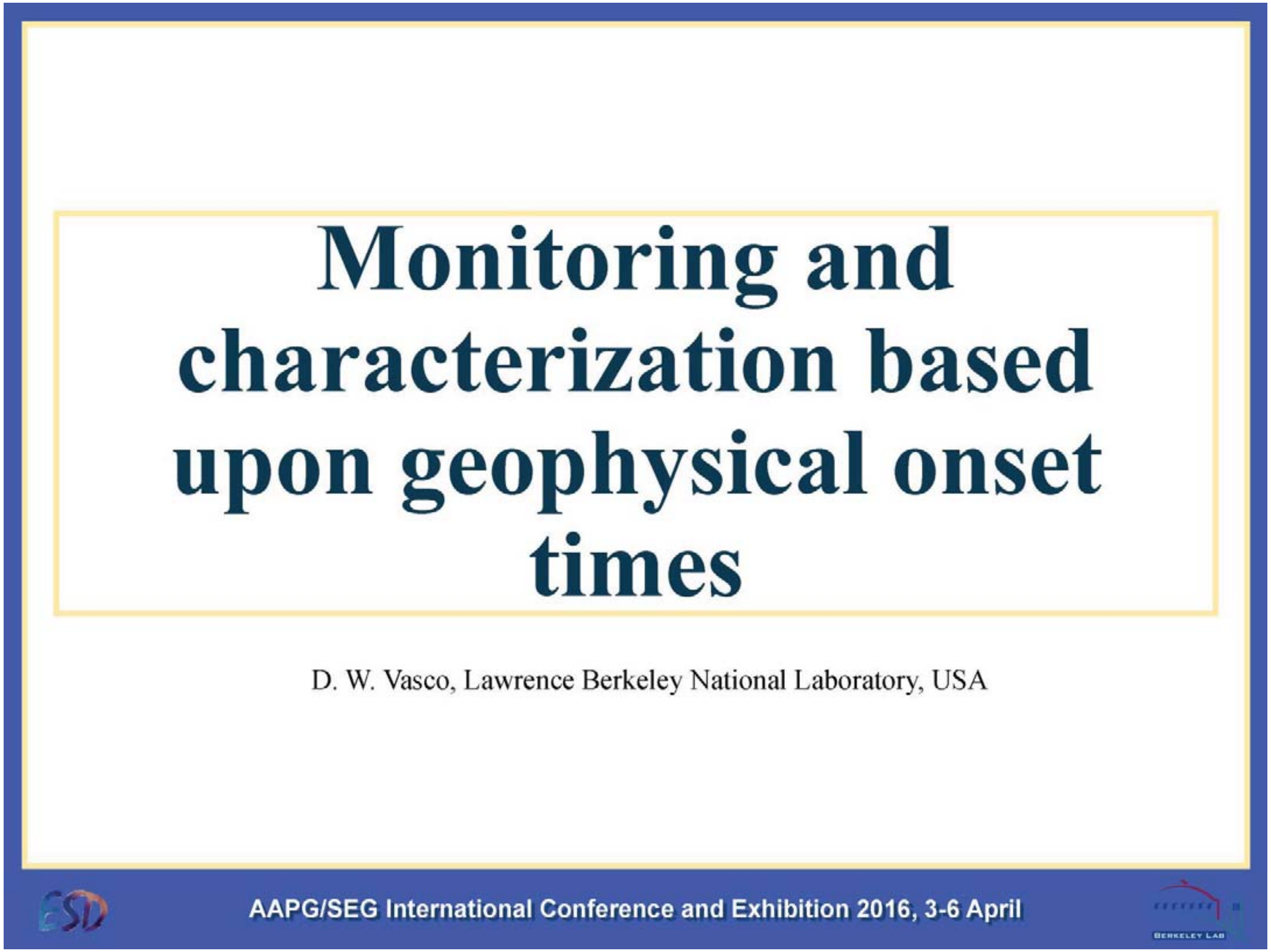
Geophysical methods are increasingly called upon to monitor fluid injection and production. Geophysical monitoring of flow related processes is hampered by difficulties in relating changes in fluid saturation and pressure to observable quantities such as seismic amplitude changes, variations in electric fields, and surface deformation. Problems are particularly acute when relating changes in the amplitudes of observable geophysical quantities to the magnitudes of fluid related changes in a reservoir. In such cases the relationship depends strongly upon the rock physics model that is chosen.

In this presentation I present an alternative approach to reservoir monitoring and characterization that is based on the notion of an onset time. An onset time is the calendar time at which a measured quantity begins to deviate from its background or initial value. In many cases involving injection and production, the onset time is related to the arrival of a fluid front or a rapid increase in pressure. Under the relatively general condition that a change in fluid saturation and/or pressure leads to a change in a geophysical attribute, it can be shown that onset times are sensitive to flow properties, such as permeability, and not sensitivity of the details of the rock physics model. Several examples of the use of onset times for monitoring and characterization will be given, involving both geodetic and seismic observations. One example involves the geodetic monitoring of ground deformation associated with the geological storage of injected carbon dioxide at In Salah, Algeria. Seismic time-lapse monitoring of injected carbon dioxide at the Frio site in Texas provides yet another example.

References Cited

Vasco, D.W., A. Bakulin, H. Baek, and L.R. Johnson, 2015, Reservoir characterization based upon the onset of time-lapse amplitude changes: Geophysics, v. 80, January-February.

Vasco, D.W., T.M. Daley, and A. Bakulin, 2014, Utilizing the onset of time-lapse changes: a robust basis for reservoir monitoring and characterization: Geophysical Journal International.



Presenter's notes:
Our goal is a very complete reservoir characterization/making use of all major data types.
Emphasis on practicality of the algorithms.
It is important to include all available reservoir engineering data as this is directly sensitive to reservoir flow properties.
Field testing is important to ensure that our methods are truly effective.
Finally, we need to get these tools into the hands of industry.

Issues:

- Would like to estimate properties such as permeability
- Geophysical data indirectly related to flow properties
- Even time-lapse observations depend upon a rock physics model

Approach:

- Avoid using the magnitude of geophysical changes due to variations in the state [saturation, pressure, stress] of the reservoir

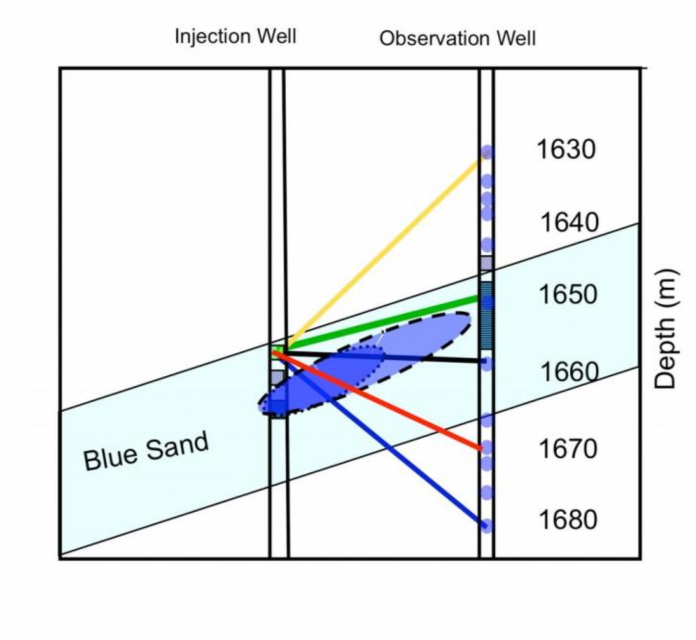
- Use the **onset time** of changes in geophysical observations

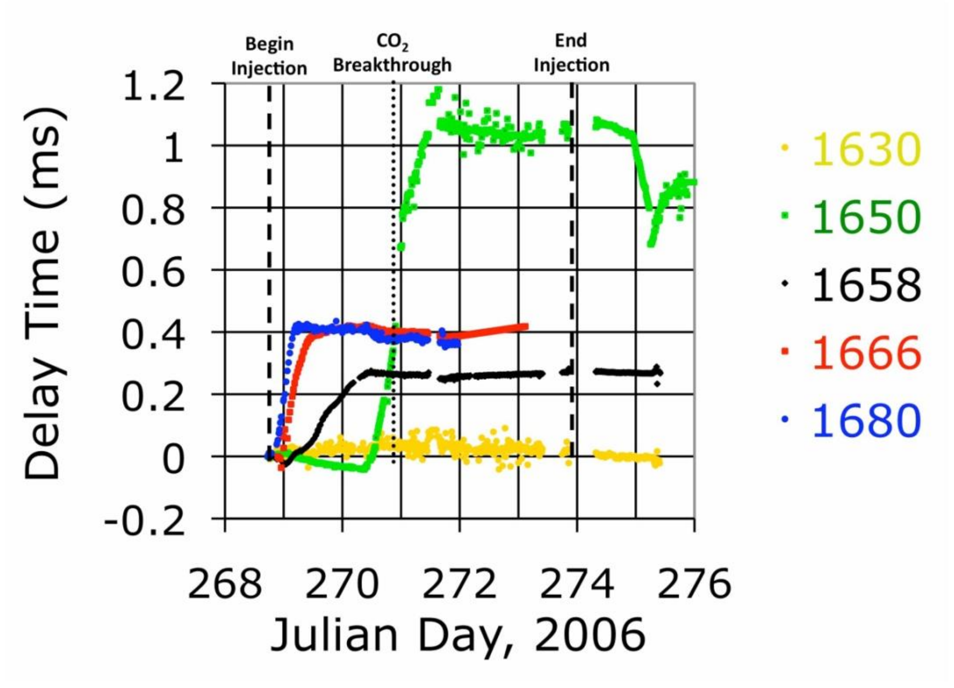
Outline:

- Onset times
- Illustration based upon time-lapse seismic amplitude changes
- Inversion for reservoir permeability
- Conclusions

Definition:

- *Onset time* - The time at which a seismic observation begins to change from its background value.



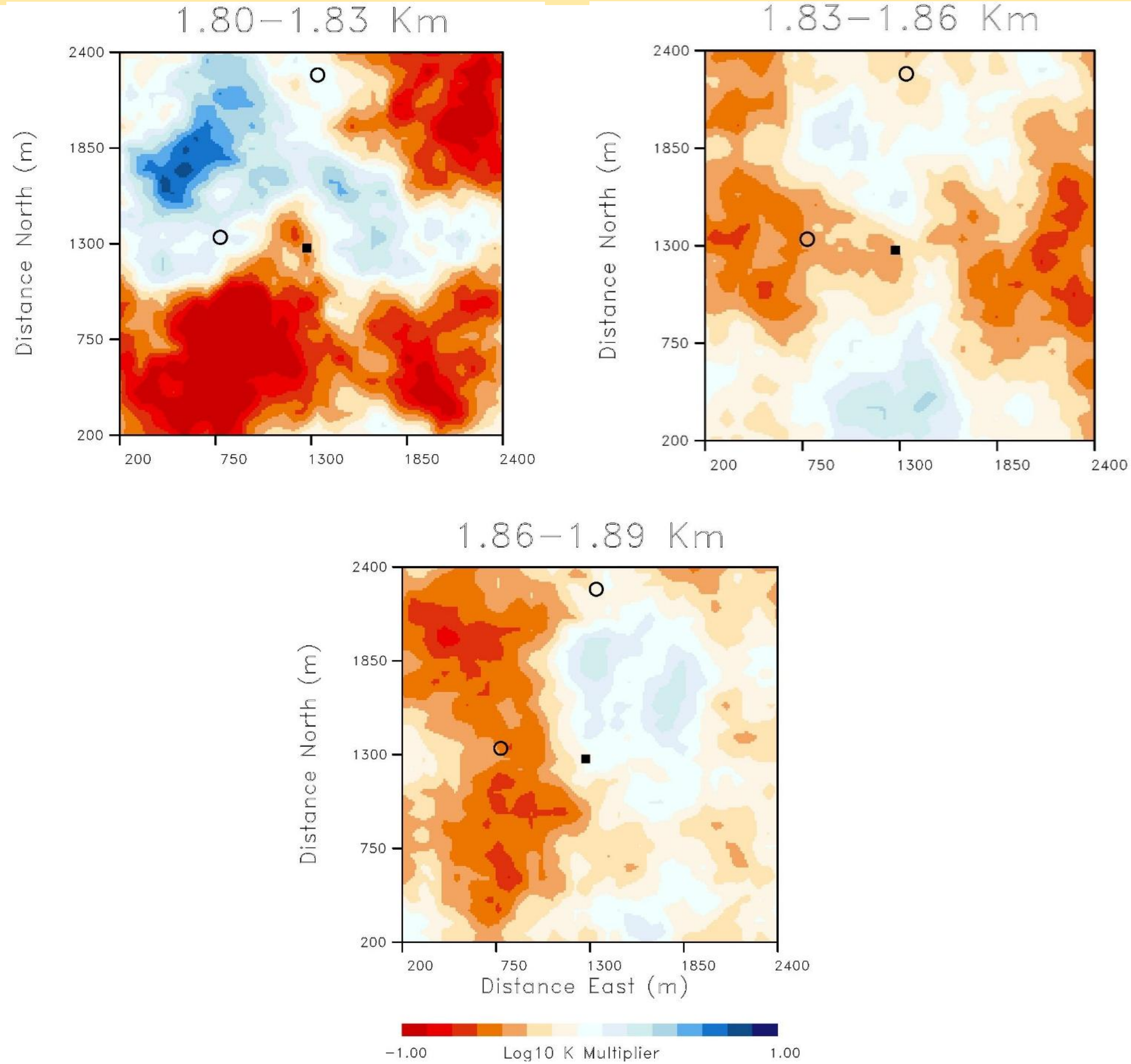


Seismic Time-Lapse Reflection Amplitudes

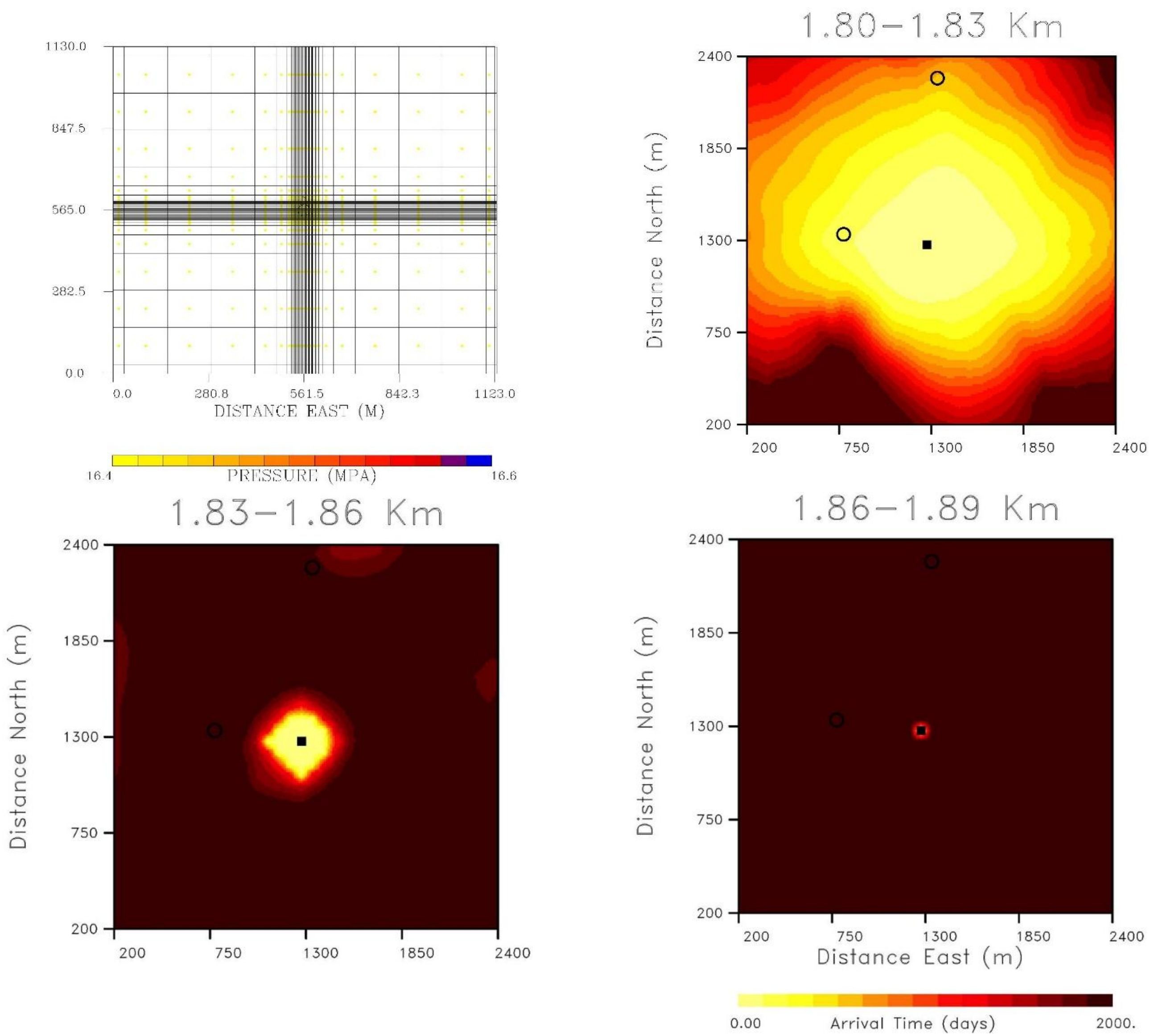
Approach:

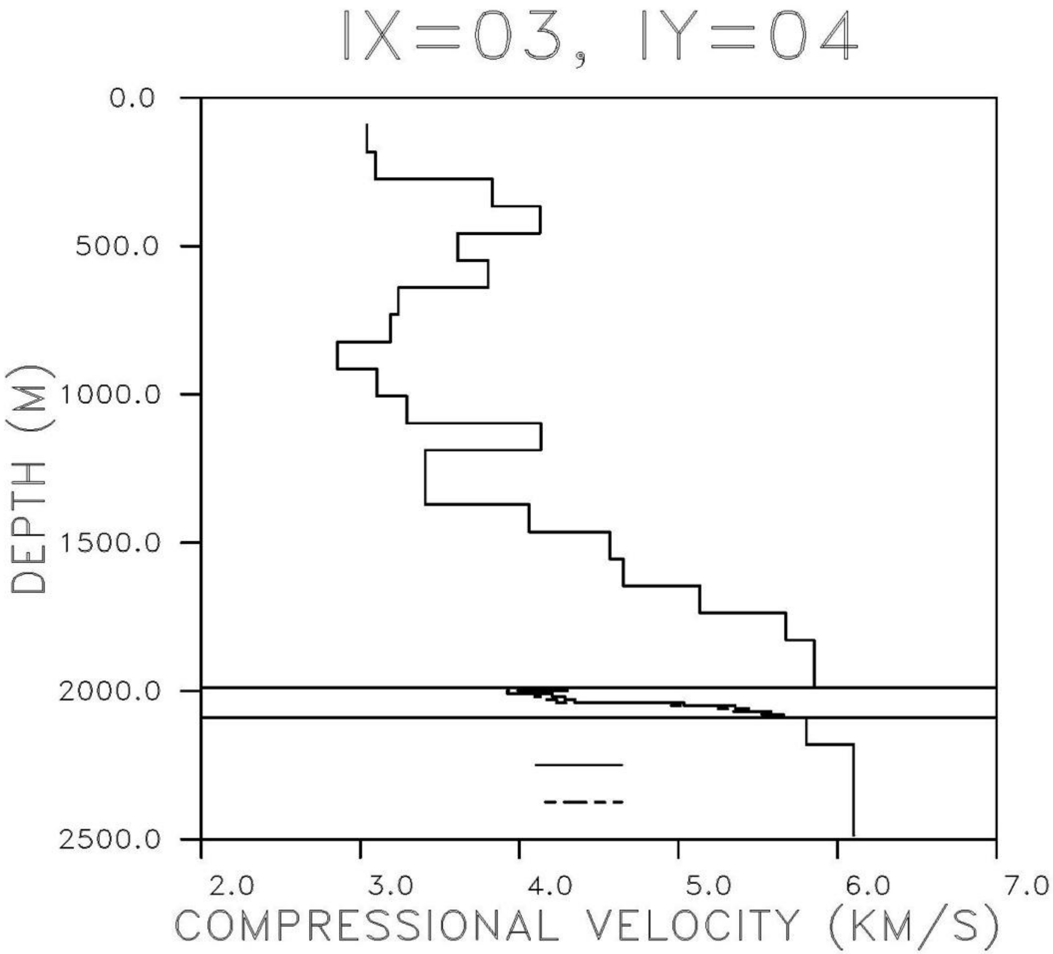
- Use reservoir model to compute seismic amplitude changes due to CO_2 injection

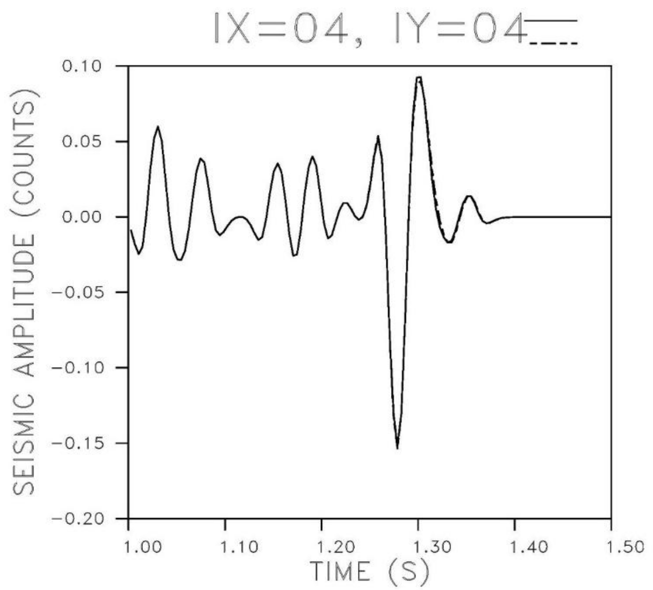
- Compare inversion based upon seismic amplitudes with one based upon‘onset times’



1.80–1.83 Km
1.83–1.86 Km
1.86–1.89 Km
Distance North (m)
Distance East (m)
2400
1850
1300
750
200
Log10 K Multiplier
−1.00
1.00


1130.0
847.5
565.0
282.5
0.0
0.0
280.8
561.5
842.3
1123.0
DISTANCE EAST (M)
16.4
PRESSURE (MPA)
16.6
1.80–1.83 Km
Distance North (m)
2400
1850
1300
750
200
200
750
1300
1850
2400
1.83–1.86 Km
Distance North (m)
2400
1850
1300
750
200
200
750
1300
1850
2400
1.86–1.89 Km
Distance North (m)
2400
1850
1300
750
200
200
750
1300
1850
2400
Distance East (m)
0.00
Arrival Time (days)
2000.


IX=03, IY=04
0.0
500.0
1000.0
1500.0
2000.0
2500.0
DEPTH (M)
2.0
3.0
4.0
5.0
6.0
7.0
COMPRESSIONAL VELOCITY (KM/S)


IX=04, IY=04
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
SEISMIC AMPLITUDE (COUNTS)
1.00
1.10
1.20
1.30
1.40
1.50
TIME (S)

Issues:

- The relationship between the reservoir state and seismic velocities is complicated

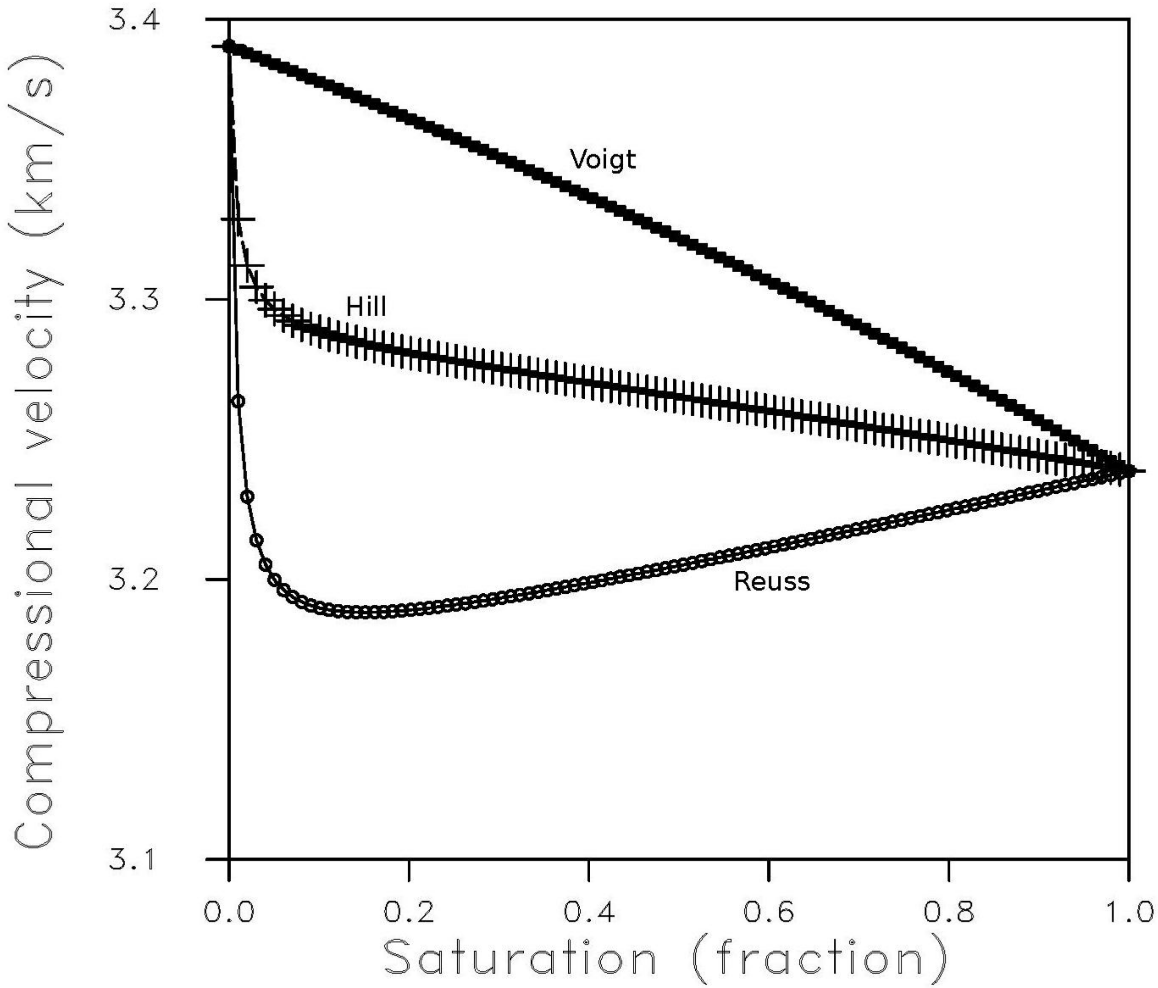
- Thought to depend upon mesoscopic [cm to m] variations in saturation, pressure, and mechanical properties

- Seismic velocities depend upon how fluids are distributed and 'averaged' by the propagating wave.

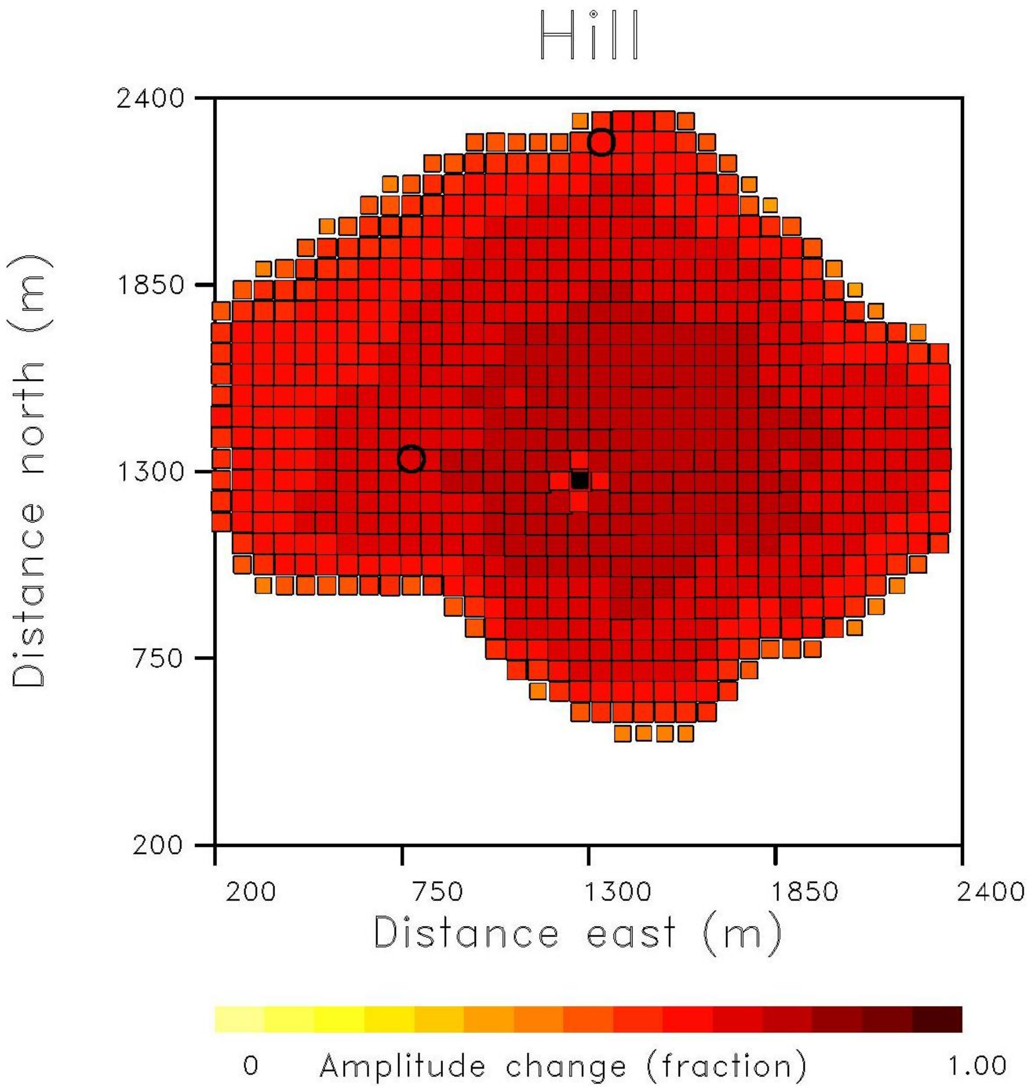
$$K_{Voigt} = \sum_{i=1}^{3} S_i K_i$$ Voigt average

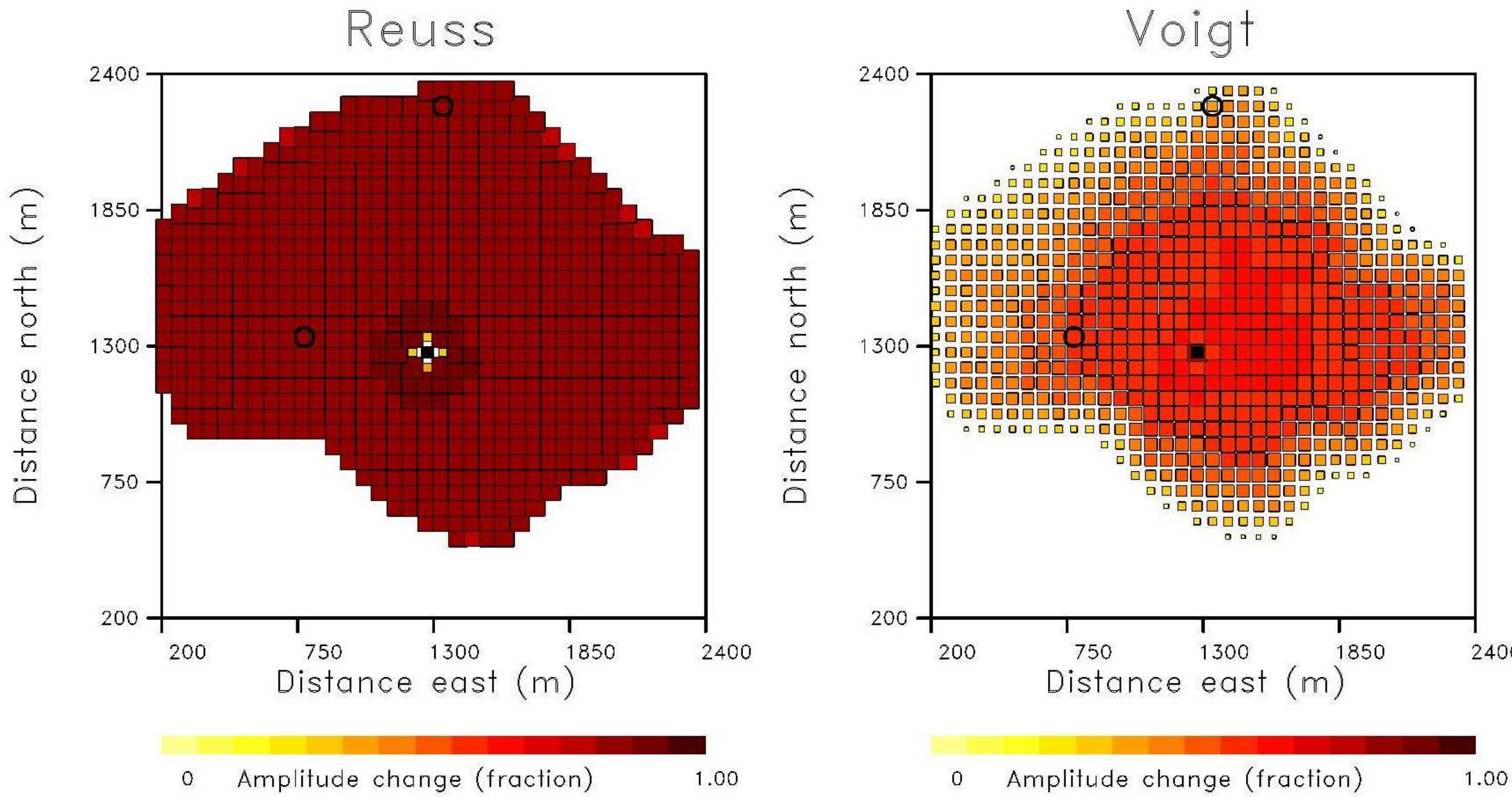
$$\frac{1}{K_{\mathrm{Re}uss}} = \sum_{i=1}^{3} \frac{S_i}{K_i}$$ Reuss average

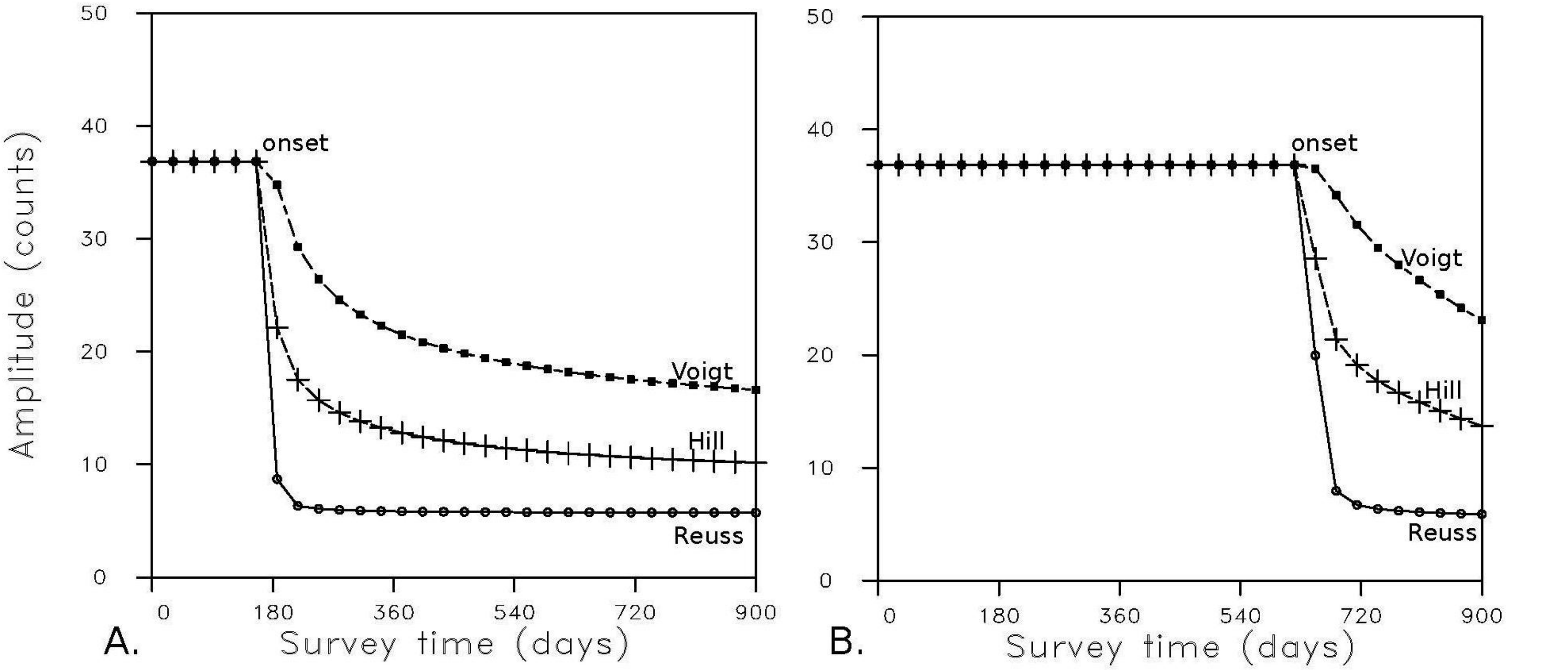
$$K_{Hill} = \frac{1}{2}\left(K_{Voigt} + K_{\mathrm{Re}uss}\right)$$ Hill average



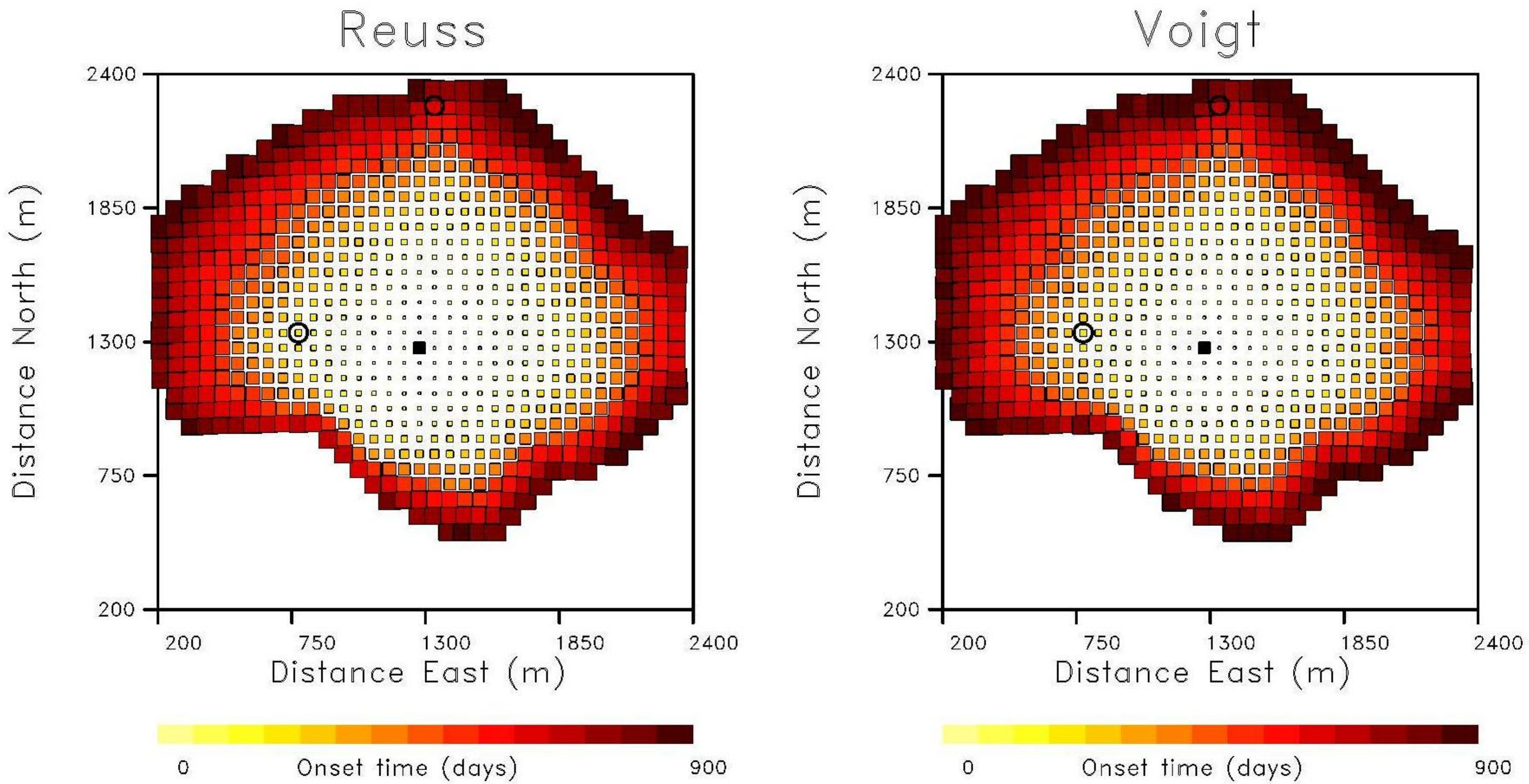
3.4
3.3
3.2
3.1
0.0
0.2
0.4
0.6
0.8
1.0
Compressional velocity (km/s)
Saturation (fraction)
Voigt
Hill
Reuss


Hill
2400
1850
1300
750
200
Distance north (m)
200
750
1300
1850
2400
Distance east (m)
0
Amplitude change (fraction)
1.00

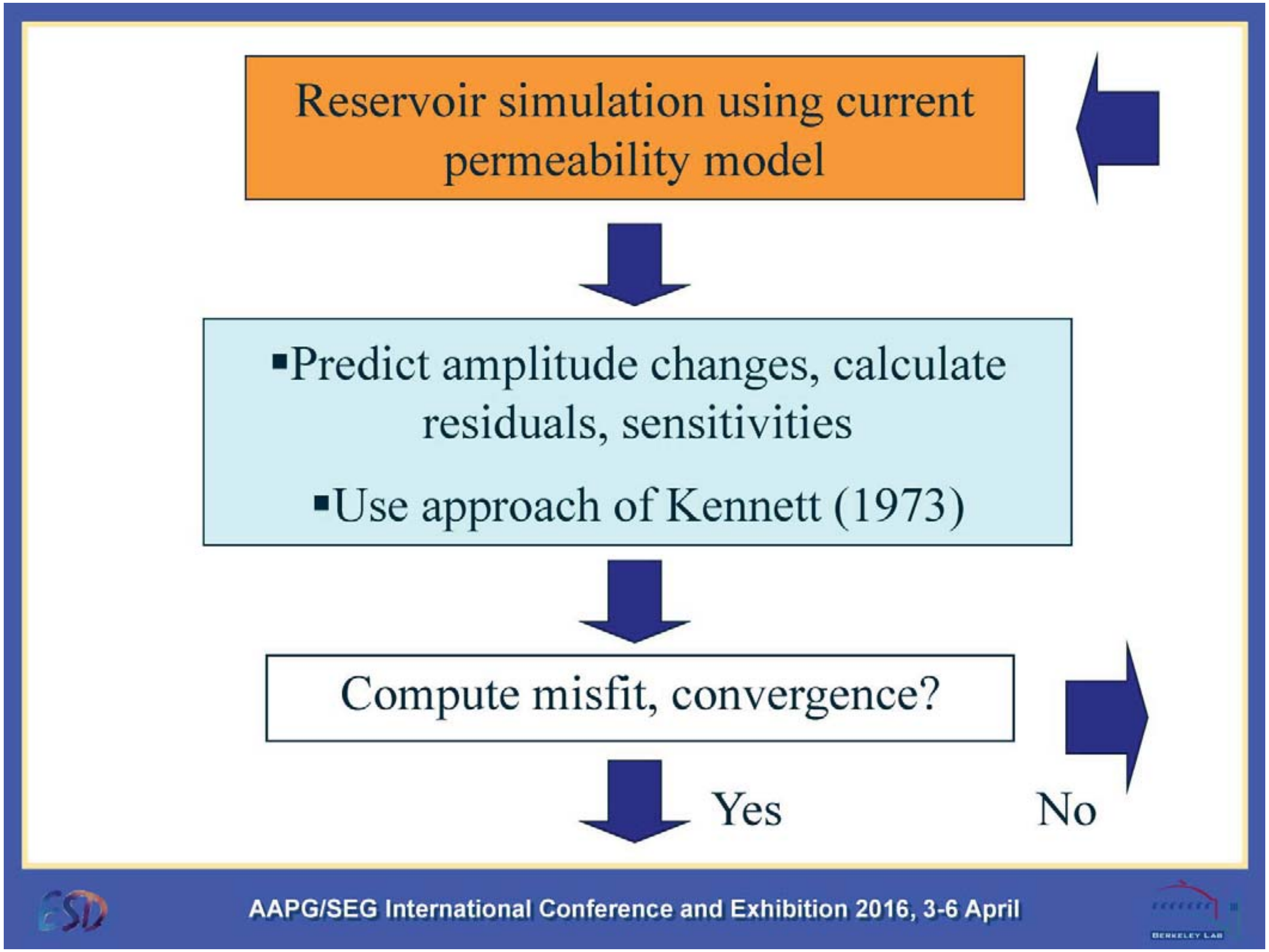

Reuss
Voigt
2400
1850
1300
750
200
Distance north (m)
Distance east (m)
0
Amplitude change (fraction)
1.00



Amplitude (counts)
50
40
30
20
10
0
onset
Voigt
Hill
Reuss
0
180
360
540
720
900
A.
Survey time (days)
50
40
30
20
10
0
onset
Voigt
Hill
Reuss
0
180
360
540
720
900
B.
Survey time (days)


Reuss
2400
1850
1300
750
200
Distance North (m)
200
750
1300
1850
2400
Distance East (m)
0
Onset time (days)
900
Voigt
2400
1850
1300
750
200
Distance North (m)
200
750
1300
1850
2400
Distance East (m)
0
Onset time (days)
900

Iterative inversion



Presenter's notes:

(1) In our approach we introduce a new method for the matching of reservoir engineering data, based upon streamline simulation.
(2) With this new method we can develop efficient ways to integrate production and seismic data.
(3) Field applications are an important part of our approach as they indicate what will be feasible.

Iterative Updating Algorithm

Iterative modification of the reservoir model to better match onset times:

$$\mathbf{K}_m = \mathbf{K}_{m-1} + \mathrm{D}\mathbf{K}_m$$

That is, to better match observations in a least squares sense:

$$Misfit = \left(d\mathbf{t} - \mathbf{A}d\mathbf{K}_m\right)^T \left(d\mathbf{t} - \mathbf{A}d\mathbf{K}_m\right)$$

Equivalent to solving the linear system:

$$\mathbf{A}^T \mathbf{A} d\mathbf{K}_m = \mathbf{A}^T d\mathbf{t}$$

Influence of the rock physics model

Time-Lapse Amplitudes

Hill Inversion – Correct Sensitivities

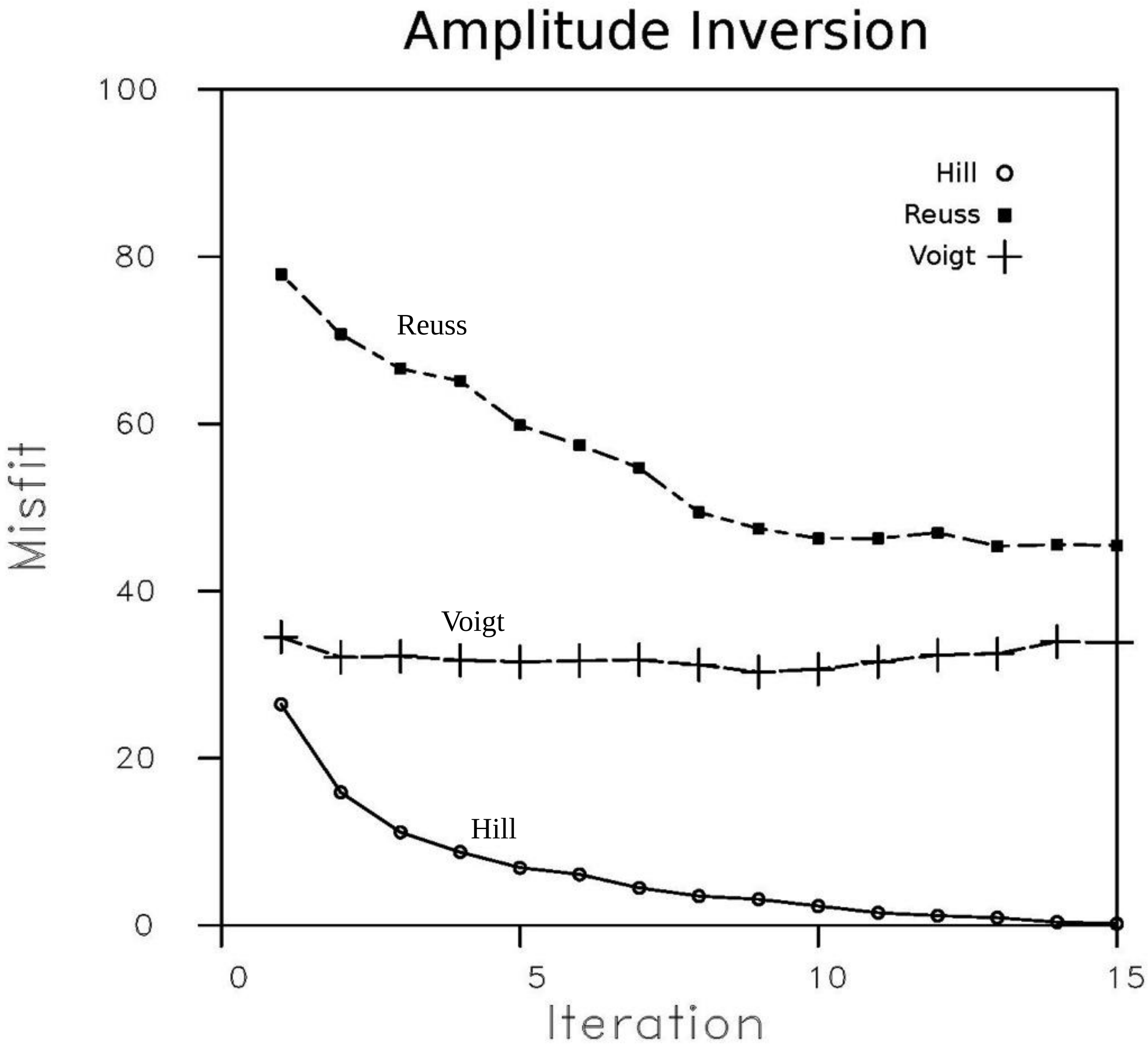
$$\mathbf{d}_{Hill} = \mathbf{F}_{Hill}(\mathbf{K}) \qquad \mathbf{A}_{Hill}{}^{T}\mathbf{A}_{Hill}\delta\mathbf{K}_m = \mathbf{A}_{Hill}{}^{T}\delta\mathbf{d}_{Hill}$$

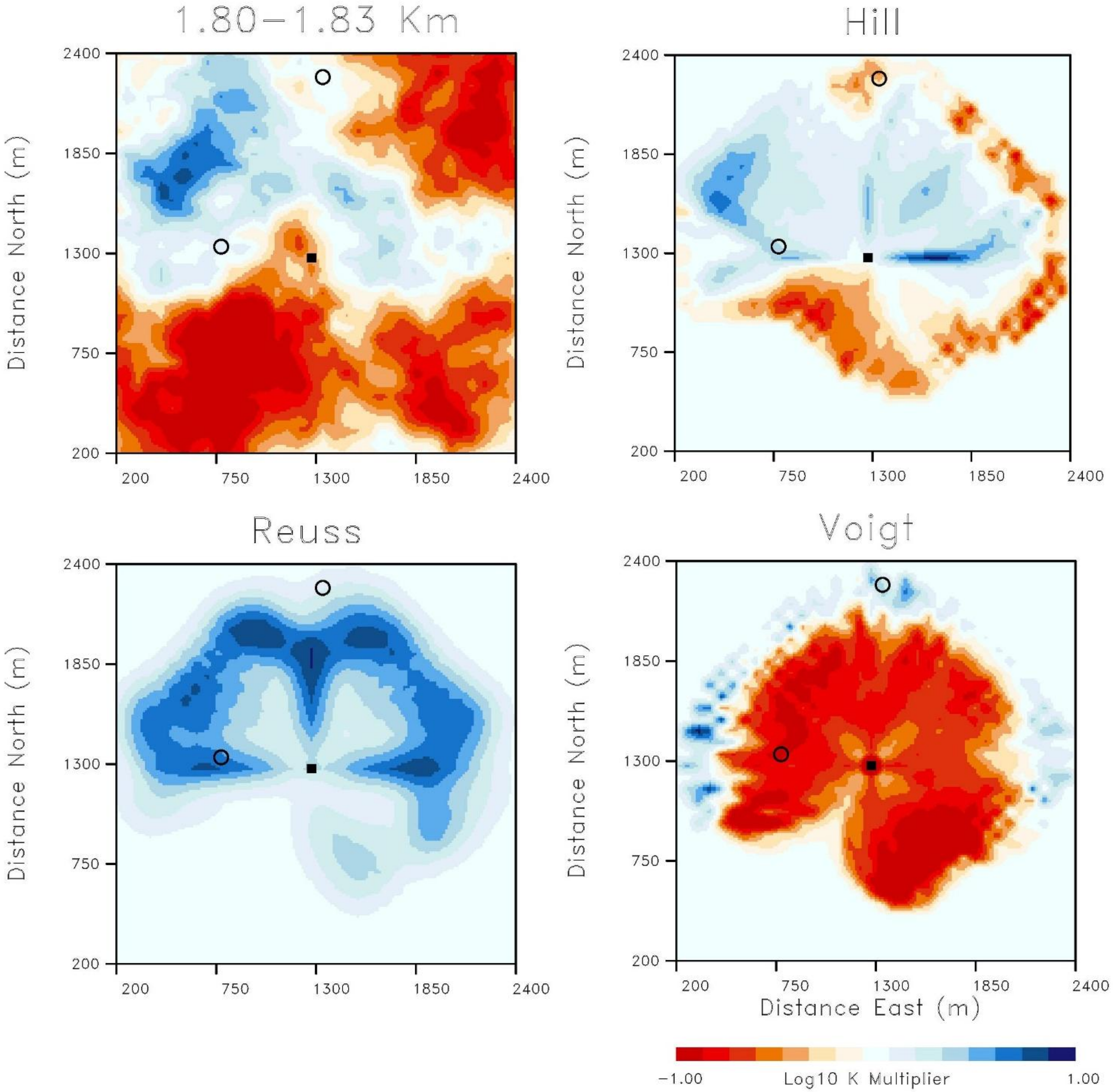
Reuss Inversion

$$\mathbf{d}_{Reuss} = \mathbf{F}_{Reuss}(\mathbf{K}) \qquad \mathbf{A}_{Hill}{}^{T}\mathbf{A}_{Hill}\delta\mathbf{K}_m = \mathbf{A}_{Hill}{}^{T}\delta\mathbf{d}_{Reuss}$$

Voigt Inversion

$$\mathbf{d}_{Voigt} = \mathbf{F}_{Voigt}(\mathbf{K}) \qquad \mathbf{A}_{Hill}{}^{T}\mathbf{A}_{Hill}\delta\mathbf{K}_m = \mathbf{A}_{Hill}{}^{T}\delta\mathbf{d}_{Voigt}$$


Amplitude Inversion
100
80
60
40
20
0
Misfit
0
5
10
15
Iteration
Hill
Reuss
Voigt
Reuss
Voigt
Hill



1.80–1.83 Km
Hill
Reuss
Voigt
Distance North (m)
Distance East (m)
2400
1850
1300
750
200
−1.00
Log10 K Multiplier
1.00

Onset times

Hill Inversion – Correct Sensitivities

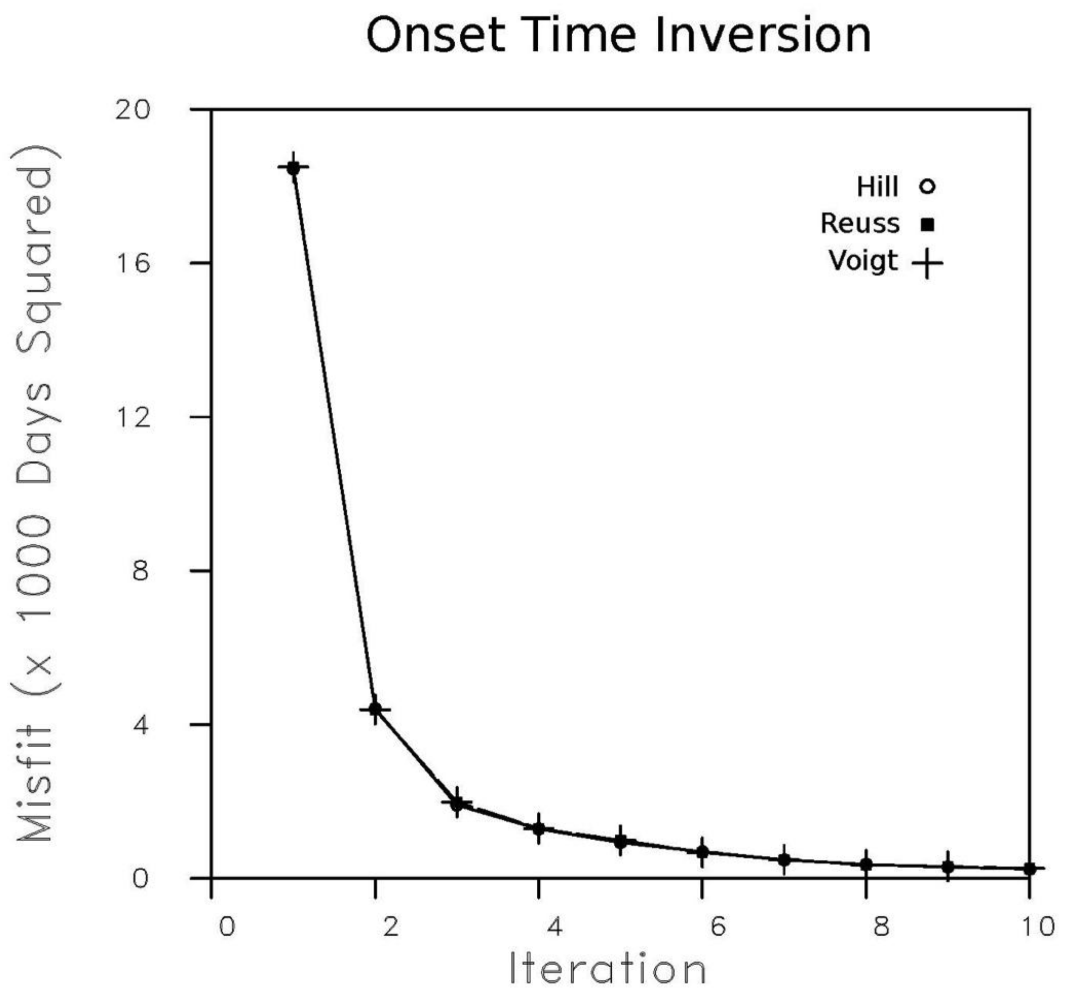
$$\mathbf{d}_{Hill} = \mathbf{F}_{Hill}(\mathbf{K}) \qquad \mathbf{A}_{Hill}{}^{T}\mathbf{A}_{Hill}\delta\mathbf{K}_{m} = \mathbf{A}_{Hill}{}^{T}\delta\mathbf{d}_{Hill}$$

Reuss Inversion

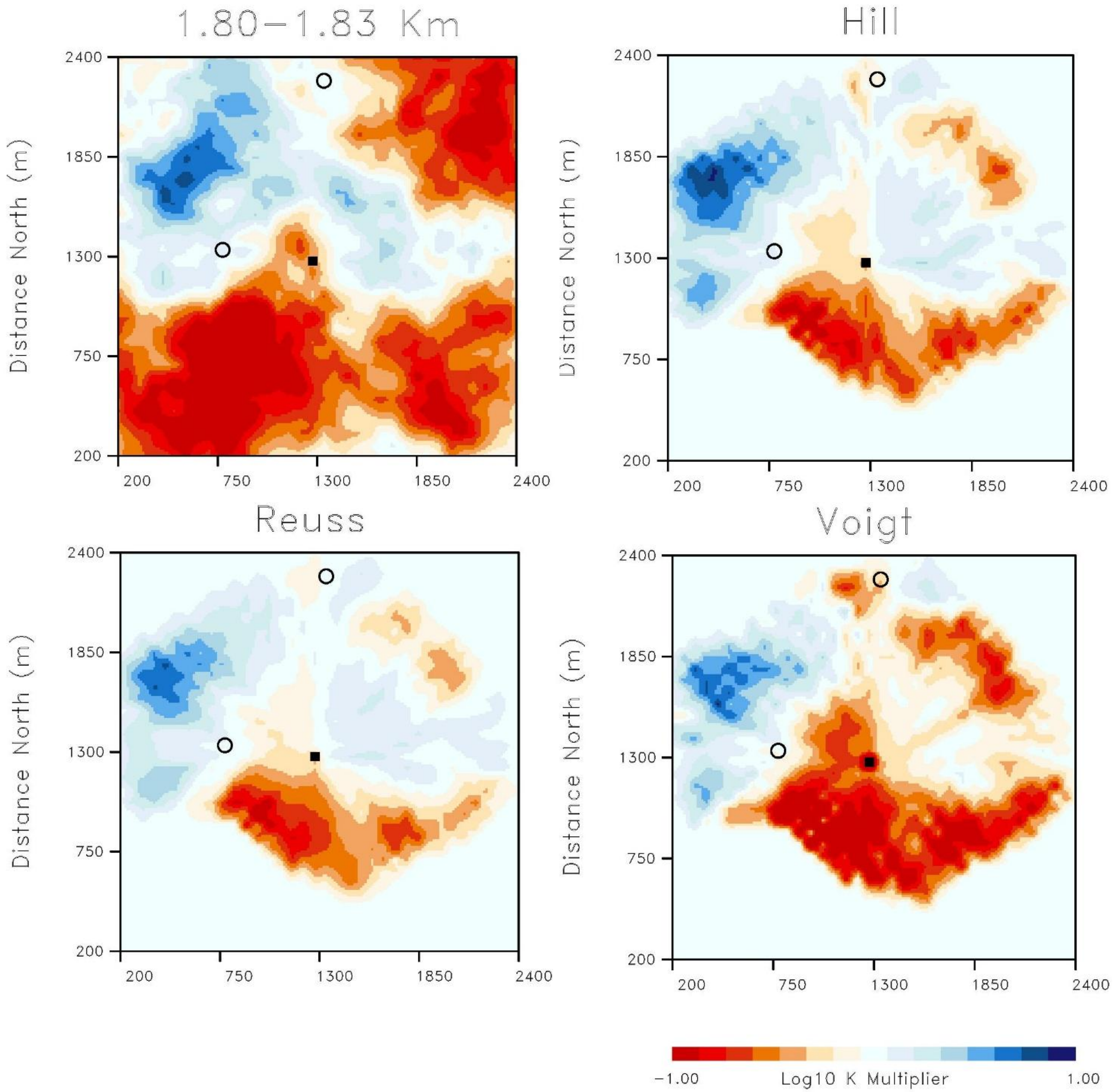
$$\mathbf{d}_{\mathrm{Re}uss} = \mathbf{F}_{\mathrm{Re}uss}(\mathbf{K}) \qquad \mathbf{A}_{Hill}{}^{T}\mathbf{A}_{Hill}\delta\mathbf{K}_{m} = \mathbf{A}_{Hill}{}^{T}\delta\mathbf{d}_{\mathrm{Re}uss}$$

Voigt Inversion

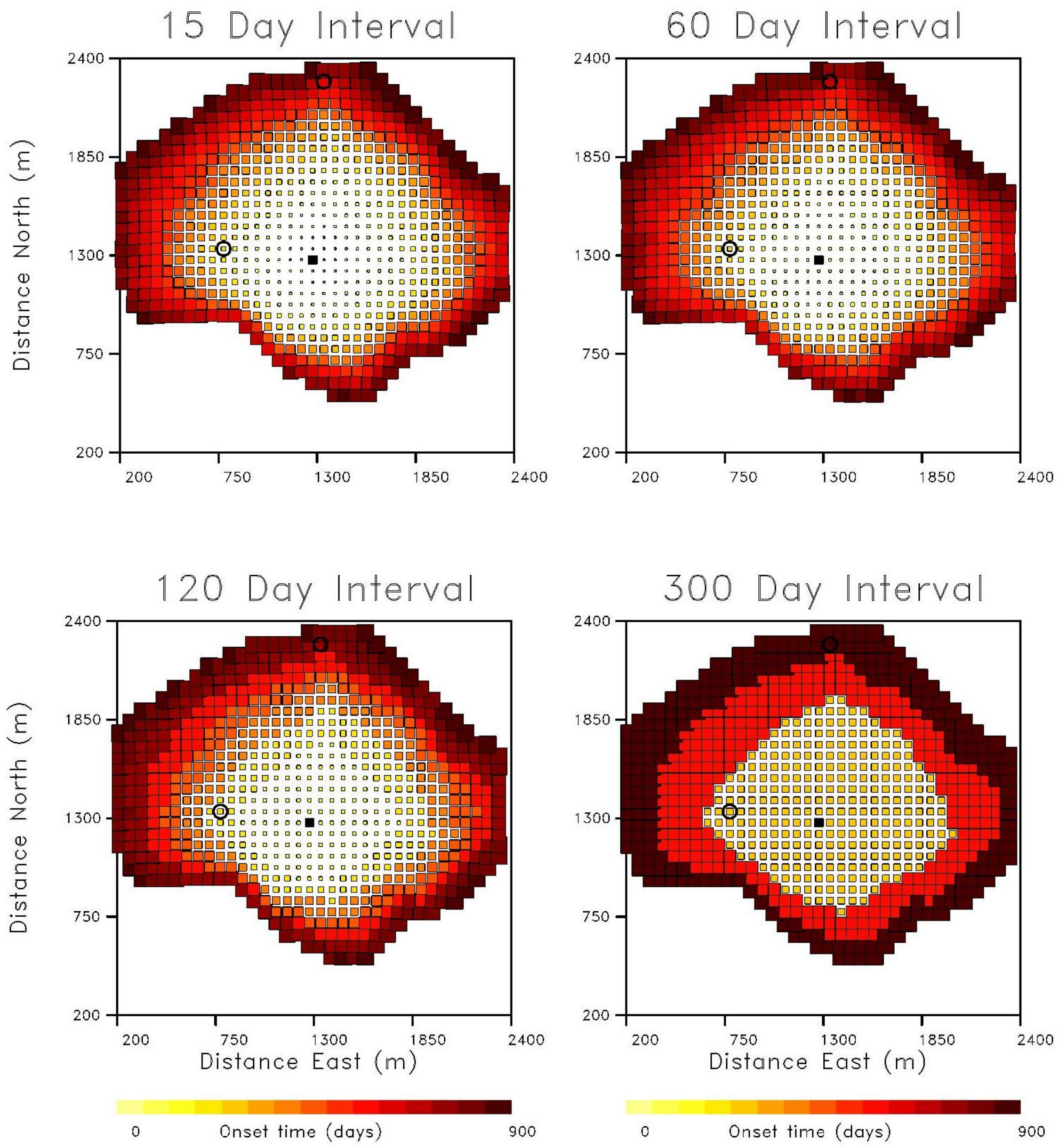
$$\mathbf{d}_{Voigt} = \mathbf{F}_{Voigt}(\mathbf{K}) \qquad \mathbf{A}_{Hill}{}^{T}\mathbf{A}_{Hill}\delta\mathbf{K}_{m} = \mathbf{A}_{Hill}{}^{T}\delta\mathbf{d}_{Voigt}$$

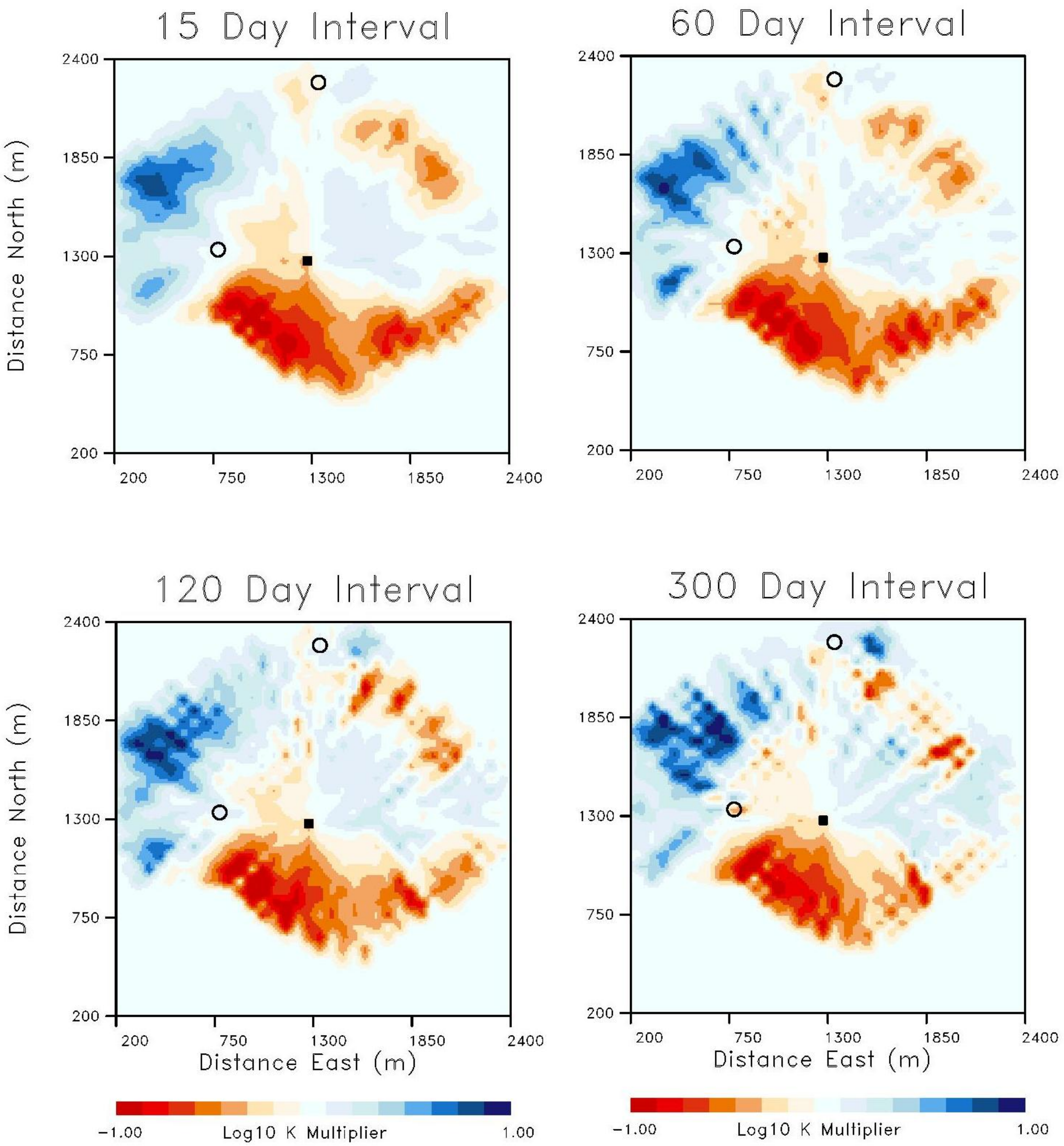


Onset Time Inversion
Misfit (x 1000 Days Squared)
Iteration
20
16
12
8
4
0
0
2
4
6
8
10
Hill
Reuss
Voigt


1.80–1.83 Km
Hill
Reuss
Voigt
Distance North (m)
2400
1850
1300
750
200
200
750
1300
1850
2400
−1.00
Log10 K Multiplier
1.00

Variation in the time inverval between seismic surveys


15 Day Interval
60 Day Interval
120 Day Interval
300 Day Interval
Distance North (m)
Distance East (m)
2400
1850
1300
750
200
Onset time (days)
0
900


15 Day Interval
60 Day Interval
120 Day Interval
300 Day Interval
Distance North (m)
Distance East (m)
2400
1850
1300
750
200
-1.00
Log10 K Multiplier
1.00

Conclusions

- Relationship between changes in the state of a reservoir and geophysical observations can be complicated and confounded by poorly known equation-of-state parameters

- Inversion based upon ‘onset times’appear stable with respect to variations in the saturation/velocity relationship

Acknowlegments

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