Measuring connectivity for better reservoir management

Jerry L Jensen
&
Danial Kaviani
Chemical & Petroleum Engineering
Geoscience

Why bother with connectivity? A sampling of 70 years' of opinions

- "…discontinuous **variations in permeability**…provide the explanation for large variations in production capacities frequently observed…" (Muskat, 1937)
- "Detailed knowledge of sand-channel … **stacking and connectedness** are essential … within fluvial systems." (Henriquez et al, 1990)
- "**Connectivity** is a useful tool for sorting reservoir models according to the best to the worst reservoir performance." (Hird and Dubrule, 1998)
- "**Connectivity** represents one of the fundamental properties of a reservoir that directly affects recovery." (Larue and Hovadik, 2006)

Many Names for Connectivity!

- Connectedness
- Continuity
- Tortuosity
- Communication
- Conductivity
- Compartmentalization
- Barriers
- Flowpath obstructions
- Thief zones

Connectivity Applications

- Model assessment
  - screen geostatistical realizations
  - compare competing geological models
  - assess impact of sed/strat characteristics
- Field management
  - screen data
  - adjust injection and production rates
  - identify & risk drilling strategies
  - assess need/effectiveness of remedial measures
  - calibrate fluid flow simulation models

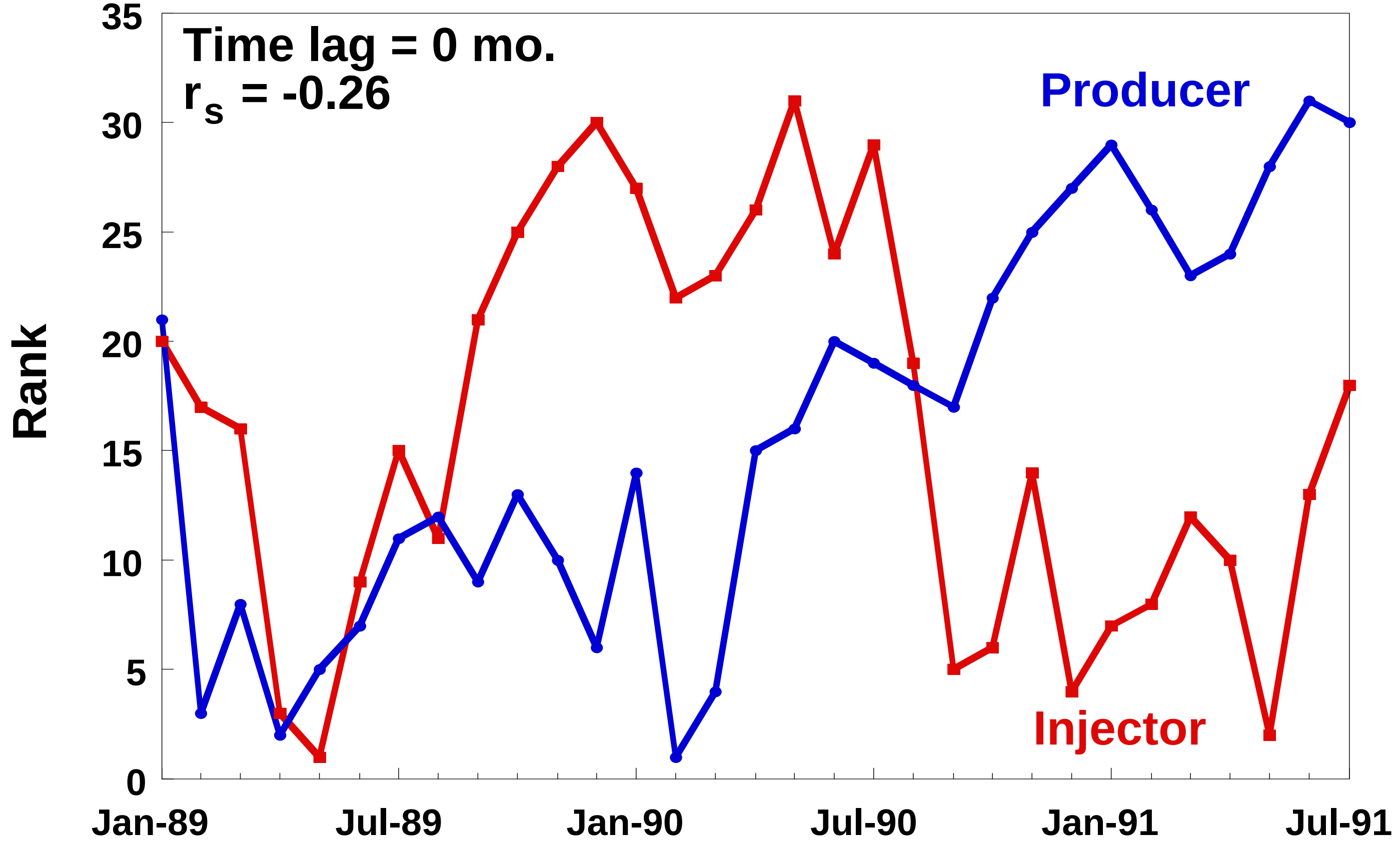
Static connectivity measures

- geometrical
  - fractional area of sandbody contact (Allen, 1979)
  - connected volume (Hovadik and Larue, 2007)
  - ratio of ‘connected’ well pairs (Wang et al., 2008)
- statistical
  - connectivity function (Allard, 1994)
  - probability of percolation (King, 1990)
  - mean sandiness (Glezen and Lerche, 1985)
- inferential
  - seismic (Yose et al., 2004)
  - environmental (Potter, 1962)

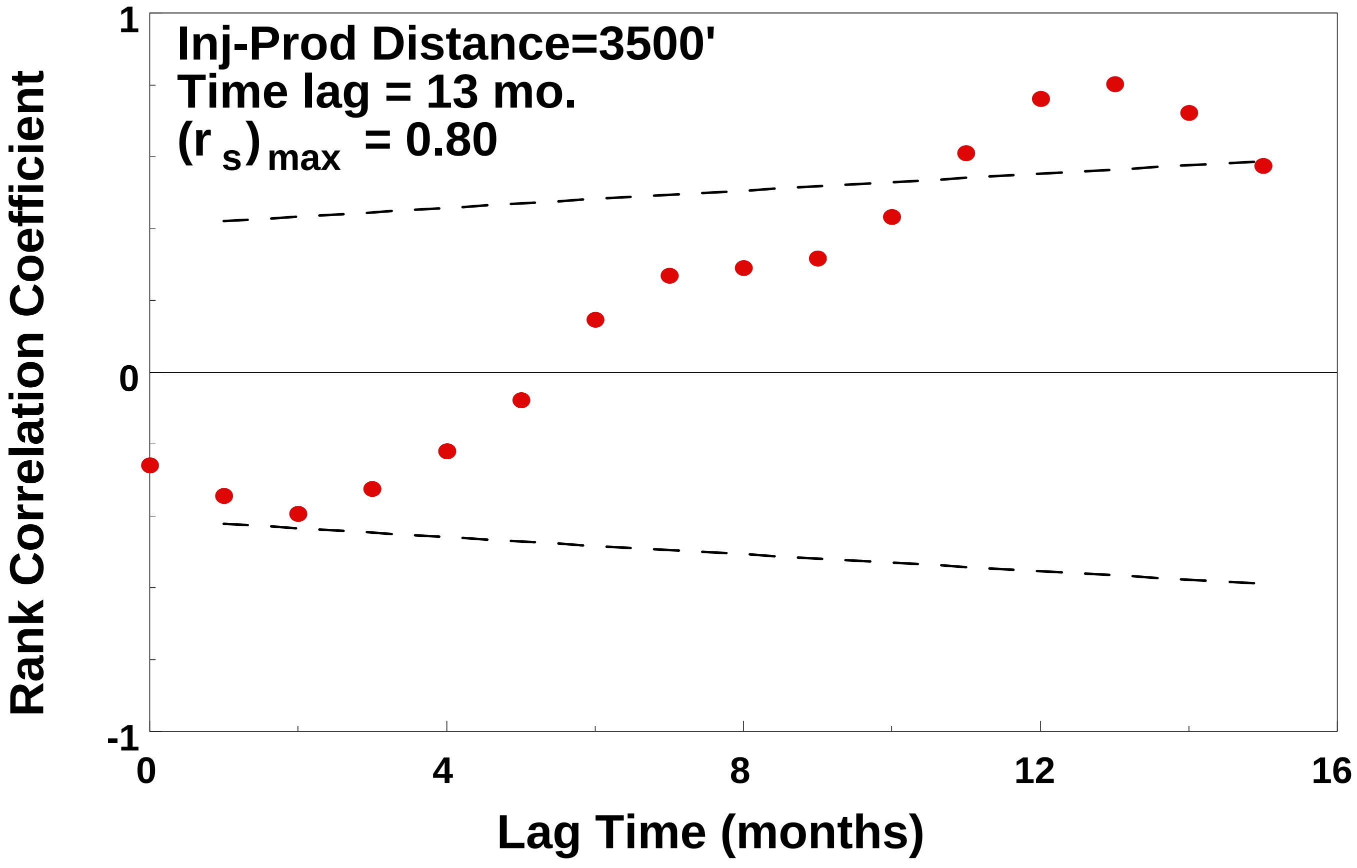
Dynamic connectivity measures

- breakthrough time (Gore and Terry, 1956)
- transmissibility (Johnson et al., 1965)
- tracer (Wagner, 1977)
  - amplitude
  - time of arrival
- inj/prod rate
  - correlation (Heffer et al., 1997)
  - influence factor (Albertoni and Lake, 2003)
  - influence and travel time (Yousef et al., 2006)

Injector-Producer Response Using Simple Correlation Analysis



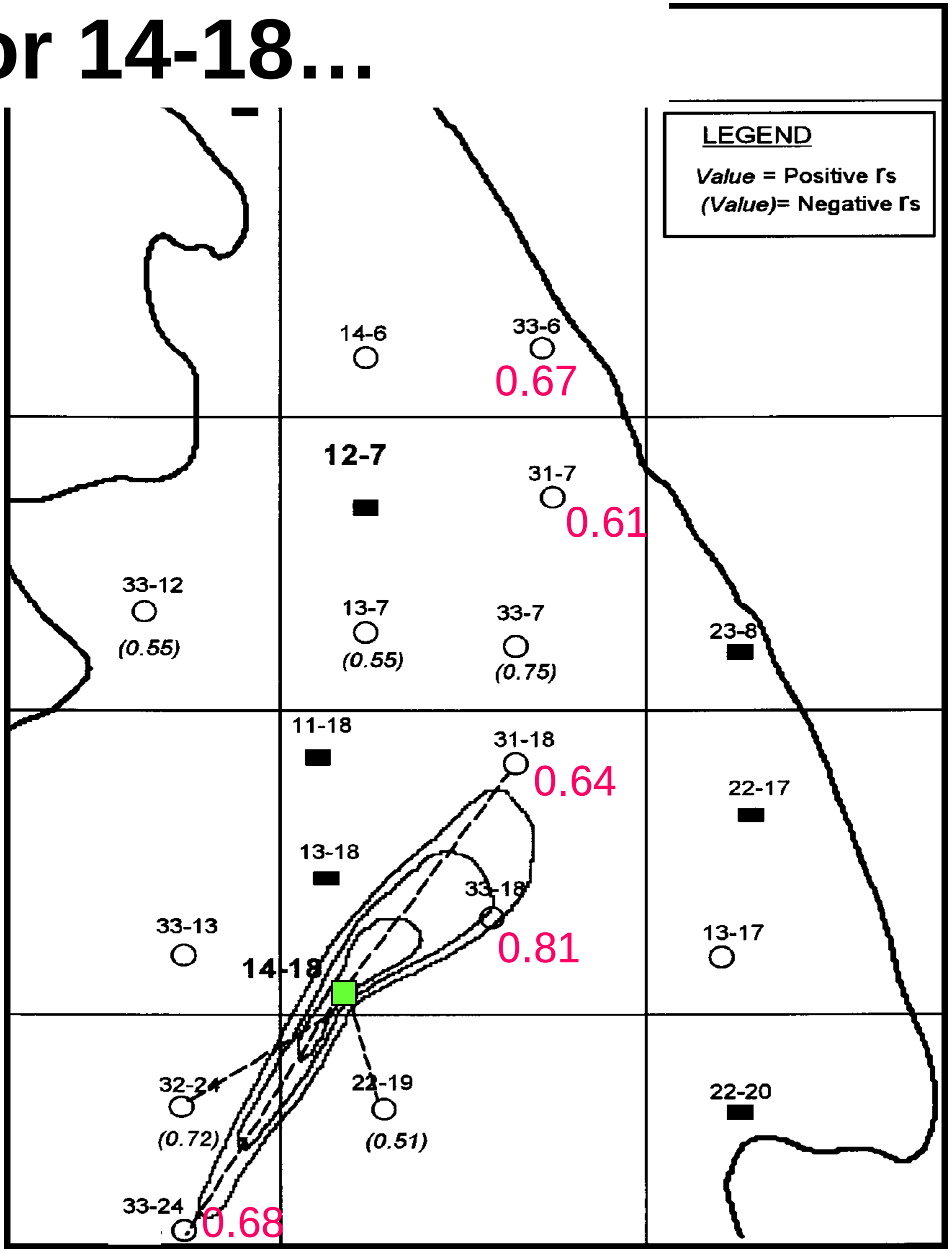
Effect of time shift on correlation value



Refunjol, 1996

Iso-Rank Correlation Coefficient Map For Buck Draw Injector 14-18…

- Fluvio-estuarine
- Flow from south
- Wells in east show limited communication
- Correlation in central part aligned with system axis
- Long distance correlations possible
- BUT need something more quantitative



After Refunjol and Lake, 1999

The woes of correlation

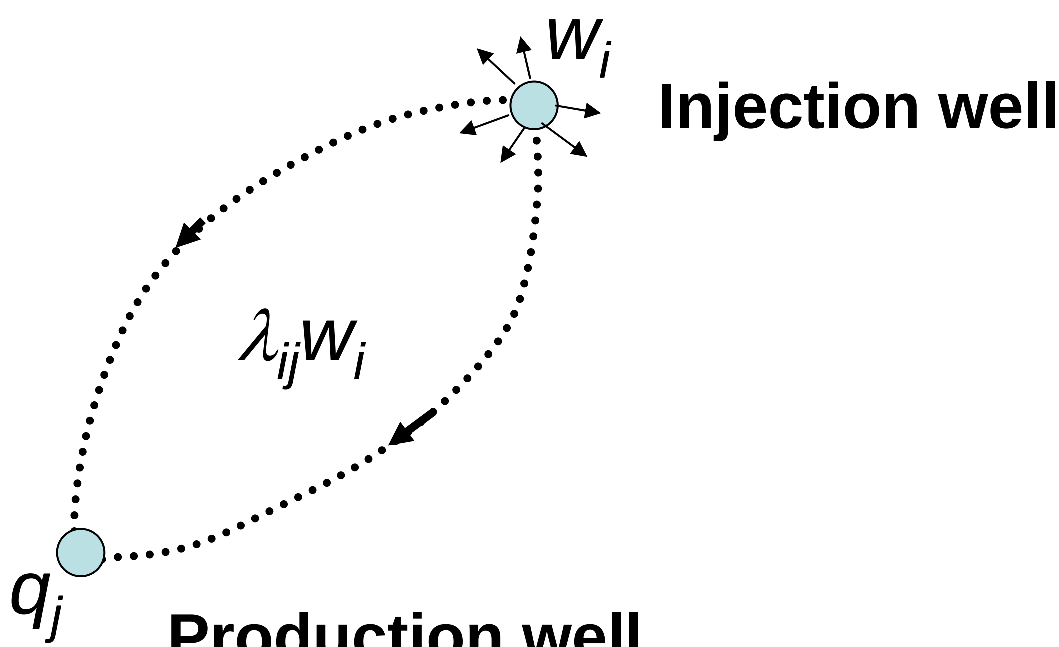
- Depends on well rates
- Confused by shut-ins, workovers, etc.
- Only gives qualitative indication

- WE NEED A METHOD THAT…
  - Uses flow rates
  - Is robust to human interventions
  - Does not need months of time & mountains of data
  - Is as flexible as simulation

A better model: Well-by-well material balance (capacitance model)

$$c_t V_p \frac{d\overline{p}}{dt} = \sum_{i=1}^{I} \lambda_{ij} w_i - q_j$$

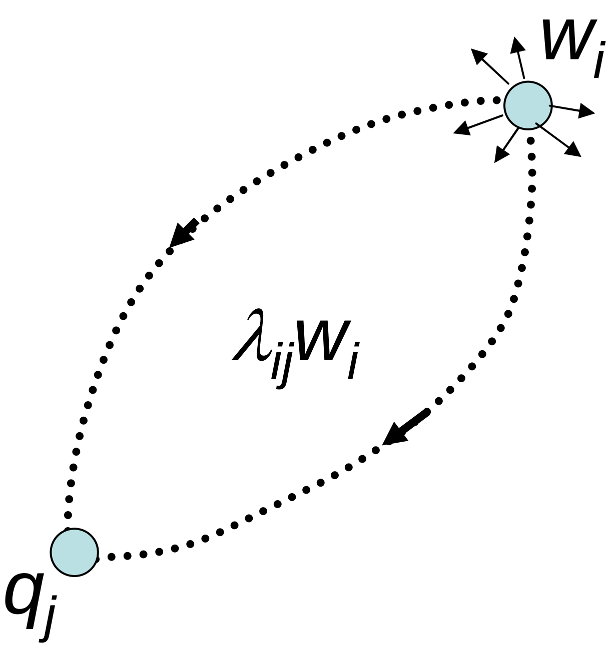
change in stored fluid = fluid in - fluid out

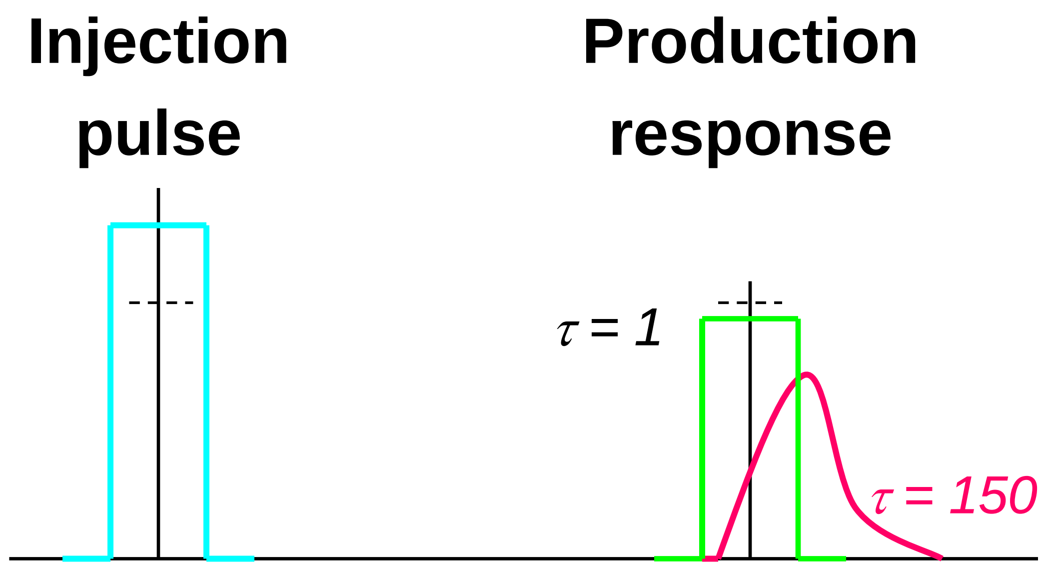


Capacitance model and time delay

- convert $\bar{p}$ to flow rate q and bottomhole press p_{wf}

$$\frac{dq_j}{dt} = \frac{1}{\tau}\sum_{i=1}^{I} \lambda_{ij} w_i - \frac{1}{\tau} q_j - J_j \frac{dp_{wf_j}}{dt}; \qquad \tau = \left(\frac{c_t V_p}{J_j}\right)$$





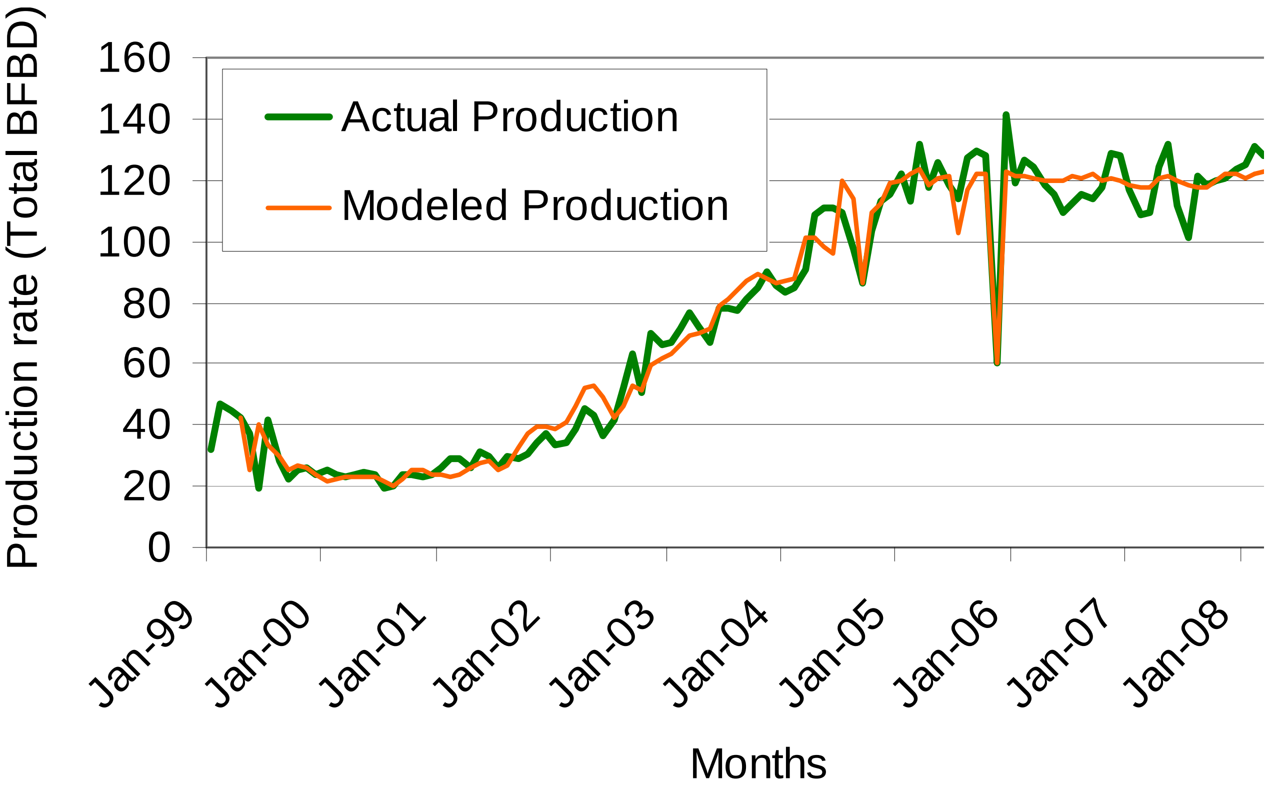
Capacitance model solution

$$\hat{q}_j(t) = \lambda_0 \left[q_j(t_b) e^{-\frac{t-t_b}{\tau_0}} \right] + \sum \lambda_{ij} \left[\left(\frac{e^{-t/\tau}}{\tau} \int e^{-t/\tau} \right) w_i(t) dt \right]$$

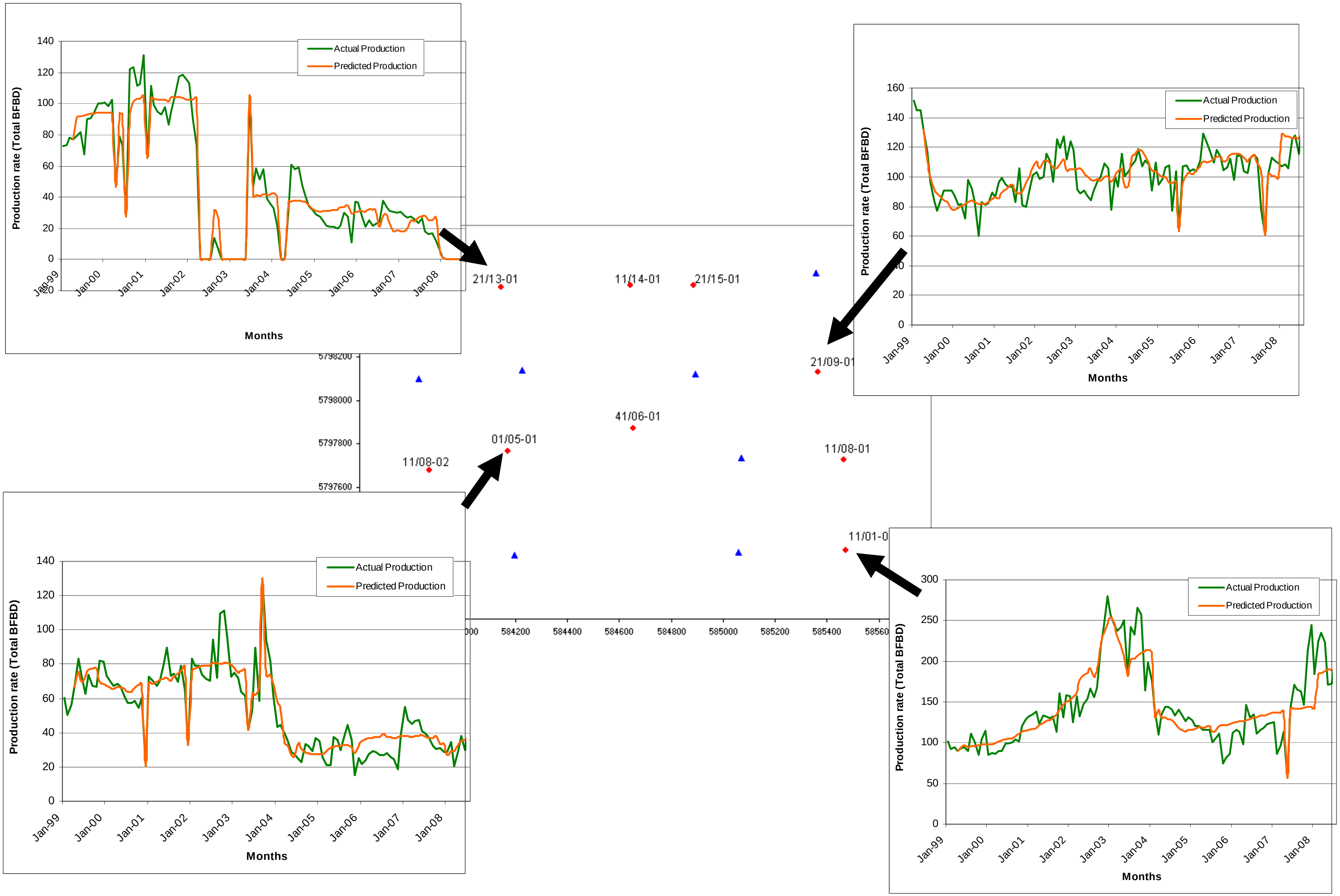
total production = primary depletion + waterflood

Calculating the λ's and τ's

- Use injection and production data
- Find λ's and τ's which give best production match

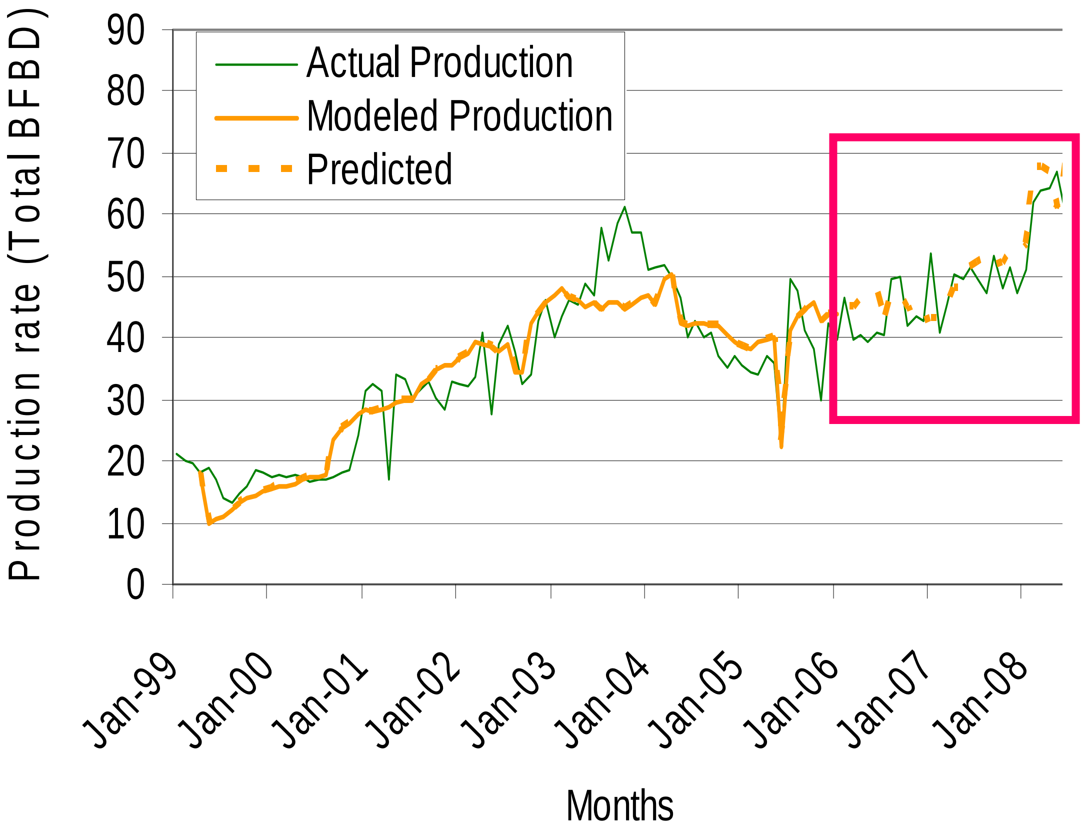


λ's and τ's for all well pairs are calculated together to give the best fit to production data: history matching



Testing the λ's and τ's

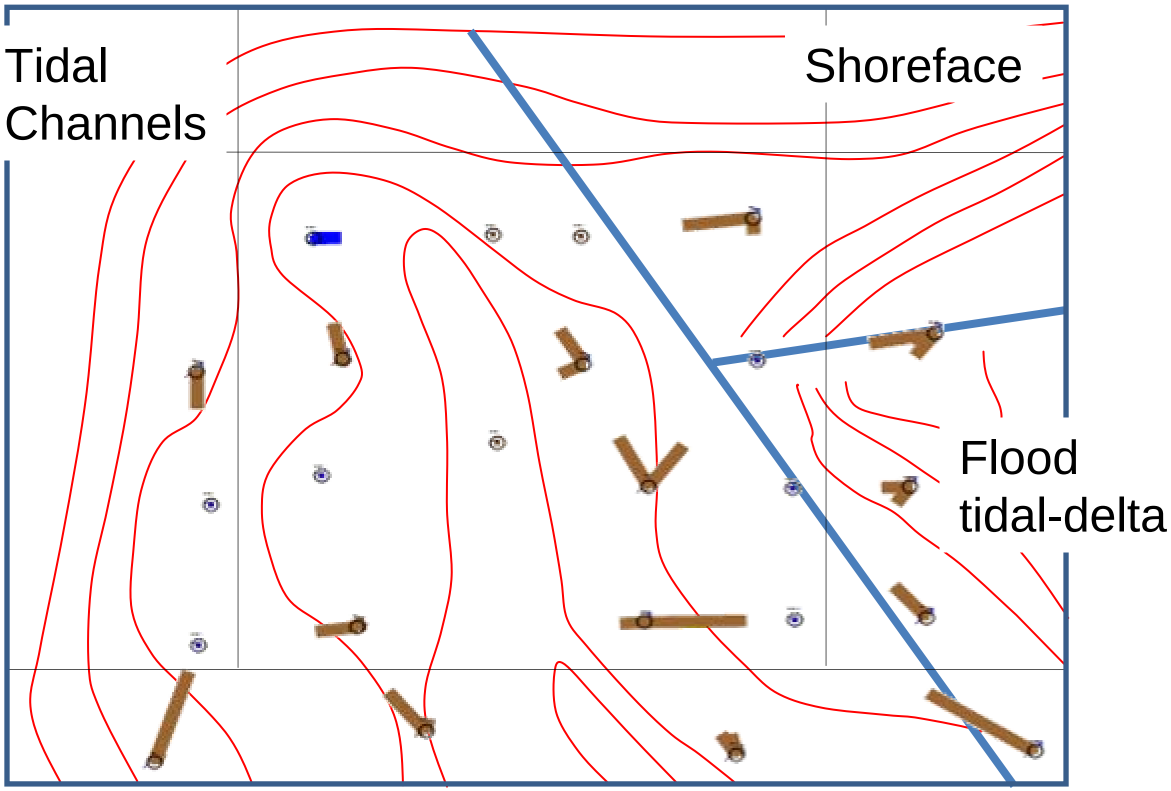
- **Compare with recent production excluded from history match**



Testing the λ's and τ's

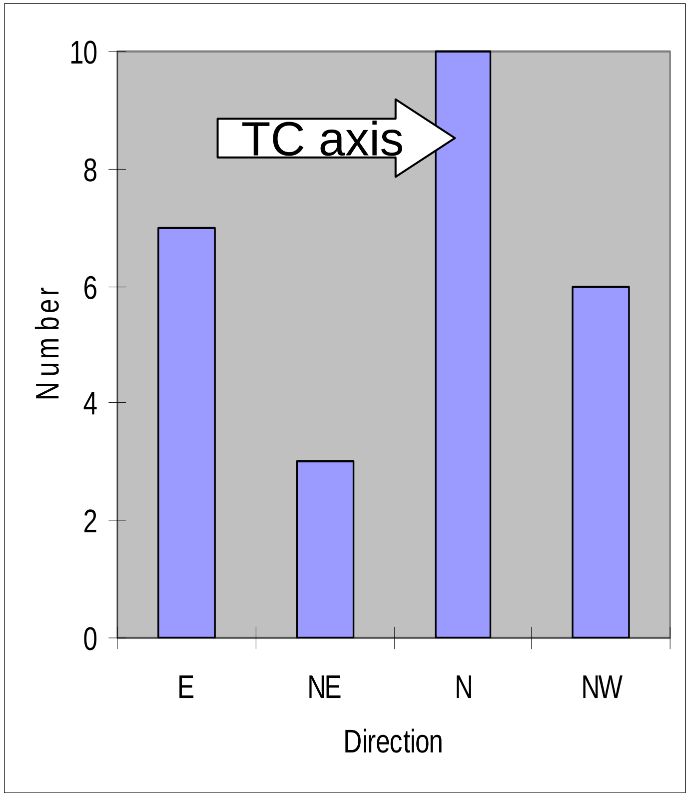
- **Compare with other data eg channel orientation**

Gross-sand thickness



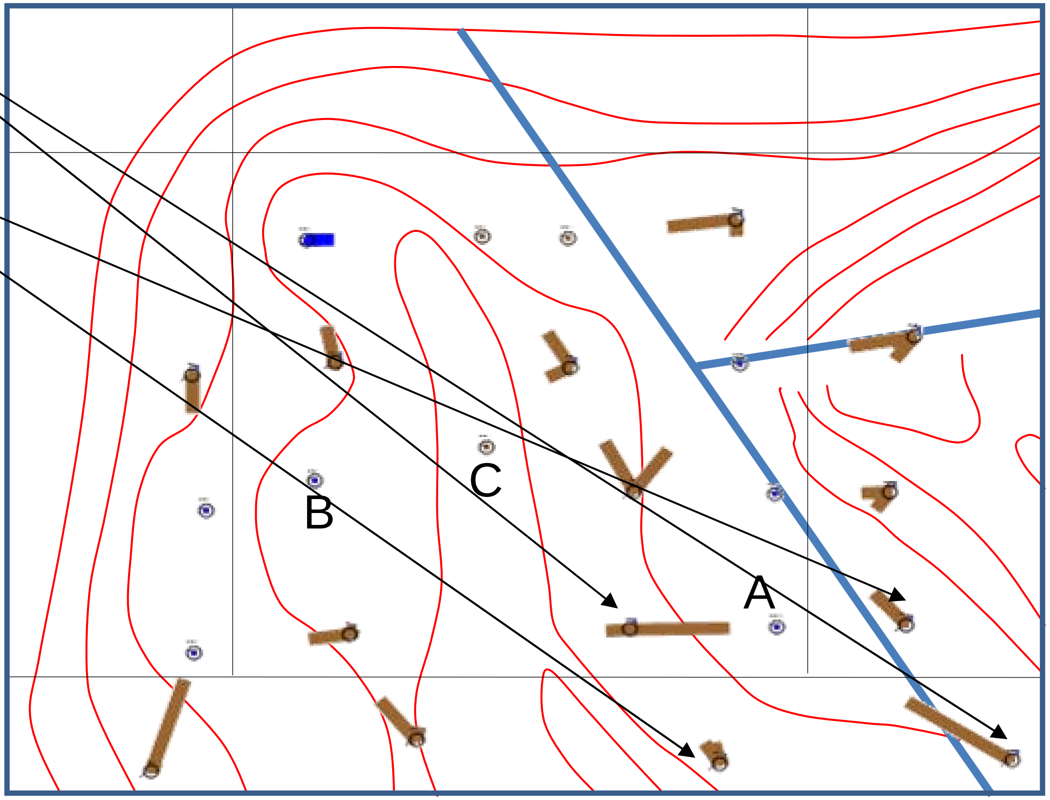
after Zaitlin and Shultz, 1990

Vector directions



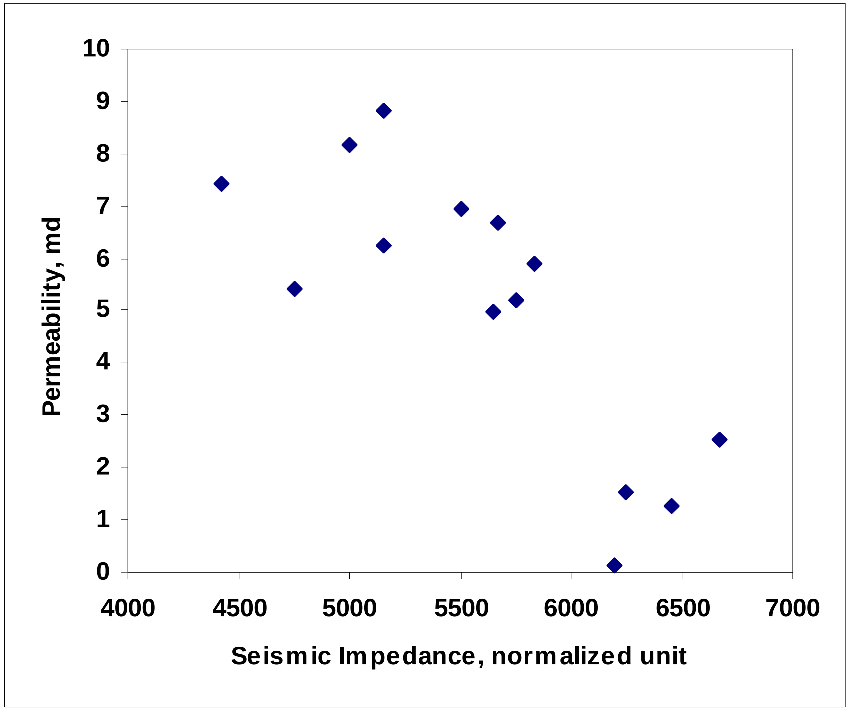
How do we use this information?

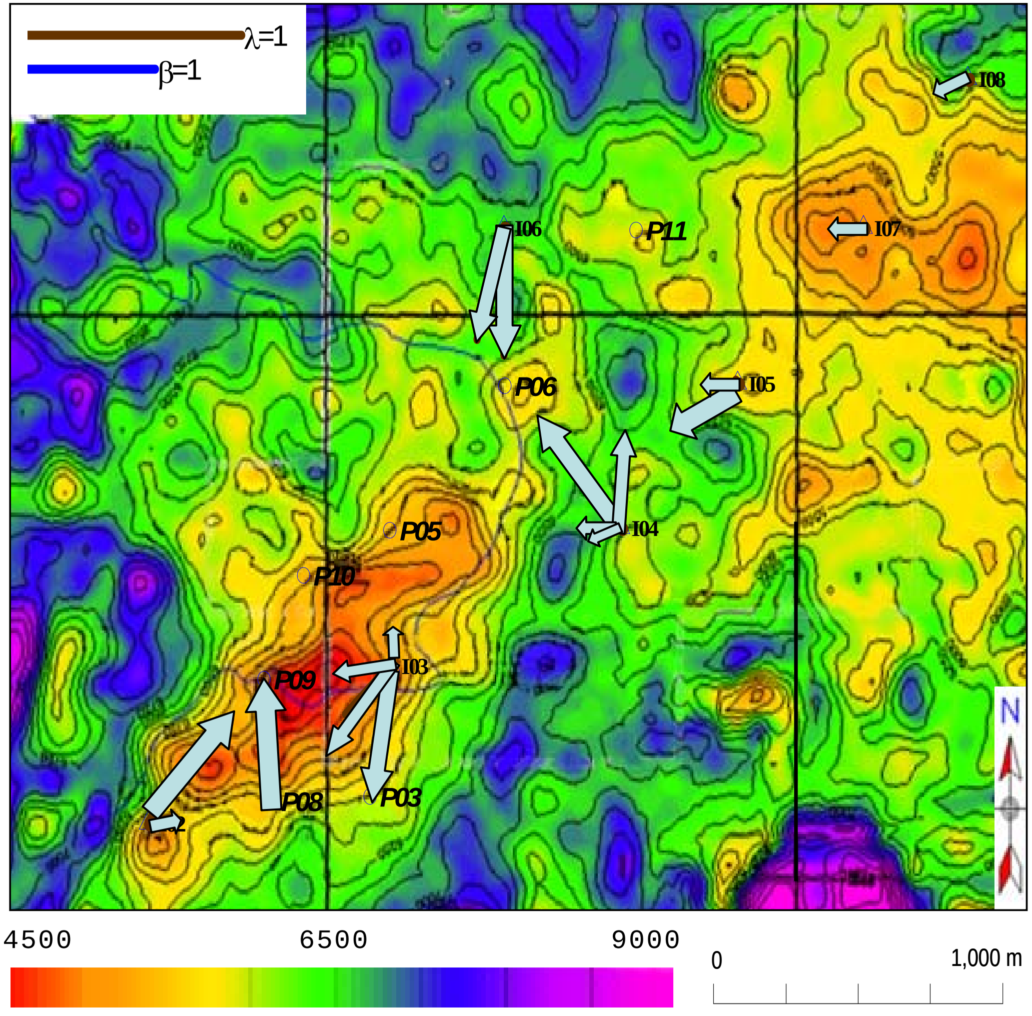
- Well A
  - 2 inj’s comm well
  - 2 inj’s weak/no comm
- Wells B & C
  - Little connection with existing inj’s
  - Needs inj wells along channel axis



Comparing Seismic and λ's: SK Carbonate

- Best comm in SW with large porosity
- Weak NE-SW comms

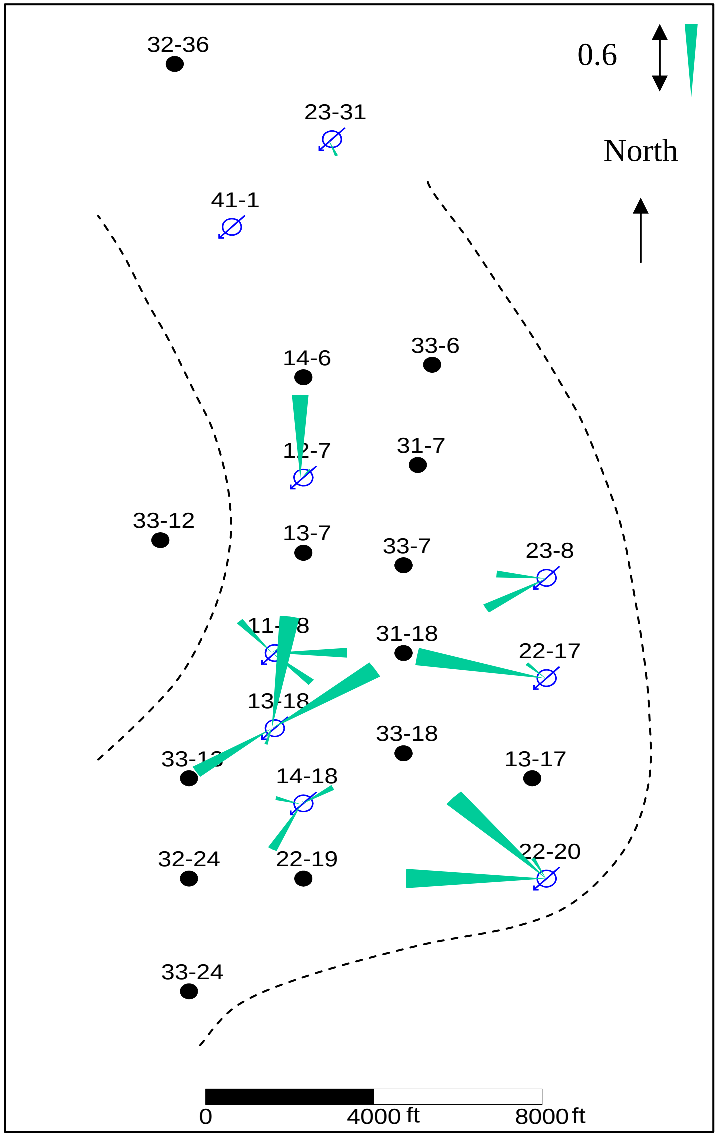


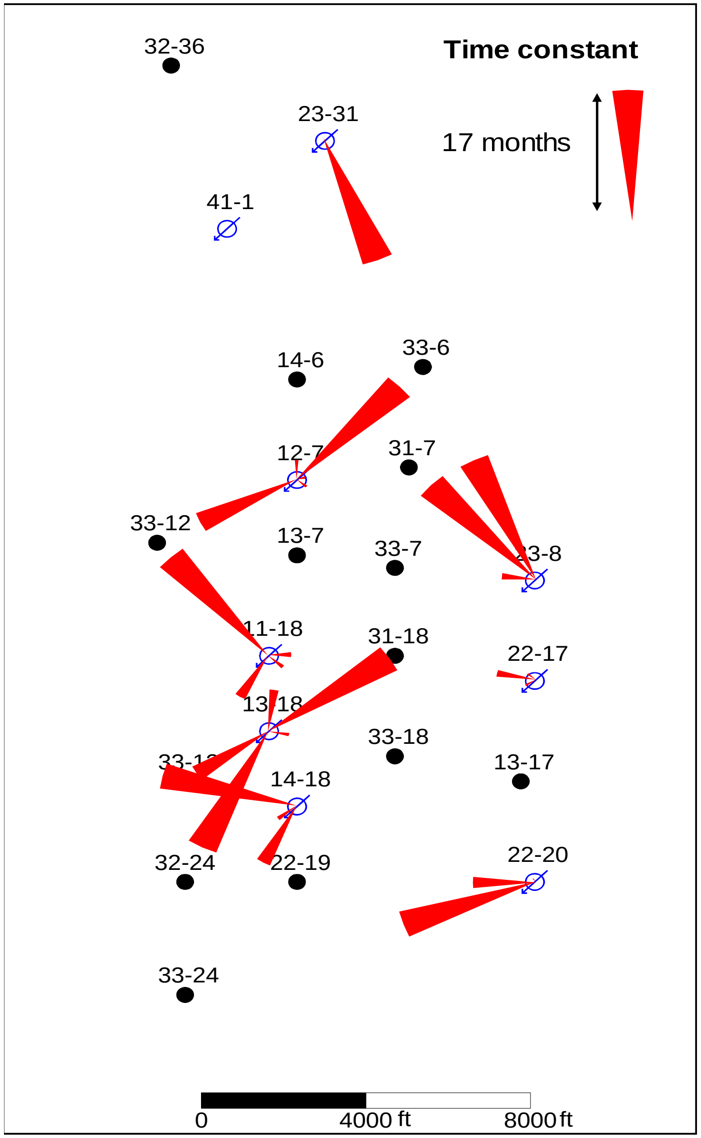


North Buck Draw

- Two proposed models
- Sellars and Hawkins (1992)
  - Stacked point bars, channels
  - Good continuity
- Gardner et al. (1994)
  - Fluvio-estuarine deposit
  - Fluvial good quality
  - Estuarine incises and reduces communication

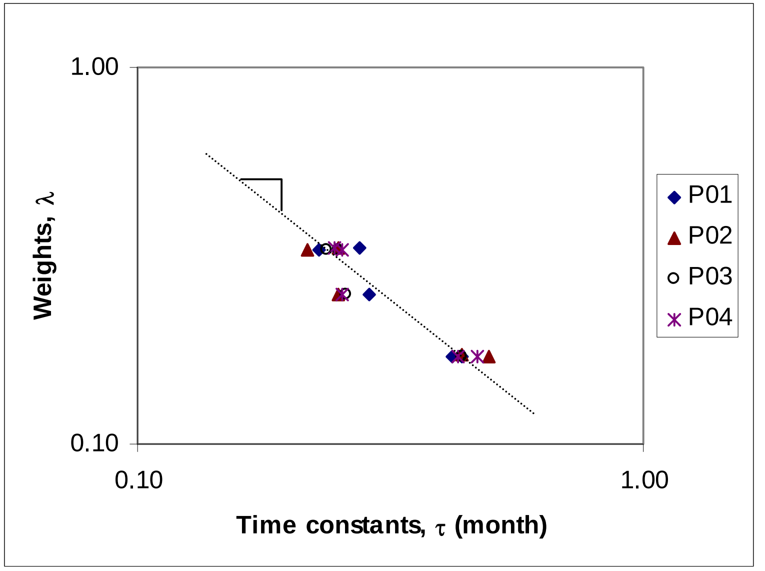
Buck Draw Results

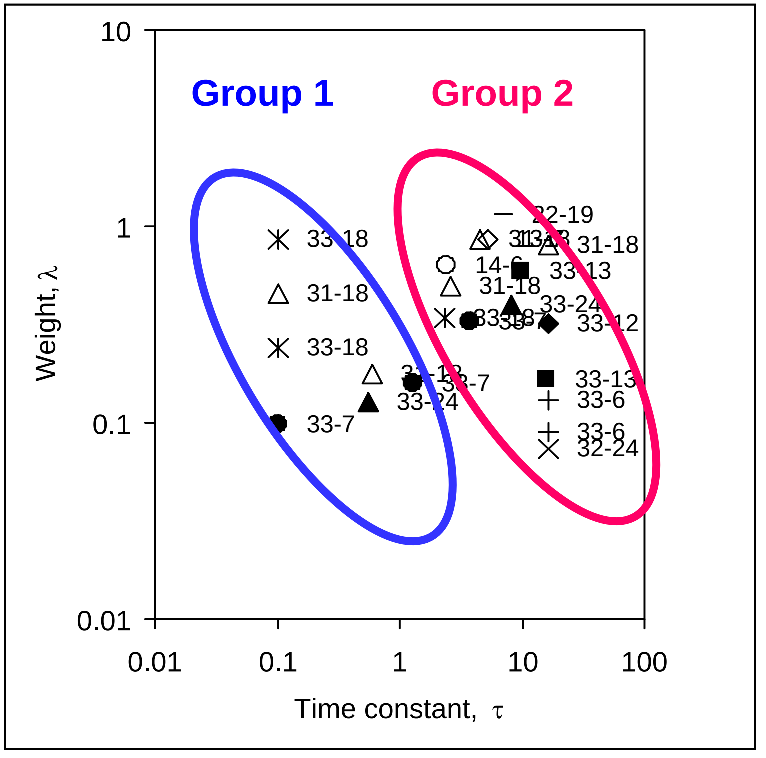




Joint analysis of λ and τ

- Two methods
  - Lorenz plot
  - log(λ) vs log(τ) plot
- log(λ) vs log(τ) method
  - Recall $\tau = c_t V_p / J$
  - $\lambda \propto J$
  - look for line, -1 slope
  - Buck Draw groups
    - #1 more fluvial
    - #2 more estuarine

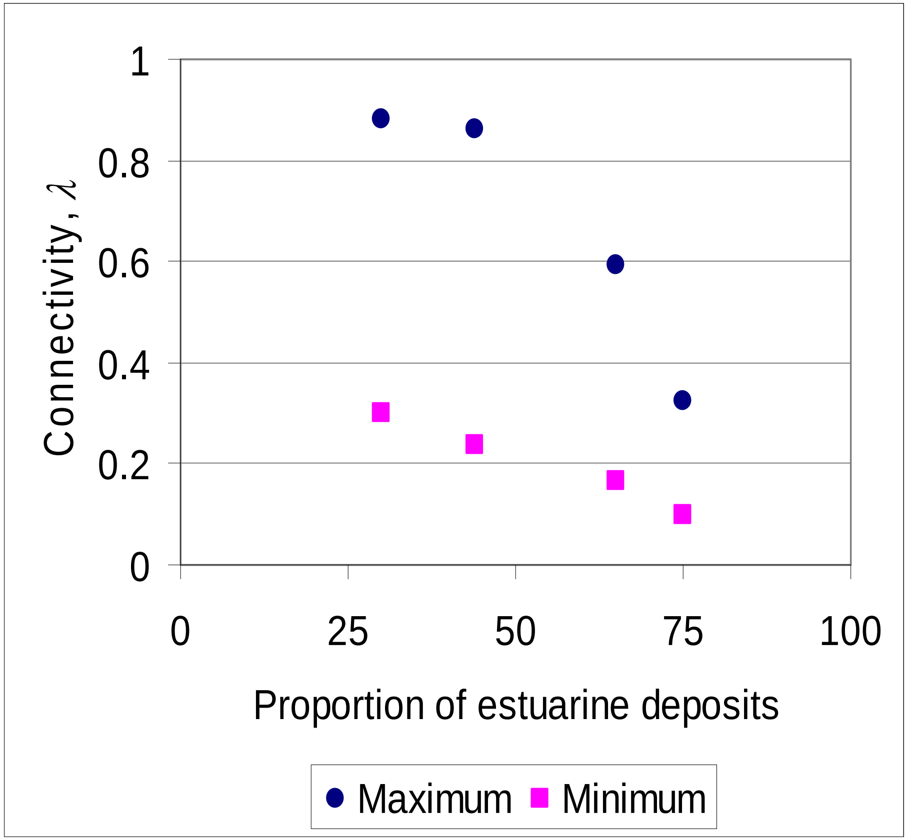




Yousef et al., 2009

Estuarine deposits and λ

- Apparent relation between estuarine deps and λ
- Agrees with geology and petrophysics
  - Fluvial good quality
  - Estuarine deposits
    - poorer quality
    - replace fluvial at the well
    - disconnect fluvial in interwell region
- Results support Gardner
- Only 4 wells with core: more evidence useful



Conclusions

- Connectivity
  - recognized as important for > 70 years
  - numerous ways to measure
  - many applications
- Capacitance model effective
  - No reservoir simulation needed
  - Can accommodate shut-ins, workovers, conversions
- Three CM field applications
  - Matched production
  - Compared well with geological, seismic maps
  - Identified wells with little support
  - Basis for choosing a geological model

Acknowledgements

Students

- Thang Bui
- Nazli Demiroren
- Ali Yousef
- Weiqiang Li

Colleagues

- Larry Lake
- Brian Willis
- Steve Hubbard
- Walt Ayers
- Duane McVay

For further information, contact…

Jerry L Jensen

University of Calgary

jjensen@ucalgary.ca