Application of Transition Probability Geostatistics in a Detailed Stratigraphic Framework

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Goal:

Develop quantified models of heterogeneity that accurately reflect:

- Geologic variability
- Multi-scale nature of stratigraphy
- Honor actual field data (core, well log)
- Can be used in groundwater models
Transition Probability Geostatistics (TPROGS)

- Method of Carle and Fogg, 1996
- Indicator geostatistical method;
- Creates geologically realistic simulations of heterogeneity;
- Models incorporate ‘soft’ geological data as well as measured parameters;
- Realizations honor known data points;
- Asymmetrical distributions modeled.
Advantages of the TPROGS Approach

Markov chain models capture:

• Mean lengths
• Facies (hydrofacies) proportions
• Juxtaposition relationships

Additionally, during simulation we can incorporate:

• Stratigraphic dips
• Stratigraphic orientations (anisotropy)
Kings River Alluvial Fan

Exposed upper fan
Modern incised valley
Lower 'active' fan

1980 Landsat MSS false color from USGS NALC program.
STEPS FOR MODELING

1. Define and model overall stratigraphy and define ‘units’ where local *stationarity* is a reasonable assumption.

2. Measure vertical transition probabilities between facies within each ‘unit’ and fit 1-D Markov chain model(s) to these measured results.

3. Measure or estimate lateral transition probabilities and estimate lateral Markov chain models for each ‘unit.’
   a. From well data
   b. From other sources (e.g., soil surveys, geological maps).

4. Simulate each ‘unit’ separately.
   a. Conditional Sequential Indicator Simulation.
   b. Simulated Quenching.

5. Combine simulation results into single realization of system.
CYCLES ON FLUVIAL FANS

Interglacial
Low accumulation space

Initial Glacial Outwash
Increasing accumulation space

Continued Glacial Outwash
High accumulation space

Transition to Interglacial
Decreasing accumulation space

Weissmann et al, 2002, JSR
Kings River Fluvial Fan

LEGEND

- Holocene Fluvial Deposits
- Holocene Lacustrine or Deltaic Deposits
- Undifferentiated Holocene and Modesto Deposits
- Upper Modesto (Proximal Fan) Deposits
- Lower Modesto (Distal Fan) Deposits
- Undifferentiated Modesto Deposits
- Riverbank Deposits
- Undifferentiated Pliocene Deposits

West Side Alluvial Fans
Older units outside basin
Water
Urban Areas

From Weissmann et al. *in press*
Kings River Alluvial Fan – Dip Section

From Weissmann et al 2002
From Weissmann et al. 2004
Identified Hydrofacies Within Sequences

• **Gravel** (channel deposits)

• **Sand** (channel deposits)

• **Muddy Sand** (coarse floodplain deposits)

• **Mud** (fine floodplain deposits)

• **Paleosol** (soils due to extended periods of exposure)
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Kings River Alluvial Fan

Open Fan Deposits
Vertical Transition Probabilities

(GAMEAS/GRAFXX)
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   a. From well data
   b. From other sources (e.g., soil surveys, geological maps).
   c. Application of Walther’s Law

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≈75 Miles of GPR data Collected (Bennett 2003)
Channel Facies Dimension Estimates

Raw GPR Data

Interpreted GPR Data

Bennett et al submitted
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4. **Simulate each ‘unit’ separately.**
   a. Conditional Sequential Indicator Simulation.
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5. Combine simulation results into single realization of system.
Realizations capture:

- Contrasting character between different stratigraphic units.
- Fining-upward successions (gravel up to sand up to muddy sand)
- Juxtapositional tendencies (fining-outward successions)
- Radial pattern of fan deposits
- Dipping beds
- Reasonable channel sand and floodplain fine distributions. It “looks” geological.
- And honor conditioning data points

Multiple realizations can be run to assess uncertainty.
Our goal:

Produce realistic heterogeneity for groundwater flow and contaminant transport modeling.
Modeling Applications to Date – Kings River Alluvial Fan

1. Evaluation of Groundwater Age Date from Chlorofluorocarbons (CFC)
   - Weissmann et al. 2002, WRR, v. 38

2. Groundwater Flow and Contaminant Transport Around Incised Valley Fill Sediments
   - Weissmann et al. 2004, SEPM Special Publication 80
Release from Well B4-2

Elevation (meter)

Dip Direction Distance (meter)

Age (years): 10 30 50 70 90

Vertical Exaggeration: 50:1
Measured vs. Simulated CFC Concentrations

A

B

Simulated CFC-11 Age (years)

Simulated CFC-12 Age (years)

Reported CFC-11 Age (year)

Reported CFC-12 Age (year)
Particle movement around paleovalley fill

Weissmann et al 2004, SEPM Special Publication 80
CONCLUSIONS

• Multi-scale, non-stationary models produced:
  • Large-scale: deterministic modeling
  • Intermediate-scale: stochastic modeling in deterministic stratigraphic framework
  • Small-scale: stochastic modeling or appropriate dispersivities

• The transition probability geostatistics approach:
  • Produces geologically reasonable realizations of aquifer heterogeneity.
  • Allows for incorporation of geological concepts into model development.

• Improved groundwater modeling and contaminant transport simulation.
  • Groundwater age date distributions (CFC age dating).
  • Models of stratigraphic influence.