A General Purpose Research Simulator (GPRS) for Numerical Simulation On CO_2 Sequestration

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Highlights

- GPRS is a next-generation research simulator developed in Stanford SUPRI-B group
- GPRS uses state-of-the-art object-oriented design and is programmed in standard C++
- GPRS is easy to extend and easy for team development
- GPRS can be used by multiple researchers with various purposes of reservoir engineering and management
- Most of SUPRI-B group's research results are tested and reflected in GPRS

Milestones

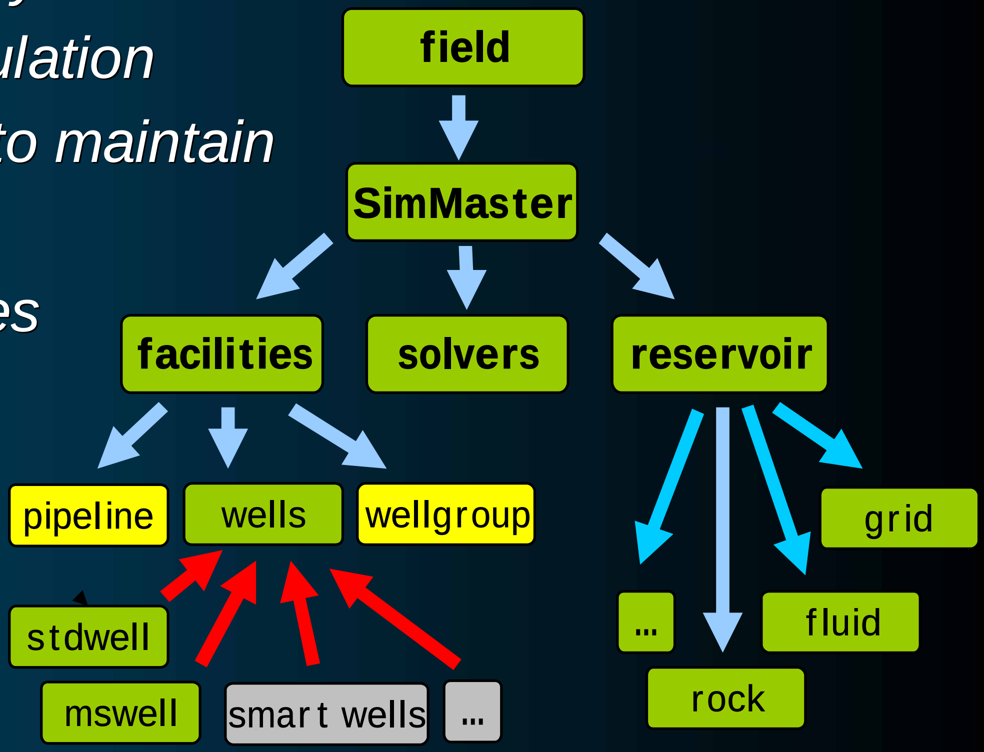
- 2002: 1st release of GPRS to SUPRI-B members: generalized unstructured, compositional formulation
- 2004: Finished Multi-segment well (MSWell) implementation
- 2005: Started to add energy equation; SLB/CVX/Total's Intersect project initiated largely following the philosophy and system design of GPRS
- 2007: Finished adding advanced upscaling features for NFR (MSR), conventional reservoirs (ALG), and near-well regions
- 2009: Finished generalized chemical-reaction formulation (multi-species)
- 2010: Started to implement auto-differential formulation; finished CO2 sequestration and CBM module; Collaborative development agreement signed between Stanford and Peking University

Features of GPRS

- State-of-the-Art Object-Oriented Design
- Full-function Reservoir Simulator
- Innovative Data Structures
- Advanced Well Models
- Compatible with Various Grids
- Powerful Formulation and Solvers
- Others

State-of-the-Art Object-oriented Design

- Major commercial reservoir simulators are still procedure-oriented design (Eclipse, CMG, VIP, etc.)
- GPRS uses object-oriented design
  - *Much more natural way to model an oilfield*
  - *Enables data-encapsulation*
  - *Clear structure, easy to maintain*
  - *Allow easy teamwork*
  - *Unlimited extensibilities*



Outline

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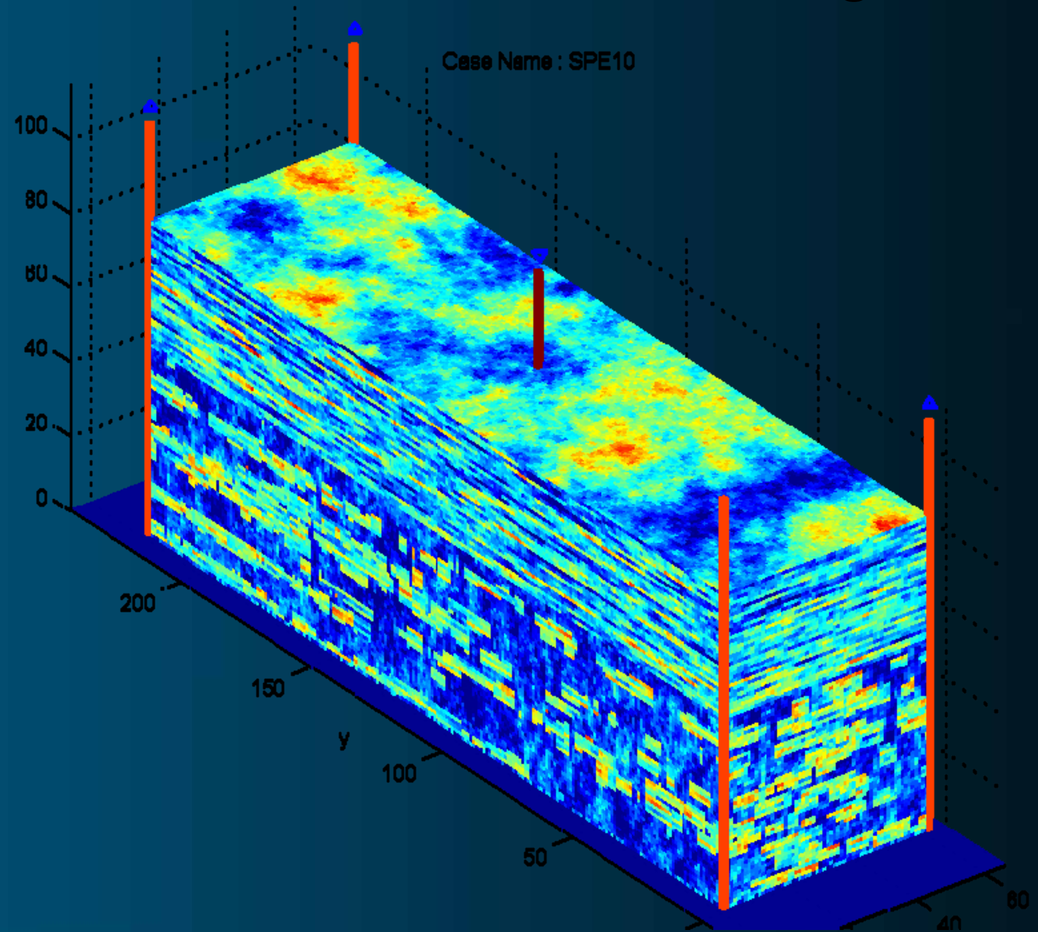
Full-function Reservoir Simulator

- A Black-Oil simulator
  - *Allow Any combination of oil-water-gas phases*
  - *A Special case of compositional formulation*
- A Compositional simulator
  - *Any number of components*
  - *Comprehensive EOS models*
  - *Fast flash calculation*
- A Chemical-Reaction Simulator
  - *Largely applied in Global Climate and Energy Project (GCEP)'s CCS research*
  - *Ready to use for CBM and Shale Gas simulation*
- and thermal
  - *On-going work*

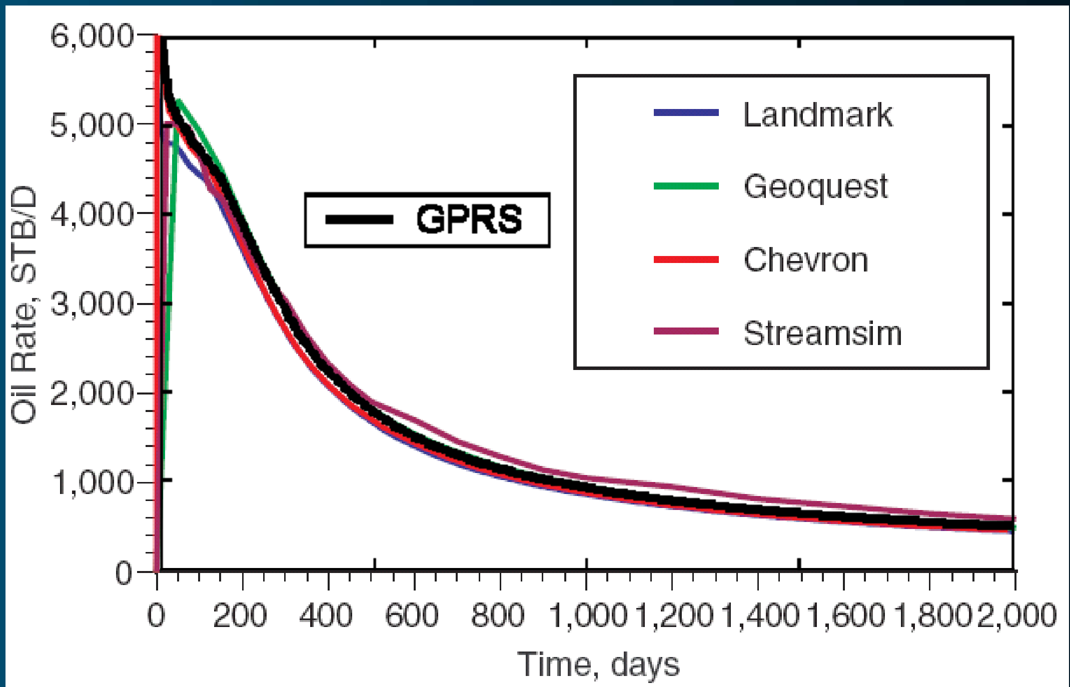
A Black-Oil Example

- 10^{th} SPE standard comparison project, example 2
- Oil-water model with 1.12 million grids



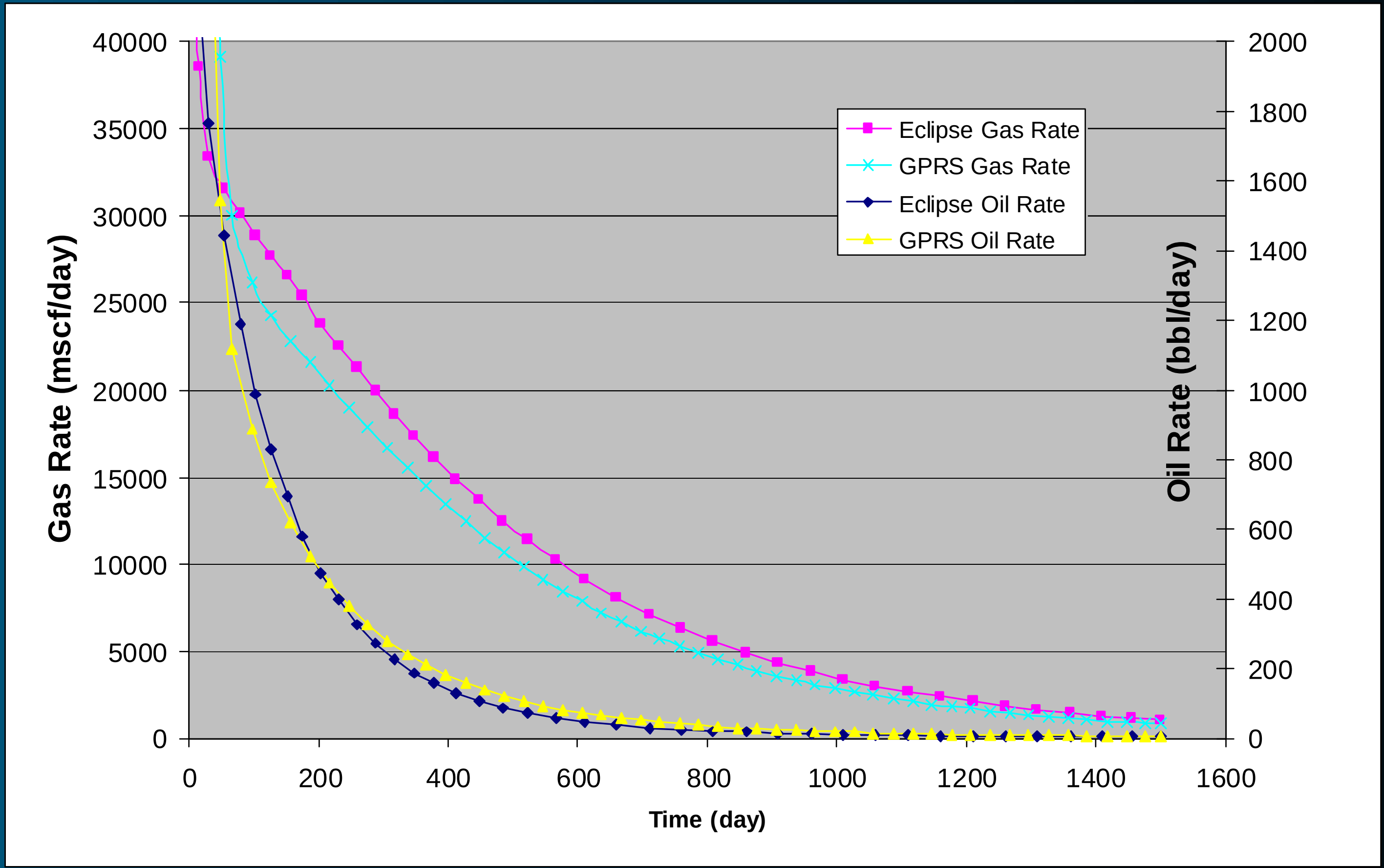
Benchmark Results

- Matched with industry simulators
- Much faster than Eclipse
  - *It takes GPRS 4.5 hrs on single CPU (2.8GHz)*
  - *It takes Eclipse 5 hrs on 8 CPUs (2.8 GHz)*



A Compositional Example

- 3^{rd} SPE standard comparison project
- Gas-Condensate model，9 HC + water



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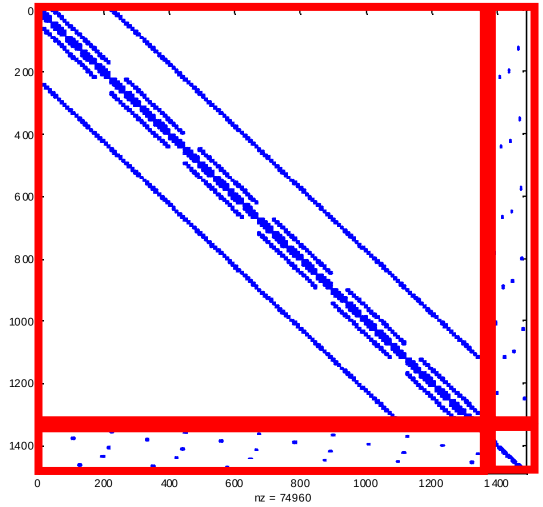
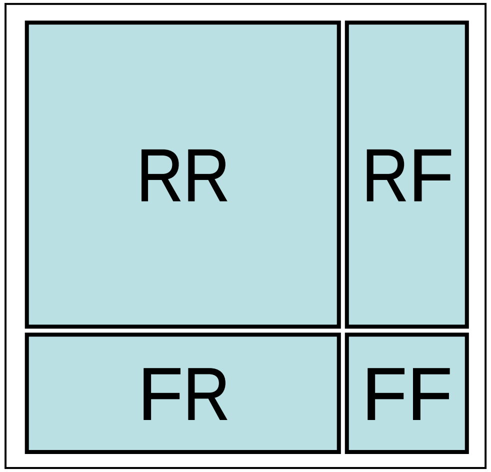
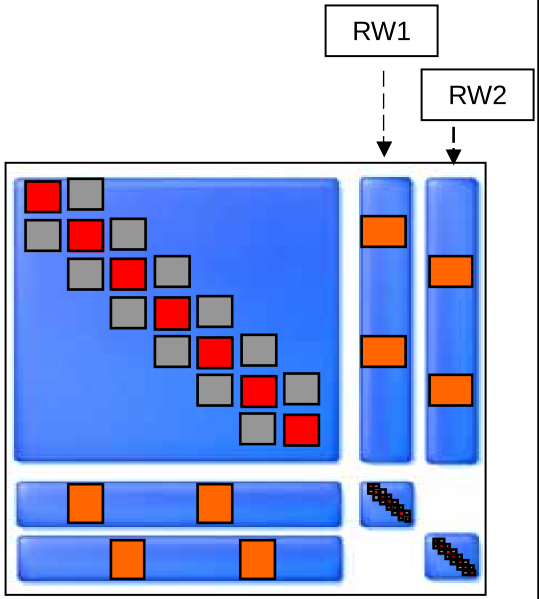
Multi-level Sparse Block Matrix



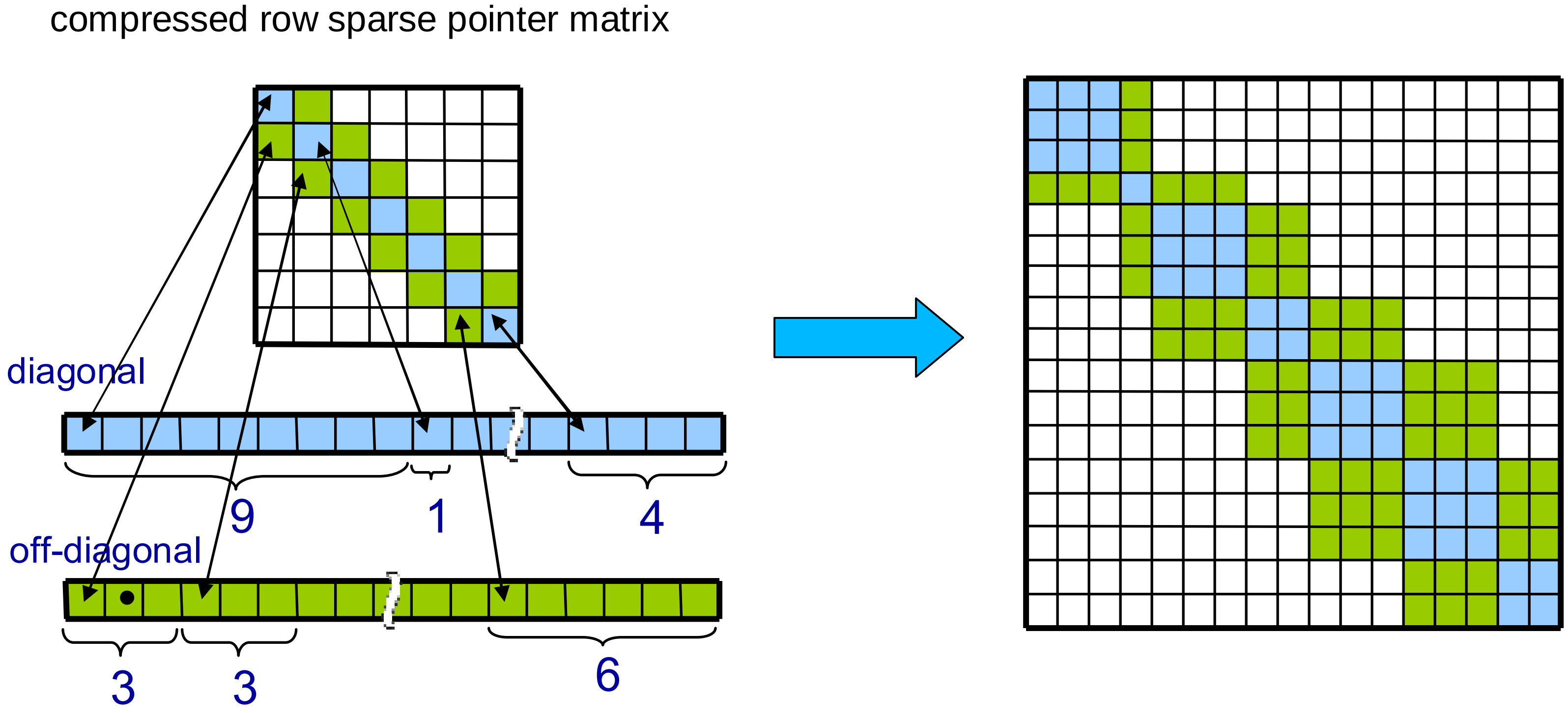


- Easy to assemble
- Efficient
- Extensible



- R ~ reservoir
- F ~ facilities
- W ~ well

Block Compressed Row Matrix



- Designed specifically for unstructured grid & AIM
- Easy to adopt new algorithms
- Better cache utilization

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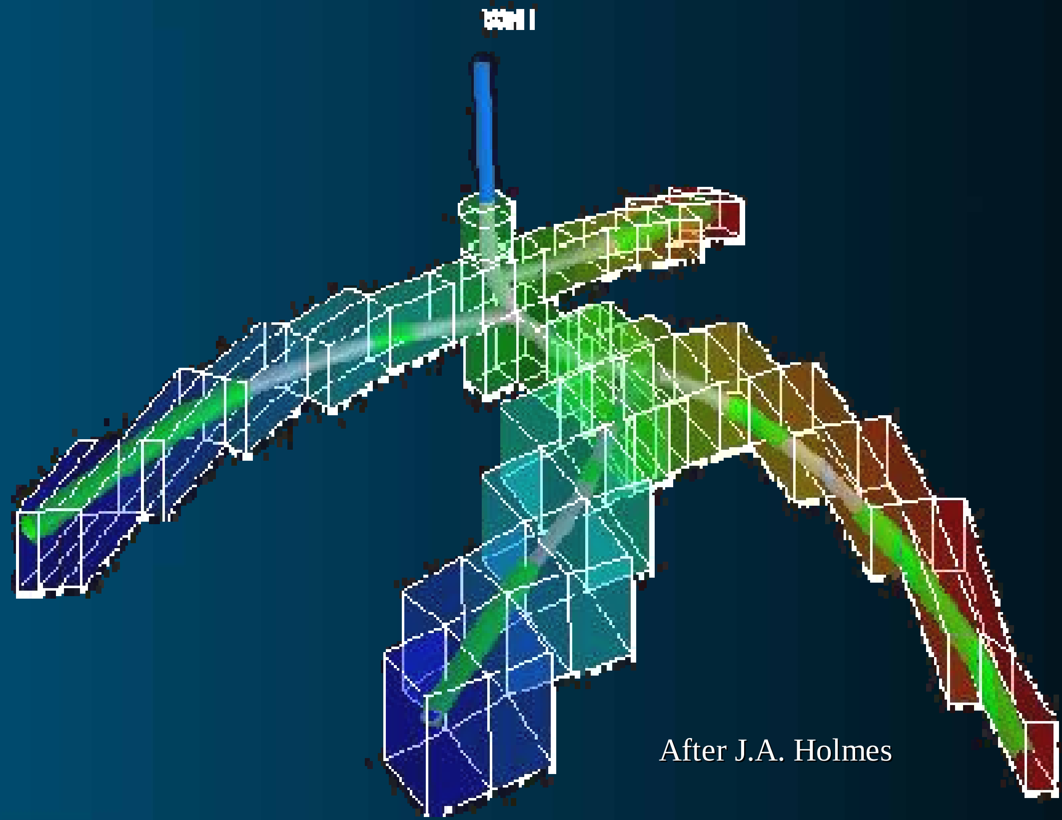
Multi-Segment Well

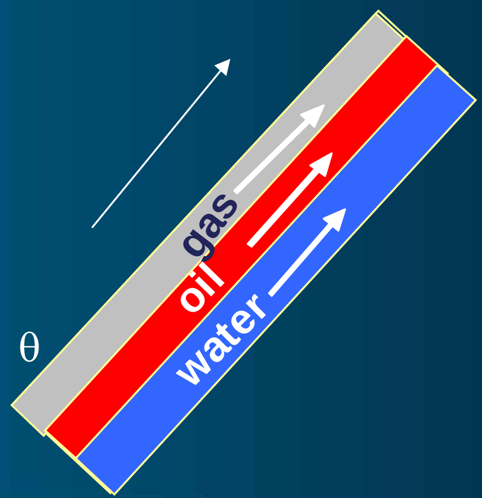
- Multi-segment well (MSWell) model describes the flow behavior inside each discretized segment of the wellbore (e.g. J.A. Holmes)

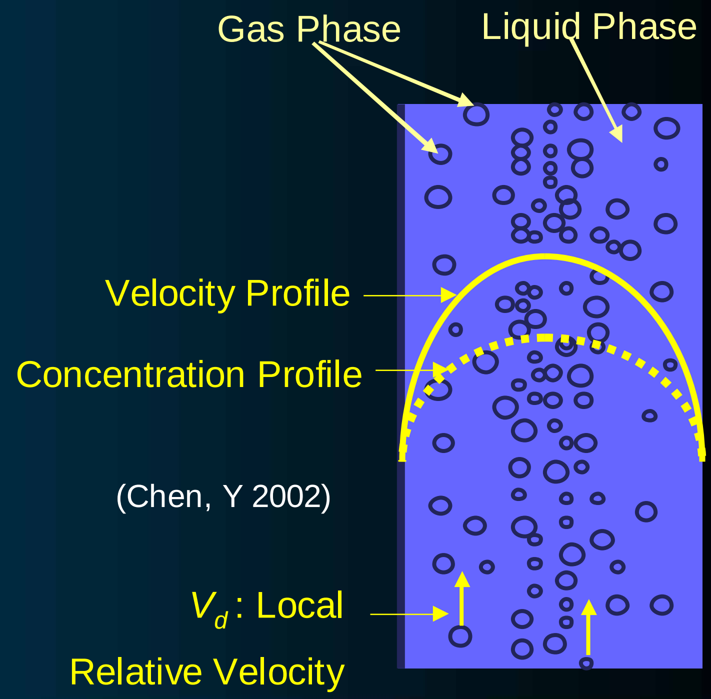


After J.A. Holmes

MSWell – More Physics

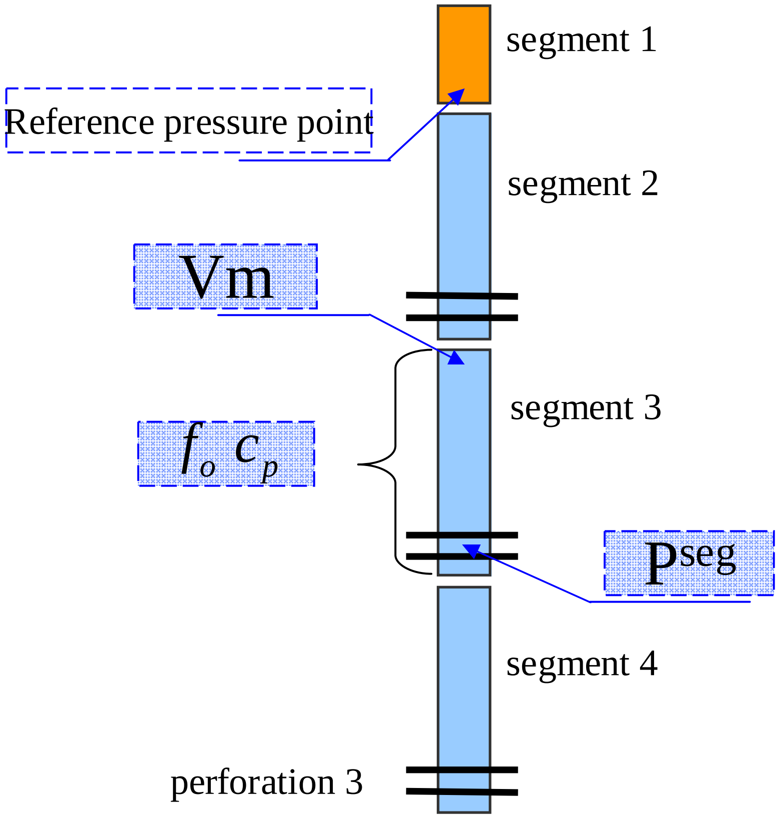
- Consider fluid gravity, friction with wellbore, and acceleration
- Consider the drift-flux between phases
- Assign variables of pressure, hold-ups, velocity along wellbore





(Chen, Y 2002)

MSWell Formulation



Variables :

P, segment pressure

V_m, mixture velocity

f_o, oil phase hold-up

f_g, gas phase hold-up

Equations:

$$R_{o,i} = (A_i^{n+1} - A_i^n)_o + (F_{i,out}^{seg} - F_{i,in}^{seg})_o - F_{in,o}^{res} = 0$$

$$R_{w,i} = (A_i^{n+1} - A_i^n)_w + (F_{i,out}^{seg} - F_{i,in}^{seg})_w - F_{in,w}^{res} = 0$$

$$R_{g,i} = (A_i^{n+1} - A_i^n)_g + (F_{i,out}^{seg} - F_{i,in}^{seg})_g - F_{in,g}^{res} = 0$$

$$\Delta P_{total} = \Delta P_h + \Delta P_f + \Delta P_a$$

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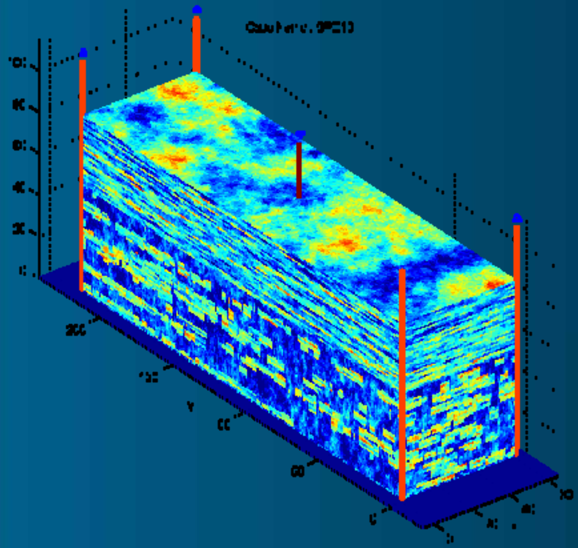
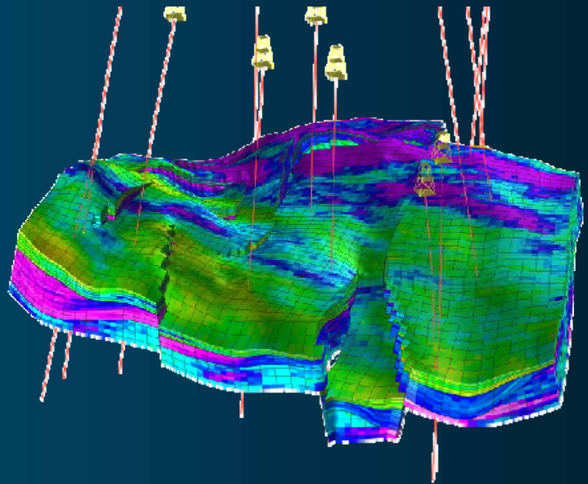
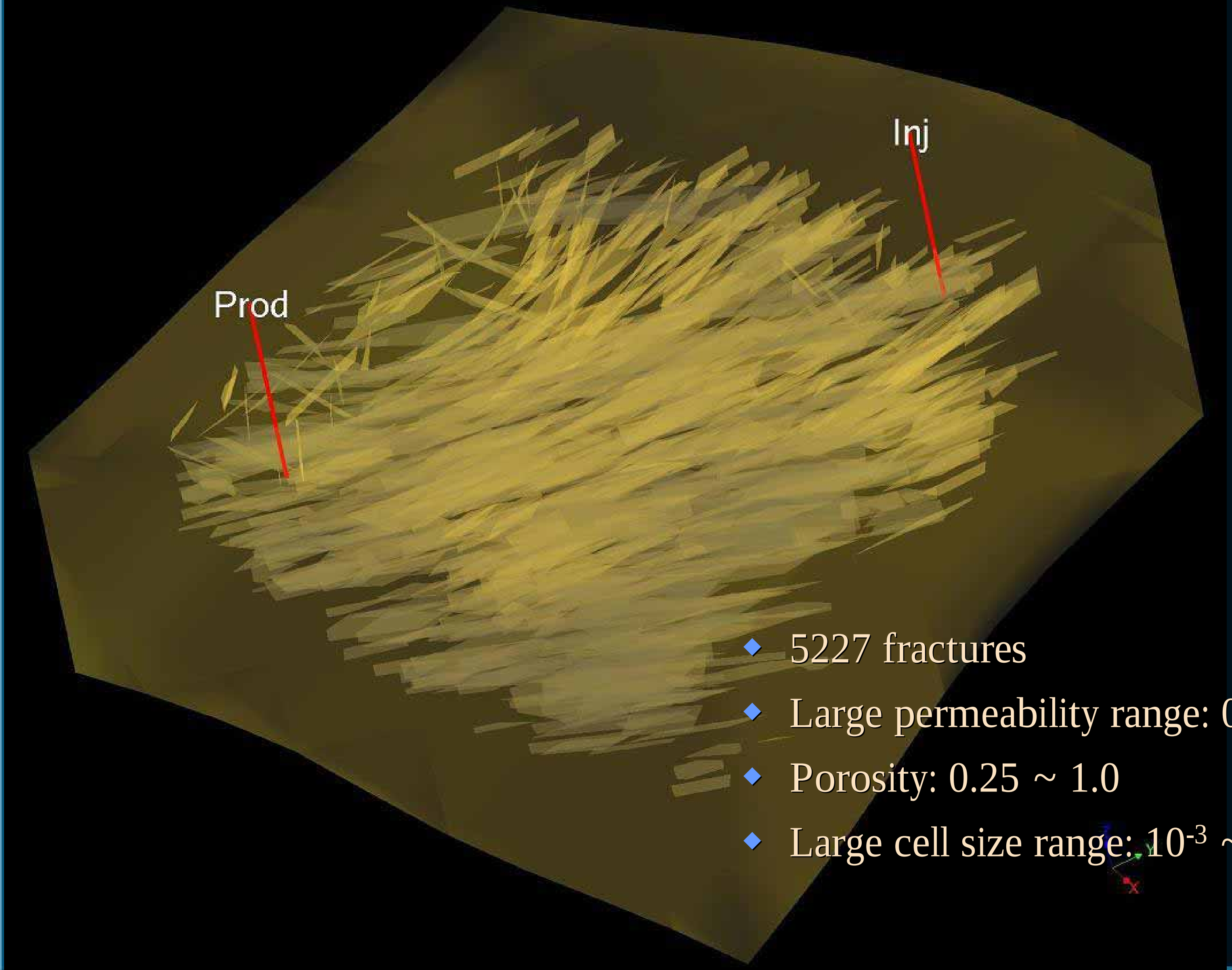
Grid Types

- GRPS supports various grid types
  - *Cartesian grid*
  - *Corner-point grid*
  - *Unstructured grid*



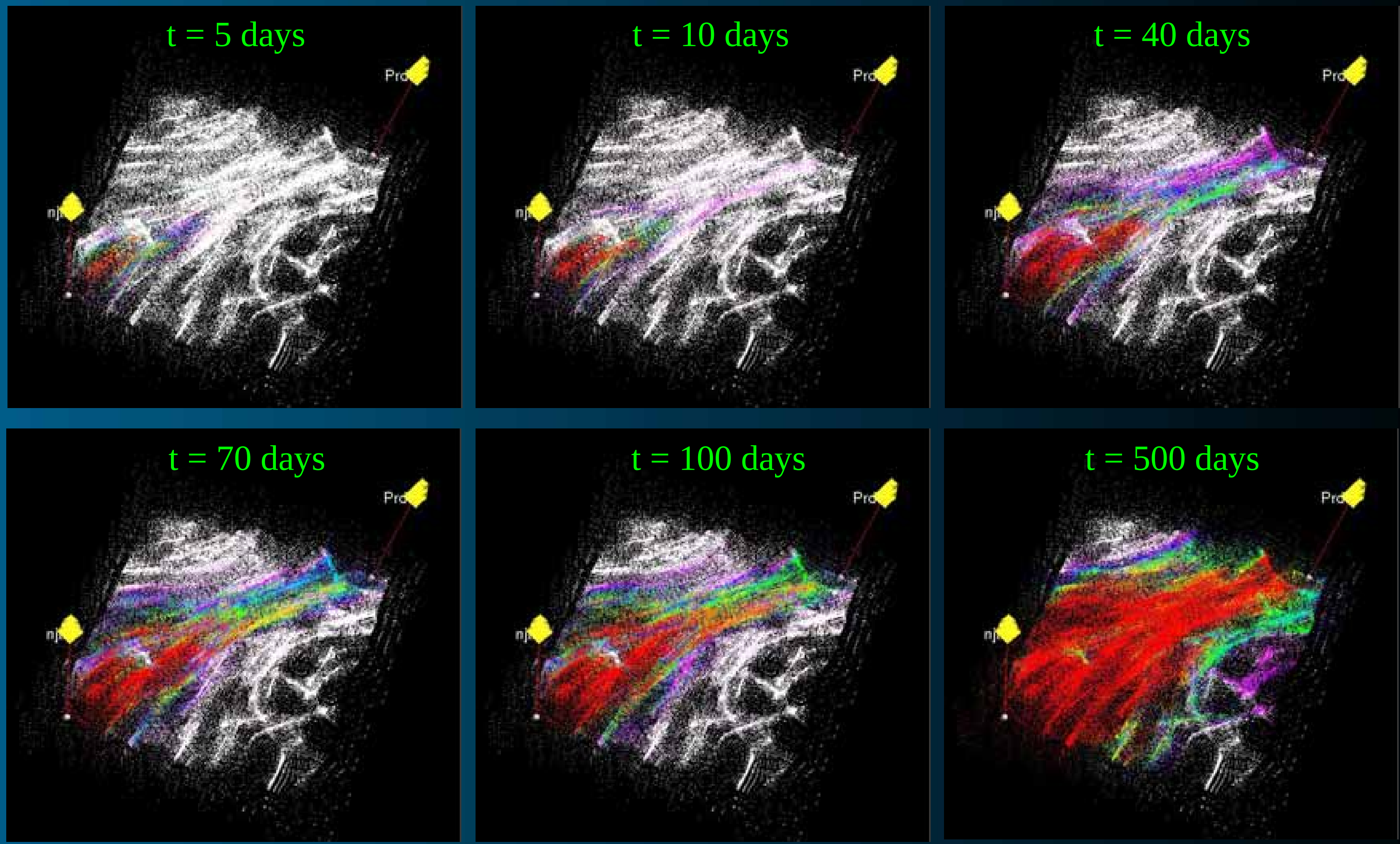


Unstructured Grid Example

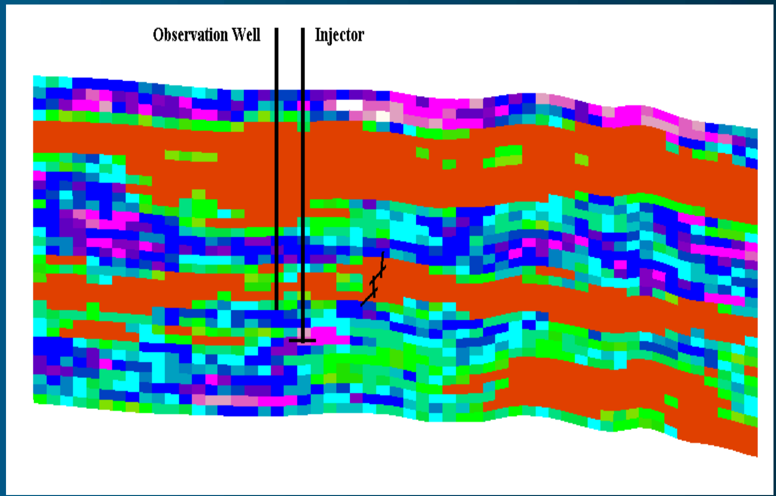


- 5227 fractures
- Large permeability range: 0.1 ~ 10^6 md
- Porosity: 0.25 ~ 1.0
- Large cell size range: 10^{-3} ~ 10^3 cft

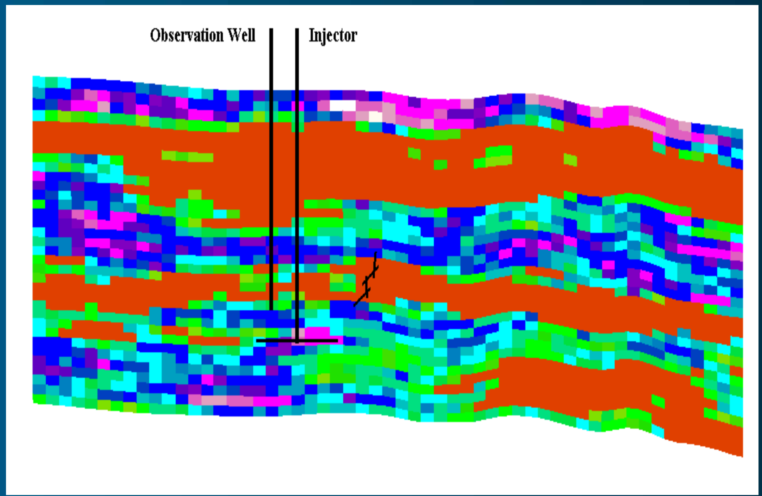
C1 Composition Maps



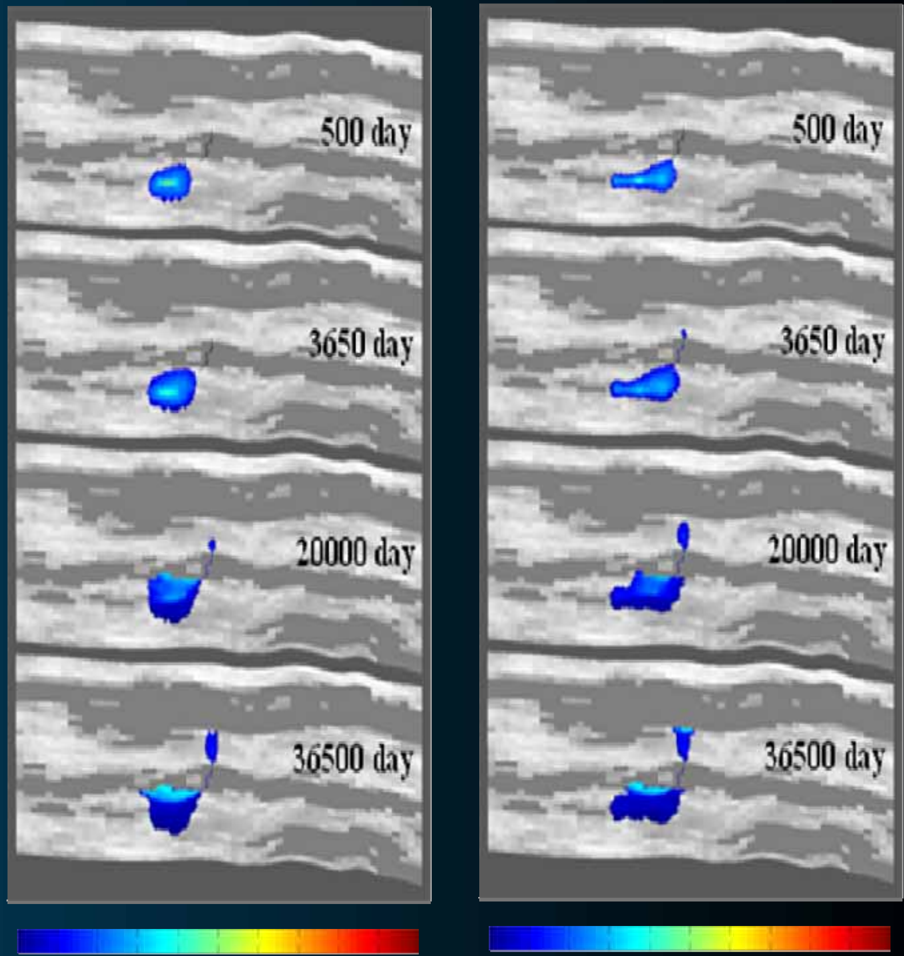
DFM Application in China's First CCS project



Hydraulic Fracture length: 100m



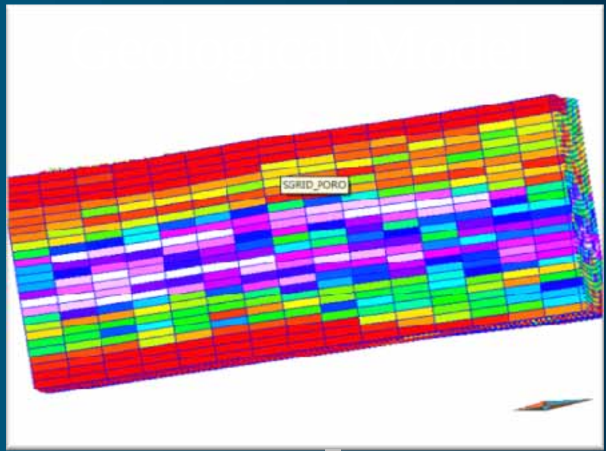
Hydraulic Fracture length: 300m

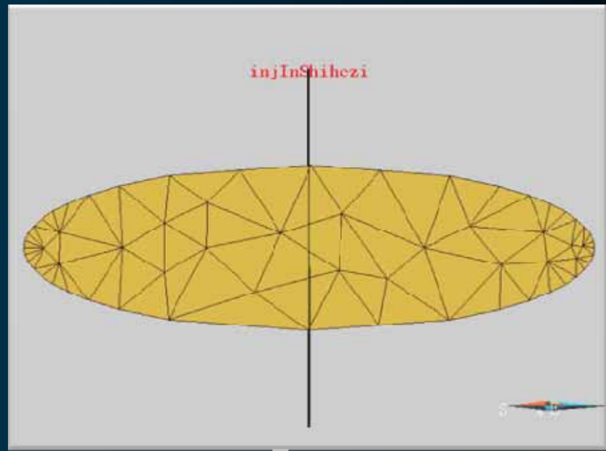


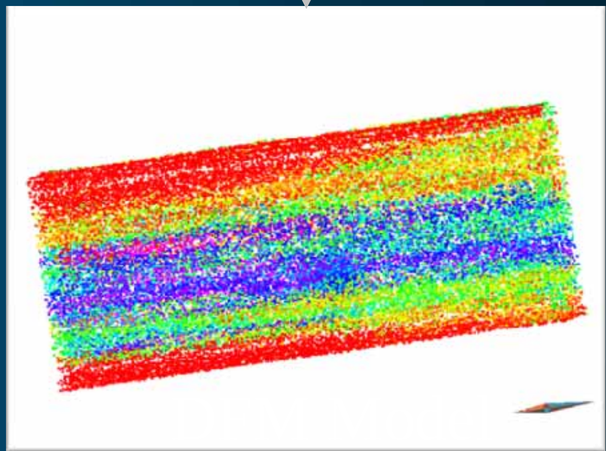
CO2 saturation profiles

3D Model with Hydraulic Fractures

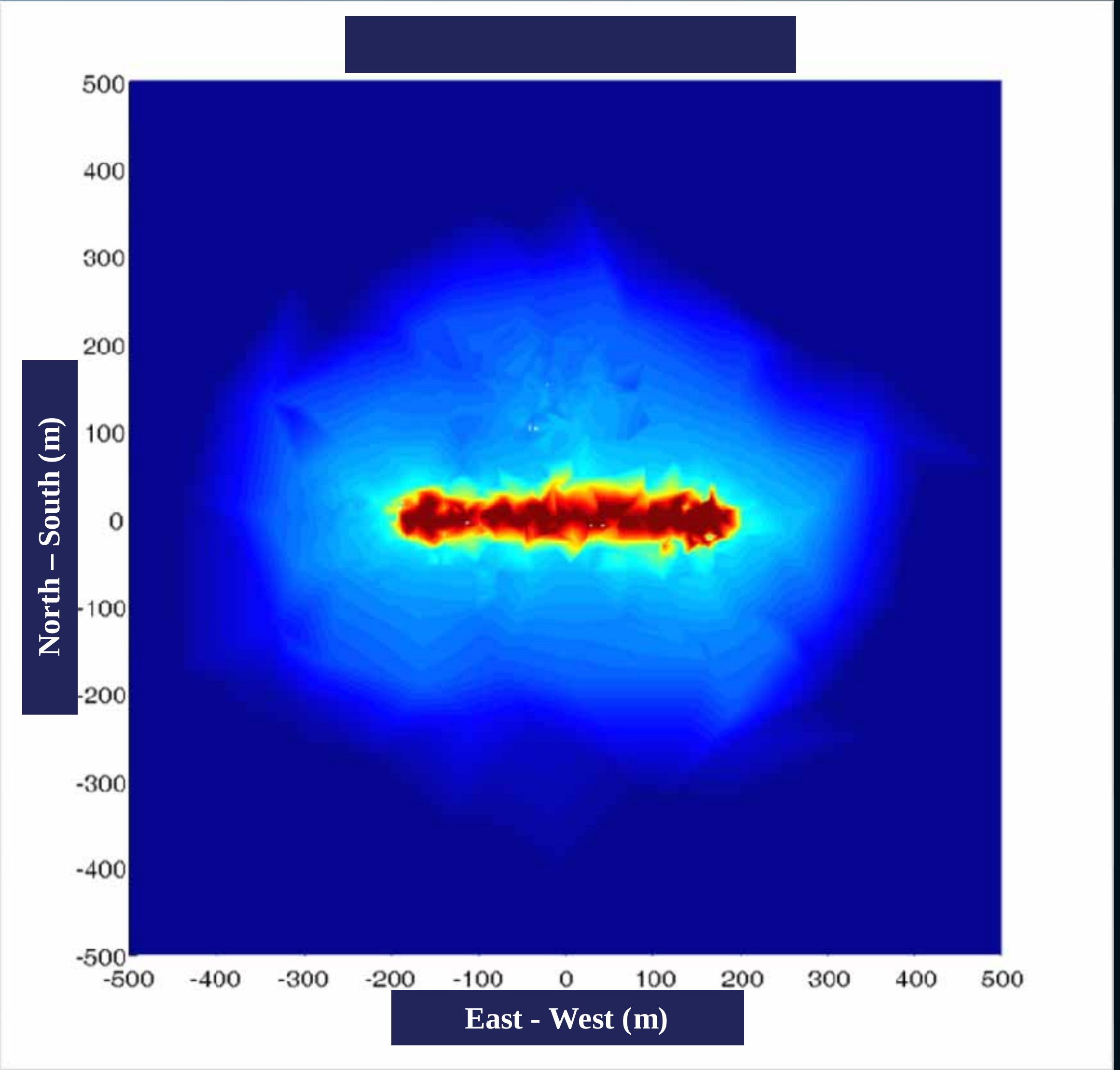
Hydraulic Fracture Model





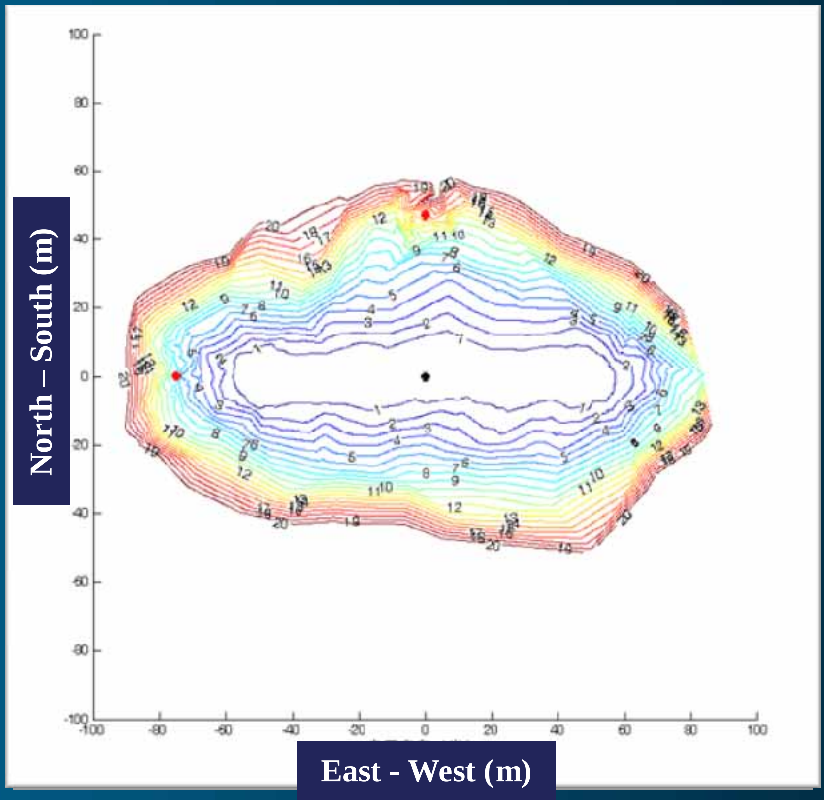


CO_2 Distribution After 5 Years' Injection

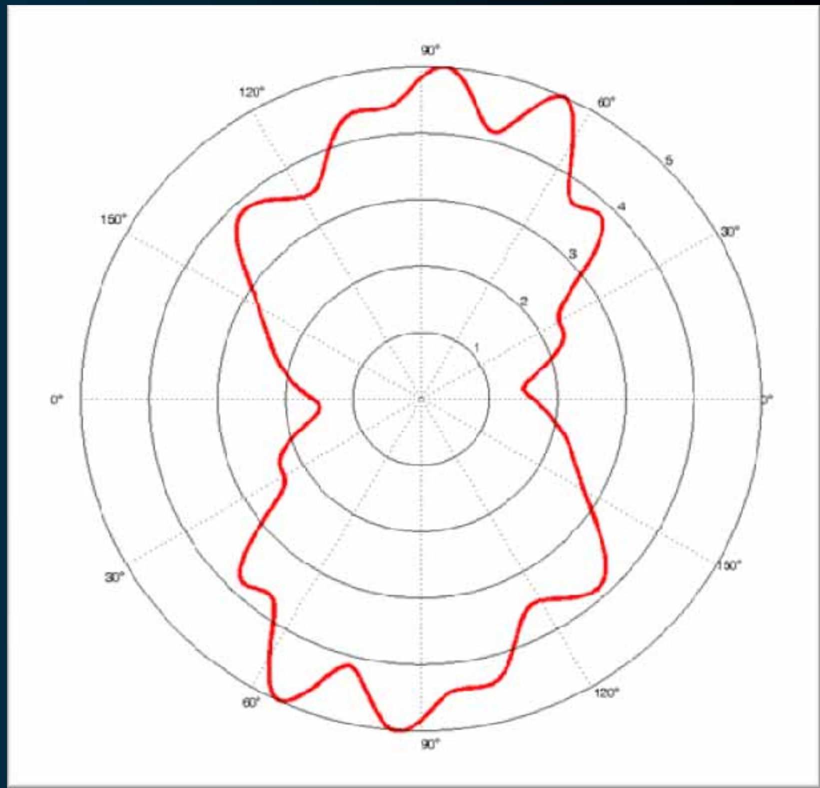


CO_2 Front Observation Time

Time contour map of CO_2 front observation time (month)



CO_2 front observation time at a specific position considering possible fracturing directions (year)



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Powerful Formulations and Solvers

- GPRS provides more flexible formulations
  - *Fully implicit (FIM) method,*
  - *Implicit pressure explicit saturation (IMPES) method*
  - *Implicit pressure and saturations and explicit component mole fractions (IMPSAT) method*
  - *Adaptive implicit (AIM) method, with any combination of above formulations*

Powerful Formulations and Solvers

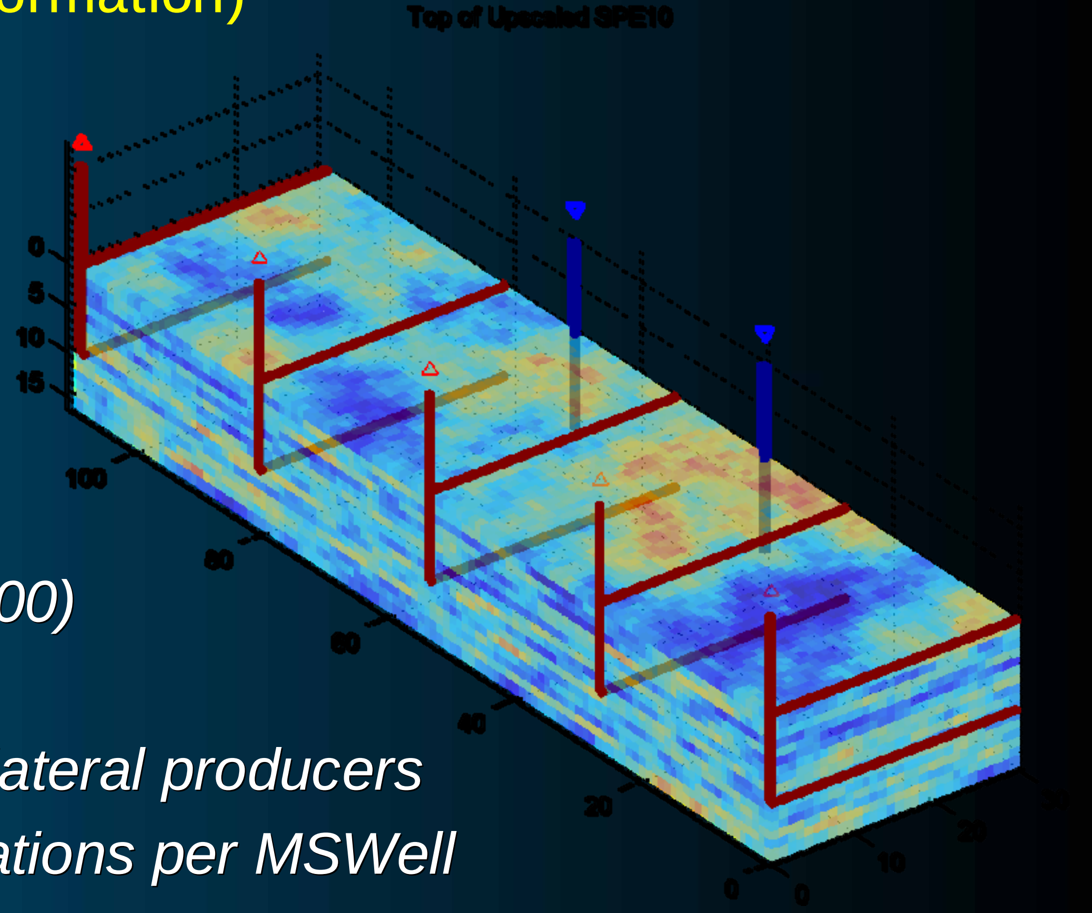
- GPRS provides a large set of powerful solvers and preconditioners
  - *LAPACK full/banded matrix direct solvers*
  - *BlitzPak iterative solver*
  - *Point-wise / block-wise GMRES iterative solver*
  - *BiCGstab iterative solver*
  - *Point-wise/ block-wise diagonal preconditioners*
  - *Incomplete LU decomposition preconditioners*
  - *Constraint pressure residual (CPR) preconditioners*
  - *AMG preconditioners*

Results

- CPR method is a two-stage preconditioner
  - *A highly accurate pressure solve as first stage*
  - *A loose ILU global solve as second stage*
- AIM formulation + block-wise GMRES solver + CPR preconditioner are the best combination for most of reservoir simulation cases
- Widely recognized by industry

Examples

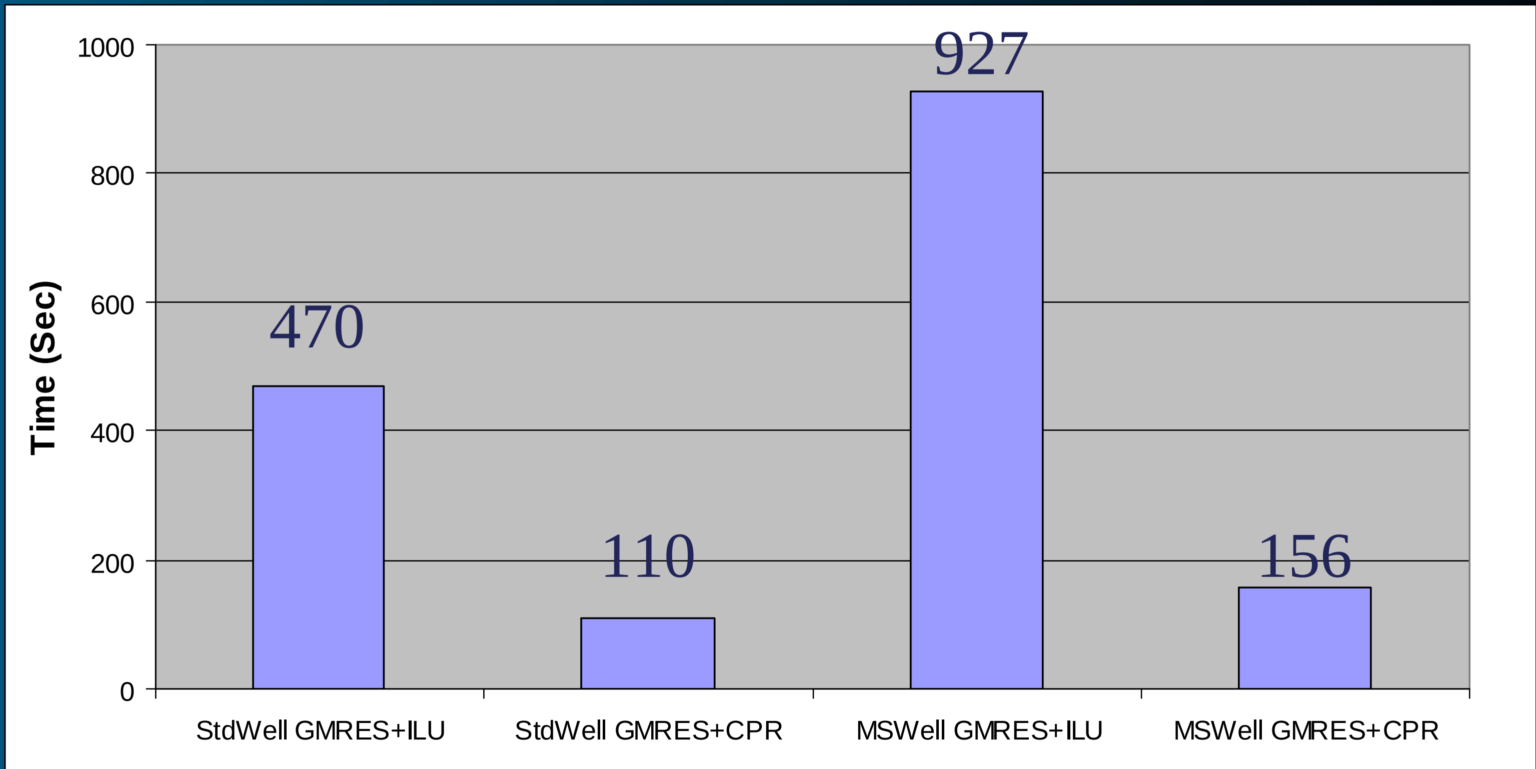
Upscaled SPE10 (top formation)



- 110x30x16 grid (52,800)
- Oil-water system
- 5 multi-segmented bilateral producers
- 9 segments, 6 perforations per MSWell
- 2 standard vertical injectors

Results

- Two scenarios: producers are modeled with MSWell or not
- CPR is 4~6 time faster than ILU



Others

- Programmed in Standard C++, ideally should work on any operating system
- Currently available in 32-bit/64-bit Windows，Linux and Unix systems

Key Reference

- H. Cao, *Development of Techniques for General Purpose Simulator*, Ph.D. thesis, Stanford University, 2002
- Y. Fan, *Chemical Reaction Modeling in a Subsurface Flow Simulator with Application to In-Situ Upgrading and CO2 Mineralization*, Ph.D. thesis, Stanford University, 2010
- L.J. Durlofsky, K. Aziz, *Advanced Techniques for Reservoir Simulation and Modeling of Non-conventional Wells*, Final Report to U.S. Department of Energy, contract no. DE-AC26-99BC15213 (2004) 213 pp. 2004

Thank You!