# Oil & Natural Gas Technology

**DOE Award No.: DE-FE0001243**

# Clean and Secure Energy from Domestic Oil Shale and Oil Sands Resources

# Quarterly Progress Report (January – March 2013)

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Prepared for:
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National Energy Technology Laboratory

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**Office of Fossil Energy**

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## Quarterly Progress Report

January 2013 to March 2013

Submitted by:
Institute for Clean and Secure Energy
155 S. 1452 E. Room 380
Salt Lake City, UT 84112

Principal Investigator: Philip J. Smith

Project Period: October 1, 2010 to September 30, 2013

Prepared for:
U.S. Department of Energy
National Energy Technology Laboratory

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## EXECUTIVE SUMMARY

The Clean and Secure Energy from Domestic Oil Shale and Oil Sands Resources program, part of the research agenda of the Institute for Clean and Secure Energy (ICSE) at the University of Utah, is focused on engineering, scientific, and legal research surrounding the development of these resources in Utah.

Efforts under Task 2, which focuses on technology transfer and outreach, included planning for two public events, the Energy Forum (held on April 2, 2013) and the University of Utah Unconventional Fuels Conference (held on May 7, 2013). Additionally, it is likely that the External Advisory Board (EAB) will be disbanded due to the impending end of federal funding for projects currently overseen by the EAB.

Task 3, "Clean oil shale and oil sands utilization with $CO_2$ management," has been focused on the development of a model for predicting oil and gas development in the Uinta Basin that can be used as an analog for predicting unconventional fuel development. The Subtask 3.1 team summarized available estimates of methane emissions associated with natural gas extraction, processing and distribution. Subtasks 3.3 and 3.4 worked jointly on a Matlab-based model that predicts oil and gas development in the Uinta Basin based on the projected profitability of a well drilled in a given year.

Task 4 projects, "Liquid fuel production by in-situ thermal processing of oil shale/sands," range from the molecular to the basin scale. At the molecular scale, Subtask 4.9 researchers continued the preparation a final publication on the details of kerogen and bitumen isolation and characterization from the three segments of the Skyline 16 core. At the core scale, Subtask 4.2 researchers hired a new student to compare oil shale pyrolysis data (oil, gas, and coke) from small core samples with modeling results from the commercial simulator STARS and from a simulator developed using the COMSOL platform. The Subtask 4.3 team hired a new student to perform kinetic modeling comparisons between Dr. Milind Deo's group at the University of Utah and Dr. Thomas Fletcher's group at BYU. Subtask 4.7 researchers brought the loading frame for the triaxial compression tests into service and performed the first test, a uniaxial test at 200°C with no confining pressure. At the production scale, the Subtask 4.1 team created generalized, rubblized oil shale bed geometries with three different positions of a heating pipe that are surrounded by solid oil shale. At the basin scale, the Subtask 4.8 team constructed and drafted detailed cross sections (both N-S and E-W) of the Green River Formation across the Uinta Basin.

The remaining subtask under Task 5, Subtask 5.3, involves an analysis of policy and economic issues associated with using simulation to assess environmental impacts. Efforts focused on augmenting the research presented in the January 2013 white paper describing existing judicial and agency approaches for estimating error in simulation methodologies used in context of environmental risk assessment and impacts analysis.

The Market Assessment, which comprises Subtasks 3.1, 6.1, and 6.3 is in the layout phase and will be released in electronic form in May 2013. A report summarizing the Canadian oil sands experience, a deliverable for Subtask 6.2, will also be released in May 2013.

Task 7 continues to follow a trajectory that is closely aligned with its industrial partner, American Shale Oil (AMSO). Subtask 7.1 researchers furthered work on segmented linearization and development of constitutive modeling surfaces on AMSO data, focusing specifically radial strain information. The Subtask 7.3 project team incorporated more complicated models for the oil shale properties – thermal conductivity, specific heat, and density – into their simulations of the AMSO heater test in order to more closely resemble the geologic oil shale layering present at the AMSO site near Rifle, CO.

## PROGRESS, RESULTS, AND DISCUSSION

### Task 1.0 - Project Management and Planning

During this quarter, there were no schedule/cost variances or other situations requiring updating/amending of the Project Management Plan (PMP). Internal budgeting reallocation occurred during this quarter as described under Task 7.0. Submission of a no cost time extension has been delayed until the first quarter of 2014.

### Task 2.0 -Technology Transfer and Outreach

Task 2.0 focuses on outreach and education efforts and the implementation of EAB recommendations. During the quarter, panelists were confirmed for the April 2, 2013 Energy Forum: Cody Stewart, Energy Advisor for the State of Utah; Matthew Rush, Regional Manager for Chevron Energy Solutions' Federal and Critical Utilities Business Unit; and Professor Andrew Jorgenson from the University of Utah. Discussion questions for the Energy Forum event were also finalized; a copy of those questions is included as Appendix A.

Planning also began for the 2013 University of Utah Unconventional Fuels Conference, which is scheduled to take place on May 7, 2013. The conference will have a slightly different format this year - it will focus on two themes with speakers and a moderated panel discussion surrounding each theme. The two themes are: (1) role of simulation in unconventional fuels development and (2) constraints on unconventional fuels development. Confirmed speakers include: Pierre Allix, Total; Lauren Birgenheier, University of Utah; Hai Huang, Idaho National Laboratory; Seth Lyman, Utah State University; Brian McPherson, University of Utah; Juan Palma, Bureau of Land Management; Neil Pogorelsky, HDR Decision Economics; Philip Smith,University of Utah; Jennifer Spinti, University of Utah; Anne Mariah Tapp, Grand Canyon Trust; Robert Wood, Renewable Tech Ventures.

After extended discussion this quarter, the decision has been made not to schedule another EAB meeting as the Board is most likely to be disbanded due to the impending end of federal funding for projects currently overseen by the EAB. It is anticipated that President David Pershing, acting in his capacity as the Director of the EAB, will make a final determination and communicate the same to EAB members next quarter.

### Task 3.0 - Clean Oil Shale and Oil Sands Utilization with $CO_2$ Management

<u>Subtask 3.1 – Lifecycle Greenhouse Gas Analysis of Conventional Oil and Gas Development in the Uinta Basin (PI: Kerry Kelly, David Pershing)</u>

During this quarter, the project team continued to focus on two objectives: (1) the calculating greenhouse gas (GHG) emissions for the market assessment (Subtask 6.3) joint publication deliverable and (2) gathering data related to fugitive emissions from oil and gas extraction. Team member also continue to monitor several potentially useful sources for validation data of GHG emissions. The milestone to complete modules in $CLEAR_{uff}$ for life-cycle $CO_2$ emissions from conventional oil & gas development in the Uinta Basin**

*(Phase I) Status of joint publication deliverable*

There is one deliverable that has not been completed for Phase I of this project. The deliverable is a paper on potential GHG emissions from Uinta Basin oil shale and oil sands development scenarios. During this quarter, the project team received updated results from Subtask 6.3 and performed supplemental analyses to generate carbon footprints for each of the scenarios as shown in Figure 1. The updated assessment results yielded reductions in GHG emissions from both the in situ and ex situ oil shale scenarios. Team members also calculated energy return on investment (EROI) values for gasoline generated from each scenario as well as GHG emissions per barrel of syncrude; see Table 1. These results are being incorporated into the assessment.

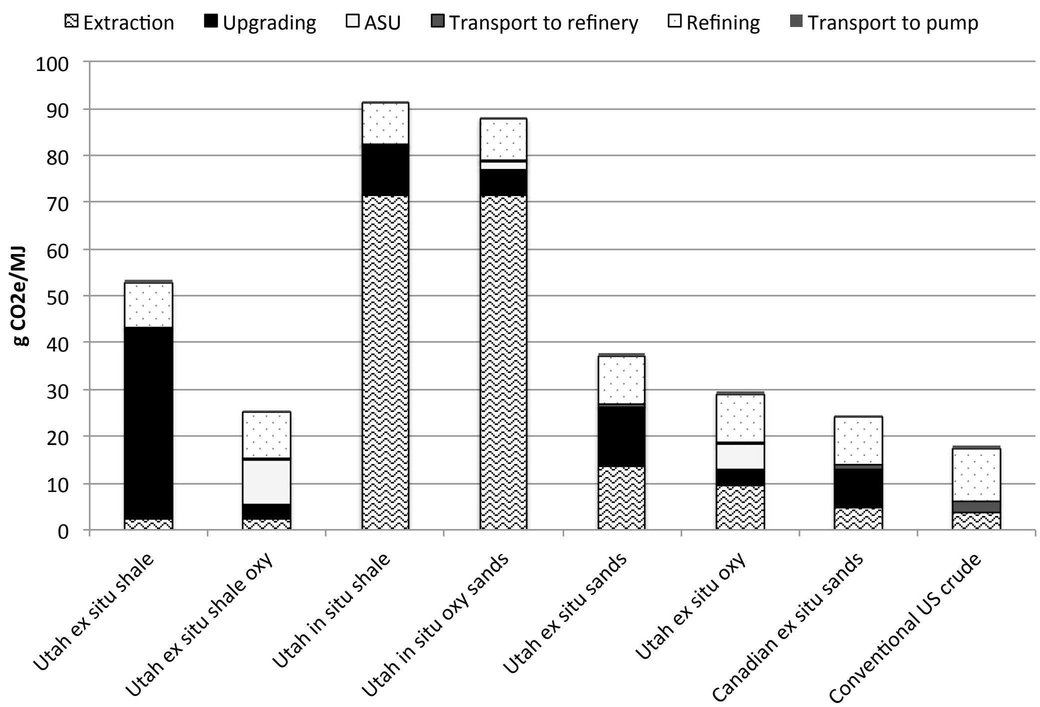


**Figure 1.** Preliminary comparison of well-to-pump GHG emissions for production of gasoline from in and ex situ production of Utah oil shale, ex situ Utah and Canadian oil sands (ANL 2012), and conventional crude oil (EPA 2009).

**Table 1**. EROI for gasoline and GHG emissions for syncrude for each assessment scenario.

| | Ex situ shale[1] | Ex situ shale oxy[1] | In situ shale[2] | In situ shale oxy[2] | Ex situ sands | Ex situ sands oxy | In situ sands | In situ sands oxy |
|---|---|---|---|---|---|---|---|---|
| lb $CO_{2e}$/ bbl SCO | 544 - 833 | 191 - 290 | 1040 | 996 | 333 | 230 | 391 | 305 |
| EROI | 2.4 - 3.9 | 2.4 - 3.8 | 0.6 – 0.8 | 0.6 – 0.8 | 5.1 | 5.0 | 2.4 | 2.3 |

[1] The more favorable values are for the Tosco II process and the less favorable values are for the Paraho Direct process.
[2] The more favorable values are for the accelerated heating rate assumption.

In preparation for the revised journal article, the project team decided to perform a sensitivity analysis which will include:

- Ex situ shale – two types of processes (complete), shale richness (in progress) and electricity source (in progress).
- In situ shale – one accelerated heating rate and one standard heating rate process (done), shale permeability (in progress), and electricity source (in progress).

- Ex situ sand – electricity source and bitumen saturation (both are in progress).

*(Phase II) Emissions associated with oil and gas extraction and processing*

Estimates of methane ($CH_4$) emissions associated with natural gas extraction, processing and distribution vary from 1 – 9% of production, with lower estimates for conventional gas and higher estimates for natural gas production associated with hydraulic fracturing. The greatest source of uncertainty in these estimates is fugitive emissions associated with liquid unloading (conventional gas) and flowback during hydraulic fracturing (unconventional gas) when the well begins producing liquids and other debris and before the well is placed online. Alvarez et al. (2012) report that in order for natural gas-generated electricity to have a net benefit in terms of global warming, $CH_4$ emissions must be less than 3.2% of production.

Tables 2 and 3 summarize activity-based estimates of the percentage of $CH_4$ and $CO_2$ emitted during natural gas extraction, processing, and distribution (Burnham et al., 2011). Estimates vary widely depending whether the source is conventional or unconventional, and whether they use bottom-up activity and emission factors or a top-down approach based on ambient concentrations of trace gases. The highest estimates, ranging from 4 – 9% of total production, are reported in top-down studies (Tollefson, 2013; Petron et al., 2012). Team members continue to evaluate data sources and collect data on specific process steps including distribution and storage, extraction, and processing.

**Table 2.** Percentage of methane emitted during natural gas production from conventional and unconventional sources.

| Activity | Conventional Average (Range) | Unconventional average (Range) | Reference |
|---|---|---|---|
| Well completion and workovers (venting) | 0.003 (0.002-0.005) | 0.46(0.006-2.75) | 1, 2 |
| Liquid unloadings (venting) | 1.20 (0.27-2.98) | NONE | |
| Well equipment (leakage and venting) | 0.73 (0.35-1.20) | 0.73 (0.35-1.20) | 2,3 |
| Processing (leakage and venting) | 0.15 (0.06-0.23) | 0.15 (0.06-0.23) | 2 |
| Transmission and distribution (leakage and venting) | 0.67 (0.29-1.05) | 0.67 (0.29-1.05) | 2 |
| Total | 2.75 (0.97-5.47) | 2.01 (0.71-5.23) | |

1 US EPA (2010); 2 US EPA (2011); 3 US GAO (2010)

**Table 3**. Methane emitted during natural gas production from conventional and unconventional sources. Units are in $CO_2$ g/MJ of natural gas (Burnham et al., 2011).

| Activity | Conventional Average (Range) | Unconventional average (Range) | Reference |
|---|---|---|---|
| Flaring & venting | 0.469 (0.389-0.549) | 0.469 (0.389-0.549) | 1,2 |
| Processing (CO2 venting) | 0.832 (0.583-1.081) | 0.832 (0.583-1.081) | 2 |
| Total | 1.301 (0.972-1.629) | 1.301 (0.972-1.629) | |

1 US GAO (2010); 2 US EPA (2010)

## Subtask 3.2 - Flameless Oxy-gas Process Heaters for Efficient $CO_2$ Capture (PI: Jennifer Spinti)

Work on the final deliverable for this task, a report detailing results of a validation/uncertainty quantification analysis, was on hold this quarter pending availability of the PI. The PI has now completed the market assessment, so this project will be completed in the next quarter.

## Subtask 3.3 - Development of Oil and Gas Production Modules for $CLEAR_{uff}$ (PI: Terry Ring)

As noted previously, the work on this subtask is being performed jointly with that of Subtask 3.4 in order to utilize the single graduate student left on the project.

At the end of the previous quarter, the project team had created a model for predicting oil and gas development in the Uinta Basin as a function of the current oil price and previous drilling activity. During the quarter, the Matlab model was reworked to instead determine the number of wells drilled based on the projected profitability of a well drilled in a given year.

Oil and gas price forecasts for the Rocky Mountain region reported in the Energy Information Administration's (EIA) 1999 – 2012 Annual Energy Outlook (2012a, 2012b), shown below in Figures 2 and 3, are used to estimate the net present value (NPV) of an oil or gas well using Equation (1):

$$NPV = \sum_{n=1}^{n} \left( Q_n P_n - C_{well_n} - O_{well_n} \right) \left( \frac{1}{(1-i)^{n-1}} \right) \tag{1}$$

where $Q_n$ is the amount of oil or gas produced in year *n*, $P_n$ is the price of oil or gas in year *n* according to the most recent EIA forecast available at the time the NPV is predicted, $C_{well_n}$ is the capital cost of the well in question (if it is drilled in year *n*), $O_{well_n}$ is the operating cost of the well in year *n*, and $i$ is the desired rate of return. $Q_n$ was determined by integrating decline curves fitted to oil production data collected from Utah's Division of Oil, Gas and Mining (DOGM) Data Research Center (DOGM, 2013) and shown in Figure 4. $C_{well_n}$ was also determined from DOGM data (DOGM, 2013) while $O_{well_n}$ was determined from EIA data (EIA, 2010). While the framework for the model has been designed to handle both oil and gas wells, researchers have thus far focused data collection efforts on oil wells.

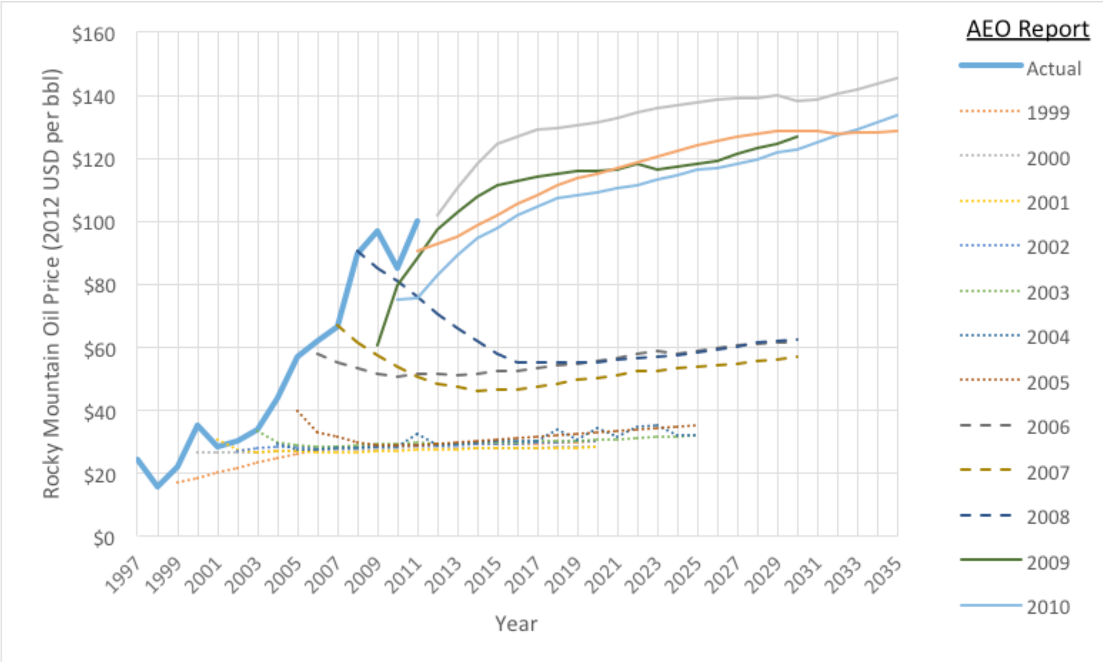


**Figure 2**. Energy Information Administration (EIA) price forecasts for Rocky Mountain crude oil (EIA, 2012a). All values are reported in real (i.e. inflation adjusted) dollars, and have been normalized to 2012 USD using the consumer price index (CPI).

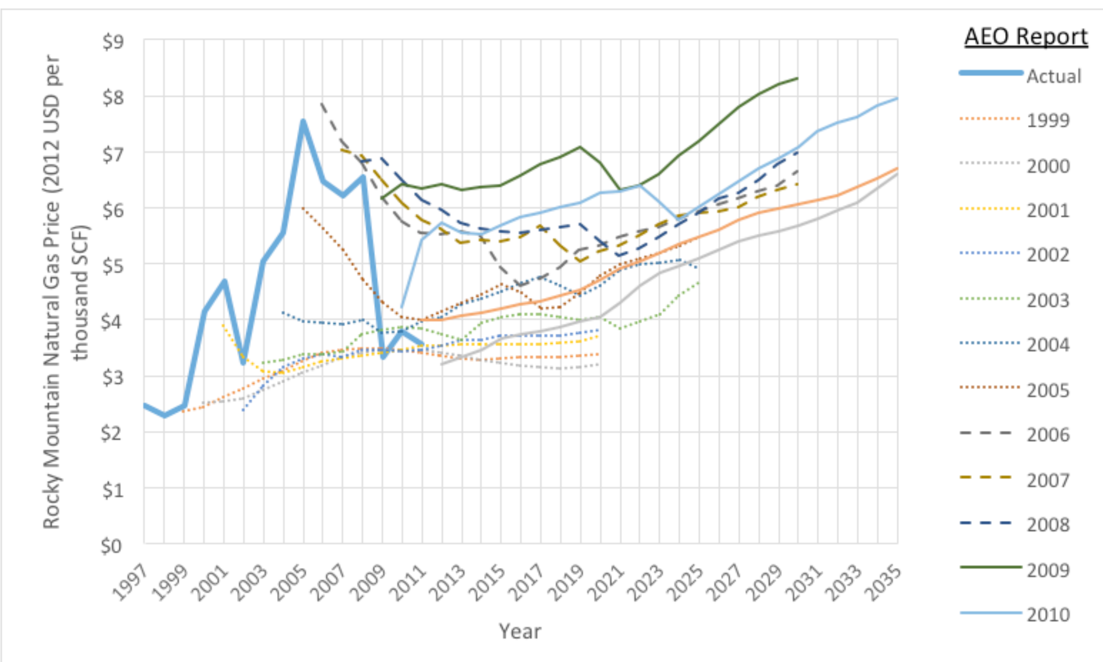


**Figure 3**. EIA price forecasts for Rocky Mountain natural gas (EIA, 2012b). All values are reported in real dollars and have been normalized to 2012 USD using the CPI.

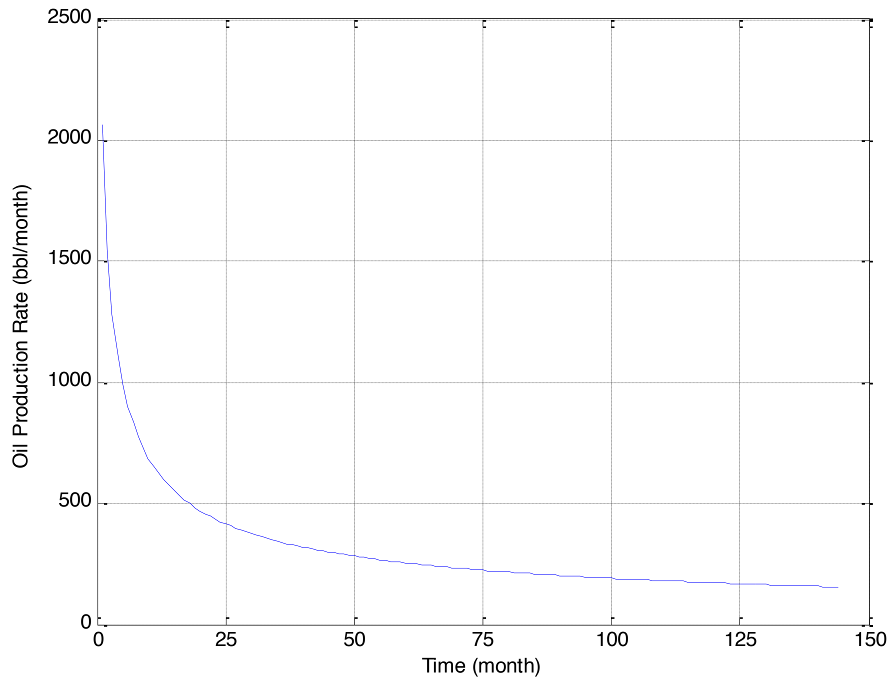


**Figure 4**. Oil production rate decline curve based on data from DOGM (2013).

If an oil well is predicted to be profitable in a given time step, the model assumes that the number of wells drilled is equal to the lowest value determined by a set of constraints. Currently, the only constraint in the model is a capital balance for drilling new wells, However, in the future, the team plans on including other constraints such as permitting, availability of drilling rigs, and availability of leases. Having predicted the number of wells drilled in the current time step, the model then calculates the total amount of oil produced and determines the revenue from oil sales based on the actual price history reported in by the EIA (2012a). Finally, the model returns plots of the amount of oil produced and wells drilled as a function of time as shown in Figures 5 and 6. These results can then be compared to actual oil and drilling data in DOGM's database. The team's next step will be to use that data to perform model validation and uncertainty quantification.

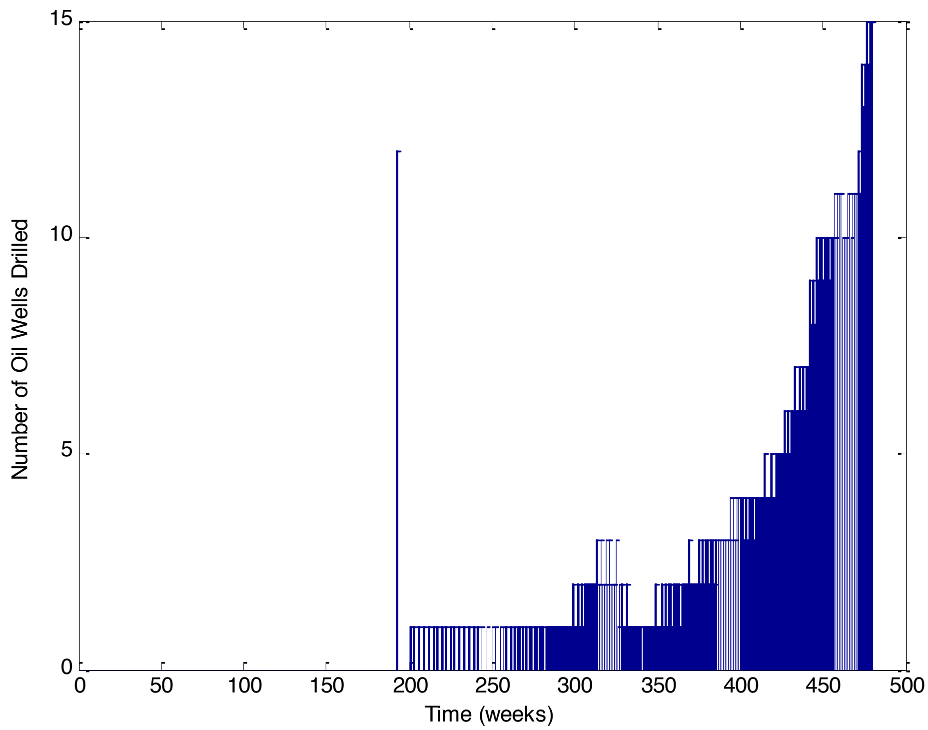


**Figure 5**. Predicted number of wells drilled from 2002-2011 assuming r = 20% and initial capital = $10 million USD.

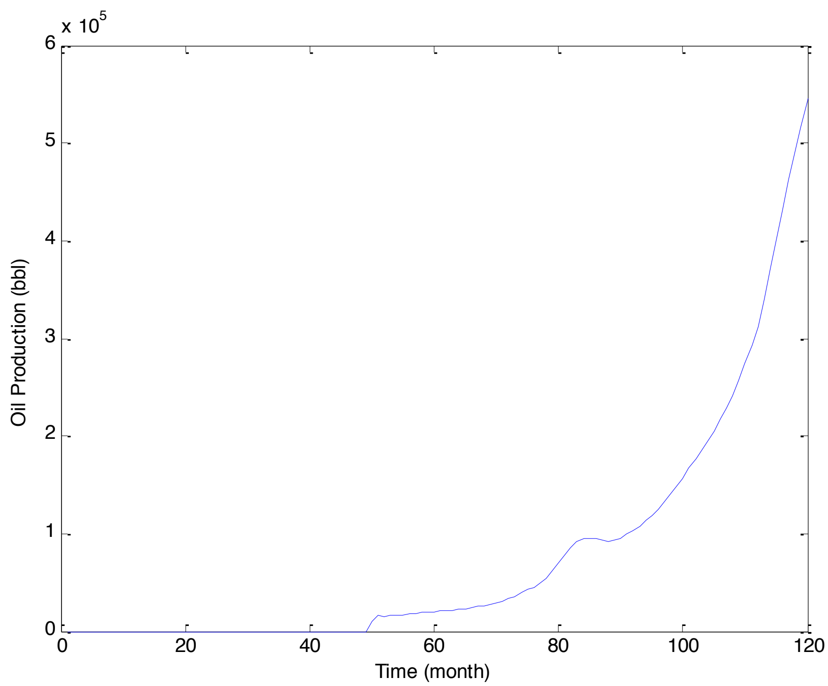


**Figure 6**. Predicted oil production per month from wells drilled in Figure 5.

Subtask 3.4 - V/UQ Analysis of Basin Scale $CLEAR_{uff}$ Assessment Tool (PI: Jennifer Spinti)

Please see the summary for Subtask 3.3 as the work for these two subtasks has been combined due to staffing issues. The milestone to demonstrate full functionality of the Validation and Uncertainty Quantification (VUQ) methodology for conventional oil & gas development in the Uinta Basin has been delayed pending model development that occurred during this quarter. Data from DOGM will be used in the next quarter to complete this milestone.

## Task 4.0 - Liquid Fuel Production by In-situ Thermal Processing of Oil Shale/Sands

Subtask 4.1 (Phase II) - Development of CFD-based Simulation Tools for In-situ Thermal Processing of Oil Shale/Sands (PI: Philip Smith)

In this quarter, researchers continued to develop their high performance computing (HPC) simulation tool used for simulations of in-situ thermal processing of oil shale. They have developed new testing geometries for their operator splitting algorithm that is used for simulations of both rubblized as well as solid pieces of oil shale. With these testing geometries, they are evaluating the effect of gaps and orientation of a heating element on the thermal distribution inside the oil shale bed as a function of time.

For the testing geometries, they have created generalized, rubblized oil shale bed geometries that are surrounded by a solid oil shale with three different positions of a heating pipe. They have also redesigned their previous generalized, rubblized oil shale geometry to address issues of inconsistent gap width. This new version of the generalized, rubblized geometry can be seen in Figure 7. The new simulation geometries with three different pipe positions can be seen in Figures 8 through 11.

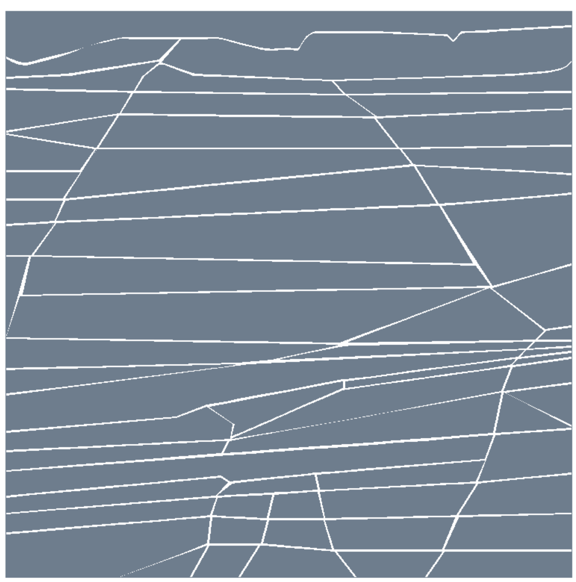

**Figure 7.** General rubblized oil shale bed.

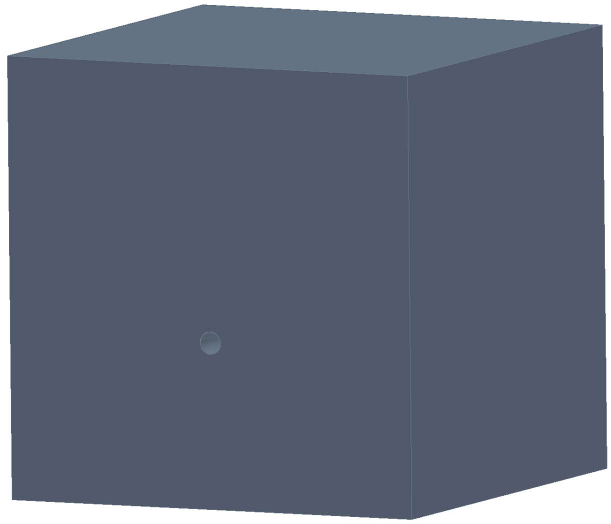

**Figure 8.** Three quarter view of the outside surface of the redesigned, rubblized oil shale bed geometry with a horizontal heating pipe element.

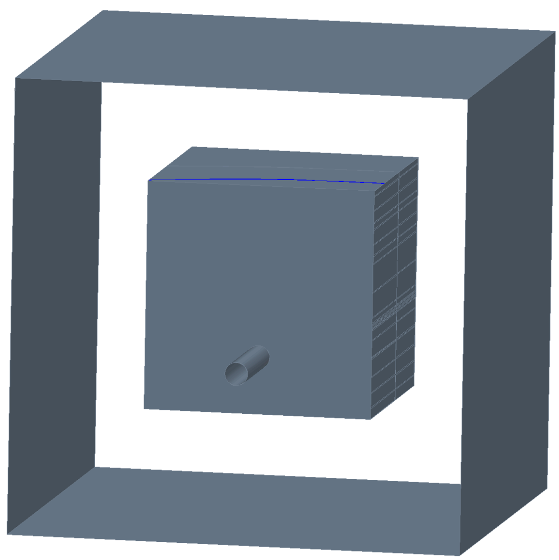

**Figure 9.** Front view showing the interior of the redesigned, rubblized oil shale bed geometry with a horizontal heating element.

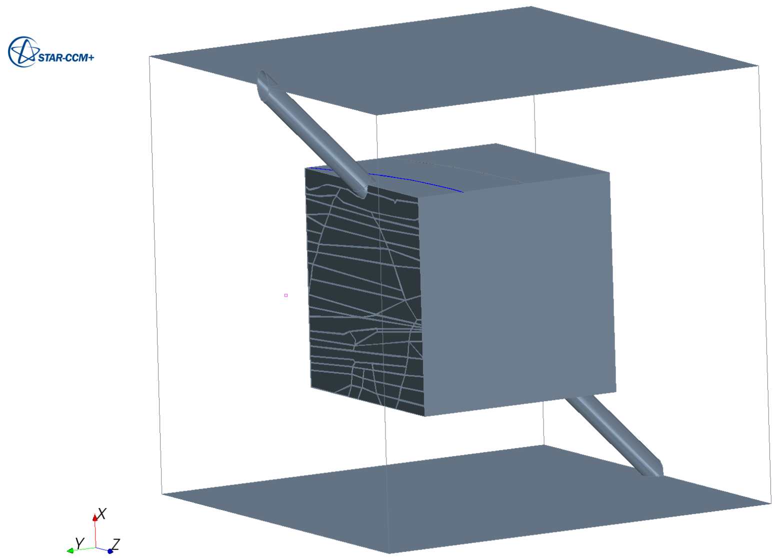


**Figure 10.** Three quarter view of the simulation geometry with heating element at 45 degree angle with respect to the interior rubblized geometry.

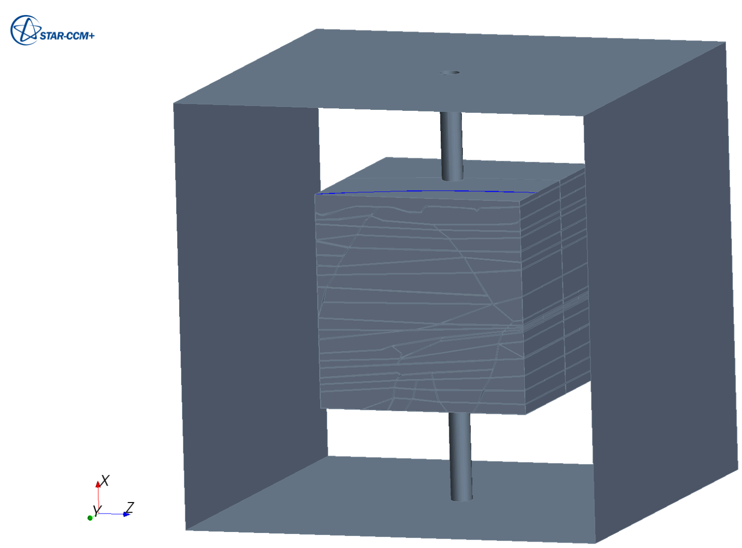


**Figure 11.** Three quarter view of the new geometry showing a vertical heating element with respect to the interior rubblized geometry.

Figures 8 and 9 show the overall view and interior view, respectively, of the simulation geometry domain with a horizontal heating element. The rubblized oil shale bed is a 1m x 1m x 1m block in the domain interior. This block of rubblized oil shale is surrounded by 0.5 m of solid oil shale on each side to form a 2m x 2m x 2m simulation domain. This geometry allows researchers to accurately represent the boundary conditions that are present in the actual in-situ conditions, where both solid and rubblized pieces of shale are present on close proximity. Figures 10 and

11 show the same oil shale geometry, except the heating element is positioned at a 45 degree angle and vertically, respectively.

Researchers have experienced difficulties while meshing the presented geometries as gaps are very small, ranging from 1 - 5 mm. Therefore, they have not yet performed any computations on the simulation geometries presented here.

Subtask 4.2 - Reservoir Simulation of Reactive Transport Processes (PI: Milind Deo)

In preparation for writing the final report, thermal simulations using STARS have been performed by the Subtask 4.2 team. The Comsol modules, developed to incorporate heat and mass transfer with kinetics, have been tested with cores of different sizes and at various conditions. Using results from STARS and from the Comsol modules, the team will be able to compare experimental core pyrolysis results with models. Additionally, a new student, Hongtao Jia, started working on the Advanced Reactive Transport (ARTS) model.

There is one remaining deliverable for this task, a topical report on validation results for core-scale oil shale pyrolysis. The task of validation was started during the Ph.D. dissertations of Pankaj Tiwari and Jacob Bauman. Both of these students graduated in 2012. Completion of this validation has been challenging due to loss of continuity and inability to acsertain data consistency.

The data available for validation are temperature profiles and amounts of products generated during pyrolysis (oil, gas and coke). Two approaches were used to model the data.: (1) use of the commercial simulator STARS and (2) use of a simulator developed using the COMSOL platform. Unfortunately, neither of the approaches has been developed to a stage where the validation is possible. The STARS model did not converge for the small geometries of the core with reaction kinetics incorporated in the model. The COMSOL model converged and produced temperature profiles qualitatively similar to those observed in the experiment.

The validation activity continues. A new student, Drew Gillespie, has been recruited to compare pyrolysis data and corresponding models, The project team expects to finish the activity by the third quarter of 2013. The topical report will be submitted along with the quarterly report for the quarter ending September 30, 2013.

Subtask 4.3 – Multiscale Thermal Processes (PI: Milind Deo, Eric Eddings)

Due to a number of factors this quarter, progress was limited. A student, Mark Jensen, was finally hired to help with the modeling comparisons between Dr. Milind Deo's group at the University of Utah and Dr. Thomas Fletcher's group at BYU. Dr. Fletcher met with Dr. Deo, and plans were made on how to share data and models. Some of the models used in Dr. Deo's group were purchased, which may complicate model sharing. Mark will also help modify the Chemical Percolation for Coal Devolatilization (CPD) model to accommodate the large alkanes that must be treated as tar.

There are two deliverables left for this project:

1. Topical report describing CPD/shale & oil generation models including summary of their applications/limitations (due March 2013)
2. Paper on combined kerogen/bitumen structures & CPD reaction model submitted to a journal such as Energy & Fuel (joint deliverable with Subtask 4.9) (due April 2013)

Team members request that the due date for both deliverables be moved to August 2013 to accommodate these staffing changes. They fell confident that they have a plan to ensure that everything is accomplished by this date.

The project team did encounter a proble with the FTIR system not communicating with the computer during this quarter. They are working on this problem.

Subtask 4.4 - Effect of Oil Shale Processing on Water Compositions (PI: Milind Deo)

This project has been completed.

Subtask 4.5 - In Situ Pore Physics (PI: Jan Miller, Chen-Luh Lin)

This project has been completed.

Subtask 4.6 - Atomistic Modeling of Oil Shale Kerogens and Oil Sand Asphaltenes (PI: Julio Facelli)

This project has been completed.

Subtask 4.7 - Geomechanical Reservoir State (PI: John McLennan)

No status update was received from the PI for the two milestones that are due: (1) complete experimental matrix, due December 2012 and (2) complete thermophysical and geomechanical property data analysis and validation, due March 2013.

The loading frame for the triaxial compression tests was brought into service during this quarter. Figures 12-14 are photographs of the commissioning of the triaxial compression apparatus. All equipment was moved to the facility with the large pressure heater. The new clamshell heater with ports for radial displacement measurements has been implemented. All electrical feedthroughs have been installed to take signals out of the pressurized vessel. Control and data acquisition, including safety fail safe operations, have been programed using OPTO 22 software.

Triaxial testing will be undertaken through the end of May 2013. Sunnyside and White River oil shale samples will be tested. The first test in the large vessel was uniaxial at 200°C with no confining pressure. This was a shakedown test to identify testing complications. Some power aberrations in the building were identified and are being resolved. Upcoming tests will add confining pressure and higher temperatures.

**Figure 12.** (left) Body of the pressure vessel. The flanges seen have been fitted with "feedthroughs" to extract cables for thermocouples, linear variable differential transducers (LVDTs), and a load cell. (right) Lowering the upper closure onto the vessel.

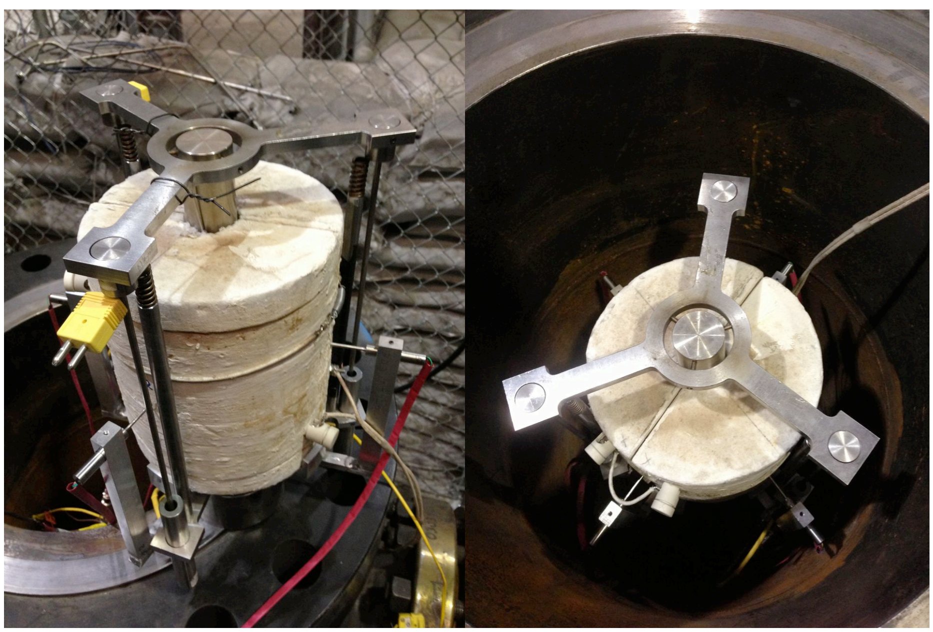

**Figure 13.** (left) Heating shroud surrounding the sample. Two of the four radial LVDTs are visible. The three arms with springs protect the fixture on sample failure and have LVDTs for measuring vertical displacement. Not visible is the hydraulic actuator and load cell for applying vertical stress. (right) Testing fixture in the pressure vessel.

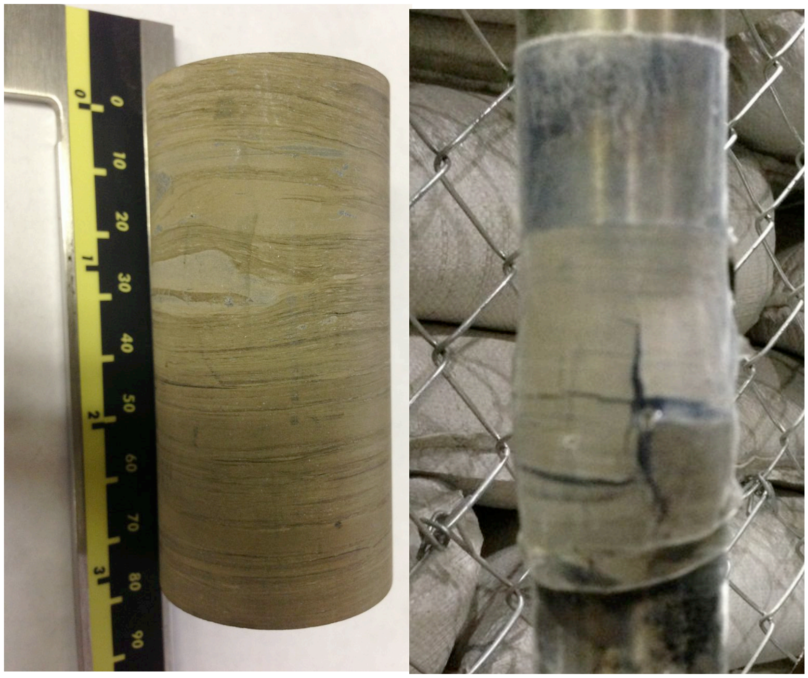

**Figure 14.** (left) White River sample prior to testing. (right) Same sample after testing. Because the temperature was only 200°C, it was possible to encapsulate the sample in shrink fit Teflon (visible). At higher temperatures, copper jacketing is needed.

<u>Subtask 4.8 - Developing a Predictive Geologic Model of the Green River Oil Shale, Uinta Basin (PI: Lauren Birgenheier)</u>

Detailed cross sections of the Green River Formation across the Uinta Basin were constructed and drafted in this quarter. These include the N-S cross section which was originally included in the deliverables. Additionally, the E-W cross section was extended further to the west. Furthermore, XRF data were drafted to show a significant change in the Ca/Mg ratio, or a dolomitic to calcitic transition across the Mahogany Zone.

<u>Subtask 4.9 - Experimental Characterization of Oil Shales and Kerogens (PI: Julio Facelli)</u>

The project team is still completing work on the final deliverable, a paper on combined kerogen/bitumen structures and the CPD reaction model. The paper has been tentatively titled “Characterization of Shale, Kerogen and Bitumen from a Green River Oil Shale Core.”

**Task 5.0 - Environmental, Legal, Economic and Policy Framework**

<u>Subtask 5.1 – Models for Addressing Cross-Jurisdictional Resource Management (PI: Robert Keiter, John Ruple)</u>

This project has been completed.

<u>Subtask 5.2 - Conjunctive Management of Surface and Groundwater Resources (PI: Robert Keiter, John Ruple)</u>

This project has been completed.

Subtask 5.3 - Policy and Economic Issues Associated with Using Simulation to Assess Environmental Impacts (PI: Robert Keiter, Kirsten Uchitel)

Efforts this quarter focused on augmenting the research presented in last quarter's white paper describing existing judicial and agency approaches for estimating error in simulation methodologies used in context of environmental risk assessment and impacts analysis. Additional work began on organization and preliminary drafting of the topical report.

**6.0 – Economic and Policy Assessment of Domestic Unconventional Fuels Industry**

Subtask 6.1 Engineering Process Models for Economic Impact Analysis (PI: Terry Ring)

The milestone to upload all models used and data collected to the ICSE website will be completed next quarter. All process models were finalized in this quarter and the results included in the market assessment report.

Subtask 6.2 - Policy analysis of the Canadian oil sands experience (PI: Kirsten Uchitel)

The draft of the topical report is being cite-checked for the final time to ensure that repeated past delays have not rendered any cited sources inaccurate or obsolete. Final submission to DOE is anticipated in the next quarter.

Subtask 6.3 – Market Assessment Report (PI: Jennifer Spinti)

Work this quarter focused on preparing the report for public release in May 2013. It will be available for download and will also be provided on a flash drive to those who request it.

**7.0 – Strategic Alliance Reserve**

Subtask 7.1 – Geomechanical Model (PI: John McLennan)

No report was received from the PI with respect to the milestone that was due for this project. The milestone, due in December 2012, was to infer permeability-porosity-temperature relationships and to develop model that can be used by other subtasks

Researchers continued with work on segmented linearization and development of constitutive modeling surfaces on AMSO data. Their focus this quarter was on the radial strain information as the axial data had previously been characterized. The research program will be accelerated by involving another post-doctoral researcher to perform commercial geomechanics software work.

Subtask 7.2 – Kinetic Compositional Models and Thermal Reservoir Simulators (PI: Milind Deo)

Project has been terminated.

Subtask 7.3 – Rubblized Bed High Performance Computing Simulations (PI: Philip Smith)

In this quarter, the project team continued to run a series of simulations for its VUQ studies of the January 2012 heater experiment test conducted by AMSO near Rifle, CO. Team members have also continued their close collaboration with AMSO scientists, who provide constant feedback on the simulations. They presented their AMSO simulation work at the latest STAR Global Conference held in Orlando in March 2013. This presentation is included as Appendix B.

The project team has further expanded and modified its VUQ matrix based on feedback from AMSO. Researchers have increased the range of thermal conductivities for the study and continue to run simulations to better understand the effect of changing properties on the thermal history of the shale formation and on the thermal response recorded by the tomography wells.

Team members have also spent significant effort to include modified properties for the specific heat. AMSO worked with a third party consulting company to obtain specific heat variations not as a function of temperature but of oil shale grade. Team members have implemented these results in their simulations. However, they are still working to address the variability in density as a function of grade. Currently, they are limited to densities for the three specific oil shale grades used in their previous simulations. They hope to address this question in the upcoming quarter.

Lastly, the project team has been provided with a new and updated set of coordinates for all of the wells in the AMSO pilot test, which includes the lower lateral well (which houses the heater), upper lateral well, production well, and all six tomography wells. Therefore, in the next quarter, researchers will need to redesign the entire base case simulation of the AMSO heater test.

## CONCLUSIONS

Several subtasks made significant progress this quarter while others were hampered by the need to hire additional personnel. Subtasks 3.3 and 3.4 are sharing a graduate student. This student made significant progress in implementing a model for well drilling activity in the Uinta Basin that is based on the project profitability of a well drilled in a given year. In Subtasks 4.1 and 7.2, the simulation tools available in STAR-CCM+ were used to model in situ oil shale production processes that involved heating both rubblized and solid oil shale. The market assessment report, which comprises Subtasks 3.1, 6.1, and 6.3, was finalized and will be published electronically in May 2013. Several of the research projects will be highlighted in presentations at the 2013 University of Utah Unconventional Fuels Conference to be held on May 7, 2013 in Salt Lake City, Utah.

# COST PLAN/STATUS

| Baseline Reporting Quarter - PHASE I | Yr. 1 | | | | | | | | Yr. 2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | | Q2 | | Q3 | | Q4 | | Q5 | | Q6 | |
| | 7/1/09 - 12/31/09 | | 1/1/10 - 3/31/10 | | 4/1/10 - 6/30/10 | | 7/1/10 - 9/30/10 | | 10/1/10 - 12/31/10 | | 1/1/11 - 3/31/11 | |
| | Q1 | **Total** | Q2 | **Total** | Q3 | **Total** | Q4 | **Total** | Q5 | **Total** | Q6 | **Total** |
| **Baseline Cost Plan** | | | | | | | | | | | | |
| Federal Share | 484,728 | **484,728** | 484,728 | **969,456** | 484,728 | **1,454,184** | 484,726 | **1,938,910** | 323,403 | **2,262,313** | 798,328 | **3,060,641** |
| Non-Federal Share | 121,252 | **121,252** | 121,252 | **242,504** | 121,252 | **363,756** | 121,254 | **485,010** | 80,835 | **565,845** | 199,564 | **765,409** |
| Total Planned | 605,980 | **605,980** | 605,980 | **1,211,960** | 605,980 | **1,817,940** | 605,980 | **2,423,920** | 404,238 | **2,828,158** | 997,892 | **3,826,050** |
| **Actual Incurred Cost** | | | | | | | | | | | | |
| Federal Share | 420,153 | **420,153** | 331,481 | **751,634** | 547,545 | **1,299,179** | 428,937 | **1,728,116** | 593,386 | **2,321,502** | 307,768 | **2,629,270** |
| Non-Federal Share | 29,456 | **29,456** | 131,875 | **161,332** | 151,972 | **313,304** | 100,629 | **413,933** | 191,601 | **605,534** | 45,101 | **650,635** |
| Total Incurred Costs | 449,609 | **449,609** | 463,356 | **912,966** | 699,517 | **1,612,483** | 529,566 | **2,142,049** | 784,987 | **2,927,036** | 352,869 | **3,279,905** |
| **Variance** | | | | | | | | | | | | |
| Federal Share | 64,575 | **64,575** | 153,247 | **217,822** | -62,817 | **155,005** | 55,789 | **210,794** | -269,983 | **-59,189** | 490,560 | **431,371** |
| Non-Federal Share | 91,796 | **91,796** | -10,623 | **81,172** | -30,720 | **50,452** | 20,625 | **71,077** | -110,766 | **-39,689** | 154,463 | **114,774** |
| Total Variance | 156,371 | **156,371** | 142,624 | **298,994** | -93,537 | **205,457** | 76,414 | **281,871** | -380,749 | **-98,878** | 645,023 | **546,145** |

*Note: Q5 and Q6 reflect both CDP 2009 and CDP 2010 SF424a projections as the award periods overlap.*

| Baseline Reporting Quarter - PHASE II | Yr. 2 | | | | Yr. 3 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q7 | | Q8 | | Q9 | | Q10 | | Q11 | | Q12 | |
| | 04/01/11 - 06/30/11 | | 07/01/11 - 09/30/11 | | 10/01/11 - 12/31/11 | | 01/1/12 - 03/31/12 | | 04/01/12 - 06/30/12 | | 07/01/12 - 09/30/12 | |
| | Q7 | **Total** | Q8 | **Total** | Q9 | **Total** | Q10 | **Total** | Q11 | **Total** | Q12 | **Total** |
| **Baseline Cost Plan** | | | | | | | | | | | | |
| Federal Share | 712,385 | **3,773,026** | 627,423 | **4,400,449** | 147,451 | **4,547,900** | 147,451 | **4,695,351** | 147,451 | **4,842,802** | 245,447 | **5,088,249** |
| Non-Federal Share | 178,100 | **943,509** | 156,854 | **1,100,363** | 36,863 | **1,137,226** | 36,863 | **1,174,089** | 36,863 | **1,210,952** | 58,906 | **1,269,858** |
| Total Planned | 890,485 | **4,716,535** | 784,277 | **5,500,812** | 184,314 | **5,685,126** | 184,314 | **5,869,440** | 184,314 | **6,053,754** | 304,353 | **6,358,107** |
| **Actual Incurred Cost** | | | | | | | | | | | | |
| Federal Share | 449,459 | **3,078,729** | 314,813 | **3,393,542** | 271,897 | **3,665,439** | 267,784 | **3,933,223** | 191,438 | **4,124,661** | 232,367 | **4,357,028** |
| Non-Federal Share | 48,902 | **699,537** | 48,835 | **748,372** | 105,695 | **854,067** | 40,652 | **894,719** | 33,092 | **927,811** | 44,294 | **972,105** |
| Total Incurred Costs | 498,361 | **3,778,266** | 363,648 | **4,141,914** | 377,592 | **4,519,506** | 308,436 | **4,827,942** | 224,530 | **5,052,472** | 276,661 | **5,329,133** |
| **Variance** | | | | | | | | | | | | |
| Federal Share | 262,926 | **694,297** | 312,610 | **1,006,907** | -124,446 | **882,461** | -120,333 | **762,128** | -43,987 | **718,141** | 13,080 | **731,221** |
| Non-Federal Share | 129,198 | **243,972** | 108,019 | **351,991** | -68,832 | **283,159** | -3,789 | **279,370** | 3,771 | **283,141** | 14,612 | **297,753** |
| Total Variance | 392,124 | **938,269** | 420,629 | **1,358,898** | -193,278 | **1,165,620** | -124,122 | **1,041,498** | -40,216 | **1,001,282** | 27,692 | **1,028,974** |

| Baseline Reporting Quarter - PHASE II | Yr. 4 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q13 | | Q14 | | Q15 | | Q16 | | | | | |
| | 10/01/12 - 12/31/12 | | 01/01/13 - 03/31/13 | | 04/01/13 - 06/30/13 | | 07/01/13 - 09/30/13 | | | | | |
| | Q13 | **Total** | Q14 | **Total** | Q15 | **Total** | Q16 | **Total** | | **Total** | | **Total** |
| **Baseline Cost Plan** | | | | | | | | | | | | |
| Federal Share | 146,824 | **5,235,073** | 146,824 | **5,381,897** | 146,824 | **5,528,721** | 133,794 | **5,662,515** | | | | |
| Non-Federal Share | 36,705 | **1,306,563** | 36,705 | **1,343,268** | 36,705 | **1,379,973** | 35,906 | **1,415,879** | | | | |
| Total Planned | 183,529 | **6,541,636** | 183,529 | **6,725,165** | 183,529 | **6,908,694** | 169,700 | **7,078,394** | | | | |
| **Actual Incurred Cost** | | | | | | | | | | | | |
| Federal Share | 128,349 | **4,485,377** | 180,613 | **4,665,990** | | **4,665,990** | | **4,665,990** | | | | |
| Non-Federal Share | 79,871 | **1,051,976** | 62,354 | **1,114,330** | | **1,114,330** | | **1,114,330** | | | | |
| Total Incurred Costs | 208,220 | **5,537,353** | 242,967 | **5,780,320** | | **5,780,320** | | **5,780,320** | | | | |
| **Variance** | | | | | | | | | | | | |
| Federal Share | 18,475 | **749,696** | -33,789 | **715,907** | | **862,731** | | **996,525** | | | | |
| Non-Federal Share | -43,166 | **254,587** | -25,649 | **228,938** | | **265,643** | | **301,549** | | | | |
| Total Variance | -24,691 | **1,004,283** | -59,438 | **944,845** | | **1,128,374** | | **1,298,074** | | | | |

**MILESTONE STATUS**

| ID | Title/Description | Planned Completion Date | Actual Completion Date | Milestone Status |
|---|---|---|---|---|
| 1.0 | Project Management | | | |
| 2.0 | Technology Transfer and Outreach | | | |
| | Advisory board meeting | Jun-13 | N/A | Decision has been made to disband EAB |
| | Hold final project review meeting in format determined jointly by DOE/NETL and ICSE | Jun-13 | | |
| 3.0 | Clean Oil Shale & Oil Sands Utilization with CO2 Management | | | |
| 3.1 | Lifecycle greenhouse gas analysis of conventional oil & gas development in the Uinta Basin | | | |
| | Complete modules in $CLEAR_{uff}$ for life-cycle CO2 emissions from conventional oil & gas development in the Uinta Basin | Mar-13 | | Milestone delayed pending further development of oil/ gas production model |
| 3.2 | Flameless oxy-gas process heaters for efficient CO2 capture | | | |
| | Preliminary report detailing results of skeletal validation/uncertainty quantification analysis of oxy-gas combustion system | Sep-12 | Oct-12 | Report attached as appendix to Oct. 2012 quarterly report |
| 3.3 | Development of oil & gas production modules for $CLEAR_{uff}$ | | | |
| | Develop preliminary modules in $CLEAR_{uff}$ for conventional oil & gas development & produced water management in Uinta Basin | Oct-11 | Dec-11 | Discussed in Jan. 2012 quarterly report |
| 3.4 | V/UQ analysis of basin scale $CLEAR_{uff}$ assessment tool | | | |
| | Develop a first generation methodology for doing V/UQ analysis | Oct-11 | Nov-11 | Discussed in Jan. 2012 quarterly report |
| | Demonstrate full functionality (integration of all modules) of V/UQ methodology for conventional oil & gas development in Uinta Basin | Mar-13 | | Will complete in 2nd quarter of 2013 |
| 4.0 | Liquid Fuel Production by In-Situ Thermal Processing of Oil Shale/Sands | | | |
| 4.1 | Development of CFD-based simulation tool for in-situ thermal processing of oil shale/ sands | | | |

| ID | Title/Description | Planned Completion Date | Actual Completion Date | Milestone Status |
|---|---|---|---|---|
| | Expand modeling to include reaction chemistry & study product yield as a function of operating conditions | Feb-12 | Mar-12 | Discussed in April 2012 quarterly report |
| 4.2 | Reservoir simulation of reactive transport processes | | | |
| | Incorporate kinetic & composition models into both commercial & new reactive transport models | Dec-11 | Dec-11 | Discussed in Jan. & July 2012 quarterly reports |
| | Complete examination of pore-level change models & their impact on production processes in both commercial & new reactive transport models | Jun-12 | Jun-12 | Discussed in July 2012 quarterly report |
| 4.3 | Multiscale thermal processes | | | |
| | Complete thermogravimetric analyses experiments of oil shale utilizing fresh "standard" core | Sep-11 | Sep-11 | Discussed in Oct. 2011 quarterly report |
| | Complete core sample pyrolysis at various pressures & analyze product bulk properties & composition | Dec-11 | Sep-12 | Discussed in Oct. 2012 quarterly report |
| | Collection & chemical analysis of condensable pyrolysis products from demineralized kerogen | May-12 | Sep-12 | Discussed in Oct. 2012 quarterly report |
| | Complete model to account for heat & mass transfer effects in predicting product yields & compositions | Jun-12 | Jun-12 | Discussed in July 2012 quarterly report |
| 4.5 | In situ pore physics | | | |
| | Complete pore network structures & permeability calculations of Skyline 16 core (directional/anisotropic, mineral zones) for various loading conditions, pyrolysis temperatures, & heating rates | Mar-12 | Mar-12 | Discussed in April 2012 quarterly report for 1 loading condition; samples never received from Subtask 4.7, so PI dropped loading condition as variable |
| 4.6 | Atomistic modeling of oil shale kerogens & oil sand asphaltenes | | | |
| | Complete web-based repository of 3D models of Uinta Basin kerogens, asphaltenes, & complete systems (organic & inorganic materials) | Dec-11 | Dec-11 | Discussed in Jan. 2012 quarterly report |
| 4.7 | Geomechanical reservoir state | | | |
| | Complete high-pressure, high-temperature vessel & ancillary flow system design & fabrication | Sep-11 | Sep-11 | Discussed in Oct. 2011 quarterly report |
| | Complete experimental matrix | Dec-12 | | PI stated that new completion date is April 2013 |
| | Complete thermophysical & geomechanical property data analysis & validation | Mar-13 | | No report received from PI |

| ID | Title/Description | Planned Completion Date | Actual Completion Date | Milestone Status |
|---|---|---|---|---|
| 4.8 | Developing a predictive geologic model of the Green River oil shale, Uinta Basin | | | |
| | Detailed sedimentologic & stratigraphic analysis of three cores &, if time permits, a fourth core | Dec-12 | Dec-12 | Discussed Jan. 2013 quarterly report |
| | Detailed mineralogic & geochemical analysis of same cores | Dec-12 | Dec-12 | Discussed Jan. 2013 quarterly report |
| 4.9 | Experimental characterization of oil shales & kerogens | | | |
| | Characterization of bitumen and kerogen samples from standard core | Jan-12 | Feb-12 | Email sent to R. Vagnetti on Feb. 6, 2012 & discussed in April 2012 quarterly report |
| | Development of a structural model of kerogen & bitumen | Jun-12 | Jun-12 | Discussed in July 2012 quarterly report |
| 5.0 | Environmental, legal, economic, & policy framework | | | |
| 5.1 | Models for addressing cross-jurisdictional resource management | | | |
| | Identify case studies for assessment of multi-jurisdictional resource management models & evaluation of utility of models in context of oil shale & sands development | Jun-11 | Jul-11 | Discussed in Oct. 2011 quarterly report |
| 5.2 | Conjunctive management of surface & groundwater resources | | | |
| | Complete research on conjunctive surface water & groundwater management in Utah, gaps in its regulation, & lessons that can be learned from existing conjunctive water management programs in other states | Aug-11 | Aug-11 | Discussed in Oct. 2011 quarterly report |
| 5.3 | Policy & economic issues associated with using simulation to assess environmental impacts | | | |
| | White paper describing existing judicial & agency approaches for estimating error in simulation methodologies used in context of environmental risk assessment and impacts analysis | Dec-12 | Dec-12 | Submitted with Jan. 2103 quarterly report |
| 6.0 | Economic & policy assessment of domestic unconventional fuels industry | | | |
| 6.1 | Engineering process models for economic impact analysis | | | |
| | Upload all models used & data collected to repository | Oct-12 | | Will complete in 2nd quarter of 2013 |

| ID | Title/Description | Planned Completion Date | Actual Completion Date | Milestone Status |
|---|---|---|---|---|
| 7.0 | Strategic Alliance Reserve | | | |
| | Conduct initial screening of proposed Strategic Alliance applications | Mar-11 | Mar-11 | |
| | Complete review and selection of Strategic Alliance applications | Jun-11 | Jul-11 | Discussed in Oct. 2011 quarterly report |
| | Implement new Strategic Alliance research tasks | Sep-11 | Sep-11 | Discussed in Oct. 2011 quarterly report |
| 7.1 | Geomechanical model | | | |
| | Infer permeability-porosity-temperature relationships, develop model that can be used by other subtasks | Dec-12 | | Partially completed as described in this report. Addn'l work will be completed in July 2013 |
| | Make experimental recommendations | Aug-13 | | |
| | Basic reservoir simulations to account for thermal front propagation | Dec-13 | | |
| | Evaluation of flow mechanics | Dec-13 | | |
| 7.2 | Kinetic compositional models & thermal reservoir simulators | | | Project has been terminated |
| | Incorporate chemical kinetics into thermal reservoir simulators | Jun-12 | Jun-12 | Discussed in July 2012 quarterly report |
| 7.3 | Rubblized bed HPC simulations | | | |
| | Collect background knowledge from AMSO about characteristics & operation of heated wells | Jun-12 | Jun-12 | Discussed in July 2102 quarterly report |
| | Perform generation 1 simulation - DEM, CFD & thermal analysis of characteristic section of AMSO rubblized bed | Sep-12 | Sep-12 | Discussed in Oct. 2012 quarterly report |
| | Perform generation 2 simulation that incorporates kinetic compositional models from subtask 7.2 and/or AMSO | Jun-13 | | |

## NOTEWORTHY ACCOMPLISHMENTS

The Subtask 4.7 team performed measurements of stress and strain in the large-scale triaxial vessel.

## PROBLEMS OR DELAYS

Several subtasks (3.3, 3.4, 4.2, 4.3, 7.1) have been delayed by the departure of students and post-doctoral fellows. Some of these subtasks have had success in hiring new students. Nevertheless, milestones and deliverables for these subtasks will be delayed as those assigned to wrap up these projects fit them in with competing research demands. In Subtask 4.7, the pressure vessel is functional under uniaxial compression. Upcoming tests will be triaxial, meaning that the confining pressure system will need to be debugged. The separator/ condensation system also need to be tested.

## RECENT AND UPCOMING PRESENTATIONS/PUBLICATIONS

R. Keiter, J. Ruple, H. Tanana and R. Holt. (2012, January). Conjunctive surface and groundwater management in Utah: Implications for oil shale and oil sands development. Submitted to the Department of Energy under DOE Award No. DE-FE0001243.

Tiwari, P.  & Deo, M. (2012, February). Detailed kinetic analysis of oil shale pyrolysis TGA data. *AICHE Journal*, *58(2*), 505-515.

Spinti, J. (2012, February 15). Presenter/panelist - *Oil sands: How Utah can improve on the Alberta model.* Utah Governor's Energy Development Summit, Salt Lake City, UT.

Deo, M. (2012, February 15). Presenter/panelist - *Oil sands: How Utah can improve on the Alberta model.* Utah Governor's Energy Development Summit, Salt Lake City, UT.

Tiwari, P. & Deo, M. (2012, April). Compositional and kinetic analysis of oil shale pyrolysis using TGA-MS. *Fuel*, *94*, 333-341.

Rosenberg, M., Birgenheier, L. & Vanden Berg, M. (2012, April) Outcrop examination and sequence stratigraphy of the lacustrine Green River Formation, Uinta Basin, Utah: Implications for conventional and unconventional oil and gas development. Presented at the American Association of Petroleum Geologists Annual Convention, Long Beach, CA, April 22-25, 2012.

Eby, D., Chidsey, T., Vanden Berg, M. & Laine, M. (2012, April). Microbial carbonates from core and outcrop, Tertiary (Eocene) Green River Formation, Uinta Basin, Utah. Paper presented at the American Association of Petroleum Geologists Annual Convention, Long Beach, CA, April 22-25, 2012.

Badu, S., Pimienta, I. S. O., Orendt, A. M. Facelli, J. C. & Pugmire, R. J. (2012). Modeling of asphaltenes: Assessment of sensitivity of $^{13}C$ SSNMR to molecular structure. *Energy & Fuels, 26(4),* 2161-2167.

Fletcher, T. H., Orendt, A. M., Facelli, J. C., Solum, M. S., Mayne, C. L. & Deo, M. (2012, May 15). Kinetics of Uinta Basin oil shale pyrolysis. Presented at the 2012 University of Utah Unconventional Fuels Conference, Salt Lake City, UT.

Ruple, J. (2012, May 15). Wilderness quality lands and unconventional fuel development. Presented at the 2012 University of Utah Unconventional Fuels Conference, Salt Lake City, UT.

Tiwari, P. (2012). Oil shale Pyrolysis: Benchscale experimental studies and modeling. Ph.D. dissertation, Department of Chemical Engineering, University of Utah.

Tiwari, P., Deo, M., Lin C. L. & Miller, J.D. (2012, October). Characterization of the oil shale core pore structure before and after pyrolysis. Presented at the 2012 AICHE Annual Meeting, Pittsburgh, PA, October 28-November 2, 2012.

Vanden Berg, M. D., Birgenheier, L. P. & Rosenberg M. J. (2012, September). Core-based sedimentologic, stratigraphic, and geochemical analysis of the lacustrine upper Green River Formation, Uinta Basin, Utah: Implications for conventional and unconventional petroleum development. Presented at the 2012 American Association of Petroleum Geologists -Rocky Mountain Section Meeting, Grand Junction, CO.

Rosenberg, M.J., Birgenheier, L.P, & Vanden Berg, M.D. (2012, October). Sedimentology and sequence stratigraphy of the Green River Formation, eastern Uinta Basin, Utah. Presented at the 32nd Oil Shale Symposium, Golden, CO, October 15-19, 2013.

Burnham, A., Day, R., Switzer, L., McConaghy, J., Hradisky, M., Coates, D., Smith, P., Foulkes, J., La Brecque, D., Allix, P., Wallman, H. (2012, October). Initial results of the AMSO RD&D pilot test program. Presented at the 32nd Oil Shale Symposium, Golden, CO, October 15-19, 2013.

Deo, M. (2012, October). *Oil shale liquefaction: Modeling and reservoir simulation*. Short course presentation to Statoil, Trondheim, Norway.

Deo, M. (2012, October). *Oil shale conversion to liquids: Experimental aspect*. Short course presentation to Statoil, Trondheim, Norway.

Fletcher, T. H. (2012, October). *Oil shale 1: Chemical structure and pyrolysis*. Short course presentation to Statoil, Trondheim, Norway.

McLennan, J. (2012, October). *Legacy and new geomechanical measurements of oil shale*. Short course presentation to Statoil, Trondheim, Norway.

Smith, P. J. (2012, October). *Multiscale simulation*. Short course presentation to Statoil, Trondheim, Norway.

Smith, P. J. (2012, October). *A description of a UQ-predictive validation framework for application to difficult engineering problems*. Short course presentation to Statoil, Trondheim, Norway.

Orendt, A. , Pimienta, I. S. O., Badu, S., Solum, M., Pugmire, R. J., Facelli, J. C., Locke, D. R., Winans, R. E., Chapman, K. W. & Chupas, P. J. (2012). Three-dimensional structure of the Siskin Green River oil shale kerogen model: A comparison between calculated and observed properties. *Energy and Fuels, 27*, 702-710.

Spinti, J. (2013, January 10). Presenter/panelist - *The real impact of oil shale and oil sands development in Utah.* 2013 Governor's Energy Development Summit, Salt Lake City, UT.

Hradisky, M., Smith, P. J., and Burnham, A. (2013, March). *STAR-CCM+ simulations of in-situ thermal treatment of oil shale*. Paper presented at the STAR Global Conference, Orlando, FL, March 18-20, 2013.

Orendt, A. M., Solum, M. S., Facelli, J. C., Pugmire, R. J., Chapman, K. W., Winans, R. E. & Chupas, P. (2013, April). Characterization of shale and kerogen from a Green River oil shale core, ENFL-535. Presented at the 245th American Chemical Society National Meeting, New Orleans, LA, April 7-11, 2013.

Birgenheier, L. P. (2013, May 7). Presenter/panelist - *Constructing a basin-wide geologic model*. University of Utah Unconventional Fuels Conference, Salt Lake City, UT.

Smith, P. J. (2013, May 7). Presenter/panelist - *Simulation of in situ production process using computational fluid dynamics*. University of Utah Unconventional Fuels Conference, Salt Lake City, UT.

Spinti, J. P. (2013, May 7). Presenter/panelist - *Assessment of unconventional fuels development costs*. University of Utah Unconventional Fuels Conference, Salt Lake City, UT.

Birgenheier, L.P., Plink-Bjorklund, P., Vanden Berg, M.D., Rosenberg, M., Toms, L. & Golab, J. (2013). *A genetic stratigraphic framework of the Green River Formation, Uinta Basin, Utah: The impact of climatic controls on lake evolution*. Paper accepted for presentation at the American Association of Petroleum Geologists Annual Meeting, Pittsburgh, PA, May 22-25, 2013.

Vanden Berg, M. D., Eby, D. E., Chidsey, T. C. & Laine, M.D. (2013). *Microbial carbonates in cores from the Tertiary (Eocene) Green River Formation, Uinta Basin, Utah, U.S.A.: Analogues for non-marine microbialite oil reservoirs worldwide*. Paper accepted for presentation at Microbial Carbonates in Space and Time: Implications for Global Exploration and Production, The Geological Society, London, United Kingdom, June 19-20, 2013.

Tiwari, P., Deo, M., Lin, C. L. & Miller, J.D. (2013). Characterization of oil shale pore structure before and after pyrolysis by using X-ray micro CT. Accepted for publication in *Fuel*.

Birgenheier, L. & Vanden Berg, M. (n.d.). Facies, stratigraphic architecture, and lake evolution of the oil shale bearing Green River Formation, eastern Uinta Basin, Utah. To be published in Springer book entitled *Stratigraphy and limnogeology of the Eocene Green River Formation*.

Bauman. J. H. & Deo, M. D. (n.d.) Simulation of a conceptualized combined pyrolysis, in situ combustion, and $CO_2$ storage strategy for fuel production from Green River oil shale. Submitted to *Energy and Fuels*.

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## APPENDIX A. 2013 Energy Forum - Final Questions.

1. What are the most effective ways to engage the American public in addressing the impacts of energy consumption and energy pricing on climate change?

2. What role should the federal government, state government, and private sector take in providing leadership on advancing sustainable energy?

3. Is our current rate of energy consumption sustainable, or are changes in our energy production and consumption patterns needed? What forces are most likely to prompt those shifts?

4. What are the most effective social and economic incentives for influencing American patterns of energy consumption?

5. What role should energy security play in engaging the public on the issue of climate change?

6. Is moving away from fossil fuels essential to addressing climate change?

7. What role does the potential for technological innovation play in shaping the sustainable energy debate and fostering public engagement? Do we rely too much or not enough on the promise of technology to support our current patterns of energy consumption?

8. As far as effecting actual shifts in attitudes on energy and climate, would it be most effective to focus on developing new energy technologies, increasing energy efficiency, or conservation?

9. What energy research and resource investments make the most sense as far as addressing climate change?

10. We often hear that it doesn't matter what the U.S. does on climate change in the absence of action by countries like China and India. What are the costs and benefits of U.S. action on greenhouse gas emissions in the absence of action by other countries?

## APPENDIX B. Presentation entitled "STAR-CCM+ simulations of in-situ thermal treatment of oil shale."

# STAR-CCM+ Simulations of In-Situ Thermal Treatment of Oil Shale

Michal Hradisky
Philip J. Smith
University of Utah

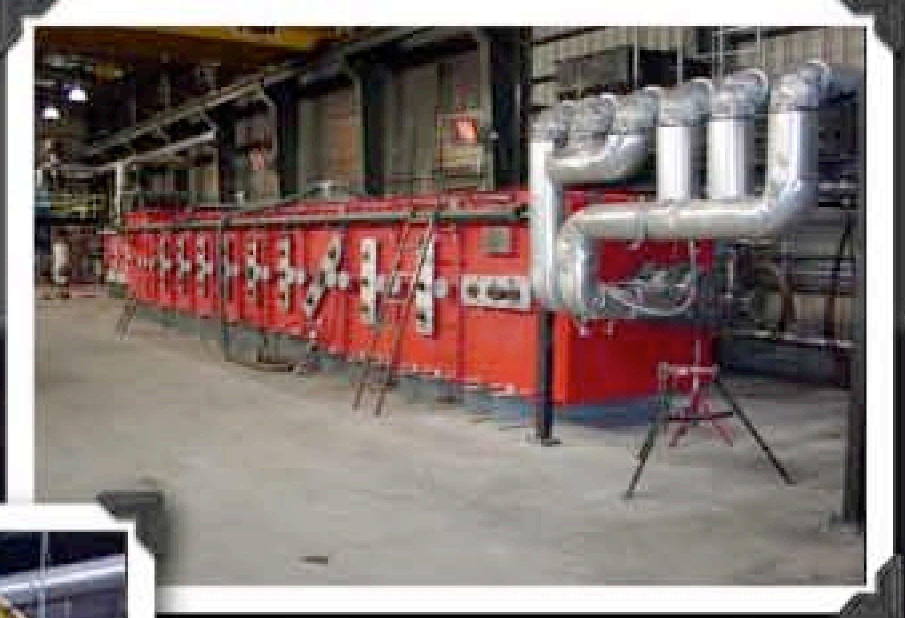
Alan Burnham
American Shale Oil, LLC

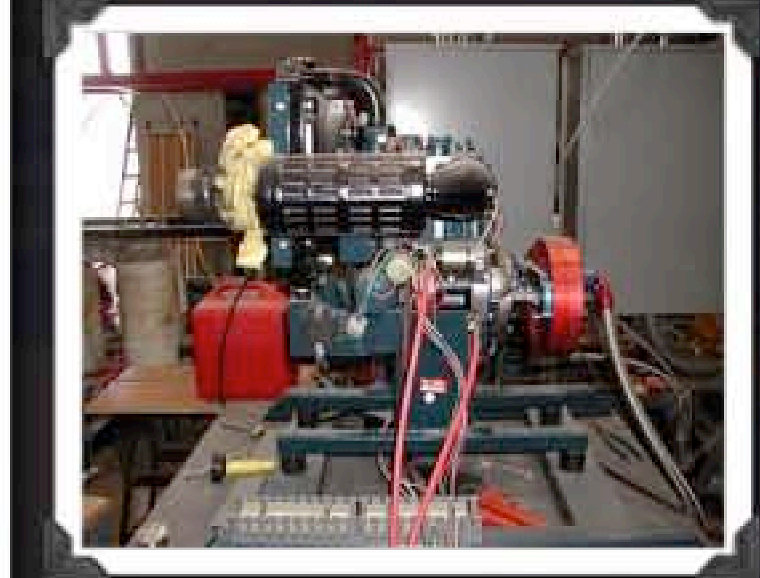
STAR Global Conference
18 - 20. 3. 2013
Orlando, FL

# Who we are ...

## Institute for Clean and Secure Energy

- Multi-disciplinary institute
  - 23 faculty - 6 colleges
  - 28 research and administrative staff
  - 60 students

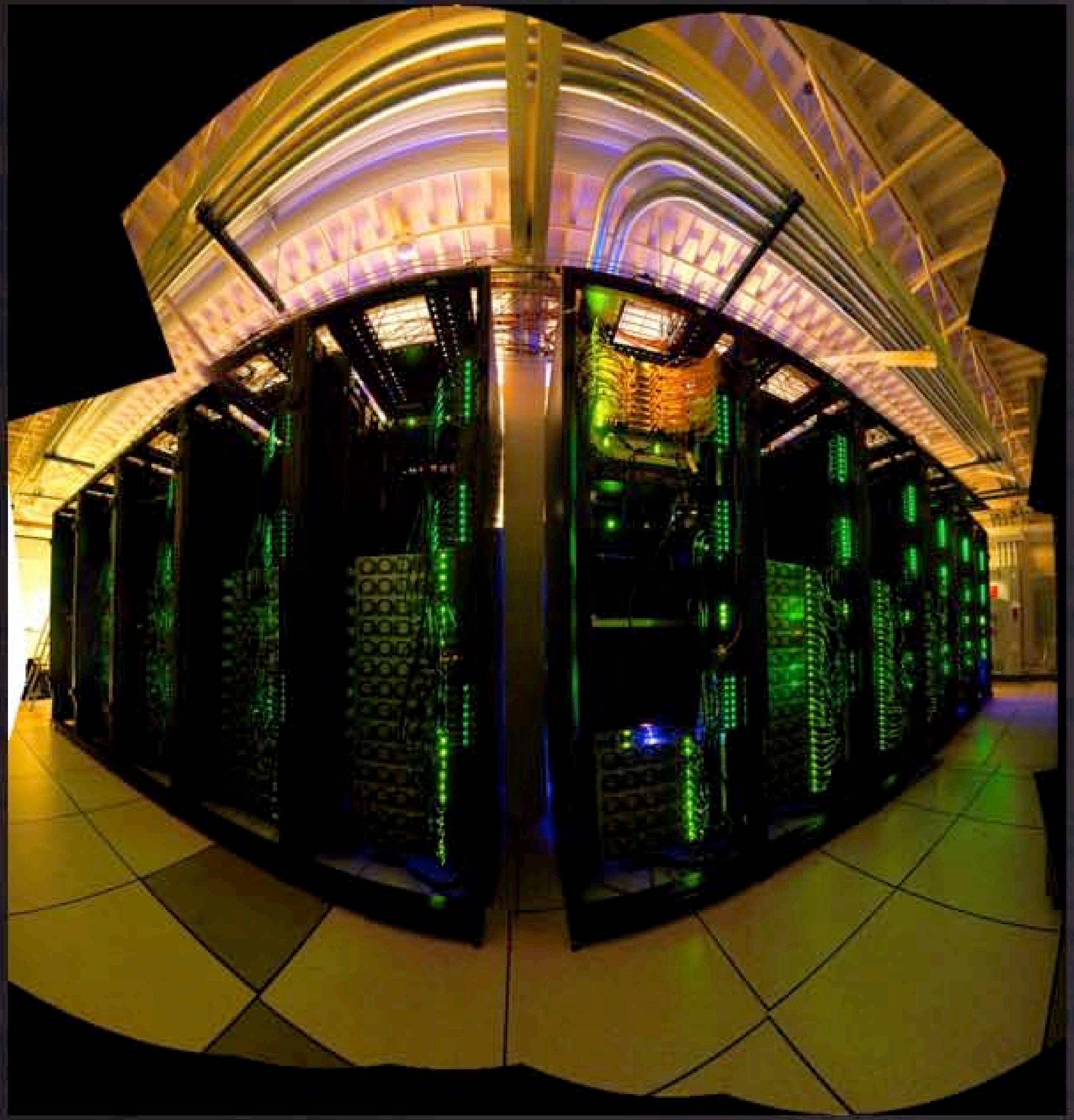




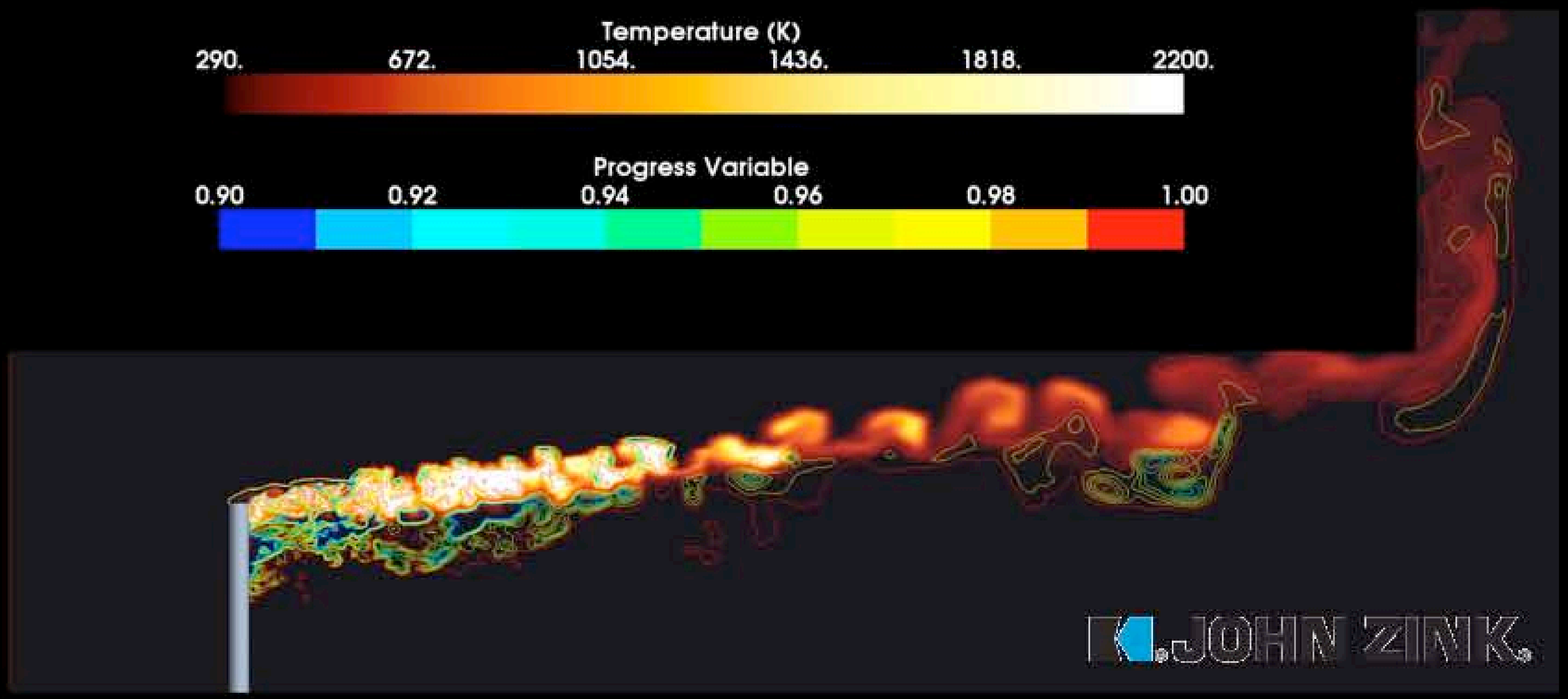
# Who we are ...

## Institute for Clean and Secure Energy

- Need new technologies, new solutions ...
  - Historically required decades to deploy
- HOW?
  - Using High Performance Computing
  - Uncertainty Quantification
  - Reduce Risk



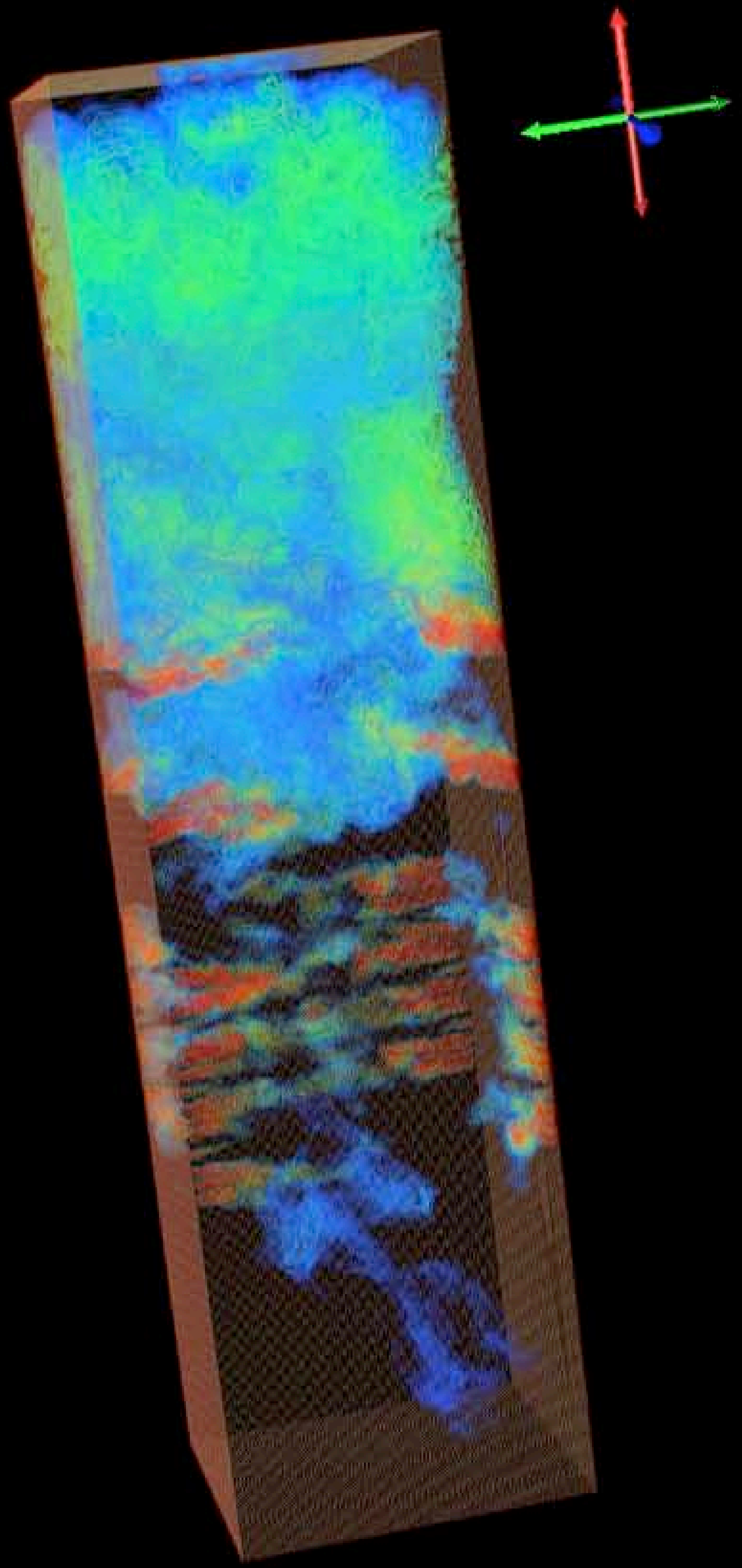
ICSE clusters (HP & Sun)
- 2.6 GHz - 6000 cores
- 140 TBytes storage
- Qlogic/Myrinet interconnect
- 24 GBytes of memory

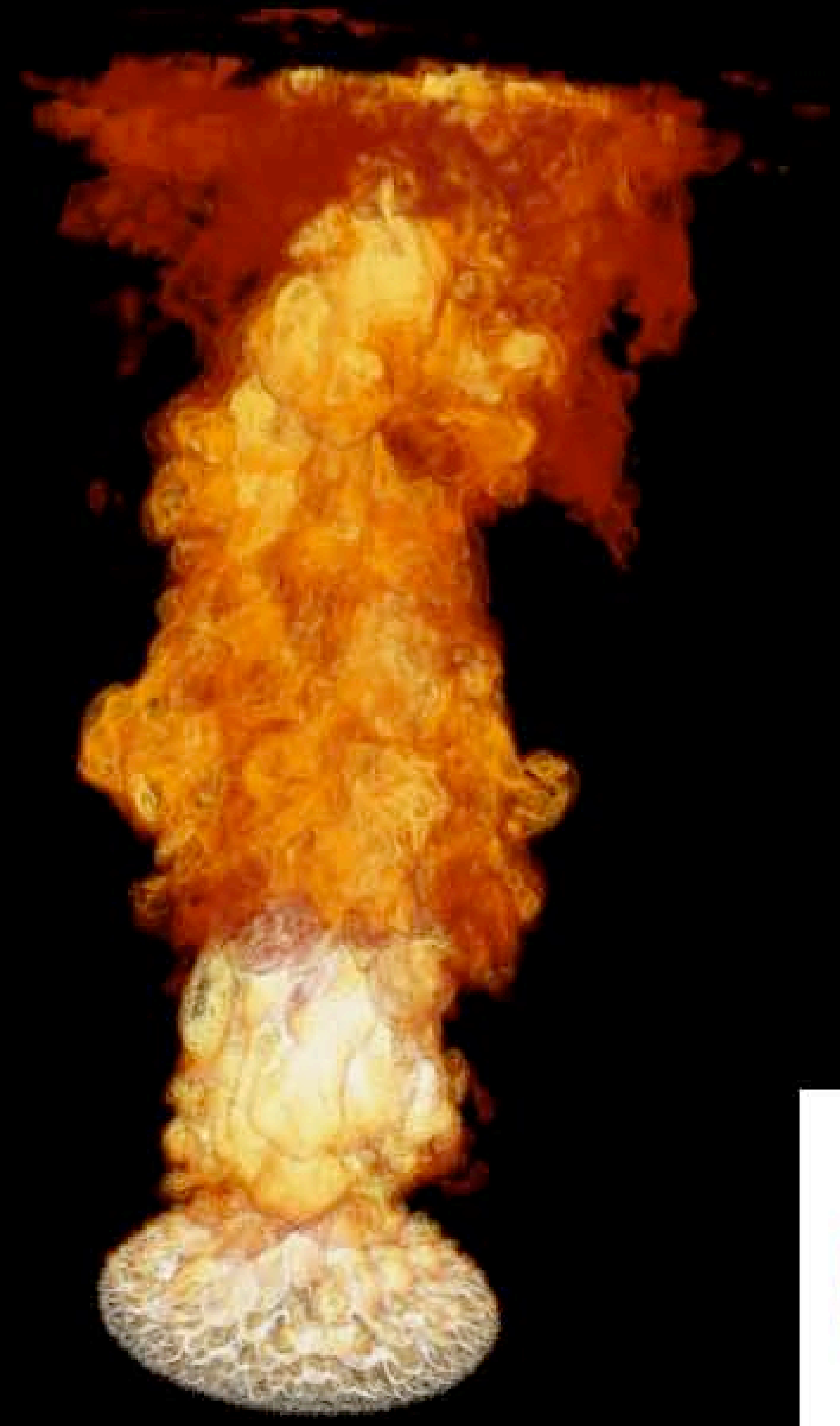



CALERA
Green Cement for a Blue Planet

AMSO
AMERICAN SHALE OIL LLC

ALSTOM






Chevron

TOTAL

# Shale Oil / Gas vs. Oil Shale

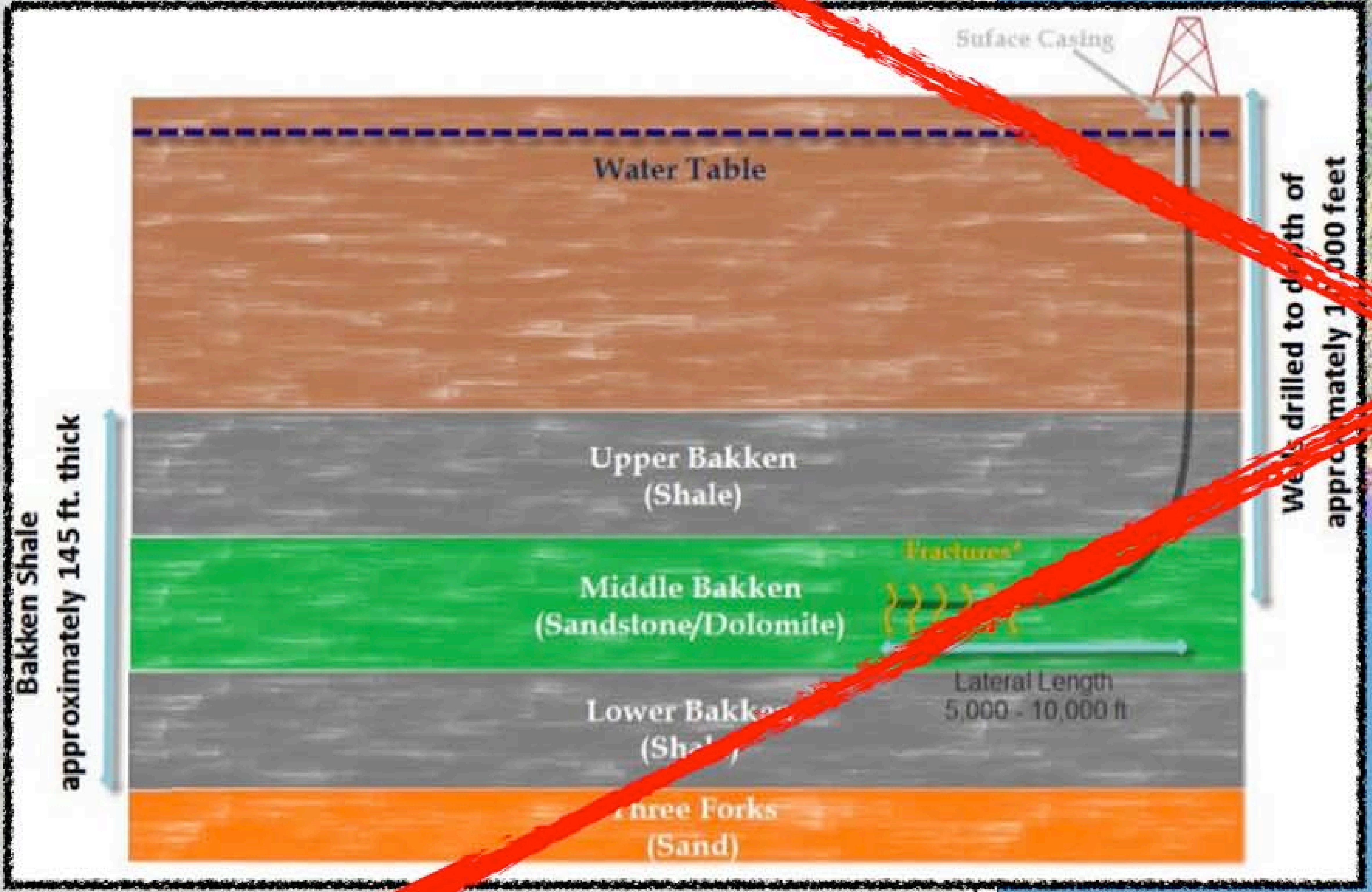
## Shale Oil / Gas

- Conventional oil / gas trapped within the shale rock or other types of rock formation
- Depths ~ 5,000 ft to 15,000 ft
- 'Mature' oil / gas - subjected to geological temperature / pressures for a sufficient period of time

## Oil Shale

- Organic-rich sedimentary rock
  - Organic material is kerogen - solid material bound within the mineral matrix
- Depths ~ 1,000 ft to 2,500 ft
- Requires heat to release the hydrocarbon vapors which must be then condensed and extracted

# North American Shale Oil / Gas Resources



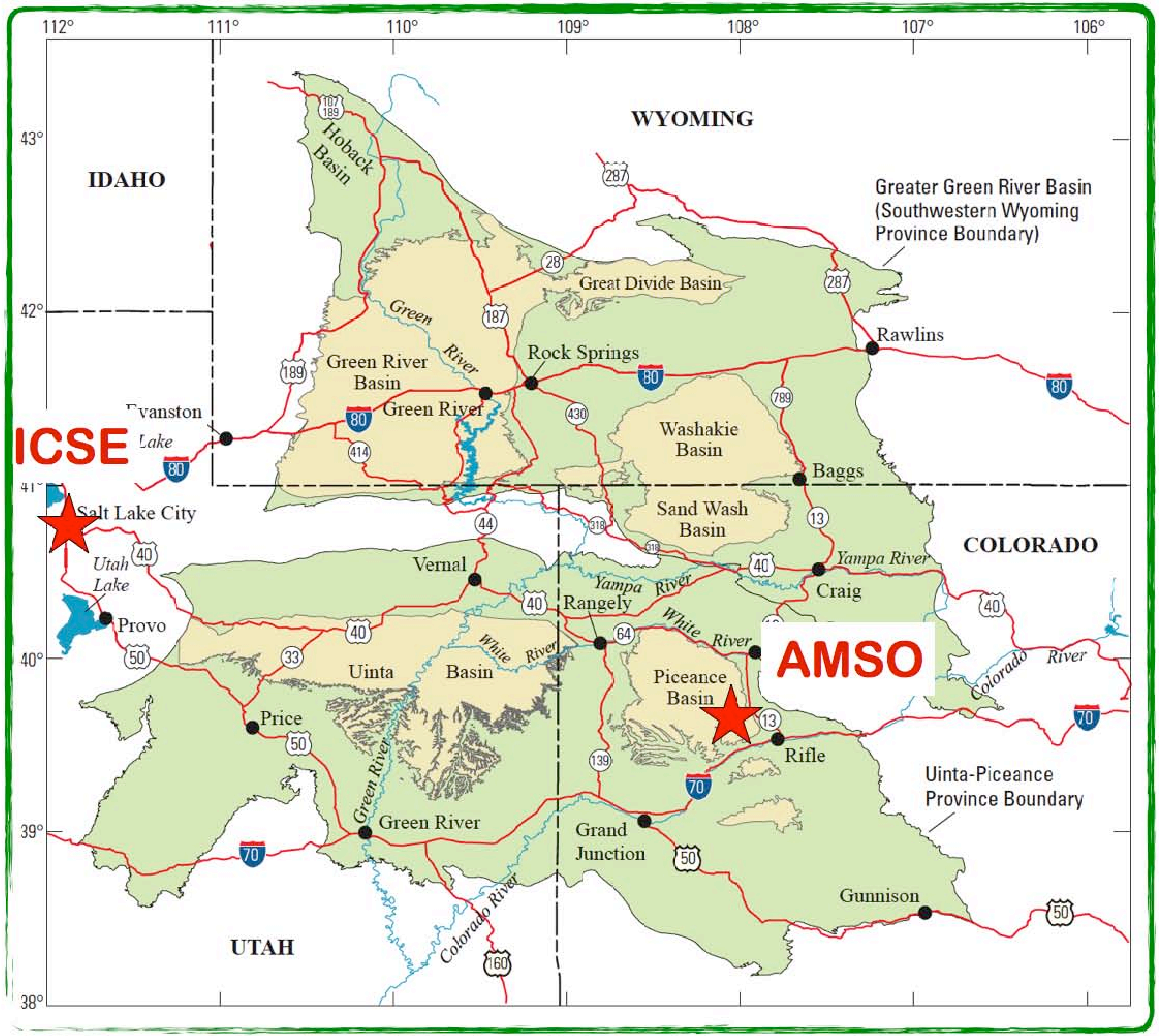

The Bakken Boom - Energy Policy Research Foundation, Aug 3, 2011


Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI.
Updated: May 9, 2011

# United States Oil Shale Formations


USGS Report 2005-5294, John R. Dyni & 2010 Survey of Energy Resources, World Energy Council

# Green River Formation

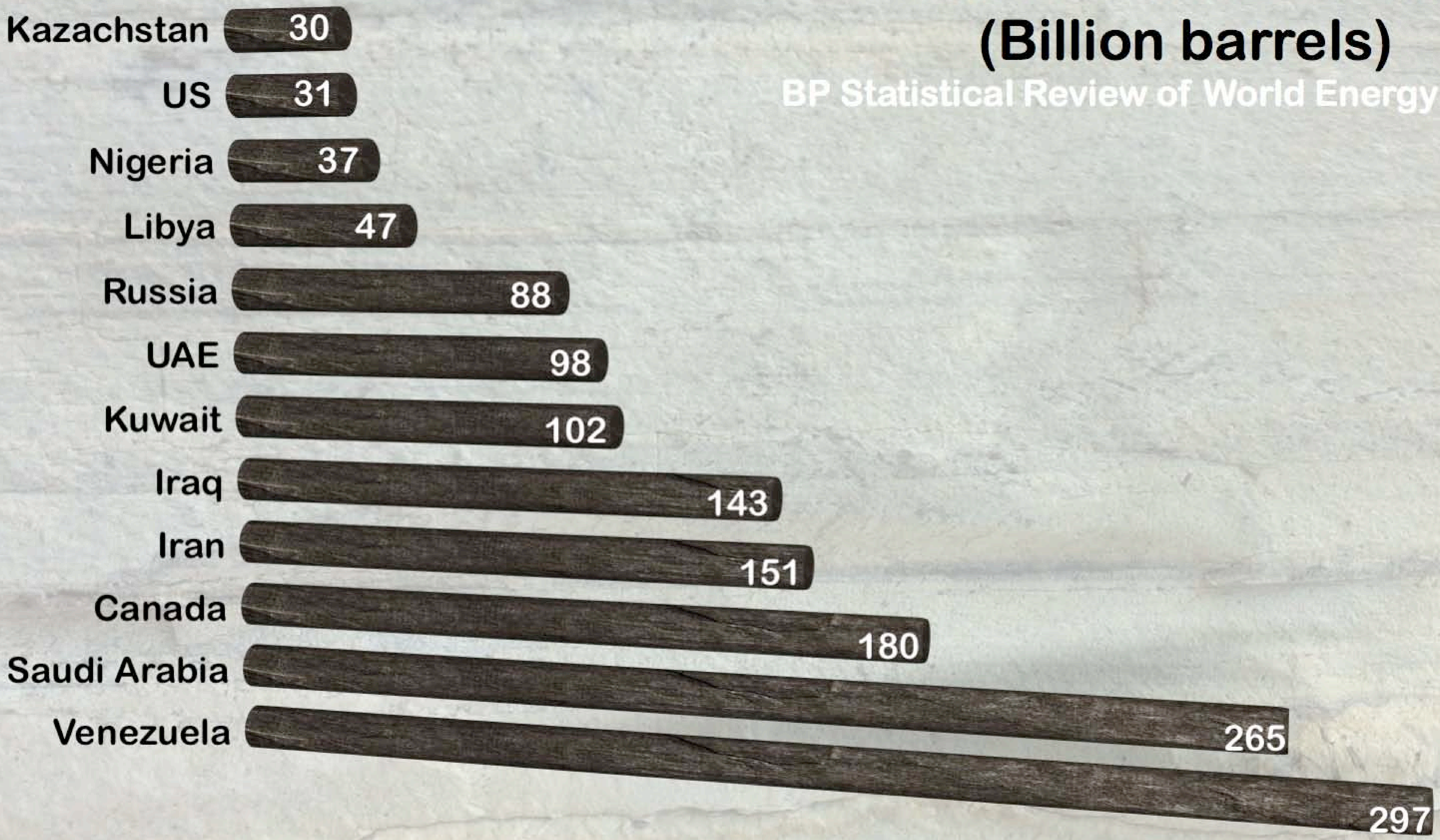

**EXPLANATION**

| | |
|---|---|
| Oil shale-bearing rocks | Major highway or road |
| U.S. Geological Survey Oil and Gas Province | City or town |

U.S. Geological Survey Oil Shale Assessment Team, 2011, Oil shale resources of the Eocene Green River Formation, Greater Green River Basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS–69–DD, 6 chapters, pages variable.

# Crude Oil Reserves (Billion barrels)

BP Statistical Review of World Energy (6/2012)



Oil Shale Potential Resources
(Billion barrels)
2010 Survey of Energy Resources, World Energy Council
USGS Fact Sheet 2012-3145, January 2013
National Energy Research Center of Jordan (nerc.gov.jo)
Commercial Production
Canada 15
Estonia 16
Australia 31
Jordan 50
Morocco 53
Italy 73
Brazil 82
Congo 100
Russia 247
Israel 250
China 354
United States 706
4285
Kazachstan 30
US 31
Nigeria 37
Libya 47
Russia 88
UAE 98
Kuwait 102
Iraq 143
Iran 151
Canada 180
Saudi Arabia 265
Venezuela 297
Recoverable
USGS Fact Sheet 2012-3145, January 2013
8.2
to
26.7%
THE INSTITUTE FOR CLEAN AND SECURE ENERGY


Oil shale outcrop
Green River Formation
Uinta Basin, UT

# American Shale Oil, LLC

- 50 / 50 Joint venture b/w Genie Energy and Total
- In-situ process
  - Hydrologic isolation of the illitic oil shale from the protected waters
  - In-direct heating with down-hole burner refluxing gas (direction combustion consumes light gases needed for high quality product)
  - Thermal mechanical fracture (no hydraulic fracking)

# American Shale Oil, LLC

- Rate determining step - Heat Transfer
  - Conduction ................ 3 years (Shell) ~ 20 sq. miles
  - Natural convection ... 3 months (Red Leaf) ~ 2 sq. miles
  - Forced convection .... 3 hours (Indirect heated retorts) ~ 10 acres


Heater wellhead and
oil and gas processing
facilities
Production wellhead
and geophysical
monitoring wells
AMSO

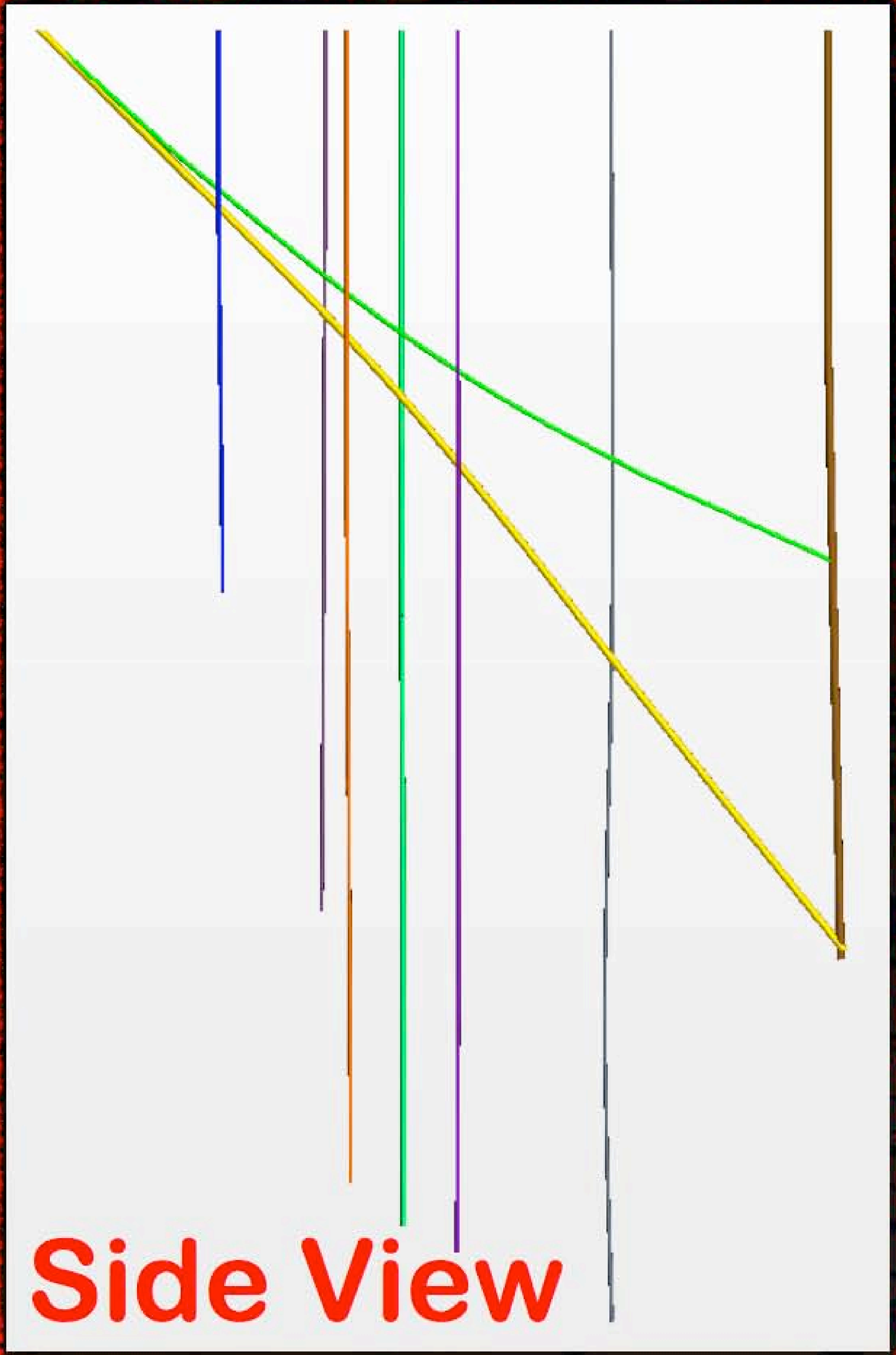
Hydrological monitoring wells (BG, L3, Wasatch)
Hydrological monitoring well (L3)
Hydrological monitoring well (L3) and staff trailers
AMSO

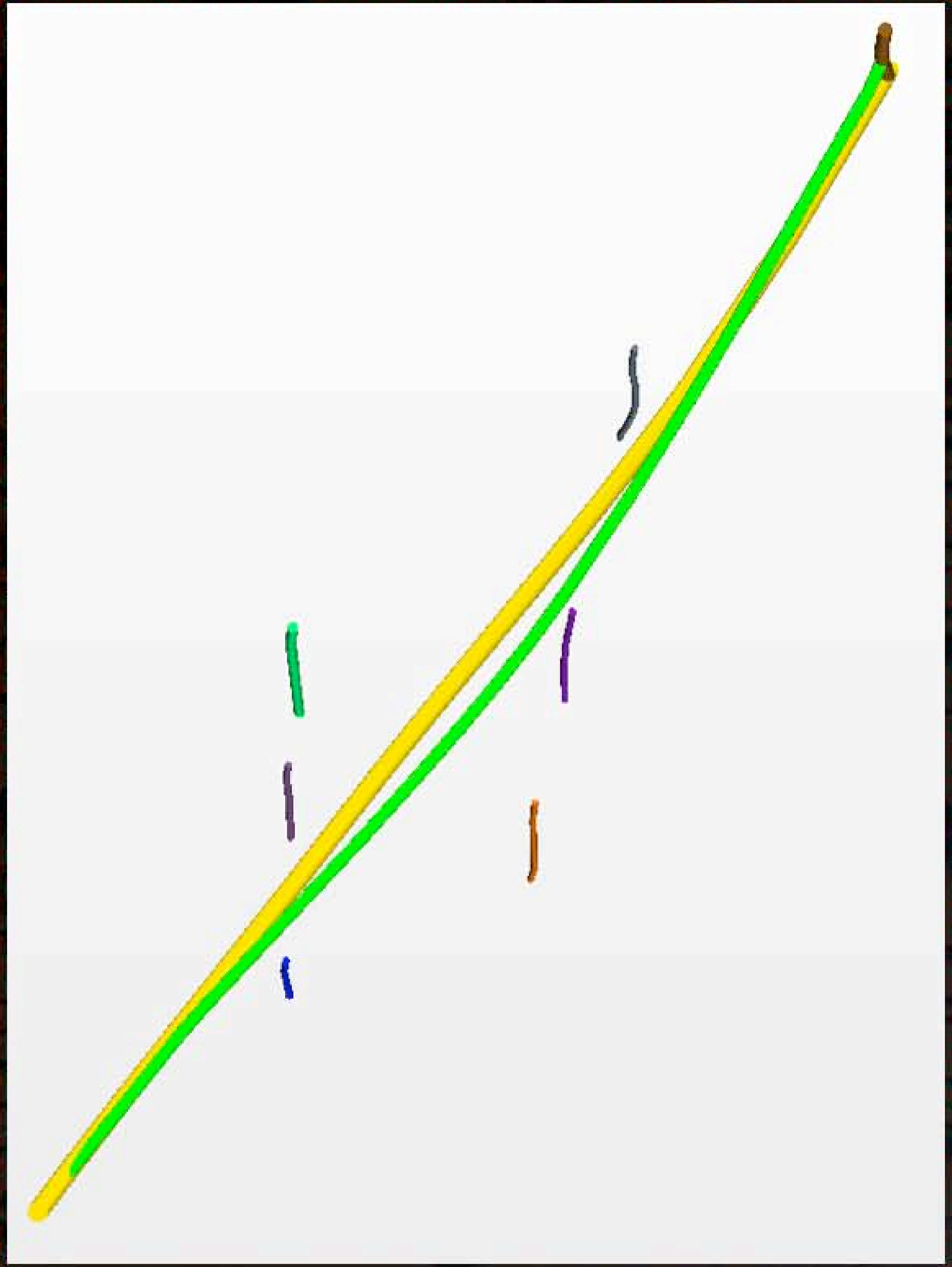

Heater Wellhead
Heater Well Trajectory
Pipes for produced and
recycled fluids
3
2
4
1
5
6
Geophysical
Monitoring Wells
Production Well
AMSO

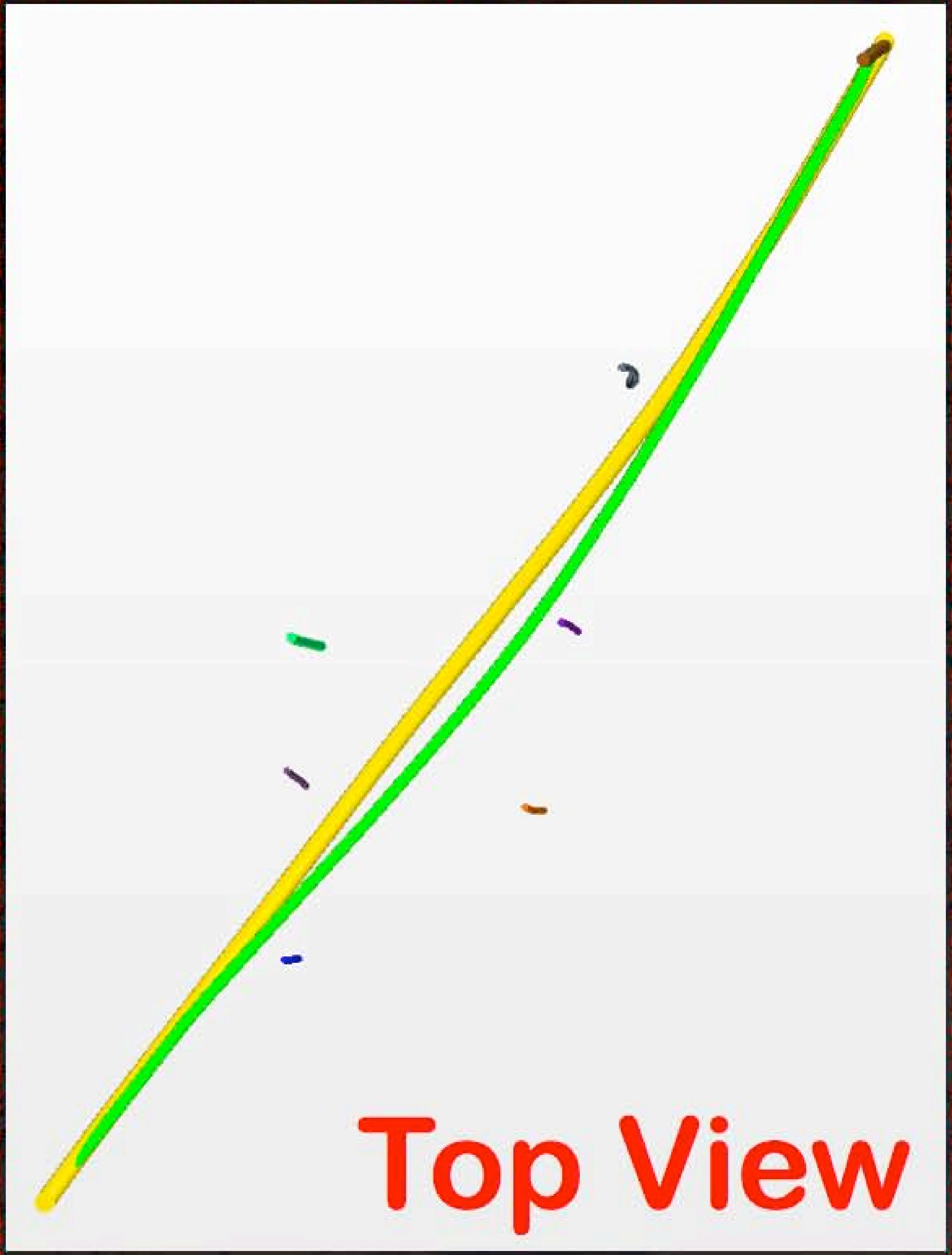

Surface processing facility
Better water quality
Aquifer system
Mahogany zone
1000 ft
oil shale
heater well (electrical cables only)
production well
monitoring wells
Dissolution surface
Saline water
Nahcolitic oil shale
2000 ft
Pilot test interval (2015-2135 ft)
~45° incline
heater
Wasatch
possible retort boundary
cased and cemented
R1
pilot test interval
vapor withdrawal point
highest vapor injection point
heater
liquid return
Triangular convection loop
AMSO


GOPT
Grade
Gallons of Oil Per Ton
STAR-CCM+ Simulation Domain
tomography wells
possible retort boundary
cased and cemented
R1
pilot test interval
vapor withdrawal point
highest vapor injection point
heater
liquid return

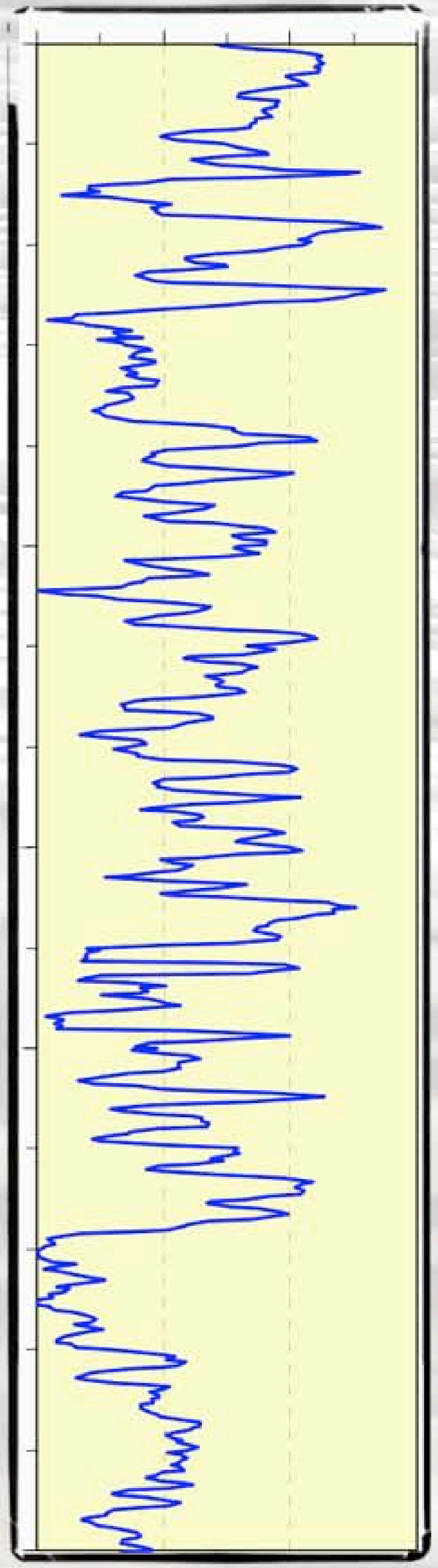
# STAR-CCM+ Simulation Domain

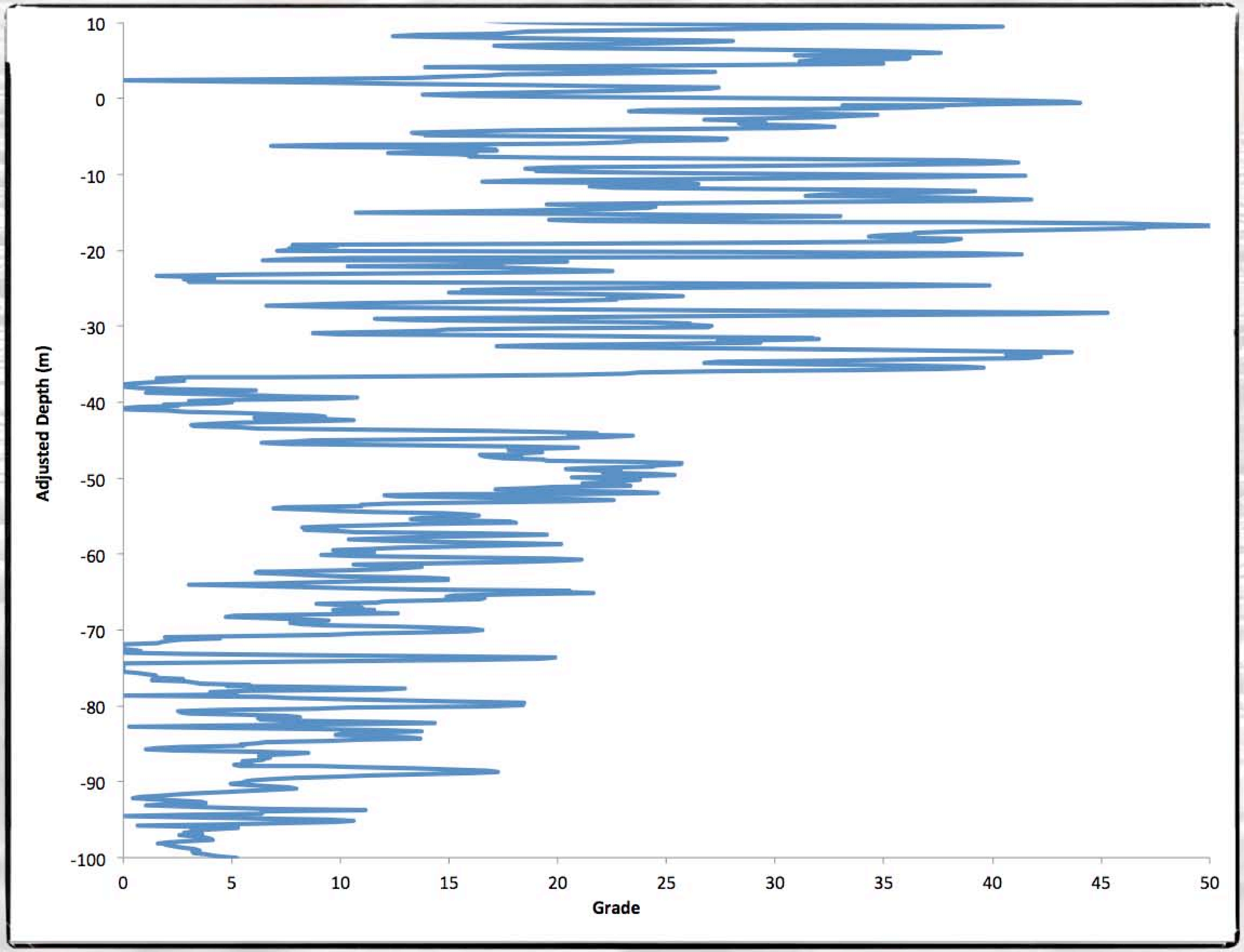




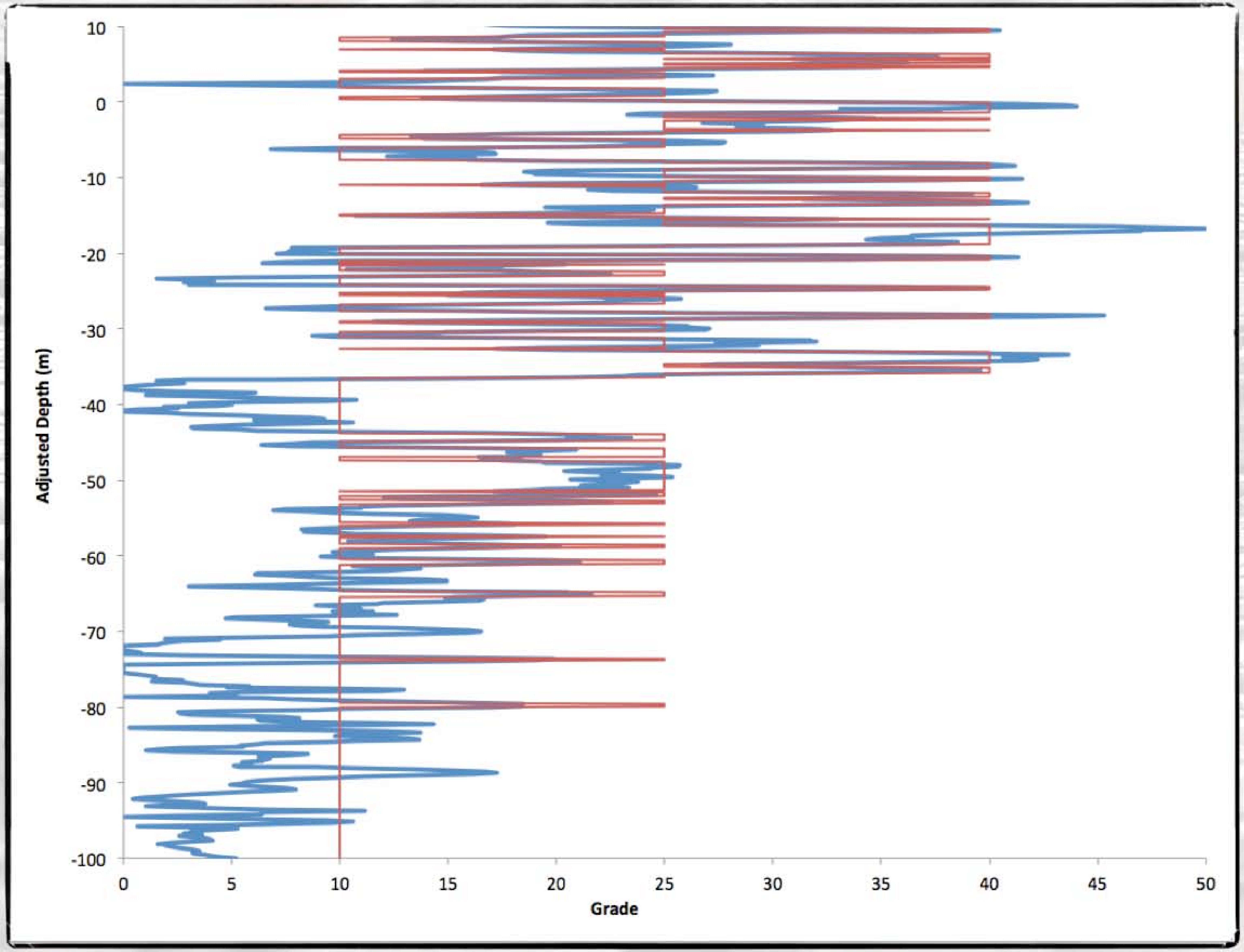
# Oil Shale Properties - Experimental



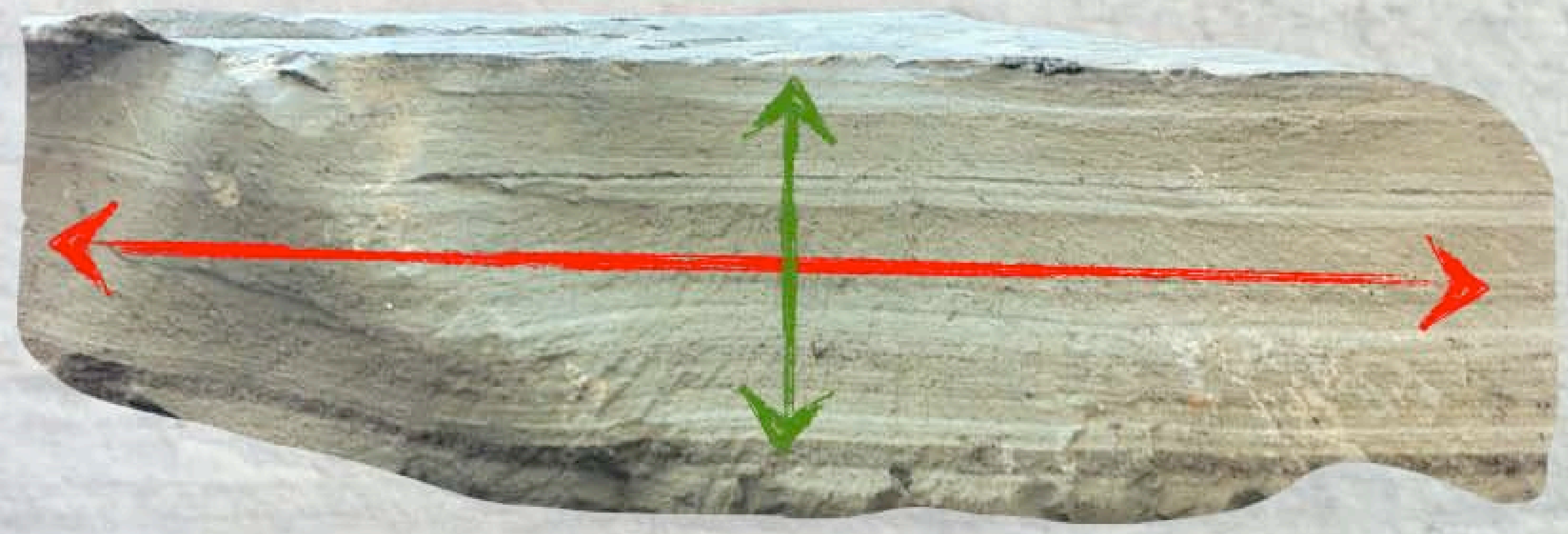


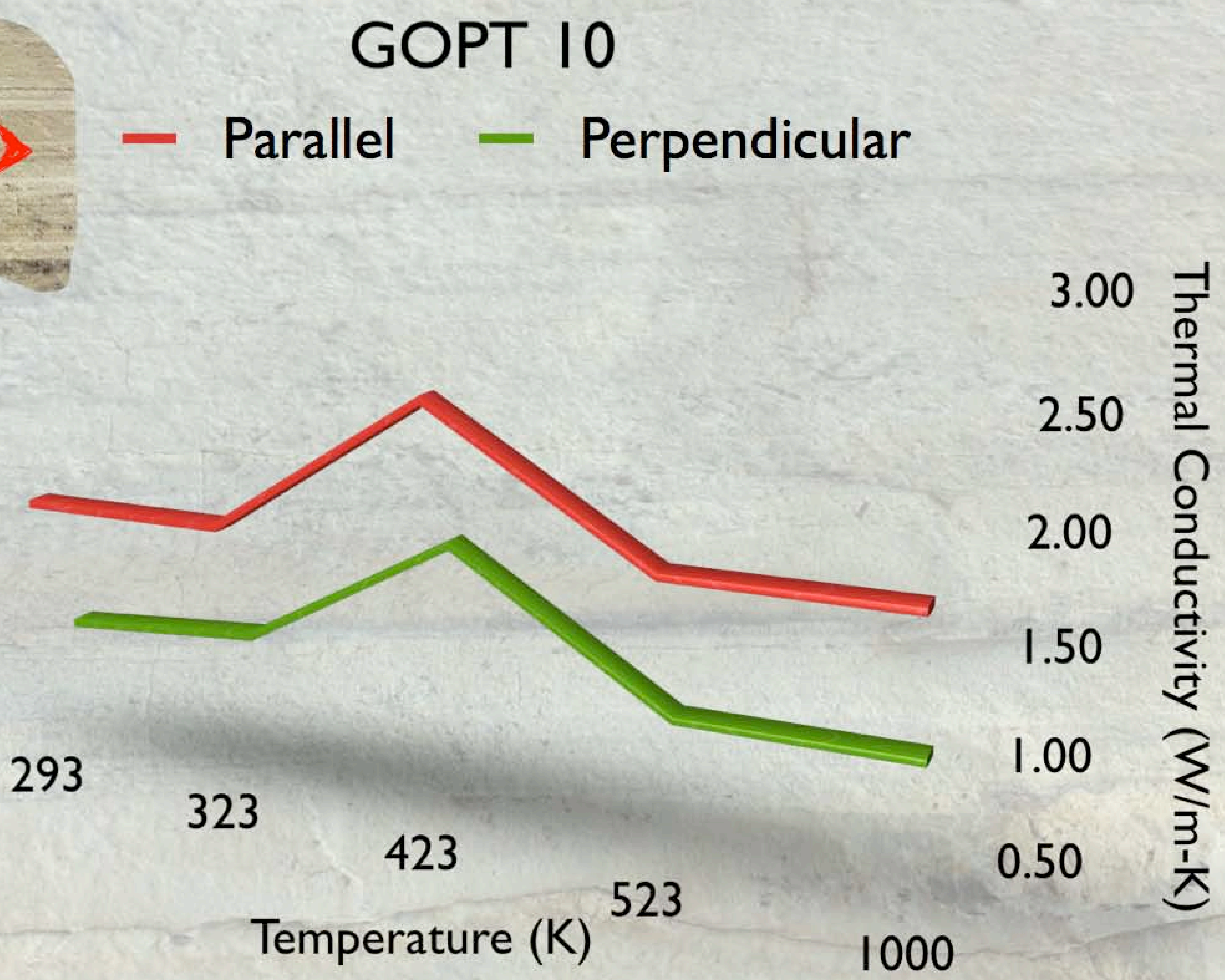
# Oil Shale Properties - Experimental

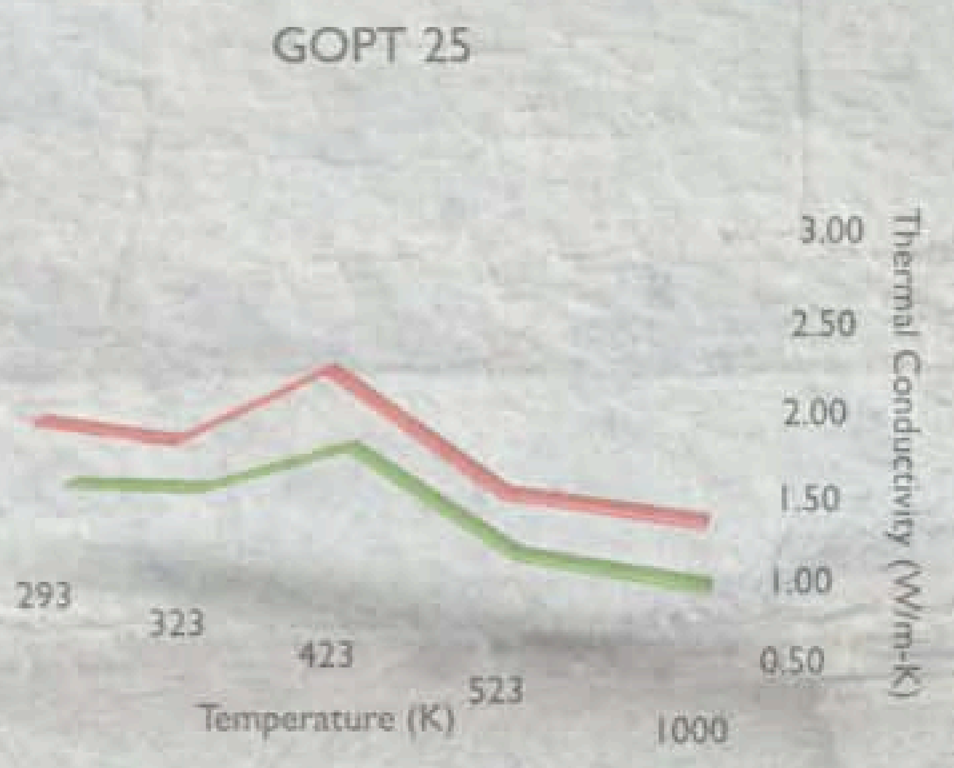
- Anisotropic properties for three grades of shale ... 10, 25, 40
- Categorized properties to fall in three groups based on grade
  - Grade < 17.5 ................ Grade 10
  - 17.5 < Grade < 32.5 ... Grade 25
  - Grade > 32.5 ................ Grade 40

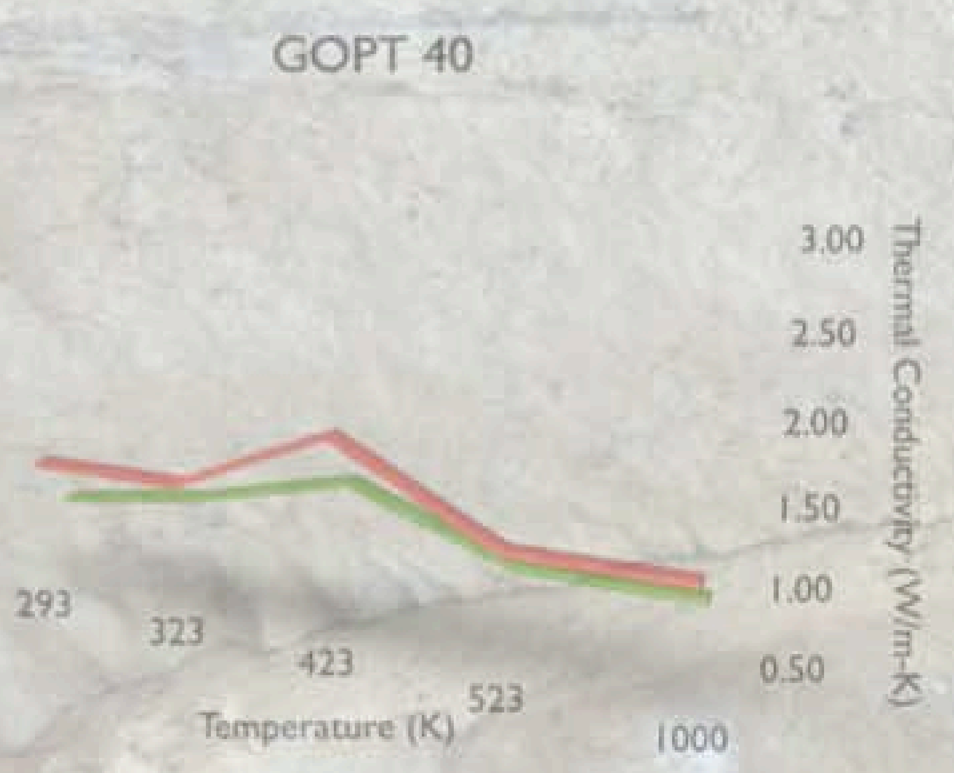


# Shale Properties - Simulation - Thermal Conductivity



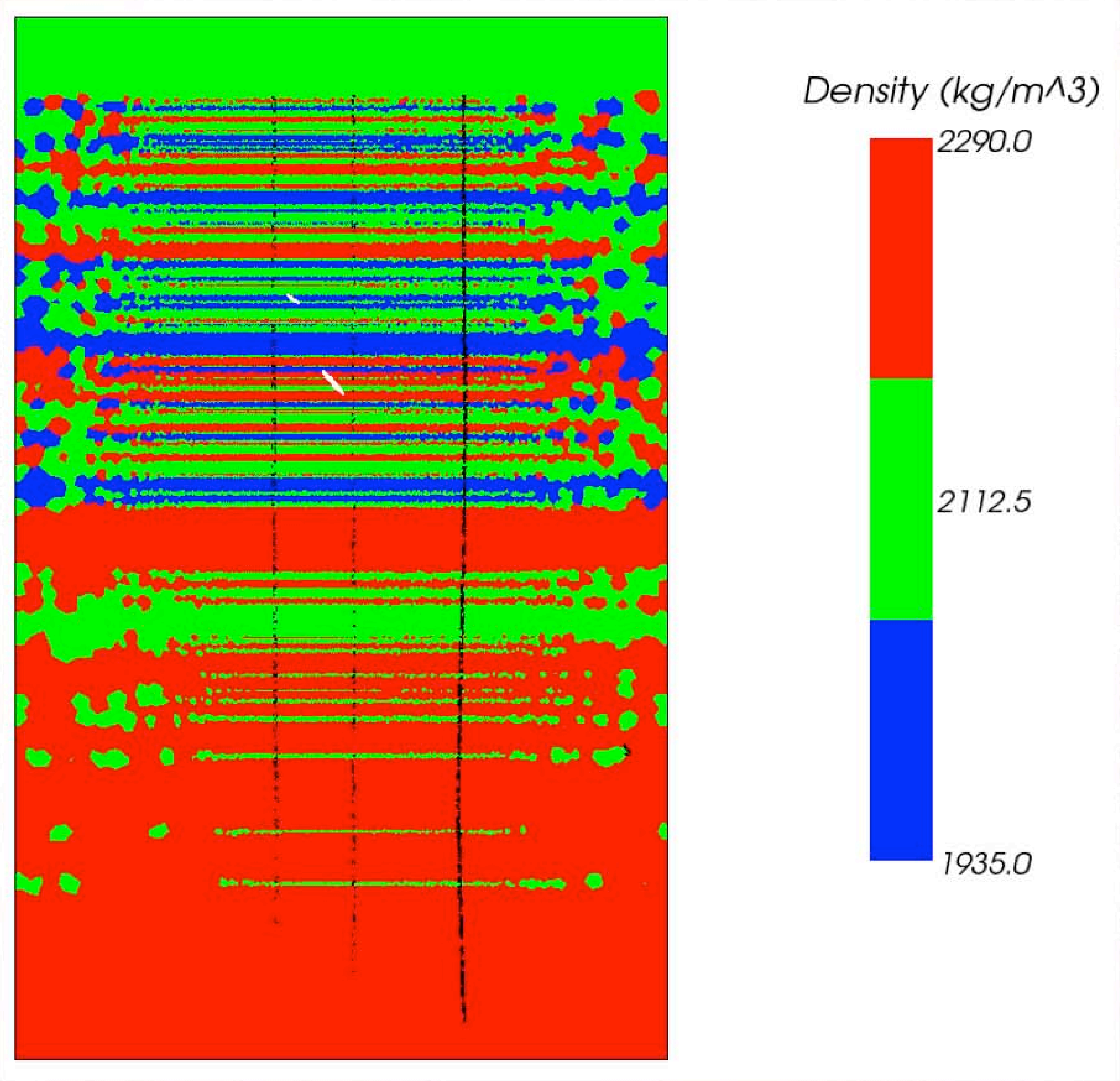


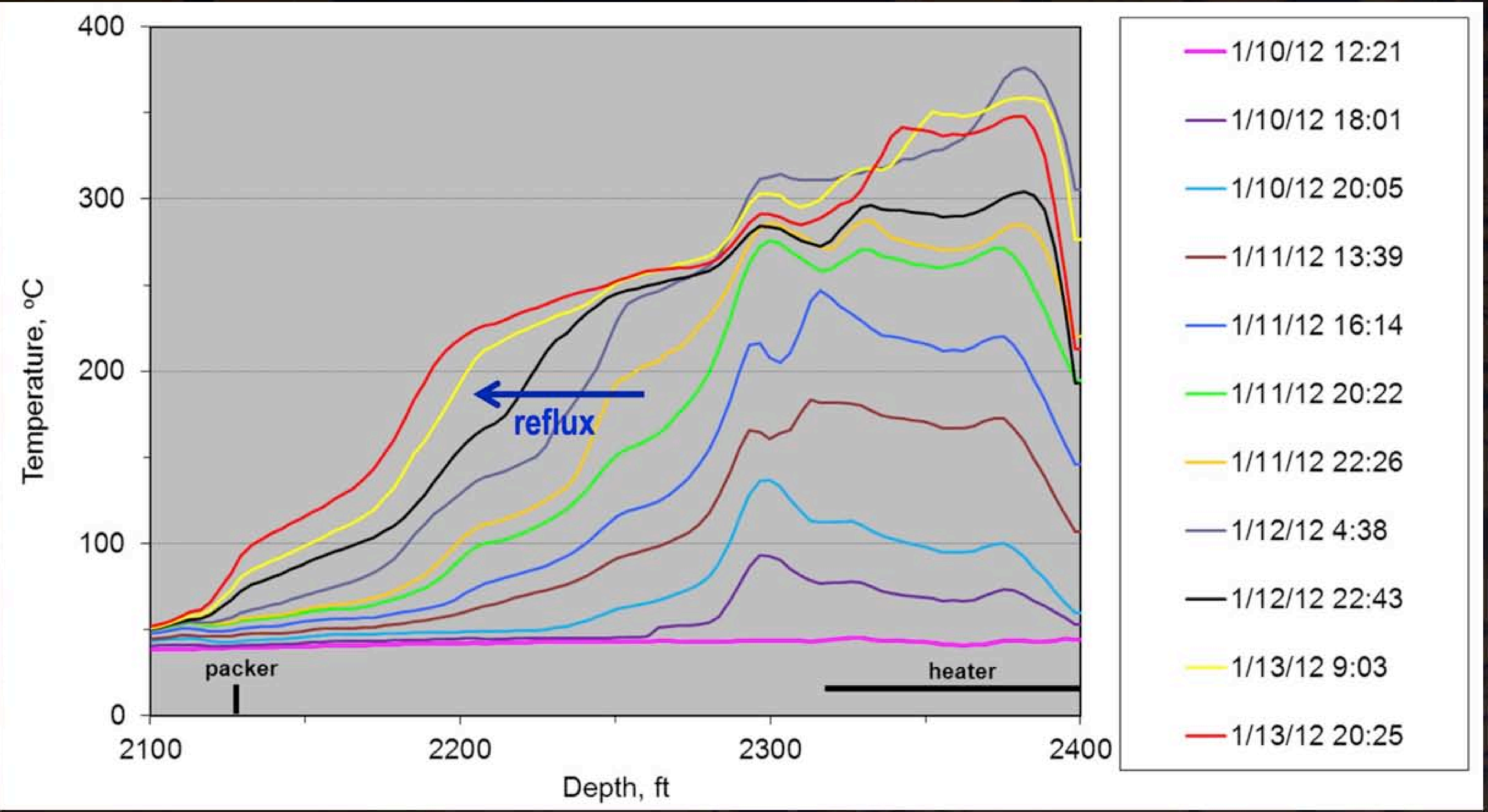



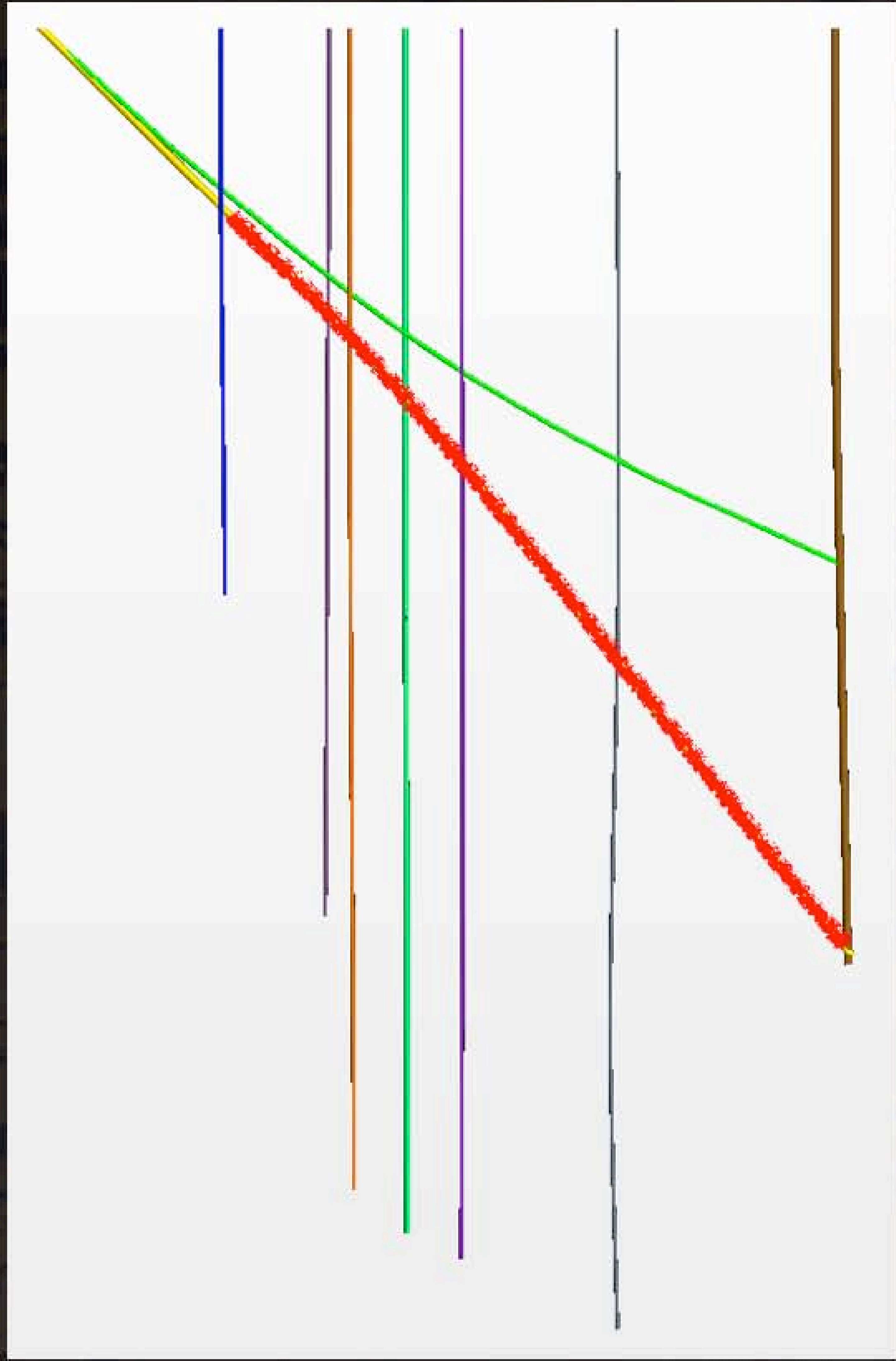
# Shale Properties - Simulation - Density

- Density falls in three groups based on grade
  - Grade < 17.5 ................ 10 ... 2290 kg/m3
  - 17.5 < Grade < 32.5 ... 25 ... 2109 kg/m3
  - Grade > 32.5 ................ 40 ... 1935 kg/m3



# Boundary Conditions

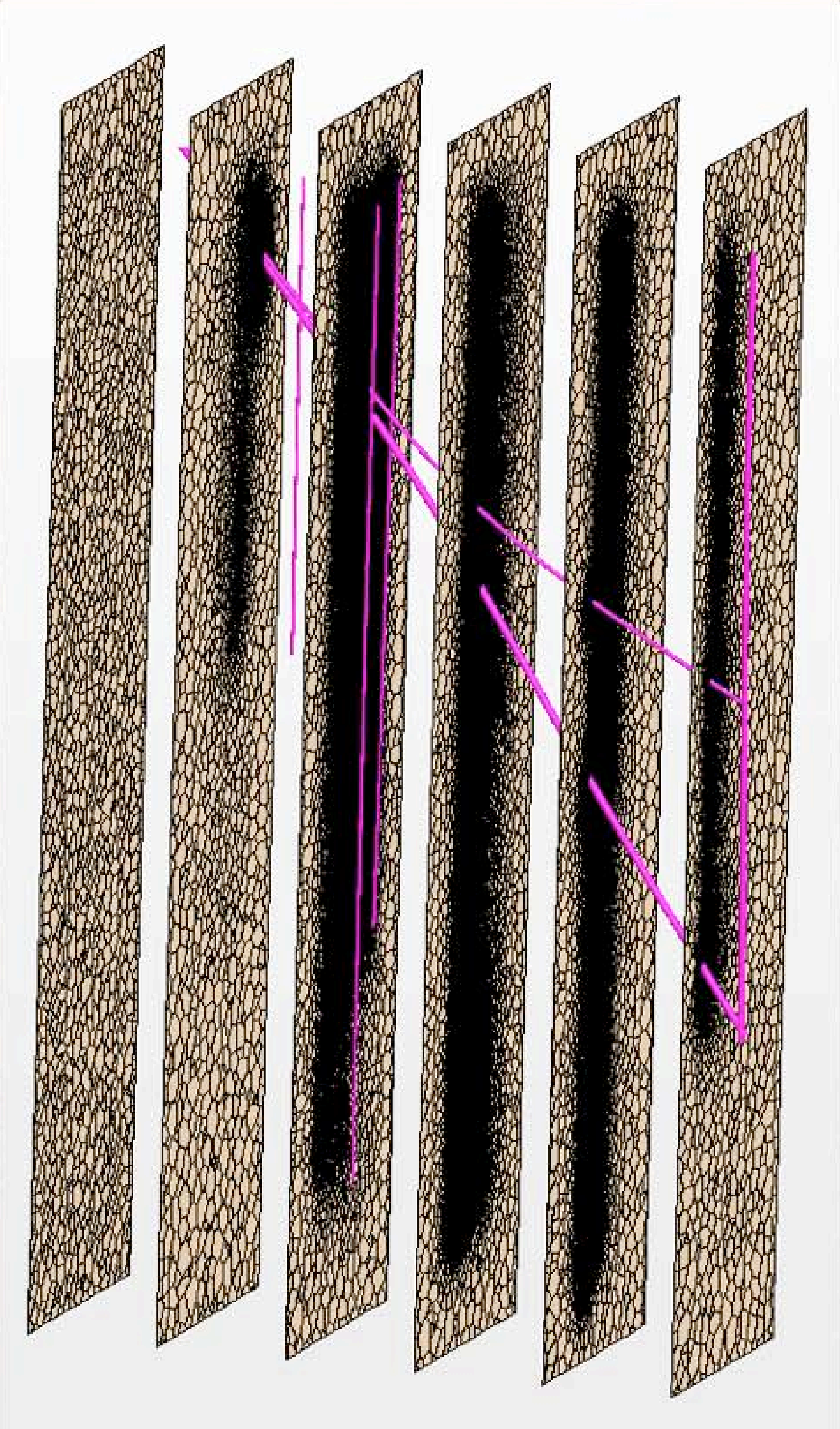


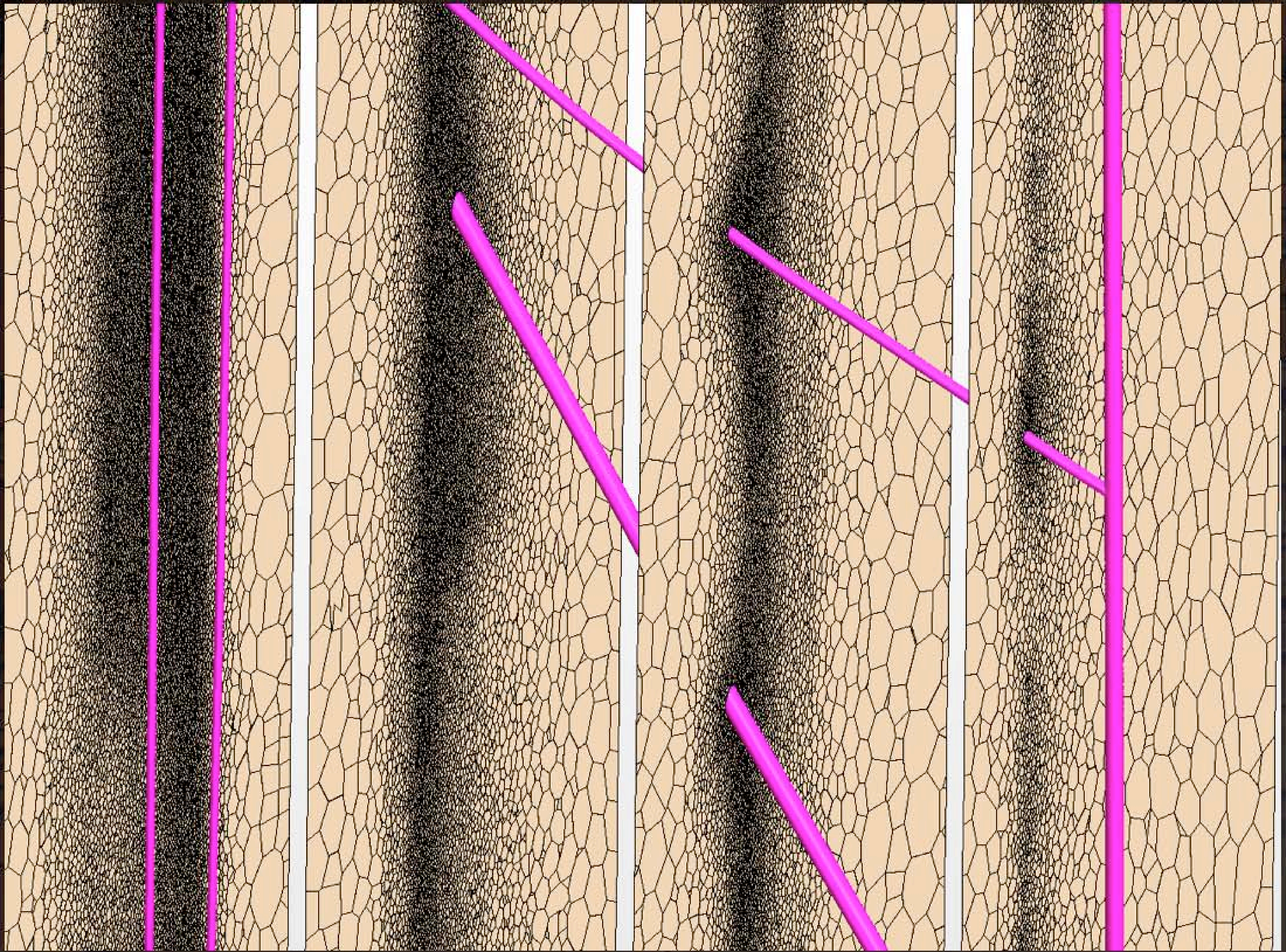



# Simulation Settings

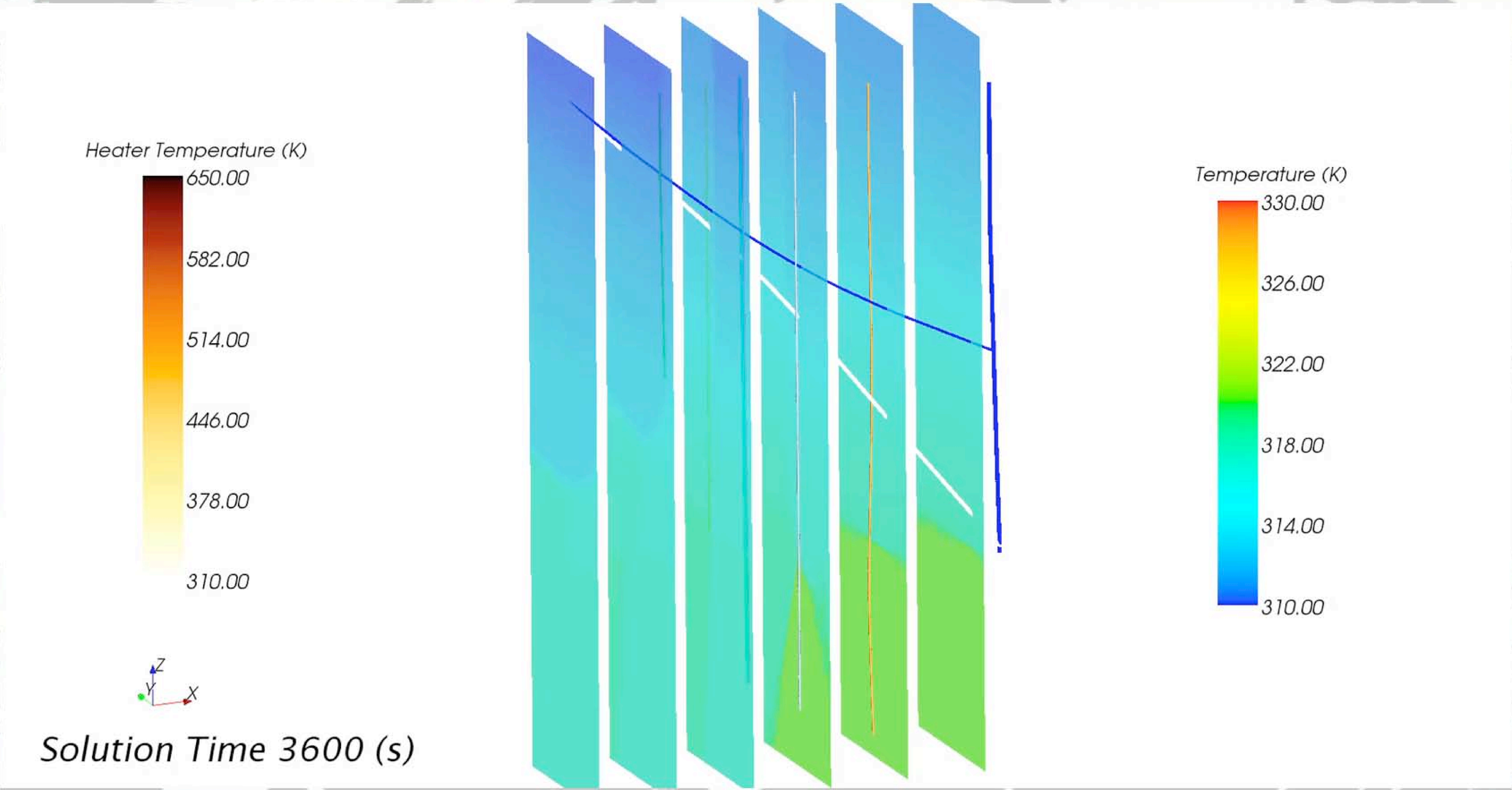
- Using 9 million computational cells to represent shale only
  - Polyhedral mesh
- Modeling solid heat transfer only
- Heater BC based on experimental data
- Tomography (TM) wells are made from concrete
- Simulation time: 160 days ~ 3 days on 480 cores (including I/O)

# Simulation - Computational Mesh

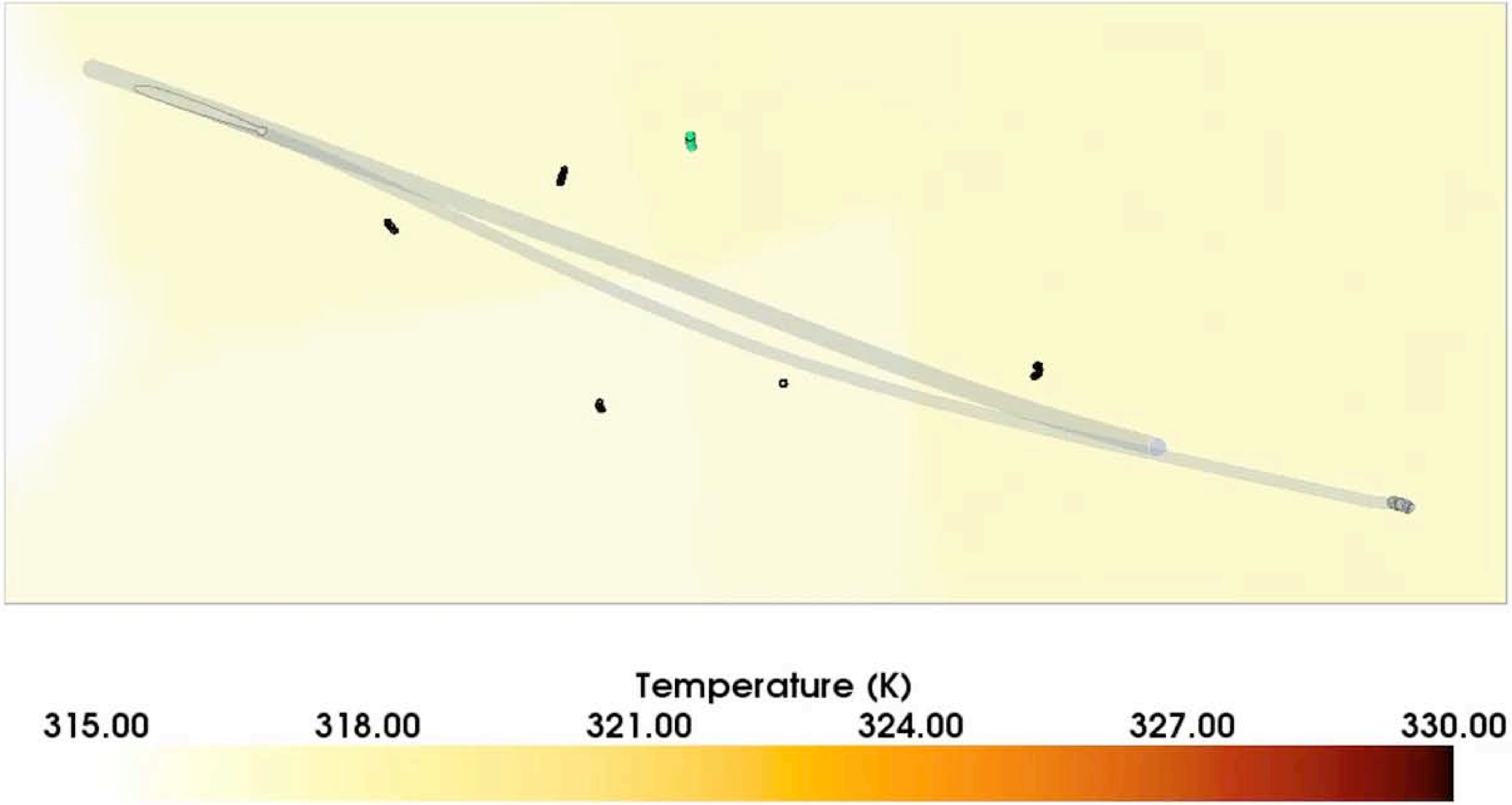




# Temperature Dissipation Results



# Temperature Dissipation Results

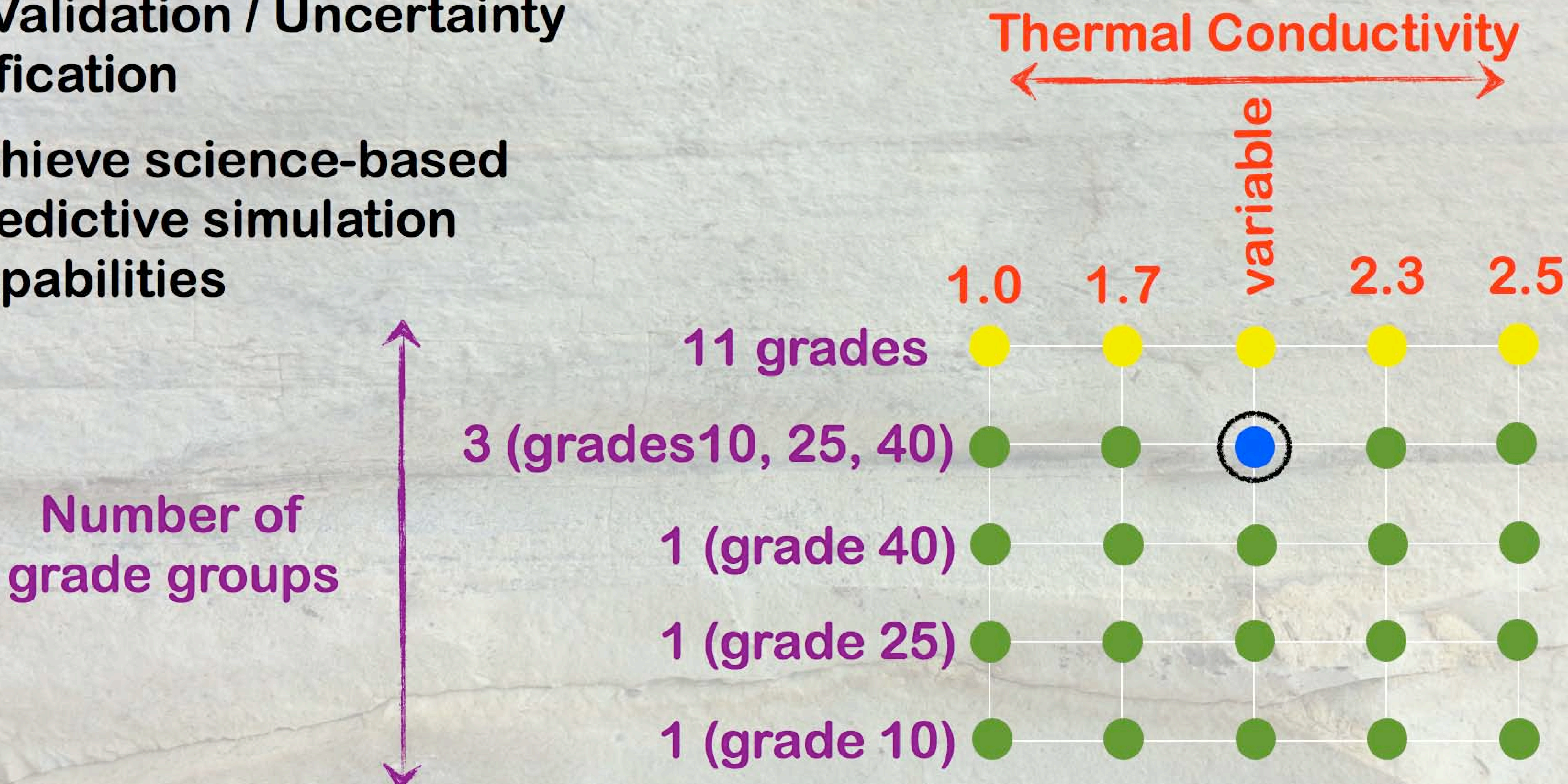



*Solution Time 3600 (s)*

# Generation 1 SIMULATION VUQ Matrix

**VUQ - Validation / Uncertainty Quantification**

- achieve science-based predictive simulation capabilities



26580
322
320
318
316
314
312
310
TM1 - TEMPERATURE (K)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
ADJUSTED DEPTH (m)

26580
322
320
318
316
314
312
310
TM5 - TEMPERATURE (K)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
ADJUSTED DEPTH (m)

# Where are we going ...

- Improving the baseline computation
  - Including properties for more grades of oil shale
- Implement reaction kinetics models
  - Track evaporation of water
  - Track production of oil
- V/UQ

# THANK YOU !

CD-adapco

U.S. DEPARTMENT OF ENERGY

AMSO™
AMERICAN SHALE OIL LLC

TOTAL

CHPC

**National Energy Technology Laboratory**

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