Partnership Progress

Natural Gas & Oil Technology Partnership

June 1996 No. 3

U.S. Department of Energy ■ National Laboratories ■ U.S. Petroleum Industry

Issues

The past nine months have seen a growing struggle develop between Congress and the Department of Energy on funding research in general and fossil energy specifically. Reduced appropriations for energy research this year, particularly for Computational Technology, have stalled a number of Partnership projects that were making extraordinary progress and had very strong collaborative industry support. If you or your organization have strong feelings about this issue, we urge you to contact the members of your congressional delegation.

From Dave Northrop and Bob Hanold

Inside

The Partnership on the World Wide Web:
http://www.sandia.gov/ngotp/

Featured Partnership Projects

Solutions Sought to Increase Recovery in Tight Reservoirs

Tight rock reservoirs, such as diatomites, chalks, and carbonates, hold almost a quarter of the world's crude oil reserves. However, these low permeability oil reservoirs are problematic. Their complex, highly nonlinear reservoir dynamics confound the prediction of well production rates and inhibit the efficiency of enhanced production methods, which in the mechanically weak diatomites cause a high rate of costly well failures as well. Lawrence Berkeley National Laboratory (LBNL) leads three Partnership projects that are searching for practical solutions to increase cumulative recovery and lower production costs at California's large diatomite reservoirs. The projects, discussed below, may yield important benefits to operators trying to produce from other tight reservoirs.

Fluid Injection into Tight Rocks

This project (formerly, Feasibility of Steam Drive and Waterflood in Diatomite) will help the petroleum industry turn steam drive into a commercially viable oil-recovery process for diatomaceous oil fields. Because of their low matrix permeability, it is extremely difficult to inject fluids essential for pressure maintenance and/or improved oil recovery, such as water, carbon dioxide, or steam, into these rocks. Current first principle fluid transport models are inadequate for designing, operating, and predicting the performance of large-scale waterfloods. Historically, the conflict between prudent reservoir management and meeting field injection-production targets has resulted in injectant recirculation and irreversible damage to reservoirs and wells, leaving oil that is unrecoverable through known technologies.

Continued on Page 2

Steam Injection Analyzed in California's Diatomites

Continued from Page 1

LBNL, Lawrence Livermore National Laboratory (LLNL), CalResources, Chevron, Crutcher-Tufts, Mobil, Santa Fe Energy Resources, and Unocal are working to (1) understand the mechanisms of oil recovery from tight rocks and how they affect primary production and production with water injection, (2) optimize conventional waterfloods, (3) develop improved oil recovery technologies, and (4) analyze the geochemistry of diatomite subjected to steam.

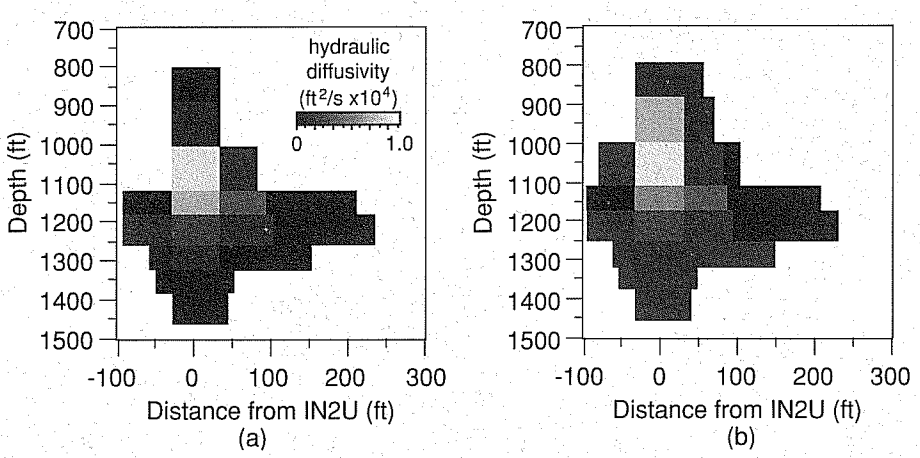

Figure 1: Side view of fracture zone and hydraulic diffusivities in Phase II upper injection fracture after (a) 547 and (b) 1230 days of steam injection.

In California's shallow diatomites, steam injection may recover twice as much oil as water. In these formations, we analyzed water injection, oil production, and well failure data by well, project, and field. Using lease-wide historical data from Mobil's Lost Hills I waterflood (Kern County, CA), we constructed several neural networks which recognize that individual well behavior may depend on well history and injection-projection conditions of surrounding wells. Similarly, we examined waterfloods conducted by CalResources and Crutcher-Tufts. Some of our neural networks accurately predict wellhead pressure as a function of injection rate for all injectors, and vice versa; other networks history-match oil and water production on a well-by-well basis and predict quarterly or semi-annual production.

We have interpreted the CalResources' Phase II Steam Drive pilot in the South Belridge diatomite. The pilot has a hydrofractured producer to either side of the injectors and six temperature observation wells. Steam injection was accomplished over the entire productive interval using two hydrofractured injectors perforated over upper and lower portions of the approximately 1000'-thick diatomite section.

We interpreted the pilot injection and temperature response using a new layered, high-resolution numerical model that combines heat conduction and heat convection by steam and hot condensate. The model generated time lapse images of the extent of steam zones. These images are consistent with temperature logs and cumulative steam injection. We inferred changes in formation permeability caused by the opening and reconnection of natural fractures, thermal stresses in the rock, rock dissolution, and changes in hydrofracture plane size and shape. Cumulative oil production in the two producers was 106,000 and 55,000 BO, respectively; incremental oil production above primary was 60,000 and 37,000 BO, respectively. This translates to total oil recovery of 9% of original oil in place (OOIP) and incremental oil recovery over primary of 6% OOIP after five years of steam injection. The cumulative oil/steam ratio (COSR) was 0.45, and the incremental COSR was 0.28. This incremental oil recovery is close to half the predicted ultimate oil recovery after 50 years of standard 1-1/4 acre waterflood.

History matching studies showed that the evolution of the heated portion of the injection hydrofractures in the pilot is a function of steam injection. Interpreting the distribution of heat within the Phase II pilot volume, we found that hydrofracture shape was asymmetrical. The shape of the hydrofracture in the upper injection well increased as steam was continuously injected near the fracturing gradient. Depths on the plot varied. One hydrofracture (Figure 1) grew upward 300 ft beyond the perforated portion of the well. Hydrofracture winglengths were roughly 260' northeast and 100' southwest after about 1000 days of steam injection.

Permeability of the formation varied across the hydrofracture area and was encoded on the hydrofracture shape. In Figure 1, black shading represents a region of the formation which does not accept steam; light gray shading represents zones with the best injection and heating. The lightest shadings are found just above the perforated interval and immediately around the wellbore. It follows that the formation adjacent to this portion of the hydrofracture accepted the largest fraction of the injected steam. These large hydraulic diffusivities in combination with rapid and extreme heating of the formation are interpreted to be a horizontal fracture or a network of fractures.

Reduction of Well Failures in Diatomite

The ultimate goal of this project is to reduce the high well failure rate in the diatomite reservoirs of Kern County, CA, where, in 1994 alone, replacement costs in the Belridge and Lost Hills fields exceeded $10 million. However, methodologies being developed will be directly applicable to many other fields where production from compactable formations resulted in well damage, including fields in the Gulf of Mexico, South America, and the North Sea.

Now in its second year, LBNL, Sandia National Laboratories (SNL), Bakersfield Energy Resources, Chevron, Crutcher-Tufts, Exxon, Mobil, Santa Fe Energy Resources, and Shell E&P work on the geomechanical analysis of well failure which includes field data analysis, laboratory measurements of time dependent material behavior, and development of an improved numerical modeling capability.

Project participants have completed a comprehensive analysis of field data from the Belridge field. All eight field operators have been given field-wide maps of subsidence, well failure data, and historical production and injection data. Providing these materials in a consistent format and coordinated system allowed operators to examine trends on a field-wide basis for the first time. Data analyses, including 3D visualizations, revealed previously unrecognized systematic trends in well damage. Spatial and temporal correlations between well failures, geologic structure, and subsidence have been identified. Well failures were found to cluster at two horizons in the overburden above the diatomite reservoir. This observation focused attention on the effects of weak layers in the overburden. Data analysis has also shown that deformations are influenced by production and injection at well spacing scales.

A 3D geomechanics model has been formulated to examine the role of effective stress gradient (resulting from local production and injection patterns) in inducing well damage. The model (Figure 2) has 374,139 elements with 437,100 nodal points and includes multiple sliding interfaces to address the role played by weak layers in the overburden that concentrate deformation. The overburden is discretized into ten layers (for which material properties can be varied independently) with three slip surfaces. The diatomite reservoir is divided into nine layers, all with independent material properties. Industry partners are carrying out 3D reservoir simulations to provide the reservoir pore pressures measured over time that are necessary for geomechanical simulation.

Although a Cray multiprocessing

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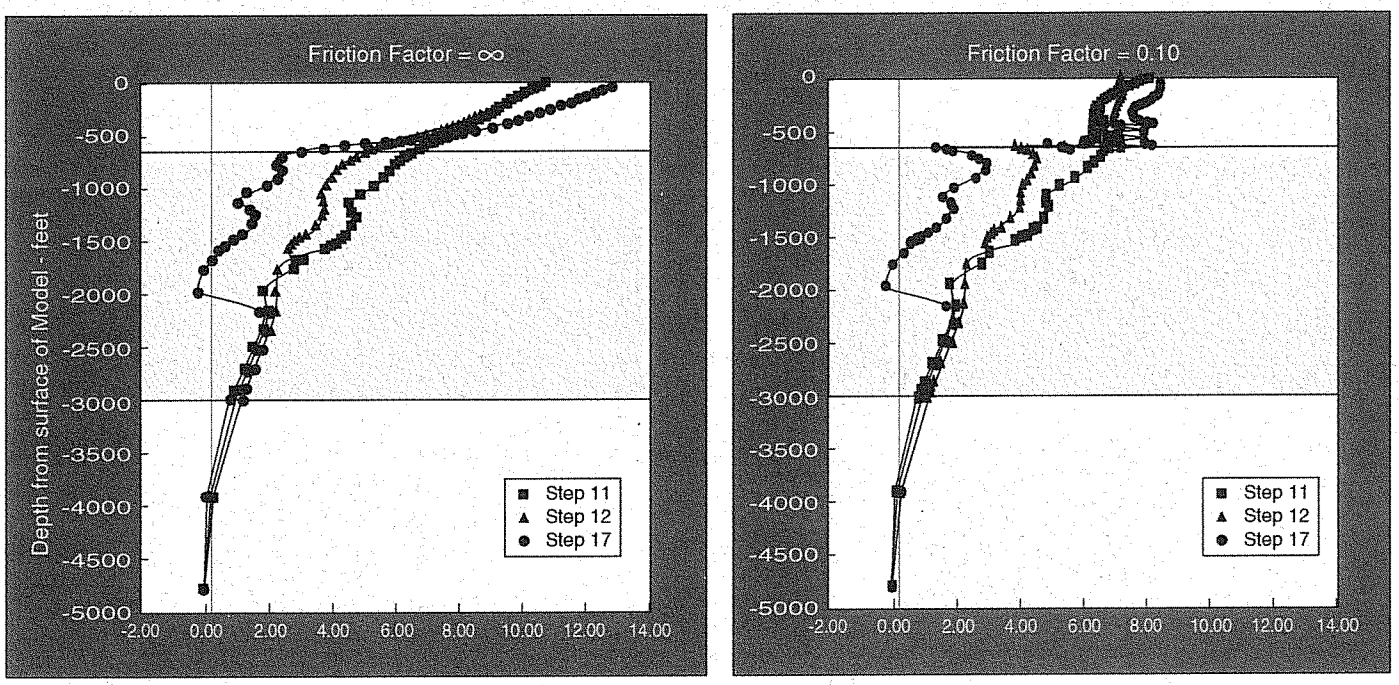

Figure 2: Horizontal displacements at three time steps (11, 12, 17) at a well location (node 5561 in a 2D finite element model) in the central portion of the field. A comparison is shown of results for two friction factors assumed for a slip surface located at the top of the diatomite (shaded region).

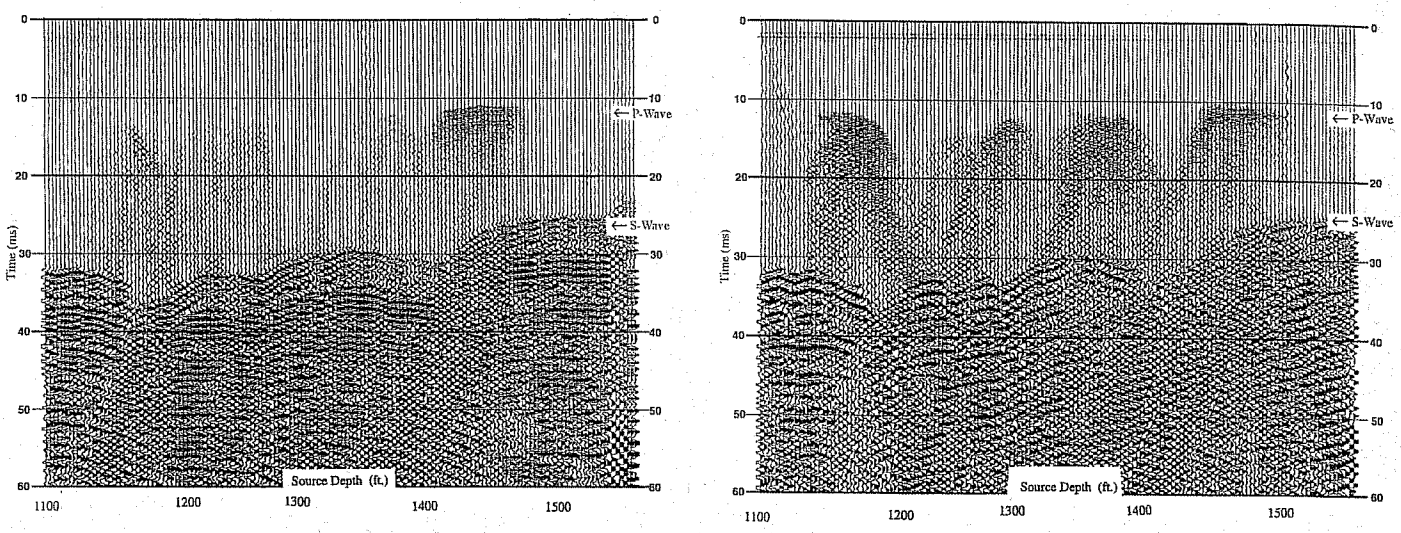

Figure 3: Seismic crosswell recordings from the same source and sensor locations from a steam injection interval of the Belridge diatomite formation, which began in July 1995. (a) Data from August 1995 (left). (b) Data from February 1996 (right) shows large increases in P-wave energy. The peak frequency of the P-waves is nearly 4000 Hz.

Mapping Steam and Water Flow in Diatomite

Conventional enhanced recovery from diatomites is mainly accomplished by hydrofracturing sections of the reservoir and injecting large volumes of water or steam to help increase permeability and push oil toward production wells. For possibly the first time, LBNL, LLNL, CalResources, Mobil, and Shell are using a combination of passive seismic monitoring, crosshole high-resolution seismic tomography, and cross-hole electromagnetic (EM) tomography to determine geometry of hydrofractures and fluid fronts.

While the value of the seismic tomography for elucidating structures between wells has long been appreciated, results from this project now show that as reservoir units become pressurized by injected fluids, those compartments appear as regions of greatly decreased P-wave attenuation (Figure 3). We believe the obvious change in P-wave propagation between surveys is likely to be caused by changes in material properties resulting from steam injection

Other breakthroughs have been made in EM imaging, which is a direct indicator of fluid conductivity and hence fluid type. Significant improvements in instrumentation (increased source strength and improved noise rejection) have increased the reliability of field measurements making it possible to operate at larger well spacings.

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Further Discussion

"Prediction of Formation Damage During Fluid Injection into Fractured Low Permeability Reservoirs via Neural Networks," SPE Paper 31103, in *Proceedings of the SPE Formation Damage Symposium*, Lafayette, LA, 14-15 Feb 1996.

"Neural Networks for Field-Wise Waterflood Management in Low Permeability, Fractured Oil Reservoirs." SPE 35721 presented at the SPE Western Regional Meeting, Anchorage, AK, May 1996.

"Evaluation of Rock/Fracture Interactions During Steam Injection Through Vertical Hydrofractures." SPE 29622 presented at the SPE Western Regional Meeting, Bakersfield, CA, 8-10 Mar 1995.

"Interpretation of Hydrofracture Geometry Using Temperature Transients I: Model Formulation and Verification," *In Situ*, v. 20, no. 3, 1996.

"Interpretation of Hydrofracture Geometry Using Temperature Transients II: Asymmetric Hydrofractures," *In Situ*, v. 20, no. 3, 1996.

Partnership News

January-May 1996

Borehole Seismic Forum

The 10th meeting of the Borehole Seismic Forum was held February 8 in Houston. Fourteen companies participated in this annual review and evaluation of proposals for the Borehole Seismic Technology area. The Partnership Office analyzed the results and formulated a recommendation that was sent to DOE. Two new projects approved for funding are summarized on Page 6.

One outcome from the review was a coordination of tasks from three proposals that dealt with single-well seismic imaging. This effort was developed in response to comments on this issue from many reviewers.

Oil Recovery Technology

The annual review and evaluation meeting for the Oil Recovery Technology area of the Partnership was held April 10 in Dallas. There were 14 proposals: 11 for ongoing projects and 3 for new projects. New this year, Panel members expressed their priorities for the proposals by suggesting funding allocations, with the total sum of allocations not to exceed available funding. A list of projects recommended for funding was sent to DOE. Two new recommended projects are summarized on Page 6.

Status and Impact Study

During January, the national laboratories prepared two-page white papers for every Partnership project which summarized the status of each project and described and quantified the impact that each project has had, or will have, on the petroleum industry and the nation. These inputs were sent to the Bartlesville Project Office.

Texas Oil and Gas Forum

The Texas Oil and Gas Forum serves as a resource for the Texas Railroad Commission by receiving information from majors, independents, professional associations, and the research community. This information is used to guide the Commission's decisions regarding legislation, planning for future reserves development, and the encouragement of research. Kathy Gaither (SNL) and Bob Whitsett (LLNL) have participated in the Forum from its inception. This laboratory and Partnership representation can be an important link to our industry customers regarding their interests, potential partnering, and funding opportunities.

Gaither and Whitsett attended the quarterly meeting held January 17 in Austin, where discussions included: (1) PTTC's finding that better definition of reservoirs and better recovery methods are the industry's primary technology needs; (2) GRI and the State of Texas development of a funding mechanism (based on production surcharge) for gas-related research in Texas; and (3) digital well log archival systems to replace historic paper archives.

DP Information Meeting

Alex Larzelere, DOE Defense Programs, presented DOE's Accelerated Strategic Computing Initiative (ASCI) to several members of the Computational Technology Industry Review Panel February 7 in Houston. The primary thrust of this program, to be conducted at DOE's weapons laboratories, is to create the leading-edge modeling and simulation capabilities needed to shift from nuclear-test-based methods to computational-based methods to integrate stockpile stewardship elements. While not specifically sought, interaction with industry is possible if there is value obtained by DOE in such efforts.

DeepStar Interactions

The annual Offshore Technology Conference was held May 5-9 in Houston. A special session between DeepStar personnel and national laboratory representatives was held May 7. The session was followed by tours of the exhibition floor to educate the laboratories about offshore challenges and technology. DeepStar is a large industry consortium formed to develop technologies to exploit the high-risk deepwater Gulf of Mexico.

DeepLook Interactions

Several national laboratory representatives attended the initial meeting of DeepLook, subtitled "Fluid Imaging for Better Reservoir Management," held February 12-14 in Houston. DeepLook teams visited LBNL, LLNL, LANL, and SNL in May. Additional visits to other laboratories are anticipated. DeepLook is a new industry consortium aimed at the detection, monitoring, and prediction of fluids and their movement in the reservoir up to 200m from the wellbore.

Partnership Office Meeting

Partnership Office members held a business and planning meeting May 20-21 in Idaho Falls, ID. The meeting emphasized planning for FY97 with the focus on creating an improved Partnership. Among the results: a nine-laboratory Partnership was affirmed, new methods were explored to improve industry interactions, steps were initiated to improve operations, and action items were adopted to address funding concerns and to take advantage of new opportunities.

New Projects

Two new Borehole Seismic Technology (BST) projects and two new Oil Recovery Technology (ORT) projects have been recommended to the Department of Energy Bartlesville Project Office for funding based on industry evaluation and prioritization of project proposals. The two BST projects have already been approved for funding.

Borehole Seismic Forum

Industry comments from the Borehole Seismic Forum meeting held February 8 in Houston resulted in the integration of three proposals that dealt with single-well seismic imaging into the Single-well Seismic Imaging System project. This project will develop source and receiver system interfaces and upgrades that will allow testing of different combinations of commercial sources and receivers in single-well data acquisition systems. Modeling of source-receiver coupling noise will guide this effort.

The second approved project, Acquisition of Borehole Seismic Data behind Production Tubing, will seek to reduce the cost of future borehole seismic surveys. As the expense of pulling tubing continues to increase so does industry need for multi-level downhole receiver systems developed to work behind production tubing. Activities will emphasize modeling of issues associated with acquiring high-quality data from behind tubing.

Oil Recovery Industry Review Panel

As part of their evaluations, ORT Review Panel members prioritized proposals by indicating funding allocations. Two proposals submitted for review during the Panel meeting held April 10 in Dallas were recommended for funding.

Successful field testing of the only perfluorocarbon salt tracer (PFT) developed for use in vapor phase tracing in gas injection EOR processes will encourage the development of others, resulting in a suite of PFTs available to industry. To test the available PFT, work in the recommended Field Demonstration and Validation of Perfluorocarbon Salt Tracers for Water Injection EOR Processes project will test PFTs in a variety of reservoir cores under a range of pressures and temperatures.

The second recommendation, the Improved Waterflooding through Control of Brine Composition and Other Factors which Affect Crude Oil/Brine/Rock Interactions project, will seek to obtain a more complete understanding of the effects of brine composition, temperature, and crude oil properties on wettability and its effect on oil recovery. Reservoir condition studies will be conducted in fields that include a range of formation brines, crude oils, and rock types. Analysis will guide research and lead to controlled field testing for both new and mature waterfloods. The final product will be a framework based on laboratory experiments and field evaluation, backed by theory, that operators can use to improve waterflood oil recovery.

Publications

Journal Articles

Alkhalifah, T., I. Tsvankin, K. Larner, J. Toldi. "Velocity analysis and imaging in transversely isotropic media: Methodology and a case study," *The Leading Edge*, v. 15, no. 5, 371-378, 1996.

Benzing, W.M., G.M. Shook. "Study advances view of geopressured seals," *Oil & Gas Journal*, 20 May 1996.

Elata, D. "On the oblique compression of two elastic spheres, LLNL report UCRL-JC-121536, *Journal of Applied Mechanics*, in press, 1996.

Elata, D., J. Dvorkin. "Pressure sensitivity of cemented granular materials," *Mechanics of Materials*, in press, 1996.

House, L., M. Fehler, F. Aminzadeh, J. Barhen, S. Larsen, "A national laboratory-industry collaboration to use SEG/EAEG model data sets," *The Leading Edge*, v. 15, no. 2, 135-136, 1996.

Myer, L., J. Jacobsen, J. Horsman, J.T. Fredrich, W.R. Wawersik, J.G. Arguello, M. Bruno, H. Qian. "Use of visualization techniques in analysis of well failures in diatomite reservoirs," *The Leading Edge*, v. 15, no. 3, 185-189.

Schoenberg, M., F. Muir, C. Sayers. "Introducing ANNIE: A simple three-parameter anisotropic velocity model for shales," *Journal of Seismic Exploration*, v. 5, 35-49, 1996.

Technical Reports and Presentations

Bethel, W., J. Jacobsen, A. Austin, M. Lederer, T. Little. "Implementing virtual reality user interfaces for the geosciences," presented at Virtual Reality in the Geosciences meeting, Halden, Norway, 24-25 Jun 1996.

Glowka, D.A., T. Dennis, P. Lee, J. Cohen, J. Chow. "Progress in the Advanced Synthetic-Diamond Drill Bit Program," *Transactions of the ASME Energy Conference Week '96*, Houston, 30 Jan-1 Feb 1996.

Nikravesh, M., A.R. Kovscek, T.W. Patzek. "Dividing oil fields into regions with similar characteristic behavior using neural network and fuzzy logic approaches," in *Proceedings of the Biennial Conference of the North American Fuzzy Information Processing Society*, Berkeley, CA, 19-22 Jun 1996.

Nikravesh, M., A.R. Kovscek, A.S. Murer, T.W. Patzek. "Neural networks for field-wise waterflood management in low permeability, fractured oil reservoirs," SPE Paper 35721, in *Proceedings of the 66th SPE Western Regional Meeting*, Anchorage, AK, 22-24 May 1996.

Ober, C., R. Oldfeld, J. VanDyke, D. Womble. "Seismic imaging on massively parallel computers," SAND 96-1112, on the WWW at **http://www.cs.sandia.gov/~dewombl/ACTI16.html**. Also presented at the Society for Computer Simulation (SCS) Multiconference, New Orleans, 8-11 Apr 1996.

Presented at the 7th International Workshop on Seismic Anisotrophy, Miami, FL, 19-23 Feb 1996:

Alkhalifah, T., I. Tsvankin, K. Larner, J. Toldi. "Velocity analysis and imaging in transversely isotropic media: A case study."

Berge, P.A. "Constraining lithology in TI sediments," LLNL report UCRL-JC-122892Abs.

Elata, D. "The effect of the mean field approximation on modeling the stress induced anistrophy of unconsolidated granular materials."

Muir, F. "Parsimonious rock descriptions."

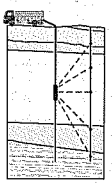
Muir, F., S. Agar. "Man-made shales under the microscope."

Presented at the European Association of Geoscientists and Engineers 58th Annual Meeting and Exhibition, Amsterdam, The Netherlands, 2-7 Jun 1996:

Al-Dajani, A.F., I. Tsvankin. "Nonhyperbolic reflection movement for horizontal transverse isotrophy."

Rommel, B.E. "Dip movement processing (DMO) for converted waves in transversely isotropic media."

Partnership Project News



Borehole Seismic Technology

January-April 1996

3-Component Vibratory Source

The electronics module underwent integration testing in December 1995. E-Systems tested the vertical vibrator with the new clamp to see if eliminating the surge chamber and using the new clamp improved the frequency spectrum. The tests showed little change. Field testing will verify source output vs. frequency.

The cable head was terminated on a section of the new heavy-duty wireline and tensile tested; it performed as desired. The electric motor and pump were tested at 92% and 88% efficiency, respectively.

Industry will fund field tests scheduled for this summer. If results are promising, DOE funding will be sought to work on the other two vibrator axes.

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Microborehole Seismic Instrumentation

A 4.5"-diameter borehole was drilled and dual-completed by cementing in two steel tubes having inside diameters of 0.75" and 2.0" at the Amoco Mounds test site to simulate a microhole test environment. Tests were conducted with the 0.5" OD microhole instrumentation packages inserted in the 0.75" pipe. A 1.68" slimhole geophone package was inserted in the 2.0" tube to collect data for comparison. Seismic waveforms were recorded from a seismic piezoelectric source deployed in a well and from small explosives detonated in a shot hole. Waveforms from the explosives were of comparable amplitude on the microgeophone and slimhole sensors. The data taken by the downhole accelerometer package were found to have good signal-to-noise ratio at frequencies well above 500 Hz and good arrival time breaks. However, a strong late-arriving 300 Hz resonance signal was observed. To identify the source of the resonance, a second field test is planned.

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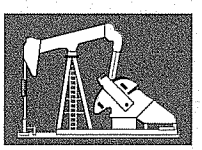

Oil Recovery Technology

January-April 1996

Applied Production Technology (APT)

Sucker Rod Failures

The third and fourth downhole dynamometer field tests were conducted near Midland, TX, in a 9000' well with a Rotoflex pump in February and a 3000' well in March. Both tests proceeded flawlessly at the surface. In the March test, pump fillage could be controlled from the surface to measure fluid pounding at different pumping speeds to determine its effect on compressive rod loading.

Automatic Casing Swab

Analysis of the potential for the ACS to impact the lubricator with excessive velocity was revised to include the effects of a pressure relief valve and shock absorbing spring. Discussion was initiated to complement the finite element analysis of the scaling of ACS cups by adapting the technology to other diameters.

Field Measurement of Oil Properties

The assembly of the portable cloud point detector was completed and field tested January 16 at the Rocky Mountain Oil Field Testing Center. Results indicate that the device will provide reproducible, high-resolution determination of cloud point in the field.

The Thickness Shear Mode (TSM) resonator (formerly called QCM) portable cloud point detector was delivered to Petrolite. Petrolite is conducting tests comparing the data from the TSM detector with viscosity and cold finger cloud point determinations for a number of different oils.

Technology Transfer, including Paraffin Control

The Joule-Thomson cooling equations contained in the hot oiling spreadsheet were converted into a Visual Basic program and added to hot oiling calculations already available on APT's World Wide Web site (**http://www.sandia.gov/apt/**). The coding of Petrolite's Windows version of the Hot Oiling Spreadsheet was reviewed and several corrections were made. Finalization of this program

Continued on Page 8

Project News (Continued from Page 7)

marks the completion of the original APT project task.

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Optimizing Reservoir Production

Pore geometry data from ultra-high resolution imaging are being used in flow simulations. Upscaling techniques were implemented and tested, using renormalization group theory (RGT), on data from Berea sandstone. Comparison of permeabilities calculated from the Lattice Boltzmann simulator against values predicted by the RGT models revealed discrepancies, and further analysis of the technique is needed.

The 3D BP Exploration code that emphasizes non-linear transport was merged with the 3D flexible gridding code of Chevron that emphasizes geological heterogeneities. The merged code uses renormalized relative permeability curves on a nonuniform grid which has been optimally coarsened to reflect the underlying heterogeneity of the reservoir.

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Wireless Telemetry Tool

The microprocessor for the downhole transmitter was acquired, and most of the programming of this circuit is finished. EDO Western is completing the fabrication of the power supply. The University of New Mexico's Electrical Engineering Department completed their signal processing study of the telemetry system. SNL has recently filed another patent application on the telemetry hardware with the U.S. Patent Office.

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Ultrasonic Reduction of Formation Damage

The prototype ultrasonic cleaning tool was field tested in two coal bed methane wells and one oil-producing well near Farmington, NM. On-site diagnostic measurements of changes in wellbore pressure during treatment were possible for only one of the methane wells. These data indicate that the tool produced positive effects on gas production during application of ultrasound. Reports from the operating company will determine if long-term increases in gas and oil production are observed.

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Extending Borehole EM Imaging

A field survey was conducted at the Lost Hills #1 oil field with one steel-cased borehole. Using low frequency (20 to 30 Hz) data, we obtained casing parameters, electrical conductivity, and magnetic permeability. Data were corrected using these parameters at all frequencies as if they had been taken in the absence of steel casing. The results were then inverted to produce a layered earth conductivity section.

Researchers determined that the formation and casing responses to EM fields are algebraically separable at low frequencies, that the measurement is sensitive to changes in formation resistivity, and that a measurable-amplitude difference exists at higher frequencies (around 300 Hz), which can be used to monitor changes in the formation resistivity.

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Fracture Mapping and Slimhole Geophone Array

Fracture Mapping

A single geophone was deployed at reservoir depth in an observation well located 500' from a line of carbon-dioxide injector wells in Texaco's Slaughter oil field in west Texas. If microseismicity is associated with the recovery operations, additional tools will be deployed to enable microseismic mapping and data interpretation.

Slimhole Geophone Array

Borehole and pressure vessel testing of the three sondes with mechanical arm assemblies was completed for pressures and temperatures up to 6500 psi and 180º C. Bench-top testing of the two-level sonde configuration with the PC surface control system was successful. Borehole testing of the two-level configuration was successful at low temperatures, but circuitry problems occurred in the electronics at higher temperatures. Borehole and bench-top oven testing is underway to identify and solve the problem.

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Tiltmeter Hydraulic Fracture Imaging

Computer code development for determining the geometry of hydraulic fractures has begun. The first objective will be to determine the distribution of opening hydraulic fractures in homogeneous and layered half-spaces using the deeper tiltmeter data.

The prototype tiltmeter tool was deployed in a 50'-deep hole in connection with Chevron's 4,900'-deep hydraulic fracturing treatment in the Lost Hills area in February. It successfully mapped the hydraulic fracturing treatment.

To provide superior data, a newly designed and fabricatedprinted circuit board for the tiltmeter will take the place of the surface datalogger. Con-

Continued on Page 9

Project News (Continued from Page 8)

struction has begun on the next generation tiltmeter, a "slimhole" design with an outer diameter of 2.5" and a new leveling device.

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Improved Prediction of Multiphase Flow

An experimental procedure was developed to obtain S-P measurements in porous media. Hydrophilic and hydrophobic tensiometers measure fluid pressures. A modern dual-energy gamma radiation system determines fluid saturations simultaneously and nondestructively.

All necessary equations were derived for a two-phase version of a hysteretic k-S-P theoretical model for oil- and intermediate-wet porous media. The model uses an index that distinguishes between water-wet and intermediate-wet pore sizes. To test the completed model, waterflood experiments were conducted in intermediate-scale flow columns using water-wet and intermediate-wet porous media.

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Surfactant Enhanced Displacement of Fracturing Fluids

A series of tests, which examined the influence of sand pack heterogeneity on fluid displacement, showed that sand pack stratification relative to fluid flow direction did affect observed fingering under low viscosity conditions.

Tests began to study treatments for enhancing gel recovery. Encouraging results were achieved with broken 40 lb HPG gel, showing that a surfactant additive decreased residual gel saturation. Similar enhancement was found for a 20/40 sand coated with a cationic surfactant. Test results, coupled with previous data, indicate that gel displacement is relatively insensitive to differential pressure, but affected by fluid viscosity.

A prototype test was run at SNL to look at displacement from matrix rock. Even for a relatively porous sandstone, over 55% of the fluid remained in the slab after displacement. Saturation profiles were noted to closely follow the textural heterogeneity of the rock.

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Drilling and Completion Technology

January-April 1996

Advanced Synthetic-Diamond Bit Technology

The Cutter Wear Test Facility was brought into operation. The control system for maintaining a constant penetration rate of the bit in rock was completed. Several test holes were drilled in Berea sandstone, both with a surface-set diamond bit and the three-cutter core bit. Performance was excellent. Calibrating the strain gages on the bit to allow the penetrating and drag forces on a test cutter to be measured is underway.

Single-cutter performance testing in support of the Security DBS Track-Set bit project also continued. All side- and back-rake tests were completed. Work began on engagement-angle and restoration-force tests using worn cutters at various stages of wear.

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Fatigue Failure in Top Drive Rigs

One of Shell's drilling operators had a top drive failure in 1995, which caused a renewed interest in testing. We are soliciting support from the drilling industry to provide a drilling platform to instrument and record data during jarring operations.

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Advancing MWD into Ultra-Deepwater Drilling in the Gulf of Mexico

Following preliminary analysis by Lamont-Doherty Earth Observatory and Schlumberger, LLNL will help interpret the results of deepwater drilling in the Gulf of Mexico.

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DEA/CEA Projects

Improvements in Drilling Using Electro-Osmosis (DEA #70, Phase 2)

Four-electrode conductivity measurements were performed on clay samples to characterize clay conductivities fully at various frequencies. Results provided a reasonable value of conductivity (0.4 S/m) that was used in a computer model to generate equipotential and current flow lines, which describe the cathode/anode system underground on the basis of Laplace's equation. Model results indicate that on field scale-up, the current densities attainable will be less than those seen in experiments.

To achieve a better understanding of the field situation, experiments continue which employ a much reduced

Continued on Page 10

Project News (Continued from Page 9)

current level to observe any deviations from extrapolations based on previous data. Experiments showed that the idea of enhancing the cement hardening process using electroosmosis is not a viable one.

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Analysis of Casing Damage Induced by Reservoir Compaction (DEA #99)

Casing damage occurrences and mitigation practices at several fields in which a total of more than 1500 wells have sustained damage were analyzed. While casing damage was the common denominator, actual causes were related to a spectrum of sources: reservoir and/or overburden compaction, shear concentrated along weak bedding planes, shear concentrated near perforations, and casing collapse related to corrosion and steam-leak weakened casing. Mitigation strategies included under-reaming, heavy-wall casing, and water injection. The specific mitigation strategy is highly dependent on the local cause of the casing damage.

Numerical simulations of the inelastic mechanics of formation-cement-casing interactions were documented.

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Air/Mist/Foam and Underbalanced Drilling (DEA #101)

The MUDLITE computer program was distributed to project participants, and demo versions were distributed to others attending the Drilling Engineering Association (DEA) forum held in Canada. One participating company evaluated the beta version of the program and found it compared favorably to in-house field data and was better than two other commercial codes that were evaluated.

Preparation of the first edition of the DEA-101 Underbalanced Drilling Manual was initiated with the target distribution date for fall 1996.

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Rheology and Proppant Transport (CEA #1)

Results of recent SNL modeling and experiments on proppant settling and transport were presented at the semi-annual meeting of the Stim-Lab Rheology and Proppant Transport Consortium partners on March 1 in Mesa, AZ. Results are consistent with those at Stim-Lab, and in some cases the SNL work elucidates earlier Stim-Lab observations.

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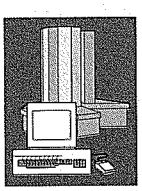

Computational Technology

January-April 1996

Near Wellbore Mechanics

Discrete Element Modeling Team

Work on the SANDMIT code began with theoretical developments on deformable arbitrarily-shaped particles, as well as on bonding methods. An assessment of the 3D contact search algorithm was also accomplished. Particle shapes in 2D for Castlegate sandstone were defined using photomicrographs. MIT will digitize 20 of these shapes. Coupling of the discrete element code, MIMES, with the Darcy fluid flow code was completed, and test cases are being exercised.

Material Testing Team

Five hydrostatic compression experiments on Castlegate sandstone were attempted during April. Two experiments were successfully completed but showed differences in the pore collapse threshold as well as the permanent strain. The other three experiments experienced jacket failures. The reasons for the failures are now understood, and the problem was corrected. The differences observed between the two successful experiments are under investigation.

Near Wellbore Stress Modeling Team

A number of subroutines were written in an attempt to develop the numerical integration schemes necessary to handle the load-angle dependence of yield in a cap plasticity model that satisfies the needs of the modeling team. One of three integration schemes was chosen and is being implemented into the SANTOS finite element code.

Perforation Induced Damage Team

Project plans include comprehensive experimental and computational work to assess the damage induced to the formation by the shaped charge. Initially, project participants will assess shaped charge penetration tests by Halliburton Explosive Products Center (HEPC) performed on concrete.

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Continued on Page 11

Project News (Continued from Page 10)

Advanced Computational Models for Deep Water Oil and Gas Production

Subtask 1: Fluid/Structure Predictive Code Development for Riser Design Tool Box

A kick-off workshop with key members of the DeepStar Committee on Risers and Umbilicals was held March 8. Work began on a vorticity-based bluff-body fluid flow solver for use in the riser design effort. A preliminary version of the 2D fast solver was completed and is undergoing verification tests. The subroutines that calculate diffusion/convection of vorticity from the wall into the fluid were completed and verified. A preliminary version of the Lagrangian remapping routine was written and is undergoing testing.

Subtask 2: Strength of Composite-to-Metal Joints

SNL personnel met with representatives of Northrop Grumman Marine Systems to discuss the composite riser design currently being developed in conjunction with the DeepStar consortium. The analyses and testing to be performed by SNL were subsequently documented, and fabrication of test specimens is underway.

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Well Log Imaging

California, Texas, Illinois, Michigan, and Kansas supplied specific fields and plays from which geophysical logs will be rasterized; these data were forwarded to MJ Systems. LLNL personnel are investigating state-of-the-art compression techniques, using sample raster images supplied by MJ Systems. They have concluded that current Group IV compression algorithms are the most efficient for this project.

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Geologic Structure and Reservoir Mechanics

Significant progress was made on the project in March and April. The second users' workshop was held April 1-3 in Albuquerque to train the partners on SNL finite element codes, to discuss the partners' experiences in running the codes, and to expand the type of applications that could be performed. Also, several new developments were added to the codes. These included installation of the Widlinger cap model in SANTOS and JAS3D and initial implementation of a 3D infinite element capability.

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Reservoir Studies and Information Delivery Tools

Project related work continues within the weapons program at LANL. Development of a distributed design environment continues. This environment will be built upon existing CORBA and World Wide Web technologies and is aimed at allowing efficient distribution of the engineering process between remote experts.

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Perforation Dynamics in Geological Media

Analysis of the Borchers Field data began. Daily injection and withdrawal flow records from each well were incorporated into artificial neural networks (ANNs). The goal is to have the ANNs "learn" the flow connectivity of the wells, the effective skin factors for each well, and the temporal variation of the skin. If this can be accomplished, it may be possible to optimize the overall injection/withdrawal strategy for the field and to have the networks suggest the best reperforation strategy.

Designing of several CALE calculations aimed at achieving better understanding of the development of the crushed zone around a perforation tunnel began. We have designed and implemented an adaptive filter that uses the wellhead pressure and flow rate data to derive the conductivity without requiring the bottom-hole pressure measurement. Our goal in the short term is to design and deliver an automated gas-field evaluation system. Over the longer term, we will attempt to improve the adaptive filter by including geophysical, well-design, and especially perforation parameters.

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Advanced Reservoir Management (ARM)

Final reports for work initiated under GONII auspices for Nance Petroleum and Berry Petroleum were issued in February. A draft report was prepared for the Ardent 3D seismic interpretation project in the state of New York.

Work began on the Lynx Petroleum project for the Reed Sanderson Unit. Geological modeling is underway for Wold, Daugherty, Midland, Spooner, Foreland, and Pacific Operators. Simulation is in progress for Midland, Belden & Blake, Berry, and Nance.

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Modeling and Processing Seismic Data

An algorithm for 3D prestack depth migration was developed for the acoustic phase-screen one-way propagator. Both the original phase-screen and the wide-angle approximation methods were tested on synthetic models. An initial computer code was implemented on the Cray T3D that demonstrates the phase-screen migration algorithm parallelizes well by

Continued on Page 12

Project News (Continued from Page 11)

having multiple processors, each working on separate subsets of wavefield frequencies.

Further theoretical tests on the wide-angle complex-screen forward modeling method revealed an instability for critical-angle incident waves. The instability is removed by allowing slowness to be complex to avoid the singularity. Numerical comparisons with finite difference and ray methods showed that the modified (complex slowness) wide-angle approximation gives the greatest accuracy of all screen methods for models.

Six extended abstracts based on work performed for this project were submitted to the Society of Exploration Geophysicists annual meeting, to be held in November, and are available in downloadable form on the project's World Wide Web site: **http://www.ees4.lanl.gov/ACTI-NEW-METHODS/ACTI-NEW-METHODS.HTML**.

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Velocity Analysis, Parameter Estimation, and Constraints on Lithology

Investigators from LLNL, Stanford, and Colorado School of Mines presented research results at the 7th International Workshop on Seismic Anisotropy held in Miami in February.

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Subsalt Imaging with Marine Magnetotellurics

Sea trials for the seaborne magnetotellurics (MT) system will begin in August. Chevron will provide a 3D interpreted top and base of salt for the area which will be used to construct a 3D magnetotelluric model.

It appears that numerically modeling the effects of having only one magnetic station on a sea floor MT line, as opposed to the standard land situation of having magnetics at each site, will not be limiting to the resolution of salt structures, as long as the inversion code is modified to account for this change. Software which can read the industry-supplied salt top and bottom interfaces and generate a 3D numerical model was prepared.

Further testing of the acoustic release system used in the sea floor instrument was done. Two units, housed in a magnetometer assembly, were deployed in 800-m water off San Diego. We could transpond to the unit over a range of 4 km. We also discovered that the second transponder/release board mounted in the instrument performed poorly because of inadequate shielding. This problem was fixed.

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Subsidence, Analysis, and Control

Work continued on expanding the grid modification to the TOUGH2 code so that fluid volume changes in each node block could automatically be converted into new nodal distances. In that way the grid used for calculations expands and contracts in response to changes in compressibility of the fluids in each volume element.

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Optimal Fluid Injection Policy and Producibility

Analysis of new data and work on developing field-wise waterflood management continue. We analyzed new data gathered from more than 180 producer wells (waterflood data from Crutcher-Tufts and Mobil) for testing our waterflood management strategy. The results were posted at our Web site: **http://patzek.berkeley.edu/**.

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Advanced Visualization and Virtual Reality

Work is in progress to modify existing spatial-search algorithms to use the original cell-based grids provided by the partners, rather than a derivative grid. The previous algorithms developed for spatial searches required only minimal cosmetic modification for use with the new grids. LBNL personnel can now demonstrate software in the laboratory's new graphics facility, which was constructed in conjunction with the move of the National Energy Research Supercomputer Center from Livermore to Berkeley. A wall-sized stereo back-projection system is used as the output device. All previous software and VR input devices functioned flawlessly in the new environment without modification.

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Synchrotron Computed Microtomography

Core samples provided by Mobil were successfully analyzed at the Brookhaven National Synchrotron Light Source (NSLS), and high-quality microtomographs were produced on BNL computers. The 3D stereographic visualization facility, a room-sized facility where the core samples can be viewed and navigated with a remarkable degree of realism and presence, was successfully installed. The entire analytic pipeline, from the NSLS instruments to the imaging computers, was put on an experimental high-speed network testbed to vastly reduce the time from data taking to analytic results. The collaboration has also conducted experiments with analysis of seal rock, and results have been encouraging.

Faster algorithms for producing microtomograms and 3D images will be investigated. The goal is to speed up

Continued on Page 13

Project News (Continued from Page 12)

the graphical presentation to provide an element of "real-time" analysis to the porosity and fluid flow investigations.

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Advanced Computational Analysis of Drill Cuttings

Baseline physical properties data for the project study rocks are being entered into a database, which stores both graphical and nongraphical data and provides analysis and data searching capability. Woods Metal porosymmetry tests were conducted in support of the modeling effort. These tests provide data on the topology of the void space in different reservoir rocks.

Sensitivity studies using the graph-theory-based program for calculating relative permeabilities of 3D pore networks continued. Non-wetting phase relative permeability values and capillary pressure curves were calculated for a variety of model parameters. Trends were observed between pore size correlation length and relative permeability magnitudes.

To examine the problem of obtaining representative cuttings at the well, cuttings samples were collected during drilling of a well in the Green River Basin targeting the Almond member of the Frontier group. Preliminary observations indicated that neither the type of bit nor the motion of the drill string had significant effects on cuttings size; however, fluid pressure has a major effect.

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Innovative Gridding and Solution Techniques

The add-mesh capability for the GEOMESH code was successfully used for creating grids with both stratigraphy and wellbores. The grids were developed separately. The stratigraphic data were used to create a site model. The wellbore model was then embedded in the site grid. This capability will be very useful in evaluating long-reach horizontal wells.

To achieve efficiency for parallel machines, we are investigating an approach in which the Schur complement is moved outside the multigrid loop. We are currently investigating a technique in which the p ∞ p system can be made diagonally dominant enough to achieve good solution by Jacobi iteration.

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Large Downhole Seismic Sensor Array

In preparation for this summer's field test, one digital electronics package was fabricated, and bench testing has begun. After bench tests are completed, six more units will be built for use in Texaco's six-level hydrophone string that is part of the field test. The analog electronics package design is complete, and components are on order. Design of the surface data-acquisition system is nearly finished.

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Gulf of Mexico Subsalt Seismic Imaging

Efforts have focused on modifying our poststack migration code used to migrate zero-offset data to handle prestack data. The prestack code now runs well on the Cray T3D. The current version uses travel times computed using our Eikonal solver. Travel times for source and receiver are calculated on a coarse grid, expanded to a grid that is the size of the image grid by interpolation. Travel time data are eliminated in regions where head-waves occur. Finally, the trace data are migrated into the image grid using the travel times.

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Increased Effectiveness of Hydraulic Fracturing

In February, SNL completed the task of adapting its patented PAVING algorithm to improve meshing and code stability in the TerraFrac code. The modular FORTRAN code was delivered to TerraTek for them to link with TerraFrac.

SNL initiated the task of comparing TerraFrac output with the GRI/DOE funded hydraulic fracture mapping project at M-Site near Rifle, CO. The resulting fracture maps look good, and the quality of the data suggest that they accurately reflect the time evolution of the fractures.

In the proppant flow task boundary element cases are being run to develop a statistical database of settling rates versus relative particle size, flow rate, and concentration. In qualitative experiments in flow and no-flow conditions, settling rate was observed to be 2.3 times higher for the flow case than for the no-flow case, a result consistent with rates determined from numerical models.

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Locating Geopressured Hydrocarbon Reservoirs in Soft, Clastic Sediments

Modeling of the vapor-lock seal continues. Various geometries of sands within the pressure transition zone have been tried. The latest runs resulted in charging a sand to nearly 80% gas saturation. Runs under consideration include sands that extend from within the transition zone to well outside the zone. The first paper describing conceptual model and initial simulations in appeared in the May 20, 1996 issue of the *Oil and Gas Journal*.

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Continued on Page 14

Project News (Continued from Page 13)

Multiphase Fluid Simulator for Underbalanced Drilling

Gas-phase compressibility was incorporated into the coding for sections that model inflow in the drill string and outflow in the annulus. Pseudo-steady-state radial profiles of the solids fraction and velocity profiles were added to the model of the annular flow.

A strategy to develop a rig-based simulator that is compatible with and evolves logically from the planned LANL desktop simulator is being developed.

The code for the basic round trip 2-1/2D flow simulator was completed and is being evaluated against analytical solutions and experimental data for air flow.

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3D Seismic Imaging of Complex Geologies

A preliminary MPP seismic imaging code, SALVO, was produced during the first part of this project. This code incorporates basic algorithms for wave propagation and several optimized computational kernels. One kernel achieves 33 Mflops/sec, which is the fastest compiled FORTRAN program for the Intel Paragon that we have been able to identify. This preliminary code has been ported to the Cray T3D.

Work continued on the next version of SALVO. We have included a new phase correction filter in the code to improve image quality. We have begun investigating the use of multiple grid methods for F-X migration, and preliminary work has identified artifacts resulting from discrete grids. We made a new version of the code available to the project members. The code has been ported and is running on the SP-2.

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Single-Well Seismic Imaging of Salt Dome Flanks

Field seismic data recording experiments will continue through early fall at Hunt Petroleum's Bayou Choctaw, LA, site. Wells #15 and #17 near the flank of the saltdome will be used for source and receiver deployment.

The ProMAX seismic data processing software was loaded on a workstation at SNL. SNL and the University of Utah are collaborating to site a 3D viscoelastic synthetic seismogram code within ProMAX. This algorithm will allow realistic simulations of the seismic data recorded in a salt flank environment.

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Coupled Rock/Fluid Mechanics

An algorithm for fracture was implemented into the smooth particle hydrodynamics (SPH) code and checked with other continuum code results.Damage models and fracture criteria that have been implemented into the SPHINX code are being tested on micro-scale grain interaction problems. These are 2D at present and will be done in 3D when a more robust grain-shape algorithm is adapted. A search for other damage and fracture modeling codes is being made to check and validate the SPH approach.

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Computer Simulation in Support of Nuclear Well Logging

A generic porosity tool model was generated using a tetrahedral gridding code. This model was then used with a preliminary tetrahedral deterministic transport code, a proof-of-principle test. Results have been very encouraging.

The QUADCAL code, which uses a quadratic finite element method, is undergoing significant upgrading. A second code, called AMTRAN, is at a somewhat earlier stage of development. It will allow automatic zoning, in Cartesian blocks, which will insure that a given problem can be run with an optimum number of zones. It also will have the capability for parallel processing.

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Oil and Gas Data Infrastructure Project

The first prototype data server, with oil and gas information from California and 12 other states, was completed and made available over the Web: **http://wildcat.ocf.llnl.gov/cgi/godb**. At the end of March, we demonstrated this server to a group of beta testers. Although the server is only a prototype, the industry is using it for production purposes.

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Development of a New Generation Petroleum Reservoir Simulator

Prototypical linear and nonlinear solvers for the black-oil equations are being tested on two-phase flow (oil/water and air/water) problems. Parallel, preconditioned GMRES and BiCGSTAB with a multistage (IMPES) preconditioner, linesearch backtracking and forcing term selection were implemented in a fully implicit two-phase flow simulator PARFLOW2.

A full tensor was incorporated into PARFLOW2. Testing of the use of a full tensor for mapping irregular, logi-

Continued on Page 15

Project News (Continued from Page 14)

cally rectangular domains to regular, rectangular computational domains is underway. Preliminary tests indicate that the linear and nonlinear solvers are sufficiently robust to handle the effect of a highly varying tensor.

Testing of the parallel part of IPARS in under way. Implementation of the EOS compositional part of IPARS is in progress and includes phase-stability analysis, flash calculation, and partial derivatives for the generation of the linear system of the governing equations of the simulator. A geostatistically-based upscaling technique for heterogenous reservoirs has been tested for two-phase problems. Testing related to three-phase flow simulations continues. A small code has been written to test the parallel code of the distributed adaptive grid hierarchy for adaptive mesh refinement. A chemical flooding compositional simulator, UTCHEM, has been modified so that its memory is dynamically managed.

Implementation of Krylov-secant methods for reducing the computational costs for solving large scale systems of nonlinear equations is finished. The method reuses the Krylov information produced by GMRES in obtaining the linear Newton equation solution. Preliminary theoretical and practical experiences reveal that the idea can be used as a framework for developing efficient high-order methods for solving nonlinear equations.

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3D Seismic Analysis using SEG/EAEG Dataset

Collection of the full 3D dataset from the physical model of the SEG/EAEG salt structure was completed in February. The elastic parameters used to compute sample 2D elastic lines through the model were revised, and new 2D elastic lines will be calculated.

Implementation of the elastic wave synthetic seismic modeling program continued on the 48 node Meiko CS-2 massively parallel processor at LLNL. This code, E3D, is similar to the IFP (Institute Français de Pétrole) code, C3D, which was used to generate the acoustic model data produced by the SEG/EAEG collaborative effort. The low-level subroutines used by E3D were optimized for the Meiko dual processor nodes.

Neural networks are being applied to the estimation of lithology and fluid saturation from well-log and pre-stack seismic data. Initial results from predictions of effective porosity are encouraging.

Hybrid finite-difference approaches to solving the acoustic wave equation are being implemented and validated. These approaches aim to combine the unconditional stability of implicit finite-difference methods with the greater computational speed of explicit finite-difference methods.

A new photo polymer recording material was tested for use in holographic visualization. This material was found to be well suited and does not require the chemical processing that conventional holographic materials do. The new photo polymer material also provides better displays.

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Reduction of Well Failures

Continued from Page 3

supercomputer runs the 3D geomechanical simulation in a week, less time-consuming 2D geomechanical simulations are being performed on workstations as scoping and parameter sensitivity studies. Simulations have shown that localized slip with displacement large enough to cause failures occurred at the overburden/diatomite interface, like those observed in the field. Results also show that significant slip occurs in the center, as well as the flanks of the subsidence bowl, as a result of localized production and injection.

Laboratory studies provide data to constrain the contribution of creep to observed reservoir compaction and to define material constitutive behavior for numerical modeling. In creep deformation, measurements show that rates increase with drawdowns in excess of 400 psi, suggesting that use of a time-dependent material model will be important for geomechanical simulations of the reservoir.

Industry Partners

A complete list of industry partners showing project affiliations is available at the Partnership's World Wide Web site:

http://www.sandia.gov/ngotp/

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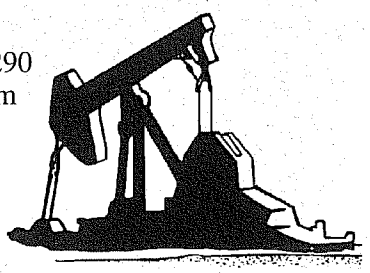

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