Oil & Natural Gas Technology

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Progress Report

Water Management Strategies for Improved Coalbed Methane Production in the Black Warrior Basin

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EXECUTIVE SUMMARY

The primary objective of this research is to analyze and develop strategies for water management in coalbed methane reservoirs of the Black Warrior basin. Management of produced waters is a subject of increasing environmental scrutiny, and the Geological Survey of Alabama (GSA) is developing a large, high-quality database and GIS that will provide a basis for the development of efficient regulatory frameworks that will protect the environment while ensuring that coalbed methane will be delivered to the marketplace. The Black Warrior basin provides a wealth of data and experience that can be used to evaluate water management practices across a spectrum of reservoir conditions and operational situations. Accordingly, the concepts and methods developed during this study will be applicable to other regions. These concepts and methods include optimizing water and gas production throughout the operational life cycle, forming strategies to minimize environmental impact, and identifying beneficial uses for produced water.

This project is employing an integrated, multidisciplinary approach to the evaluation and development of water management strategies for coalbed methane reservoirs. Work has commenced with an evaluation of reservoir geology and basin hydrology, which control fluid composition and yield. This project considers the full range of geologic and hydrologic variables that affect coalbed methane reservoirs, including stratigraphy, structural geology, petrology, fluid chemistry, reservoir pressure, and basin hydrodynamics. As the hydrogeologic framework is developed, work will shift toward characterizing reservoir performance and the life cycle of coalbed methane operations. The study will conclude by developing a comprehensive approach to produced water management that emphasizes environmental protection, optimization of reservoir performance, and beneficial use of produced water. A vigorous technology transfer program will be conducted throughout the study that will include assembly of a project advisory committee, development of a project web page, and dissemination of project results through the internet, publications, presentations, and workshops.

This project is proceeding according to schedule and budget. Technology transfer activities last quarter (Task 2.0) included preparation of a manuscript for a special issue of the International Journal of Coal Geology on the potential environmental impacts of unconventional energy development. An abstract also was submitted to the Unconventional Resources Technology Conference. Sampling of fluids from coalbed methane wells continued this quarter under Task 6.0, and arrangements are being made to complete all the sampling next quarter. Investigation of petrology (Task 7.0) has been completed ahead of schedule. Results indicate that authigenic mineralization is restricted mainly to natural fractures. Calcite veins provide critical insight into the depth, timing, and temperatures of late-stage methanogenesis in the Pottsville Formation. Decline curve analysis (Subtask 8.1) is revealing complex relationships among water and gas production. Moreover, the shape of decline curves can be affected by a number of maintenance and operational issues, including fines problems, mineral scaling, and pumping rate. Maps of cumulative, peak, and annual gas and water production have been completed and are being used to analyze the life cycle of coalbed methane operations and to inform the development of water management strategies under Task 9.0. Investigation of deep disposal wells indicates that natural fracturing is the primary source of injectivity in deep carbonate formations, which facilitates rapid loss of injectivity. Accordingly, deep disposal does not appear

to be an economically viable strategy at current natural gas prices. Tasks 6.0 through 8.0 are on schedule to be completed next quarter, and all subsequent project activities will shift to Task 9.0.

RESULTS OF WORK DURING REPORTING PERIOD

Approach

The Black Warrior basin is a cradle of the modern coalbed methane industry that has provided a wealth of experience and has guided coalbed methane development around the globe. More than 2.2 Tcf of coalbed gas has been produced from the basin, and 4,869 wells are active in 17 coalbed methane fields (fig. 1). Annual gas production has been between 105 and 121 Bcf since 1993, and although the basin is considered mature, exploration and drilling operations are highly active. Cumulative water production now exceeds 1,340 MMbbl, and annual production was higher than 78 MMbbl in 2007. Water production has been rising since 2001 in response to renewed expansion of the coalbed methane industry in Alabama, and so water management issues continue to be of high concern.

The hydrologic and geochemical complexity of coalbed methane reservoirs in the Black Warrior basin favors the application of diverse technologies for produced water management, yet the coalbed methane industry is reliant mainly upon instream disposal, which is a subject of increasing environmental scrutiny. Currently, no integrated system for water management exists that can be used to optimize production operations, manage instream and subsurface disposal, and identify opportunities for beneficial use. A basic need is an integrated analysis of water chemistry, basin hydrology, and operational infrastructure that can be used to make decisions about produced water management. GIS technology, moreover, is an ideal vehicle for the synthesis of this analysis that facilitates the construction of a robust and effective water management plan.

To assist the coalbed methane industry in filling this need, the Geological Survey of Alabama (GSA) is conducting a three-year study that provides a conceptual framework for the management of produced water from coal. This study employs an integrated, life-cycle approach that draws on a spectrum of geologic disciplines (fig. 2). This investigation employs a spectrum of geologic, hydrologic, geochemical, petrologic, GIS, and other computational techniques to characterize the reservoir geology and basin hydrology of the Black Warrior basin to develop new water management strategies that ensure environmental protection, foster beneficial use of produced waters, and improve reservoir performance. The wealth of data and the geological diversity of the Black Warrior basin provides an unparalleled opportunity to evaluate water management strategies across a spectrum of reservoir conditions. Accordingly, this research will help natural gas producers develop basic geologic, hydrologic, and water management concepts that can be applied to coalbed methane plays throughout the world.

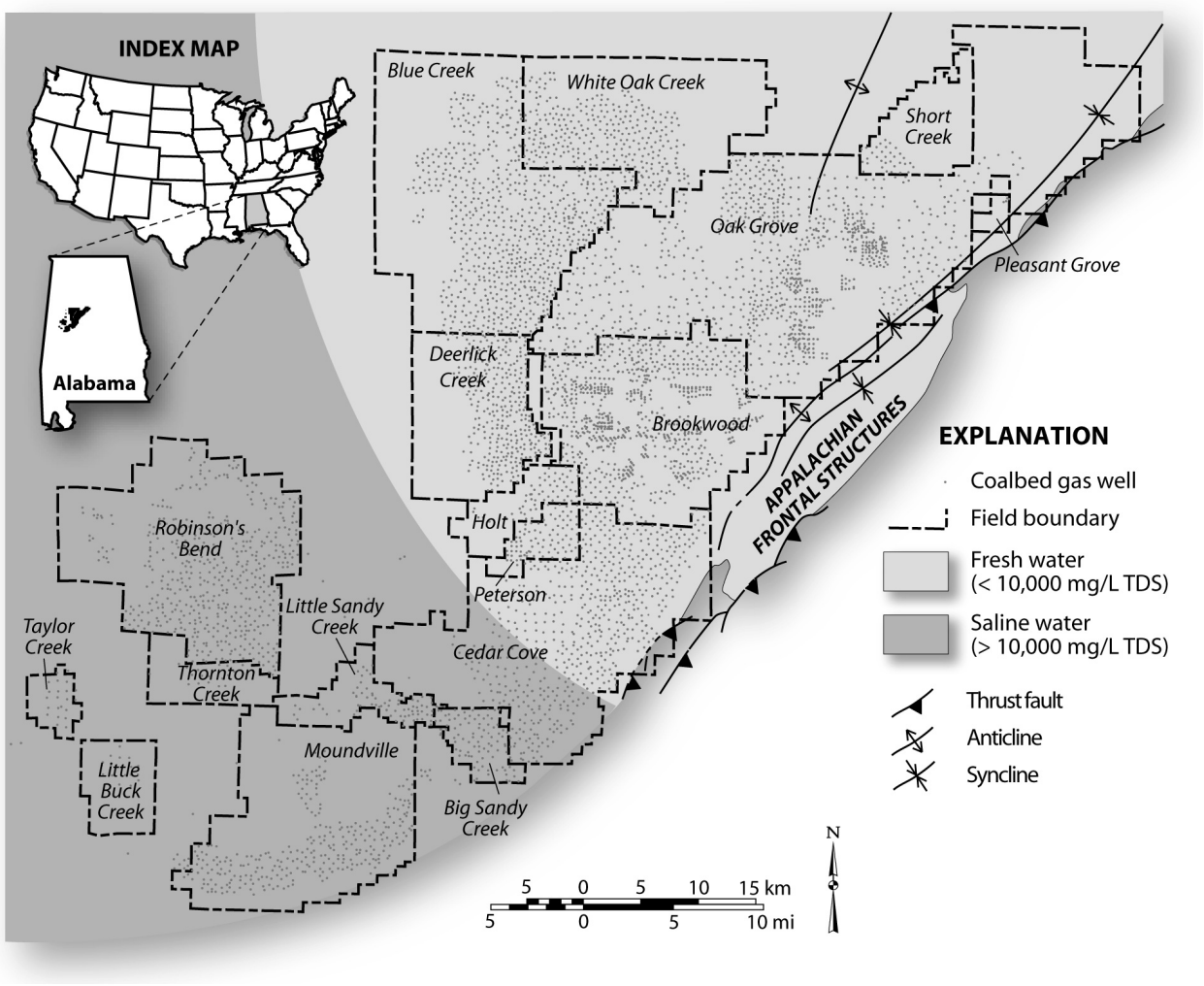

Figure 1.—Coalbed methane fields of the Black Warrior basin, west-central Alabama.

Results and Discussion

Work on this project is coordinated into a series of tasks aimed at project management, technology transfer, and the performance of technical activities (fig. 3). Task 1.0 focuses on project management, whereas Task 2.0 encompasses all technology transfer activities associated with this project. Tasks 4.0 through 9.0 include all technical activities required to meet the goals of this research. Work is in progress on Tasks 2.0 and Tasks 6.0 through 9.0, and this report summarizes the progress made during the most recent quarter of study.

Technology transfer activities last quarter included manuscript preparation and submission of an abstract to a technical meeting. Jack Pashin is preparing a manuscript a special volume of the International Journal of Coal Geology that is being edited by Daniel Soeder of the U.S. Department of Energy National Energy Technology Laboratory and Mark Engle of the U.S. Geological Survey. The volume focuses on the potential environmental impacts of unconventional fossil energy development, and the paper explores the interrelationships between water and gas chemistry in mature coalbed methane reservoirs of the Black Warrior basin. Dr.

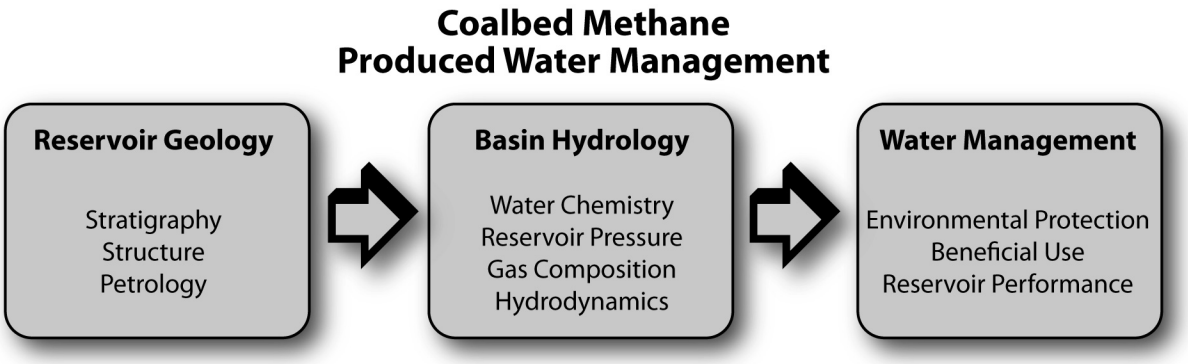

Figure 2.—Conceptual framework outlining proposed study of the relationships among reservoir geology, basin hydrology, and water management strategies in coalbed methane reservoirs.

Pashin also submitted an abstract to the Unconventional Resources Technology Conference, which will be held in Denver during August 2013. The abstract is entitled, "Dynamics of Thermogenic and Late-Stage Biogenic Gas Generation in Coalbed Methane Reservoirs of the Black Warrior Basin," and considers the effects of burial, unroofing, and changing water chemistry on the generation, migration, and chemistry of hydrocarbons in bituminous coal.

Sampling of coalbed methane wells continued last quarter under Gas Composition (Task 6.0). Last quarter, samples were obtained from 47 wells that were made available by Energen Resources. Arrangements have been made to obtain samples from 23 wells operated by El Paso Petroleum and Walter Black Warrior Basin between January 10 and February 13, 2013. Discussions are underway with Kavanaugh Petroleum, Chevron U.S.A., and Saga Petroleum to obtain samples from an additional 23 wells next quarter, which will complete the sampling program. Thus, it appears that all well sampling will be completed according to schedule by the end of March 2013.

Investigation of Petrology (Task 7.0) has been completed ahead of schedule. Petrology is an important component of Critical Path Milestone 6, which is scheduled to be met by the end of March 2013. Results from analysis of Authigenic Mineralization (Subtask 7.1) indicates that framework sandstone composition has had no tangible impact on authigenesis. Upper Pottsville sandstone is predominantly litharenite containing a high proportion (20-60 percent) of low-grade metamorphic rock fragments and reworked argillaceous sedimentary rock fragments. These grain types are highly compactible. Porosity in Pottsville litharenite is characteristically lower than 5 percent, and microdarcy-class permeability is typical. The highest permeability in our database is only 60 microdarcies, indicating that even the most permeable streaks in sandstone have limited fluid transmission potential. Intergranular cement within litharenite is limited to clay coats and minor interstitial calcite masses. Ferroan calcite and saddle dolomite, which are late burial cements are conspicuously absent, indicating that porosity was occluded by compaction early in the burial process.

Indeed, authigenic cement is dominated by calcite and pyrite, which lines the walls of natural fractures, specifically cleats in coal and joints in shale and sandstone. Cleating in Black Warrior coal is thought to be associated with late Paleozoic thermal maturation, and cleat systems are

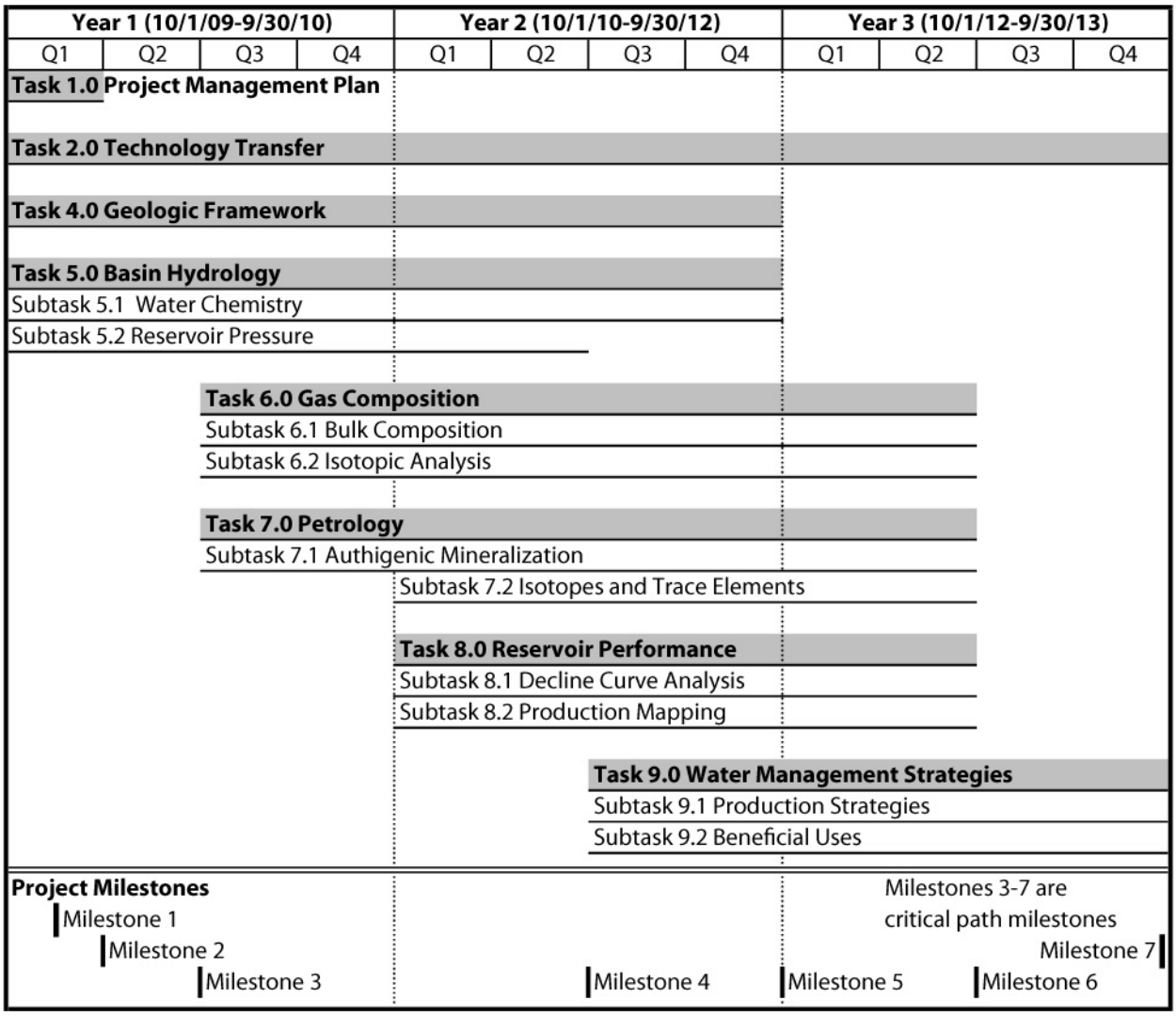

Figure 3.—Gantt chart showing scheduling and relationships among project tasks and milestones.

best developed in coal seams that have entered the thermogenic gas window. Joints, by contrast, have been interpreted as stress-release fractures that formed during latest Paleozoic-Mesozoic unroofing. Stable isotopic analysis of calcite cement under Subtask 7.2 provides exceptional insight into the origin of authigenic fracture-filling cement in the upper Pottsville. Oxygen isotopic ratios ($\delta^{18}O$) can be used as paleothermometers, thus providing insight on when diagenesis occurred during the regional burial history. Isotopic values from the upper Pottsville indicate that cementation began locally early in the unroofing process ($\delta^{18}O$ = -18 to -14 per mil) (fig. 4). However, most samples are strongly enriched in ^{18}O, indicating cementation late in the unroofing process, specifically at or near modern burial depth($\delta^{18}O$ > -10 per mil). $D^{13}C$ data indicate that initial cementation began in formation water with marine affinity. The bulk of the cement is strongly enriched in ^{13}C, indicating an association with late-stage bacterial methanogenesis along a CO_2 reduction pathway. Calcite is most enriched near the recharge zone at the southeastern basin margin. Calcite with significantly depleted ^{13}C ratios (< -5 per mil

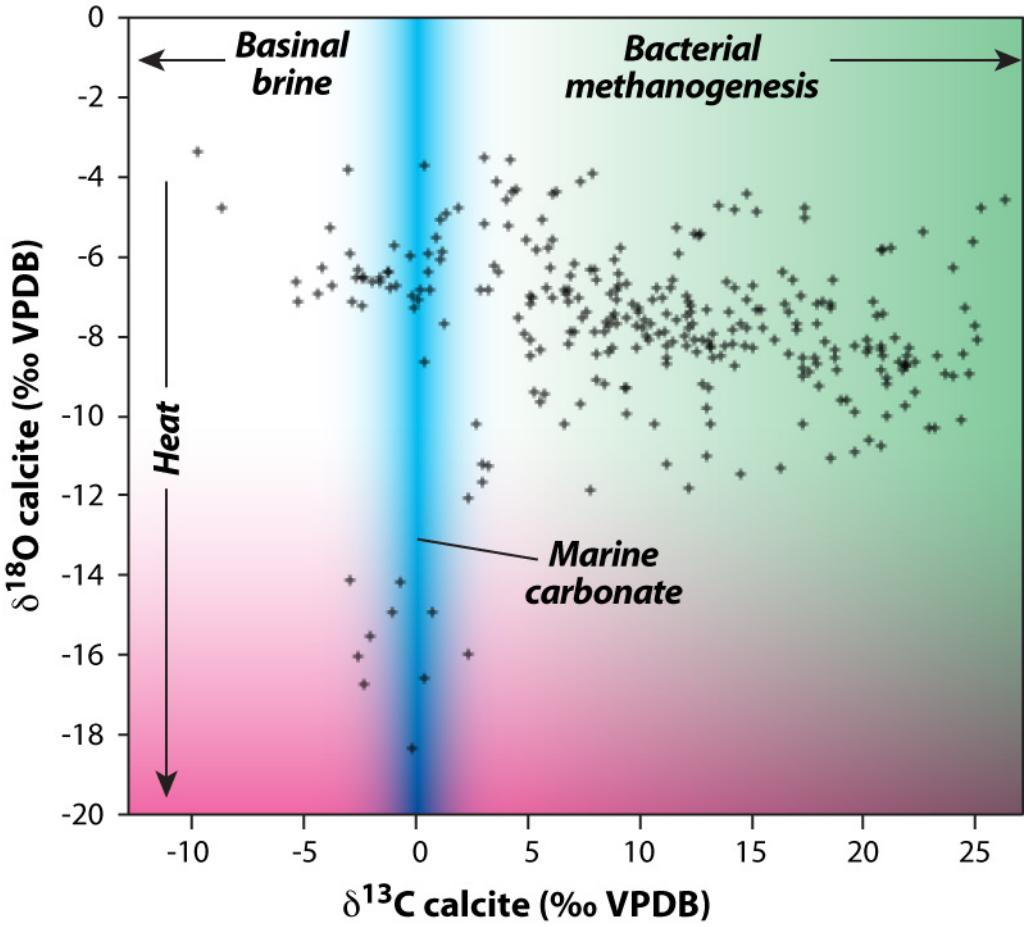

Figure 4.—Crossplot showing relationship between oxygen and carbon isotopes in fracture-filling calcite in the upper Pottsville Formation.

occurs locally in deep strata below the Gulf of Mexico coastal plain and is associated with basinal brine with dissolved solids content higher than 60,000 milligrams per liter.

Activity performed under Reservoir Performance (Task 8.0) last quarter focused on Decline Curve Analysis (Subtask 8.1) and Production Mapping (Subtask 8.2). Under Subtask 8.1, decline curves are being compiled and analyzed from more than 400 wells throughout the coalbed methane producing areas. Numerous types of production decline have been identified, and some types of decline curves are characteristic of specific producing areas. For example, areas with high initial water production typically exhibit hyperbolic decline of water rate coupled with exponential decline of gas rate. After about a decade of production, however, gas production flattens, reflecting a transition from production driven by pressure reduction to production that is dominated by steady-state diffusion of gas from coal matrix. In areas with little or no water production, many wells can maintain a constant gas production rate from initial production onward. Many wells have erratic production histories, which tend to reflect two major factors. The first is frequent well maintenance related to coal fines and scaling. The second factor is related to management of pumping rates. In this case, where wells cannot be pumped to full

capacity, water pumping rates are commonly changed several times over the life of a well, resulting in erratic production histories. Inability to pump a well to capacity, moreover, commonly results in reduced production rate. In cases where water pressure cannot be reduce sufficiently, the result is inefficient gas recovery.

The production maps scheduled to be made under Subtask 8.2 have been completed. Maps of cumulative and peak water and gas production through the end of 2011 show significant local and regional variation of production volume (figs. 5, 6). Maps of annual water and gas production have also been completed that show the geographic evolution of the coalbed methane industry and the temporal changes in fluid volume. Analyzing these changes is central to our evaluation of water management strategies in the basin and developing a long-term plan for the Black Warrior coalbed methane industry.

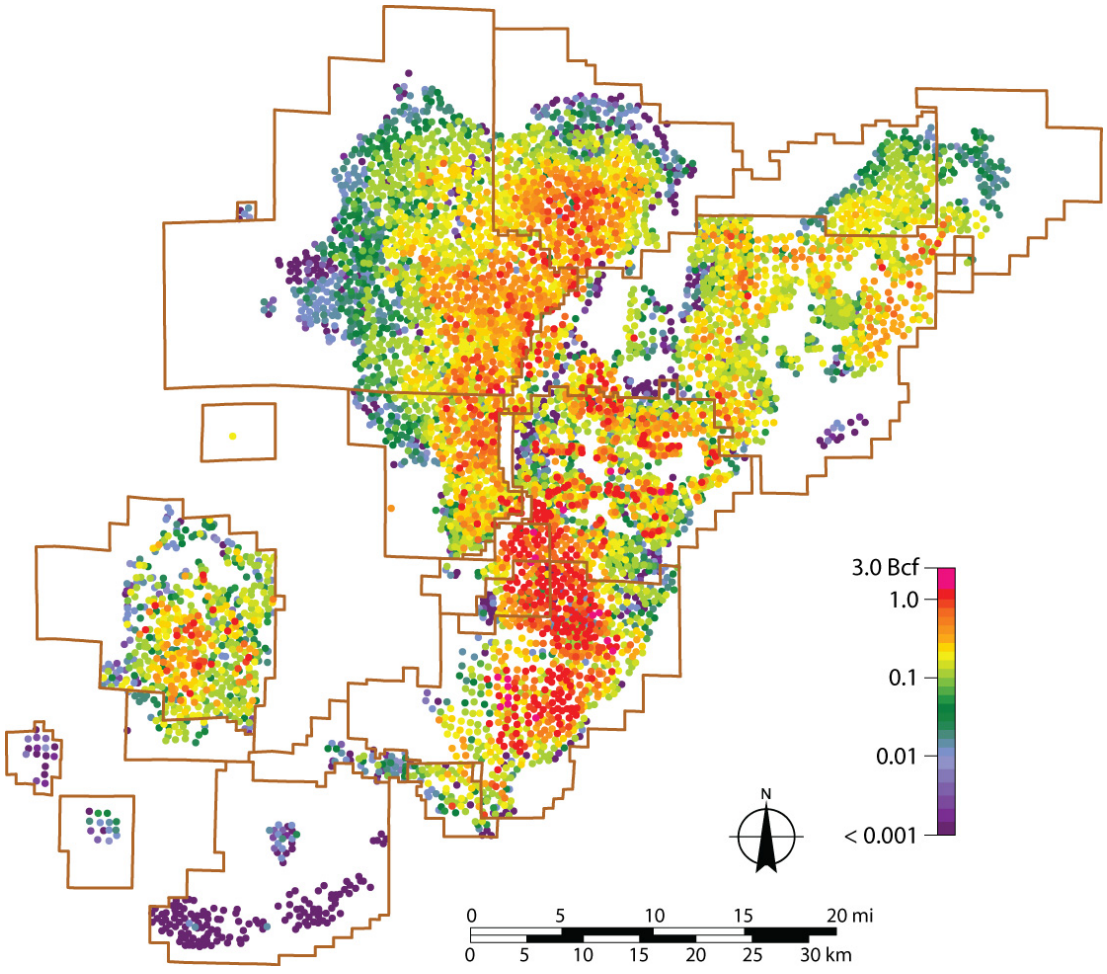

Figure 5.—Map of cumulative gas production in the Black Warrior coalbed methane fields.

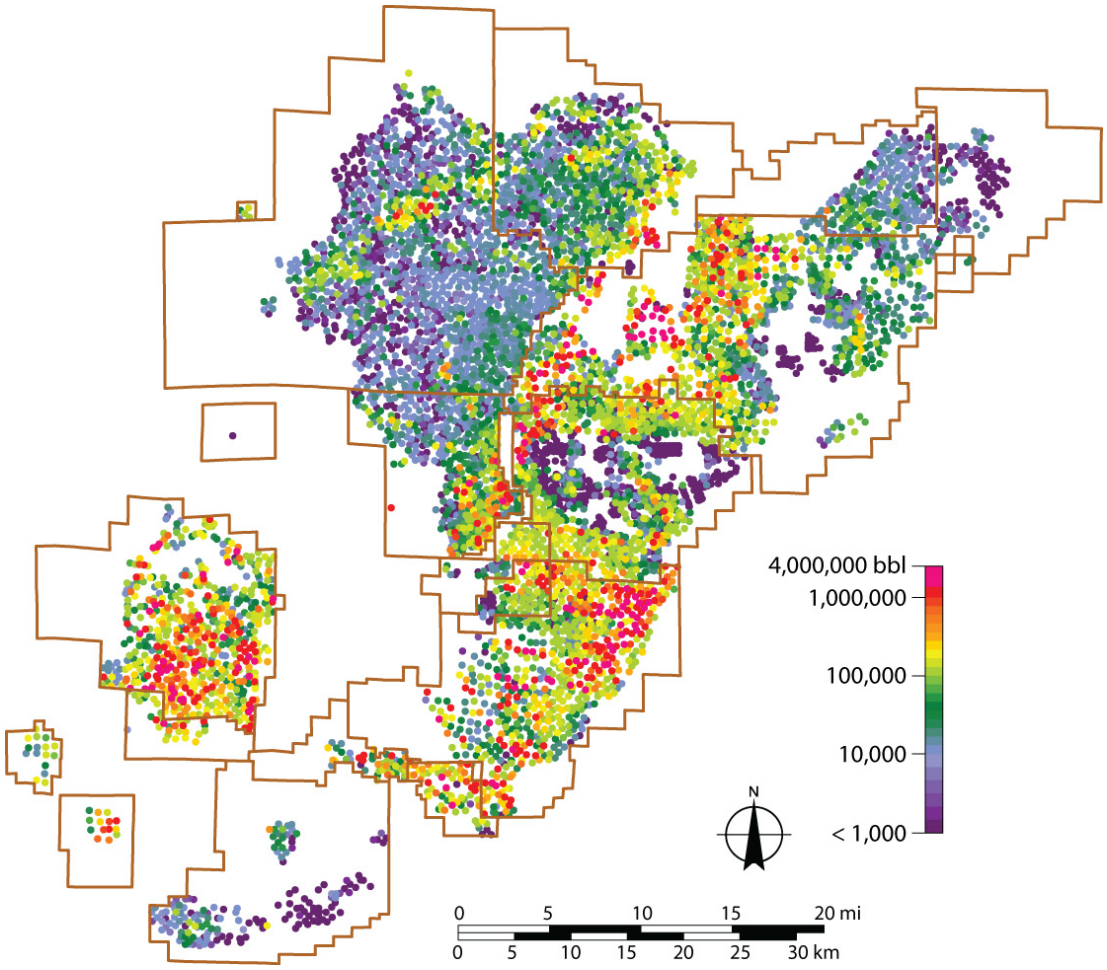

Figure 6.—Map of cumulative water production in the Black Warrior coalbed methane fields.

Work continued last quarter on Water Management Strategies (Task 9.0). The Black Warrior coalbed methane industry is currently dependent solely on instream disposal of produced water, which limits production in some areas where coalbed methane reservoirs yield large volumes of hypersaline brine. Reverse osmosis is used locally, but is expensive and of questionable effectiveness. Another option is underground injection, and the best options in the basin are in Cambrian through Devonian carbonate rocks. Class II injection wells in Robinson's Bend and Cedar Cove Fields found significant injectivity in the Cambrian-Ordovician Knox Group and in an unnamed cherty limestone of Devonian age. Wells in Robinson's Bend Field reported initial capacity of 3,500 to 10,800 barrels per day in a 1,000-foot column of the Knox Group. However, these wells were of limited use due to rapid buildup of back-pressure. Examination of the geophysical well logs indicates no significant matrix porosity in these strata, suggesting that natural fractures provided the available injectivity. A formation micro-imager log from a recent exploratory well just north of the coalbed methane fields indicates that fractures with imageable aperture are common in the Knox Group. The predominance of fracture porosity helps explain the rapid buildup of back-pressure in these wells. Horizontal drilling may help facilitate

commercial brine disposal in the Cambrian-Devonian section, but this option is probably not viable in the current environment of depressed natural gas prices.

Next quarter, research will continue on Tasks 6.0 through 9.0. Tasks 6.0 through 8.0 are scheduled to be completed at the end of the quarter. Following completion of these tasks, project effort will shift to Water Management Strategies (Task 9.0) for the remainder of the project.

Conclusion

This project is proceeding according to schedule and budget. Technology transfer activities last quarter (Task 2.0) included preparation of a manuscript for a special issue of the International Journal of Coal Geology on the potential environmental impacts of unconventional energy development. An abstract also was submitted to the Unconventional Resources Technology Conference. Sampling of fluids from coalbed methane wells continued this quarter under Task 6.0, and arrangements are being made to complete all the sampling next quarter. Investigation of petrology (Task 7.0) has been completed ahead of schedule. Results indicate that authigenic mineralization is restricted mainly to natural fractures. Calcite veins provide critical insight into the depth, timing, and temperatures of late-stage methanogenesis in the Pottsville Formation. Decline curve analysis (Subtask 8.1) is revealing complex relationships among water and gas production. Moreover, the shape of decline curves can be affected by a number of maintenance and operational issues, including fines problems, mineral scaling, and pumping rate. Maps of cumulative, peak, and annual gas and water production have been completed and are being used to analyze the life cycle of coalbed methane operations and to inform the development of water management strategies under Task 9.0. Investigation of deep disposal wells indicates that natural fracturing is the primary source of injectivity in deep carbonate formations, which facilitates rapid loss of injectivity. Accordingly, deep disposal does not appear to be an economically viable strategy at current natural gas prices. Tasks 6.0 through 8.0 are on schedule to be completed next quarter, and all subsequent project activities will shift to Task 9.0.

COST STATUS

Table 1. Comparison of costs budgeted for Budget Period 3 and actual expenditures through December 31, 2012.

	Budgeted Costs			Actual Expenditures		
Category	**DOE***	**Participant**	**Total**	**DOE**	**Participant**	**Total**
Personnel	$77,180	$41,592	$118,772	$12,909	$12,909	$25,818
Fringe Benefits	26,241	14,141	40,382	4,260	4,260	8,520
Travel	6,197	0	6,197	1,059	0	1,059
Equipment	0	0	0	0	0	0
Supplies	968	0	968	0	0	0
Contractual	0	0	0	0	0	0
Construction	0	0	0	0	0	0
Other	51,460	0	51,460	3,050	0	3,050
Total Direct Charges	162,046	55,733	217,779	21,278	17,169	38,447
Indirect Charges	46,802	25,221	72,023	7,741	7,741	15,482
Totals	$208,848	$80,954	$289,802	$29,019	$24,910	$53,929

SCHEDULE STATUS

This project is moving ahead according to schedule and budget (fig. 3, tables 2 and 3). Several components of Critical Path Milestone 6 (table 3) have already been met ahead of schedule, and the remaining components are expected to completed next quarter according to plan.

Table 2. Status of project schedule by task and subtask.

Task	Anticipated completion	Actual completion	Status
Task 1.0 Project Management Plan	11/15/09	11/13/09	Complete
Task 2.0 Technology Transfer	9/30/13		In progress
Task 4.0 Geologic Framework	9/30/12	9/28/12	Complete
Task 5.0 Basin Hydrology	9/30/12	9/28/12	Complete
Subtask 5.1 Water Chemistry	9/30/12	9/28/12	Complete
Subtask 5.2 Reservoir Pressure	3/31/12	3/31/11	Complete
Task 6.0 Gas Composition	3/31/13		In progress
Subtask 6.1 Bulk Composition	3/31/13		In progress
Subtask 6.2 Isotopic Analysis	3/31/13		In progress
Task 7.0 Petrology	3/31/13		In progress
Subtask 7.1 Authigenic Mineralization	3/31/13		In progress
Subtask 7.2 Isotopes and Trace Elements	3/31/13		In progress
Task 8.0 Reservoir Performance	3/31/13		In progress
Subtask 8.1 Decline Curve Analysis	3/31/13		In progress
Subtask 8.2 Production Mapping	3/31/13		In progress
Task 9.0 Water Management Strategies	9/30/13		In progress
Subtask 9.1 Production Strategies	9/30/13		In progress
Subtask 9.2 Beneficial Uses	9/30/13		In progress

Table 3. Milestone schedule. Milestones 3 through 7 are critical path milestones.

Milestone	Description	Scheduled completion	Actual completion
1	Completion of initial Project Management Plan and Technology Status Assessment (Task 1.0)	11/15/09	11/13/09
2	Posting of project web site on internet (Task 2.0).	12/31/09	12/24/09
3	Completion of design of databases for Task 4.0, Geologic Framework, and Task and 5.0, Basin Hydrology	3/31/10	3/19/10
4	Characterization of reservoir pressure complete (Subtask 5.2)	3/31/11	2/18/11
5	Tasks 4.0 and 5.0 complete.	9/30/12	9/28/12
6	Completion of analysis of Gas Composition (Task 6.0), Petrology (Task 7.0), and Reservoir Performance (Task 8.0)	3/31/13	
7	Completion of Water Management Strategies (Task 9.0).	9/30/13	

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