TOPIC PAPER #21

EXPLORATION TECHNOLOGY

On July 18, 2007, The National Petroleum Council (NPC) in approving its report, *Facing the Hard Truths about Energy,* also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the Task Groups and their Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached Topic Paper is one of 38 such working document used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix E of the final NPC report provides a complete list of the 38 Topic Papers and an abstract for each. The printed final report volume contains a CD that includes pdf files of all papers. These papers also can be viewed and downloaded from the report section of the NPC website (www.npc.org).

NATIONAL PETROLEUM COUNCIL

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I. Executive Summary

The sub-group identified five core exploration technology areas in which future developments have the potential to significantly impact exploration results over the next 25 years. Although the future of these technologies is bright, it is still likely that the trend of decreasing volumes of hydrocarbons discovered with time will continue, although the exploration success rate may continue to improve.[1] Many suggest that improved methods of exploring for unconventional resources might reverse the trend, however it should be noted that many unconventional resources have already been "discovered" and await new exploitation technologies. The core technology areas are:

- Seismic—utilization of naturally occurring and man-made acoustic waves to image the underlying geology has been a key tool for exploration success. There is high potential for technical advances in the areas of high and ultrahigh density acquisition technologies facilitated by advancements in rapid data processing that could significantly improve seismic resolution of complex subsalt, deep or subtle geologic features.
- Controlled source electromagnetism—uses the contrast in resistivity between hydrocarbon-saturated and water-saturated reservoirs to identify subsurface hydrocarbon accumulations. Two key potential improvements are: 1) development of fast 3D modeling and inversion to reduce the number of erroneously identified "anomalies" (false positives) and 2) extension of the technology to shallow-water and onshore settings.

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[1] Boutte D: "The Role Of Technology In Shaping The Future Of The E&P Industry," *The Leading Edge* 23, no. 2 (2004): 156-158.

- Interpretation technology—interpreters struggle with the sheer volume and complexity of data and the need for increasingly quantitative interpretations. Two advances that could have significant impact are: a) better integration of geophysical and geologic data to develop quantitative interpretations and b) development of seismic search engines to interrogate increasing data volumes.[2]
- Earth-systems modeling—modeling natural systems of basin formation, fill, and fluid migration is becoming increasingly common. Advances in the modeling of more integrated earth systems along with capturing the uncertainties in potential scenarios and parameters could significantly help in the identification of new plays and "sweet spots."
- Subsurface measurements—measurement of subsurface properties (fluid type, porosity, permeability, temperature, etc) are crucial to exploration success. Advances in sensor types, durability, sensitivity, and deployment could impact exploration programs significantly by identifying both penetrated and bypassed pay.

Unconventional resources were highlighted by this sub-group as a special category of resources in the early stages of understanding (both exploration and exploitation), to which many of the core exploration technologies could have potential application. Two key advances were identified that could improve the effectiveness of exploration for unconventional resources: a) improved measurement capabilities and predictive modeling of the geologic factors controlling hydrocarbon distribution and deliverability and b) significant improvements in exploration or exploitation technologies that could help define resource targets ("sweet spots") and the technologies needed to identify or characterize them.

The sub-team also identified the following auxiliary technologies in which future developments or applications have the potential to significantly impact exploration results by 2030.

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[2] Barnes A: "Seismic Attributes in Your Facies,: *CSEG Recorder* (September 2001): 41–47.

- Drilling technology—Projected technical advances could improve the ability to tap new environments and encourage more exploration drilling of higher risk, new play types via reduced drilling costs
- Nanotechnology—the most likely opportunities for applications are in increased sensor sensitivity, improved drilling materials & faster and more powerful computing
- Computational technology—improvements in speed, memory and cost will impact data acquisition, processing and interpretation industry-wide.

Suggestions for accelerating the development and use of technology include:

1) Government-supported research (both governmental and academic), with clear accountability, into fundamental science areas that would underpin advances in commercial technologies (e.g. acoustic wave field research). Sustained public sector research into high-risk and high-impact technologies with long lead times, such as nanotechnology, would be complementary to industry research. Furthermore greater government support of academic institutions will ensure availability of highly-trained researchers and staff to develop these technological advances.[3]
2) Judicious governmental sharing of technologies developed for defense or security applications, but that have significant potential for applications to hydrocarbon exploration and exploitation (e.g. sensors, advanced image-analysis capabilities, high-resolution gravimeters).
3) Exploration companies need to be willing to accept and implement new technology at a faster pace. Many authors have noted the slow pace of adoption of oil and gas technology over the last several decades.[4] Recent workshops by the SPE and others have resulted in recommendations that could be helpful.

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[3] Haraldsen O S: "National Level RD & D," IEA Seminar on Oil and Gas Innovation in the Fossil Fuel Future, Royal Windsor Grand Place, Brussels (22 February 2006).

[4] See for example: Hirsch J M, Luppens J C, and Shook MT: "Accelerating Technology Acceptance: The Role of Culture of the Oil and Gas Industry in Technology Acceptance," SPE 98515 presented at the SPE Annual Technical Conference, Dallas, Texas (9–12 October 2005).

4) Industry and academia need to improve technical integration: companies and universities are often structured in ways that hinder the development and application of cross-cutting technical concepts that originate along the boundaries of different technical disciplines.
5) Although not universally accepted, there is the suggestion that increased industry investment into research could pay off in accelerated technology development. Proponents of this position note that there has been a significant drop in oil and gas R&D spending in the last decade.

II. Overview of Methodology

The evaluation of exploration technology and potential impact on volumes in 2030 was based both on discussion among the Exploration Technology Sub-Group (see Appendix 1) and colleagues in our companies and academic departments, as well as extensive use of published literature. The literature resources are documented in Appendix 2—this literature database should not be regarded as exhaustive.

Identified potential core technologies and auxiliary technologies were prioritized by polling the sub-group team members and tested via subsequent conversations with co-workers. From this prioritization came those technology areas just discussed—each of these technology areas is discussed in more detail in the technology area appendices.

Additional technologies that were recognized but not considered as first tier opportunities were: gravity, magnetics, remote sensing, extended use of earthquake seismometer arrays, and biotechnology (auxiliary).

III. Background

A. Historical Evolution:

Exploration technology has evolved significantly since the first commercial oil well in the United States was drilled adjacent to an oil seep in 1859. The technological evolution of petroleum exploration until the 1970s is described in detail by Owen.[5]

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[5] Owen EW: “Trek of the Oil Finders: A History of Exploration for Petroleum,” American Association of Petroleum Geologists Memoir 6 (1975): Chapter 11.

Perhaps the most significant technological advancement was the development of reflection seismology (2D) in the 1920s. The emergence of 2D seismic lines with improved processing led to the discovery of many of the world's largest oil and gas fields in the following decades. In the 1990s, 3D seismic technologies became the industry standard, with improved resolution and characterization of the subsurface geology. In addition, the improved understanding of wavefield physics and subsurface rock and fluid properties has led to the development of improved acquisition parameters and processing routines with a resulting better signal content. A significant contributor to seismic technology improvements has been the rapid increase in computing power and reduction in computer costs that have led to more rigorous processing streams.[6]

Interpretation technologies also evolved rapidly going from moveout tables and colored pencils in the early days to advanced workstations, visualization centers and immersive caves using computer-aided, semi-automated interpretation tools. New ways of looking at seismic data focus on specific attributes and derivative properties that enhance identification of hydrocarbon prospects (e.g. direct hydrocarbon indicators) as well as computer tools that aid in quantitative interpretation of rock and fluid properties.

Subsurface measurements have also evolved from simple observations of cuttings, cores and fluids recovered at the surface to include sophisticated downhole measurement of many rock and fluid properties (sonic, electrical, radioactivity, neutron scattering, pressure, etc.) as well as subsurface fluid sampling (DST, RFT, MDT, etc.). Initially, measurements were made on separate wireline trips but over the last 20 years, many measurements have been made while drilling by sensors located near the drill bit.

Initially, earth-systems modeling focused on developing the fundamental science to enable modeling of individual geological processes (e.g. timing and volumes of hydrocarbon generation from source rocks). With improvements in fundamental

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[6] Paul D: "The Role of E&P Technologies," Trends in Oil Supply and Demand and Potential for Peaking of Conventional Oil Production, National Resource Council Workshop (October 2005).

scientific understanding and computing power, earth-systems models are becoming increasingly integrated and complex, as well as predictive. At the recent research conference "The Application of Earth System Modeling to Exploration," models included paleo-climate, ocean circulation, and sediment processes in attempting to realistically model petroleum systems.[7]

Exploration for unconventional resources has a much shorter history. Low-permeability gas, with a U.S. experience of about 50 years in the Rockies and the Gulf Coast area, is the most developed resource, but exploration and exploitation have been highly dependent upon the development of new drilling and stimulation technologies as well as on the economic environment. The geologic understanding of low permeability gas remains somewhat limited—crude, early basin-centered gas models attempting to explain the continuous nature of the Rocky Mountain resources were developed in the 1990s and continue to be improved.

Exploitation of coal-bed methane (CBM) has evolved since 1976 and now delivers approximately 10% of the U.S. gas production.[8] Exploiting shale gas is more recent still, depending on advances in reservoir physics models for CBM and low-permeability gas and improvements in horizontal and multilateral drilling and stimulation techniques. Geologic understanding and predictive models of shale gas plays and prospects are rapidly evolving, but much is left to be learned. Hydrates and oil shales in the U.S. are not currently commercially produced, but hydrates were produced in the Yamal Peninsula and several global oil shale locations have been mined throughout history.

The application of controlled-source electromagnetism (CSEM) technology became possible in the 1990s with the advent of receivers with orders of magnitude of

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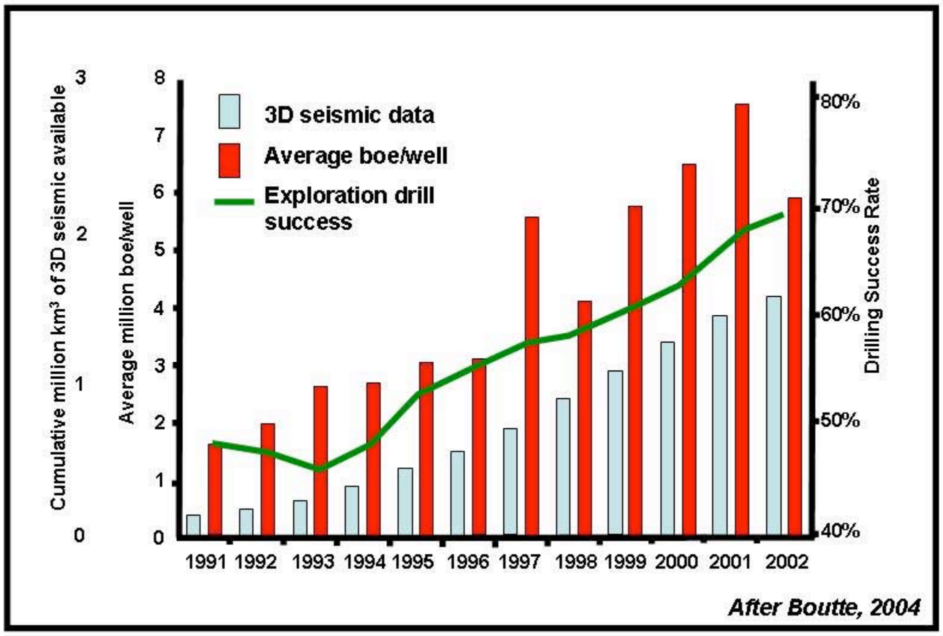
[7] Markwick P, Curiale J, and Suter J: "The Application of Earth System Modeling to Exploration," Joint SEPM-GSL Research Conference, Snowbird, Utah (July 11 - 13, 2006). Available at www.sepm.org/activities/researchconferences/earth%20systems/ES-AbstractsWeb.pdf . 2006.

[8] Brownell N: Testimony of Nora Brownell, Commissioner, Federal Energy Regulatory Commission Before the Permanent Subcommittee on Investigations Committee on Homeland Security and Governmental Affairs United States Senate (February 13, 2006). Available at www.ferc.gov/eventcalendar/Files/20060216145159-Nora-Brownell-02-13-06.pdf . 2006.
United States Geological Survey, "The U.S. Geological Survey Energy Research Program: 5-Year Plan" (2005). Available at http://energy.usgs.gov/PDFs/USGS-ERP_5-Year-Plan.pdf.

improvement in sensitivity, and development of advanced and affordable computational capabilities. Applications of CSEM are currently restricted to subsurface targets beneath deep water due to difficulties in maintaining adequate signal-to-noise ratios in shallow water or onshore environments.

B. Historical Impact:

Improvements in exploration technology have had a significant impact on discovering resources, reducing finding costs, and improving exploration success rates (e.g. Bohi contrasts exploration success rates drilled on the basis of 2D vs. 3D seismic data) both in the U.S. (an increase of 50% over the last 10 years) and globally (see Figure IIIB.1).[9]



After Boutte, 2004

Figure IIIB.1. Global discovery success rate and total additional reserves per discovery well (from 70 largest publicly traded energy companies as reported to SEC) have increased

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[9] Bohi DR: "Changing Productivity in U.S. Petroleum Exploration and Development," Resources for the Future Discussion Paper, Washington DC (1998): Table3.1. Available at www.rff.org/documents/RFF-DP-98-38.pdf.
Lynch MC: "Forecasting Oil Supply: Theory And Practice," *The Quarterly Review of Economics and Finance* 42 (2002): 373-389.

significantly since 1991, as has the use of 3D seismic data [Boutte, reference 1].

As discussed by Bohi and by Voola, the increased application of 3D seismic technology had a substantial effect across the 1980s to 2006 period.[10] Due to technological improvements, costs for 3D seismic fell by almost a factor of 5 from 1990 to 2001.[11] However since 2001, the annual amount of 3D seismic shot globally has remained relatively constant—a stark contrast to the rapid annual increases seen from 1994 to 2000.[12] Since 2001, costs have also increased due to higher sampling frequency and a tighter supply of seismic crews.

As more and more of the globe becomes covered with 3D seismic surveys, the challenge for new exploration opportunities is not in recognizing the obvious traps which have now been identified, but in finding subtle traps. Some well-known explorers argue that basin modeling that helps develop an improved understanding of the petroleum systems of new plays is becoming increasingly important.[13] There is also a concern that sometimes technology becomes a substitute for thinking rather than a tool to help explorers think.

Despite the substantial improvements in exploration technology and reduction in deployment costs since the 1970s, oil and gas explorers have not maintained the high discovery volumes of that earlier period (see Figure IIIB.2). This decrease is in spite of the increased amount of 3D seismic being shot over the period. As shown for the deepwater (> 1000 m), the discovery volumes from 1995 to 2005 have not increased with an increasing rig count.[14] The geologic factors are such that industry tends to

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[10] Bohi, reference 9.
Voola J: “Technological Change And Industry Structure: A Case Study Of The Petroleum Industry,” *Economics of Innovation and New Technology* 15, no. 3 (2006): 271–288.

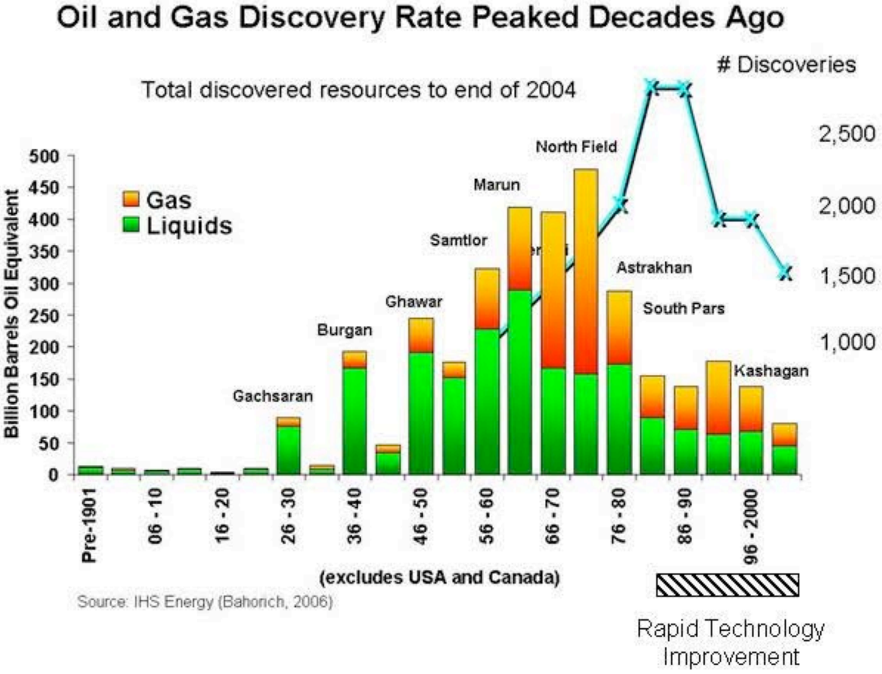
[11] Voola, reference 10.
Voola JJR, Osaghae O, and Khan JA: “Risk Reducing Technology and Quantity Competition: The Seismic Story,” paper SPE 88583 presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Perth, Australia (18-20 October 2004)..

[12] Stark P and Chew K: “The Exploration Dilemma in the Age of Energy Supply Anxiety,” Exploring Exploration Forum, Houston, Texas (2006)..

[13] Nestvold W, Hubbard R, Fisher WL, Schneidermann N, Griffiths E and Masters J: “Exploration Technology in an Era of Change,” *Oilfield Review* 6, no. 1 (January 1994): 40–50.

[14] Bahorich, M: “End of Oil? No, It's a New Day Dawning,” *Oil & Gas Journal* (August 21, 2006): 30–34.

find the largest fields first in new plays or opportunities. The NPC North American Gas Study states that "future prospect sizes are projected to continually decline over time."[15] However the discovery volume decline could be somewhat exaggerated by the fact that new volumes discovered in a previously identified field are commonly shown as revisions to the original field volume. In the period 1995 to 2003, the revisions to pre-1995 discovered resources were 457 billion bbls (including new additions and enhanced recoveries), whereas the total of new discoveries during the period was 144 billion bbls.[16]



Source: IHS Energy (Bahorich, 2006)

Figure IIIB.2. Evolution of oil discovery volumes with time with a significant marked decline since the 1960s and 1970s [Bahorich, reference 14].

Hirsch et al. note that the substantial improvements in exploration technologies in the 1980s to 2000 resulted in improved exploration success rates (also shown above in Figure IIIB.1), while at the same time, the total oil reserves discovered

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[15] National Petroleum Council: "Technology Impact on Natural Gas Supply," Chapter 5 in "Balancing Natural Gas Policy: Fueling the Demands of a Growing Economy: Volume 4" (2003): 5-2.

[16] Stark and Chew, reference 12.

declined significantly.[17] Over the same time period, the improved exploration technology led to increased average discovery volume per well (Figure IIIB.1). The combination of improved exploration success rate and increased discovery volumes per well with an overall reduction in discovery volumes is a result of more targeted exploration and declining exploration opportunities, somewhat influenced by geopolitical factors. The conclusion drawn by a number of authors is that improved exploration and exploitation technology has prevented a more drastic decline in discovery volumes.[18] However modeling the precise impact of technology improvements on discovery volumes is very difficult.[19] In the future, the need for technology advances will be greater in order to meet the challenges of finding the smaller fields, more subtle traps, and traps in hard-to-explore areas.

It is also important not to neglect the link between the evolution of discovery volumes and advances in exploitation and drilling technology. Without the technological development of the capability to drill and exploit deepwater reservoirs, exploration in the deepwater which has been the site of many recent large discoveries (e.g. GOM and West Africa) would have been delayed or might never have happened. Of course, the discovery decline curve also includes other factors that are not necessarily technologically related, such as the evolution of access to politically sensitive or physically difficult exploration areas,[20] as well as changes in hydrocarbon prices.[21] As shown by Dahl and Duggan, drilling rates are likely to depend on oil

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[17] Hirsch et al, reference 4..

[18] Cuddington JT and Moss DL: "Technological Change, Depletion and the U.S. Petroleum Industry: A New Approach to Measurement and Estimation," Georgetown University Working Paper #96-10R (1998).

[19] Lynch, reference 9.

[20] For example: Halbouty MT: "Exploration into the New Millenium," Keynote Address: Second Wallace E. Pratt Memorial Conference on "Petroleum Provinces of the 21st Century," San Diego, California (Jan 12–15, 2000),
Zucchetto J: "Trends in Oil Supply and Demand, The Potential for Peaking of Conventional Oil Production, and Possible Mitigation Options: A Summary Report of the Workshop," National Research Council of the National Academies, The National Academies Press, Washington, DC (2006).

[21] Bohi, reference 9: Figure 1-3.

price and profits and, to some extent, the cumulative discovery volumes are related to cumulative drilling.[22]

Analogously, improvements in fracturing and completion technology have facilitated the opening of new opportunities for exploration—particularly in the area of unconventional resources. A near-term example is the evolution of completion practices for the Barnett Shale in north Texas, which, along with a supportive price environment, has led to the exploration for trillions of cubic feet of gas that was previously of no or little interest.[23]

Historically, Daneshy and Bahorich note that during the period 1990 to 2002, the upstream R&D expenditures of major U.S. energy companies fell from $600 million to $400 million per year, whereas service company expenditures for R&D increased.[24] This trend is also true for those same sectors outside of the USA.[25] In the 1980s and 1990s, there emerged a belief by some major companies that individual companies did not realize sufficient value for their technology development expenditures, and that the value proposition was in being the “fast follower.”

As pointed out by Boutte, Daneshy and Bahorich and others, newly developed exploration (e.g. 3D seismic) and auxiliary technologies have taken years to decades to reach full market penetration.[26] The NPC 2003 study points out that more rapid technology adoption occurs when the new technology is developed within a company as opposed to by an outside service company. Anand and Hirsch et al recognize the

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[22] Dahl C and Duggan TE: “Survey of Price Elasticities From Economic Exploration Models of U.S. Oil and Gas Supply,” *Journal of Energy Finance & Development* 3, no. 2 (1998): 129-169.

[23] Shirley K: “Barnett Shale Living Up To Potential,” *Amer. Assoc. Petrol. Geol. Explorer* (2002). Available at www.aapg.org/explorer/2002/07jul/barnett_shale.cfm.

[24] Daneshy AA and Bahorich M: “Accelerating Technology Acceptance: Overview,” paper SPE 98553 presented at the 2005 SPE Annual Technical Conference and Exhibition, Dallas, Texas (9-12 October 2005).
NPC, reference 15.

[25] IEA: “Resources to Reserves: Oil & Gas Technologies for the Energy Markets of the Future,” International Energy Agency (2005): Figure 1.14.

[26] Boutte, reference 1,
Daneshy and Bahorich, reference 24.

problem with "oilpatch inertia" with regards to technology and present recommendations and strategies for improving technology uptake.[27]

IV. Tables of Advances

The sub-group distinguished between two types of improvements in exploration technology: a) those technologies currently being pursued with potential for significant near-term application (by 2010, see Table IV.1) and b) technologies that are being pursued or are likely to be pursued, in which significant improvements may occur farther in the future (Table IV.2). As all of these technologies have a risk of not being successful (either commercially or technically), the sub-group also created corresponding matrices plotting estimated likelihood of success versus potential impact (Figures IV.1 and IV.2). Estimating the rate and impact of exploration technology uptake is extremely difficult as discussed above.

Advances currently being pursued for near-term (by 2010) application are shown below in Table IV.1. A summary of the team's assessment of impact versus likelihood of success is shown in Figure IV.1.

Technology	Significance	Brief discussion
High-density seismic data and rapid data processing	High	Higher density seismic data acquisition with greater signal-to-noise ratios result in greater resolution, which allows for more robust interpretations of reservoir character and hydrocarbon potential to be made. However, for higher-density data to have commercial impact, substantial improvements in processing methods must be made.
Subsalt imaging (seismic)	High	Salt is a highly distorting acoustic lens which creates "blind spots" beneath it. Considerable efforts have been made to produce high-quality subsalt images resulting in drilling success in the

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[27] Anand P: "E&P Technology Follows Leaders: Selling New Technology Requires Leaders Who Inspire Their Teams to Overcom Oilpatch Inertia," *Harts E&P* (July 4, 2006).
Hirsch et al, reference 4.

		Gulf of Mexico and West Africa. Enhanced subsalt imaging will undoubtedly result in new discoveries and improved economics.
Fast CSEM 3D modeling and inversion	High	CSEM can discriminate between scenarios which are indistinguishable via seismic amplitudes; e.g. commercial oil versus residual (non-commercial) gas. However, false positives are common; e.g. hydrates, salts and volcanics can yield a response similar to a commercial petroleum response. Fast 3D modeling and inversion capability can help discriminate against such false positives.
Integration of CSEM with structural information from seismic	High	An important approach to increase the resolution of information obtained via CSEM methods.
Advances in drilling high-pressure, high-temperature (HPHT) wells	Medium	The National Energy Technology Lab (NETL)'s DEEPTREK research program, among others, is addressing a number of significant issues associated with drilling deep HPHT wells.[28] The chance of improvements is stated as significant,[29] which would result in increasing access to new prospects.
Ability to log and sample ultra-HPHT wells	Medium	Major new discoveries are expected in deep, high pressure, high temperature, wells. Many service equipment providers are developing technologies to be able to make measurements in these wells.[30]
Improvements in coiled tubing drilling	Medium	Ongoing work at drilling companies and NETL is focused on extending the depth range for common use in unconventional resources and via

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[28] Schlumberger Data and Consulting Services: "Benchmarking Deep Drilling : Final Report," U.S. Dept of Energy Contract No. DE-AM26-99FT40465 Concurrent Technologies Corporation Task FT50201H (2005). Available at www.netl.doe.gov/technologies/oil-gas/publications/EP/DeepTrek_Benchmark-All.pdf.
Spross RL: "Halliburton Sperry-Sun DOE High Temperature LWD Project," DOE Technical Report Contract Number AC26-97FT34175 (2005).

[29] National Driller.com: "New Drill Bit Technology—The Deep Trek Program" (2006). Available at www.nationaldriller.com/copyright/c3fd796fd00ae010VgnVCM100000f932a8c0____?view=print.

[30] Diamond S and Woertman R: "Logging While Drilling Success in HPHT Well Technology," Shell EPE Technology Learning Publication 16 (2005) Available at: http://www.cairnstone.co.uk/PDF%20Files/Technology_Issue_Sixteen.pdf.
Morris S: "A 275°C Downhole Microcomputer Chip Set," 2006 Drilling Engineering Association Workshop, Moody Gardens Hotel, Galveston, Texas, USA (June 20-21, 2006) (abstract).

[31] Spears & Associates (U.S. Dept of Energy): "Microhole Initiative Workshop Summary" (2003).

/microholes		microholes to reduce costs significantly.[31]
Modeling of global processes that impact prediction of play elements	Medium	Greater inclusion of modeling of global processes like climate modeling and plate tectonics that influence important elements of hydrocarbon systems.[32]
Improved modeling of extensional systems to identify new plays	Medium	Advances in modeling of extensional systems are focused on improved understanding and inclusion of more technical components to aid in identifying new play concepts and sweet spots—particularly in areas of poor data or resolution. New work is moving to more and more multi-dimensional simulations.[33]
Ultra-extended reach wells	Medium	Continued increases in ability to drill long distances from distant locations will improve access from sensitive surface environmental areas as well as potentially reduce costs.[34]
Improved Quantitative Seismic Interpretation	Medium	Will see more quantitative seismic interpretation with better integration of geological and geophysical data.[35]

National Energy Technology Laboratory: "DOE-Funded Technology That 'Looks Ahead' of Drillbit Commercialized: Revolutionary 'Smart' Drill Pipe Creates Downhole" (in press) May 16, 2006. Available at: http://www.netl.doe.gov/publications/press/2006/06026-Intellipipe_Goes_Commercial.html.
Perry K, Batarseh S, Gowelly S and Hayes T: "Field Demonstration of Existing Microhole Coiled Tubing Rig (MCTR) Technology," Final Technical Report (DOE report DOE Contract DE-FC26-05NT15482) 2006.
Perry K and Barnes J: "Microhole Coiled Tubing Drilling Successful in Niobrara Gas Play," *Gas Tips (Gas Technology Institute Publication)* (Summer 2006): 13–16.

[32] Jacques JM and Markwick PJ: "Contrasting Plate Tectonic Models for the Circum-Arctic and Their Influence on the Results of Earth System Modeling: Inferences on the Contemporary Distribution and Quality of Play Elements (Source, Reservoir and Seal)" AAPG Annual Convention, Calgary, Alberta, (June 19–22, 2005) Volume A67 (abstract).
Bohacs KM and Fraticelli CM: "The Critical Role of Contingency, Scaling, and Conditioning in Applying Earth-systems Models to Hydrocarbon Play-element Prediction in Continental Settings," The Application of Earth System Modeling to Exploration: Joint SEPM-GSL Research Conference, Snowbird, Utah (July 11 - 13, 2006): 9–10 (abstract) Available at http://www.sepm.org/events/researchconferences/earth%20systems/ES-AbstractsWeb.pdf.

[33] Duppenbecker S and Marzi R: "Introduction: Multidimensional Basin Modeling," in Duppenbecker S and Marzi R (eds): *AAPG/Datapages Discovery Series* No. 7 (2003): ix–xiv.

[34] Mason C: "Multilateral / Extended Reach," *Journal of Petroleum Technology* (July 2006). Available at: http://www.spe.org/spe/jpt/jsp/jpttopic/0,2437,1104_11038_5362883_5384795,00.html.

[35] Avseth P, Mukerji T and Mavko G: *Quantitative Seismic Interpretation: Applying Rock Physics to Reduce Interpretation Risk,* Cambridge University Press, (2005): 359.

Inclusion of more data dimensions (e.g. multi-dimensional attributes, geological data)	Medium	Will integrate more data dimensions (currently limited to a small number) using advanced statistical techniques that also allow uncertainty to be addressed.[36]
Greater automation to better use data and reduce interpretation time	Medium	There is significant work going on in the vendor companies and the universities to increase the degree of automation (e.g. automatic fault and horizon mappers). Recent efforts focus on a collaborative work flow between the interpreter and the advanced statistical tools .[37]
Integration of CSEM with structural information from magnetotellurics and potential fields	Medium	Better background resistivity models, resulting in improved capability to interpret the data.
Increased integration of basin modeling with geophysical data	Medium	Increase the integration of geophysical data and geologic data to validate basin modeling and geophysical interpretations as well as clarify the uncertainty.[38]
New physical measurements downhole	Medium	Addition of new sensor types to add to the information about the formation (e.g. key measures of unconventional resources—CBM absorption, unconventional productivity measures)

Table IV.1. Summary of near-term (by 2010) technologies in priority categories.

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[36] Barnes A: “Seismic Attributes in Your Facies,” *CSEG Recorder* (September 2001): 41–47.

[37] Pedersen SI, Skov T, Randen T and Sonneland L: “Automatic Fault Extraction Using Artificial Ants,” in Iske A and Randen T (eds): *Mathematical Methods and Modeling in Hydrocarbon Exploration and Production,* Springer-Verlag (2005): 107–116.

[38] Hedberg Conference 2007: *Basin Modeling Perspectives: Innovative Developments and Novel Applications*, AAPG Hedberg Conference (2007). Available at: http://www.aapg.org/education/hedberg/netherlands/index.cfm.

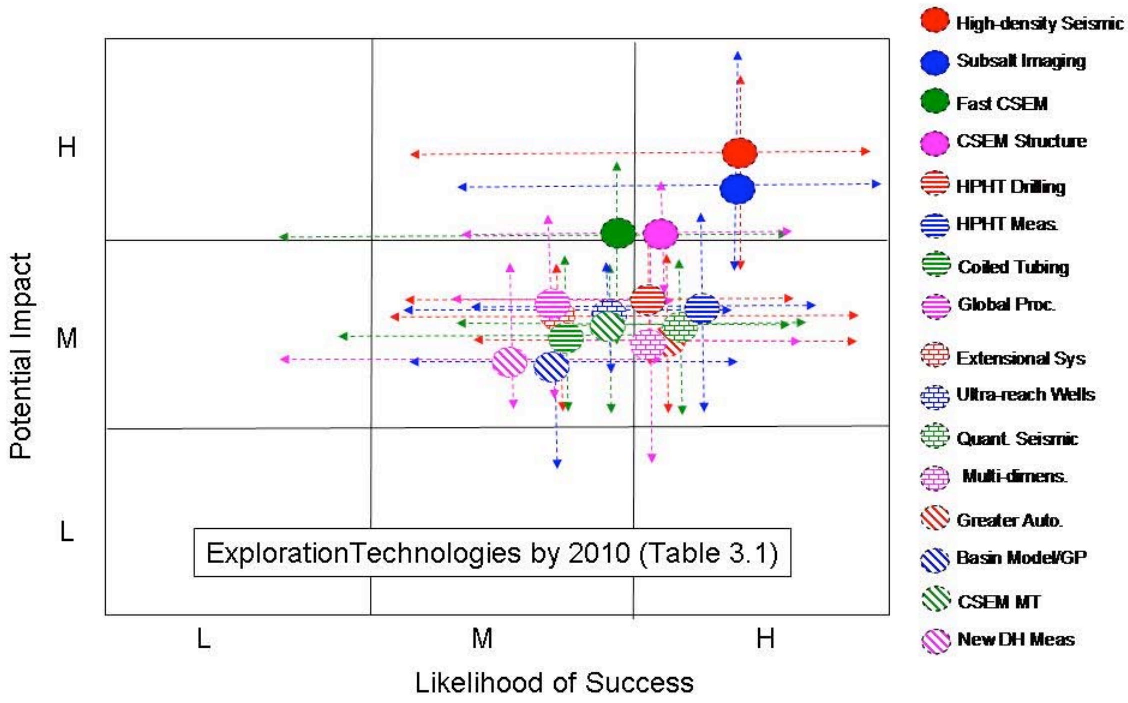

Figure IV.1. Potential impact versus likelihood of success for nearer-term technology advances. The dots represent the approximate median of the sub-group votes, whereas the arrows indicate the range in potential impact and likelihood of success of the votes.

Prioritizing the longer-term technologies in the following Table IV.2 is very difficult due to the large uncertainty in whether or not the proposed technology advance is likely to be successful (either scientifically or commercially). Some of the technical concerns relate to fundamental science problems that, if solved, will have tremendous impact—the question is when if at all. An example is the onshore CSEM effort: the key question is whether or not the currently overwhelming noise can be dampened without losing signal. A summary of the team's assessment of impact versus "Do-ability" is shown in Figure IV.2.

In some cases, acceleration of technological advancement and deployment is possible through substantial investment of resources (money or people) that may require the resources of multiple organizations—an example might be radical drilling technology improvements that historically have had government funding. In other cases, a fundamental science breakthrough is required and resources are not necessarily the primary issue.

Technology	Significance	Brief discussion
Shallow water CSEM	High	The shallow-water environment is much noiser than the deepwater environment for CSEM techniques. Substantial advances are needed to enable robust signal acquisition and analysis in such an environment. But if successful, it can open up the application domain for CSEM beyond deepwater basins.
Onshore CSEM	High	The onshore environment is much noisier than the deepwater environment for EM techniques. Substantial advances are needed to enable robust signal acquisition and analysis in such an environment. But if successful, it can open up the application domain for CSEM beyond deepwater basins.
Ultra high-density data and processing	High-Medium	Data density and processing continue to improve at incremental steps. However, if extremely high density data could be acquired and processed rapidly and at low costs, game-changing breakthroughs could occur. These include new hydrocarbon discoveries as well as exploitation efficiencies.
Wave theory research (seismic)	Potential high impact but with attendant high risk	Basic research into wave theory is a continuing effort in both industry and academia. Synergistic collaboration between the two has certainly led to gradual improvements in processing and could result in large leaps forward. For example—it should enable more accurate quantitative modeling of key seismic data.
Deep CSEM	High-Medium	Even in deep water, current application is limited to relatively shallow reservoirs (2 to 3 km below sea floor). Advances in penetration depth can open up applications in several new basins.
Deeper imaging (seismic)	Medium	Incremental gains in increasing signal-to-noise ratios and enhanced methods for generating seismic waves have permitted imaging of deeper basins. Imaging at greater depths, although not game-changing, provides the opportunity for making significant finds in deep basin plays.
Development of an automated ‘seismic search	Medium-High	As described by Barnes, this type of technology would take advantage of advances in computational power, pattern recognition

engine' to find new opportunities		technology, geophysical data and geological concepts in a highly automated fashion.[39]
Self-contained robotic drilling for subsurface measurements at much lower costs	Medium with a high risk factor	The only publicly described robotic drill is the Badger, which is being researched to provide cost-effective, self-contained drilling requiring neither mud nor casing.[40] The potential impact is to afford relatively rapid but most of all cost-effective drilling of exploration wells. Several key hurdles remain to be overcome before viability can be ensured.
Pumping sensors into formation.	Medium (for exploration) with a high risk factor	If sensors could be pumped into the pores of the formation they could collect information over a very broad area of the reservoir. Current systems are much too large.[41] Many orders of magnitude improvement are needed in order to use in formation pores.
Widespread application of earth-systems modeling to unconventional resources	Medium	Currently, key fundamental components of the system are not well understood. Improvements in the fundamental understanding of the formation of unconventional resources with good recovery potential combined with modeling could lead to identification of new opportunities as well as sweet spot identification.[42]
Integrated earth systems	Medium	Increased integration of basin-forming, sedimentation, deformation, fluid flow and reactive fluid transport as well as inclusion of global process modeling should help identify new subtle hydrocarbon opportunities.[43] Requires advances in science of basic processes, ability to satisfactorily address uncertainty in both inputs and outputs and the computational ability to model simultaneously at multiple scales.
Improved	Moderate	Many contractional systems are notorious for

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[39] Barnes A: "Seismic Attributes in Your Facies," *CSEG Recorder* (September 2001): 41–47.

[40] "Badger Explorer AS (BXPL)—a Revolutionary New Method for Oil and Gas Exploration," company presentation (2006).

[41] For an example, see http://www.dust-inc.com.

[42] For example, see Law BE: "Basin-Centered Gas Sytems," *American Association Petroleum Geologists Bulletin* 86, no. 11(2002): 1891–1919.

[43] Hedberg Conference 2007: *Basin Modeling Perspectives: Innovative Developments and Novel Applications*, AAPG Hedberg Conference (2007). Available at: http://www.aapg.org/education/hedberg/netherlands/index.cfm.
Tuncay K and Ortoleva P: "Quantitative Basin Modeling: Present State and Future Developments Towards Predictability," *Geofluids* 4, no. 1 (2004): 23.

understanding of contractional systems		poor data quality and complex deformation processes and timing that hinder prediction of hydrocarbon occurrences.[44] Even the most advanced models of these systems are relatively simplistic and have limited predictive capability.[45]

Table IV.2. Summary of longer-term technologies in priority categories.

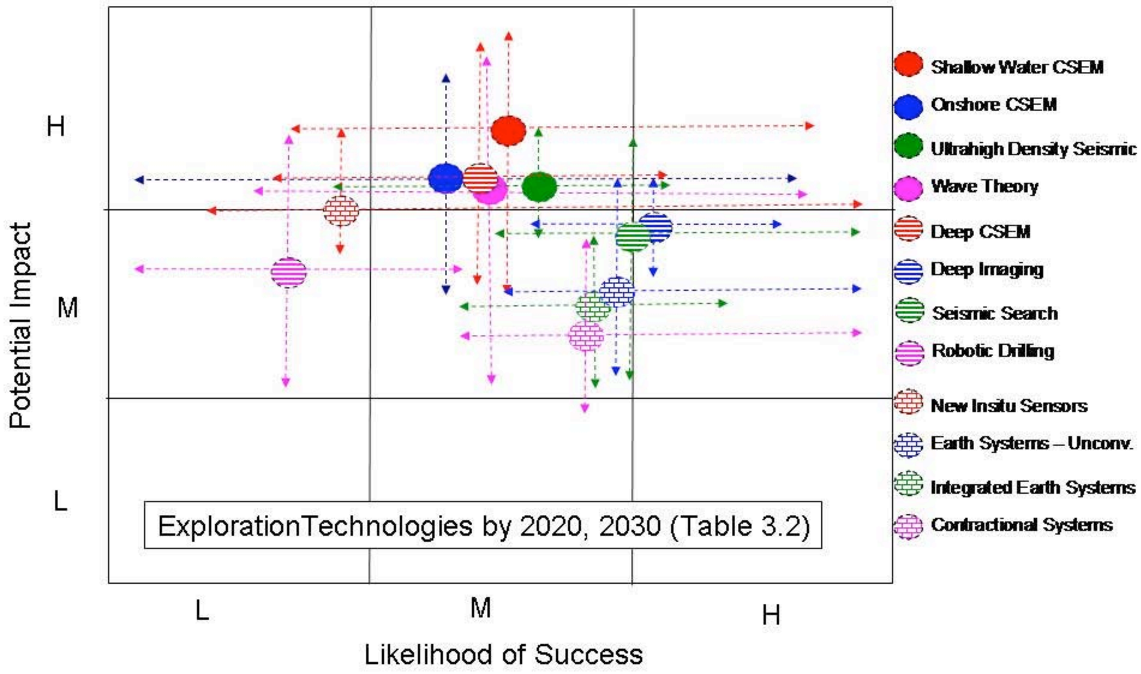

Figure IV.2. Potential impact versus likelihood of success for longer-term technology advances. The dots represent the approximate median of the sub-group votes, whereas the arrows indicate the range in potential impact and likelihood of success of the votes.

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[44] Newson AC: "The future of natural gas exploration in the Foothills of the Western Canadian Rocky Mountains," *The Leading Edge* 20, no. 1 (2001): 74–79.
Lindquist S: "The Santa Cruz - Tarija Province of Central South America: Los Monos - Machareti (!) Petroleum System," U.S. Geol. Survey Open-File Report 99-50-C (1998): 28.

[45] Moretti I, Lepage F, and Guiton M: "KINE3D: a New 3D Restoration Method Based on a Mixed Approach Linking Geometry and Geomechanics," *Oil & Gas Science and Technology - Revue de l'Institut Français du Pétrole* 61, no. 2 (2006): 277–289.

V. Discussion

Advances in exploration technologies that have the potential to play a significant role in improving discovery results in the time period leading up to 2030 fall into the following categories:

1) Improvements in measurements (e.g. high-density seismic, CSEM sensors, wellbore sensors, identification of sweet spots in unconventional reservoirs, much lower cost wells that allow cost effective testing of more or riskier alternatives)
2) Improvements in data processing and interpretation (CSEM, deep imaging, subsalt imaging, more quantitative seismic interpretation, seismic search engines, etc.)
3) Improved conceptual understanding leading to new ideas that will generate new plays and prospects (earth-systems modeling at multiple scales, wave theory research, integration of data and concepts across multiple disciplines)
4) Improved drilling capabilities (drilling HPHT wells, deeper drilling of unconventional resources, extended-reach wells for environmentally sensitive areas).

If the technology continues to develop along a baseline ("business as usual") trend, it is difficult to see a significant change to the current slope of the discovery volume decline curve—at least for those areas that are generally accessible to the global industry. One could argue that without substantial step changes in technology, the negative slope of the discovery decline curve will become more negative—technology will be less and less able to offset the geological limitations. With the uncertainty in the rate of technological innovation and development, predicting an incremental change by 2030 is extremely difficult.[46]

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[46] Lynch MC: "Forecasting Oil Supply: Theory and Practice," *The Quarterly Review of Economics and Finance* 42 (2002): 373–389.

If, however, there is a step change in exploration technology, through a rapid and radical change in any of the four areas described above, then there is potential to halt the discovery volume decline rate for some period of time, as witnessed in the early 2000s. This change in decline rate was in large part the result of opening up deepwater opportunities due to advances in deepwater drilling and exploitation technology and a fundamental reinterpretation of the hydrocarbon systems in deepwater, as well as the application of modern technology to former Soviet Union republics. It is unclear whether radical improvements in technology would affect the declining gross discovery volume—it may enable companies to go after smaller opportunities that are currently considered too risky or marginally economic.

At the moment, CSEM technology is the least mature core technology with the perceived highest potential to impact exploration. This technology also has a high uncertainty with regards to its potential for successful development and application outside of its current deepwater niche. Successful development of this technology could change exploration from a dominant focus on structural traps (which are more readily identifiable on seismic data) to focus areas such as stratigraphic traps (which are challenging to screen using seismic data).

For future exploration, there is likely to be a greater appreciation of Wallace Pratt's statement (1952) that "Where oil is first found, in the final analysis, is in the minds of men."[47] Improved earth-systems modeling and development will probably play an increasing role in identifying new opportunities, as key hydrocarbon system elements of remaining plays are not well-imaged or where data are limited (e.g. arctic). Development of new paradigms may be equally important for unconventional and conventional resource discovery.

At present, in terms of origin, distribution, and produciblity characteristics, unconventional reservoirs are not as well understood as conventional reservoirs. Furthermore, the technology to explore for unconventional resources is still rapidly evolving. Advances in technology to identify and high-grade unconventional

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[47] Pratt WE: "Toward a Philosophy of Oil-Finding," *American Association Petroleum Geologists Bulletin* 36, no. 12 (1952): 2231–2236.

resources could play an important role in determining future hydrocarbon supplies in the year 2030.

Table V.1 outlines the exploration areas that could potentially benefit from the application of the prioritized technology advances.

Areas of Potential Exploration Impact	Technology Advances
Find new plays and large prospects (overlaps with access technology)	All CSEM technology advances High-density and ultradensity seismic Subsalt imaging Modeling of global processes that impact prediction of play elements Integration of basin modeling with geophysics Use of more dimensions and greater interpretation automation Wave theory research Deeper imaging Seismic search engine Robotic drilling Extensional systems Contractional systems Integrated earth systems
Find near-field opportunities	Improved quantitative seismic interpretation Use of more dimensions and greater interpretation automation New physical measurements downhole Wave theory research Seismic search engine Emplacing wireless sensors into formations
Access to difficult environments	HPHT drilling HPHT logging and sampling Dual-gradient drilling Logging while drilling (pressure while drilling) Robotic drilling
Enhance potential of economic success	Coiled tubing drilling Earth-systems modeling of unconventional resources
Mitigate potential environmental concerns	Riserless mud recovery (RMR) Ultra-extended reach wells

Table V.1. Potential impact of identified exploration technology advances (significant overlap between categories)

A. Previous Estimate of Exploration Technology Impact

The 2003 NPC study assumed averages of 0.87%, 0. 53%, and 0.08% (high, median, and low cases) improvement per year in the exploration-well success rate, based on collective expert opinion. The EIA made similar projections for the U.S. onshore and offshore, ranging from 0.25 to 0.75% improvement per year in exploration well success rate for the onshore and similarly 0.5 to 1.5% for the U.S. offshore.[48] A difficulty with this approach is that it doesn't capture the other key terms in the equation—the volumes discovered per well and the number of exploration wells drilled. Instead the 2003 NPC Study focused on the improvement in estimated ultimate recovery per well, which combines the impact of both exploration and recovery technologies.

B. Possible Barriers to Technology Development and Application

There are several business issues that could impede rapid development of either baseline or step-change technologies.

- Technology uptake: As pointed out by Boutte, Daneshy and Bahorich and others, newly developed exploration (e.g. 3D seismic) and auxiliary technologies have taken years to decades to reach full market penetration.[49] The NPC 2003 study points out that more rapid technology adoption occurs when the new technology is developed within a company as opposed to by an outside organization. Anand and others recognize the problem with "oilpatch inertia" with regards to technology but argue that there are practical solutions to accelerate technology acceptance.[50]

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[48] Energy Information Administration: "Assumptions to the Annual Energy Outlook 2006: Oil and Gas Supply Module," Report no. DOE/EIA-0554 (2006): Table 53.

[49] Boutte D: "The Role Of Technology In Shaping The Future Of The E&P Industry," *The Leading Edge* 23, no. 2 (2004): 156–158.

Daneshy AA and Bahorich M: "Accelerating Technology Acceptance: Overview," paper SPE 98553 presented at the 2005 SPE Annual Technical Conference and Exhibition, Dallas, Texas (9-12 October 2005).

[50] Anand P: "E&P Technology Follows Leaders: Selling New Technology Requires Leaders Who Inspire Their Teams to Overcom Oilpatch Inertia," *Harts E&P* (July 4, 2006).

- Development of new breakthrough technologies commonly requires long-term commitment with significant pre-investment. Many of the capital-intensive breakthrough technologies are funded jointly to a large extent by national governments as well as large energy and service companies. Two examples are: 1) the Badger Explorer robotic drill program, which is funded by the Norwegian Research Council, Statoil, Shell and ExxonMobil, and 2) microhole drilling with coiled tubing for exploiting unconventional resources, which has been heavily supported by the U.S. government.

However in the USA, governmental spending appears to be declining. The Dept. of Energy R&D spending for oil and gas technologies has declined from $76 to 78 M/yr in 2004–2005 to $64.4 M/yr in 2006 to $0 in 2007.[51] However as written in the Energy Policy Act of 2005, $37.5 M/ yr of oil and gas royalties is dedicated to research and technology development for ultra-deepwater, unconventional natural gas and small producer challenges and an additional $12.5M is allocated for running the National Energy Technology Laboratory for a total of $50 M/yr.[52] Stewardship of the $37.5 M/yr research and technology development budget was awarded by the Department of Energy in January 2007 for a 10-year period to the Research Partnership to Secure Energy for America. The effort by the USGS in Natural Oil and Gas Resources has remained steady between $13 and $14M/yr for the last three years. Similarly the National Science Foundation R&D effort in earth sciences has remained between $690 and $713M/yr for the last three years—although it is unclear how much of this research is relevant to oil and gas exploration.

- Company Investment Strategy and Amounts: Historically, Daneshy and Bahorich note that during the period 1990 to 2002, the overall upstream R&D expenditures of major U.S. Energy companies fell from $600M to $400M per

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[51] Department of Energy (DOE): *FY 2006 DOE Budget Request to Congress*: 109, 121. Available at: http://www.mbe.doe.gov/budget/06budget/Content/Programs/Vol_7_INT_1.pdf.
Department of Energy (DOE): *FY2007 Congressional Budget Request*: 6. Available at: http://www.cfo.doe.gov/budget/07budget/Content/orgcontrol.pdf.

[52] United States Government: “Energy Policy Act of 2005: Public Law 109-58 (August 8, 2005),” Section 999H. Available at: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=109_cong_public_laws&docid=f:publ058.109.pdf.

year, whereas service company expenditures for R&D increased.[53] This domestic trend for reduced R&D spending was mirrored by international energy companies over the same time period.[54] In the 1980s and 1990s, some major energy companies developed the belief that individual companies did not realize sufficient value for their technology development expenditures and that the increased value proposition was in being the "fast follower" rather than the developer or investor.

- There are concerns about the future availability of highly trained and experienced staff to drive the new technological developments. The skewed demographics of the current workforce (towards older age) combined with the reduced numbers of graduating scientists and engineers (at least domestically) entering into the petroleum industry may impact the rate of technological advancements. Furthermore the reduction in governmental funding of oil and gas research at U.S. universities is perceived to be a substantial issue in recruiting the brightest and the best talent to this field.

There are several technical issues that could be impeding more rapid development of either baseline or breakthrough technologies:

- Overcoming fundamental lack of understanding of key scientific issues—in almost all of the described technology areas, significant advancement will depend on developing new understandings and concepts. Examples include wavefield analysis, innovations in sensors, addressing uncertainty in physical processes, etc. Many of these advances will occur along the interface between different disciplines, and will probably require better integration of technical disciplines and development of cross-disciplinary staff.

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[53] Daneshy AA and Bahorich M: "Accelerating Technology Acceptance: Overview," paper SPE 98553 presented at the 2005 SPE Annual Technical Conference and Exhibition, Dallas, Texas (9-12 October 2005).

[54] International Energy Agency (IEA): "Resources to Reserves: Oil & Gas Technologies for the Energy Markets of the Future," International Energy Agency (2005): Figure 1.14.

- Several of the technologies are highly dependent on computing resources; for example, seismic and CSEM processing. Advances in these areas will be linked to concomitant improvements in computing technology.
- Although perhaps more a business issue, a number of the tests of technological developments will be very expensive and consequently potentially slow to be done. A challenge will be to identify faster and more cost-effective ways to test key concepts.

There is also the possibility that environmental issues could become a barrier to the development and application of new technology advances during the period from now until 2030. Two areas of potential concern to exploration activity in the marine environment are: 1) the impact of drilling and 2) the impact of noise generated by exploration activity on marine life.

C. *Suggestions to Overcome Barriers and Accelerate the Development and Use of Technology*

1) Barrier: Rate of technology uptake

- Exploration companies need to be willing to accept and implement new technology at a faster pace. Many authors have noted the slow adoption of oil and gas technology over the last several decades.[55] As a result of the recent 2004 SPE and Journal of Petroleum Technology Workshop and a 2005 SPE Panel discussion, a number of potential solutions have been proposed that could be helpful.[56]

2) Barrier: Development of new breakthrough technologies—Funding

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[55] For example: Hirsch JM, Luppens JC, and Shook MT: "Accelerating Technology Acceptance: The Role of Culture of the Oil and Gas Industry in Technology Acceptance," paper SPE 98515, presented at the SPE Annual Technical Conference, Dallas, Texas, October 9–12, 2005.
Bell M: "A Case for Nanomaterials in the Oil & Gas Exploration & Production Business," presented at the International Congress of Nanotechnology, San Francisco, California (November 7–11, 2004).

[56] Daneshy AA and Bahorich M: "Accelerating Technology Acceptance: Overview," paper SPE 98553 presented at the 2005 SPE Annual Technical Conference and Exhibition, Dallas, Texas (9-12 October 2005).
Hirsch JM, Luppens JC, and Shook MT: "Accelerating Technology Acceptance: The Role of Culture of the Oil and Gas Industry in Technology Acceptance," paper SPE 98515, presented at the SPE Annual Technical Conference, Dallas, Texas, October 9–12, 2005.

- Encourage sustained government-supported research (both governmental and academic) with clear accountability into fundamental science areas that would underpin advances in commercial technologies (e.g. acoustic wave field research). Public-sector research into high risk and high impact technologies with long lead times, such as nanotechnology and robotic drilling, would be complementary to industry-funded research. Authors such as Weinberg have stated that both U.S. Government and industry funding is inadequate.[57] Haraldsen argues for a comprehensive and collective approach to oil and gas research on a national level as illustrated in Norway's Oil and Gas in the 21st Century strategy.[58]

3) Barrier: Company investment strategy for R&D

- As noted by a number of authors, there has been a significant reduction of industry expenditures in R&D in the last two decades. Funding for R&D has leveled off for the last few years.[59] Industry (both producers and service companies) should re-evaluate the value of R&D to the commercial bottom-line and consider the potential impact of greater investment.

4) Barrier: Availability of highly-trained and experienced staff

- This concern is recognized as a potential issue in the USA, where there were noted declines in U.S. graduates in geoscience and engineering in the late 1980s followed by relatively low, but constant numbers through today.[60] The academic members of this sub-group argued that sustained and greater government support of relevant research at academic institutions can help ensure availability of highly trained researchers and staff to develop the needed technological advances.

5) Barrier: Lack of understanding of key scientific issues

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[57] Weinberg DM: "Why Oil and Gas R&D?" *The Leading Edge* 21, no. 9 (2002): 886–893.

[58] Haraldsen OS: "National Level RD & D," IEA Seminar on Oil and Gas Innovation in the Fossil Fuel Future, Royal Windsor Grand Place, Brussels (February 22, 2006).

[59] International Energy Agency (IEA): "Resources to Reserves: Oil & Gas Technologies for the Energy Markets of the Future," International Energy Agency (2005).

[60] American Geological Institute (2006), www.earthscienceworld.org/careers/stats/historicaldegrees.html. Heinze LR: "Petroleum Talent Shortage," presented at Energy Summit, Texas Tech University, Lubbock, Texas, USA, September 13–14, 2006. Available at: http://www.depts.ttu.edu/peWeb/department/general/PE%20Talent%20Shortage%20TTU%20Midland%202006.ppt.

- Industry, academic and governmental research needs to improve its technical integration—research efforts are often segregated artificially (e.g. departmentalized), hindering the development and application of technical concepts that originate along the boundaries of different technical disciplines. Many of the technological developments with greatest impact have come from sharing of technologies across these interfaces.
- Judicious governmental sharing of technologies developed for defense or security applications could have significant potential for applications to hydrocarbon exploration and exploitation (e.g. sensors, advanced image analysis capabilities and high-resolution gravimeters).

Research into technologies that could mitigate potential environmental impacts will continue to be important. Examples of active areas of research include

- Riserless mud recovery, which reduces discharge
- Ultra-extended reach drilling, which can help avoid sensitive surface environments
- Research into seismic sources as alternatives to conventional seismic airgun arrays.

Complementary research efforts on marine biology and other topics could provide better data to improve informed risk assessment, public debate, and informed decision-making by regulatory agencies.

VI. Appendix 1: Exploration Technology Sub-group Team

Stephen M. Cassiani	President, ExxonMobil Upstream Research Company
Michael Bahorich	SEG representative: Executive Vice-President, Exploration and Production Technology, Apache Corporation—2003 President, Society of Exploration Geophysicists
David R. Converse	Division Technical Coordinator, ExxonMobil Upstream Research Company
William L. Fisher	Professor and Barrow Chair, Jackson School of Geosciences The University of Texas at Austin
David Nichols	Research Director, Western Geco
W.C. (“Rusty”) Riese	Amer.Assoc. Petrol. Geol. Representative: Geoscience Advisor, BP America
Wolfgang E. Schollnberger	Energy Advisor, Potomac, MD
Saad J. Saleh	Program Manager -- Frontier Opportunities R&D, Shell International Exploration and Production Inc.
Nafi Toksoz	Robert R. Shrock Professor of Geophysics, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology

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VIII. Appendix 3: Seismic Technologies

Exploration Technology Sub-group

Technology leader: Mike Bahorich
Date submitted: January 29, 2007

A. Executive Summary

Seismic technologies have been crucial to oil and gas exploration efforts since seminal studies were conducted in the 1920s. Many large discoveries made during the 1950s and 1960s were directly attributable to advances in two-dimensional (2D) seismic surveys; many of the world's largest fields were discovered during this time. Three-dimensional (3D) seismic technology became the industry standard in the 1990s, and it has permitted better interpretations of reservoir characteristics and has led to improved economics in many fields.

Historically, seismic technologies have experienced gradual, incremental advances with occasional game-changing technological jumps (e.g. transition from 1D to 2D to 3D seismic). Since the advent of 3D seismic, most gains have been in small incremental steps that involve collecting higher-density data, imaging deeper basin levels, and refining data processing to produce higher-resolution models. These advances have been key for exploration and production efforts in several areas, including subsalt reservoirs, structurally complex basins, small targets in mature fields, and unconventional resources.

Future advances in seismic technology will likely include higher spatial resolution, greater signal-to-noise ratios, increased data density, improved data processing, integration with other technologies, and application of seismic techniques in novel settings (e.g. the borehole environment). These advances will be crucial in future exploration efforts, as well as in optimizing development of existing fields.

B. Overview of Methodology

The information in this section was largely derived from peer-reviewed publications, government studies, and proceedings from international meetings. Most of the information is found in the references included in Appendix 2 of the exploration technology sub-group report.

C. Background

Seismic technologies utilize the response of acoustic waves (both naturally occurring and man-made) moving through the Earth's crust to image the underlying geologic substrate (Figure VIIIC.1). Images produced by these technologies have been the cornerstone of oil and gas exploration for more than sixty years, and remain important both for the discovery of new fields and for optimizing development strategies in existing fields. Nearly all major discoveries made during the last few decades were the result of enhanced seismic-acquisition studies.

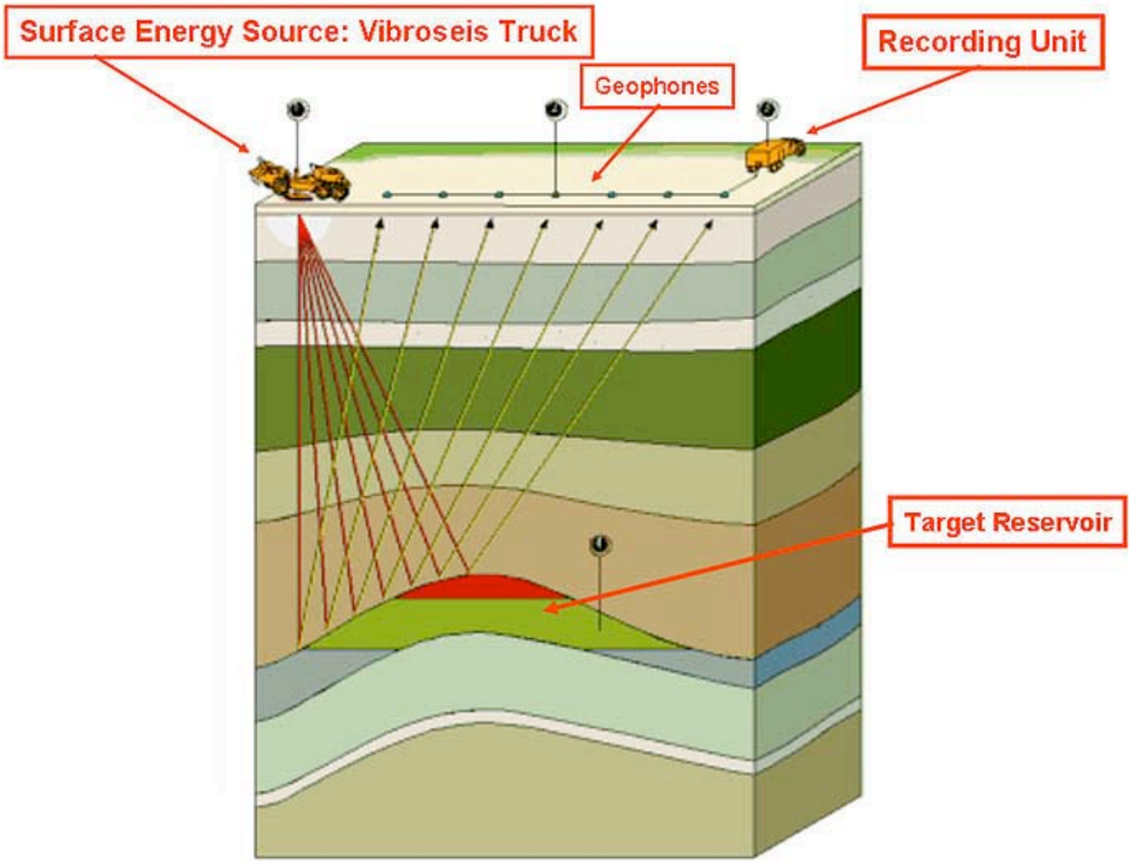

Figure VIIIC.1. Illustration of seismic data acquisition. Seismic data is typically collected by generating seismic energy, in this case using a vibrating truck, which propagates through the underlying rock. The seismic waves reflect off contacts between rock layers (and fluids) and are recorded by geophones. This data are then processed to produce an image of the underlying substrate [courtesy of Apache Corporation].

1. Historical Evolution

Early seismic technologies were developed to assist in locating artillery during World War I. These technologies were subsequently adapted for the purpose of oil and gas exploration; the first field trials for petroleum exploration were conducted near Oklahoma City, OK, in 1921. Seismic technology progressed quickly from the seminal one-dimensional reflection studies in the 1930s to multifold 2D seismic surveys, which became the industry standard for exploration in the 1950s. The analog-to-digital revolution brought with it significant benefits to seismic processing, enabling far superior images to be generated through digital signal processing technology. Multifold 3D seismic data acquisition began in the 1970s, and became the most common seismic application during the 1990s. Time-lapse 3D seismic surveys (sometimes referred to as 4D) have enabled detailed monitoring of fluid movements, which has helped the understanding of petroleum development and has led to a better understanding of potential exploration targets. During each of these transitions to higher-dimension studies, sampling density increased, which provided continuous improvements in resolution. Improvements in both computer hardware and software have had profound impacts on seismic technologies. These improvements have led to reduced data-processing time, facilitated higher-density sampling, and have allowed for more robust imaging algorithms to be applied.

2. Historical Impact

Seismic surveys permit data collection over large areas on short time-scales at low costs compared to drilling campaigns; this directly results in lower exploration costs. Seismic technologies reduce the number of expensive exploratory holes needed to understand the geologic character and hydrocarbon potential of oil and gas fields, and focus drilling activities in areas with the highest potential for hydrocarbon accumulation.

Several of the largest hydrocarbon discoveries that were made during the 1950s and 1960s resulted from applying 2D seismic techniques to exploration. These include several of the largest hydrocarbon fields that will likely ever be discovered, and provided the largest historical increase in volumes of known hydrocarbon inventories.

Because most of the Earth's giant fields in areas that have been accessible to industry were discovered by the 1970s, higher resolution 3D seismic surveys have not resulted in similar increases of hydrocarbon reserves. However, 3D seismic has been instrumental in locating smaller hydrocarbon accumulations and for interpreting structurally complex areas that were beyond the capabilities of 2D seismic. 3D seismic has been especially useful for lowering risk and decreasing the number of dry holes drilled in economically marginal targets, which could not be satisfactorily characterized using traditional 2D seismic methods. Much of the increase in hydrocarbon reserves in and around mature fields can be attributed to increased efficiency brought about by 3D seismic studies.

D. Tables of advances

Seismic technologies are rapidly evolving at all stages from acquisition to processing and interpretation. Table VIIID.1 lists the most promising technologies that could have a significant impact by 2010. The technologies identified in Table VIIID.2 are potential contributors to exploration results in the 2020 to 2030 time frame and include advances that may be categorized as more breakthrough in nature. Due to the longer time frame, there is also greater uncertainty both as to technical feasibility and potential commercial impact.

Technology	Significance	Explanation
High-density data and rapid data processing	High	Higher-density seismic data acquisition with greater signal-to-noise ratios result in greater resolution, which allows for more robust interpretations of reservoir character and hydrocarbon potential to be made. However, for higher density data to have commercial impact, substantial improvements in processing methods must be made.
Subsalt imaging	High-Medium	Salt is a highly distorting acoustic lens which creates "blind spots" beneath it. Considerable efforts have been made to produce high-quality subsalt images, resulting in drilling success in the Gulf of Mexico and West Africa. Enhanced subsalt imaging will undoubtedly result in new discoveries and improved economics.
Time-lapse 3D seismic	Medium-Low (exploitation focus)	Time-lapse seismic (often called 4D seismic) allows for near real-time monitoring of changing reservoir conditions (e.g. pressure changes and fluid movements). 4D seismic is already impacting reservoir management strategies and enhancements in the technique may facilitate a better understanding of reservoir character and flow properties and could lead to enhanced recovery.
Improved velocity models	Medium-Low	Because seismic techniques are essentially probing the "unknown," many assumptions have to be made

		regarding the ability of the rocks to transmit seismic energy. Improving these assumptions would allow for more accurate images to be made.

Table VIIID.1. Summary of near-term (by 2010) technologies in priority categories.

Technology	Significance	Explanation
Ultra high-density data and processing	High-Medium	Data density and processing continue to improve at incremental steps. However, if extremely high-density data could be acquired and processed rapidly and at low costs, game-changing breakthroughs could occur. These include greater efficiency in economically marginal areas, enhanced recovery, and new finds.
Wave theory research	High-low	Basic research into wave theory is a continuing effort in both industry and academia. Synergistic collaboration between the two has certainly led to gradual advancements and could result in large leaps forward.
Deep imaging	Medium	Incremental gains in increasing signal-to-noise ratios and enhanced methods for generating seismic waves have permitted imaging of deeper basins. Imaging at greater depths, although not game-changing, provides the opportunity for making significant finds in deep basin plays.
3D borehole seismic	Medium-Low (exploitation focus)	Although borehole seismic has been used for 20 years, considerable advances could be made if 3D vertical seismic profiling were fully utilized. These techniques may be especially useful for enhancing hydrocarbon recovery.
Integration with other data types	Medium-Low	Seismic data has often been used in isolation or only integrated with well data. Possible integration with electromagnetic data could enhance exploration efforts.

Table VIIID.2. Summary of longer-term technologies in priority categories.

E. Discussion

All of the aforementioned advances in seismic technologies could be accelerated in the correct economic environments if proper measures were taken at all levels. The main hindrances to technological advancement predominantly occur as a result of:

1) Economic strategies in both the service and oil and gas company sectors that focus on near-term reduction in the costs associated with finding, developing, and producing hydrocarbons, with less focus on the potential future impacts new technologies could have on these costs.
2) Insufficient integration—companies are often segregated into divisions that hinder the ability of groups to interact with one another. Furthermore, different groups (e.g. geophysicists and reservoir engineers) that could utilize similar technologies often have different needs for technology deployment (strategic or planning vs. immediate).
3) Lack of technical aptitude and continual training—end users of technology may be reluctant to try new techniques because they do not understand it or appreciate its potential benefits.
4) Fundamental science—it is imperative that fundamental science be continually advanced in order to provide the environment for breakthroughs in seismic and other technologies.
5) Risk of testing new technologies—individuals often prefer to have other companies first prove a technology before applying it to their problem because a failed technology trial may cause oil production targets to be missed.[61]

Incremental advancements in seismic technologies will no doubt result in improved economics and new hydrocarbon discoveries. The most promising advancements that will

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[61] Daneshy AA and Bahorich M: "Accelerating Technology Acceptance: Overview," paper SPE 98553 presented at the 2005 SPE Annual Technical Conference and Exhibition, Dallas, Texas (9-12 October 2005).

occur in a "business-as-usual" incremental step model are in collecting higher-density data sets. Higher density directly results in better resolution of the underlying geologic substrate and better understanding of reservoir characteristics. Advances in this area will make it possible to go after marginal targets that are currently either poorly understood or considered too risky. These types of targets are extremely important in mature fields in the United States, many of which have been producing for nearly 100 years. Much of the development and on-going exploration that continues in the continental United States has been made possible by 3D seismic studies that have identified increasingly smaller targets in and around existing fields; for exploitation of hydrocarbon deposits to continue in these areas higher-resolution data must be collected.

Enhanced subsalt imaging is crucial for continued exploration in areas where the presence of salt is today a technological barrier. Many of the new discoveries in the Gulf of Mexico in the 1990s resulted from enhanced subsalt imaging, and many of the future prospects there and elsewhere are subsalt targets. In order for these hydrocarbon reservoirs to be economically developed, better subsalt imaging is a requirement. Subsalt fields present numerous technical challenges in their development, and if risk can be limited through enhanced imaging then it is likely that undeveloped and underdeveloped fields will contribute to future production in the Gulf of Mexico.

Time lapse 3D seismic (4D) has demonstrated the potential of enhanced recovery and field optimization. However, there are several impediments to this technology. It is expensive to deploy (requires either multiple deployments or permanent recording stations), is data intensive and requires increased data processing, and requires better communication between reservoir engineers and geophysicists who have different operational functions. Deployment of this technology in mature and offshore fields is often not economically feasible, and would therefore only be of marginal importance in U.S. oil fields.

Seismic data is progressively being acquired from deeper structural levels. Data density increases and signal-to-noise ratio improvements have made imaging extremely deep targets a reality. As improvements in those areas continue, enhanced imaging of deep plays and fields will continue. This is very pertinent to both onshore and offshore exploration and production efforts in the United States. Some of the largest untapped reservoirs may well lie in deeper portions of previously discovered and developed basins, which cannot be adequately defined at present. Large offshore discoveries are likely to continue to be made in the Gulf of Mexico as seismic technologies that can produce high-quality images of deep basins are deployed (e.g. recent announcement of Jack #2 discovery—being reported as a 3 to 15 billion barrel trend in Lower Tertiary rocks).

New seismic technologies will inevitably contribute to new discoveries, enhanced recovery, and better economics, even if only incremental gains are made. However, the development of new technologies must accelerate in the near future if resource development is to continue at its current pace in the United States. The costs to develop any of the technologies listed in Tables VIIID.1 and VIIID.2 are highly variable and will not be recouped until much later. This requires that proper incentives be in place for both exploration and production companies and service companies developing the technologies, and the management and employees that must deploy it.

IX. Appendix 4: Controlled-Source Electromagnetic Methods

Exploration Technology Sub-group

Technology leader: Saad Saleh
Date submitted: January 29, 2007

A. Executive Summary

The seismic method is the most widely used geophysical technique for petroleum prospecting. Although direct detection of oil and gas using seismic techniques is possible via a number of methods, such as bright spots and amplitude-variation-with-offset (AVO), the seismic method remains largely an *indirect* technique for detecting hydrocarbons, and its application is often motivated by its utility as a structural delineation tool. Even in cases where seismic amplitudes can be used to identify subsurface fluids, there are typically indistinguishable fluid scenarios that result in significant uncertainty. For example, a low-saturation gas reservoir can often look essentially identical to a high-saturation oil reservoir.

The shortcomings of seismic techniques in the area of direct detection of hydrocarbon have been recognized in the industry for several decades, and have been a source of one of the most important challenging open research problems in exploration geophysics. It has also been well-known for many years that electromagnetic techniques can in theory offer solutions to these outstanding problems, because resistivity contrasts, which are measured by electromagnetics, are typically much more sensitive to fluid variations than corresponding acoustic or elastic-impedance contrasts, which are measured by the seismic method. However, only recently have advances in the application of electromagnetic methods, especially controlled-source electromagnetics (CSEM), managed to achieve the depth of penetration needed for successful petroleum exploration. Ever since the publication of these advances, CSEM has become recognized as one of the most promising emerging geophysical technologies. Not only does CSEM hold the potential for reducing exploration risk by removing some of the ambiguities related to seismic direct hydrocarbon detection, but on a larger scale it can also help wean the oil industry off a shrinking portfolio of predominantly structural traps, and help fuel new exploration campaigns focused on stratigraphic traps that have been traditionally difficult to see using seismic methods. However, CSEM is still at a relatively early stage of development, and a substantial increase in the level of research funding is needed to accelerate advances in CSEM if its potential as a breakthrough technology with significant impact on oil and gas exploration within the next two decades is to be determined.

B. Overview of Methodology

The information in this section is based largely on publications in the open literature. Most of this information can be found in the following references by Cox, 1981, Nabhighian, 1987,1991, Sinha et al., 1990, Srnka, 1986, Smit and Dragoset, 2006, Srnka et al., 2006, Moser et al., 2006, MacGregor et al, 2006, Houck and Pavlov, 2006, and Hacikoylu et al., 2006, which are contained in Appendix 2.

C. Background

Controlled-source electromagnetic methods are used mainly as a tool for direct detection of commercial hydrocarbon accumulations in the subsurface. To explain, note that the resistivity of a hydrocarbon-saturated reservoir can be one or two orders of magnitude larger than the resistivity of a brine-filled reservoir with identical parameters. Since electromagnetic methods are designed for measuring subsurface resistivities, their utility for direct detection of commercial hydrocarbon accumulations is evident.

In general terms, the Earth is a conductor. The challenge associated with using electromagnetic energy for petroleum exploration stems from the fact that electromagnetic waves undergo rapid attenuation upon entering a conductor. The degree of expected attenuation is a function of the frequency used, which in turn is related to the resolution and depth of expected penetration—the higher the frequency, the larger the attenuation. For example, conventional borehole EM techniques use relatively high frequencies, making them very useful for fluid identification at the reservoir scale, the price being that they can “see” only in the area immediately adjacent to the borehole. Similarly, airborne EM methods are used in the mineral exploration industry, where relatively high frequencies limit the application to the shallow subsurface—on the order of 100 or 200 meters. At the other end of the spectrum, passive electromagnetic methods, such as the magnetotelluric (MT) method, use low frequencies to achieve very deep penetration into the subsurface, the price being that only very large structures can be identified—much larger than reservoir structures.

Although the methods mentioned above, such as borehole EM, airborne EM, and magnetotellurics, have been in existence for several decades, the goal of detecting a relatively deep hydrocarbon-saturated reservoir via surface-based electromagnetic measurements remained an elusive target, largely because of the technical tradeoff outlined in the previous paragraph. However, recent advances in applying electromagnetic methods for studying the oceanic lithosphere got the attention of the oil industry (particularly ExxonMobil and Statoil) in the 1980s and 1990s. Coupled with exploration shifts towards deeper water in 1990s as well as continued advances in instrumentation, field trials and experiments aimed at the direct hydrocarbon detection problem began to take off in the last few years (Figure IXC.1).

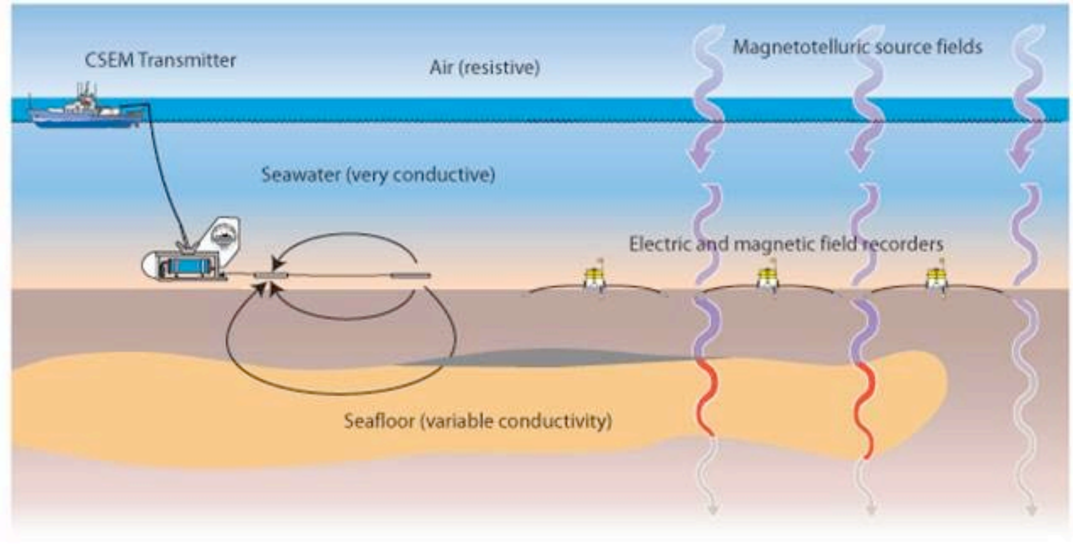

Figure IXC.1. CSEM method (courtesy Steven Constable, Scripps Oceanographic Institute).

The role played by deepwater exploration is significant here for two reasons. The first is purely economical: expensive deepwater wells provide a strong incentive to invest in exploration technologies, especially those related to direct hydrocarbon detection. The second reason is a technical one: A thick layer of sea water above the sources and receivers, which are typically positioned on or near the sea floor, provides effective insulation from electromagnetic noise propagating from the air layer above the water surface.

By 2003, the field trials had begun to produce convincing results with regard to the feasibility of this technology for direct detection of hydrocarbons. Since then, the industry has witnessed rapid growth in this area. Hundreds of surveys have been acquired by several oil companies in the last few years. In spite of its young age, the technology has already had a significant impact on exploration success. For example, in geological environments where petroleum traps with leaky seals are common, CSEM has been used to distinguish between commercial and non-commercial fluid scenarios that are indistinguishable via conventional seismic fluid-identification techniques. An example has been to use CSEM to discriminate against structures containing low-saturation gas (Moser et al., 2006).

D. Tables of Advances

CSEM technologies are rapidly evolving at all stages from acquisition to processing and interpretation. Table IXC.1 lists the most promising technologies that could have a significant impact by 2010. The technologies identified in Table IXC.2 are potential contributors to exploration results in the 2020 to 2030 time frame and include advances that may be categorized as more breakthrough in nature. Due to the longer time frame, there is also greater uncertainty both as to technical feasibility and potential commercial impact.

Technology	**Significance**	**Brief discussion**
Fast 3D modeling and inversion	High	CSEM can discriminate between scenarios which are indistinguishable via seismic amplitudes; e.g. commercial oil versus residual (non-commercial) gas. However, false positives are common; e.g. hydrates, salts and volcanics can yield a response similar to a commercial petroleum response. Fast 3D modeling and inversion capability can help discriminate against such false positives.
Integration with structural information from seismic	High	An important approach to increase the resolution of information obtained via CSEM methods.
Integration with structural information from magnetotellurics and potential fields	Medium	Better background resistivity models, resulting in improved capability to interpret the data.

Table IXC.1. Summary of nearer-term (by 2010) technologies in priority categories.

Technology	Significance	Brief discussion
Shallow water EM	High	The shallow water environment is much noiser than the deepwater environment for CSEM techniques. Substantial advances are needed to enable robust signal acquisition and analysis in such an environment. But if successful, it can open up the application domain for CSEM beyond deepwater basins.
Onshore EM	High	The onshore environment is much noisier than the deepwater environment for EM techniques. Substantial advances are needed to enable robust signal acquisition and analysis in such an environment. But if successful, it can open up the application domain for CSEM beyond deepwater basins.
Deep CSEM	High-Medium	Even in deepwater basins, current application is limited to relatively shallow reservoirs (2 to 3 km below sea floor). Advances in penetration depth can open up applications in several new basins.

Table IXC.2. Summary of longer-term technologies in priority category.

E. Discussion

If CSEM technology continues to advance along the lines of a “business as usual” mode, it will no doubt influence exploration in very important ways; e.g. it could significantly reduce exploration risk in certain geological environments, such as thrust belts (Moser et al., 2006), where breached traps are common and the ability to distinguish between commercial oil and residual gas is crucial—an ability that is substantially enhanced via CSEM methods. But its utility is expected to continue to be limited to relatively shallow reservoirs in deepwater environments if such a baseline mode of technical progress is followed. The technology’s utility for reducing exploration risk can be enhanced tremendously if advances can be made to enable cost-effective implementation in shallow water and onshore environments as well as to increase the depth of penetration by roughly a factor of three. In fact, such advances could change the exploration game in a profound manner as they can have important consequences for shifting exploration efforts from a predominant focus on structural traps, which can be more readily identified on seismic data, to new focus areas such as stratigraphic traps, which are much more challenging to screen using seismic data.

The important technical advances mentioned above require a substantial acceleration effort in research and development to have meaningful impact in the period of this study. Significant barriers need to be removed to enable such breakthroughs. In some cases, such as "deep CSEM," the barriers are related to fundamental questions in physics related to the nature of electromagnetic energy propagation in rocks. To achieve a substantial increase in depth of penetration, fundamental research in this area of physics is needed. Other, perhaps less serious, barriers are related to the cost associated with conventional CSEM surveys (receivers deployed and retrieved in a deepwater environment). To overcome such barriers, new innovations in instrumentation and data acquisition methodologies as well as in advanced processing techniques to increase the signal-to-noise ratio are needed. To do this, the investment in CSEM R&D needs to increase significantly.

X. Appendix 5: Interpretation Technologies

Exploration Technology Sub-group

Technology leader: Dave Converse

Date submitted: January 29, 2007

A. Executive Summary

Improvements in interpretation technology played a significant role in the historical impact of 3D seismic data on exploration success rates. The adaptation and improvement of visualization and interpretation tools developed for other industries (e.g. medical imaging) combined with a rapid increase in computing power provided interpreters with the ability to visualize and interpret seismic data in 3D—tasks that were not commonly possible in the 1980s.

With the advent of improved seismic technologies, increasing numbers of meaningful seismic attributes and acquisition volumes of increasing size—interpreters now struggle with the sheer volume and complexity of data. Furthermore with the improved understanding of subsurface rock and fluid properties, and higher resolution seismic data, there is an increasing demand for quantitative interpretations to predict rock and fluid characteristics (e.g. porosity, saturation).

To address these issues, ongoing research in interpretation technologies are focused on: 1) better integration of geophysical and geologic data to develop quantitative interpretations; 2) inclusion of more data dimensions; and 3) increasing automation of interpretation tasks, including the capability to search a 3D volume for correlatable events in high-dimensional space (beyond the ability of human interpreters). All of these approaches have had a fair amount of success with a promising future. As suggested by

Barnes (2001), development of seismic search engines to sift through the data may become a reality that could impact 2030 supplies.

B. Overview of Methodology

The interpretation technology evaluation was based primarily on literature resources and discussion among the Exploration Technology Sub-Group and colleagues in our companies and departments. The literature resources are documented in the Appendix 2.

C. Background

1. Historical Evolution:

Interpretation of seismic and other geophysical data has evolved significantly over the last 100 years in conjunction with changes in data acquisition and processing as well as improvements in computing capabilities. No longer are seismic data hand-migrated and interpreted with colored pencils—interpretations are done with advanced visualization engines on workstations, visualization centers and immersive caves. Much of the visualization approach was heavily borrowed from the medical imaging community (Wolfe and Liu, 1988). More and more interpretation is done with heavily computer-aided, semi-automatic techniques (e.g. horizon interpolation, fault picking). New ways of looking at seismic data and their derivatives were developed to enhance key geologic features (e.g. development of new seismic attributes such as a coherency cube (Bahorich and Farmer, 1995) and more recently, spectral decomposition to look at features in specific frequencies (Partyka et al., 1999).

At the same time, qualitative interpretation of seismic attributes is giving way to an increasingly quantitative interpretation approach (Chopra and Marfurt, 2005). With a greater number of quantitative attributes being used in interpretations both for exploration and reservoir description, there is a greater use and reliance on advanced statistical techniques such as neural networks (Nikravesh and Aminzadeh, 2001), self-organizing maps (Strecker and Uden, 2002) and Bayesian frameworks (Larsen et al., 2006).

2. Historical Impact:

One impact of advances in interpretation technology has been to enable the recognition of hydrocarbons that were previously difficult to see or perceived as too risky. The Goldeneye Discovery in the UK North Sea required the use of optical smashes (summing traces from multiple adjacent seismic sections in a 3D cube) to enhance the flat spot representative of the hydrocarbon-water contact (Wilson et al., 2005). In Angola, Fahmy et al. (2005) used spectral decomposition to identify a previously unseen oil pay. Carlson et al (2004) used a template-matching process that was calibrated against existing wells to identify new opportunities in the Bay of Campeche, Mexico.

A second but related impact has been the improved exploration success rate in areas with high quality geophysical data (Center for Energy Economics case study, Morgan, 2005). Part of the success can be attributed to the improved data quality, but part is due to the improved techniques in interpreting the data (e.g. AVO analysis—Allen and Peddy, 1993).

A third impact of improved interpretation technology has been a reduction in interpretation time—this number is less easy to quantify but regarded as significant. Many of the highly manual tasks of interpretation have been greatly sped up by the use of semi-automatic or user-guided approaches in a visualization environment.

D. Tables of Advances

Interpretation technologies are rapidly evolving. Table XD.1 lists the most promising technologies that could have a significant impact by 2010. The technologies identified in Table XD.2 are potential contributors to exploration results in the 2020 to 2030 time frame and include advances that may be categorized as more breakthrough in nature. Due to the longer time frame, there is also greater uncertainty both as to technical feasibility and potential commercial impact. Estimating the rate of uptake is difficult. Sternbach (2002) in his 20 year retrospective on seismic interpretation technology notes that "adoption of the most exciting improvements in seismic interpretation … is much slower than predicted … due to outdated but entrenched work flows, and computer software costs."

Technology	Significance	Brief discussion
Improved quantitative seismic interpretation	Medium	Will see more quantitative seismic interpretation (Avseth et al., 2005) with better integration of geological and geophysical data
Inclusion of more data dimensions (e.g. multi-dimensional attributes, geological data)	Medium	Will integrate more data dimensions (currently limited to a small number) using advanced statistical techniques that also allow uncertainty to be addressed. (Barnes, 2001)
Greater automation	Medium	There is significant work going on in the vendor companies and the universities to increase the degree of automation (e.g. automatic fault and horizon mappers). Recent efforts focus on a collaborative work flow between the interpreter and the advanced statistical tools (Pedersen et al., 2005).

Table XD.1. Summary of near-term (by 2010) technologies in priority categories.

The following table contains technological advances that might be in commercial use to affect exploration by 2020 and 2030.

The priority is determined by the difference in impact between a business as usual case and an accelerated technology case, listed with greatest impact first.

Technology	Significance	Brief discussion
Development of an automated 'seismic search engine' to find new opportunities	Medium-High	As described by Barnes (2001), this type of technology would take advantage of advances in computational power, advanced statistical techniques, geophysical data and geological concepts in a highly automated fashion.
Integration of other technologies to improve interpretation	Medium	Advances in human cognition (Welland et al., 2006) as well as advances in pattern recognition technology for military, imaging and security purposes may play an important role.

Table XD.2. Summary of longer-term technologies in priority categories.

E. Discussion

Geophysical interpretation technology is critically important for identifying new hydrocarbon volumes, and has had significant success in the past, as discussed above. As reviewed by Sternbach (2002) and Barnes (2001), these technologies have advanced greatly in the last two decades.

Ongoing research and development in interpretation technology has been focused in at least three major areas:

1) Developing quantitative interpretation through the integration of rock physics with seismic, geologic and fluid data along with consideration of uncertainty: Avseth et al. (2005)'s recent book *Quantitative Seismic Interpretation: Applying Rock Physics Tools to Reduce Interpretation Risk* is a good example of the current state of knowledge. In their discussion of future trends in quantitative seismic interpretation, they state (p. 256) "We see some clear trends in quantitative seismic interpretation: more rigorous modeling and inversion of the wave propagation phenomena; combining sedimentologic and diagenetic modeling with rock physics modeling to obtain more realistic predictions of seismic properties; probabilistic Monte Carlo simulations to capture uncertainties in both rock physics and inversion results; and incorporation of geostatistical methods to account for spatial correlations in reservoir properties." Advances in this area are being actively pursued by both industry and academic institutes both in terms of continuous rock and fluid properties as well as fracture orientations (Perez et al., 1999) and other properties.
2) Including more data and data derivatives in the geophysical interpretation: Much of the recent focus has been on the development of novel attributes (e.g. coherency, spectral decomposition). However there is also a significant effort to include more and more attributes (both geological and geophysical) in the interpreter's interpretation of seismic data (Chopra and Marfurt, 2005; Schlaf et al., 2005). One of the issues has been the proliferation of attributes, not all of which are unique (Barnes, 2006), that can overwhelm the interpreter (Chopra and Marfurt, 2005). This issue has led to, and will continue to lead to, a greater use of

advanced statistical techniques like clustering, neural networks, Bayesian frameworks, self-organizing maps, hidden Markov chains, and support vector machines to help guide the interpreter to key data structures.

3) Increasing the degree of automated interpretation: Both academic institutes and commercial entities are working hard to improve the degree of automation and limit labor-intensive tasks in interpretation. Changes in the major software packages for seismic interpretation clearly indicate a premium on reducing interpretation time and simplifying linkages between data sets and peripheral interpretation tools. There are also numerous papers on developing improved techniques for both horizon tracking and fault picking (Adamasu and Toennies, 2004; de Rooij and Tingdahl, 2002; Gibson et al., 2005; Dorn and James, 2005; Pedersen et al., 2005).

If the technology continues to develop along a baseline ("business as usual") trend, then there is likely to be a moderate impact on the volume of hydrocarbon resources available in 2030. There is considerable time and money being invested in this area by both academic institutes and industry. More than 100 U.S. patent applications have been filed in this area since 2001. The assessment of moderate impact is based on the fact that even with the very substantial improvements in seismic acquisition, processing, and interpretation technologies in the last three decades, the exploration discovery volumes continue to decline with time (on average; Bell, 2004). An analogy might be that improvement in these technologies has lead to a sharpening of focus on exploration opportunities but not a radically new method to identify new exploration opportunities.

There are several barriers to the more rapid advancement in interpretation technology: 1) limited understanding of rock physics (e.g. degree of anisotropy—Avseth et al., 2005; mixing rules, etc.) and considerable uncertainty in the inputs to the rock physics models that limit usability; 2) computational restrictions on speed and memory that affect development and deployment of complete rock physics models and inversion routines; 3) difficulty in incorporating geologic knowledge into automated tools for horizon, facies and fault mapping, which leads to significant numbers of erroneous results—approaches to address like meta-attributes (deRooij and Tingdahl, 2002) have had some success; and 4) incorporating advanced statistical techniques that are optimized for seismic interpretation. Another concern expressed by Sternbach (2002) is whether or not appropriate training at the universities or in industry exists to produce individuals with both the geophysical and geological expertise needed for these advancements.

A potentially high impact item would be to develop a "seismic search engine" as described by Barnes (2001) to help find specific features. Potentially this approach could radically change the exploration vision and result in significant new exploration opportunities, especially if combined with advanced earth-systems models. Successful development of a "seismic search engine" would depend on the solution to all of the previously described barriers.

To accelerate interpretation technologies and their impact will require a significant sustained commitment of resources as well as extensive adaptation of advanced statistical techniques. It will probably require encouragement of the development of individuals or integrated teams with skills across the geological-geophysical-statistical spectrum. The rapid rate of increase in computing capabilities coupled with cost reduction may render computing limitations moot. The rock physics improvements are likely to be difficult to accelerate due to the difficulty and expense in obtaining high-quality data.

The potential prize is the opportunity to identify nonobvious, undiscovered hydrocarbon accumulations for both conventional and unconventional resources. This prize may be particularly significant in the 2030 time frame for the USA due to the highly mature state of exploration in the USA that has already resulted in discovery of most "obvious" hydrocarbon accumulations.

XI. Appendix 6: Earth Systems

Exploration Technology Sub-group

Technology leader: Dave Converse, Bill Fisher, and Wolfgang Schollnberger

Date submitted: January 29, 2007

A. Executive Summary

Earth-systems modeling is the modeling of complex earth processes, which include both global processes (e.g. climate, plate tectonics, and eustasy), regional processes (e.g. basin formation, uplift and erosion, and sediment transport), and local processes (e.g. local sediment depositional geometries and fault geometries).

Initially, modeling of earth processes focused on the prediction of specific geologic process behavior as opposed to modeling of an integrated earth system. The purpose of modeling was designed to test concept understanding and evolution under different geological conditions. This approach was successful in identifying areas and times that were likely to have developed key elements of hydrocarbon systems, but are inadequate to address variations in hydrocarbon-system elements that resulted from nonlinear interactions that are common in earth systems.

Attempts to model earth systems are becoming increasingly common, because explorationists are searching for increasingly subtle hydrocarbon accumulations that depend upon the successful combination of several elements of the hydrocarbon system, which each may have significant variability. The ability to model potential variable combinations (along with the attendant uncertainties) of hydrocarbon-system elements, allows explorationists to play a series of “what-if” scenarios to test different hypotheses. The promise of improving the capability to model more integrated earth systems is to identify new plays or prospects that are not obvious with current analysis methods (either due to nonlinear interactions or due to limitations in data or fundamental lack of scientific understanding) or the explorationist's experience. The modeling should also highlight areas that require fundamental improvements in scientific understanding. A major application is likely to be in the identification of "sweet spots" in the currently less well-understood unconventional hydrocarbon systems.

B. Overview of Methodology

The earth-systems evaluation was based primarily on literature resources and discussion among the Exploration Technology Sub-Group and colleagues in our companies and departments. The literature resources are documented in the Appendix.

C. Background

1. Historical Evolution:

Initially modeling of earth processes focused on the prediction of specific geologic-process behavior as opposed to modeling of an integrated earth system. The purpose of modeling was designed to test concept understanding and evolution under different geological conditions. For example, early modeling related to petroleum exploration was focused on predicting the timing and volumes of hydrocarbons released by maturing source rocks (Nunn et al., 1984). Examples included prediction of tectonic behavior, sediment fill patterns, structural geometries and styles, heat flow, hydrocarbon maturation and yield, hydrocarbon migration, and diagenesis (Paola, 2000; Marzi and Crowley, 2003). With improved scientific understanding and computational power, the specific models have evolved from simple analytical approximations to simplistic 1D models to more complex multi-dimensional models (Duppenbecker and Marzi, 2003).

With success in modeling of individual technical components, there has been a greater push to include more and more technical components together with their complex interactions to create systems models of the Earth (Paola, 2000, Paola et al., 2006). As an example, Jacques and Markwick (2005a, b) combined plate tectonic modeling, paleo-climate modeling, ocean and sediment modeling to predict the distribution of source rocks, reservoirs and seals—all key hydrocarbon system elements. With increasing computer power, more and more processes can be included in an earth system; a major difficulty becomes how to evaluate the validity of a complex model (Paola, 2000) and to understand the uncertainty.

2. Historical Impact:

Earth-systems models have helped exploration for hydrocarbons in three distinct ways:

4) Identification of new plays via an improved understanding of the hydrocarbon system (Ahlbrandt and Klett, 2005). For example, the study by Westphal et al. (2003) identified previously unrecognized source intervals in a mature basin. The work by Rasmussen et al. (2003) helped identify the presence of a large oil accumulation in chalk with a complex depositional, structural, migration and trapping history.
5) Use of earth-systems models for sweet spot identification (Karlsen and Skeie, 2006)—an example is the use of basin models to identify sweet spots in basin-centered gas (Law, 2002).
6) Use of systems models to aid in prospect risking based on modeling results. In the greater Utsira High, source, maturation, and migration modeling were used by Isaksen and Ledje (2001) to assess the likelihood of hydrocarbons being present in structural closures as well as the likely trapped phase (gas or oil).

D. Tables of Advances

Earth-systems modeling is rapidly evolving. Table XID.1 lists the most promising technologies that could have a significant impact by 2010. The technologies identified in Table XID.2 are potential contributors to exploration results in the 2020 to 2030 time frame and include advances that may be categorized as more breakthrough in nature. Due to the longer time frame, there is also greater uncertainty both as to technical feasibility and potential commercial impact..

Technology	Significance	Brief discussion
Improved Modeling of extensional systems to	Medium	Large volumes of reservoir hydrocarbons occur in extensional basins. Advances in modeling of extensional systems are focused on improved understanding and inclusion of more technical

identify new plays		components (e.g. basin formation, sedimentation, deformation, and fluid transport) to aid in identifying new play concepts and sweet spots—particularly in areas of poor data or resolution. New work is moving to more and more multi-dimensional simulations (Duppenbecker and Marzi, 2003).
Increased integration of basin modeling with geophysical data	Medium	Increase the integration of geophysical data and geologic data to validate basin modeling and geophysical interpretations as well as clarify the uncertainty (Hedberg Conference 2007).
Modeling of global systems	Medium	Greater inclusion of modeling of global processes like climate modeling and plate tectonics that influence important elements of hydrocarbon systems (Jacques and Markwick, 2005a; Bohacs and Fraticelli, 2006)
Improved use of all data as well as reducing the uncertainty limits.	Medium	Current models do not make use of all available data for both computational reasons and inability to deal effectively with uncertainty in both inputs and outputs. (Hedberg Conference, 2007)

Table XID.1. Summary of near-term (by 2010) technologies in priority categories.

The priority is determined by the difference in impact between a business as usual case and an accelerated technology case, listed with greatest impact first.

Technology	Significance	Brief discussion
Modeling of integrated earth systems	Medium	Increased integration of basin-forming, sedimentation, deformation, fluid flow and reactive fluid transport as well as inclusion of global process modeling should help identify new subtle hydrocarbon opportunities (Hedberg Conference 2007, Tuncay and Ortoleva, 2004). Requires advances in science of basic processes, ability to satisfactorily address uncertainty in both inputs and outputs and the computational ability to model simultaneously at multiple scales.
Improved understanding of contractional systems	Medium	Many contractional systems are notorious for poor data quality and complex deformation processes and timing that hinder prediction of hydrocarbon occurrences (Newson, 2001; Lindquist, S., 1998). Even the most advanced models of these systems are relatively simplistic and have limited predictive

		capability (Moretti et al., 2006).
Widespread application to unconventional resources	Medium	Currently, key fundamental components of many unconventional resource systems are not well understood. Improvements in the fundamental understanding of the formation of unconventional resources with good recovery potential combined with modeling could lead to identification of new opportunities (e.g. Law, 2002) as well as sweet spot identification.

Table XID.2. Summary of longer-term technologies in priority categories.

E. Discussion

Earth-systems modeling serves a particularly important role as a vehicle to capture conceptual understanding, to provide context to understand geological, geophysical, and engineering data, and to allow the testing of “what if” scenarios. Historically these models have played a significant role in the identification of new hydrocarbon resources as discussed above.

The technology of earth-systems modeling is becoming increasingly quantitative and involves modeling more and more complex interactions at multiple scales. The modeling is not restricted to geophysics and geologic components but also is beginning to include more sophisticated biological models and their interactions (Parkes et al., 2005). Experience says that systems with many interacting parts can behave in unexpected ways, rendering theoretical and numerical modeling ineffective unless paired with appropriate analytical observations. Much the same can be said for the necessity of rock-based (field) models, at least until reliable and predictive models are developed. Systems modeling therefore should be committed to advancing numerical modeling and collection of targeted analytical observations hand in hand, as well as perfecting rock-based models. The pace and accuracy of discovery will be significantly improved by moving these lines of research forward in partnership with one another. There is, however, a significant concern that if more and more processes are included in the earth-systems modeling, that at some point, the resulting solution space may become too broad to use for predictive purposes.

In the future, earth-systems modeling is likely to play an increasingly important role in identifying new opportunities where key hydrocarbon system elements are not well-imaged or are subtle, or where data in general are limited (e.g. arctic). This role is likely to be equally as important for unconventional resources (e.g. shale gas, coal-bed methane, and tight gas) as for conventional resources.

If the technology continues to develop along a baseline ("business as usual") trend, then there is likely to be a moderate impact on the volume of hydrocarbon resources available in 2030. There is a substantial amount of work ongoing in the universities, particularly in earth processes and process response modeling with a good chance that this work will hit critical mass in a decade or so. The pace of the research in universities will depend on the level of public and private funding support, as well as the availability of highly trained students and faculty who can integrate the processes across multiple disciplines. Individual companies and joint industry programs are also addressing a number of these areas.

An example of a line of research into the fundamental science that could influence future earth-systems modeling is the research into high-resolution stratigraphy and absolute age dating. New methods are emerging that combine and integrate high-precision biostratigraphy, sequence stratigraphy, the dating of magnetic reversals, and cyclostratigraphy with absolute radiometric age dating (e.g. Ar/Ar) and that include all of these factors in seismic interpretations. Success could lead to the capability to achieve temporal resolution down to 10,000 years as far back as 100 million years and to about 100,000 years as far back as 500 million years ago (Schollnberger, 2001).

There are three principal barriers to the more rapid advancement in the technology of earth-systems modeling: 1) lack of fundamental understanding of key scientific processes and their interactions as well as validation of process modeling; 2) difficulty in addressing uncertainty in terms of inputs, processes, process interactions, and outputs to create useful results; and 3) inadequate computing speed and memory.

To accelerate this technology and its impact will require a significant sustained (many year) commitment of resources to develop the fundamental underpinning behind the underlying technical components as well as to understand the complex interactions at multiple scales. As discussed above, much of the scientific advancement is likely to occur in university settings that will use both private and public funds. The needs are particularly acute for contractional systems that are highly deformed and poorly imaged as well as environmentally difficult or sensitive areas with limited data coverage (e.g. arctic).

The problem associated with uncertainty in data, processes, interactions, and possible outcomes is a problem that is common to modeling most natural systems—advances made in modeling other natural systems (e.g. weather prediction) may provide the breakthrough. Encouragement of research in nonlinear systems modeling in conjunction with encouraged technological development in advanced statistical sciences may result in a mathematical framework that can be used for earth-systems modeling.

The rapid rate of increase in computing capabilities coupled with cost reduction may render computing limitations moot.

The prize is a more robust prediction of nonobvious, undiscovered hydrocarbon accumulations for both conventional and unconventional resources. This prize may be particularly significant in the 2030 time frame for the USA due to the highly mature state of exploration in the USA, which has already resulted in discovery of most “obvious” hydrocarbon accumulations.

XII. Appendix 7: Subsurface Measurements

Exploration Technology Sub-group

Technology leader:	Dave Nichols
Date submitted:	January 29, 2007

A. Executive Summary

Measurements of the Earth's properties have been made in boreholes for over eighty years. These measurements provide the "ground truth" information that is used in developing geological models for exploration and development. Subsurface measurements initially focused on electrical properties, but have expanded over the decades to include magnetism, gravity, radioactivity, nuclear magnetic resonance, acoustic, images, pulsed neutron, and subsurface fluid sampling (to name a few). In the last few decades, advances in technology have enabled real-time well logging that has led to improved well steering, better resource delineation and managed pressure drilling. In addition advances in material properties and electronics have allowed logging of increasingly hostile environments. Improvements in computing have led to greater subsurface processing as well as better modeling of complicated subsurface environments (e.g. thin beds).

Active research in the near term is focused on: a) improving measurements while drilling (LWD/MWD) which is particularly important for drilling high-pressure wells (managed-pressure drilling); b) new physical measurements (deeper reading tools, permeability, and fluid samples); c) improved data telemetry to increase data transmission rates; d) drilling of small microboreholes; e) improving accuracy and resolution of reservoir and fluid properties (e.g. correcting for effect of high-angle formation penetration, anisotropy, etc.); and f) improved measurements of key properties of unconventional resources (e.g. coal bed methane-sorption characteristics).

Most new measurement technologies in this area have been developed by the oilfield service companies. Both the service companies and oil and gas companies have ongoing research and development in improving the interpretation of the measurements and their use in model building.

On the longer-term horizon, two main opportunities exist for technology improvements that could significantly improve exploration (resource identification) and production. These technology advances are based on developing novel techniques for designing and emplacing new sensors in subsurface formations and for developing new measurements for characterizing unconventional resources. Research in these areas is being undertaken now by groups of companies funding universities or joint research initiatives. This style of research spreads the risk among the sponsors. However, due to a relatively short-term focus, early failures in these projects could result in abandonment of these longer-term research approaches. The U.S. government could perhaps encourage longer-term research and development by sustaining basic research with clear accountability in key topic areas at universities or government institutions.

B. Overview of Methodology

The information in this section was largely derived from public information provided by the major oilfield service companies, oil and gas companies, peer-reviewed publications, government studies, and proceedings from international meetings. All references are in included in Appendix 2.

C. Background

Measurements of physical properties of the subsurface from boreholes have been made for at least 80 years (Allaud, 1977; Pike and Duey, 2002). For most of this time, the measurements were made using wireline logging, which consists of lowering a measurement sonde into the well on a wireline cable that provided both power and telemetry to the sonde. Figure XIIC.1 shows such a tool in a well. The earliest measurements made were electrical properties of the rock formations (Spies, 1996). Over the years, many new physical properties have been measured to infer more information about the rock formations and fluids. These measurements include acoustic data, magnetism, gravity, radioactivity, neutron scattering, and nuclear magnetic resonance as well as downhole images. One major technology advance was the development of the ability to sample fluids from the reservoir more accurately and to test the flow of fluids from the reservoir into the well (Ayan et al., 2001).

Figure XIIC.1. Schematic illustration of a logging tool [courtesy Schlumberger].

In the last twenty years, an additional method of deployment was developed (Prensky, 2006). Now, sensors deployed on an assembly behind the drill bit (Figure XIIC.2) can make many of the same measurements as wireline instruments (Denney, 2006). This approach permits data to be collected while drilling and saves the extra time needed to lower a sonde on a wireline into the well. This “logging-while-drilling “(LWD) or “measurement-while-drilling” (MWD) technology has replaced wireline measurements in many situations (e.g. Heysse and Jackson, 1997; Prensky, 2006). Advances in LWD and MWD technology have led to greatly improved “geo-steering,” resulting in more accurate well placement, improved management of drilling (using new formation-pressure while drilling technology plus other drilling parameters), and improved delineation of resources through real-time interpretation.

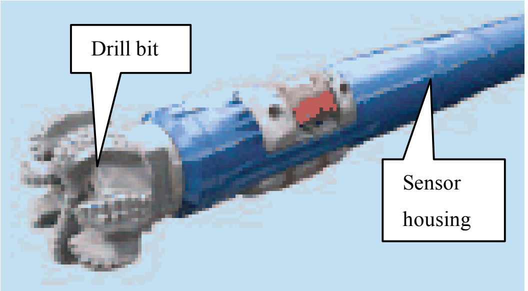

Figure XIIC.2. Schematic illustration of sensor housing behind a drill bit [courtesy Schlumberger].

The main limitation of this type of measurement has been the low bandwidth available for sending information back up the well while drilling (Gonfalini, 2004). The transmission rate for mud pulse telemetry while drilling is several bits per second compared with many thousand of bits per second for wireline-deployed measurements. This limited data-transmission rate means that some information that would be useful for making drilling decisions is not available until the whole drilling assembly is retrieved from the well and the data recovered from the data-storage device. As summarized in Prensky (2006) service companies are actively working to improve data transmission rates (e.g. wired-pipe telemetry, induced coupling, etc.). Simultaneously, through improvement in computing capabilities, many more of the tool corrections (e.g. temperature effects), interpretations, and modeling of subsurface measurements are being made downhole, increasing the ability for real-time decision making.

Modeling log responses for rock and fluid properties is becoming increasingly more sophisticated and accurate as well as integrated with other subsurface data analysis (Nieto et al., 2004). An important exploration example is the improved recognition of thinly-bedded pay, which contains significant hydrocarbon resources, through the combined use of advanced modeling of multiple logging tools for inversion to better estimate true log responses (Quinn et al., 2006). At the same time as the modeling for vertical wells has improved, it has been recognized that quantitative logging of high-angle and horizontal wells is much more difficult than originally recognized (Rendeiro et al., 2005), and this topic is now an industry research focus.

In the last few decades, there have also been significant improvements in the ability of the tools to function at high pressures and temperatures (Larson et al., 2005). Recent wells in the North Sea have successfully recorded subsurface properties at temperatures in excess of 175°C (Morris, 2006).

Technology to collect downhole fluid samples has evolved considerably from the early drill-stem tests and formation-interval tests of the 1970s to sophisticated devices with multiple collection arrangements to compute permeability, reduce contamination, measure pressure as well as significant downhole analysis capabilities (Del Campo et al., 2006; Elshahawi et al., 2006).

Prior to 1970, most major oil and gas companies had research and development groups for logging tools. From the early 1970s to the 1990s, these firms focused their R&D on the interpretation of the measurements and the best use of the information in building geological models, with the service companies taking the lead for new developments in well-logging devices.

D. Impact

The measurement of formation properties made by either of these methods are the “ground truth” measurements used to develop the earth models used for exploration and development of oil and gas fields. New formation evaluation techniques are being continually developed by the major service companies and by many smaller vendors.

Some recently quoted examples of the impact of new technologies on reservoir reserves are:

1) A new 3D induction measurement identifying “45% additional net pay when compared to conventional analysis” in turbidite reservoirs (Gomes et al., 2002).
2) An NMR tool interpretation leading to an accurate determination of water injection efficiency in a North Sea reservoir (Howard et al., 2001)
3) Improvements in fluid sampling using new formation testers has led to the acquisition of more representative fluid samples in offshore exploration wells in less time in a costly environment (Del Campo et al., 2006).

E. Tables of Advances

Subsurface measurements are rapidly evolving in terms of sensor development, deployment and interpretation. Table XIIE.1 lists the most promising technologies that could have a significant impact by 2010. The technologies identified in Table XIIE.2 are potential contributors to exploration results in the 2020 to 2030 time frame and include advances that may be categorized as more breakthrough in nature. Due to the longer time frame, there is also greater uncertainty both as to technical feasibility and potential commercial impact.

The following two tables address new developments that can affect the discovery and evaluation of conventional reservoirs as well as potential developments that could affect the exploration for unconventional (very heavy oil, coal-bed methane, low-permeability gas reservoirs, shale gas, oil shale, and methane hydrates) reservoirs. The conventional (oil and gas) reservoirs may be in geological settings that are already explored or in new, more challenging basins such as ultra-deepwater or arctic environments. Economic characterization of the unconventional hydrocarbon reservoirs requires novel property measurements; many of the techniques to make these measurements have not been widely developed in the past. The technology advances for unconventional reservoirs are unlikely to impact production in a major fashion until after 2015.

Technology	Significance	Brief discussion
Ability to log and sample ultra HPHT wells	Medium	Major new discoveries are expected in deep, high-pressure, high-temperature (HPHT) wells. Many service equipment providers are developing technologies to be able to make measurements in these wells (Diamond and Woertman, 2005; Morris, 2006).
New physical measurements downhole	Medium	The continued addition of new sensor types to add to the information about the formation. (e.g. fluid typing and composition from downhole spectroscopy—Elshahawi et al., 2006; Muller et al., 2006).
New telemetry methods for	Medium-Low	Better decisions can be made during the drilling process if new methods can increase the information

measurements while drilling.		transmitted while drilling (e.g. Prensky , 2006, http://www.intellipipe.com). Lowers drilling risk.
Microboreholes drilled away from main well.	Medium-Low	More information about the subsurface can be gathered by drilling very small boreholes away from the main borehole. E.g. http://ees-www.lanl.gov/Capabilities/advsense/as_mdrill.shtml.

Table XIIE.1. Summary of near-term (by 2010) technologies in priority categories.

Technology	Significance	Brief discussion
New deployment method for subsurface measurements.	Medium with a high risk factor	If economic subsurface measurements could be made without drilling any type of well, this would enable much more information collection and hence better subsurface information. (e.g.. Badger project to have a tool to drill into formation for measurement only without retaining the borehole http://www.bxpl.com/).
Measurement of absorption and production properties of coalbed methane, shale gas, and low-permeability gas reservoirs	Medium	Sorption characteristics presently require core samples and laboratory analysis (Utley, 2005). Production characteristics, specifically the determination of relative and absolute permeabilities as well as fracture permeabilities, require new measurement techniques (e.g. Garbutt, 2004) or lengthy multi-well pilot tests.
Measurement to predict highly productive "fairways" in shale gas reservoirs and coalbed methane	Medium	Both shale gas and CBM are very sensitive to marginal economics. The identification of either fracture networks, cleat networks, or areas of higher organic content (Utley, 2005) may open development in areas that might otherwise be ignored.
Pumping sensors into formation.	Medium	If sensors could be emplaced in the pores of the subsurface formation and transmit information, information could be collected over a very broad area of the reservoir. Current sensor systems are much too large (e.g. http://www.dust-inc.com) Many orders of magnitude improvement needed in order to insert in formation pores.

Table XIIE.2. Summary of longer-term technologies in priority categories.

F. Discussion

Subsurface measurements are central to the exploration and appraisal of new reservoirs. New measurements developed over the last forty years have contributed greatly to our understanding of reservoir properties and hence estimates of hydrocarbons in place and hydrocarbon productivity.

If development continues as expected in the baseline scenario, we expect that new measurements and new sensor emplacement techniques will make moderate contributions to future reserves and production. The baseline scenario includes:

- Improvements in high-pressure and high-temperature measurements and sampling
- Improved telemetry for while-drilling measurements
- Evolutionary improvements to sensors, measurements, and their interpretation.

Two attractive opportunities exist for improving subsurface measurements in conventional reservoirs:

- Novel deployment methods for subsurface sensors without conventional wells
- Wireless sensors emplaced into a large area of the formation from conventional wells.

The goal of both approaches is to acquire more and better-quality subsurface information at less expense so as to improve resource recognition and delineation, as well as to reduce exploration and development risks or costs. The two approaches require major breakthroughs in drilling and sensor technologies, and are perceived by the exploration technology sub-group as having low chances of successfully being developed within the time window of this study. But if successful, the potential impact was viewed as moderate to high.

While some oil and gas companies are currently funding research along these two lines of investigation, there is a significant risk that if initial tests are negative, the development and consequently application of these technologies in the oil industry could lie fallow for years. Often new technologies that fail in their first application are ignored.

Since 1995, Gartner (www.gartner.com) has used “hype cycles” to characterize the over-enthusiasm or hype and subsequent disappointment that typically happens with the introduction of new technologies. If the two technology approaches fall into the “trough of disillusionment,” it would delay their application to hydrocarbon exploration and exploitation. Longer-term research into these areas could be sustained by government funding in the basic technology areas required to meet the goals of more cost-effective gathering of subsurface information.

The remaining opportunities for large impacts on hydrocarbon exploration, delineation, and exploitation come in the arena of subsurface measurements of unconventional resources. Most of the existing downhole measurement technologies were targeted at conventional oil and gas reservoirs. The measurement physics and design decisions for the tools were based on detecting rock and fluid types in either sandstone or carbonate reservoirs. Thus, current logging measurements may not be optimal for other formation or resource types.

Two types of attractive reservoirs stand out in this regard: a) shale gas reservoirs and b) coal bed methane (CBM) reservoirs. Both types of reservoir have large deposits in the USA and the world but the resources are widely dispersed and have until recently been marginally economic. Optimal resource and reserve identification depends on exploration and production technologies that are under development or have yet to be developed.

In particular, there is a current lack of measurement tools to determine surface chemistry of coal beds and the small scale fracture distributions in shale that could control reserves and productivity. Investment in research in either of these areas could result in the addition of significant new hydrocarbon resources and reserves by 2030. Acceleration of these technologies could be assisted by government funding of fundamental research (with accountability) in these areas at universities.

Several of the well logging techniques use radioactive sources which require special environmental and security precautions (Ferguson et al., 2003, Grimm and Campbell, 2005, Nuclear Regulatory Commission, 2006). These sources are also becoming more difficult and costly to acquire. Research into alternative sources or logging techniques might be able to mitigate these concerns (Gibson, 2006).

XIII. Appendix 8: Drilling Technology

Exploration Technology Sub-group

Technology leader: Dave Converse
Date submitted: January 29, 2007

A. Executive Summary

Advances in drilling technology have and probably will continue to impact hydrocarbon exploration in the following ways:

- Enabling drilling in difficult-to-drill areas that are either physically difficult environments (high-pressure, high-temperature (HPHT), ultradeep water, or shallow hazards) or environmentally sensitive areas
- Reducing drilling and stimulation costs such that currently subeconomic conventional or unconventional resources can become exploration targets
- Dramatically reducing drilling costs to the point where significantly more exploration wells can be drilled for the same investment costs, allowing explorationists to test more risky concepts.

Incremental technology advances in the first two areas have been evolving slowly but steadily and are well documented (e.g. Lambert et al., 2005). More breakthrough-like or step-change technology advances, such as expandable solid tubulars and dual-gradient drilling, have taken a long time (are still) to be adopted industry-wide (Bell, 2004; Hannegan and Stave, 2006). Due to the large potential financial exposures associated with drilling with new technology, drillers are very wary.

The technology advances mentioned above are fairly limited when compared with the technology advances (e.g. robotic drilling) currently being considered for dramatically reducing drilling costs. Achieving these new technology advances are perceived as very difficult with little likelihood of significantly impacting exploration volumes by 2030.

To accelerate the development and adaptation of significant new drilling technologies will likely require some approach that either spreads the risk (e.g. industry consortia) or provides a financial incentive (government support). Otherwise it is likely that significant advances in drilling technology will continue to evolve and be adapted at a "business as usual" pace.

B. Overview of Methodology

The drilling-technology evaluation was based primarily on literature resources and discussion among the Exploration Technology Sub-Group and colleagues in our companies and departments. The literature resources are documented in Appendix 2—this literature database should not be regarded as exhaustive.

C. Background

1. Historical Evolution:

Drilling technology has evolved gradually over the decades since the development of rotary drilling (Payne, 2003). Some of the relatively recent developments have enabled the drilling of high angle and horizontal wells with extended-reach capabilities, drilling of ultra-deepwater wells and drilling of high-pressure, high-temperature wells. In addition, progress has been made to reduce drilling costs using coiled tubing and underbalanced drilling (Payne, 2003, Perry et al., 2006; Spears & Assoc., 2003, von Flatern, 2006a).

A recently developed drilling technology is the expandable solid tubular, which can be used in either open or cased holes to mitigate drilling or production issues. Since the introduction in 1999 of expandable solid tubulars in the Gulf of Mexico (GOM), there have been several hundred applications globally (Burrows, 2005; Grant and Bullock, 2005). However as an indication of the rate of technology acceptance, it is only recently that the technology is being used proactively instead of reactively after running into operational problems (von Flatern, 2006a). Furthermore as pointed out by Woodall

(2003), these concepts were first discussed more than a decade ago. Next generation developments are moving towards a true monobore (Burrows, 2005; von Flatern, 2006b) with improved well-control and production performance.

There have also been significant improvements in well-stimulation technologies that have opened up new unconventional resources (e.g. shale gas resources in the Barnett Shale, Texas; Shirley, 2002).

Not discussed here, are changes in mud systems, drill bits (NationalDriller.com, 2006), measurements while drilling (Adeleye et al., 2005, Rocha et al., 2003), managed pressure techniques (Rommetveit, 2005), vibration control, well steering, surface blowout preventers (BOPs) on floaters, and many other factors that have led to significant improvements in drilling reliability, wellbore integrity, drilling rates, and costs (Lambert et al., 2005).

2. Historical Impact:

Advances in drilling technology have enabled exploration in deep water (where wells were previously thought to be undrillable due to small differences between pore pressure and fracture pressures in the shallow weakly consolidated sections (Rocha et al., 2003; Cahuzac, 2004), weight of equipment as well as difficult ocean currents (Payne, 2004) among other challenges). Similarly, improvements in drilling technology (novel materials, measurements while drilling, and real time intervention) have led to the relatively common drilling of high-pressure, high-temperature wells, although there can still be significant difficulties. Increases in the distances that wells can be drilled from a remote location (extended reach) have led to improved access to resources—for example, the Sakhalin Chavyo Field is being tapped by onshore wells with 8 to 10 km reach offshore (Viktorin et al., 2006).

Improvements in coiled tubing drilling have led to its widespread usage in Canada for exploiting coalbed methane as well as shallow gas (Anon. 2005). It is becoming increasingly used for the deeper U.S. coalbed methane opportunities with technology adaptation (NETL, 2006). Recent experiments in the USA using coiled tubing drilling have indicated the possibility for more rapid, cheaper drilling (ca. 38% cheaper—Perry and Barnes, 2006).

D. Tables of Advances

Drilling technologies are rapidly evolving on many fronts from materials to sensors to data transmission. Table XIIID.1 lists the most promising technologies that could have a significant impact by 2010. The technologies identified in Table XIIID.2 are potential contributors to exploration results in the 2020 to 2030 time frame and include advances that may be categorized as more breakthrough in nature. Due to the longer time frame, there is also greater uncertainty regarding both technical feasibility and potential commercial impact. Estimating the rate of drilling technology uptake is difficult—Payne (2003), Hinkel (2006), and Bridges (2005) all indicate that the drilling industry has been notoriously slow to adapt to new technology.

Technology	Significance	Brief discussion
Advances in high-pressure, high-temperature wells	Medium	The NETL's DEEPTREK research program (Schlumberger, 2005; Spross, 2005) among others, is addressing a number of significant issues associated with drilling deep HPHT wells. The chance of improvements is stated to be significant (Nationaldriller, 2006), increasing access to new prospects. One promising area is in managed pressure drilling (Rommetveit, 2005).
Improvements in coiled tubing drilling and microholes	Medium	Ongoing work at drilling companies and the National Energy Technology Lab (NETL) is focused on extending the depth range for common use in unconventional resources and via microholes to reduce costs significantly (Spears & Assoc, 2003, NETL, 2006, Perry et al., 2006; Perry and Barnes, 2005)).
Ultra-extended reach Wells	Medium	Continued increases in ability to drill long distances from distant locations will improve access to environmentally sensitive areas as well as potentially reduce costs (Mason, 2006).
High-speed telemetry	Medium	Enables more accurate placement (geosteering) as well as quicker operational responses to subsurface drilling conditions (NETL May 2006) plus better formation evaluation to find hydrocarbons while drilling.

New materials	Low	Composite-material lightweight drill pipe that offers better flexibility for deviated wells (NETL); could result in reduced-weight risers to enable more rigs to drill in deep water.
Dual-gradient drilling (riserless mud recovery)	Low	Addresses the difficulty associated with drilling shallow rock sections in deepwater wells where the drilling-fluid pressure can exceed the fracture gradient unless multiple casing strings are used—would reduce costs. Also enables zero mud discharge to the environment, which is critical to drilling in a number of areas. Had recent success in Caspian, Sakhalin and North Sea (Schubert, 2006, Hannegan and Agave, 2006, Elieff, 2006, AGR Subsea, 2006, Francis, 2006).
Expandable casing, tubulars, or monobores	Low	Enables drilling of nearly constant diameter well with depth and could enable some wells to avoid being shut-down because of "running out of hole" (Burrows, 2005) as well as reducing overall drilling costs.

Table XIIID.1. Summary of near-term (by 2010) technologies in priority categories.

The priority is determined by the difference in impact between a business as usual case and an accelerated technology case, listed with greatest impact first.

Technology	Significance	Brief discussion
Self-contained robotic drilling for subsurface measurements at lower cost	Medium, but with a high risk factor	The only publicly described robotic drill is the Badger (Badger AS), which is being researched to provide cost-effective, self-contained drilling requiring neither mud nor casing. The potential impact is to afford relatively rapid, but most of all cost-effective drilling of exploration wells. The drilling rates will be slow but no rig will be required. Several key hurdles remain to be overcome before viability can be demonstrated.
Laser drilling	Low-Medium—could result in lower drilling costs and improved production rates; may open up new environments	Laser drilling has been a topic of research over several decades but recent advances (e.g. Gahan and Shiner, 2004; Xu et al., 2005, Xu et al., 2004, Pooniwala, 2006) in both lasers and concepts provide optimism regarding possible commercial applications in hydrocarbon exploration. However it is still unclear whether a commercial version will be developed and widely applied within the time scope of this study (2030). Should be able to drill faster in hard (deeper) rocks than conventional drilling methods.

Seabed drilling	Low with a high risk of failure	Active research area with some challenging problems to solve, but may be completed within the time frame (Ayling et al., 2003; Seabed Rig AS website. World Oil, 2004a,b). Could reduce costs and expand drilling opportunities.

Table XIIID.2. Summary of longer-term technologies in priority categories.

E. Discussion

Advances in drilling technology have the potential to play a significant role in improving exploration results by the year 2030 for the following reasons:

- Developing technology that enables drilling in difficult-to-drill settings—examples include ultra-deepwater provinces, HPHT provinces, arctic areas, environmentally sensitive areas, etc. Technologies like high-speed telemetry drilling (NETL), advances in HPHT drilling (NETL), new material wells (NETL) and seabed drilling (Seabed Rig AS) all could result in this advance. Riserless mud recovery (dual-gradient) technology may become more important as it can enable zero mud discharge to the seafloor (AGR Subsea, 2006).
- Reducing drilling costs (particularly offshore) to the point where significantly more exploration wells can be drilled for the same investment cost (e.g. Badger AS). In this scenario, companies might be willing to drill riskier opportunities.
- Reducing drilling and stimulation costs such that currently marginal or subeconomic conventional or unconventional resources can become exploration targets (e.g. advances in coiled tubing drilling for deeper unconventional resources NETL, 2006; microholes). Other technologies in this category include dual-gradient drilling (Hanegan and Agave, 2006) and expandable tubulars (Burrows, 2005).

If the technology continues to develop along a baseline (“business as usual”) trend, then there is likely to be a small to moderate impact on the volume of hydrocarbon resources available in 2030. Incremental improvements in drilling technology historically have led to gradual improvements in exploration volumes (opening up deepwater resources in the GOM, West Africa, Brazil, etc.) as well as HPHT resources in the North Sea, GOM and elsewhere around the globe.

If, however, there is a breakthrough in drilling technology—either through the development of robotic drills, new drilling processes (e.g. laser) or other processes that lead to substantial (orders of magnitude) reductions in costs, then a significant increase in exploration activity and success might result. In some ways, assessing the magnitude of this problem is akin to the problem of estimating exploration drilling rates with changes in hydrocarbon prices (Dahl and Duggan, 1998). However at this point in time, the chance of a breakthrough technology significantly impacting production in 2030 is low.

There are two principal barriers to the more rapid development of either baseline or step-change technologies.

- As described by several authors (Payne (2003), Hinkel (2006), and Bridges (2005)), there is a great resistance to rapidly adapting new drilling technologies. As drilling costs are a substantial fraction of companies' investment (the cost of current deepwater wells can exceed US$100M—Gold, 2006), the possibility of increasing costs further by serving as a pilot for new technology is understandably unattractive, although the potential reward may be high.
- Second, development of new, breakthrough, drilling-technology advances is necessarily long-range and requires significant pre-investment. All of the breakthrough technologies are funded to a large extent by national governments as well as large oil and gas companies. The Badger Explorer robotic drill program is funded by the Norwegian Research Council, Statoil, Shell and ExxonMobil. The Seabed Drilling Project was initially developed in 2003 to 2004 under the non-profit Industry Technology Facilitator (comprised of oil and service companies and the UK Department of Trade and Industry) and is now seeking funding to continue. Both the laser drilling and the microhole drilling projects have been heavily supported by the U.S. government.

Although, development of drilling technology advances and implementation can occur naturally through economic pressures (von Flatern, 2006a), accelerated breakthrough technology development and implementation will probably require governmental incentives to entice "early technology adopters" as well as sustained long-term funding either of joint industry research programs or governmental programs with clear accountability.

The potential prize is that drilling technology advances may lead to the more rapid or more complete identification of undiscovered hydrocarbon accumulations for both conventional and unconventional resources. This prize may be particularly significant in the 2030 time frame for the USA for unconventional resources, environmentally sensitive areas, difficult-to-drill environments, and deepwater offshore resources.