Montana Characterization Study – Comprehensive Report

Deliverable Gd30 (Task 15)

March 2012

U.S. Department of Energy (DOE)
National Energy Technology Laboratory (NETL)
DOE Award Number: DE-FC26-05NT42587

Submitted by: Dr. Lee Spangler

BSCSP Principal Investigator and Director
Montana State University
P.O. Box 173905
Bozeman, MT 59717
spangler@montana.edu
http://www.bigskyco2.org
Phone: (406) 994-4399
Fax: (406) 994-3745

Principal Authors:
David Bowen, MSU/Vecta Oil and Gas
John Talbott, MSU

Contributors:
David L. Lageson & Frankie Jackson, MSU
David Eby, Eby Petrography
Bryan DeVault & Richard Pate, Vecta Oil and Gas

Disclaimer

Abstract

This report reviews the potential of Kevin Dome, a geologic formation located in north central Montana, as a potential underground large-scale sequestration site. In assessing and characterizing the commercial viability of Kevin Dome, this report provides carbon sequestration estimates of similar geologic domes in Montana. This report is a Big Sky Carbon Sequestration Partnership (BSCSP) Phase II deliverable and addresses Task 15 as outlined in the Statement of Project Objectives. The study results suggest a process to adequately characterize and utilize Montana's geology to (1) commercially produce CO_2 for enhanced oil recovery, (2) commercially store CO_2 for future enhanced oil recovery, (3) encourage the use of CO_2 as a tertiary oil recovery methodology to improve oil and gas production and spur the economic activity and state tax revenue growth that will accompany such an exploitation of these resources, and (4) provide a commercial site to permanently sequester CO_2 to minimize potential environmental impacts of releasing CO_2 into the atmosphere.

Table of Contents

Executive Summary 8
1. Introduction 9
2. Project Overview 10
 2.1 Proposed Objectives 10
 2.2 Background Information and Technology 11
 2.3 Clean Energy Options for Montana 11
 2.4 Trapping of CO_2 in Geologic Media 11
3. Results – Site Characterization 12
 3.1 CO_2 Sequestration through Enhanced Oil Recovery and Depleted Oil and Gas Fields 12
 3.2 Sequestration in Saline (Brine) Aquifers 12
 3.3 Geology of Kevin Dome and Evidence for CO_2 Accumulation at Kevin Dome 13
 3.4 Geology of Similar Domes 13
 3.5 Oil and Gas Fields of Montana 14
 3.6 Regional Geologic Setting 16
 3.7 Structural Characterization 19
 3.8 Tectonic History 20
 3.9 Origin of CO_2 at Kevin Dome 20
 3.10 Stratigraphic Characterization and Reservoir Geology 21
 3.11 Reservoir and Seal (Caprock) Relationships: Petrographic Analysis 38
 3.12 CO_2 Volumetric Calculations 41
 3.13 Principal Requirements for Sequestration 43
4. Results – Commercialization Plan 45
 4.1 CO_2 Production for use in Enhanced Oil Recovery (EOR) 46
 4.2 Commercialization of Carbon Sequestration 49
 4.3 Commercialization Economic Impacts 51
5. Conclusions 57
6. References 60
7. Acronyms 63

Figures

Figure 1: Location map of Kevin Dome, Montana **9**

Figure 2: Cross-section diagram of Kevin Dome geologic formation. **13**

Figure 3: Oil and gas fields map of Montana showing the location pipeline infrastructure, and the location of large domes across the state that may have the potential to sequester large volumes of CO2 from clean energy sources (modified from Montana Board of Oil **14**

Figure 4: Tectonic map of Montana showing the location of the Sweetgrass Arch in Montana. (modified from Vuke et al., 2007) and **17**

Figure 5: Structure contour map at the top of the Duperow Formation depicting the Sweetgrass Arch in Montana. **18**

Figure 6: Surface geologic map of Kevin Dome and the Sweetgrass Hills (modified from Vuke et al., 2007) **19**

Figure 7: Oil and gas wells penetrating Kevin Dome. Structure contour map of the top of the Cretaceous Blackleaf Formation is drawn. **21**

Figure 8: Stratigraphic column for Kevin Dome. Expanded section displays type logs of the upper Devonian section showing the two CO2 bearing regional porosity zones of the Duperow. **22**

Figure 9: Hydrodynamic units across the northern Great Plains region. (modified from Peterson, 1987, and Downey, 1986) **23**

Figure 10: Location map of cross-section correlation grid. Only those wells that penetrate the Duperow Formation are shown by the small dots with those used in the cross-sections highlighted by the blue circles. **24**

Figure 11: Correlation cross-section XS_NS1 **24**

Figure 12: Correlation cross-section XS_EW0 **25**

Figure 13: Correlation cross-section XS_EW1 **25**

Figure 14: Correlation cross-section XS_EW2 **26**

Figure 15: Correlation cross-section XS_EW4 **26**

Figure 16: Correlation cross-section XS_EW5 **27**

Figure 17: Correlation cross-section XS_EW6 **28**

Figure 18: Structure contour map top Souris River Formation **29**

Figure 19: Structure contour map top lower Duperow porosity zone **29**

Figure 20: Structure contour map top middle Duperow porosity zone **30**

Figure 21: Structure contour map top of Duperow Formation **30**

Figure 22: Structure contour map top of Nisku Formation **31**

Figure 23: Structure contour map top of Potlatch Anyhdrite **31**

Figure 24: Lower Duperow net porosity >6% isochore (lower porosity zone) 32
Figure 25: Middle Duperow net porosity >6% isochore (upper porosity zone) 32
Figure 26: Upper Duperow isochore (caprock facies) 33
Figure 27: Nisku isochore (local reservoir and additional caprock facies) 33
Figure 28: Potlatch Anhydrite isochore (regional caprock facies) 34
Figure 29: Lower Duperow porosity zone trapping configuration. CO2 test rates are shown for well tests in the Duperow Formation 35
Figure 30: Upper Duperow porosity zone trapping configuration. CO2 test rates are shown for well tests in the Duperow Formation. 35
Figure 31: Drilling depth to the top of the lower Duperow porosity zone 36
Figure 32: Drilling depth to the top of the upper Duperow porosity zone in the middle Duperow 37
Figure 33: 3-d geologic model of Kevin Dome structural datums. Note the very large numbers of shallow well penetrations compared to deep well penetrations (red lines) 38
Figure 34: Outcrop belt of the Devonian Duperow Formation near Monarch, Montana and locations of measured sections 39
Figure 35: Outcrop photograph and measured section along Dry Belt Creek Road, Monarch, Montana. Note open marine fauna in picture on right. 39
Figure 36: Outcrop of Devonian Duperow Formation in Sun River Canyon, Montana Disturbed Belt west of Kevin Dome; Lower-Upper Devonian (Frasnian) 40
Figure 37: Devonian Duperow from outcrop in Montana Disturbed Belt west of Kevin Dome. Note dissolution / precipitation of secondary minerals 40
Figure 38: Generalized capacity of similar domes in Montana (Half of the current major point source emissions for the next 100 years ~7.5 GT: Resource Estimate for 3 Domes ~5.3 GT 43
Figure 39: Map of total dissolved solids in brine water tested from the Duperow Formation. Water is of sufficiently poor quality to not be a limiting factor for sequestration. 44
Figure 40: Potentiometric surface map in the vicinity of Kevin Dome (closure shown by blue line). Water flow vectors are toward the dome, a favorable relationship for sequestration on the flanks of the dome. 45
Figure 41: Incremental Oil production from EOR for the U.S. 46
Figure 42: Advanced coal plants with CCS are currently uncompetitive in 2012 and 2020 (EIA's AEO 2008 Reference Case) 49

Tables

Table 1: Major oil fields productive along the Sweetgrass Arch in Montana. (data source: Montana Board of Oil and Gas Commission online data) 15

Table 2: Description of Devonian Units, Sun River Canyon... 41

Table 3: Volumetric calculations of CO2 in the two Duperow porosity zones 42

Table 4: Sources of CO_2 for EOR in North America.. 47

Table 5: Relationship of CO_2 sales price to cost offsets in the coal-fueled power sector (Year 2020) (Kuuskraa, 2008) 50

Table 6: Economic benefits to Montana of building three new advanced coal plants 52

Table 7: Economic benefits to Montana of operations and maintenance of new plants............... 53

Table 8: Regulatory Requirements 56

Table 9: Estimated CO2 capacity of selected Montana reservoirs 58

Executive Summary

Montana has vast natural resources including 25 percent of the nation's coal and an expanding oil and natural gas reserve. There is a growing realization that the continued use of carbon intensive fossil fuels may require carbon dioxide (CO_2) mitigation. The maturity of Montana's oil fields means declining production, however evidence indicates that production can be increased in declining fields by the injection of CO_2 into oil-bearing formations in a process referred to as enhanced oil recovery (EOR). The investment in research of potential CO_2 EOR projects and commercializing those that show promise, as well as identifying potential long term mitigation options and strategies for fossil fuel based energy production, makes economic sense. Characterization of potential carbon sinks is thus a critical step for development and implementation of clean energy technologies in the state of Montana.

Kevin Dome, a large structural culmination along the Sweetgrass Arch in north central Montana, has naturally trapped large volumes of CO_2 (potentially greater than 10 trillion cubic feet) over geologic time. This accumulation of CO_2 has economic potential as a resource for use in EOR, provides a natural analog for sequestration of CO_2, and presents a unique opportunity for sequestration of additional CO_2 below the gas water contact at Kevin Dome. Geologic sequestration is predicated on the availability of suitable geologic formations to store CO_2 in secure subsurface environments for significant durations of geologic time. EOR utilizing CO_2 is assumed to be enhanced by the cost-effective and abundant supply of CO_2. Consequently, Kevin Dome is an ideal study area for applied research on both these topics as well as a promising setting for:

- Locating a CO_2 gas storage reservoir,
- Removing CO_2 from a known reservoir during times of peak demand for EOR, and
- Sequestering CO_2 captured within Montana from clean coal projects.

This study provides a process to continue to use the Montana's vast coal resources by characterizing a large potential sequestration target, Kevin Dome, and by identifying similar geologic features favorable for sequestration in the state. The study also identifies and characterizes a large naturally trapped CO_2 resource that could be tapped for use in EOR projects thus potentially slowing the decline of the State's mature oil fields.

The characterization of Kevin Dome provides the foundation for utilizing this feature for underground carbon sequestration and EOR operations related to its potential as a CO_2 gas storage reservoir. The first commercial activity that is likely to occur is to provide naturally trapped CO_2 to mature oil fields in the immediate region of the dome for EOR projects. Leasing of CO_2 rights toward this end is currently underway by several companies. The evaluation of the potential of the site for commercial scale sequestration is also continuing. The next phase of research and development will involve a large-scale injection test within the Kevin Dome to demonstrate the commercial feasibility and viability of underground carbon capture and storage technologies within the Big Sky region and similar settings.

1. Introduction

Kevin Dome is a very large structural culmination along the Sweetgrass Arch north of Great Falls, Montana (Figure 1). This dome encompasses greater than 750 square miles. Within this dome, a significant volume of rock at depths of approximately 3,000 feet to 4,500 feet has been tested by oil and gas exploration wells and demonstrates great promise to contain significant producible quantities of CO_2. This CO_2 could stem the decline of old, depleted oil fields in the region. Additionally, large volumes of pore space within these same geologic formations, deeper but still contained by the dome, are not saturated with CO_2 and thus provide the potential for sequestration of large volumes of CO_2 that could be captured at industrial sites and transported to this carbon sink.

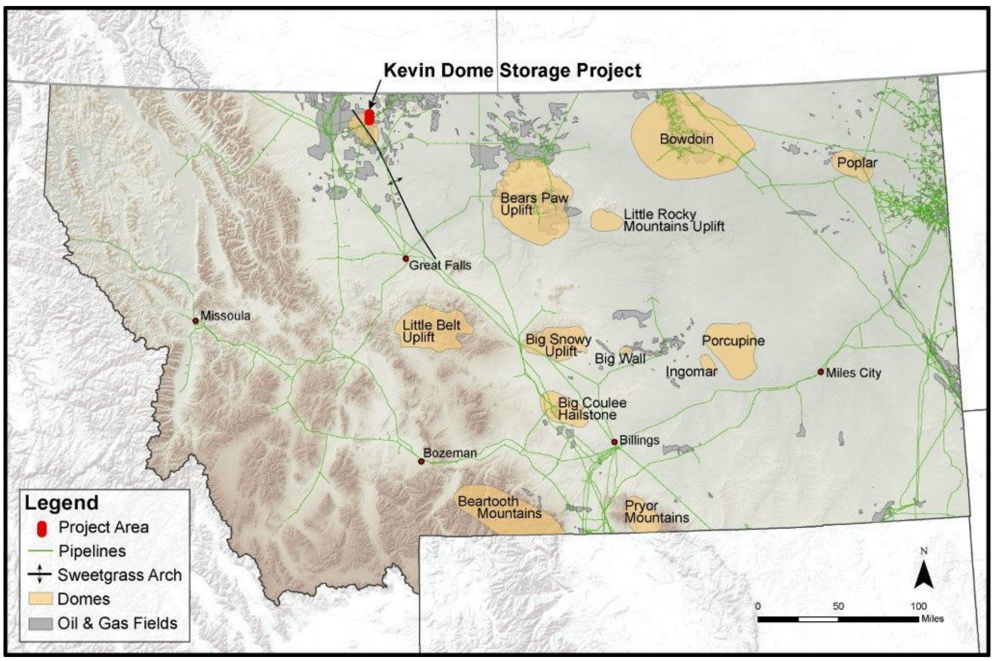

Figure 1: Location map of Kevin Dome, Montana

2. Project Overview

2.1 *Proposed Objectives*

The primary objectives of this research were:

- To provide a detailed subsurface geologic characterization of the Kevin Dome structural feature located north of Great Falls, Montana;
- To determine the volume of CO_2 resource in place and available for EOR, the volume currently occupied by brine water thus indicating the sequestration potential, and the potential deliverability of CO_2 from Kevin Dome;
- To understand, based on the characterization work, the processes responsible for naturally trapped CO_2 at Kevin Dome;
- To regionally characterize other large scale geological domes across the state in light of the knowledge gained from studying Kevin Dome to discern their potential as sequestration sites;
- To provide a commercialization plan which includes an economic assessment of the commercial viability of using Kevin Dome and similar structures for sequestration under alternative economic and policy scenarios; and
- To evaluate the potential for expanded EOR efforts related to the commercial development of naturally occurring CO_2 sources for storage and sequestration of anthropogenic CO_2.

The characterization work resulted in a three-dimensional depiction of the subsurface geology of Kevin Dome including (1) the distribution and thickness of CO_2 bearing porosity zones within the dome, (2) the presence and configuration of confining unit caps, (3) the structural configuration of geologic units, (4) the location of fracture zones, faults, and other potential leakage pathways, and (5) the hydrodynamic regime of the area incorporating subsurface temperature and pressure distributions, migration routes and rates of fluid movement.

These objectives are essential to providing a scientifically based determination that Kevin Dome and similar geologic features can contain and continue to sequester significant volumes of CO_2 over geologic time scales. The plan provides a roadmap for facilitating the commercialization of the Kevin Dome as a long-term geological storage site.

Also, this research provides an in depth assessment and understanding of the potential of Kevin Dome as a commercial-scale brine aquifer CO_2 sequestration site (a very different CO_2 sequestration option), replacing down-dip brine aquifer waters within contained regions of the dome. Future legislation may require CO_2 mitigation for coal-fired power plants and other industrial CO_2 emitters. Geological formations within the Montana, including those at Kevin Dome, have the potential to be used as: a) vast CO_2 gas storage reservoirs with CO_2 removed as demand necessitates and b) CO_2 injected clean energy projects as capture and sequestration evolve. These combined activities of EOR and clean energy options are significant economic development opportunities for the state of Montana.

2.2 *Background Information and Technology*

The review of background information and technology falls into several main categories, which include the following:

1. Clean energy options for Montana
2. Movement and trapping of CO_2 in geologic media
3. CO_2 sequestration through enhanced oil recovery and depleted oil and gas fields
4. Sequestration in saline (brine) aquifers
5. Geology of Kevin Dome and evidence for CO_2 accumulation at Kevin Dome
6. Geology of Similar Domes in Montana
7. Oil and gas fields of Montana

2.3 *Clean Energy Options for Montana*

An abundance of coal resources and a similarly significant amount of geologic sinks, foster the opportunity for the deployment of clean coal technologies in Montana for CO_2 sequestration. The emergence of tested technologies including Integrated Combined Cycle Gasification (IGCC), Coal-to-Liquids (CTL), Underground Coal Gasification (UCG), and other various gasification processes that produce natural gas from coal has spurred renewed interest in development of Montana's coal resources. Montana has a unique opportunity to employ these technologies and through an *ad valorum* approach export clean electrons rather than raw coal. All these new technologies can be developed with carbon capture and storage as a primary rationale for construction of new plants.

To date, numerous large corporations have expressed interest in siting these types of plants in Montana. The availability of coal; the current construction plans for DC power lines from Canada to California, Arizona and Nevada; and the availability of massive geologic sinks in this region make commercialization of sequestration possible. As Montana's Governor, Brian Schweitzer stated in his 2007 State of the State Speech, "If we're going to sell into the California market, we will have to sell using wind power and coal gasification with sequestration. California will not accept and Montana should not put carbon dioxide in our atmosphere."

2.4 *Trapping of CO_2 in Geologic Media*

The fundamental trapping mechanisms of CO_2 in subsurface geologic media include physical trapping and chemical trapping features. Physical mechanisms involve the trapping of CO_2 in a gaseous, liquid, or supercritical state (a function of reservoir temperature and pressure) as a free-phase substance occupying void space in geologic units. Physical traps fall in the categories of static geologic traps of both stratigraphic and structural configurations, hydrodynamic traps of very slowly migrating plumes of CO_2 in large-scale (basin-wide) flow systems, and cavern trapping in large scale man-made cavities such as salt caverns or mines. Alternatively, chemical mechanisms involve the trapping of CO_2 as a result of various chemical reactions between CO_2 and the fluids or rocks contacted in the subsurface. Chemical traps include solubility traps by dissolution of CO_2 in formation water or oil, ionic trapping whereby CO_2 breaks down into its ionic components, mineral trapping as CO_2 combines with other ions and precipitates into mineral phases, and adsorption trapping onto a coal matrix. Of all of the potential geologic sequestration options, enhanced oil recovery (EOR) and enhanced coalbed methane (ECBM) sequestration options are the most likely to occur first in the absence of legislative incentives, because of the economic benefits of producing additional oil or natural gas (Bachu and Adams, 2003; Baines and Worden, 2004; Gale, 2004). The Kevin Dome project proposes to involve static physical trapping of CO_2 associated with EOR projects in the vicinity of the dome as well as physical trapping of CO_2 below naturally trapped CO_2 within the structural closure of Kevin Dome itself. This physical trapping would be augmented by chemical trapping mechanisms with CO_2 dissolving into both brine waters and oil and by precipitation of mineral phases.

3. Results – Site Characterization

3.1 *CO_2 Sequestration through Enhanced Oil Recovery and Depleted Oil and Gas Fields*

CO_2 has been used in EOR projects for over 50 years. Incremental oil recovery associated with the process has been shown to be between 10% and 30% of the original oil in place (Brock and Bryan, 1989; Goodrich, 1980; Holt et al., 1995). Two types of CO_2 injection methods are used for EOR: water-alternating-gas (WAG) and cyclic injection (Worden and Smith, 2004). WAG injection involves injecting CO_2 on the periphery of a field which is alternately injected with water. CO_2 is injected at a temperature and pressure to be miscible with the oil, which decreases the viscosity of the oil allowing it to flow more easily to the production wellbores and increases the pressure gradient between the injection wells and the production wells, allowing greater production efficiency (Worden and Smith, 2004). In the cyclic process, CO_2 is injected at immiscible conditions and enhanced recovery is believed to be a volume increase or swelling of the oil that forces it out of the reservoir pores (Worden and Smith, 2004). WAG miscible flooding is the expected methodology to be utilized for EOR in the fields surrounding Kevin Dome (Wennekers, 1985).

Another sequestration option is to inject CO_2 into depleted or exhausted oil and gas fields. These types of fields have the benefit of having proven trapping capacities and lowered reservoir pressures allowing easier re-injection. However, caution is necessary due to the potential for leakage along abandoned wellbore paths and the potential to damage caprock integrity when re-pressurizing the traps with CO_2 (Chadwick et al., 2004). This option is not being considered within the primary scope of this project.

3.2 *Sequestration in Saline (Brine) Aquifers*

Saline aquifers are geologic units that contain formation water but do not have any potential to act as sources of potable water (Baines and Worden, 2004). Sequestration into saline aquifers occurs through the injection of supercritical phase CO_2 into saline aquifers at depths generally greater than 800 meters. Flow velocities in these aquifers are on the order of 1 -10 cm/year (Gunter et al., 1996) allowing for very slow movement of the created CO_2 plume and creating of a hydrodynamic trap. During the course of flow over geologic time, mineral trapping and solubility trapping contribute to the sequestration potential (Gunter et al., 1996). Part of the sequestration strategy for Kevin Dome is injection of CO_2 into saline aquifers below the naturally occurring CO_2 trap of the dome. However, the fluid flow is expected to be relatively static because of structural trapping associated with the dome. Secondary mineral trapping and solubility trapping is still a potential occurrence.

3.3 *Geology of Kevin Dome and Evidence for CO_2 Accumulation at Kevin Dome*

Kevin Dome is a very large structural feature associated with the Sweetgrass Arch in northern Montana (Romine, 1929, Dobbin and Erdmann, 1955). Oil and gas were first discovered on Kevin Dome in 1922, and the dome has had a long history of exploration and production. However, less than 5% of all wells on the dome have drilled below the Madison Formation to a depth necessary to encounter the Devonian Duperow Formation, which has a naturally occurring accumulation of CO_2 trapped on the dome (Figure 2) (Nordquist and Leskela, 1969; Romine, 1929; Wennekers, 1985). Also, no detailed characterization of the Duperow Formation reservoir and associated caprock exists. This study accomplishes this geologic characterization.

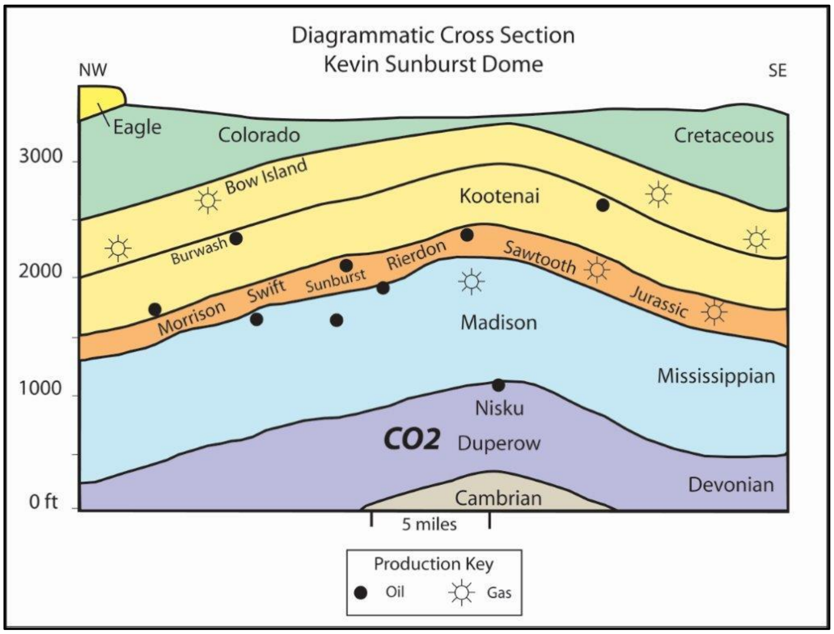

Figure 2: Cross-section diagram of Kevin Dome geologic formation.

3.4 *Geology of Similar Domes*

Several similar domes in terms of scale, structural style, and stratigraphic architecture exist in the state of Montana (Figure 3). These domes are first priority sites for evaluation as potential saline aquifer sequestration sites, because hydrodynamic trapping is enhanced by buoyancy (structural and stratigraphic) trapping. These domes include Bowdoin Dome, Porcupine Dome, Poplar Dome, Big Coulee - Hailstone Dome, Ingomar Dome, and Big Wall Dome.

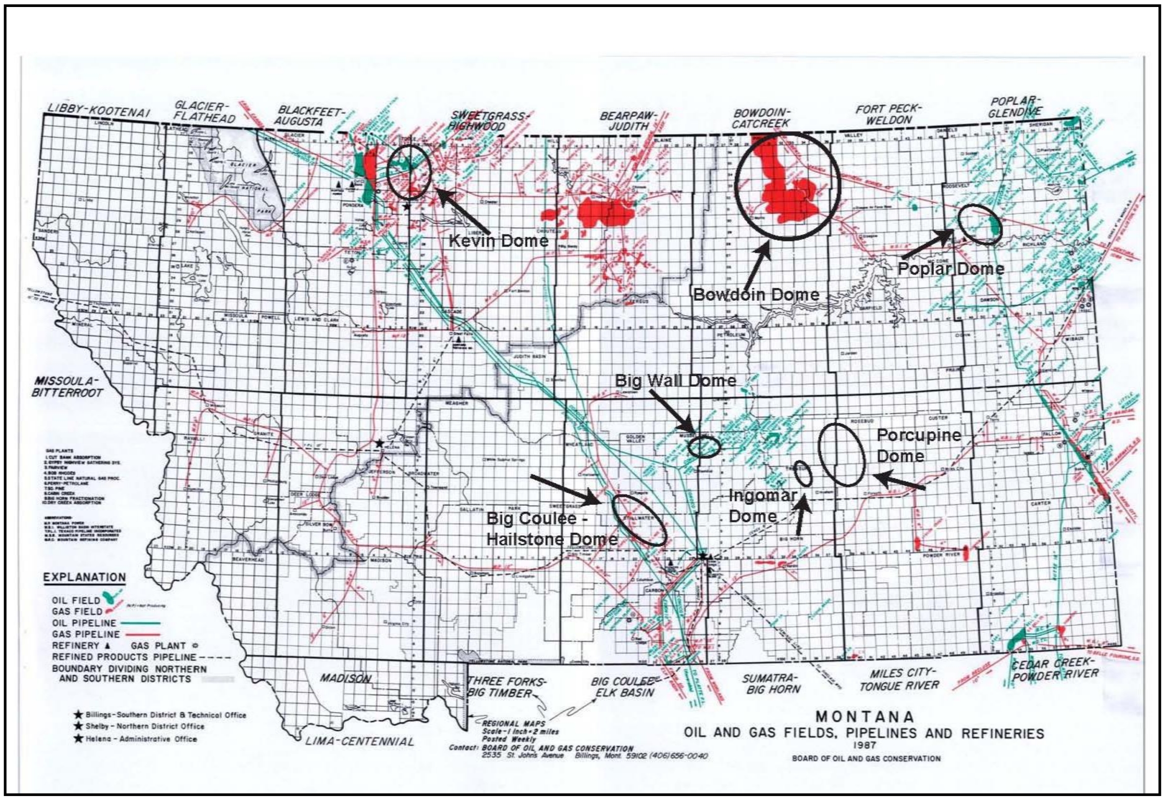

Figure 3: Oil and gas fields map of Montana showing the location pipeline infrastructure, and the location of large domes across the state that may have the potential to sequester large volumes of CO2 from clean energy sources (modified from Montana Board of Oil

3.5 *Oil and Gas Fields of Montana*

Montana has a long history of oil and natural gas production, with cumulative production of approximately 1.5 billion barrels of oil (Oil and Gas Journal, 1/27/2003). The Montana Geological Society has published excellent field papers in a series of guidebooks entitled *Oil and Gas Fields of Montana*, first published in 1958 and periodically updated in 1961, 1969, 1975, 1985, and 2006. These papers contain field scale maps and critical reservoir data for each of the oil and gas fields in the state. The data within these reports is useful for screening the oil and gas fields in the state for potential EOR operations and associated CO_2 sequestration. Additionally, Advanced Resources International (2006), published a report prepared for the U.S. Department of Energy entitled “Basin Oriented Strategies for CO_2 Enhanced Oil Recovery: Williston Basin” that ranks potential fields for CO_2 EOR in the states of Montana, North Dakota, and South Dakota. In summary, there are numerous opportunities in Montana for fields that would favorably respond to CO_2 EOR, including many in the area of Kevin Dome (Wennekers, 1985; Table 1). The bigger issue is identifying a source of CO_2 for these projects. This study demonstrates the potential for a large source of CO_2 at Kevin Dome.

Table 1: Major oil fields productive along the Sweetgrass Arch in Montana. (data source: Montana Board of Oil and Gas Commission online data)

Field	Cumulative Production (oil)
Bannatyne	493,218
Bears' Den	799,361
Blackfoot	1,836,127
Border	1,511,376
Brady	277,217
Cut Bank	171,835,512
Flat Coulee	5,822,079
Fred and George Creek	13,830,657
Gypsy Basin	521,085
Highview	137,029
Kevin East	939,144
Kevin-Sunburst	83,679,243
Laird Creek	635,938
Miner's Coulee	436,305
Pondera	29,238,707
Pondera Coulee	135,851
Prichard Creek	167,514
Reagan	10,601,860
Red Creek	7,201,819
Utopia	1,001,660
West Butte	344,568
Whitlash	5,921,732
Whitlash West	153,483
	337,521,485

The geologic characterization of Kevin Dome was completed using the following methodology:

1. A complete literature review was performed to understand the state of knowledge of the geology of Kevin Dome and the surrounding area.
2. Outcrops of equivalent strata to the Devonian Duperow Formation (the CO_2 bearing strata at Kevin Dome) were studied in the Montana Disturbed Belt to the west of the study area and in the Little Belt Mountains to the south of the study area to help understand the genesis of porosity and permeability in the Duperow Formation.
3. All available subsurface data was compiled to integrate into the study. IHS Energy, Inc. data was licensed to provide well data from oil and gas wells including well spot locations, elevation data, formation tops data, drill stem test data, cored intervals, and initial production data. Raster images of all wells on Kevin Dome were licensed from IHS Energy, Inc. and formation tops were normalized to provide structural datums for key geologic boundaries and reservoir petrophysical data (porosity and lithology data). Water quality data was obtained from the U.S. Geological Survey (USGS) produced waters database (http://energy.cr.usgs.gov/prov/prodwat/). CO_2 analyses were found through a published source (Nordquist and Leskela, 1969) and from a well file found at the Montana Board of Oil and Gas Commission Office in Billings, Montana. Core data

and thin sections from wells west of Kevin dome were studied to integrate with the subsurface interpretation; however, no cores were available from Kevin Dome.

4. A cross-section grid was constructed to detail the correlation framework for Kevin Dome.
5. Structure contour maps were constructed for principal geologic horizons.
6. Porosity values of the CO_2 bearing zones were determined from well logs for all Duperow penetrations of Kevin Dome and these values were used to create porosity isochore maps for the two CO_2 bearing zones.
7. The structure maps and porosity maps were integrated to interpret the trap geometries of CO_2 reservoirs across Kevin Dome.
8. Isochore maps were made from well formation tops data of critical caprock / seal intervals.
9. Water quality distribution was mapped from the USGS produced waters database.
10. Potentiometric data from drill stem test data of the Duperow Formation was mapped to determine fluid flow vectors.
11. Overburden maps (drilling depth maps) to the upper and lower porosity zones of the Duperow Formation were constructed from digital elevation models and structure maps of the two porosity zones. These maps were used to help estimate costs associated with potential project implementation and for estimating reservoirs temperatures to determine CO_2 properties in the reservoir.
12. Available 2-d seismic data was licensed and this data was interpreted to help visualize subsurface relationships.
13. Potential trapped volumes of CO_2 on Kevin Dome were estimated.
14. Potential storage space in the down-dip Duperow Formation brine aquifer was estimated.
15. This information was integrated to form a commercialization plan.
16. Economic impacts resulting from this study were determined.

3.6 *Regional Geologic Setting*

Kevin Dome (often referred to as "Kevin-Sunburst" Dome in petroleum-oriented geologic literature) forms a large structural culmination on the much larger and segmented Sweetgrass arch in northwest Montana and southern Alberta (Figure 4-6). The Sweetgrass arch lies east of the Sevier fold-and-thrust belt and has insignificant topographic expression, except that produced by very small differences in differential erosion of surface formations. Despite the broad, gently-dipping nature of the Sweetgrass arch, it nevertheless has a well-defined crest (Kevin Dome) and is slightly asymmetric. The slightly steeper west limb of the arch has a regional dip of ~1.5-2.0^{o} W beneath the highly deformed, thin-skinned fold-and-thrust belt of northwest Montana, whereas the east limb dips gently towards the Williston Basin in eastern Montana with minor perturbations (such as the Sweet Grass Hills intrusive complex). The Sweetgrass arch consists of three distinct, offset arches, from north-to-south: (1) Bow Island Arch (NNE-trending, ≈200 km long), (2) Kevin-Sunburst Dome (NW-trending, ≈150 km long), and (3) South Arch (NW-trending, ≈100 km long) (Lorenz, 1982). This part of north-central Montana is underlain by several prominent NE-trending magnetic anomalies in the Precambrian basement, notably the

Pendroy fault, Joplin structure, Rock Creek–Bynum trend, and Scapegoat-Bannatyne trend (Mudge, 1982; Sims et al., 2004). By virtue of their "high relief" on regional aeromagnetic maps, these zones were previously thought to be mafic dikes and/or deep-seated fault zones in the basement (and mafic rocks may indeed be coincident with them), but it is now thought that they comprise an array of NE-trending ductile shear zones (mylonite) and basement terrane boundaries collectively known as the Trans-Montana Orogen (Sims et al., 2004).

The Trans-Montana Orogen is ~200-km wide and transects Montana from southwest-to-northeast; the orogen formed as a zone of convergence and cratonic collision between 1.9-1.8 Ga (Paleoproterozoic) (Sims et al., 2004). The continuity of the Kevin-Sunburst Dome is interrupted at the south end by the Pendroy fault, a branch or extension of the "Joplin structure" in underlying basement rocks of the Archean Medicine Hat block. The Pendroy-Joplin trend dextrally offsets Kevin-Sunburst from the South Arch by ~50 km. The southwest end of the Pendroy-Joplin trend is coincident with the Blackleaf oil field along the Rocky Mountain Front (where it projects from beneath the fold-and-thrust belt), and it continues N60^{o}E to form the south end of the Kevin-Sunburst Dome. To the south, the Scapegoat-Bannatyne trend (N40^{o}E) crosses the South Arch, but does not appear to interrupt the continuity of the arch. However, the Scapegoat-Bannatyne trend is marked by deflected structure contours drawn on the base of the Colorado Group and by lateral ramps and tear faults in the fold-and-thrust belt to the southwest (Mudge, 1982).

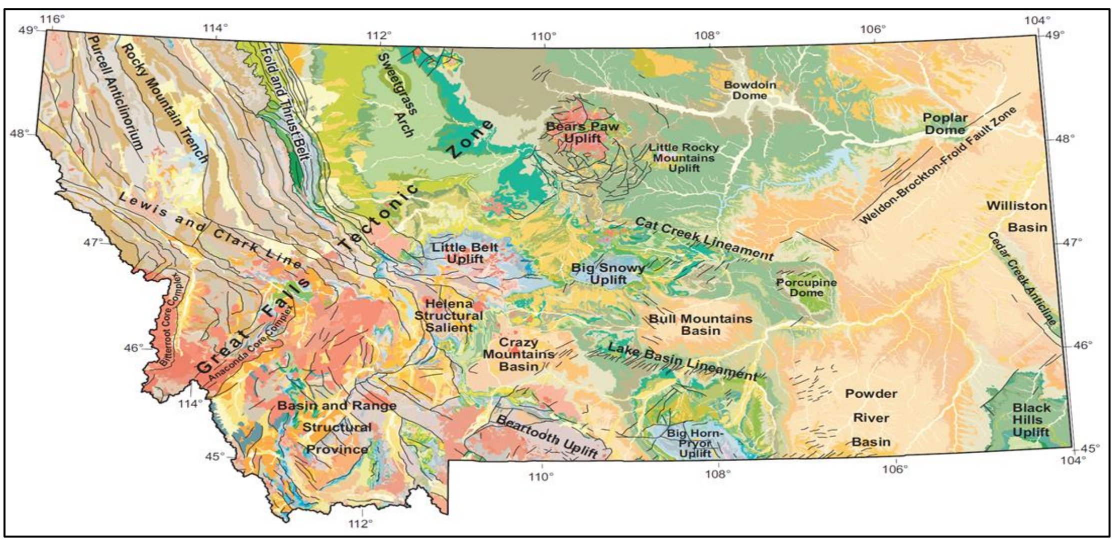

Figure 4: Tectonic map of Montana showing the location of the Sweetgrass Arch in Montana. (modified from Vuke et al., 2007) and

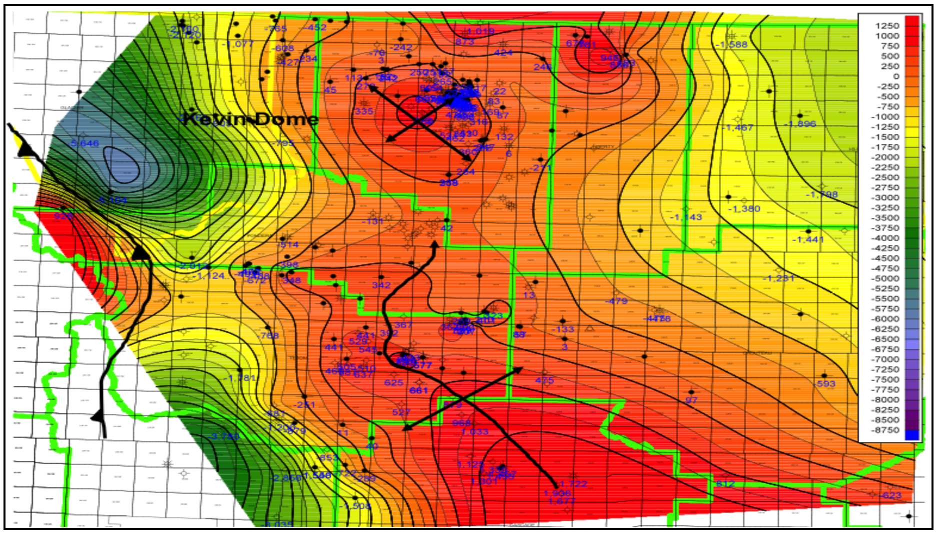

Figure 5: Structure contour map at the top of the Duperow Formation depicting the Sweetgrass Arch in Montana.

These NE-trending magnetic lineaments and fault zones are important because they have structurally partitioned the overall continuity of the Sweetgrass arch, affecting subsurface migration paths for hydrocarbons and CO_2. In addition, they may have been important avenues for the upward circulation of hydrothermal water and the creation of secondary (or tertiary) vuggy porosity in Devonian dolostone reservoirs at Kevin Dome, the primary repository for naturally occurring CO_2.

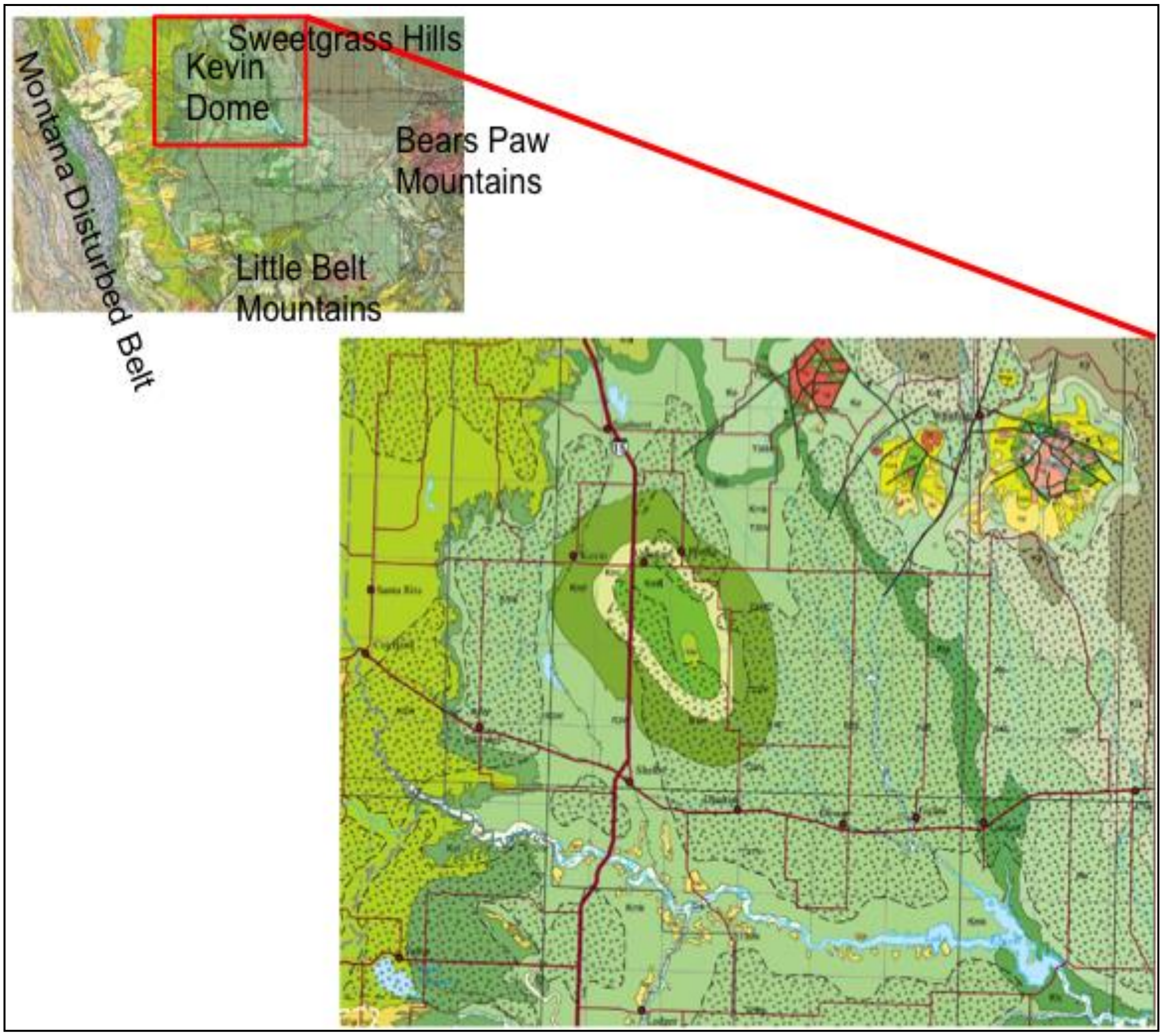

Figure 6: Surface geologic map of Kevin Dome and the Sweetgrass Hills (modified from Vuke et al., 2007)

3.7 *Structural Characterization*

The Sweetgrass arch (Kevin-Sunburst Dome) has been interpreted in various ways over the years. Stratigraphic evidence suggests that the arch has had subtle tectonic relief at various times since the Precambrian (see section below). However, its present structural relief and orientation suggest that amplification of the arch was significantly enhanced by mountain building forces during the late Cretaceous and early Tertiary (Laramide and Sevier orogenies). For example, early workers believed the arch was related to horizontal compression of the crust during the Laramide Orogeny, whereas others suggested that drag folding adjacent to the NW-trending Lewis and Clark Line (to the south) was responsible for uplift of the arch (Lorenz, 1982). However, the parallelism of the arch to the Rocky Mountain Front (Sevier fold-and-thrust belt) led Lorenz (1982) to suggest there was a fundamental elastic-flexural response of the lithosphere to vertical stacking of thrust sheets to the west. In this context, the Sweetgrass arch and its dextrally offset southern continuation, South Arch, may be interpreted as a "forebulge" peripheral to the Rocky Mountains (Lorenz, 1982). This interpretation seems consistent with other basement arches that are adjacent to (and parallel with) thickened fold-and-thrust belts, such as the Moxa arch in western Wyoming. As previously mentioned, Kevin Dome forms a broad structural culmination along the trend of the Sweetgrass arch. Kevin Dome is located due east of the Lewis thrust sheet, a massive thrust sheet along the Rocky Mountain Front that consists of a thick section of Mesoproterozoic Belt Supergroup rocks. The Lewis thrust also occupies the apex of a large convex-east salient in regional trend of the fold-and-thrust belt, having ~70 km of relative eastward tectonic transport (Mudge & Earhart, 1980). It is reasonable to conclude that tectonic loading of the Lewis thrust salient contributed to an enhanced flexural response of the lithosphere at Kevin Dome. In this regard, the tectonic setting of Kevin Dome on the Sweetgrass arch is very similar to the LaBarge Platform on the Moxa Arch in western Wyoming, the latter of which also contains significant volumes of natural CO_2 gas at Shute Creek field.

The Moxa Arch in western Wyoming has been uplifted through a combination of folding and brittle faulting at the level of the Precambrian basement. Balanced cross-sections and seismic data suggest that basement faulting on the Moxa Arch is contractile, similar in geometry to nearby Laramide uplifts, but with much less structural relief (Garing & Tainter, 1985). However, given the data available at present, there is no direct evidence of significant structural offset of the Precambrian basement beneath Kevin Dome and the Sweetgrass arch, although the possibility of minor faulting cannot be ruled out – in fact, it should be expected.

3.8 *Tectonic History*

Lorenz (1982) has documented the history and recurrent tectonic instability of the Sweetgrass arch. During the latest Precambrian time, the Sweetgrass arch marked the hingeline of a trailing continental margin. Cobban (1956) has shown that the arch was well established prior to Middle Jurassic time. By mid-Mesozoic, relief on the arch relative to the Williston Basin to the east was approximately 1,400 meters (Lorenz, 1982). Episodic amplification of the arch continued through the late Cretaceous and Paleocene, broadly concurrent with episodic thrusting in the Sevier orogen and deposition of the Two Medicine Formation in the foredeep basin between the thrust belt and the arch (Lorenz, 1982). Amplification of the arch reached a maximum during the Paleocene through a combination of (1) crustal compression and buttressing as the thrust belt advanced relatively eastward (likely scenario, given the fact that the arch was established prior to thrusting), (2) shear along the Lewis and Clark lineament (not likely, given the limited displacement along the lineament), (3) elastic-flexural bending of the lithosphere in response to the mountain immediately to the west (likely, perhaps acting in concert with #1 above), and/or (4) crustal back-thrusting in front of the Sevier orogen (similar to the Moxa arch).

3.9 *Origin of CO_2 at Kevin Dome*

Large volumes of naturally occurring CO_2 are trapped in a Devonian dolostone reservoir, the Duperow Formation, which has closure under most of the dome. CO_2 was likely generated during intrusion of Eocene laccoliths through the Paleozoic carbonate section, less than 20 miles east in the Sweetgrass Hills intrusive complex. The timing of intrusion is constrained by K-Ar radiometric dating, with most dates lying between 54-50 Ma (Lopez, 1995). NE-trending basement structures and near-surface fractures have not compromised the trap integrity of the Duperow reservoir since the Eocene, given the excellent sealing/caprock attributes of the overlying Potlatch anhydrite and higher shale formations. Therefore, the integrity of CO_2

entrapment has been maintained in a stable geologic setting for tens of millions of years, making this site ideal for carbon sequestration.

3.10 *Stratigraphic Characterization and Reservoir Geology*

Exploration and development drilling for oil and natural gas reservoirs have created a substantial database of subsurface information useful to understanding the geology of units important for trapping CO_2 on the dome and for benefit as potential sequestration reservoirs below the gas/water contacts in CO_2 reservoirs (Figure 7).

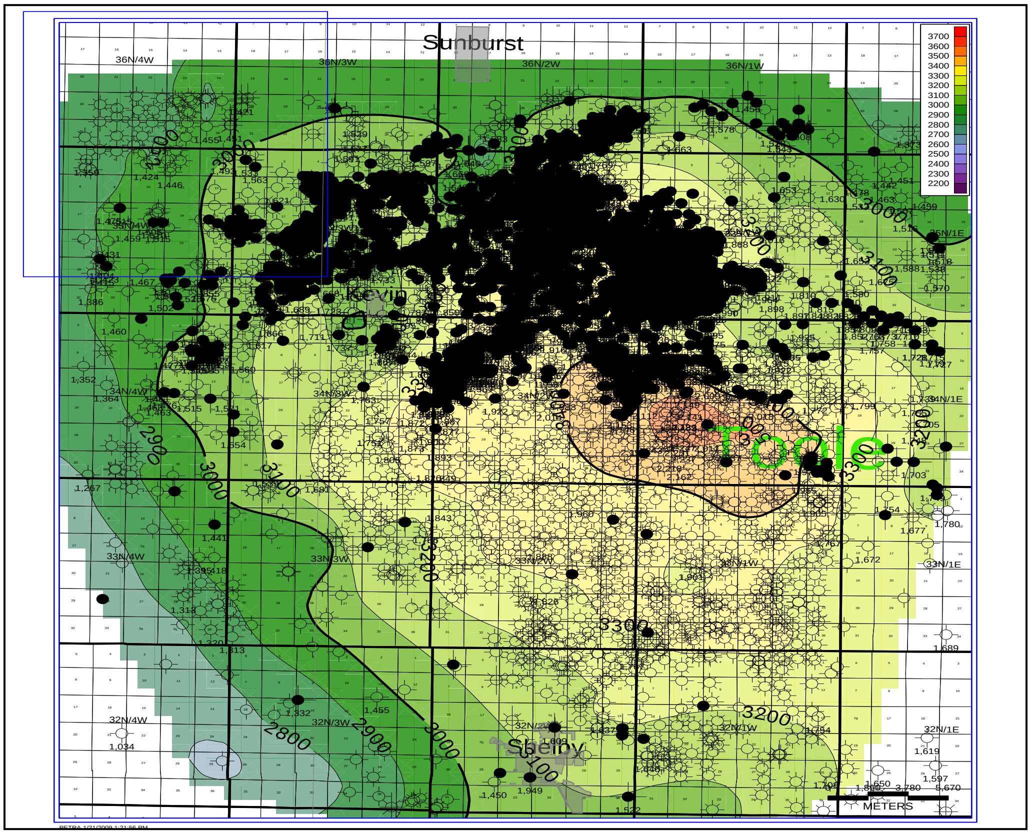

Figure 7: Oil and gas wells penetrating Kevin Dome. Structure contour map of the top of the Cretaceous Blackleaf Formation is drawn.

Lower Tertiary through Cambrian strata are present across the dome with Cretaceous through the Upper Devonian Nisku Formations being important oil and natural gas reservoirs on Kevin Dome and in the surrounding area (Figure 8). The Devonian Duperow is also a well-documented CO_2 reservoir.

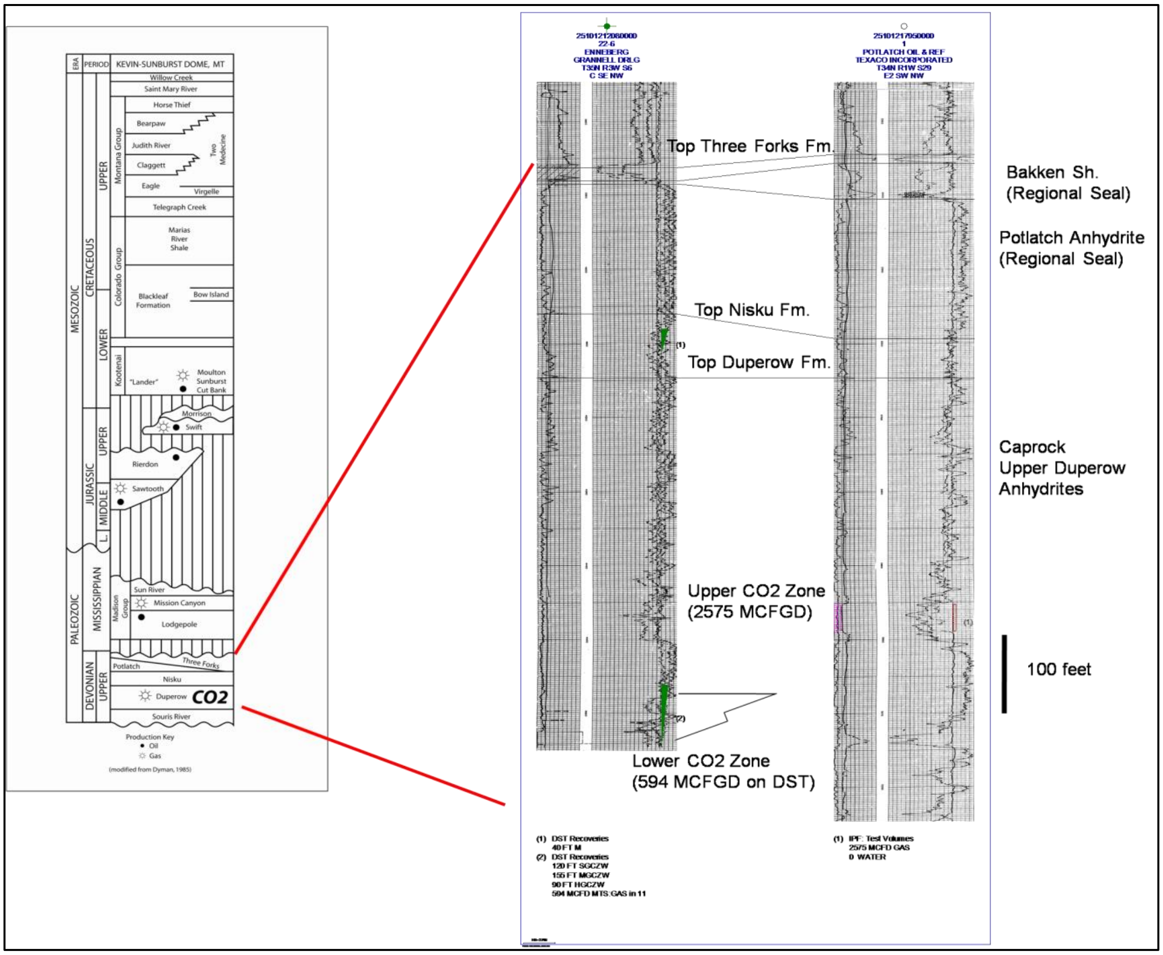

Figure 8: Stratigraphic column for Kevin Dome. Expanded section displays type logs of the upper Devonian section showing the two CO2 bearing regional porosity zones of the Duperow.

The lower Mississippian/Upper Devonian lower Lodgepole/Bakken/Banff/Exshaw Formation through Devonian Souris River Formation strata are most important from the standpoint of trapping CO_2 as a potential resource for EOR projects and as a brine reservoir for potential sequestration projects. These strata define two important hydrodynamic systems (Figure 9). The lower of these is the Souris River to Potlatch Anhydrite system that has limited reservoirs/brine aquifers in the Souris River Formation, aquitards in the upper Souris River and lower Duperow Formations, a regional lower porosity zone that is a brine aquifer/CO_2 reservoir in the lower Dupperow, aquitards in the middle Duperow, a second regional upper porosity zone that is a brine aquifer/CO_2 reservoir in the middle Duperow, aquicludes in the upper Duperow, localized aquifer/oil and gas reservoirs in the Nisku Formation, and a regional aquiclude overlying that is the Potlatch Anhydrite. Overlying this Devonian CO_2/brine aquifer system is the Exshaw/Bakken petroleum system that is the focus of a current oil resource exploration play of regional significance. The Exshaw/Bakken Formations are the source rocks for this system with reservoirs in the Three Forks, Exshaw/Bakken, Banff, and lower Lodgepole Formations. Top seal for the system are tight limestones in the lower Lodgepole. This system provides a secondary sealed system above the CO_2 systems providing enhanced sequestration security.

Above these units, additional reservoirs and regional seals are present in the Mississippian Madison Formation and throughout the Mesozoic System above.

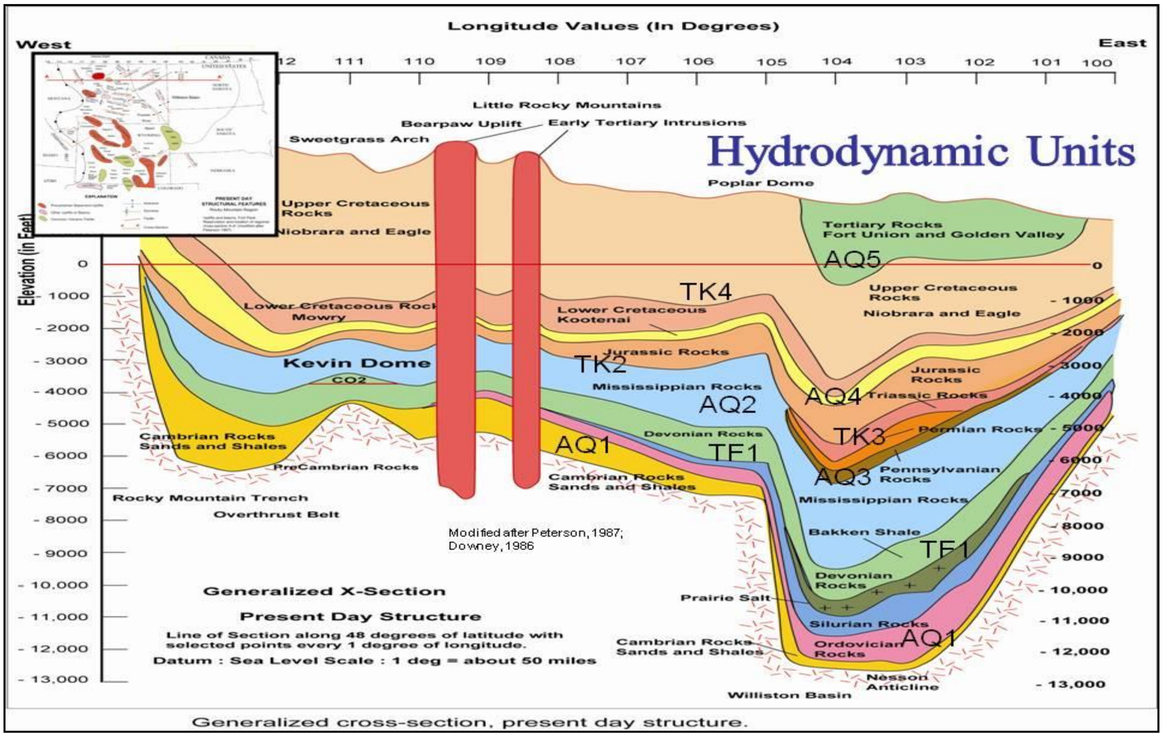

Figure 9: Hydrodynamic units across the northern Great Plains region. (modified from Peterson, 1987, and Downey, 1986)

A detailed cross-section grid was constructed to facilitate correlation of these units and to properly designate porosity zones of interest. The grid location map for these cross-sections and the cross-sections themselves are shown on Figures 10-17.

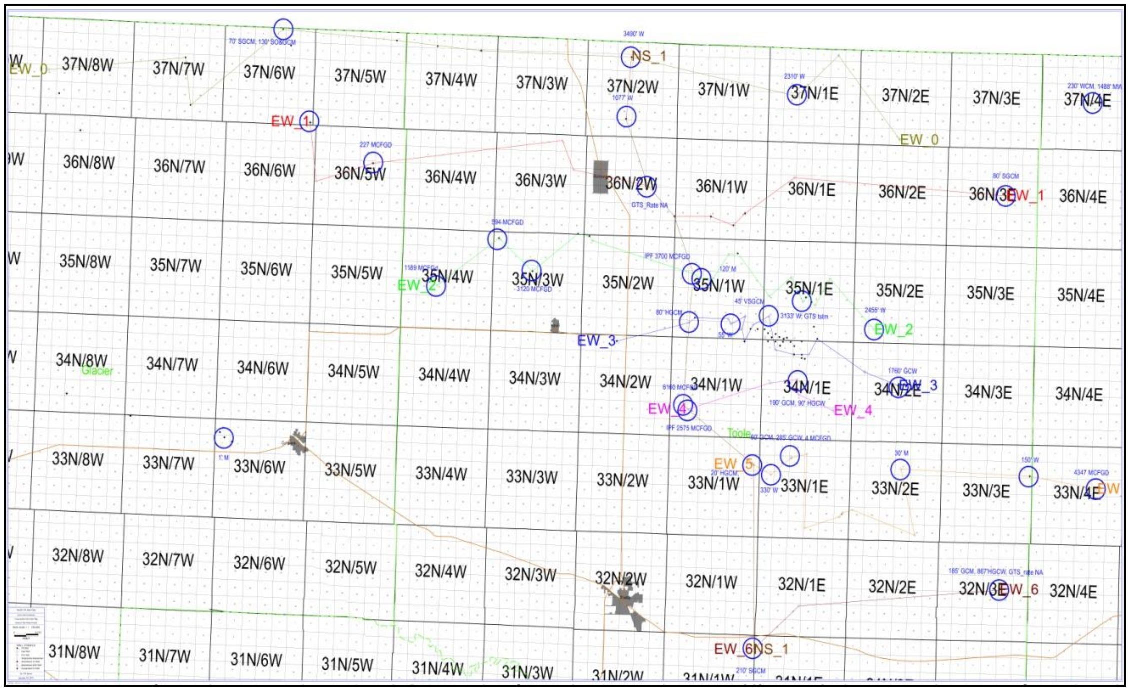

Figure 10: Location map of cross-section correlation grid. Only those wells that penetrate the Duperow Formation are shown by the small dots with those used in the cross-sections highlighted by the blue circles.

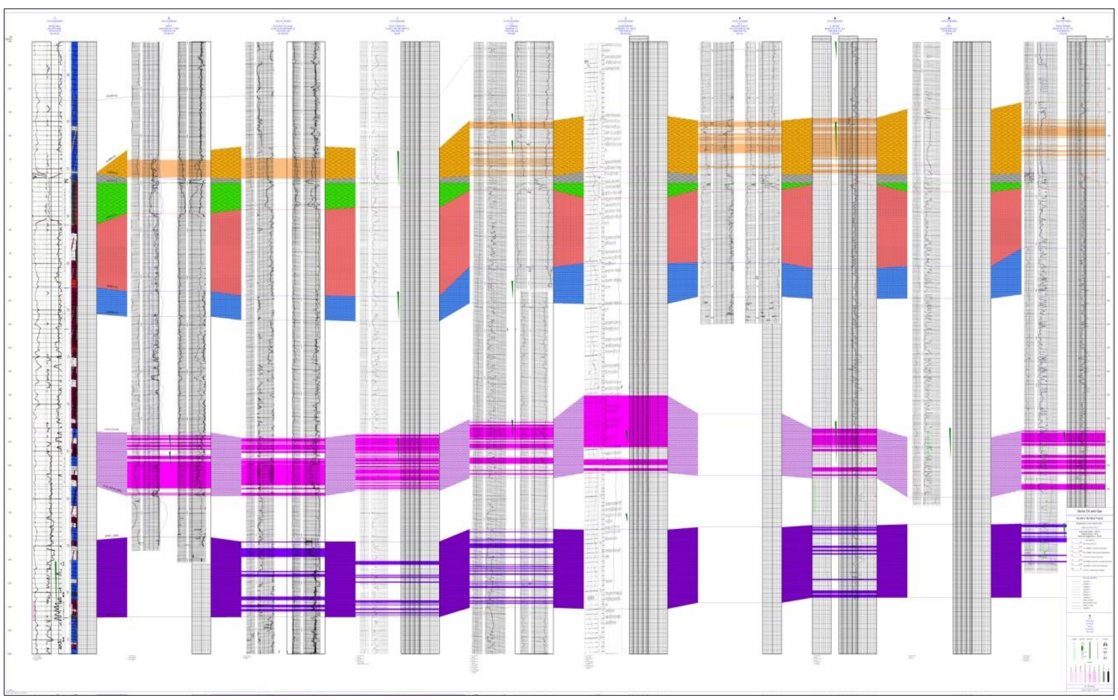
Figure 11: Correlation cross-section XS_NS1

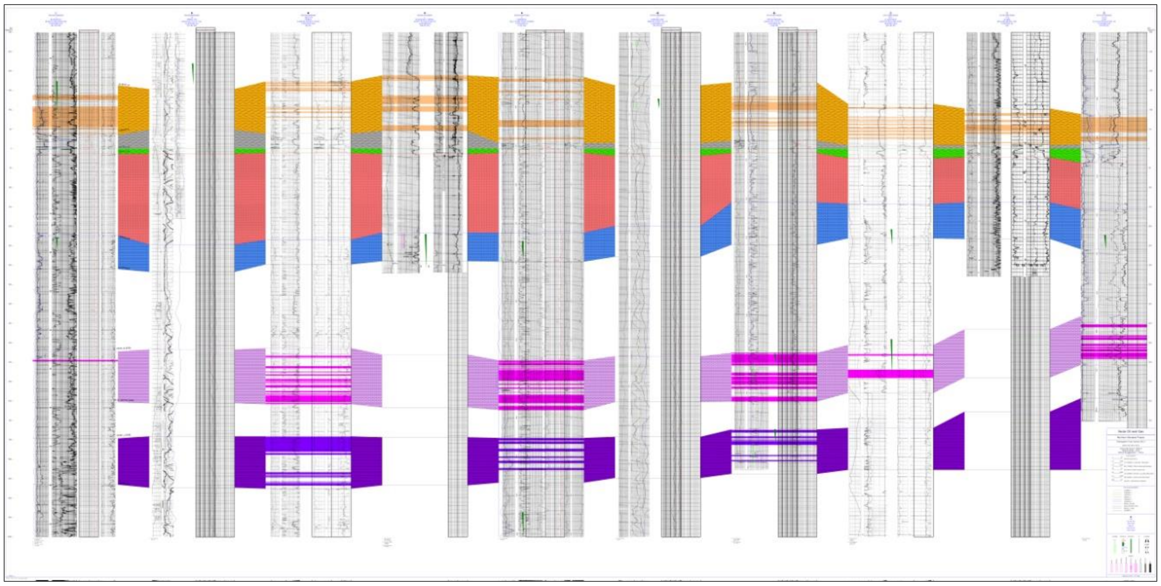

Figure 12: Correlation cross-section XS_EW0

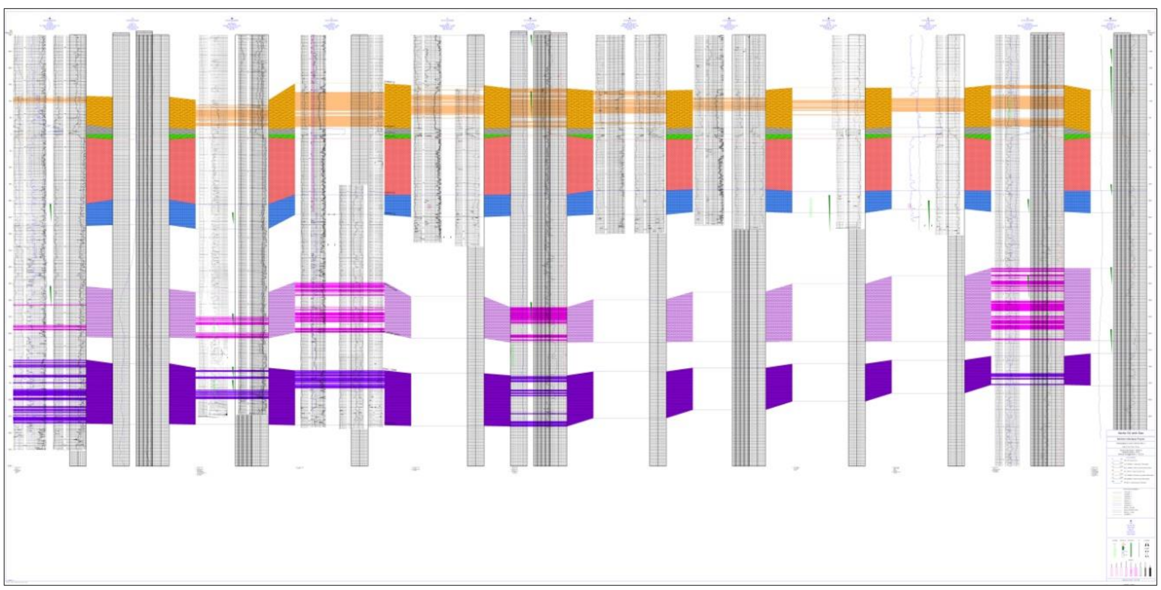

Figure 13: Correlation cross-section XS_EW1

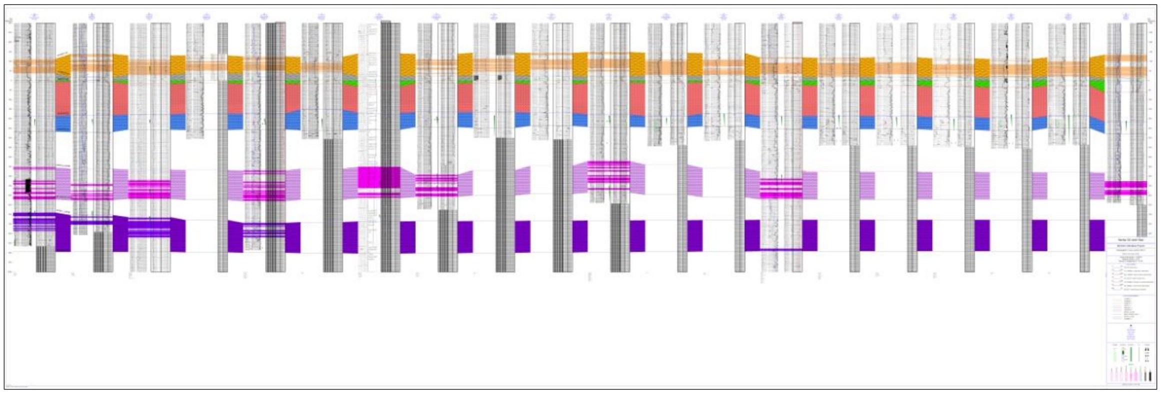

Figure 14: Correlation cross-section XS_EW2

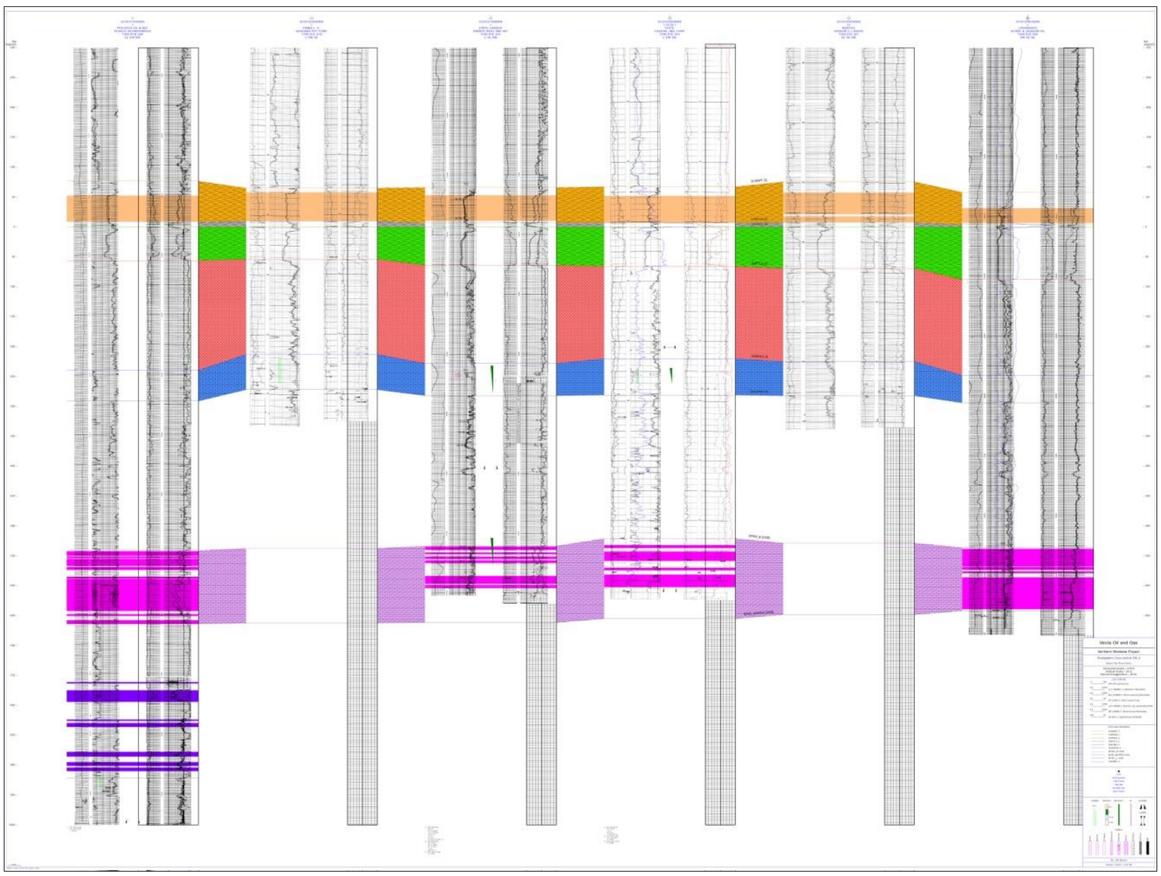

Figure 15: Correlation cross-section XS_EW4

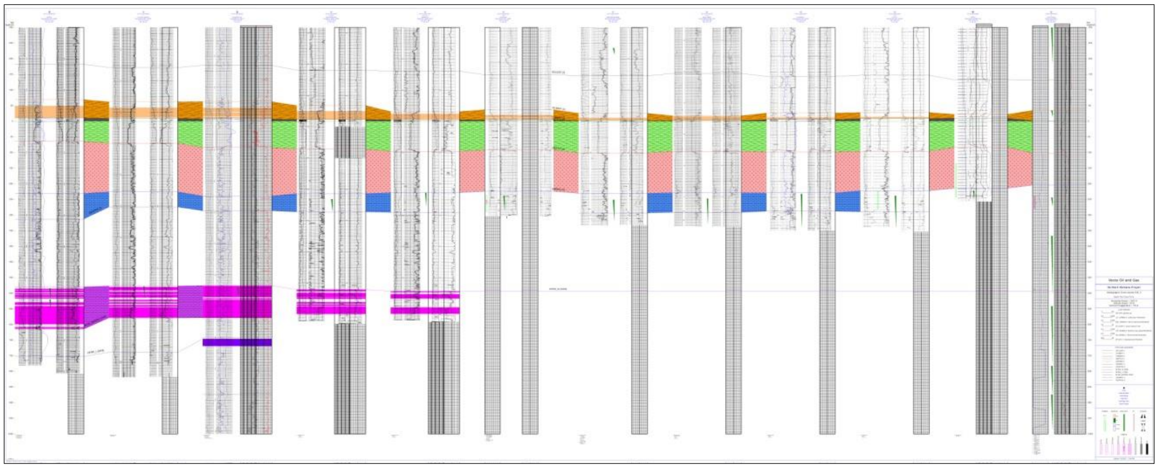

Figure 16: Correlation cross-section XS_EW5

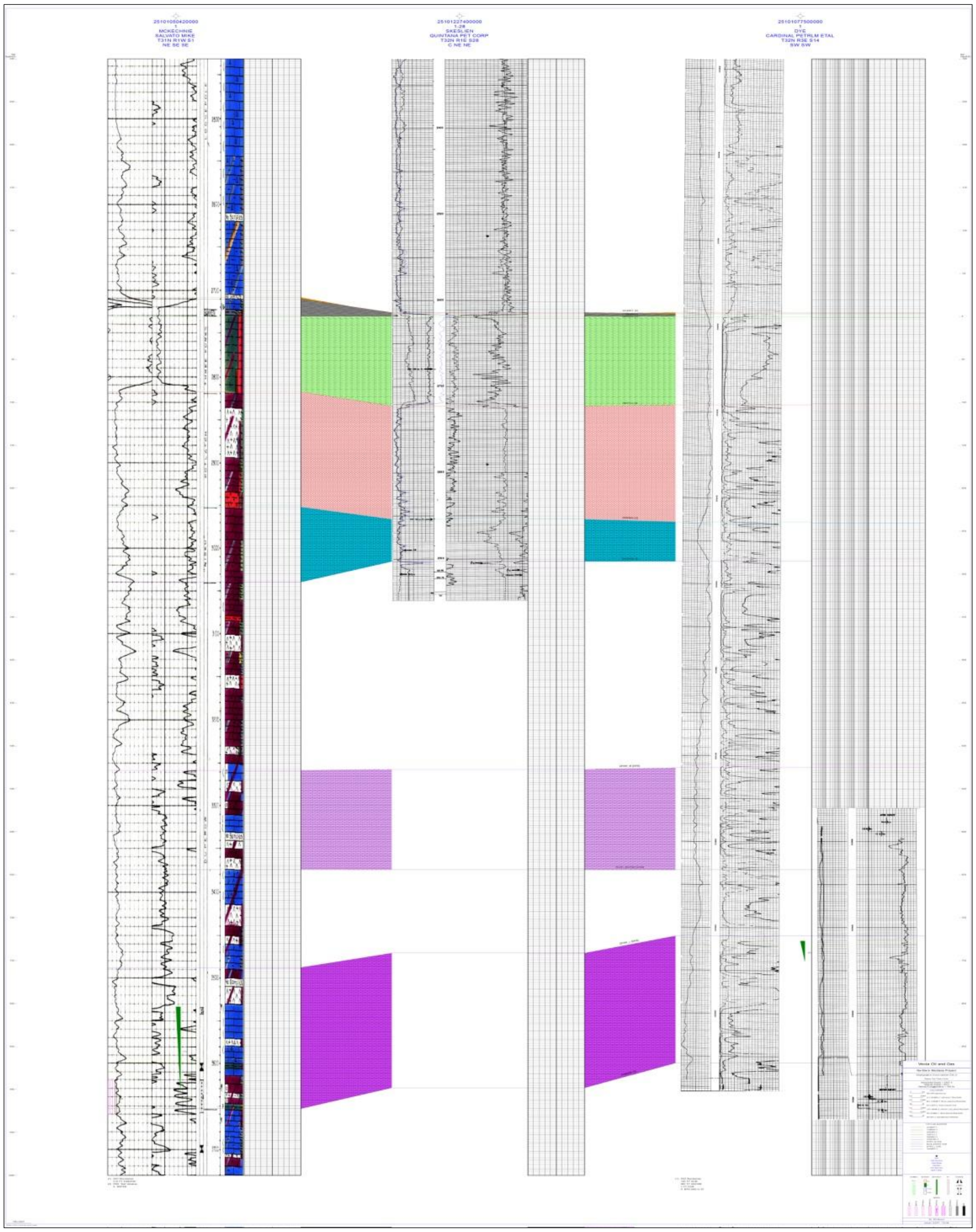

Figure 17: Correlation cross-section XS_EW6

This cross-section grid was used as a framework to guide the designation of formation datums. The research team used these datums to construct structure contour maps of key horizons and isochore maps of key intervals. They were also used as the correlation framework in determining thicknesses of net porosity in the Duperow reservoir zones. These maps are shown on Figures 18-28.

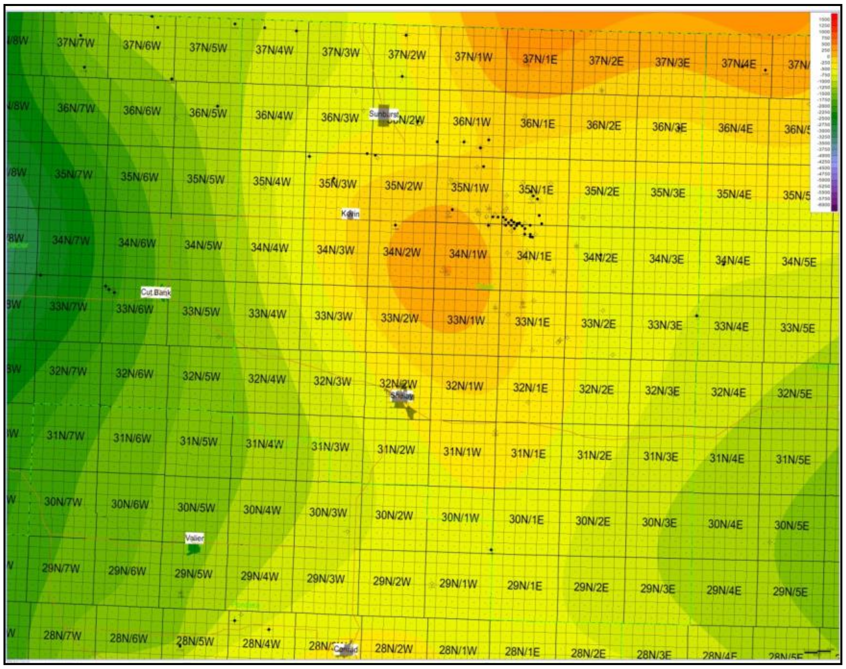

Figure 18: Structure contour map top Souris River Formation

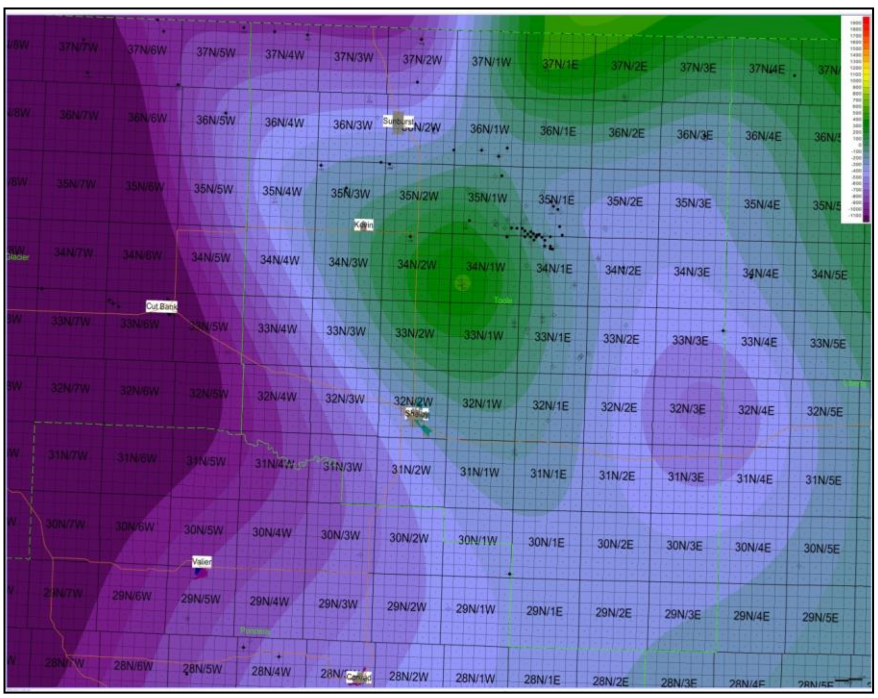

Figure 19: Structure contour map top lower Duperow porosity zone

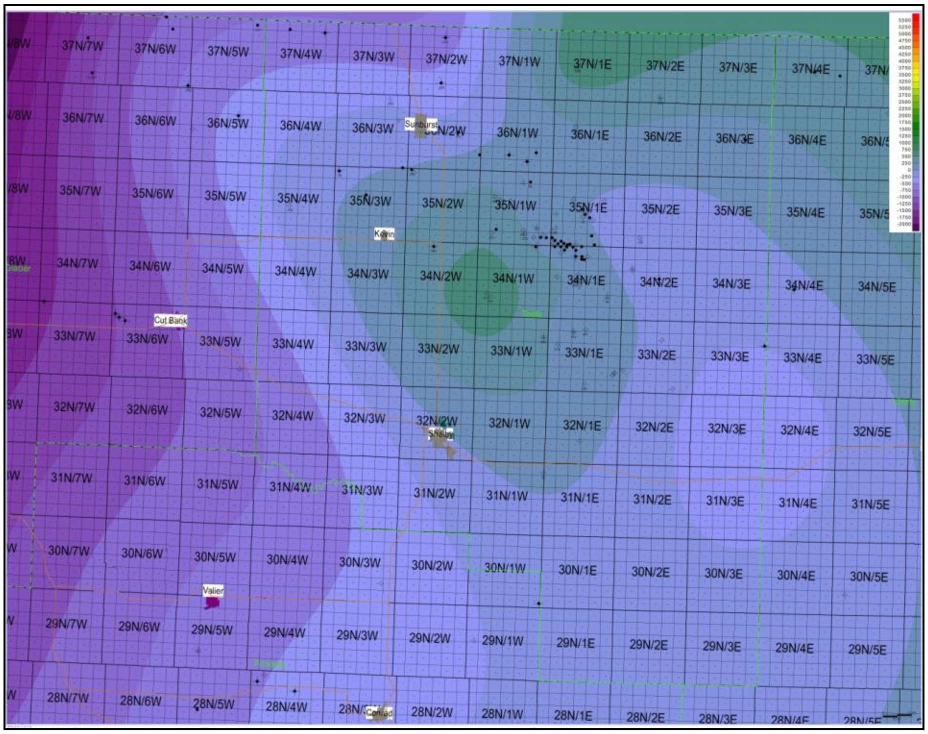

Figure 20: Structure contour map top middle Duperow porosity zone

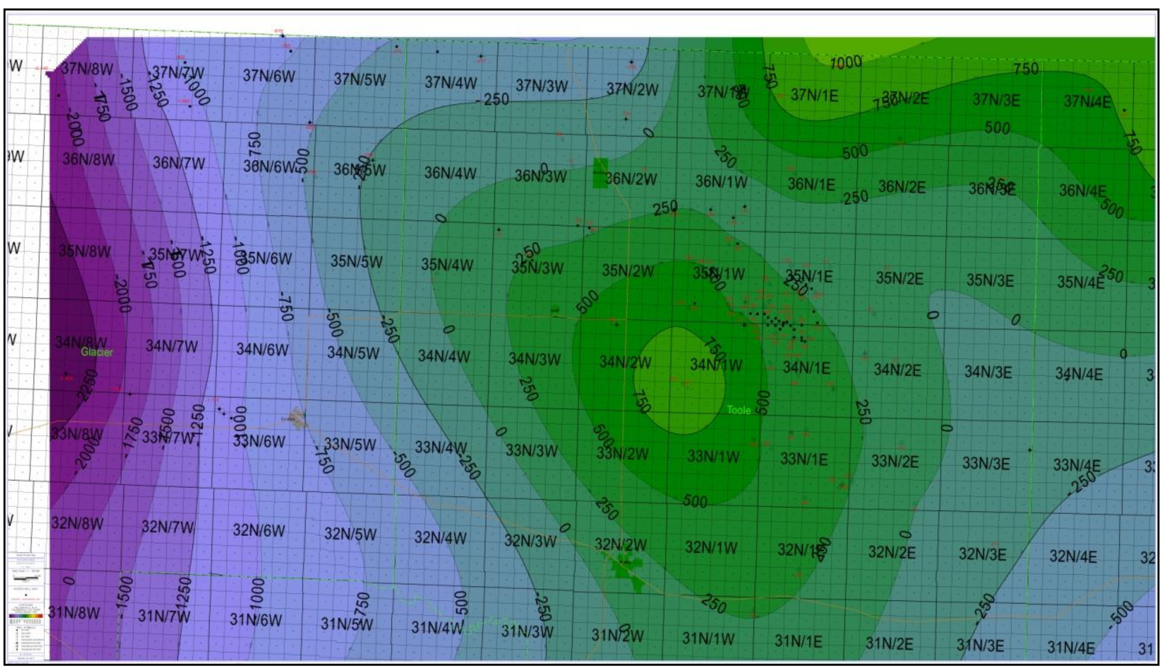

Figure 21: Structure contour map top of Duperow Formation

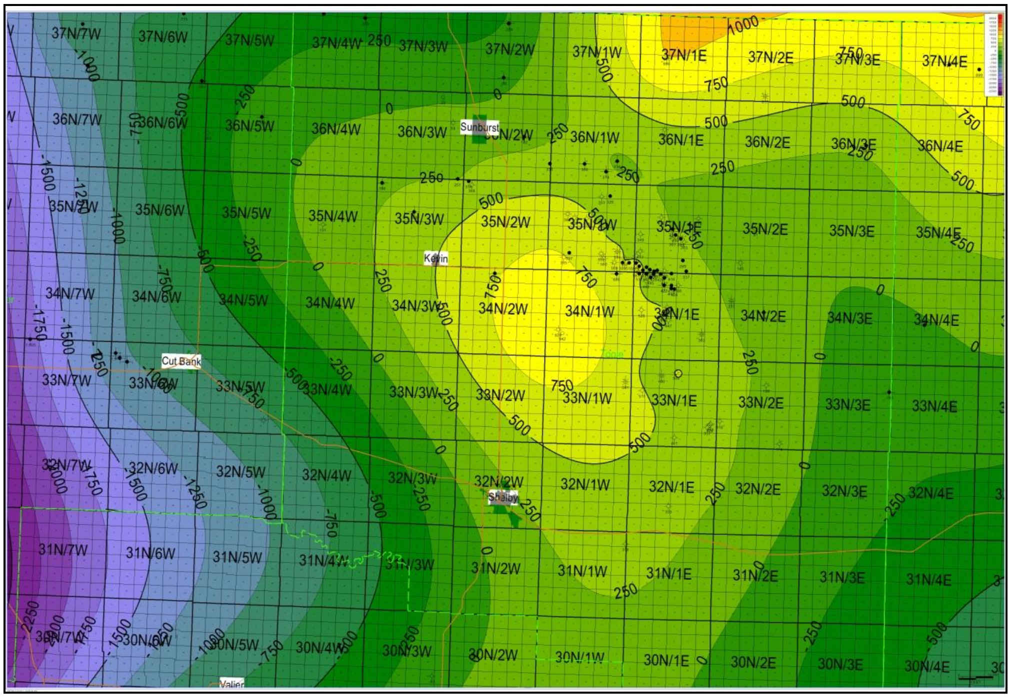

Figure 22: Structure contour map top of Nisku Formation

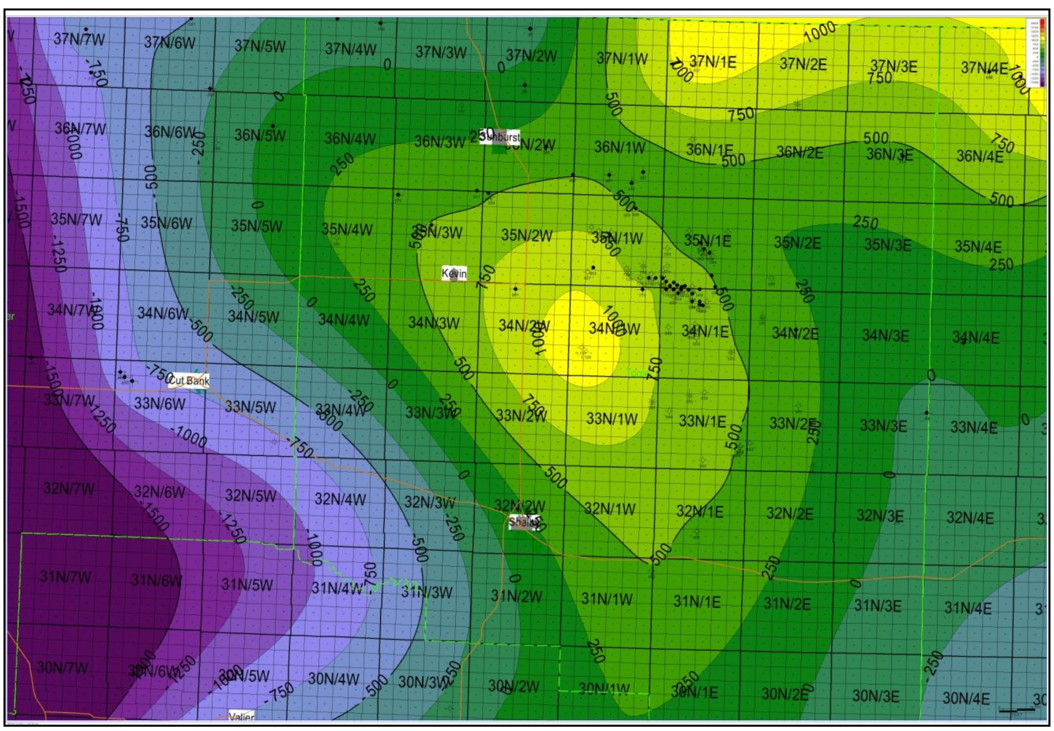

Figure 23: Structure contour map top of Potlatch Anyhdrite

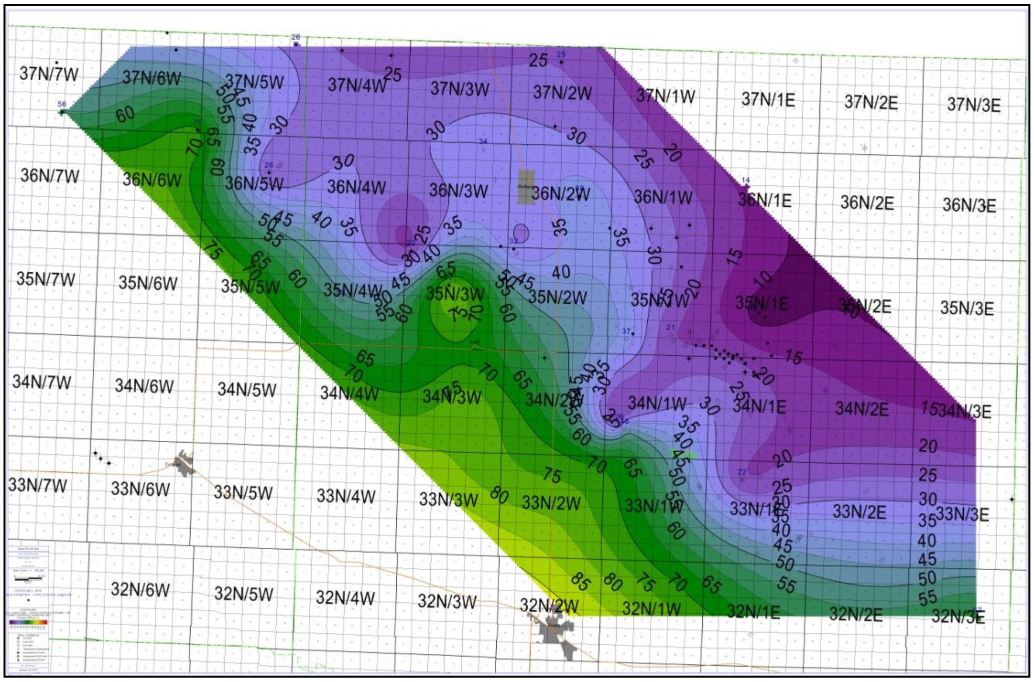

Figure 24: Lower Duperow net porosity >6% isochore (lower porosity zone)

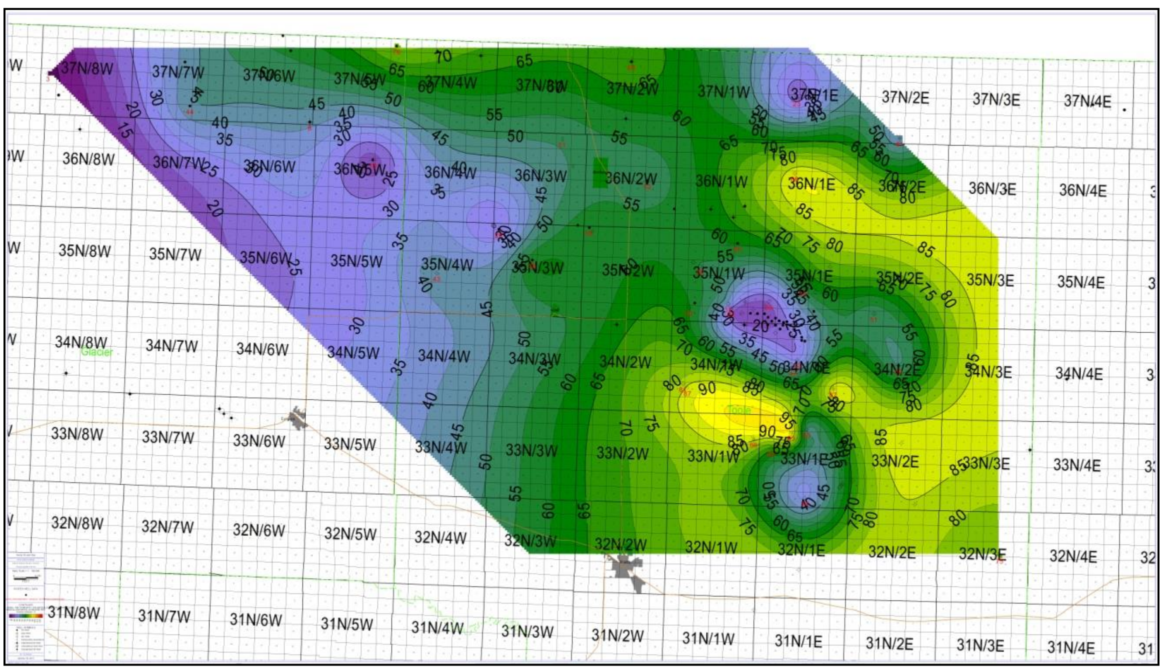

Figure 25: Middle Duperow net porosity >6% isochore (upper porosity zone)

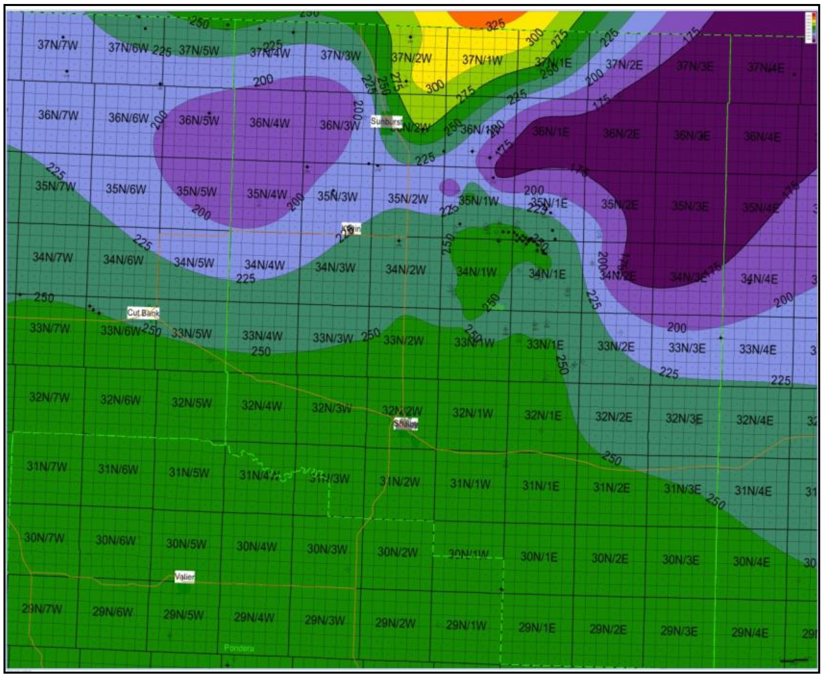

Figure 26: Upper Duperow isochore (caprock facies)

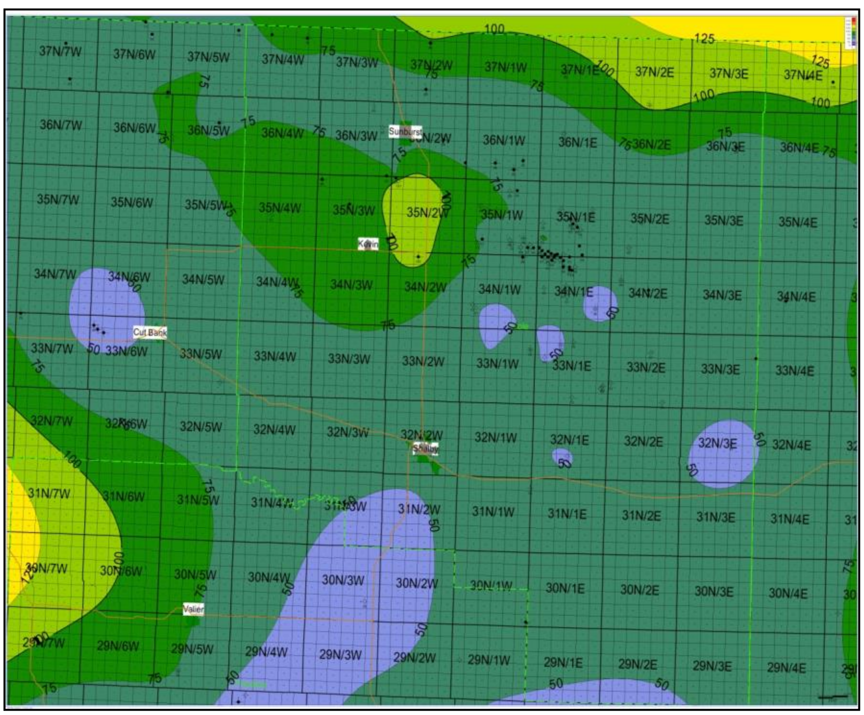

Figure 27: Nisku isochore (local reservoir and additional caprock facies)

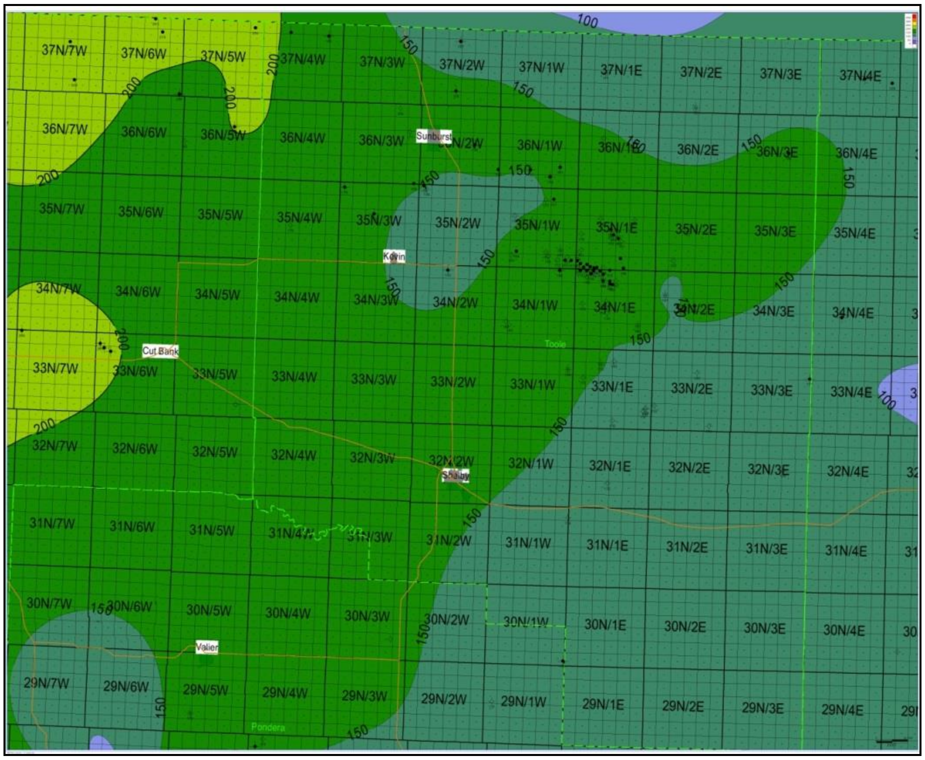

Figure 28: Potlatch Anhydrite isochore (regional caprock facies)

The reservoir and seal (caprock) properties defined by this series of maps define the critical geometries for trapping configurations, the volume of potential reservoir space, and the thicknesses of sealing strata. The trapping geometry of the lower Duperow porosity zone is on the overlay of the lower Duperow net porosity isochore with the associated structure contour map (Figure 29). The trapping geometry of the upper Duperow porosity zone is shown on the overlay of the middle Duperow net porosity isochore with the associated structure contour map (Figure 30).

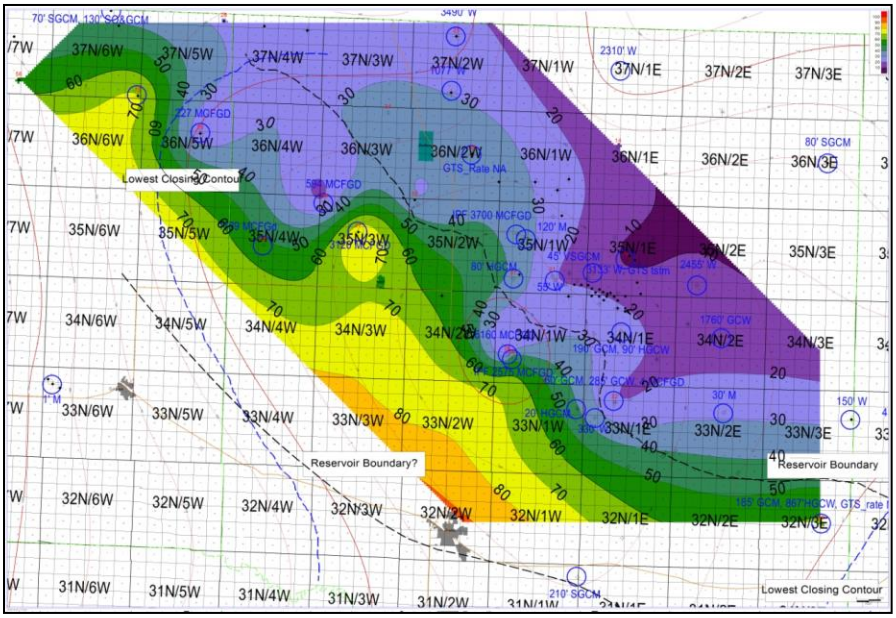

Figure 29: Lower Duperow porosity zone trapping configuration. CO2 test rates are shown for well tests in the Duperow Formation

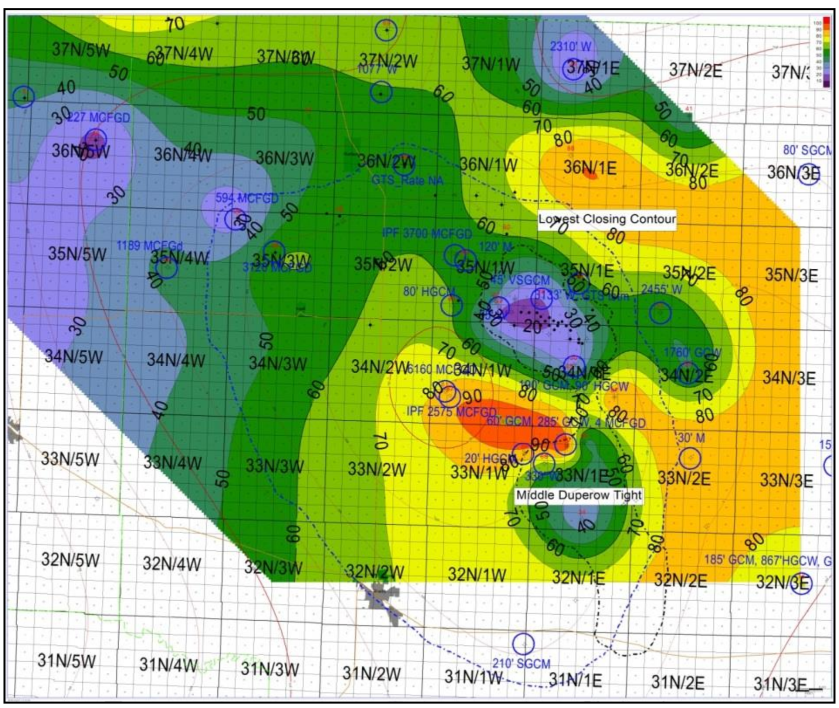

Figure 30: Upper Duperow porosity zone trapping configuration. CO2 test rates are shown for well tests in the Duperow Formation.

Also important for reservoir fluid considerations is the drilling depth to each of these reservoir zones, as this controls the calculation of reservoir temperature for determining CO_2 properties for volumetric calculations as well as economic factors related to drilling and completion costs. Figure 31 and Figure 32 are maps of drilling depth to these zones.

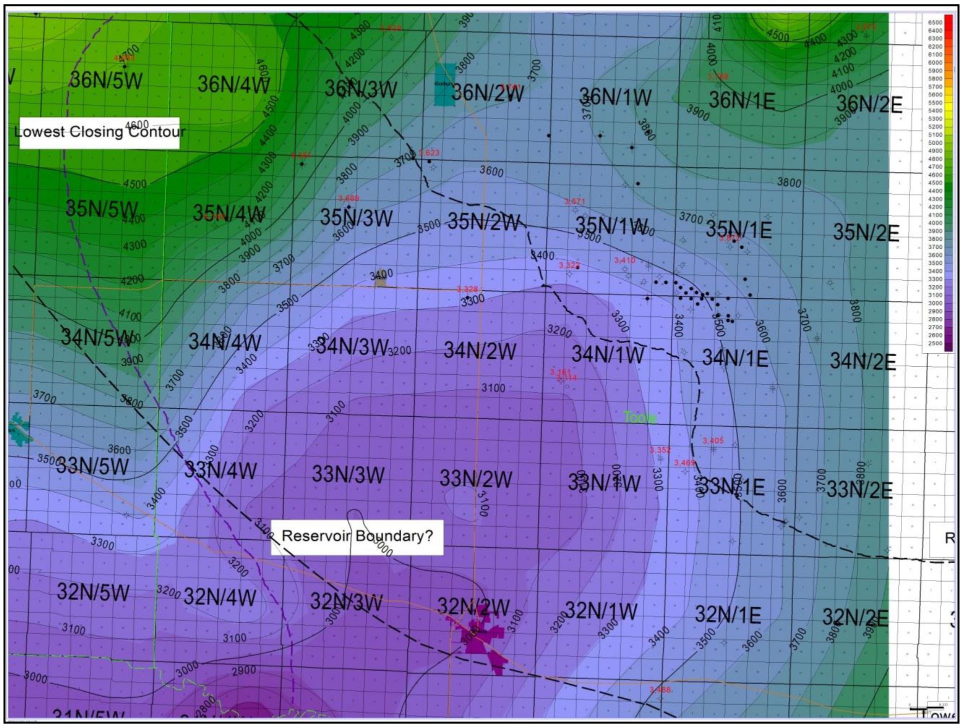

Figure 31: Drilling depth to the top of the lower Duperow porosity zone

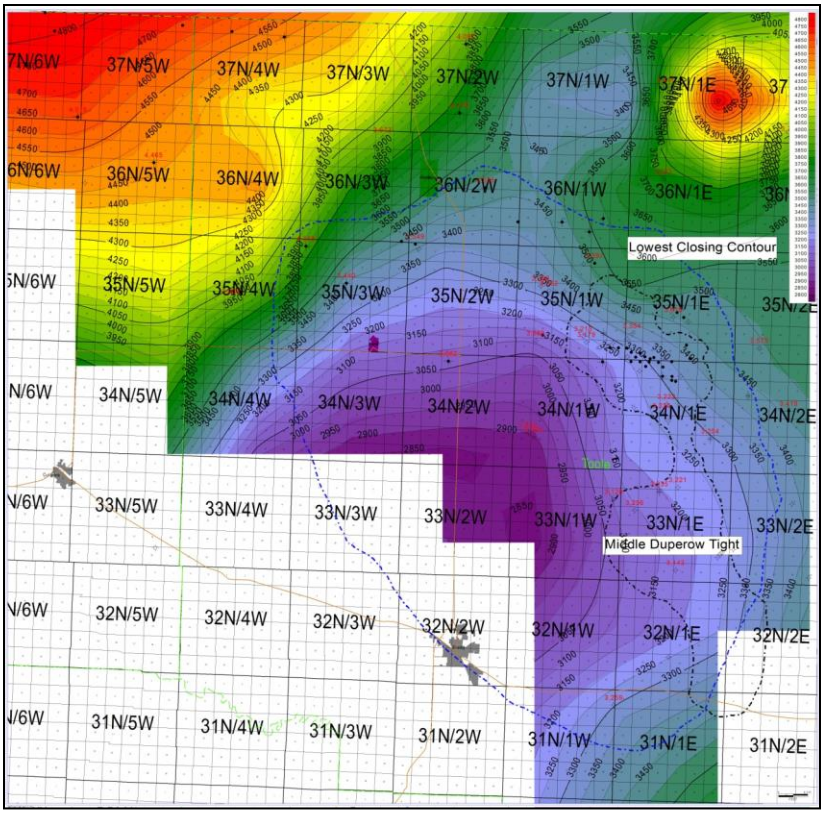

Figure 32: Drilling depth to the top of the upper Duperow porosity zone in the middle Duperow

The number of old well bores penetrating the potential sequestration objective is significant from the sequestration perspective. It is clear from Figure 33 that the number of wells that penetrate the deeper objectives are far less than the shallow objectives. Literally thousands of wells penetrate the shallow Cretaceous section on Kevin Dome while only 80 wells penetrate the Devonian Duperow Formation.

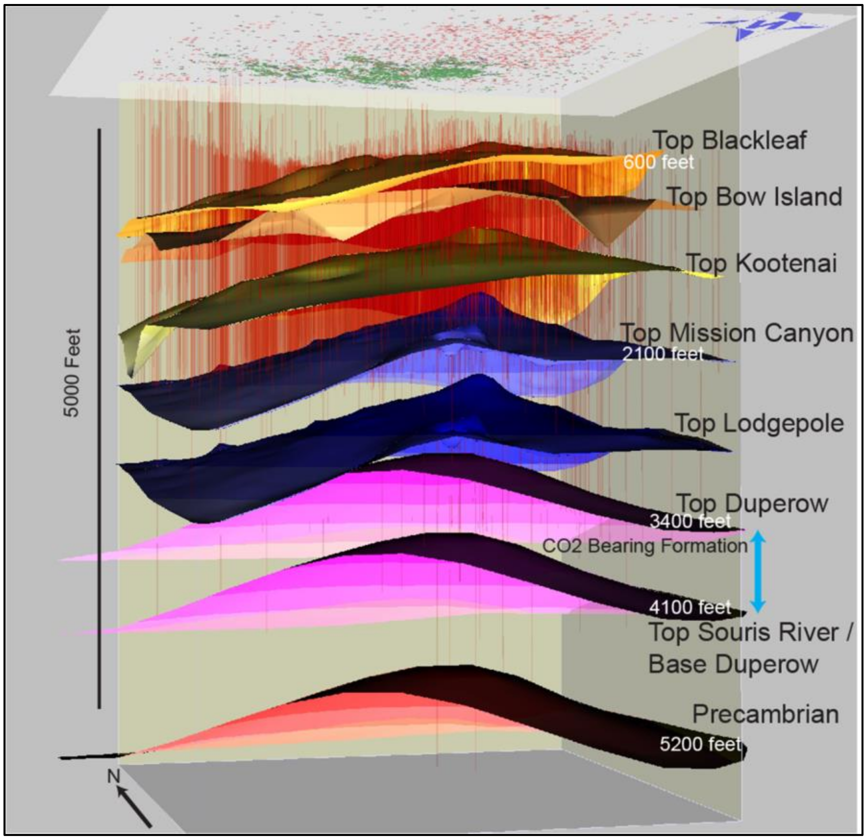

Figure 33: 3-d geologic model of Kevin Dome structural datums. Note the very large numbers of shallow well penetrations compared to deep well penetrations (red lines)

3.11 *Reservoir and Seal (Caprock) Relationships: Petrographic Analysis*

The reservoir for the majority of CO_2 tested at Kevin Dome is the Devonian Duperow Formation. The Duperow is predominantly limestones and dolostones with anhydrite present in the upper part of the formation. Two distinct porosity intervals are responsible for containing the CO_2 as shown on previous cross-sections and maps. Outcrop and core study define these carbonates as open shelf deposits with periodic restriction of circulation allowing evaporite deposits to develop. The regional porosity zones in the Duperow result from secondary dissolution of limestone and dolomite and have high permeability as evidenced by high flow rates of CO_2 from associated tests.

The primary seal is a series of interbedded anhydrites and tight carbonates in the upper part of the Duperow and between the upper and lower porosity zones in the Duperow. Numerous secondary seals exist between the Duperow and the ground surface and have resulted in many oil and gas traps in shallower formations.

Two field areas were studied for the petrographic analysis: the outcrops along the north plunge of the Little Belt Mountains near Monarch, Montana (Figure 34 and Figure 35) and along the Montana Disturbed Belt near Sun River Canyon (Figure 36 and Figure 37 and Table 2).

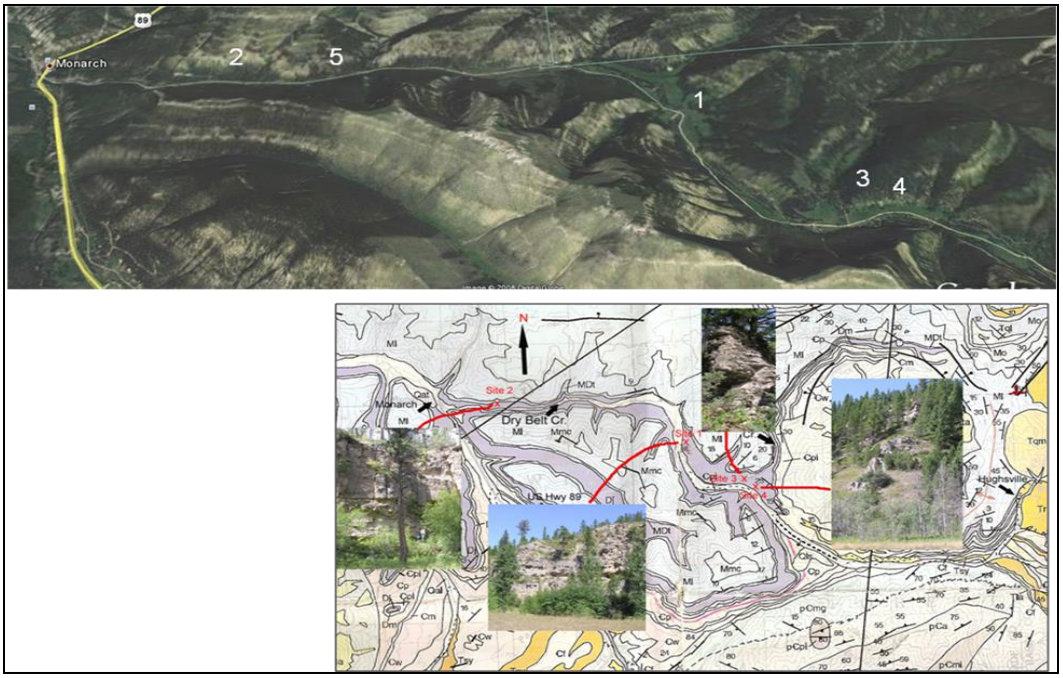

Figure 34: Outcrop belt of the Devonian Duperow Formation near Monarch, Montana and locations of measured sections

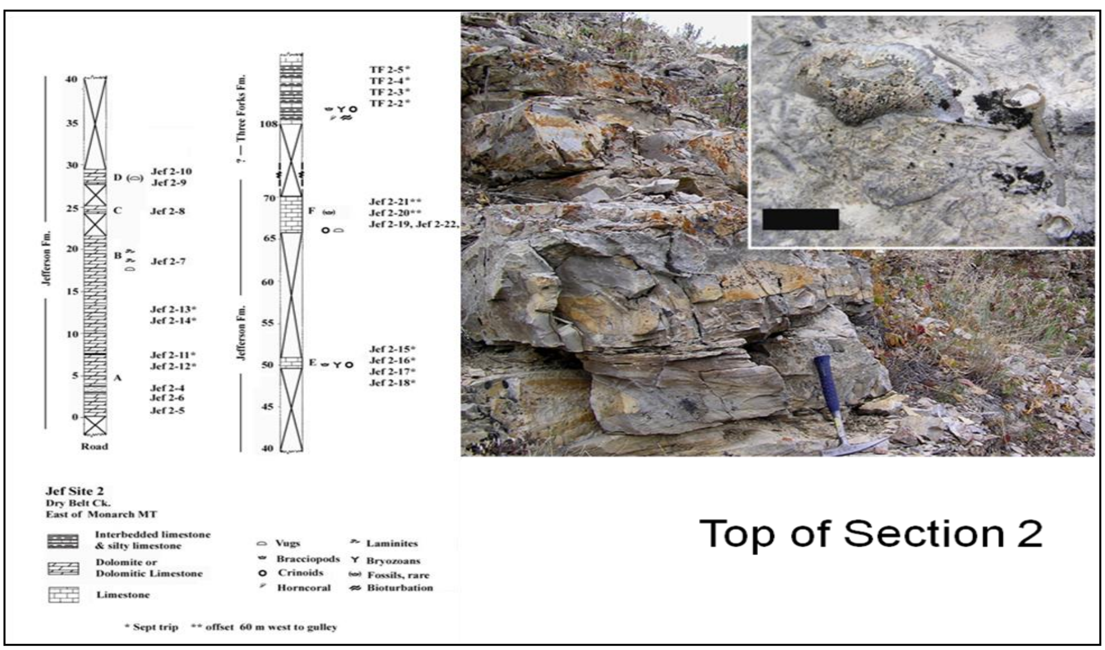

Figure 35: Outcrop photograph and measured section along Dry Belt Creek Road, Monarch, Montana. Note open marine fauna in picture on right.

Figure 36: Outcrop of Devonian Duperow Formation in Sun River Canyon, Montana Disturbed Belt west of Kevin Dome; Lower-Upper Devonian (Frasnian)

Figure 37: Devonian Duperow from outcrop in Montana Disturbed Belt west of Kevin Dome. Note dissolution / precipitation of secondary minerals

Table 2: Description of Devonian Units, Sun River Canyon

Stage	Group	Formation	Description
Famennian		Three Forks	Limestone & calcitic dolomite, gray-brown to tan-gray, massive-bedded; intraformational breccia in lower ½ which forms massive ledges; fossiliferous in upper part; 100-175 ft. thick
Frasnian	Jefferson Group	Birdbear (Djb)	Dolomite & calcitic-dolomite, finely crystalline, tan-gray to light gray-brown; thin-bedded in upper part, pinch-and-swell bedding in lower part; sparse fossils; 150-225 ft. thick
Frasnian		Duperow (Djl)*	Dolomite, some thin beds of limestone & calcitic dolomite in lower half; fine-to-medium crystalline; gray-brown except for a few medium- to light-gray beds; mostly in beds 1-3 feet thick; fetid; sparse dark-gray chert nodules; one or more thin lenticular intraformational breccias in lower halt; 450-625 ft. thick
Frasnian		Maywood/Souris River*	Dolomite and calcitic dolomite with some dolomitic mudstone in lower part, dark-gray to gray-brown, thin-bedded; carbonates are very fine-grained; upper beds are brownish-gray mottled with tan; Allanaria sp. Common; mudstone is gray-green and contains interbedded tan thin-bedded dolomite; basal unit is sandy; about 150 ft. thick

*Cyclic sequence: grayish-brown limestone grading into dolomitic limestone, then dolomite, then dolarenite & anhydrite interbedded with greenish-gray siltstone and shale

3.12 *CO_2 Volumetric Calculations*

The detailed characterization work and petrographic analysis were used to create a static geologic model. Well bore data including logs and a limited number of drill stem tests and other data were used to calculate in-place and recoverable volumes of CO_2 for each of the two porosity zones in the Duperow (Table 3).

Table 3: Volumetric calculations of CO2 in the two Duperow porosity zones

Upper and Lower Duperow Formation
CO2 Reserves - GIP and Recoverable Reserves
Vecta Oil and Gas (VOG)

Februaury 2011 **D. Pate**

	Upper Duperow		Lower Duperow		Comments
	Avg. Depth - 3200 fee		Avg. Depth - 3600 fee		
	High Case	Low Case	High Case	Low Case	
Rsvr Depth-avg.(feet)	3200	3200	3600	3600	***Basis:*** Dr. D. Bowen(VOG) structure maps
Net Pay (feet)	50	50	25	25	***Basis:*** Dr. D. Bowen(VOG) petrophsical analysis of OH logs (cut-off 6% porosity)
Initial Rsvr Press-avg (psia)	1167	1167	1311	1311	***Basis*** : DST's : Range of 0.33 to 0.39 psi/ft (use average of 0.36 psi/ft & avg Rsvr Depth)
Initial Rsvr Temp-avg(deg F)	88	88	94	94	***Basis*** : DST's/OH log info (use 45 F surf temp & temp grad of 0.0135 F/ft and avg Rsvr Depth)
Porosity (decimal)	0.10	0.08	0.10	0.08	***Basis*** : OH logs - density and sonic porosity
Sw(decimal)	0.20	0.20	0.20	0.20	***Basis*** : Estimate from CO2 producing analog fields: Bravo Dome/Sheep Mtn - avg 20%
CO2 (%)	92.6	82.3	92.6	82.3	***Basis*** : Gas Analysis from G-Agen #1 (92.6% CO2); P-Valley Oil #2(82.3% CO2)
z(initial)	0.41	0.53	0.38	0.5	***Basis*** : Method of add.vols., CO2 compress chrt - Amyx, Bass, Whiting(Petroleum Rsvr Engr Book)
z(abandonment)					***Basis*** : Method of add.vols., CO2 compress chrt - Amyx, Bass, Whiting(Petroleun Rsvr Engr Book)
a. 300 psia (FTP-surf)	0.84	0.86	0.86	0.87	***Basis:*** D.Pate (VOG) evaluation report(2/11/11); Analogs_Bravo Dome and Sheep Mtn Fields
b. 400 psia(FTP-surf)	0.79	0.81	0.81	0.82	***Basis:*** D.Pate (VOG) evaluation report(2/11/11); Analogs_Bravo Dome and Sheep Mtn Fields
OGIP (MCF/Ac-ft)	639.8	395.7	768.0	466.7	***Volumetric Equation (Note: 1.). Original gas-in-place: MCF per acre-feet***
OGIP (BCF-all gas)	20.5	12.7	12.3	7.5	***640 acres: Original gas in-place reserves per section***
OGIP (BCF-CO2)	19.0	10.4	11.4	6.1	
Recoverable Reserves - CO2					***640 acres: Recoverable gas reserves per section (Note: 2.)***
a. 300 psia (FTP-surf)	15.5	8.1	9.3	5.0	
b. 400 psia (FTP-surf)	14.4	7.3	8.5	4.6	

RESERVE SUMMARY	Total Gas Stream		CO2 Gas Stream	
U&L DUPEROW	High Case	Low Case	High Case	Low Case
OGIP (BCF) per section	32.8	20.1	30.3	16.6
Recover. Reserves (BCF)				
1. 300 psi (aban. press)			24.9	13.2
2. 400 psi (aban. press.)			22.9	11.9

Recoverable CO_2 resources are estimated to be 7.3-15.5 BCF/section for the upper porosity zone and 4.6 - 9.3 BCF/section for the lower porosity zone. Approximately 430 sections are under closure at the level of the upper porosity zone, and approximately 675 sections are under closure at the level of the lower porosity zone. Recoverable resource estimates are thus 3.14 - 6.67 TCF for the upper porosity zone and 3.1-6.28 TCF for the lower porosity zone. Converting the volume of gas to tons yields recoverable resource estimates of 179.5 million – 381.2 million tons for the upper porosity zone and 177.1 million – 359 million tons for the lower zone.

Equivalent potential CO_2 sequestration volumes on a per section basis in the saline aquifer based on equalized volumetric considerations alone (no consideration of CO_2 dissolution trapping) can be estimated using a conversion factor of 17.5 Mcf/ton. This yields a range of values of 417,000 tons – 885,714 tons/section for the upper porosity zone (179.31 million tons – 380.86 million tons) and 179,429 tons – 531,429 tons/section for the lower porosity zone (121.12 million tons – 358.72 million tons). This suggests sequestration potential in the upper and lower porosity zones of 300 million to 740 million tons. A much larger volume of rock is occupied by brine fluids than $CO_{2,}$ demonstrating the tremendous potential for commercial scale sequestration.

The research team also prepared estimates for other geologic domes in Montana, in particular, the Bowdoin Dome and Porcupine Dome (Figure 38). These domes do not contain naturally occurring CO_2 but offer many of the same trapping characteristics, porosity and permeability to act as potential storage sites for anthropogenic CO_2. As the following graphic indicates, Bowdoin and Porcupine domes could sequester nearly 2.9 billion tons and 1 billion tons respectively of anthropogenic CO_2. Additional characterization work is needed to verify these numbers, but these domes and Kevin Dome have the potential to sequester 70% of the total point source emissions for the next 100 years for Oregon, Washington, Idaho, Montana, Wyoming, and South Dakota.

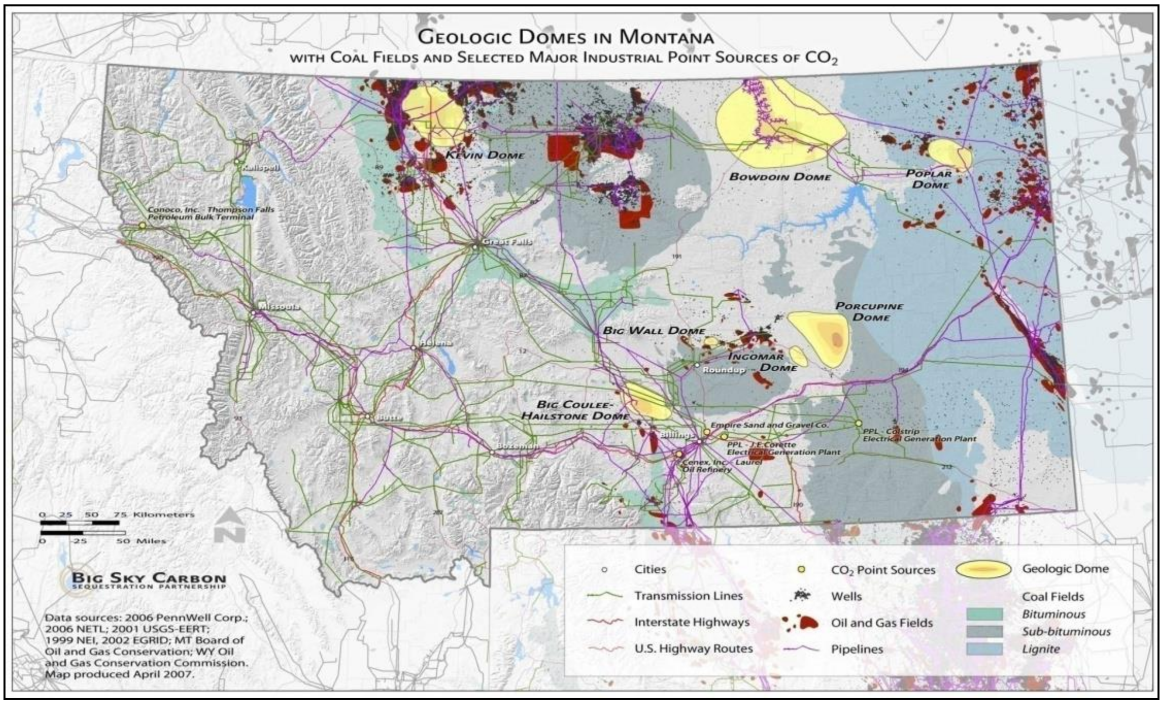

Figure 38: Generalized capacity of similar domes in Montana (Half of the current major point source emissions for the next 100 years ~7.5 GT: Resource Estimate for 3 Domes ~5.3 GT

3.13 ***Principal Requirements for Sequestration***

This study suggests that Kevin Dome and other analogous domes in Montana meet the requirements for additional characterization work to evaluate their potential as commercial sequestration sites. Since this study was initiated, Porcupine Dome and Hailstone Dome have seen substantial leasing activity to acquire rights from surface owners to the pore space underlying these domes in anticipation of future sequestration sites. As noted in previous sections, Kevin Dome and the other domes under review meet the primary requirements for sequestration as follows:

- Reservoir Depth below ~2500 feet such that CO_2 remains in a supercritical state.
- High reservoir porosity and permeability such that there is sufficient storage and injectivity addressed with porosity values for the two Duperow porosity zones shown on the well logs of the cross sections
- Large reservoir compartment size to minimize the number of injection wells needed, maximize injection well life, and avoid geopressuring of the reservoir.
- Geochemical compatibility of the reservoir and caprock with CO_2 (demonstrated by long term seal efficacy over geologic time trapping CO_2 in these reservoirs).

- Adequate seals, preferably multiple seals (see many earlier comments regarding seals and caprocks).
- Lack of leakage pathways to shallower aquifers or the surface, such as fault zones, fractures, and old well bores (demonstrated by trapping over geologic time at Kevin Dome).
- Sufficiently poor water quality in the targeted reservoir (>10,000 ppm TDS) (Figure 39 and Figure 40).
- Cultural acceptance, legislative compliance (yet to be determined).

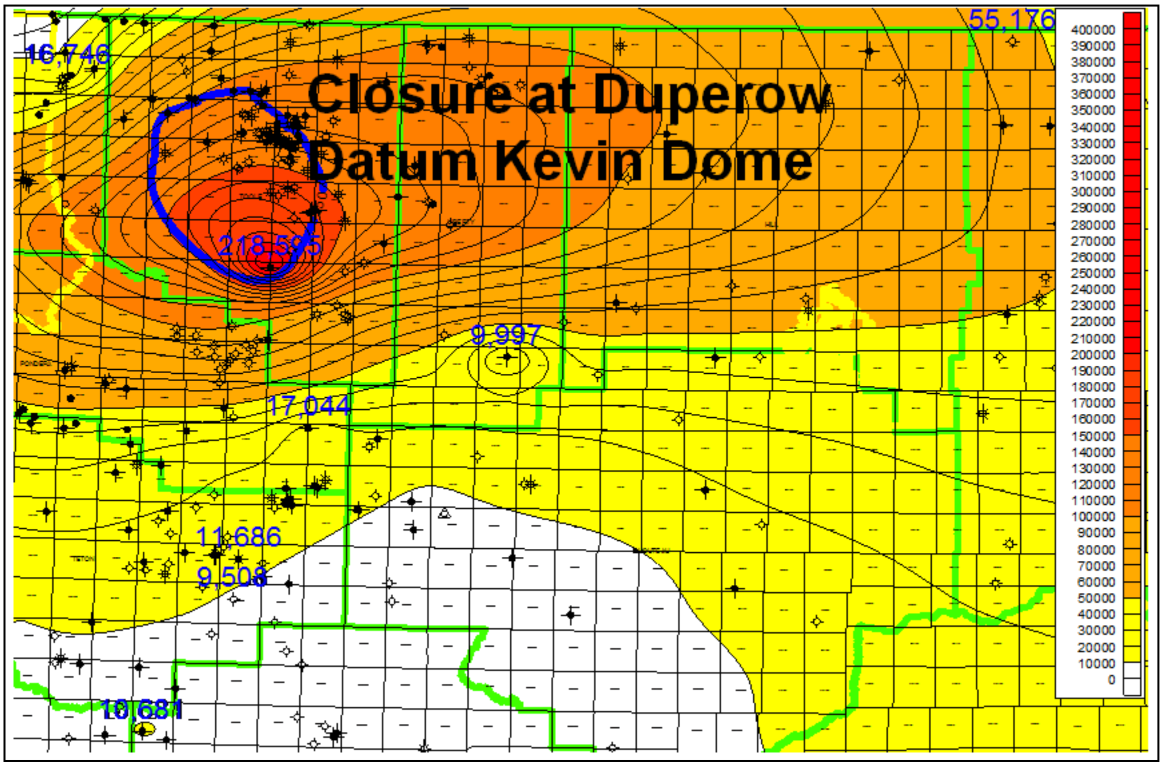

Figure 39: Map of total dissolved solids in brine water tested from the Duperow Formation. Water is of sufficiently poor quality to not be a limiting factor for sequestration.

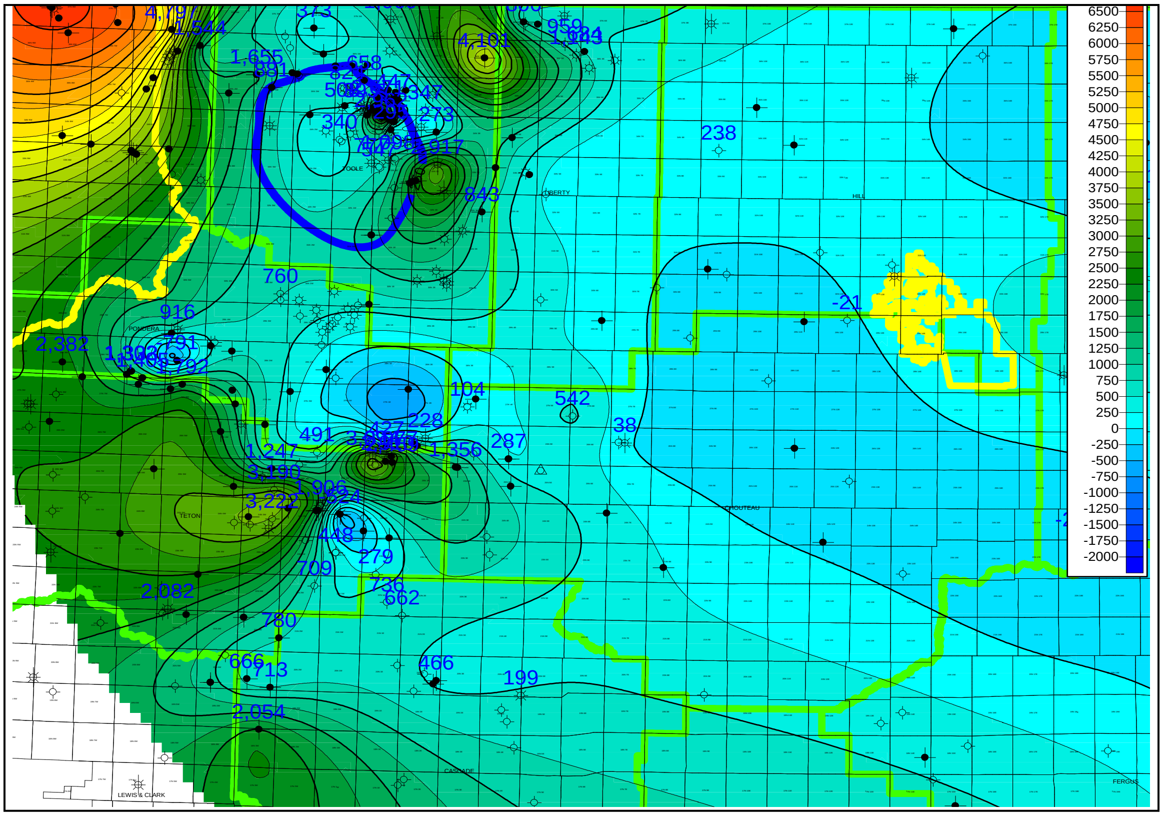

Figure 40: Potentiometric surface map in the vicinity of Kevin Dome (closure shown by blue line). Water flow vectors are toward the dome, a favorable relationship for sequestration on the flanks of the dome.

Large volumes of CO_2 are trapped at Kevin Dome and could be a significant resource for EOR projects in the state. Attributes of the Devonian hydrodynamic systems deem it to be highly favorable for future sequestration activities.

4. Results – Commercialization Plan

Based on the previous analysis, there appears to be commercialization opportunities for utilizing CO_2 sequestration for EOR and for meeting the requirements for clean coal with reduced CO_2 emissions. Both activities would be centered in Montana and provide excellent income opportunities for Montana and private landowners who also own the mineral estate. The captured CO_2 can be used for EOR and the geologic traps for long term geological storage to meet any future carbon mitigation policies. The information below supports the commercialization basis and the business concepts of economic feasibility and viability of study.

The study results suggest a process to adequately characterize and utilize Montana's geology to (1) commercially produce CO_2 for enhanced oil recovery, (2) commercially store CO_2 for future enhanced oil recovery, (3) encourage the use of CO_2 as a tertiary oil recovery methodology to improve oil and gas production and spur the economic activity and state tax revenue growth that will accompany such an exploitation of these resources, and (4) provide a commercial site to permanently sequester CO_2 to minimize potential environmental impacts of releasing CO_2 into the atmosphere.

4.1 *CO_2 Production for use in Enhanced Oil Recovery (EOR)*

This research reflects a response to an existing market demand for CO_2 in EOR and a future market for areas to permanently sequester CO_2. Wennekers (1985) estimated demand for CO_2 in oil fields lying within the Sweetgrass Arch as significant. "Out of the 38 possible candidates, 25 fields were initially selected to have susceptibility for [CO_2] recovery. These 25 fields contain a total of about 900 million barrels (bbl) of oil-in-place. An estimated 300 million bbl might be recoverable with [CO_2] recovery." To date, insufficient information exists to warrant the investment necessary to produce the CO_2, transport the CO_2 to an existing field, and begin the process of conducting EOR. With proper characterization of the resource potential and with information concerning the economic feasibility of the commercialization of the resource, the amount of uncertainty will be reduced and the prospect for development is subsequently enhanced. Wennekers (ibid) states: "Two very important factors affecting the economic success for a miscible CO_2 flood recovery project are the source and cost of the carbon dioxide. Large volumes of natural CO_2 in close proximity to oil fields susceptible to miscible CO_2 recovery almost insure economic success."

The most comprehensive review of the status of EOR projects around the world is the biennial EOR survey published by the *Oil and Gas Journal*, the most recent issue of which was published in April 2010. This study reports that the number of CO_2 EOR projects and the level of production are increasing in the Permian Basin, as well as other regions of the United States, particularly in the Gulf Coast and the Rockies (Figure 41). Notably, this growth was sustained in spite of two oil price crashes. In fact, low oil prices did not deter this underlying historical growth in the CO_2 EOR industry but only curtailed its acceleration.

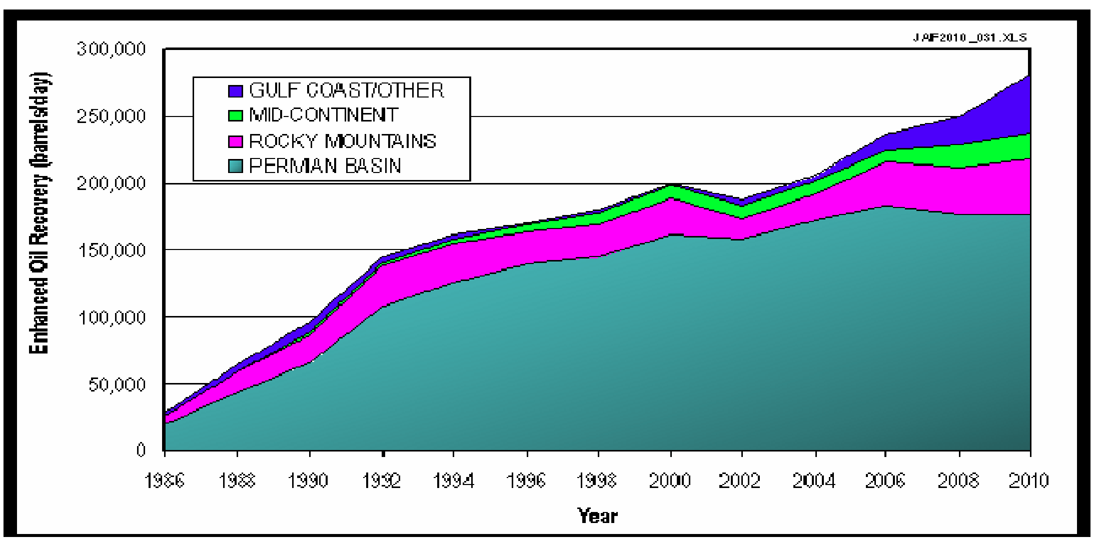

Figure 41: Incremental Oil production from EOR for the U.S.

Natural CO_2 fields are the dominant source of CO_2 for the U.S. CO_2 EOR market, providing CO_2 supplies amounting to 45 million metric tons per year (2.35 billion cubic feet per day (Bcfd), Table 4). However, anthropogenic sources account for steadily increasing volumes of this CO_2

supply, currently providing 10 million metric tons per year (529 million cubic feet per day (MMcfd)) of CO_2 for EOR.

Table 4: Sources of CO_2 for EOR in North America

State/Province (Storage Location)	Source Type (Location)	CO_2 Supply (MM Metric Tons/year)			CO_2 Supply (MMcfd)		
		Natural	Anthropogenic	Total	Natural	Anthropogenic	Total
Texas-Utah-New Mexico-Oklahoma	Geologic (Colorado-New Mexico) Gas Processing (Texas)	32	2	34	1,670	104	1,774
Colorado-Wyoming	Gas Processing (Wyoming)		4		-	230	230
Mississippi-Louisiana	Geologic (Mississippi)	13		13	683	-	683
Michigan	Ammonia Plant (Michigan)		0	0	-	15	15
Oklahoma	Fertilizer Plants (Oklahoma)		1	1	-	30	30
Saskatchewan	Coal Gasification (North Dakota)		3	3	-	150	150
Total		**45**	**10**	**56**	**2,353**	**529**	**2,882**

Source: Advanced Resources International, 2010; numbers do not add exactly due to rounding.
MMcfd of CO_2 can be converted to million metric tons per year by first multiplying by 365 (days per year) and then dividing by 18.9 Mcf per metric ton.

The largest single source of anthropogenic CO_2 used for EOR is the capture of four million metric tons per year (230 MMcfd) of CO_2 from the Shute Creek gas processing plant at the La Barge field in western Wyoming. This is followed by the capture of about three million metric tons per year (150 MMcfd) of CO_2 from the Northern Great Plains Gasification plant in Beulah, North Dakota and its transport, via a 320 kilometer (km) (200 mile) cross-border CO_2 pipeline, to two EOR projects (Weyburn and Midale) in Saskatchewan.

The steady growth of CO_2 flooding in the Permian Basin, as well as in other areas, offers a case history for possible extrapolation to other regions. A review of the history of CO_2 EOR shows that it is generally successful in fields that meet the technical criteria for achieving miscibility (defined primarily in terms of reservoir depth and oil viscosity), that have a relatively large volume of unrecovered oil after primary and secondary recovery (water flooding), and where there is a good source of sufficient, predictable, sustainable volumes of high purity CO_2 supplies at affordable costs. Over time, other factors that contribute to success are operator knowledge, comfort and willingness to use CO_2 EOR technologies, the willingness and ability of the applicable regulatory regime to permit CO_2 EOR projects, and the availability of government financial incentives to promote CO_2 EOR.

In the past, CO_2 EOR project "failures" have generally resulted from either collapses in oil prices, as occurred in 1986 and 1998, or the unwillingness of companies to "see the projects through." CO_2 EOR requires large up-front investments and is relatively slow in yielding financial returns on those investments. As a result, internal rates of return are traditionally not robust. The advantage of CO_2 EOR is that it has lower risks than exploration projects, that it can be deployed faster if the infrastructure is in place, and that large reserves associated with its application can be booked. Most oil companies are exploration-oriented and can be misled by the “unrisked” rates of return present in exploration projects. Historically, some companies have set unreasonable expectations on CO_2 EOR projects and when these projects, in their view, underperformed, management made the decision to cut losses and abandon CO_2 injection. As a result, in some cases, the “potential” for CO_2 EOR was not realized in practice by those companies, whereas companies that acquired those fields managed to secure profitable operation in the long run.

A recent report released by Advanced Resources International (Kuuskraa, 2008) projects that nearly 2.5 billion barrels of oil could be produced from the Williston Basin of Montana and North Dakota using EOR techniques. The amount of CO_2 required to produce that amount of oil is equivalent to 130 million metric tonnes or roughly nine years of CO_2 emissions from Colstrip. The net value of the CO_2 to the Colstrip plant if sold to an EOR operation at $25/tonne is estimated to be $3.2 billion. Using an oil price of $70 per barrel (Base Case), assuming a delivered CO_2 cost of $25 per metric ton, and subtracting $10 per metric ton for transportation and handling, the revenue potential offered by the CO_2 EOR market [within the United States] could reach $150 billion. In addition, the sale of captured CO_2 emissions to the CO_2 EOR industry would enable power companies to avoid the costs and challenges of storing CO_2. The result is that by 2020, over 40,000 jobs could be created from CO_2 EOR, rising to approximately 350,000 by 2030 (NRDC online data).

ARI data indicates that the use of next generation EOR requires approximately 0.22 tons of CO_2 for each barrel of incremental oil produced. Kevin Dome recoverable CO_2 volumes calculated earlier indicate that the CO_2 present on Kevin Dome could produce incremental oil of nearly 1.6 billion barrels to 3.36 billion barrels in adjacent fields in Canada and the Williston Basin.

Like most products, the price of CO_2 is dependent upon the market demand. CO_2 EOR has not been contemplated in Montana primarily because the lack of availability made CO_2 too expensive to be considered for EOR. Currently, CO_2 would have to be transported by rail (at a cost exceeding $120/T) or by pipelines that do not exist because of the expense and permitting issues associated with acquiring pipeline right-of-ways. Access to CO_2 for EOR will ultimately determine the price as will production costs, infrastructure and the predicted benefits in terms of increased oil production. Alternatively, our proposal seeks to make a significant return on investment to the state of Montana by virtue of increased oil production. Using Wennekers’ estimates, the production of an additional 300 million barrels of oil would be equivalent to 10 years of the total state production for 2007. That is equivalent to a $3 billion increase in state tax revenues over the period of production of this resource.

Preliminary cost estimates derived from a comprehensive analysis of production and transportation costs for Kevin Dome indicate that the CO_2 can be commercially produced for $12-15 per ton. The marginal cost of future production would decrease significantly as the infrastructure build out is completed, and as economies of scale for compression and transportation reduce costs. These costs are less than the cost of CO_2 being produced at Shute Creek, Madden, and Dakota Gasification and represent a substantial commercialization opportunity for Montana.

4.2 *Commercialization of Carbon Sequestration*

Over the last several years the U.S. Energy Information Administration (EIA) has conducted a number of carbon management studies (USDOE 2006, 2007a, and 2007b). These studies have found that, in general, carbon capture and sequestration (CCS) is not considered, as of yet, a key part of the solution. The reason, according to EIA's cost model, is that using CCS with coal- or gas-fired power is not economically competitive with other options for generating power with low CO_2 emissions, as shown on **Error! Reference source not found.**.

As set forth in EIA's cost model, incorporation of CCS with new advanced coal-fueled power plant currently adds over $20 per MWh of costs, making this a higher cost option than advanced nuclear power and subsidized wind- or biomass-based electricity generation. Even by 2020, assuming modest technology progress for advanced coal and CCS, adding CCS to a coal-fueled power plant would increase electricity generation and transmission costs by nearly $19 per MWh, keeping this a high cost option.

Figure 42 shows that, according to EIA's Reference Case for 2020, advanced coal with CCS would entail costs of $81 per MWh of electricity compared to $60 per MWh for pulverized coal without CCS and $66 per MWh for advanced nuclear.

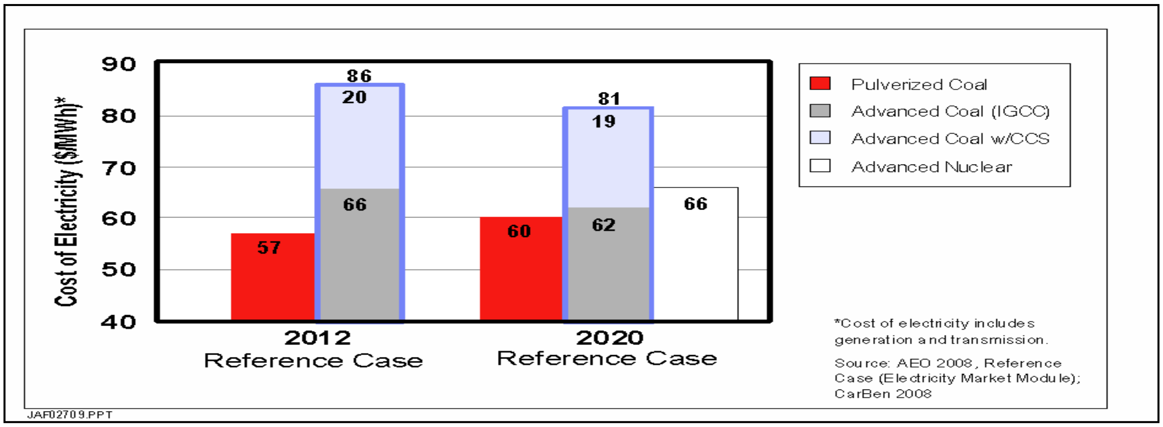

Figure 42: Advanced coal plants with CCS are currently uncompetitive in 2012 and 2020 (EIA's AEO 2008 Reference Case)

However, revenues from selling captured CO_2 emissions into the CO_2 EOR market can change the competitive outlook. For example, as shown in Table 5, the sale of captured CO_2 emissions at $25 to $35 per metric ton can reduce the costs of power generation with CCS by $17 to $24 per MWh, significantly offsetting the costs of installing CCS with new coal-fueled power plants. As the cost of oil continues to rise, the market price of CO_2 increases on an indexed basis and prices of CO_2 of $25 to $35 per ton are certainly within reason.

Table 5: Relationship of CO_2 sales price to cost offsets in the coal-fueled power sector (Year 2020) (Kuuskraa, 2008)

Sale of CO2	**Sale of CO2**
@ $25/mt CO2	@ $35/mt CO2
7,920 btu/kWh x	7,920 btu/kWh x
94 MMmt CO2/QBtu x	94 MMmt CO2/QBtu x
90% Capture	90% Capture
Cost Offset: $16.80/MWh	Cost Offset: $23.50/MWh

A second and perhaps larger market may also exist. The Kyoto Protocol and newer proposed treaties currently under negotiation at the international level will require a reduction in net CO_2 emissions to offset environmental impacts of global warming. Most of the emission reductions will occur as a result of CCS, primarily from large stationary sources, or through the increased use of renewable energy sources or nuclear energy. Over the next 50 years, fossil fuels will continue to provide the bulk of the nation's energy needs and the principal source of these fuels will be coal. Montana's vast coal reserves will offer a unique opportunity for the State to use its coal to produce clean energy through CCS. If Montana were to begin to reduce its emissions (< 50%) through CCS for existing sources, the need exists for sequestration sites capable of storing approximately 20 MMT of CO_2/yr. As clean coal technologies continue to be deployed, the amount of sequestration required will rise exponentially. Knowledge concerning the availability of sequestration sites for permanent storage or for temporary storage for EOR purposes will further the development of clean coal technologies and produce economic activity associated with this process.

Internationally, large scale demonstrations of geologic storage have been conducted at several locations including Sleipner in Norway, Salah in Algeria, the Weyburn Project in Saskatchewan, and the Gorgon Project in Australia. Within the U.S., a large (> 1,000,000 tonnes/year) project is ongoing in Louisiana and six additional large scale projects are slated to begin within the next two years. Numerous pilot projects have been completed in deep saline aquifers, shales, and deep unmineable lignite and bituminous coal seams. A pilot scale injection in mafic rocks (lava flows) is planned for 2012. The Global CCS Institute (2010) lists the following projects worldwide:

- 80 large-scale integrated projects at various stages of the asset lifecycle, an increase of 13 projects since 2009
- 9 operating large-scale projects and two projects under construction
- 69 potential projects in various stages of development planning
- 21 projects performing feasibility studies and preliminary engineering design (most mature)
- 24 projects conducting pre-feasibility studies and initial cost estimates (moderately mature)
- 24 projects undertaking scoping studies (least mature)
- Additionally there is over $26 billion world-wide in proposed government support for large-scale CCS projects

4.3 *Commercialization Economic Impacts*

Full chain CCS projects[1] within the U.S. are currently limited by commercial scale deployment of capture technology. Most projects currently remove a slip stream from the power plant flue gas (~ equivalent to 15-25MW of generation output) and then transport and sequester the CO_2. Due to the lack of captured CO_2, many of the large scale projects are currently using CO_2 produced from naturally occurring reservoirs in Texas and Louisiana or from natural gas stripping facilities. The Big Sky Carbon Sequestration Partnership is proposing a project that includes producing one million tonnes of naturally occurring CO_2 from Kevin Dome and sequestering the gas deep underground at a site in north central Montana. Funding recently released under DOE's Regional Carbon Sequestration Partnership Program, the Clean Coal Power Initiative, and the American Recovery and Reinvestment Act will result in the deployment of capture facilities within the next several years that can capture, transport, and sequester one million tonnes of CO_2 from existing ethanol and coal fired generation plants and the new FutureGen plant to be constructed in Illinois.

Most experts agree that commercial scale deployment of all available technologies for capture and storage will be available by 2020.

Retrofitting the existing fleet of coal fired power plants, ethanol plants, refineries, and other industrial sources of GHG emissions would be a daunting exercise. In many cases, it may make more economic sense to retire older coal fired power plants and replace that generation capacity with new generation coal facilities, natural gas fired facilities, or renewable energy such as wind or solar. In any case, the construction of capture facilities for existing plants would have a sizeable, albeit currently unquantified, impact on manufacturing and construction jobs.

Maintenance and operation of the plants will require skilled workers and there will be the indirect production of employment to supply the solvents, sorbents, and other expendable resources associated with the facility.

Construction of new generation coal facilities to replace existing facilities would require installation of 2,500 MW of generating capacity. If all this capacity were coal fired and included CCS, a variety of economic and job impacts can be estimated and are provided in the following sections.

Coal would continue to be used to supply the new supercritical pulverized coal plants or integrated gasification combined cycle (IGCC) plants. Montana coal mines produce approximately 42 million tons of coal per year with approximately 10 million tons of the coal used for generation at the State's seven coal fired generation facilities. Plants fitted with CCS are predicted to incur an energy penalty of 30% or "parasitic load" that is additional power required to power the CCS facility. Consequently, an additional 750 MW of power generation capacity would be needed to meet existing base load and that would require an additional three million tons of coal to meet the requirement. Montana coal mining operations currently employ 950 miners. Therefore, the additional coal production would increase mining employment by 71 workers.

---

[1] Full chain CCS projects are those projects that include capture, transportation and sequestration. An example would be a capture facility placed on a coal fired power plant that captures, compresses, and transports the CO_2 to an injection site for storage and long term monitoring, verification and accounting.

The use of CCS on existing or new power plants will increase the demand for water, because cooling requirements increase with the implementation of this technology. Although water use for CCS is not as high per kilowatt hour as solar or biofuels, water demand is a concern. The state of Wyoming is currently pursuing a project to investigate use of saline aquifer waters displaced as a result of CO_2 injection to be used for plant cooling or treatment of these waters for irrigation and other purposes.

Nationally, CCS is expected to create an additional 6,000 manufacturing jobs for manufacturing components of the capture facility and pipelines (Clean Air Task Force, 2010). These jobs will be located in heavy industrial areas such as Pennsylvania and the Upper Midwest. Very few of these jobs are expected to be located in Montana.

Using a national scenario to replace 65 GW (6,500 MW) of generation capacity, British Broadcasting Corporation (BBC) Research and Consulting (Jeavons, 2009) reports that three advanced coal CCS facilities could be constructed by 2025 in Montana based on the geographic distributions from prior U.S. Environmental Protection Agency (EPA) studies. For this analysis, researchers assume that these plants would replace the existing fleet in Montana and that a range of values for use of the CO_2 for EOR is reasonable and possible, particularly for early adopters of CCS technology.

Retrofitting existing plants to allow for CCS is not examined in this report as data does not currently exist, beyond jobs created throughout the energy sector by transitioning to clean energy. Additionally, due to the lack of a national policy on limiting greenhouse gases (GHG's), the range of capture (20% - 90%) greatly influences the cost of construction of the capture facility, the maintenance and operations of the plant, and the parasitic load imposed on the plant. Plants that capture 40% of produced CO_2 (emissions equivalent to a conventional natural gas fired facility) or 60% of produced CO_2 (emissions equivalent to a new generation natural gas combined cycle plant) can remain competitive with natural gas if natural gas prices remain in the $4 to $6 per MMbtu range, given existing capital construction costs.

Estimated construction costs of building the three new advanced coal facilities are approximately $6.3 billion. The construction is anticipated to support a cumulative total of 83,000 job-years in various sectors through 2025 (Table 6). The construction and operation of facilities in other parts of the country may lead to additional economic benefits in Montana. Except for coal mining effects, these secondary effects are not captured in the estimated state-level economic benefits (Jeavons, 2009).

Table 6: Economic benefits to Montana of building three new advanced coal plants

Economic Benefits from Construction (one-time)		
Economic Measure	**Direct Benefit**	**Total Benefit**
Output	$6.3 Billion	$11.3 Billion
Value-added	$2.6 Billion	$5.2 Billion
Employment	43,129 Job-years	82,961 Job-years
Labor Income	$2.3 Billion	$3.9 Billion

Using the same scenario described above for deployment of three new supercritical coal plants with CCS in Montana, the annual maintenance and operations costs are expected to be $486 million (including coal mining), which represents nearly 3,400 jobs (Table 7). Again, the figures below do not include the potential for jobs created through the oil and gas industry's use of the CO_2 for EOR. In Texas, where EOR now accounts for 20% of its oil production, it is estimated the benefits of EOR production will result in additional revenue of $200 billion and will create 1.5 million jobs (SBI Energy online data).

Table 7: Economic benefits to Montana of operations and maintenance of new plants

Economic Benefits from Operations & Maintenance (annual)		
Economic Measure	**Direct Benefit**	**Total Benefit**
Output	$0.5 Billion	$0.8 Billion
Value-added	$0.3 Billion	$0.4 Billion
Employment	1,019 Jobs	3,364 Jobs
Labor Income	$0.1 Billion	$0.2 Billion

CCS is an emerging technology and as such will require training in a number of the hard sciences including but not limited to (1) chemical, mechanical, environmental, industrial, systems, reservoir, and electrical engineering, and (2) geology, geochemistry, geophysics, hydrogeology, and reservoir geology. Other disciplines that address permitting, regulatory compliance, public involvement, business planning, economics, public and private finance, plant and sequestration site operations, and geospatial representations will also be required. The U.S. DOE recently awarded $7 million in grants to begin the process of training current and future instructional staff to allow integration of these skills into existing curricula and skilled training programs.

CCS that involves storage in other geologic media including basalts and unmineable coal seams will require specialized expertise. Due to the rapid mineralization of CO_2 in basalts and coal swelling associated with adsorption of the CO_2 to coal cleats, other technological expertise will be required. Increased monitoring of underground sources of drinking water (USDW) and saline fluids that can be displaced into USDW will require a skilled work force to continually monitor USDW and ground water sources for potential contamination. Because proposed federal regulations governing CCS will require monitoring of the geologic sites for 50 years or more after injection ceases, the workforce requirements will exceed one generation of workers.

Early deployment of CCS will likely result in a substantial increase in the use of CO_2 for EOR and ECBM. This will require expansion of the existing workforce as demand for skilled workers in engineering and geology disciplines grows; a similar expansion would occur in the construction trades for skilled workers to construct and operate recycling plants, pipelines, and other ancillary operations.

Because EOR and ECBM produce additional fossil fuels resulting in the emissions of additional amounts of CO_2, the EPA is considering additional monitoring and reporting requirements to insure that more CO_2 is sequestered than produced. This will require a skilled workforce to adequately monitor injection, production, and emissions, involving voluntary or involuntary markets in addition to a linked increase in demand for finance and accounting jobs.

If CCS proves cost effective for providing base load power with much reduced emissions, there will likely be an increase in coal mining in order to provide coal for expanding markets in the third world and rapidly industrializing nations such as India and China. This would involve a significant increase in coal mining jobs and educational requirements to support training of that workforce.

Designing, manufacturing, and building the components for CCS capture facilities are emerging technologies. Once plants reach commercial scale, there will be a need for specialized education and experience to build the plants, because each facility must be tailored to the unique needs of the plant and the installation location, particularly for retrofitted plants. Newer generation facilities including supercritical plants, IGCC, oxycombustion, or circulating fluidized bed plants will require some adaptation of the capture facility to accommodate the capacity, efficiency, altitude, and potential for disposal or use of the CO_2.

Geologic storage will require specialized education and experience to properly characterize the site; develop the permitting plan; develop the outreach and education plan; and develop the monitoring, verification, and accounting (MVA) plan. Once planning is complete, actual monitoring of the CO_2 will require expertise for modeling and imaging the plume, conducting geochemical and geo-mechanical tests of the target layers and confining layers, leakage detection, and ongoing protection of USDW.

A recent study commissioned by the Interstate Natural Gas Association of America (INGAA) Foundation focused on the pipeline infrastructure requirements for CCS in connection with compliance with mandatory GHG emissions reductions. The major conclusion of the study was that, while CCS technologies are relatively well defined, there remain technological challenges in the capture and storage components of the technology. There are fewer technological challenges in connection with the transportation of captured carbon.

The study forecasts that the amount of pipeline needed to transport CO_2 will be between 15,000 miles and 66,000 miles by 2030, depending on how much CO_2 must be sequestered and the degree to which EOR is involved. The upper end of the forecast range is of the same order of magnitude as the miles of existing U.S. crude oil pipelines and products pipelines (Pipeline and Gas Technology online data).

There are currently 3,600 miles of CO_2 pipelines in the U.S. As with all activities related to siting of pipelines, CO_2 pipelines can encounter difficulties for a variety of reasons. Siting of new CO_2 pipelines is not regulated by any Federal agency. Both the Federal Energy Regulatory Commission (FERC) and the Surface Transportation Board (STB) have declined jurisdiction over CO_2 pipelines. Siting is currently left to the individual states. Rates charged by CO_2 pipelines are not regulated by any federal agency, except that the STB will hear complaints about rates. There is no federal eminent domain for CO_2 pipelines, but recent attempts to grant eminent domain for CO_2 pipelines (provided the CO_2 is produced from fuel combustion or gasification) in Montana have prevailed (HB338-2009).

If a pipeline crosses federal land, the responsible parties will need to acquire permits from federal agencies and comply with NEPA requirements. Bureau of Land Management (BLM) can regulate CO_2 pipelines under the Mineral Leasing Act (MLA) as a commodity shipped by a common carrier. EOR pipelines are regulated under MLA, or BLM can regulate under Federal Land Policy Management Act (FLPMA).

Currently, numerous researchers as well as companies involved in CCS are developing technologies and best practices to ensure that CCS is safe, effective, and minimizes environmental impacts. Numerous state and federal regulations will govern the permitting, operations, monitoring, and closure of CCS projects. For projects that involve obtaining federal permits, the environmental review guidelines under National Environmental Policy Act (NEPA) must be followed. This review process will result in either a categorical exclusion, an environmental assessment, or an environmental impact study. In Montana, depending on project location and ownership of surface and mineral rights, CCS activities and the permitting thereof will also be governed by several land management agencies. Table 8 shows an example of the environmental considerations and regulatory requirements that must be addressed for the proposed project at Kevin Dome by the Big Sky Carbon Sequestration Partnership.

Because the current site selected for the proposed injection does not include any lands or minerals administered by BLM, the responsible land management agency for this project will be the Montana Department of Natural Resources Conservation (DNRC). The DNRC administers the surface and mineral estates of state trust lands. The Montana Department of Environmental Quality, the Montana Board of Oil and Gas (MBOG), and the EPA all have statutory and regulatory authority governing other components of the proposed project. The MBOG within the DNRC will oversee drilling of oil and gas wells and injection wells. The production wells and monitoring wells will be permitted by MBOG and the injection well will be permitted by EPA. The necessary permits, respective agencies, and estimated time necessary for approval are identified in the table below.

Table 8: Regulatory Requirements

Permitting Activity	Responsible Agency	Time Requirements (in days)
Drilling		
File Application for Permit to Drill (APD)	Montana Board of Oil and Gas (MBOG), Montana Department of Natural Resource Conservation (DNRC), Montana Department of Environmental Quality (DEQ) and the Environmental Protection Agency (EPA)	120
Drilling Plan	MBOG, DNRC, DEQ, EPA	180
Surface Use Plan of Operations (SUPO)	MBOG, DNRC	180
Pipeline Permitting		
	MBOG, DEQ, Office of Pipeline Safety (OPS), DNRC. ROWs to be obtained from individual landowners	180
On Site Visit		30
Cultural Survey	State Historic Preservation Office (SHPO)	120-240
Threatened and Endangered Species Survey	U.S. Fish & Wildlife Service (USFWS) or MT Dept. of Fish, Wildlife and Parks (FWP)	120 -240
UIC Application		
Class VI Injection Well	DEQ, EPA, MBOG	180-365
Monitoring Wells	MBOG	120
Water Rights	DEQ	5 days – investigation only as the need for a water right is not expected
Temporary Use Permit	DNRC	60
NEPA and MEPA – Categorical Exclusion (CX) or Environmental Assessment (EA)	DEQ, EPA, MBOG, DNRC	365
Record of Decision (ROD)	EPA, MBOG, DEQ, DNRC	180-365
Stipulations	DNRC, FWP, MBOG, SHPO, Surface Owner	90

5. Conclusions

The principal political constraint to deployment of CCS is the lack of legislative action that places a price on carbon. The price signal can be deployed as a “cap” on total emissions or as a tax to emit carbon. The EPA has proposed to begin to restrict emissions under the Clean Air Act (CAA) as a result of the Supreme Court’s decision in *Massachusetts v. EPA* that concedes that CO_2 and other GHGs can be considered a pollutant under CAA. It is likely that attempts by EPA to limit emissions will remain in litigation for many years or that the Congress will intervene by amending the CAA, such that CO_2 would be precluded from regulation until Congress adopts supporting legislation.

There is significant opposition from electric power generation groups and other stationary sources of CO_2 emissions to any regulation that would increase power costs. Similarly, the U.S. Chamber of Commerce and representatives of the mining industry and agricultural groups also oppose limits placed on GHGs, citing concerns that these initiatives will slow job creation by sending jobs overseas to countries without limits on GHG emissions.

The challenge of mitigating the contributing factors to global warming while maintaining energy supplies has become a major international issue. While conservation, energy efficiency, and alternatives to carbon intensive energy fuels are a critical part of this mitigation, energy demand nationally and globally requires the use of fossil fuels and biofuels for many decades to come. Montana, with its vast energy resources and potentially favorable sequestration opportunities, can lead the country in clean-energy development. Focused applied research is the first step along this path. This research will move Montana forward in developing commercial scale sequestration opportunities.

Also, Montana’s agricultural economy may become a major supplier for biofuels development and associated ethanol plants. These operations are large CO_2 emitters and will benefit from this research by understanding and identifying potential sequestration sites necessary to expand this industry as a clean energy provider.

Montana has a long history of oil production that has significantly contributed to Montana’s tax revenues for many years. A significant number of these fields are in late stages of decline and would greatly benefit from CO_2 EOR operations. The oil fields in the region of Kevin Dome fall in this category and a local CO_2 supply could facilitate increased production and profitability from these fields, would sequestration of CO_2 in voided pore space from oil production, and increased tax revenues to the state of Montana.

Without non-market-based incentives, CO_2 sequestration in many geologic sinks is not generally economically viable under current market systems. However, EOR miscible flooding is a proven, economically viable technology for CO_2 sequestration that can provide a bridge to conducting non-EOR-based geologic sequestration. For example, a portion of the revenue generated by CO_2 EOR activities can pay for the infrastructure necessary for future geologic sequestration in brine formations. It is expected that unitized oil fields subjected to this type of recovery process should retain all of the injected gas (including the amount recycled during production) as a long-term storage solution. The process of CO_2 injection with respect to EOR has been engineered to reduce the amount of CO_2 needed for injection while maximizing incremental oil production. One approach to implementing geologic sequestration is to use the 30 years of experience injecting CO_2 into reservoirs in an effort to maximize CO_2 sequestration, with incremental recovery becoming a benefit rather than an objective.

As production matures, the fields that were not unitized, have not undergone EOR, and will be considered depleted and abandoned will become prime candidates for CO_2 sequestration. Sequestration can be accomplished in these fields by initiating EOR with CO_2 miscible flooding or by simply considering the reservoir for storage and filling it to capacity.

Oil production in Montana is currently one fourth of the total production in 1968, due to depletion of existing fields and only a modest production increase from new wells (Table 9). Total production for Montana for 2007 is estimated at approximately 31 MMBO. Using the figures from above and assuming that all existing fields in Montana have characteristics favorable to CO_2 EOR and sequestration, a conservative estimate of 4.7 MMBO/yr of oil could be produced from existing sources while sequestering 37,000,000 Mcf of CO_2. Current estimates indicate that there may be in excess of 37 billion barrels of recoverable oil in the United States utilizing CO_2 EOR with the potential to sequester approximately 5.7 Giga Tons of CO_2 (Tinker 2006).

Table 9: Estimated CO2 capacity of selected Montana reservoirs

Field Name	**Producing Pool**			**Est.** CO_2 **Capacity MMT**	**Est.** CO_2 **Sequestration Capacity, Bcf**
	Group	**Formation**	**Subformation**		
Pine	Interlake	Nonspecific		184	2998
Kevin- Sunburst		Nisku/Madison/ Sawtooth	Nonspecific	114	1856
Little Beaver East	Big Horn	Red River	Nonspecific	104	1700
Pine	Big Horn	Red River	Nonspecific	99	1608
Bell Creek		Cretaceous Muddy	Nonspecific	93	1511
Cabin Creek		Interlake	Nonspecific	75	1217
Poplar East	Madison	Madison	A, B, and C	72	1167
Little Beaver	Big Horn	Red River	Nonspecific	71	1154
Cabin Creek		Interlake	Horst Block	66	1074
Sioux Pass North		Mission Canyon, Nisku	Nonspecific	53	871
Poplar, East	Madison	Charles	B	52	850
Cabin Creek	Big Horn	Red River	Nonspecific	49	802
Dwyer	Big Horn	Red River	Nonspecific	46	742
Pennel	Interlake	Nonspecific		39	635
Cabin Creek	Madison	Madison	Mission Canyon	39	632
Cabin Creek		Interlake	East Block	38	620
Cabin Creek		Red River–Interlake	Nonspecific	37	606
Cabin Creek	Madison	Madison	Horst Block	36	588
Monarch		Interlake, Red River	Nonspecific	34	561
Pennel	Big Horn	Red River	Nonspecific	33	540
Total Potential Storage in Selected Pools				**1333**	**21,734**

Adair and Rickard (2006) estimated the total value of tax revenue for current oil and gas production in Montana to be $297 million. A 15% increase in production would provide a net gain in tax revenue of $45 million. The value of the CO_2 using a range of prices currently paid in Wyoming of $0.25 to $0.50 per Mcf would be $9 – 19 million. Although the research team has not computed the potential economic impact of job creation or the increased equipment, property, and pipelines that would accompany such an effort as that described above, the potential is significant.

Finally, Montana's current stationary source CO_2 emissions exceeds 40 million metric tons (EPA 2004). Montana remains a net exporter of energy and Montana's vast coal reserves will likely be developed along with other sources to meet a growing national energy demand that is expected to increase approximately 30% by 2030. Sequestration of CO_2 can support efforts to meet this energy demand while reducing emissions. This study demonstrates the potential for increasing energy production and economic activity while deploying new technology for the permanent and safe storage of CO_2.

6. References

Adair, A., and S. Rickard. 2006. Economic & Fiscal Impacts of Montana's Petroleum and Natural Gas Industry. Montana State University, Billings.

Bachu, S. and J.J. Adams, 2003, Sequestration of CO_2 in geological media in response to climate change: capacity of deep saline aquifers to sequester CO_2 in solution, Energy Conversion and Management, v. 44, p. 3151-3175.

Baines, S. J., and R.H. Worden, 2004, Geological storage of carbon dioxide, in Baines, S.J., and R.H. Worden (eds.), Geological Storage of Carbon Dioxide, Geological Society, London, Special Publication 233, p. 1-6.

Brock, W.R., and L.A. Bryan, 1989, Summary results of CO_2 EOR field tests, 1972-1987, SPE Paper 18977.

Burke, R. B., and R. Nelms. 2004. Is CO_2 enhanced oil recovery technology applicable for recovering additional North Dakota oil reserves. North Dakota Geological Survey Newsletter 31:10-11.

Chadwick, R.A., S. Holloway, M.S. Brook and G.A. Kirby, 2004, The case for underground CO_2 sequestration in northern Europe, in Baines, S.J., and R.H. Worden (eds.), Geological Storage of Carbon Dioxide, Geological Society, London, Special Publication 233, p. 17-28.

Clean Air Task Force, 2010. Estimating the Economic Impacts of Carbon Capture and Storage, April, 2010.

Dobbin, C.E. and C.E. Erdmann, 1955, Structure contour map of the Montana plains, USGS Oil and Gas Investigations Map, OM 178 A.

Downey, J.S., 1987, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Prof. Paper 1402-E, p. E1-E87.

EPA. 2004. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002. EPA 430-R-04-003, U.S. Environmental Protection Agency, Washington, D.C.

Gale, J., 2004, Why do we need to consider geological storage of CO_2?, in Baines, S.J., and R.H. Worden (eds.), Geological Storage of Carbon Dioxide, Geological Society, London, Special Publication 233, p. 7-15.

Garing, J.D., and Tainter, P.A., 1985, Greater Green River Basin regional seismic line, *in* Gries, R.R., and Dyer, R.C., 1985, Seismic exploration of the Rocky Mountain region: The Rocky Mountain Association of Geologists and the Denver Geophysical Society, p. 233-238.

Global CCS Institute, 2010. Global CCS Institute, Status of CCS Projects, Interim Report

Goodrich, J.H., 1980, review and analysis of past and ongoing carbon dioxide injection field tests, SPE Paper 8832.

Gunter, W.D., S. Bachu, D.H.S. Law, V. Marwaha, D.L. Drysdale, D.E. MacDonald, and T.J. McCann, 1996, Technical and economic feasibility of CO_2 disposal in aquifers within the

Alberta Sedimentary Basin, Canada, Energy Conversion and Management, v. 37, p. 1135-1142.

Holt, T., J.I. Jenson, and E. Lindeberg, 1995, Underground storage of CO_2 in aquifers and oil reservoirs, Energy Conversion and Management, v. 36, p. 535-538.

IPCC. 2005. Special Report on Carbon Capture and Storage. Intergovernmental Panel on Climate Change.

Jeavons, D., 2009. Employment and Other Economic Benefits from Advanced Coal Electric Generation With CCS, BBC Research and Consulting, Denver, CO.

Kuuskraa, V., Ferguson, R., 2008, Storing CO_2 with Enhanced Oil Recovery, DOE/NETL-402/1312/02-07-08

Lopez, David A., 1995, Geology of the Sweet Grass Hills, North-central Montana: Montana Bureau of Mines and Geology, Memoir 68, 35 p.

Lorenz, John C., 1982, Lithospheric flexure and the history of the Sweetgrass arch, northwestern Montana, *in* Powers, R.B., editor, Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, Denver, p. 77-89.

Mudge, M.R., 1982, A resume of the structural geology of the northern Disturbed belt, northwestern Montana, *in* Powers, R.B., editor, Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, Denver, p. 91-122.

Mudge, M.R., and Earhart, R.L., 1980, The Lewis thrust fault and related structures in the Disturbed belt, Northwestern Montana: U.S. Geological Survey Professional Paper 1174, 18 p.

Nordquist, J.W., and W. Leskela, 1969, Natural gas in the Sweetgrass Arch area, northwestern Montana, *in* Beebe, B.W. and B.F. Curtis, Natural Gases of North America, AAPG Memoir 9, p. 736-759.

NRDC online data, http://switchboard.nrdc.org/blogs/ljohnson/comprehensive_climate_and_ener.html

Peterson, J.A., 1987, Pre-thrusting regional stratigraphy and paleotectonics, northern Rocky Mountains and adjacent Cordilleran shelf, U.S., in W.R. Miller, ed., The thrust belt re-visited: Casper, Wyoming, Wyoming Geological Association, 38th Field Conference Guidebook, p. 17-26.

Pipeline and Gas Technology online data. http://www.pipelineandgastechnology.com/Construction/ForecastsReviews/item55699.php

Romine, T.B., 1929, Oil fields and structure of Sweetgrass Arch, Montana, AAPG Bulletin, p. 779-797.

SBI Energy online data, http://www.sbireports.com/EOR-Enhanced-Oil-2523826/

Shaw, J., and S. Bachu. 2002. Screening, evaluation, and ranking of oil reservoirs suitable for CO_2-flood EOR and carbon dioxide sequestration. Journal of Canadian Petroleum Technology 41:51-61.

Sims, P.K., O'Neill, J.M., Bankey, V., and Anderson, E., 2004, Precambrian basement geologic map of Montana – An interpretation of aeromagnetic anomalies: U.S. Geological Survey, Scientific Investigations Map 2829, 1:100,000.

Smith, S. A., B. B. Burke, L. D. Helms, D. W. Fischer, J. A. Sorensen, W. D. Peck, E. N. Steadman, and J. A. Harju. 2005. Sequestration Potential of Petroleum Reservoirs in the Williston Basin. Plains Carbon Dioxide Reduction Partnership, University of North Dakota.

Tinker, S. 2006. The Nuts and Bolts of Carbons Sequestration. (http://www.rrc.state.tx.us/commissioners/williams/energy/Tinker.ppt).

U.S. DOE 2006 Energy Market Impacts of Alternative Greenhouse Gas Intensity Reduction Goals, U.S. DOE, Energy Information Administration, March, 2006.

U.S. DOE 2007 (a) Energy Market and Economic Impacts of a Proposal to Reduce Greenhouse Gas Intensity with a Cap and Trade Systems, U.S. DOE, Energy Information Administration, January, 2007

U.S. DOE 2007 (b) Energy Market Impacts of a Clean Energy Portfolio Standard - Follow-up, U.S. DOE, Energy Information Administration, February, 2007.

Vuke, S.M. and others, 2007, Geologic Map of Montana, Montana Bureau of Mines and Geology: Geologic Map 62D.

Wennekers, J.H.N., 1985, CO_2 enhanced oil recovery in a new "new" Montana oil province: Sweetgrass arch, Oil and Gas Journal, p. 147-150.

Worden, R.H. and L.K. Smith, 2004, Geological sequestration of CO_2 in the subsurface: lessons from CO_2 injection enhanced oil recovery projects in oil fields, in Baines, S.J., and R.H. Worden (eds.), Geological Storage of Carbon Dioxide, Geological Society, London, Special Publication 233, p. 211-224.

7. Acronyms

BBC	British Broadcasting Corporation
BLM	Bureau of Land Management
BSCSP	Big Sky Carbon Sequestration Partnership
CAA	Clean Air Act
CO2	Carbon Dioxide
CTL	Coal-to-Liquids
DNRC	Montana Department of Natural Resources Conservation
DOE	Department of Energy
ECBM	Enhanced Coalbed Methane
EIA	U.S. Energy Information Administration
EOR	Enhance Oil Recovery
EPA	Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
FLPMA	Federal Land Policy Management Act
GHG	Greenhouse Gas
IGCC	Integrated Combined Cycle Gasification
IGCC	Integrated Gasification Combined Cycle
INGAA	Interstate Natural Gas Association of America Foundation
MBOG	Montana Board of Oil and Gas
MLA	Mineral Leasing Act
MVA	Monitoring, Verification, and Accounting
NEPA	National Environmental Policy Act
STB	Surface Transportation Board
UCG	Underground Coal Gasification
USDW	Underground Sources of Drinking Water
USGS	U.S. Geological Society
WAG	Water-Alternating-Gas