CENTRALIA (WASHINGTON STATE) GEOLOGIC FORMATION CO_2 STORAGE ASSESSMENT

Scott Stevens
Advanced Resources International, Inc.

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Abstract

As part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), Advanced Resources International, Inc. evaluated the CO_2 storage potential of deep coal seams and interbedded sandstone saline aquifers in the Centralia-Chehalis basin of west-central Washington State. These reservoirs could be used for long-term geologic storage of CO_2 captured from TransAlta's 1,404-MW coal-fired steam power plant near Centralia, Washington.

Identified coal seam targets at Centralia could store an estimated 13 years of CO_2 emissions (50% capture). Saline aquifers interbedded with the coals may provide an additional 9 to 73 years of storage capacity. However, reservoir storage capacity and quality is highly uncertain. A corehole testing program would be needed to refine these estimates as well as the feasibility of a commercial-scale CO_2 injection and storage project.

Corehole data from the Centralia coal mine provided by study partner TransAlta, as well as coalbed methane pilot production testing in the region, allow detailed evaluation of the coal seam storage potential. Lithologic and petrographic data and a limited number of wells logs permit a more generalized view of the saline-aquifer sandstone storage potential. A combined coal seam and saline aquifer test program, involving 3-5 coreholes, would be needed to measure reservoir properties at Centralia and better define their CO_2 storage characteristics and capacities.

CO_2 storage may be feasible in deep coals and sandstone saline aquifers near TransAlta's 1,404-MW coal-fired power station at Centralia. Eocene Skookumchuck Formation coal seams of sub-bituminous rank total approximately 18 m thick and buried at depths of 150-500 m could store an estimated 22 m^3/t of CO_2. Geologic mapping and analysis indicates that about 52 million t of CO_2 could be stored in coal seams, equivalent to about 13 years of current emissions (50% capture). While not large, this capacity could be augmented by deep coals elsewhere in the Centralia-Chehalis or greater Puget Sound region.

In addition, thick sandstone saline aquifers occur in the Eocene Cowlitz, Northcraft, and Skookumchuck Formations. Most are of poor reservoir quality, comprising hydrothermally altered and poorly sorted volcanic-derived sediments. However, some sandstones have good reservoir quality, with porosity as high as 30% and permeability of up to 3 darcys. Anticlines near Centralia could provide structural traps. Comparable reservoirs and traps occur at the Jackson Prairie storage field near Centralia. The lateral and vertical distribution of saline aquifer sandstones at Centralia is uncertain given sparse available well log control.

Centralia's interbedded coals and sandstones with limited individual capacity make the site a candidate for the "Stacked Storage" strategy, being pursued by SECARB in the Appalachian region for example, where multiple lower-quality zones are targeted for enhanced storage with reduced risk of leakage. Low land costs ($1/acre) typical in the Northwest would benefit a storage project. On the other hand, a major risk at Centralia appears to be significant structural

deformation, ubiquitous folding and faulting—some potentially active. In addition, the individual coal deposits are of relatively small size and partly mined out, while the coals and sandstones have been intruded by igneous dikes and sills. A low-cost reservoir testing program could mitigate these risks and help define the commercial viability for CO_2 capture and geologic storage at Centralia, which currently appears to be one of the best such opportunities in the Pacific Northwest region.

Executive Summary

This report serves as a preliminary evaluation of the CO_2 storage potential of deep coal seams and saline aquifers in the Centralia-Chehalis basin of west-central Washington State, performed by Advanced Resources International, Inc. as part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB). It was written to assess the feasibility of a potential CO_2 injection and storage test near TransAlta's 1,404-MW coal-fired steam power plant near Centralia, Washington. Our preliminary estimate is that deep coals and interbedded saline aquifer sandstones within an identified target area may have 90 to 345 million tonnes of storage capacity, sufficient for 22 to 86 years of Centralia emissions (assuming 50% capture rate).

Corehole data from the Centralia coal mine provided by study partner TransAlta, as well as coalbed methane pilot production testing in the region, allow detailed evaluation of the coal seam storage potential. Storage data for sandstone saline aquifers at Centralia is more limited—mainly lithologic and petrographic data as well as analog data on underground gas storage and natural gas production fields in the region—permitting only a more generalized view of their storage potential.

Carbon dioxide captured at the 1,404-MW coal-fired Centralia power station could be injected into nearby deeply buried coal seams, the mining of which ceased in 2006. Thick, well-developed, sub-bituminous rank coal seams in the Eocene Skookumchuck Formation are capable of storing about 20 m^3/t of CO_2 at typical depths of 150-500 m. Coalbed methane testing in the region, though not commercially successful to date, has recorded encouraging levels of permeability (1-7 mD) and methane content (5-15 m^3/t). CBM testing experience indicates that land costs are low ($1/acre) and drilling services can be available with good planning.

Geologic mapping indicates that approximately 52 million t of CO_2 could be stored in coal seams adjacent to the power station, equivalent to about 13 years of current emissions (50% capture). Scoping reservoir simulation indicates that 0.16-km^2 (40-acre) injector spacing using vertical frac wells would be the most efficient and cost-effective design for CO_2 storage, minimizing breakthrough, swelling, and fracture gradient risks. This capacity could be augmented by saline aquifers or deep coals elsewhere in the Centralia-Chehalis or greater Puget Sound region.

Thick sandstone saline aquifers also occur in the Eocene Cowlitz, Northcraft, and Skookumchuck Formations. The vast majority of these are of poor reservoir quality, comprising poorly sorted volcanic-derived sediments that have been hydrothermally altered with secondary chlorite, zeolite, and quartz mineralization. However, certain Skookumchuck sandstones interbedded with the coals have good reservoir quality, with porosity as high as 30% and permeability of up to 3 darcys. Anticlines near Centralia could provide structural traps. Comparable reservoirs and traps occur at the Jackson Prairie storage field 20 km south of Centralia, which holds 650 million m^3 (23 Bcf) of natural gas. However, the lateral and vertical distribution of saline aquifer sandstones at Centralia is uncertain given sparse available well log control and additional testing is required to gather key data. Our initial estimate is that sandstone aquifers interbedded with the coal seams could store roughly 38 to 292 million t, adding 9 to 73 years of storage capacity (at 50% capture).

Certain geologic characteristics at Centralia appear to be unfavorable for a CO_2 injection project. The Centralia region is strongly folded and faulted, including some potentially active faults. Fault compartmentalization may hinder effective CO_2 injection and storage and increase the number of injection wells required. The individual coal deposits are of relatively small size and partly mined out. The coals and sandstones are intruded by igneous dikes and sills. These challenges have hindered the commercial production of coalbed methane throughout the Pacific Northwest.

Centralia's interbedded coals and sandstones with limited individual capacity make the site a candidate for the "Stacked Storage" strategy, being pursued by SECARB in the Appalachian region for example, where multiple lower-quality zones are targeted for enhanced storage with reduced risk of leakage. Given the routine permitting experience of CBM and gas storage operations in Washington to date, a CO_2 injection test at Centralia should be low cost and straightforward to permit and implement. Success would provide a rare opportunity to advance CO_2 capture and geologic storage in the challenging Pacific Northwest region. A joint coal seam and saline aquifer test program, involving 3-5 coreholes, would be the next step to measure coal seam and saline aquifer reservoir properties at Centralia and better define their CO_2 storage characteristics and capacities.

1.0 Introduction

Options for sub-surface CO_2 storage in geologic strata are relatively less abundant in Washington and Oregon than in many other regions of the US, such as the Gulf Coast or Midcontinent, where large structurally simple sedimentary basins along with oil and gas production provide huge capacity and commercial storage opportunities. However, one of the best candidates for large-scale CO_2 capture with geologic storage in the Pacific Northwest is near Centralia in west-central Washington State, where TransAlta operates a major 1,404-MW coal-fired power plant. Although data control is incomplete, it appears that the deep coal and saline aquifer sandstone deposits that occur near this plant could provide long-term CO_2 storage.

This study, by Advanced Resources International, Inc. as part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), provides a preliminary assessment of the storage capacity of the sub-surface targets near Centralia, as well as recommendations for future testing that could provide the basis for an industrial-scale storage project. The report is organized into the following sections:

- **1.0 Introduction.** An overview of the WESTCARB project, geologic storage targets in the Northwest; TransAlta's power plant and coal mine operation at Centralia; and the research approach employed for the current CO_2 storage study.

- **2.0 CBM, UGS, UCG Near Centralia.** This section discusses energy industry activities in the Pacific Northwest that provide general data and insights for CO_2 storage at Centralia. It includes an introduction to coalbed methane production technology; CBM exploration drilling results in Washington and Oregon; the Jackson Prairie underground natural gas storage field; and an underground coal gasification test program that USDOE conducted at Centralia during 1979-82.

- **3.0 Coal and Sedimentary Deposits in the Centralia-Chehalis Region.** This section discusses coal deposits in Washington and Oregon; the geologic history of the Centralia-Chehalis region; Cenozoic sedimentary rocks in the region, with emphasis on the stratigraphy and lithology of saline aquifer formations; structural geology and tectonics; as well as coal seam thickness, distribution, and physical properties. Because well log data on saline aquifers at Centralia is limited, the descriptive data on sandstone texture, mineralogy, and geochemistry discussed here are of particular importance.

- **4.0 CO_2 Storage Capacity and Pilot Design.** This section covers estimation of CO_2 storage capacity in deep coals and saline aquifers near Centralia. Scoping reservoir simulation, comprising six sensitivities, provides insights for CO_2 storage dynamics. Finally, the design of delineation drilling and a recommended CO_2 injection pilot is discussed.

WESTCARB Project

The West Coast Regional Carbon Sequestration Partnership is one of seven research partnerships established in 2003 and co-funded by the U.S. Department of Energy (USDOE) to characterize regional carbon sequestration opportunities and to develop action plans for pilot-scale validation tests. WESTCARB is evaluating opportunities in a six-state region (California, Oregon, Washington, Nevada, Arizona, and Alaska) for removing carbon dioxide (CO_2) from the atmosphere by enhancing natural processes and by capturing it at industrial facilities before it is emitted; both will help slow the atmospheric buildup of this greenhouse gas and its associated climatic effects.

A key part of the project is identifying subsurface locations to store the captured CO_2. These geologic sinks are expected to include deep formations (such as oil and gas reservoirs as well as saline aquifers) that are essentially leak-proof. These potential sinks will then be matched with major anthropogenic CO_2 sources, such as large utilities and industrial emitters.

DOE's intention is to combine WESTCARB's findings with those of the other six partnerships to create a national "carbon atlas" to better understand how sequestration technology can help the United States reduce the carbon intensity of its economy and mitigate climate changes. On the basis of the source and geologic characterization, WESTCARB will prioritize geologic sequestration opportunities within the region and will propose pilot-scale projects that combine industrial CO_2 capture, CO_2 transport via pipeline, and injection into geologic formations for storage or enhanced oil and gas recovery.

Geologic CO_2 Storage in the Northwest

Due to the extensive distribution of igneous and metamorphic rocks, as well as active tectonics in the Pacific Northwest, opportunities for geologic CO_2 storage in sedimentary strata in this region perhaps are less abundant compared with other U.S. regions with thicker sedimentary sequences with proven reservoir quality, such as the Gulf Coast or Midcontinent.

However, the deep coal seams and associated sandstone saline aquifers in Washington State appear to offer significant locally attractive storage potential for anthropogenic CO_2 sources. The main coal deposits are of Eocene age and occur in several correlative formations, including the Skookumchuck Formation at Centralia as well as the Carbonado Formation in the Puget Sound region (**Figure 1**).

In addition, sandstone saline aquifers occur in the Skookumchuck and overlying Oligocene Lincoln Formation. Although these sandstones are volcanic-sourced, poorly sorted, and generally have limited porosity and permeability, they can be of good reservoir quality locally, such as at the Mist gas field and Jackson Prairie gas storage field.

One recently developed concept that may have application at Centralia is the "Stacked Storage" model. The Southeast Regional Carbon Sequestration Partnership (SECARB) is employing this strategy in the Central Appalachian region.[1] Coal seams here are relatively thin while the adjacent sandstones are low in permeability. However, defining a stack of multiple injection targets makes CO_2 storage more feasible. It also helps to increase the surface area available for chemical reactions and permanent storage of CO_2 through mineralization within the thin intervals. This approach seems very relevant to Centralia.

Phase 1 of this study examined deep coals in three regions of Washington State (**Figure 2**).[2] The Bellingham Basin in northwestern Washington holds some potential, but there has been almost no coalbed methane testing here. Few data exist to characterize coal reservoir quality. Also, the Bellingham basin is located far from anthropogenic CO_2 sources. The Coos Bay Basin in southwestern Oregon has small deep coal deposits that have undergone much more CBM testing, but reservoir quality is uncertain and it is even more remote from CO_2 sources.

By far the greatest potential for carbon sequestration in coal seams is in the coals of central Washington State, in the Puget Sound region south and east of the Tacoma-Seattle metropolitan area and the Centralia-Chehalis region. These coals have been more extensively tested by coal mining and coalbed methane exploration companies, thus their CO_2 sequestration potential can be more readily characterized.

The other type of target for geologic CO_2 storage in the Pacific Northwest are the saline aquifers, mainly sandstones, in the Cenozoic sedimentary basins which extend throughout western Washington into Oregon. These saline aquifers were discussed regionally by Golder Associates Inc. as part of a parallel WESTCARB project.[3] Although data at Centralia are limited, the potential of these saline aquifers near the power plant is examined in more detail in Sections 3 and 4 of this report.

TransAlta Centralia Power Station and Coal Mine

The focus of this report is a detailed evaluation of the CO_2 storage potential of deep coal seam and saline aquifers near the 1,404-MW Centralia power plant. TransAlta, which operates the Centralia power station and its related coal mine, participated in the WESTCARB study as an active partner, providing essential data, site access, and local geologic and mining expertise. TransAlta also leads Project Pioneer, Canada's first fully-integrated carbon capture and storage (CCS) plant. Planned for operation in 2012, the project aims to capture 1 Mt of CO_2 from an existing coal-fired power plant near Edmonton and utilize it for enhanced oil recovery or inject it into a geological storage site.[4]

TransAlta operates coal-fired, gas-fired, and hydroelectric power plants at Centralia. The coal-fired plant produces 1,404 megawatts, enough electricity to supply a city the size of Seattle (**Figure 3**). TransAlta also operates a 58-km^2 (14,450-acre) coal mine at Centralia, which until recently had supplied about 70% of the coal used by the adjacent power plant. The open-pit Centralia mine started up in 1971 and had typically recovered about 4 million tons annually. TransAlta also operated drilling rigs which were used for corehole drilling to define coal resources and plan mine operations (**Figure 4**).

Early in 2006 TransAlta had considered expanding the Centralia mine and filed permits to open “Pit Seven” later in the year. They also considered leasing an additional 7-8,000 acres of prospective land adjacent to the current mines, suggesting that coal resources in the area remain abundant. However, in November 2006, TransAlta finally decided to close the Centralia coal mine and switch the plant’s supply entirely to Powder River basin coal delivered from Wyoming and Montana. A number of factors influenced this decision, including depletion of coal reserves in the currently held acreage and the relatively high cost of operations. Lewis County officials also cited conditions sought by the state Department of Ecology, the USEPA, and the U.S. Army Corps of Engineers as influencing factors.[5]

The closure of the Centralia coal mine actually improves the outlook for CO_2 storage in deep coals at this location. More of the identified coal resource is likely to remain undisturbed and available for future CO_2 storage. It also potentially opens up access to the deeper coal seams remaining at the mine, underneath the shallow mining targets, which previously were off limits due to active mining operations near the surface (**Figure 5**). And while reclamation work continues as the mined-out pits are restored and replanted (**Figure 6**), these activities are less likely to conflict with CO_2 storage operations. Refilling the mined-out pits will restore reservoir pressure to the remaining underlying coal seams and increase their CO_2 storage capacity. Meanwhile, the detailed geologic database developed by the mine over several decades is available to guide CO_2 storage planning.

Site Location and Description

The Centralia-Chehalis coal field is located in west-central Washington State, about midway between the major cities of Seattle and Portland in the Pacific Northwest region of the US (**Figure 7**). The nearest cities are Centralia and Chehalis, 3 km apart, with populations of 15,000 and 7,000, respectively. Local industry includes timber, farming, distribution, and tourism. Interstate 5, the major north-south highway along the West Coast, runs near the cities, as do major passenger and freight rail lines. Numerous smaller paved and unpaved mining and timber roads provide access essentially to the entire mining area.

Surface topography in the mining area is defined mainly by low rounded hills, which range in elevation from 130 to 300 m (**Figure 8**). The Chehalis River drains the area in a generally northwest direction, discharging ultimately into the Puget Sound. The main tributaries of the Chehalis are the Skookumchuck and Newaukum Rivers, draining the western Cascade Foothills. With a moist temperate climate, local river flows vary widely by season, being heaviest in the winter months.

Flooding of low areas is not infrequent. For example, heavy rains in December 2007 closed a 30-km stretch of Interstate 5 for several days. However, the coal mining areas are 100 m or so above the flood plains and, apart from deep active pits which eventually will be backfilled and restored, generally less prone to flooding. Second-growth coniferous forests dominate the hills, while the lower valley terraces generally are farmed or ranched.

Research Approach

For this study, Advanced Resources International, Inc. (ARI) worked with Centralia power plant and coal mine operator TransAlta, as well as with other WESTCARB participants. ARI gathered and integrated geologic, geochemical, and geophysical data from a variety of sources. The most useful data and insights came from working with TransAlta's coal mining professional staff and data files during several site visits.

We also gathered supplementary data from conventional oil and gas exploration and production wells, coalbed methane pilot testing programs, underground coal gasification coreholes, underground gas storage operations, and water production and quality monitoring wells at Centralia and nearby locations. We reviewed published information on the lithology, coal geology, surface geologic mapping, tectonics, and seismic hazards of the Centralia region. We integrated this information using GIS mapping and compared Centralia with other sites where CO_2 injection has taken place. Finally, we modeled the CO_2 injection potential and dynamics at Centralia using reservoir simulation based on measured and inferred data.

This report is intended to be a preliminary evaluation and pre-feasibility study of the CO_2 storage potential at Centralia. Should an actual storage project be initiated, the first step would be to select and characterize specific locations for 3-5 test coreholes, which would gather, for the first time at Centralia, measurements of the actual reservoir quality and injectivity of sandstone saline aquifers and deep coal seams. Next, a small-scale CO_2 injection test should be site-selected and implemented. Only then—using the full set of information gathered from the CO_2 injection test, the coreholes, and this study—could a full-scale commercial injection program be properly designed and implemented at Centralia.

2.0 CBM, Underground Gas Storage, & Underground Coal Gasification Near Centralia

No field tests of geologic CO_2 storage in coal seams or saline aquifers have occurred to date in Washington or Oregon. The region is not considered to be particularly well endowed with sub-surface storage resources, although opportunities do exist locally as documented in this study. And while not major energy production centers, these two states have experienced certain energy-related activities that are potentially relevant to geologic CO_2 storage at Centralia. This section examines industry's experience in Washington and Oregon with coalbed methane exploration, underground natural gas storage, underground coal gasification, as well as conventional petroleum exploration and production activities.

CBM Production Technology

Production of natural gas from deep coal seams—coalbed methane (CBM)—is commercially mature technology widely applied today in the United States, Canada, and Australia. Fostered by initial R&D funded by USDOE and GRI in the 1970s and 80s, industry has invested a cumulative total of over $20 billion since 1988 to drill over 50,000 CBM wells in the United States alone.

By 2007, CBM production had reached 50 billion m^3 (1.75 Tcf; 4.8 Bcfd) from 620 billion m^3 (21.9 Tcf) of proved reserves.[6] In relative terms, CBM accounted for 10% of total natural gas production and 9% of natural gas reserves in the United States. During the past decade, CBM development also has gone commercial on a large scale in Canada (1 Bcfd), Australia (0.5 Bcfd), and China (0.1 Bcfd).[7] CBM testing is underway in a dozen other countries.

The design of CBM production wells varies depending on local geologic and reservoir conditions.[8] The simplest configuration is the vertical, open-hole, unstimulated completion of a single coal seam, common in the Powder River basin in Wyoming. More typical are vertical, cased, hydraulically fractured CBM wells that complete multiple coal seams (Uinta, Raton, and many other basins). The most complex and costly design is the horizontal, multi-branched well that may complete as much as 10 km of total coal length in-seam (Central Appalachian and other basins). Each of these designs could be tested and adapted to Centralia. However, the vertical frac well seems best suited for Centralia's multi-seam, low-permeability coal setting.

Unlike conventional natural gas reservoirs, coal seams store natural gas mainly by adsorption under the pressure of overburden, which is transmitted by formation water.[9] Gas production typically starts out low, as this formation water must be pumped off first to reduce reservoir pressure and induce the methane to desorb from the coal. Gas production usually increases gradually for several years as the well dewaters, then plateaus for several more years, followed by gradual decline over the well's 10-50 year productive lifespan. Commercial success depends on favorable geologic conditions, principally thick coal, high initial adsorbed gas content and saturation, and adequate permeability. Low capital and operating costs along with high gas sales price also are key success factors.

Coalbed methane (CBM) production and CO_2 storage in deep coal seams are separate but related activities that follow similar reservoir principles and operational methods. Basins with a track record of established commercial CBM production offer real advantages for subsequent CO_2 storage projects. The reservoir data collected during years of production history from thousands of CBM wells provides an invaluable foundation for the selection, evaluation, design and operation of a CO_2 storage project.

In addition, having access to CBM drilling rigs, completion units, and existing production infrastructure at the surface can lower the costs of CO_2 storage. So too can the economic benefit of improving methane recovery, a process called enhanced CBM recovery (ECBM). Environmental and regulatory permitting procedures generally are more established in mature CBM production areas. This is why the San Juan basin, long the leading CBM production region, also is the most advanced site for CO_2 storage demonstrations.[10]

To date, neither the Centralia-Chehalis region nor the other coal basins in Oregon/Washington have experienced successful commercial CBM production. There is no established CBM reservoir description or surface infrastructure for a CO_2 injection project to build on. However, there have been a handful of CBM pilot tests in the region, discussed in detail below, which provide limited but still useful data on coal reservoir properties, operational costs, and permitting procedures essential for planning a CO_2 storage operation at Centralia.

CBM Exploration Activity in Washington/Oregon

Successful commercial development of coalbed methane resources is probably the best single indicator that an enhanced coalbed methane or deep coal CO_2 storage project can succeed, because these two different types of projects share many similar reservoir and surface requirements. Despite test programs by roughly a dozen companies over the past two decades, commercial CBM production has not yet been achieved in Washington and Oregon. However, the data collected by these commercial projects are invaluable for evaluating the CO_2 storage potential at Centralia.

The initial phase of CBM exploration activity took place during 1982-93, when the CBM industry was just beginning and the wells qualified for temporary Section 29 non-conventional gas tax credits, which expired at the end of 1992. These projects were unsuccessful due to structural complexity, faulting, steep dips, and poor well completion practices, as well as relatively low prevailing wellhead gas prices in the \$2/Mcf range.[11]

A second CBM testing phase started about 2000 and continues today, stimulated by higher gas prices (>\$5/Mcf), new exploration concepts, and improved well completion technology. These more recent projects, though still not economically successful, have tested encouraging levels of coal seam gas content and permeability in the region. This tends to support the concept of CO_2 storage in deep coal seams at Centralia.

Early CBM Exploration Testing

The very earliest CBM project in the Pacific Northwest occurred during the early 1980's, when Amoco drilled several test wells in the Carbonado and Black Diamond regions south of Seattle (**Figure 9**). Although these wells penetrated over 30 m of coal, production results were disappointing. In 1987, Carbon River Energy completed a five-well pilot in the Carbonado field. Gas content and production results were promising but the venture was ultimately shut-in and abandoned.

Palo Petroleum, Texaco, and Boeing teamed up in 1992 to drill three wells near Black Diamond. One of the wells was hydraulically fractured with nitrogen foam and sand. The other two wells were completed with open-hole cavitation. One of the cavitated wells tested 1,000 to 6,000 m^3/day of methane with no water from Eocene coal seams at depths of 800 to 1000 m, probably reflecting free gas in the coal and adjacent sandstones rather than desorbed CBM. Steep dips in this area led to severe borehole deviation during drilling and caused hole collapse during the cavitation operations.

After a period of no or little CBM drilling during 1993-2000, several companies have recently conducted CBM leasing and/or exploration drilling in the Centralia area. These include Duncan Oil, El Paso Corporation, Torrent Energy, and Comet Ridge Ltd. Considerably more information is available on these more recent CBM projects.

El Paso Corp. and Duncan Oil (Black Diamond, Carbonado, Storm King)

El Paso Corp. and Duncan Oil tested the largest CBM pilot attempted to date in the Northwest. Starting in 2000 Duncan leased a large position and tested CBM in the Black Diamond field (west of Seattle), the Carbonado field (southwest of Tacoma), and the Storm King prospect (southwest of Mt. Rainier). In 2001, El Paso Corp. purchased a half interest in the Duncan project and become operator. El Paso expanded the pilots but eventually abandoned the project due to high water and low gas production.

El Paso's Carbonado CBM project covered 1,070 km^2 (264,014 acres) in King and Pearce Counties, located 45 km SE of Tacoma.[12] A total of 14 CBM production wells and 4 coreholes were drilled, targeting more than two dozen coal seams in the Puget Group totaling nearly 25 m thick at depths of approximately 900 m. **Figure 10** shows a typical lithologic log for a well in the Carbonado field, which is worth examining as there are no comparable complete well logs for deep coals at Centralia. The individual coal beds are often thin (1 m) with high ash content (avg. 60%) and are separated by 50 m or so of sandstone and shale. Intrusive dikes and sills occur sporadically. Coal rank was high-medium volatile bituminous. Gas content varied with depth and location, with highest values in the southern part of the prospect. Using a minimum 600-m depth cutoff, the average in-situ gas content was reported to be 15 m^3/t (d.a.f.).

All 14 production wells were hydraulically stimulated, using a variety of fluids (**Figure 11**). Eight of the wells were frac'd using nitrogen foam with sand proppant, pumped at a rate of 4-5 m^3/minute (25-30 bbl/min) and injecting 90 t of sand in each zone. Four wells were frac'd using slickwater KCl fluid, pumped at 1.3 to 2 m^3/minute (8-12 bbl/min) with 23 t of sand per zone. Two of the wells utilized polymer fluid, pumped at 1.3 to 2 m^3/minute with 42 t of sand injected per zone. Fracture gradients ranged from 0.7 to 1.5 psi/foot.

El Paso did not release detailed production data. Their later wells reportedly produced at high water rates, sometimes exceeding the 170-m^3/day (1000-Bwpd) installed pump capacity (**Figure 12**). Based on injection/falloff testing and production analysis, the company estimated coal seam permeability to range from 1 to 300 mD, with a regional average 1 to 7 mD. This is lower permeability than found in the San Juan and Powder River basins, but similar to the levels encountered in the Warrior basin of Alabama.

Produced water was quite fresh and discharged into surface streams under permit from the State of Washington. Discharge capacity constraints required some of the water to be trucked to a local water utility. El Paso estimated drilling, completion, and stimulation costs to be $640,000 per well (a useful benchmark for costing out a potential CO_2 storage project at Centralia). Despite operating in what many consider to be an environmentally restrictive part of the country, El Paso had no issues obtaining drilling permits because the locations were situated on private timberlands that were scheduled for clear cutting anyway. Had the project proceeded, access to Northwest Pipeline's 76-cm diameter trunk line would have required construction of a 16-km connecting pipeline.

Torrent Energy, Duncan Oil, Inc., Comet Ridge Ltd. (Chehalis Basin, Washington)

Torrent Energy Corporation recently conducted two CBM exploration projects in the Pacific Northwest region, one in the Chehalis basin of Washington about 20 km southwest of the Centralia coal mine, and the second in the Coos Bay basin of southwestern Oregon. At the Chehalis project, Torrent targeted CBM in the Cowlitz Formation, along with natural gas trapped in conventional sandstone reservoirs. The company had planned to introduce horizontal drilling, improve hydraulic stimulation and well completion, and reduce costs.

During the 1980s Kerr-McGee had drilled shallow coal exploration coreholes along the southwest flank of the Chehalis basin (**Figure 7**). These coreholes remain confidential but reportedly encountered gas shows in both coals and sandstones. One of the coreholes was offset by Duncan Oil, Inc. in 2001, flow testing 714 Mcfd from a shallow (750') sandstone zone. Duncan reportedly was able to map a sizeable prospect area using seismic data.

Duncan farmed out its project to Torrent Energy in 2004. During 2004-2008, Torrent Energy conducted CBM leasing and exploration programs in Washington and Oregon. Some of Torrent's Washington leases were adjacent to the Centralia CO_2-ECBM project area, in the Centralia-Chehalis coal district of the Morton and Toledo coal fields. Unfortunately, Torrent's funding ran out before it could establish commerciality and the company filed for bankruptcy protection in June 2008.

At its peak holding in June 2007, Portland-based Torrent Energy held 176,000 acres of mineral leases in the Chehalis basin and an additional 107,000 acres in the Coos Bay basin. Torrent had executed a 1-year lease option agreement with Weyerhauser Company on August 9, 2005, to lease 100,000 acres selected from an overall 365,000-acre block in the Chehalis Basin. Given the high risk and lack of commercial CBM development in the Pacific Northwest, Torrent paid a relatively low signing bonus of $100,000 or $1/acre (by comparison signing bonuses in proven commercial CBM basins such as the Powder River basin typically are $500/acre or more.) Torrent later acquired additional acreage in the Cowlitz and Lewis County portions of the Chehalis basin at similar terms. (Again, these land costs are quite relevant to a potential CO_2 storage project at Centralia.)

The Torrent projects represent the most recent CBM activity in the region of the Centralia project and thus provide useful technical, economic, and regulatory insight. Torrent considered the access to its Chehalis acreage to be excellent year-round via logging and fire control roads maintained by the forest service or the timber industry. Timber recovery staging areas provided potential drill sites and the company (through subsidiary Cascadia Energy Corp.) drilled three stratigraphic data holes in 2007 (data remains confidential).

Comet Ridge Limited, based in Sydney, Australia, invested in Torrent's Chehalis project and remains a partial owner. Its subsidiary St. Helens Energy LLC is conducting a CBM and conventional gas exploration project in the Grays Harbor area southwest of Seattle, where they hold mineral rights to 202 km^2 (50,000 acres) and a $1 million lease option for another 1,700 km^2 (420,000 acres). Note that the land bonus costs here are very low (<$0.50/acre). The company has completed a 3D seismic survey in the block and is nearing completion of a 2D seismic shoot. After processing and interpreting the seismic data, Comet Ridge plans its first test well during 2009.[13]

Torrent Energy (Coos Bay Basin, Oregon)

Although Torrent did not production test its acreage in the Chehalis basin, it conducted extensive CBM testing at its Coos Bay block further south in southwestern Oregon. The project was located along the Pacific coast, about 300 km south of the Columbia River and 120 km north of the California border (**Figure 13**). The Coos Bay basin is the southernmost of a series of coal-bearing Tertiary sedimentary basins (the Puget-Willamette Trough) that stretch from southern Oregon to northern Washington.

Coos Bay basin contains a thick section of nonmarine Eocene coal-bearing sediments forming the Coos Bay coal field (**Figure 14**).[14] Coal seams are contained in the Lower and Upper Members of the Middle Eocene Coaledo Formation, which correlates approximately with the Eocene Skookumchuck Formation at Centralia. Net coal thickness totals up to 20 m and 10 m, respectively, in the Lower and Upper Coaledo units. Coal mining began in 1854 and continued through the mid-1950s. The coal rank ranges from sub-bituminous to high-volatile bituminous, with heating value of 8,300 to 14,000 Btu/lb. Approximately 20 conventional oil and gas exploration wells were drilled in the Coos Bay basin between 1914 and 1993, many of which encountered gas kicks in the coal seams penetrated during drilling.

Torrent's Oregon acreage typically comprised 5-year leases with options for an additional 5-year renewal.[15] Annual payments were a relatively low $1/acre, comparable to the company's Washington State leases. Royalty was 12.5% on gross sales. There was an additional 4% overriding royalty to be paid to the project originators. An independent volumetric estimate placed total gas in place on Torrent's acreage at approximately 34 billion m^3 (1.2 Tcf).

Torrent commenced an initial multi-hole CBM coring program at Coos Bay in October 2004. The company drilled and tested a total of 12 exploration wells in three pilot areas : Beaver Hill (5 wells), Radio Hill (2), and Westport (5). In May 2008, Torrent completed initial fracture stimulation of 5 CBM wells at Beaver Hill and started production testing. Torrent claims the coal seams were saturated with pipeline-quality natural gas, but the project did not book proved reserves and was placed on hold due to the company's financial difficulties.

Core samples from 11 coal seams at the three test sites were desorbed at the well site. Data analysis was completed by mid-2005. Based on initial results, the Beaver Hill corehole site was selected for a 5-well production pilot.[16] Its original corehole was cased and converted to a production well. Four new wells were directionally drilled around it in a pattern from the same drilling location. All five wells penetrated multiple Lower Coaledo coal seams at depths of 1,280 to 1,340 m. The 5-m thick "D" seam in each well was stimulated with a nitrogen frac. Short-term rates of 5,700-14,000 m^3/day (200-500 Mcfd) were reported.

Torrent tested one well at its Radio Hill site, completing 10 Lower Coaledo coal seams at depths of 830-1200 m and with a cumulative net coal thickness of 10 m. The coals were stimulated with nitrogen fracs. Reported gas rate was much lower than at the Beaver Hill pilot, about 1,000 m^3/day (30 Mcfd) with about 1 m^3/day of water. The low water rates at both pilots suggests that produced gas may be free rather than desorbed, and could be coming from sandstones as well as coal seams.

Produced water chemistry was not reported but appears too saline for surface discharge. The produced water from the Torrent pilots was trucked to a dilution facility adjacent to the municipal water-treatment plant at Coos Bay. Torrent had planned to evaluate fractured basalts beneath the Coaledo Formation at its Westport project site as a possible injection zone for produced water. The Oregon Department of Environmental Quality would require an approved water disposal/containment plan for any commercial-scale CBM production and has ruled out surface discharge.[17]

Even though it was did not progress to the commercial phase, the Coos Bay CBM pilots at least showed that fairly high short-term flow rates were possible from Eocene coals in the Pacific Northwest region.

Duncan Oil, Inc. (King County)

The company drilled 4 test wells in King County and desorbed gas contents of up to 86 scf/ton in the 40′ thick Blue Seam in Duncan's NWCH 42-9A test well.[18]

Jordan Exploration Company (Bellingham Basin)

Jordan Exploration Company, LLC (Traverse City, MI) acquired 61,000 acres of mainly fee lands in the Bellingham basin of northwestern Washington State. Coal targets are in the 4-km thick mid-late Eocene Huntington Formation and the underlying Cretaceous-Early Eocene Chuckanut Formation. Coal rank ranges from sub-bituminous C to anthracite, with most of the coal in the high-volatile C to B bituminous range. Individual coal seams are 0.3 to 5 m thick, with the 7 best developed seams 2 to 5 m thick. The Sumas gas trading hub is located at the eastern edge of the lease block. Two 36″ diameter gas lines cross Jordan's leases.

Insights from CBM Testing

Reservoir Quality. Although none of the CBM projects conducted to date in Washington and Oregon achieved commerciality, nearly all tested thick coal seams with decent permeability (>1 mD) and initial methane saturation (close to 100%). The main challenge seems to have been structural complexity (faulting and folding), which hindered beneficial communication between the production wells. Another challenge was poor well completion, notably ineffective hydraulic stimulation and cavitation. These issues are likely to reoccur in a CO_2 storage project and require additional efforts to position wells between structures as well as to improve the effectiveness of well completions.

Land Costs. Lease bonus and royalty terms for CBM projects to date in Washington and Oregon have been economical, typically $1/acre or less with a 12.5% royalty. Landowners in other parts of the United States with more intense oil and gas activity often demand much more onerous terms, with bonuses in the range of $100 to $10,000/acre and 25-30% royalties. Low land costs would greatly benefit a CO_2 storage project in the Northwest, given the large area and long time scale required.

Permitting. The CBM test projects to date demonstrate that drilling activities are not unreasonably difficult to permit in many portions of Washington and Oregon, particularly where forestry and mining has already been occurring. For example, Duncan Oil obtained its drilling permit from the Washington State Department of Natural Resources under routine oil and gas permitting procedures. The company also obtained a Conditional Use Permit from King County to drill and test four CBM wells on private timberland owned by Weyerhauser and Plum Creek – Burlington. These agencies likely would be involved in the permitting of a CO_2 injection test at Centralia, although large-scale storage will probably require new specific regulations.

Operations. Again, the experience of CBM operations in the Northwest indicates that suitable rigs, completion, and production equipment can be available for CO_2 injection projects, albeit at higher cost than for areas such as the Rockies, which have a much larger level of activity and more competition among service company. In addition, access is generally good in the Northwest, including Centralia, thanks to the numerous timber and mining roads supplementing the paved road system.

For example, Duncan utilized a truck-mounted drill rig slightly larger than a standard water well rig to drill four wells to total depth of 1050 m. Each drill site occupied 0.5 to 1.0 acres during drilling and testing. The sites were near existing private access roads on the timberland company's property. Roads and drill pads were surfaced with crushed gravel. Drill sites were kept a minimum of 60 m from any surface water body or wetland area and 90 m from any structure. During testing, produced gas was collected from the wells to a central flare via buried PVC lines.

Duncan's drilling and testing operations were conducted 24-7 with an on-site supervisor present during all operations. Surface casing was set at least 30 m into the bedrock and then cemented back to the ground surface to isolate and protect overburden soils and groundwater from potential contamination with drilling fluids and/or saline produced water. After completion, the well was plugged with cement per state regulations and abandoned.

Petroleum Exploration in the Centralia-Chehalis Region

Despite sporadic exploration wells since 1900, there has been little commercial production of oil and gas in Washington State.[19] Due to the low geothermal gradient the shallow wells drilled to date have not penetrated deeply into the gas-generative window.

The only significant commercial field in the Pacific Northwest region is the Mist gas field. Located in the Astoria-Nehalem basin of northwestern Oregon (**Figure 7**), Mist field produces from sandstone reservoirs in the Eocene Cowlitz Formation, which are overlain by sealing mudstones in the Cowlitz (**Figure 15**). (Note that that the Skookumchuck Formation coals in the Chehalis basin are of similar age and lithology.) Gas composition at the Mist field is high in nitrogen which, along with isotopic data, suggests the gas was of biogenic rather than thermogenic origin.

One of the better studied recent gas wells at Mist field, OM-41A-10, penetrated 191 m of Clark and Wilson reservoir sandstone in the Cowlitz Formation.[20] It recovered a coarsening upward sequence of moderately to well-sorted, fine-grained, micaceous sandstone with minor laminated dark grey siltstone. The top contact of the Clark and Wilson member with the overlying upper mudstone member of the Cowlitz Formation is identified by a sharp positive deflection of spontaneous potential log response, while the base is more gradational. The better-quality reservoir portions of the core had porosity ranging from 30-36% (average 33%) and horizontal permeability from 331-1104 mD (average 721 mD).

The Clark and Wilson sandstones are overlain by the upper mudstone member of the Cowlitz Formation, which comprises coaly siltstone and mudstone facies. At a depth of 700 m, the calcareous concretions within this mudstone had 2.1% porosity and 0 mD measured permeability. This is probably the sealing unit at the Mist gas field.

As the individual gas pools became depleted at Mist field, a few were converted to underground gas storage fields. Gas is injected and stored in the Clark and Wilson sandstone units of the Upper Eocene Cowlitz Formation at depths of 370 to 820 m.[21] These are marine deltaic sandstones with good porosity and permeability. The field is structurally complex and recent wells are horizontal for better access to the various structural blocks (**Figure 16**).

Several petroleum wells dating to the 1920s have been drilled in the Centralia-Chehalis basin close to the mining area (**Figure 19)**. Unfortunately, none of these old wildcat wells have detailed well logs or lithologic descriptions available. In 1962, Shell drilled the Thompson No. 1 well to total depth of 3,300 m about 15 km south of the Centralia mine at the southern edge of the Centralia-Chehalis basin (**Figure 7).** The well penetrated 2,220 m of coal-bearing, marginal marine clastic rocks in the Eocene Skookumchuck Formation and 1,070 m of volcanic rocks in the Eocene Northcraft Formation. The well bottomed near the gas generation window, which is fairly deep in this basin due to the low geothermal gradient. The Chehalis block was one of five areas nominated by the state of Washington for its 2005 lease auction.[22]

Recently, a promising new sub-basalt tight gas play is undergoing testing by EnCana, Shell, and other companies in the Columbia basin about 100 km east of Centralia. This play targets low-permeability Tertiary lacustrine sandstones at depths of 4,400 m, which are buried beneath about 1 km of flood basalt. However, the Columbia basin is an entirely separate province with different geologic characteristics than those at Centralia.[23]

Jackson Prairie Underground Gas Storage Field

Puget Sound Energy (PSE), a privately owned utility, operates the Jackson Prairie underground natural gas storage facility located about 15 km south of the city of Chehalis in Lewis County (**Figure 7**).[24] Although the facility is used for short-term storage of natural gas, it also demonstrates that geologic traps and reservoirs suitable for CO_2 storage may be present near Centralia. Note that carbon dioxide, as a much larger molecule than methane, is less buoyant and should be less prone to leakage. Thus seals capable of storing natural gas should also contain CO_2.[25] The positive experience at Jackson Prairie also suggests that an industrial facility comparable to a CO_2 injection and storage project can be permitted, safely operated, and achieve broad public support in the region.

The Jackson Prairie site was discovered by a petroleum exploration well drilled in 1958. Although this well failed to locate commercial quantities of hydrocarbons, it penetrated thick wet sandstone saline aquifers with good porosity and permeability **(Figure 17a).** An anticlinal structure provides closure to trap the buoyant natural gas within the sandstones at depths of 300 to 900 m. Comparable sandstones and structural closures occur in the vicinity of the Centralia power plant and could be used for long-term CO_2 storage.

In 1963, Washington State passed a law authorizing underground gas storage. The Jackson Prairie storage facility was developed in the late 1960's, the first such facility in the state but today one of some 400 similar UGS facilities in North America. The field covers an area of 13 km^2 (3,200 acres; **Figure 17b**). PSE leased the land from approximately 60 individual landowners, who maintain control of nearly all of the surface and typically use it for farming, forestry, housing, or other uses.[26] The field has been in operation continuously since 1970 with no significant safety or leakage incidents.

Jackson Prairie field consists of 45 injection/withdrawal wells and surface pipeline, dehydration, and compression facilities to handle gas off take and re-injection into the main pipeline. The surface facilities and footprint are not dissimilar to those anticipated for a CO_2 injection and storage project at Centralia (**Figure 17c**). This provides an indication that industrial facilities of this type can be permitted and constructed in Washington State, particularly in areas of low population density such as the Centralia-Chehalis coal region (at least outside of the cities proper).

Natural gas at Jackson Prairie field is injected during low-demand summer months and then withdrawn in winter months when seasonal and daily demand is higher. Working capacity of the field currently is 650 million m^3 (23 Bcf). PSE expanded the field during 2007-8, drilling 10 wells and installing new pipe and compressors to boost withdrawal capacity to 32.6 million m^3/day (1.15 Bcfd), ranking it in the upper 5% of U.S. storage fields on deliverability.

With further expansion underway, working storage capacity is scheduled to reach 708 million m^3 (25 Bcf) by 2012. Including the "cushion gas" volume, which remains in the reservoir throughout the year and provides pressure for the working gas, the total gas volume injected and stored underground will be 1.4 billion m^3 (48 Bcf). PSE owns the 3,200-acre reservoir jointly with Avista and Williams, holding leases for subsurface natural gas storage. Most of the surface acreage is privately owned and used for timber production or livestock grazing.

The storage reservoirs at Jackson Prairie field are good quality sandstones in the Eocene Skookumchuck and Oligocene Lincoln Creek Formations at a depth of about 600 m. (Note that these are the same geologic formations, lithologies, structures, and depths as occur at Centralia 20 km to the north.) One of the Lincoln Creek sands tested 25% porosity with 1800 mD of permeability,[27] while other sands at the field tested up to 36% porosity and average 1500 mD.[28] Reservoirs with such high porosity and permeability are fairly unusual in the Pacific Northwest region, where poorly sorted and clay-rich sandstones predominate. Native gases in the sandstones tested at 12 of the field wells were primarily methane (60-74%) and nitrogen (26-30%).

One interpretation of the trapping mechanism at the Jackson Prairie field, based on 3D seismic and repeated sections seen in several well logs, attributes the field to gouge along a high-angle reverse fault.[29] Smectite clays within the fault gouge are thought to form an impermeable seal to gas within the reservoir, including across sand-on-sand fault contacts. Fault motion is dated to middle Oligocene to Miocene (36 to 24 Ma), becoming inactive prior to Columbia River Basalt time (Grande Rhone, Miocene), as it does not offset these flows. The fault has throw of up to 150 m and juxtaposed Eocene Skookumchuck sandstone over Oligocene Lincoln Creek mudstone. Smaller faults also occur in the field but apparently do not hinder gas communication across the reservoir.

Underground Coal Gasification Field Test at Centralia

During 1978-82, the U.S. Department of Energy conducted a site characterization and field test of underground coal gasification (UCG) technology at Centralia. This process involves introducing oxygen to combust deep coal seam in situ and then producing the gasified coal to the surface for utilization. Due to technical and economic challenges, UCG technology has not yet achieved commercial operation. However, higher energy prices and new drilling technologies have reignited interest in the UCG process in recent years.[30]

U.S. DOE's Sandia and Lawrence Livermore National Laboratories conducted most of the work on the Centralia project.[31] One conclusion reached by the project was that a UCG demonstration test at Centralia, targeting the 14.5-m-thick Big Dirty coal seam at a depth of 180 m, could be feasible. Although the demonstration did not progress to the commercial stage, the activities conducted by this project—which included surface seismic and logging of several coreholes, and the collection of detailed data on the Tono syncline portion of the Centralia Mine—are useful for the current deep coal seam CO_2 sequestration evaluation.

In selecting Centralia for the UCG test, the USDOE evaluated coal deposits throughout Washington State using these basic geologic screening criteria:

- Coal thickness of at least 1.8 m.
- Burial depth in the range of 90 to 300 m.
- At least 50 million t of coal in situ.
- Overlying and underlying strata are relatively competent, impermeable, and free of aquifers.
- Simple geologic structure, preferably free of faulting and folding.
- Close to an existing power station and easy to access.

Based on these screening criteria, USDOE concluded that none of the coal basins in Washington State was a perfect fit. The search was narrowed to three areas with adequate coal reserves: the Bellingham coal field in Whatcom County, the Roslyn coal field in Kittitas County, and the Centralia-Chehalis coal field in Lewis and Thurston Counties. As a result of the screening, the Centralia-Chehalis basin was selected, being the largest coal field in Washington as well as close to the Centralia steam electric power plant.

USDOE further evaluated three possible sites at Centralia for the UCG test. These included the Thompson and Snyder Creek synclines, the Mendota syncline, and the Tono basin. The Tono basin was selected because the Big Dirty seam is up to 15 m thick, up to 300 m deep, and relatively less mined out at the time.

USDOE selected a drilling site in the northwest edge of the Tono basin (**Figure 18**), a small coal deposit within the Centralia mine. Low-resolution (by today's standards) 2D seismic reflection, seismic refraction, and electromagnetic surveys were shot to define the local structure prior to drilling. Although the geologic structure in this area was known to be fairly complex, many of the coreholes that USDOE drilled encountered additional faults not detected by seismic, demonstrating that the structure was even more complex than initially believed.

In all, USDOE drilled and tested eight coal exploration coreholes and two hydrology wells in a small area of the Tono coalfield in 1979. Cores retrieved were described and tested for coal proximate, ultimate, free swelling, and equilibrium moisture content. Physical and chemical properties of some sandstones also were measured, showing that siltstones above the coals would act as effective gas seals. The coreholes also were logged using fairly conventional gamma ray, density, sonic, and resistivity logs. The two hydrology wells demonstrated that groundwater intrusion into the coal zone was minimal.

Following the corehole tests, several experimental burns of increasing scale were performed at the surface to try to simulate UCG processes. Short-term (3-day) experimental burns were conducted within cavities excavated approximately 15 m behind the mining face of the Big Dirty seam, providing indications of anisotropic permeability.[32] A longer-term (30-day) experimental burn in a 274-m long borehole drilled along the 14º structural dip angle of the Big Dirty seam demonstrated that this coal seam is stable enough to support horizontal drilling.[33] While these tests represented useful steps for demonstrating UCG technology, their principal contribution to the current CO_2 storage project is the data collected by the coreholes. These are discussed in further detail in Section 3.

3.0 Coal and Sedimentary Deposits in the Centralia-Chehalis Region

Coal Deposits of Washington and Oregon

During late Eocene time, clastic sediments including significant coal deposits formed within a north-south striking depositional system that extended from the Seattle area south into northwestern Oregon.[34] These coal-bearing units have been given a variety of names, reflecting local terminology and the intertonguing nature of the coal deposits (**Figure 1**), but they are genetically related. Coal-bearing formations include the Cowlitz, Skookumchuck, Carbonado, Spiketon, Tiger Mountain, and Renton Formations, as well as the undivided Puget Group. Coals in the Centralia-Chehalis basin are mainly within the Skookumchuck Formation.

The Oregon-Washington Eocene depositional system was segmented by faults and influenced by the intrabasinal Tukwila and Northcraft volcanic centers. Paleobotanic studies indicate that the climate was coastal, warm, and humid with moderate rainfall, while paleocurrent data indicate that sediment transport was from east to west across the basin. Sandstone composition within the basin is arkosic (clay-rich) and was mainly derived from crystalline rocks in the east. The proportion of volcanic detritus generally increases upward in the section, but also varies locally as a function of proximity to volcanic centers.

Coal-bearing formations in the Oregon-Washington trough were deposited in a variety of deltaic, fluvial, brackish, and shallow-marine environments.[35] Fluvial and distributary channel deposits typically form thick cross-bedded sandstone bodies. Inter-channel deposits formed within a variety of sandstone, mudstone, and coaly facies deposited in crevasse channels and splays, floodbasins, shallow lakes, and mires. Shallow-marine and brackish water deposits consist mainly of stratified to massive sandstone and mudstone deposited in tide- and wave-influenced shoreface, mouthbar, and shallow shelf environments. Coals are bracketed by both nonmarine and brackish or shallow marine facies and developed in both upper and lower delta and coastal plain settings.

Previous work by Golder Associates Inc. as part of the WESTCARB project evaluated the regional CO_2 storage characteristics of non-coal strata in the sedimentary basins of Washington and Oregon.[36] The coalbed methane potential of the region has been investigated sporadically,[37] but there has been no rigorous resource assessment based on detailed mapping of the relatively complex coal basins in the Pacific Northwest region.

Centralia-Chehalis Coal Basin

Initially described by various researchers in the early 1900s, the Centralia-Chehalis coal region was mapped, cored at a reconnaissance level, and interpreted more extensively by the U.S. Geological Survey in the 1950s.[38] Coal mining companies later drilled thousands of proprietary coreholes, which helped to further define the geology of the coal deposits, although none of this information has been published. During the late 1970s and early 1980s, the USDOE conducted coring and geophysical measurements as part of a small-scale field test of underground coal gasification technology in one of the Centralia-Chehalis coal fields.[39] In addition, there have been several deep petroleum exploration test wells drilled in the basin. This information was compiled and synthesized in the current study, resulting in hopefully a more complete geologic interpretation of the Centralia-Chehalis basin.

Eocene to Quaternary rocks are exposed in the Centralia-Chehalis region, comprising a total sedimentary sequence about 4 km thick. The deepest petroleum exploration well in the basin was the Shell Thompson 1 State was drilled in 1962 to a total depth of 3,300 m at the southern edge of the Centralia-Chehalis basin (**Figure 19).** The well penetrated 2,220 m of coal-bearing, marginal marine clastic rocks in the Eocene Skookumchuck Formation and 1,070 m of volcanic rocks in the Eocene Northcraft Formation. A regional seismic and magnetotelluric geophysical study identified 3 to 5 km of sedimentary rock in this southern portion of the Centralia-Chehalis basin (**Figure 20**).[40]

Potential saline aquifers in these formations would appear to be deep enough to store CO_2 in the supercritical phase (about 800 m), although current data does not allow detailed depth mapping on a regional scale. For deep coal storage, the storage mechanism is by adsorption on the coal. Thus, significant volumes of CO_2 can be stored even at shallow depths, depending on the shape of the sorption isotherm curve, and the 800-m depth threshold is not significant.

Sedimentary rocks in the Centralia-Chehalis basin typically include marine, brackish-water, and non-marine sedimentary rocks with interbedded volcanics. The rocks have been folded and faulted along a NW-SE trend, reflecting NE-SW compression. Basalt dikes and gabbro sills have intruded the Eocene and Oligocene rocks. At the surface they are extensively overlain by unconsolidated glacial till and outwash dating from Quaternary to Recent.

The Centralia-Chehalis region has a number of sub-bituminous and lignite coal fields, lying in a trough between the eastern margin of the Coastal Ranges and the western margin of the Cascades (**Figure 7**). Coal-bearing regions include the Centralia-Chehalis coal district in the north—the largest mining area—as well as the Morton coal field in the east and the Toledo coal field in the south. These relatively small individual coal basins are separated by faults and erosional highs.

Compared with commercially developed coalbed methane basins elsewhere in the US, Canada, and Australia, the Centralia-Chehalis coal deposits are much less continuous and structurally more disrupted. **Figure 21** shows the relative size and structural complexity of the Centralia-Chehalis coal fields compared with the Powder River basin CBM basin, shown at identical scale. By comparison, the Centralia-Chehalis coal fields are much smaller and have more rapidly changing reservoir parameters such as depth, strike direction, and dip angle.

Stratigraphy (Eocene-Recent)

Eocene to Quaternary rocks are exposed in the Centralia-Chehalis district, comprising a sedimentary sequence totaling about 4 km thick. These rocks include marine, brackish-water, and non-marine sedimentary rocks with interbedded volcanics. The rocks have been folded and faulted. Basalt dikes and gabbro sills have intruded the Eocene and Oligocene rocks. At the surface they are extensively overlain by unconsolidated glacial till and outwash dating from Quaternary to Recent. **Figure 19** shows the surface geology of the Centralia-Chehalis district.

The Cenozoic sedimentary and igneous intrusive formations at Centralia-Chehalis are discussed in order from oldest to youngest, as follows:

Eocene Cowlitz (or McIntosh) Formation. The Cowlitz Formation (or McIntosh as referred to by the early USGS reports) is the basal sedimentary unit in the Centralia-Chehalis basin. Although a few sporadic and poorly developed coals occur in the Cowlitz, most of the organic material occurs in high-ash carbonaceous shales. Not considered a mining target, neither do the Cowlitz coals appear to be attractive targets for CO_2 storage. And while sandstones in this formation are common, they are poorly sorted, hydrothermally altered, and appear to have very low porosity and permeability in this region. Overall, the Cowlitz coal seams and sandstones are not considered attractive targets for CO_2 storage.

The Cowlitz crops out east of the mining area, where it consists of mainly siltstone with massive arkosic sandstone and coal beds. Further west where the formation is structurally deeper, the Mottman #1 well (Section 12-T16N-R2W) penetrated more than 1 km of siltstone, sandstone, and interbedded volcanic pyroclastic rock, while the Chehalis #1 well (Section 17-T14W-R3W) logged nearly 500 m of siltstone and sandstone. These deposits are interpreted as deepwater marine siltstone with near-shore arkosic and basaltic sandstone in the lower and upper parts. In the deep test wells, porphyritic basaltic flows and pyroclastic rocks are interbedded with siltstone and sandstone.

Rocks in the Cowlitz Formation mainly consist of dark-grey, well-indurated tuffaceous siltstone and claystone with thin interbeds of tuff. Carbonaceous material (coal) and pyrite are common. Although some beds are massive, most are laminated. The lower portion is dark-grey basaltic sandstone interbedded with light-grey arkosic sandstone. The upper 75 m of the Cowlitz is a massive arkosic sandstone, which has been quarried for building stone near the city of Tenino. Sandy strata with interbedded carbonaceous layers east of the mining area defines the paleo shoreline during deposition.

Petrographic analysis of the arkosic sandstone within the Cowlitz Formation shows it to consist of 75-90% clastic grains, with matrix accounting for the remaining 10-25%. Plagioclase, mainly andesine as expected by the andesitic volcanoes of this region, accounts for 25-40% of the clastic grains. Quartz, commonly sub-rounded and strained, accounts for 15-30% of the rock. Biotite and muscovite micas form 10-15%, while basalt fragments are generally <10%. The matrix consists of calcite, clay minerals, chlorite, and altered volcanic glass components.

Interbedded volcanic rocks within the Cowlitz are massive porphyritic and vesicular basalt flows, dominated by plagioclase feldspar and pyroxene phenocrysts. Pyroclastic material in the rock is mainly tuff, consisting of basalt fragments and crystals of plagioclase, augite, and magnetite. Tuffs in outcrop appear so highly welded that they resemble basalt flows. Hydrothermal alteration formed chlorite, biotite, kaolinite, magnetite, and zeolites.

Eocene Northcraft Formation. The Northcraft Formation is a sequence of volcanic and sedimentary rocks conformably overlying the Cowlitz Formation.[41] The Northcraft crops out in the north and east of the coal mining area and was penetrated at depth in several wells further west. It ranges in thickness from 220 to 300 m.

The lower portion consists mainly of coarse basaltic conglomerate, sandstone derived from basalt, and pyroclastics. Voids are filled with secondary zeolites, chalcedony, or chlorite. The upper unit consists of ferromagnesian basaltic lavas, breccia, and pyroclastic rocks. The lava flows are largely andesite, with some basalt. Textures range from vesicular, trachytic, porphyritic, to aphanitic. Some flows contain breccia with andesite or basalt blocks 2 m in diameter. Secondary quartz, calcite, and zeolite minerals fill irregular joints and voids.

Even more so that the Cowlitz, the Northcraft Formation does not appear to be a suitable reservoir for CO_2 storage. There are no coal seams. The clastic rocks are primarily volcanic-derived. Though porous at one time, they have experienced extensive secondary mineralization. They are unlikely to have significant porosity and permeability.

Eocene Skookumchuck Formation. The Skookumchuck Formation contains most of the coal deposits in the Centralia-Chehalis region and also contains sandstone with promising reservoir characteristics. Thus, it is the focus for this evaluation and should be considered the primary target for a possible CO_2 storage pilot at Centralia.

The Skookumchuck Formation is present throughout the Centralia-Chehalis basin and consists of marine, non-marine, and brackish sedimentary rock, with occasional thick and economically mineable coal seams. It mostly conformably overlies the Northcraft Formation, apart from a local angular unconformity in the mining area near the outcrop. Up to 1 km thick, the Skookumchuck generally includes a lower and upper sandstone units separated by a westward-thickening siltstone unit in between. Lithologies change rapidly vertically and laterally, reflecting the alteration of marine and non-marine deposition near the littoral zone. Massive cross-bedded and thinly laminated sandstones and siltstones reflect shallow-water deposition. This is inter-tongued with marine, fine-grained sandstones, and siltstones.

Sandstone in the Skookumchuck is blue-grey, fine- to medium-grained, micaceous and carbonaceous (coaly), basaltic and andesitic, and locally contains fine tuff. Poorly sorted generally, some of the more massive beds exhibit better sorting. Mostly friable, in places it may be cemented with calcite, iron oxide, and silica derived from volcanic glass. Some of the sandstones contain as much as 40% calcite. Sandstone beds are lenticular but some may be traced out for several kilometers.

Petrographic analysis of Skookumchuck sandstones shows they consist mainly of angular feldspar (andesine; 10-40%), sub-rounded quartz (10-40%), muscovite and biotite (up to 10%), and sub-rounded lithic fragments of tuff, basalt, and andesite (5-80%). In total, clastic grains account for 50-80% of the rock. Matrix and cement comprise the remaining 20-50%, consisting of calcite, clay minerals, chlorite, and altered volcanic glass.

Siltstone in the Skookumchuck ranges from dark brown to greenish grey and is finely micaceous, carbonaceous, tuffaceous, and often fissile. Conglomerate, uncommon in the Skookumchuck, does occur at the base of the formation near the eastern outcrop. Derived from the underlying Northcraft Formation, the conglomerate comprises 6-60 m of poorly sorted basaltic and andesitic sandstone and conglomerate.

Laboratory analysis of shallow cores from the Skookumchuck sandstones showed porosity ranged from 5.3 to 35.2% and permeability from 1.42 to 3,506 mD. The thicker, more massive beds generally have better reservoir characteristics.

Economically important coal and related carbonaceous shales are interbedded with the clastic sedimentary rocks in the Skookumchuck Formation. Individual coal seams range from several centimeters to 5 m in thickness. Coal seams grade laterally and vertically to carbonaceous shales. The coal beds usually have sharp contacts with the overlying and underlying sedimentary rocks. In place, the upper parts of some coal seams are cut by erosional channels filled with sandstone.

Oligocene Lincoln Formation. Comformably overlying the Eocene Skookumchuck Formation, the Lincoln Formation in the Centralia-Chehalis region is a 600-m thick sequence of tuffaceous and basaltic marine sandstone and siltstone. Continental deposits derived from volcanic and pyroclastic sources also occur. The basaltic sandstone member of the Lincoln, best developed east of the Chehalis River at 500 m thick, consists of massive, well-indurated, fine-grained tuffaceous sandstone and siltstone. At its base, pebble conglomerates of basalt and andesite occur. In contrast to the Skookumchuck sandstones, the Lincoln Formation sandstones consist primarily of volcanic material with only minor feldspar, quartz, and mica. The volcanic material includes rounded basalt and andesite fragments, probably derived from the Northcraft Formation. Pyroclastic pumice and glass shards also occur. The basaltic sandstone is more resistant than the underlying Skookumchuck and erodes to form rugged topography.

Petrographic analysis of the Lincoln basaltic sandstone shows that clastic grains are 40-60% rounded basalt or andesite, 5-25% angular plagioclase (andesine or labradorite), and up to 10% magnetite. The matrix consists of altered volcanic glass, chlorite, zeolites, and clay. Thin (< 1 m) pyroclastic tuff beds, consisting largely of volcanic glass and pumice, also occur sporadically.

The Lincoln tuffaceous sandstone member consists mainly of fine-grained to very fine-grained tuffaceous sandstone and siltstone. It is massive apart from occasional thin inter-beds of basaltic sandstone. Petrographically, the tuffaceous sandstone consists of volcanic glass (34%), basalt and andesite fragments (26%), plagioclase (oligoclase; 25%), chlorite (6%), hornblende (5%), and magnetite (4%). Though it appears impermeable, calcite is often leached out of the siltstone to a depth of 8 m in outcrop.

Miocene Astoria Formation. Uncomformably overlying the Oligocene Lincoln Formation is a sequence of continental and marine conglomerate, sandstone, and siltstone up to 150 m thick of the Miocene Astoria Formation. An episode of folding and faulting in the region had preceded deposition of the Astoria. Completely eroded in the coal mining area today, the Astoria occurs only in three widely separated areas in the Centralia-Chehalis district. The largest preserved Astoria deposits are found in the Centralia and Chehalis Synclines southwest of the coal mine. The lower portion of the Astoria Formation consists of a friable, medium-grained, tuffaceous sandstone. The upper portion is fine-grained arkosic sandstone with abundant siltstone fragments and quartzite pebbles. Petrographic analysis of the Astoria sandstones shows they consist mainly of volcanic lithic fragments derived from the underlying Lincoln Formation, plagioclase, and quartz. Fossil wood, including tree stumps, is common in this continental deposit.

Miocene Columbia River Basalt. Flood basalt occurred widely in Washington State during Miocene and later times. However, this Columbia River Basalt is not present in the mining area, where it was never deposited or has been eroded. It currently is found only in the southwestern portion of the Centralia-Chehalis area, within the Centralia and Chehalis Synclines, which were paleo lows. There it is 20-30 m thick and consists of dark grey, aphanitic, basalt that rests unconformably on sedimentary rocks of the Lincoln and Astoria Formations. It is jointed in prismatic, columnar, or rosette styles 3 to 5 m in length.

Pleistocene Logan Hill Formation. This unit comprises glacial till, outwash, and glaciofluvial deposits formed by Pleistocene glaciation of the western Cascade Mountains rests on the Columbia River Basalt. The Logan Hill Formation consists of partly consolidated gravel and sand, which form flat-topped eroded partly plateaus throughout the Centralia-Chehalis region. 20-60 m thick, its tilted surface demonstrates that sourcing came from the east. It is weathered and frequently forms landslides along stream cuts.

Intrusive Rocks. Identified igneous intrusions are not common in the Centralia-Chehalis region but are difficult to detect and may well be more prevalent than current mapping indicates. Intrusions have been identified when they are exposed by stream cuts or rock quarries or when penetrated by exploration wells. The intrusions appear to become more numerous towards the coal mining area in the eastern side of the region.

Igneous dikes and sills that have been identified are mainly gabbro porphyry and porphyritic basalt, which intrude the Eocene to Oligocene sedimentary section. The intrusions do not affect Miocene or later strata, thus are dated late Oligocene. These two rock types are probably of similar age. Similar-aged intrusions occur in the Coastal Ranges of Oregon.[42]

Two petroleum exploration wells encountered intrusions in the vicinity of the mining area. The Bannse #1 (22-T15N-R2W), located about 5 km northwest of the mining area, encountered an igneous intrusion and was abandoned at a total depth of 1,280 m. It consisted of gabbro porphyry, similar to that better exposed at the Columbia rock quarry (11-T15N-R1E), where it is massively jointed, medium grained, and has granular and porphyritic texture. Plagioclase (labradorite) phenocrysts form about 60% of the rock. Augite in the groundmass, about 10-25% of the rock, has been altered to chlorite and biotite. Hydrothermal alteration has added biotite, chlorite, zeolites, calcite, and hematite.

The Wulz #1 exploration well (29-T13N-R1W), located about 5 km south of the mining area, encountered a porphyritic basaltic intrusion between depths of 692 m and 875 m in the upper part of the Skookumchuck Formation. Its total thickness of about 180 m makes this the thickest sill recorded in the region. The basaltic intrusions in the Centralia-Chehalis region typically are dark greenish grey with porphyritic and vesicular texture and contain significant volcanic glass. Zeolites and chlorites fill most of the vesicles. Plagioclase phenocrysts ranging from andesine to labradorite form about two-thirds of the rock, with altered augite the remainder. Hydrothermal alteration, similar to that affecting the gabbro porphyry, also has added biotite, chlorite, zeolites, calcite, and hematite.

Structural Geology

Surface mapping augmented with detailed coal coreholes and oil and gas exploration wells helps define the structural geology of the Centralia-Chehalis region (**Figure 22**). Eocene and Oligocene coal- and sandstone-bearing strata have been deformed into a series of NW-SE trending faults and folds. Dip angles generally are moderate (0-30º) but can reach vertical close to faults.

Faults are mainly high-angle reverse or normal faults; there are no apparent low-angle thrusts. The main faults generally trend NW-SE and are downthrown on the southwest side. Fault geometry suggests that they could have a right lateral strike-slip component given the generally east-west compression stress orientation, but this has not been demonstrated. The faults usually transect the larger folds in the region.

There are four main reverse faults in the Centralia-Chehalis region. These include the west-trending Doty Fault, and the NW-trending Kopiah, Newaukum, and Coal Creek Faults. Sedimentary strata adjacent to these faults exhibit fault drag, dipping at high angles, or are overturned in places to the southwest. Coal beds affected by faults often exhibit bedding plane slip as well as a crush zone 30 cm wide.

The four main reverse faults are, in order from the mining area in the northeast toward the southwest:

- ***Coal Creek Fault.*** A high-angle reverse fault, the Coal Creek fault parallels the southwest side of the Coal Creek anticline. Displacement is approximately 120 m. It becomes difficult to map south of Hanaford Creek, where it disappears in the volcanic rocks of the Northcraft Formation. The Coal Creek fault defines the northeastern limit of the TransAlta mining lease, although coal deposits continue northeast of the fault within the Snyder Creek and Thompson Creek synclines.
- ***Newaukum Fault.*** This reverse fault, also down on the south, generally parallels the Coal Creek and Kopiah faults. Displacement is uncertain. Towards the north close to the mining area the Newaukum fault disappears beneath the Meridian Hill Anticline.
- ***Kopiah Fault.*** Extending a distance of some 30 km, the Kopiah fault west of the mining area is the principal reverse fault in the Centralia-Chehalis region. It generally trends northwest, apart from an abrupt deviation to EW trend for a distance of 5 km south of Centralia. Displacement is about 150 m, down on the southwest side as demonstrated by the overturned sedimentary strata. The Kopiah fault splits and displacement decreases to about 70 m.
- ***Doty Fault.*** This EW-trending, high-angle reverse fault extends from the western edge of the basin to the Chehalis River valley, southwest of the mining area, where it apparently terminates against the Salzer Creek fault. Displacement increases to the west, ranging from 60 to 120 m of throw. Downthrown on the south, this fault caused drag folding of sedimentary strata adjacent to it. The Doty fault is inferred to be an active transform fault related to subduction.[43]

In addition to the major reverse faults, smaller normal faults also occur in the Centralia-Chehalis region. Normal faults are typically oriented west to northwest and can have up to 450 m of throw, but generally much less. These include the Salzer Creek, Scammon Creek, and Chehalis faults. Smaller normal faults, with throws typically 3 m or less, are commonly observed in the coal mines. Nearly all of the USDOE underground coal gasification coreholes penetrated faults that had not been previously mapped or identified by seismic and geophysical surveys, which had been run specifically to find them (**Figures 23** and **24**).

The main normal faults are, in order from the mining area in the northeast toward the southwest:

- ***Salzer Creek Fault.*** The largest normal fault in the region, it extends westward about 20 km from Deep Creek almost to South Hanaford Creek. Displacement (high-angle and down to the north) reaches maximum 450 m west of the Chehalis River, decreasing to the east as it cuts the north part of the Chehalis anticline.
- ***Scammon Creek Fault.*** This NW-trending normal fault (also down to the north) extends just south of the town of Independence southeastward about 15 km, disappearing under Chehalis River alluvium. Maximum displacement is about 300 m north of Lincoln Creek.
- ***Chehalis Fault.*** West-trending from near the head of Coal Creek, where throw reaches 250 m, and disappearing beneath alluvium of the Chehalis River valley. It cuts the south-plunging Chehalis anticline. Motion along the Chehalis fault pre-dated Miocene strata, which are uncut.

Folds. A number of anticlinal and synclinal folds parallel the major NW-SE trending faults in the Centralia-Chehalis region. Sedimentary strata in the region range from flat-lying to near vertical, generally dipping at moderate angles towards the fold axes. Folds are relatively open in in the western region and become tighter towards the mining area in the east. Major folds are likely related to basement faults, while some smaller folds resulted from fault drag.

The main synclines are, in order from the mining area in the northeast toward the southwest:

- ***Snyder Creek and Thompson Creek Synclines.*** These two adjacent and closely related synclines, each about 8 km in length, are tight, narrow folds within the Skookumchuck Formation. Trending NW-SE in the northeastern part of the mining area, they are separated by an equally tight, unnamed anticline. Dips are moderate, apart from the east limb of the Thompson Creek syncline, which terminates against a high-angle reverse fault and dips quite steeply (30-60º). These synclines have not been extensively mined and contain significant undisturbed coal resources that could be used for CO_2 storage.
- ***Hanaford Creek Syncline.*** Another NW-trending fold, about 7 km in length, is divided into two elliptical basins by a cross-folded arch. The arch portion of the syncline, its structurally highest point, has been extensively mined and little usable coal resource remains. However, some undisturbed coal resources probably remain in the southeast and northwest portions of the syncline.
- ***Mendota Syncline.*** The largest syncline in the mining area, the Mendota, extends a length of about 20 km in a NW-SE direction southeast of the Centralia power station. The central portion of this syncline has been extensively mined and contains little usable coal resource, apart from its unmined far southeastern and northwestern extents.
- ***Tono Basin.*** Unique in this area in being more circular than elongate, the Tono basin is a broad, shallow downwarp with gentle 10º dipping flanks. The Tono No. 1 seam has been extensively mined but deeper coals are still extant and could be used for CO_2 storage. The

Tono basin was the site of the USDOE underground coal gasification test conducted in the early 1980s (discussed separately).

- ***Centralia Syncline.*** A broad, shallow, NW-SE trending downwarp about 25 km in length located west of the mining area and passing directly through the city of Centralia. The Centralia syncline has not been mined and it is possible that significant coal resources are present, although if present they are probably quite shallow. The population center of Centralia may inhibit CO_2 injection along this portion of the syncline, but much of its length passes through lightly populated areas.

The main anticlines are, in order from the mining area in the northeast toward the southwest:

- ***Coal Creek Anticline.*** Plunging to the northwest, the Coal Creek anticline is asymmetric, with a high-angle reverse fault along its steeply dipping southwestern limb. Coal Creek anticline merges into the Coal Creek fault.
- ***Meridian Hill Anticline.*** Paralleling the Coal Creek anticline and with a similar high-angle reverse fault on its southwest limb, the Meridian Hill anticline separates the important coal mining basins defined by the Hanaford Creek and Mendota synclines.
- ***Tenino Anticline.*** The sole major NE-SW trending fold of note in the region, the Tenino anticline partly defines the northwesternmost extent of coal in the mining area. Coal outcrops to the southeast generally parallel its trend.
- ***Lincoln Creek Uplift.*** This is the main structural fold in the region, a broad NW-SE trending, SE-plunging anticline that has been cut by faulting. Structural relief is about 1 km and the limbs dip at 20º to 70º angles. The eroded core of this flexure exposes the Skookumchuck Formation.
- ***Chehalis Anticline.*** West of the mining area, this narrow, SE-plunging fold extends from the Salzer Creek fault across the city of Chehalis. The Chehalis anticline is the southeastern extension of the Lincoln Creek uplift but is more tightly folded.

Structural History. The Cenozoic structural history of the Centralia-Chehalis region began with downwarping along a north-south trend during Eocene time, probably associated with oblique subduction of the Kula plate with North America during the Late Cretaceous to Early Eocene,[44] resulting in deposition of the Cowlitz (McIntosh) Formation. Right-lateral strike-slip faulting and associated pull-apart rifting probably accompanied the oblique subduction.

This was followed by upwarping and volcanic activity along the margins of the region in mid to late Eocene that formed the pyroclastic flows of the Northcraft Formation, dividing the basin into a number of smaller sub-basins. Deposition continued in the troughs as the Skookumchuck and Lincoln Formations formed during late Eocene to early Oligocene time. Significant deformation and erosion then occurred in Miocene time, forming the structural elements recognized today.

Slight downwarping during the middle Miocene led to deposition of the Astoria Formation. Local extensional tectonics led to small-scale igneous and volcanic activity including the Columbia River Basalts.

Faulting continues today with active seismicity in the Pacific Northwest region related to subduction of the Juan de Fuca plate,[45] although the Centralia area appears to be a fairly inactive area. **Figure 25** shows the distribution of historical earthquakes in Washington State. There is a gap in recent seismicity near Centralia. **Figure 26** shows a more detailed distribution of historical earthquakes by magnitude and decade of occurrence. There have been several small seismic events near the mining area, but these have generally magnitude 3.0 or smaller. Much more intense seismic activity has occurred in the foothills of the Cascades about 30 km southeast of Centralia.

Coal Geology

Extensive coal deposits occur within the Eocene Skookumchuck Formation in the Centralia-Chehalis area. The coal seams are affected by local structure and dip at varying angles up to vertical. They are also affected by faulting and, as planes of weakness, can be sheared by bedding-plane slip and become brecciated.

A total of nine laterally persistent, mineable coal seams occur in the upper coal group of the Skookumchuck Formation (**Figure 27).** The coal seams are named after the geographic localities where they occur. The clastic rocks interbedded with the coal seams are generally arkosic and tuffaceous sandstones and siltstones (**Figure 28**). The coals generally have low ash content, high moisture content, and increase in rank from top to bottom (**Table 1**), as follows:

Table 1 : Typical Coal Properties at Centralia[46]

				Proximate Coal Analysis				
Seam	Thickness (m)[1]							
	Min	Max	Avg	Moisture	Ash	Volatile Matter	Fixed Carbon	BTU /lb
Tono 1	3.05	6.10	4.57	29.1	8.0	32.0	30.9	7940
Tono 2	1.22	1.83	1.52	24.4	9.3	32.4	33.9	8270
Upper Thompson	1.22	1.83	1.52	25.5	11.6	32.1	30.8	7824
Lower Thompson	2.44	3.66	3.05	26.1	12.0	31.0	30.9	7810
Big Dirty	7.62	15.24	11.43	21.6	12.2	32.7	33.5	8622
Little Dirty	0.61	1.52	1.07	28.7	11.1	33.8	33.0	8615
Smith	2.44	4.57	3.51	21.3	10.9	33.2	34.7	8800
Penitentiary	2.13	2.74	2.44	19.5	13.8	33.1	33.6	8657
Mendota	2.74	3.35	3.05	20.4	13.2	32.8	33.6	8626
Total			32.16					
Big Dirty + Smith + Mendota			**17.99**					

- ***Tono No. 1.*** Laterally the most continuous coal seam in the Centralia-Chehalis district, the Tono No. 1 averages about 4.57 m thick, with low 8% ash content. The underlying **Tono No. 2** seam also has low ash content (9.3%) but is less well developed at only 1.52 m thick. Moisture for the two Tono seams is fairly high, 29.1% and 24.4%, respectively, reflecting their low thermal maturity (approximately 8,000 Btu/lb heat content). The Tono seams are considered to have lower potential for CO_2 injection because they are stratigraphically and structurally shallow, have high moisture, low rank, and probably low CO_2 storage capacity.

- ***Upper Thompson.*** Persistent throughout the Centralia-Chehalis district, this coal seam averages 1.52 m thick (**Figure 30**). Moisture content is fairly high at 25.5%, but ash is moderately low at 11.6%. Several tuffaceous siltstone partings about 30 cm thick commonly occur near the middle of the seam. The **Lower Thompson** seam is thicker (3.05 m) and has similar ash and moisture (12.0% and 26.1%, respectively) but is more lenticular and thus laterally quite variable. Locally it is an important mining target.

- ***Big Dirty.*** The thickest coal seam, most prominent stratigraphic marker in the Centralia-Chehalis district, and probably the main target for CO_2 storage, the Big Dirty averages 11.43 m thick and can exceed 15 m in places. However, it thins markedly in the Thompson Creek and Snyder Creek synclines, where it is less than 2 m thick. The Big Dirty is slightly higher in rank than the overlying coal seams, with 8622 Btu/lb heat content, 33.5% fixed carbon, and reduced 21.6% moisture. Ash is moderately low (12.2%), though partings totaling several meters in thickness can occur (**Figure 31**). Overall, the Big Dirty probably represents the best individual coal seam target for CO_2 storage in the Centralia region. The ***Little Dirty*** seam is much thinner than the Big Dirty seam at only 1 m thick.

- ***Smith.*** A substantial coal seam averaging 3.51 m thick, the Smith frequently is scoured by sandstone channels. Silicified tree logs and stumps are fairly common, inhibiting mining operations. The Smith seam has moderate moisture (21.3%), low ash (10.9%), and relatively high heat content (8800 Btu/lb). It probably is the next most prospective seam for CO_2 storage after the Big Dirty.

- ***Penitentiary.*** Locally developed, notably along the western Tono basin and NE flank of the Kopiah fault, the Penitentiary seam is not a laterally widespread target. It averages 2.44 m thick, with slightly reduced 19.5% moisture, slightly higher 13.8% ash content. It is high in sulfur (1.6-4.4%), which makes it less attractive for mining but is not a significant factor for CO_2 storage.

- ***Mendota.*** Best developed around Kopiah and Mendota, it averages 3.05 m thick with moderate 13.2% ash content and 8626 Btu/lb heat content. It often contains “cannel” coal, a type of tectonically sheared coal high in wax content. The cannel coal is easily ignited with a match and has anomalously high heat content of 12,380 Btu.

Coal Rank. Most of the coal suitable for mining at Centralia is sub-bituminous C in rank, contains 14-35% moisture, 5-25% ash, and has a heating value of 8,300-9,500 Btu/lb. As discussed in Section 4, coal rank directly affects sorption behavior, with higher rank permitting more adsorption of methane and CO_2.

Coal Permeability. The most valid test for coal seam permeability is to conduct single-phase injection/falloff testing in a CBM test well under in-situ conditions of reservoir pressure, stress, and equilibrium moisture. This type of well test has not yet been performed at Centralia at depth. As part of the USDOE underground coal gasification program, the permeability of the Big Dirty seam was tested in a hydrologic corehole at very shallow depths (about 20 m).[47] Permeability tends to decrease sharply with depth and so it is not surprising that the Big Dirty seam tested fairly high permeability (3.2 to 38 mD).

To the north of Centralia, El Paso tested at coal seam permeability at more typical CBM reservoir depths of about 600 m in four CBM test wells.[48] Coal here is higher rank (high-volatile bituminous) than at Centralia and probably better cleated with higher permeability. Injection/falloff permeability ranged from 1 to 13 mD near the wellbore, while the production information suggested 1 to 7 mD.

Permeability at the target CO_2 storage depth of about 500 m at Centralia likely would be an order of magnitude lower than that measured by USDOE at very shallow depths. For simulation purposes, we estimated permeability to range from 0.1 to 10 mD, with a most likely value of 1.0 mD.

Coal Mining

Coal mining began in the Centralia-Chehalis area as early as the 1870s. With mostly steep dips, mining progressed quickly to underground operations. However, coal conditions are not favorable for underground mining, as the roof of most seams is friable, unstable sandstone. Ground water seeped into the mines and required continuous pumping. Numerous faults also caused delays and added costs in repositioning the mining face.

Coal production reached about 300,000 t/year in the 1920s but then declined to low levels. During this earlier period, more than 50 coal mines were active, mostly quite small. Mining increased dramatically around 1970, when the Centralia power plant was constructed and open-pit mining was established on a large scale in the relatively flat-lying portions of several synclines. However, today all of the mines have been closed due to depletion of coal reserves and the relatively high cost of production.

The largest and most recently active mine in the state was TransAlta's 57-km^2 (14,000-acre) Centralia mine, which recently produced about 4.3 million t per year.[49] Coal mined at Centralia was used locally to power TransAlta's 1,404-MW Centralia Steam power station, which was built in 1971 (TransAlta also operates a smaller 248-MW gas-fired plant built in 2002 and a 1-MW hydroelectric plant built in 1970).

The Centralia mine comprises four separate open pits targeting coal seams in the Skookumchuck Formation. These pits are easily visible on an aerial photograph of the mining area (**Figure 32**). Coal seams mined were the Upper and Lower Thompson, the Big Dirty and Little Dirty seams, and the Smith seam.

TransAlta closed down its 35-year-old Centralia coal mine in December 2006, citing high production costs and stricter safety regulations.[50] The Centralia power station has switched to utilizing coal shipped from the Powder River basin. Surface reclamation work continues at the Centralia mine to backfill and replant the abandoned pits. As recently as early 2006, TransAlta had applied for permits to increase mining to about 5 million t/year, lease additional acreage outside the current holdings, and extend the life of Centralia mine for another 25 years. Clearly, a significant coal resource remains which, though not economic to mine, could be targeted for CO_2 injection and storage.

4.0 CO_2 Storage Capacity and Testing

CO_2-ECBM/Storage Project Screening Criteria

Geologic and surface conditions need to be reasonably favorable for a CO_2-ECBM/Storage project to succeed. At this early stage of technology development, with only a handful of small-scale CO_2-ECBM/Storage pilots having been tested, a preliminary but probably accurate understanding of screening pre-conditions has emerged. These reservoir screening criteria may be summarized as follows:[51]

- **Homogeneous Reservoir:** The coal seam reservoir(s) should be laterally continuous and vertically isolated from surrounding strata. This ensures containment of injectant within the reservoir as well as efficient lateral sweep through the reservoir.

Note that Centralia coal seams are reasonably laterally continuous, on a scale of several kilometers. They are vertically isolated from surrounding strata by impermeable shales, which should ensure containment of CO_2 within the coal seams. And the UCG coreholes found permeability to be fairly isotropic, at least in laboratory samples.

- **Simple Structure:** The reservoir should be minimally faulted and folded. Closely spaced faults can compartmentalize the reservoir into isolated blocks, inhibiting effective sweep. The faults themselves may divert injectant away from the reservoir, reducing the efficiency of enhanced recovery and sequestration. In addition, structurally complex areas frequently have damaged coal cleat systems and low permeability.

Centralia fares poorly on this criterion. The geologic structure is relatively complex, with considerable folding and faulting on close spacing. Structure is much more complex than at any successful commercial CBM development. Complex structure has been a principle cause for commercial failure for CBM exploration pilots in China, Poland, and other countries.[52]

- ***Adequate Permeability:*** Although no minimum permeability criterion can be specified, preliminary simulation indicates that at least moderate permeability is necessary for effective ECBM (1 to 5 mD).

Coal seam permeability has not yet been measured in situ in the Centralia area at target depth (500 m). The USDOE coreholes tested 3.2-38 mD but at very shallow depth (20 m). Other CBM projects in similar Eocene coal seams located in other parts of Washington and Oregon have tested low-moderate levels of permeability (1-10 mD). This suggests that permeability may be adequate at Centralia, although that would need to be confirmed by in-situ testing.

- ***Optimal Depth Window:*** Just as for conventional CBM projects, CO_2 storage projects have an optimal depth window that will vary by basin. Minimum depth depends on the shape of the sorption isotherm, while permeability declines mark the maximum workable depth.

We assumed 150-m minimum depth cutoff at Centralia as having a reasonable threshold of storage capacity based on the isotherm. Maximum depth is probably in the 1500-m depth range, where permeability is typically minimal. However, Centralia coals are mapped to remain fairly shallow near the power plant, well above the 1500-m cutoff.

- **Coal Geometry.** For well completion efficiencies, geometrically concentrated coal deposits with fewer thicker seams would be preferred to basins with equal total coal thickness but dozens of thin individual seams.

Fortunately, much of the coal resource at Centralia is concentrated in a half-dozen individual coal seams. We assumed the Big Dirty, Smith, and Mendota seams—being thick, deeper, and higher in rank—offer the primary targets for CO_2 storage at Centralia.

- **Gas Saturation.** Although methane saturation does not affect CO_2 storage capacity, coal seams that are initially methane saturated have better economic prospects, in terms of more and earlier natural gas production.

No desorbed gas content data are available for deep coal seams at Centralia. CBM testing in other areas of Washington have indicated close to saturated initial conditions. The scoping reservoir simulation, discussed below, included sensitivities for 75% and 100% gas saturation.

Overall, apart from the issue of excessive structural complexity, reservoir conditions look favorable at Centralia for CO_2 storage and enhanced CBM recovery. Structural complexity could be addressed by identifying and selecting areas with few faults and minor folding.

Sorptive Capacity and Isotherms

Coal adsorbs methane, CO_2, and other gases under pressure under a relationship defined by the Langmuir equation ($V_i = P_i * V_L / (P_i + P_L)$), where actual adsorbed volume (V_i) approaches the coal seam's maximum adsorption capacity (V_L) as reservoir pressure (P_i) increases. Unlike conventional gas trapping, the relatively shallow coal seams at Centralia can adsorb significant levels of CO_2 even at shallow depths of 150-500 m.

No sorption isotherms were available for Centralia. Even had they been available, these sorption isotherm curves for surface coal samples would have to be adjusted to reflect the different capacity of deeper CO_2 storage targets, where coal rank is higher and moisture content lower. Instead, we used published sorption isotherm data for Washington State and Canada coal samples, selecting the CO_2 and CH_4 curves for Horseshoe Canyon coal in Alberta, which is of comparable sub-bituminous rank (R_o=0.46%; **Figures 33, 34**).[53,54] Should coal rank be found to different in other parts of the Centralia-Chehalis basin, a linear relationship between rank and the sorption equation parameters was defined to allow adjustments (**Figures 35, 36)**.

The isotherms are also useful because there is no direct desorption data for coal seam gas content at Centralia. Coal seam desorbed gases in Washington State typically are high in methane (95-98%), with low CO_2 and other constituents. Thus, we inferred actual methane content for the coal seams based on the sorption isotherms. Absent reservoir pressure data, we further assumed hydrostatic conditions (0.433 psi/foot).

Using these curves, the CO_2 storage capacity at Centralia for coals at a depth of 150 m (500 ft) is estimated to be approximately 11.5 m^3/t (368 scf/ton). The methane storage capacity would be approximately 2.9 m^3/t (94 scf/ton). Note that the ratio of CO_2/CH_4 adsorption at this pressure is about 3.9, which is typically elevated for low-rank coals. Higher-rank coals such as the Fruitland in the San Juan basin tend to have lower CO_2/CH_4 ratio of 2 to 3.[55] This means that low-rank coal reservoirs such as at Centralia actually are more efficient at storing CO_2 than their modest methane content might suggest.

Depth-Prospective Area

Although significant coal resources remain in the deeper parts of the Centralia mine, much of the current mining area is partly to completely mined out. We focused instead on the Centralia syncline area immediately southwest of the Kopiah fault (**Figure 37**). This area is one fault block southwest of and adjacent to the current mining area, close to the Centralia power plant, and contains a large, relatively undisturbed area with coal seams at attractive depth for CO_2 storage (>150 m). It appears this area has not been mined extensively because the Big Dirty seam is deeper and somewhat thinner here than in the Centralia mine area to the northeast.

We obtained lithologic description logs from 53 water and environmental observation wells in the six townships that surround the Centralia region (out of a total 1,000 water wells drilled). Individual coal seams were not specifically named in these logs but often could be identified by their thickness and vertical spacing. The Big Dirty seam, although thinner here than in the mining area, remains the primary target at 5.2 to 11.6 m (17-38 ft) thick. Ten of the wells had penetrated the Big Dirty seam and provided direct data. Twelve other wells penetrated only the upper coal seams, such as the Tono or Thompson beds, but the depth to the Big Dirty seam could be inferred from coal seam stratigraphy and spacing.

We mapped out the Big Dirty seam in these water well data points and, following the surface geology trends as well as the structure of the Centralia syncline and adjacent faults, identified an area where the seam appears to be buried at least 150 m (500 ft; **Figure 38**). Maximum depth to the Big Dirty seam along the axis of the Centralia syncline is not known, since the water wells are too shallow, but could be 500 m (1640 ft) or deeper. The west and south edges of this prospective area are less well constrained and rather arbitrarily truncated beyond existing data control. Before a CO_2 injection test takes place at Centralia, we recommend first gathering any proprietary corehole data that may exist in the syncline, shooting seismic data, and drilling exploratory coreholes to further refine the preliminary structural interpretation.

The total area of the high-graded target is 107 km^2. However, internally the area is likely to be more structurally complex than currently mapped, with additional unidentified faults and shallow regions, much like the Centralia coal mining area, broken into individual pits. In addition, the western portion of the target area underlies the city of Centralia and thus may be off limits to CO_2 storage. To compensate for these uncertainties, we assumed three-quarters of the high-graded area would be prospective for CO_2 storage (80 km^2), with the remaining one-quarter not available due to faulting, shallow depth, surface constraints, and other factors.

Outside of the Centralia syncline area, a single isolated water well southeast of the Centralia mine enabled us to infer that the Big Dirty seam is about 177 m (582 ft) deep (**Figure 34**). There are likely to be many additional areas outside of the mapped Centralia syncline in the Centralia-Chehalis basin that have CO_2-prospective deep coal resources. However, these deposits would be further away from the Centralia power plant and were not included in our storage capacity estimate.

CO_2-Prospective Coal Resources and CO_2 Storage Potential

The high-graded CO_2 prospect area within the Centralia syncline, described above, has estimated in-situ coal resources prospective for CO_2 storage of approximately 1.43 million t (**Table 2**). Based on the methane sorption isotherm, we calculate in-situ coalbed methane gas content to range from 4.16 to 5.54 m^3/t (dry, ash-free basis), depending on assumptions of initial gas saturation levels (75% and 100%). Thus, accessible CBM resources are calculated volumetrically to be 7.19 to 9.59 billion m^3 (191-254 Bcf) in place.

Table 2: Estimated Coal Seam CO_2 Storage Capacity for Centralia Syncline Prospect

Coal Mass	Prospective Area		Depth	Press.	Coal Thickness		Ash	Moisture	Density	Coal Mass Billion daf		
	km^2	acres	m	psi	m	ft	%	%	ton/ac-ft	t	tons	
Total Centralia Syncline Prospect	107	26400	500	725	18	59	12	20	1800	1.73	1.91	
Adjusted Net 75% Area	80	19800	500	725	18	59	12	20	1800	1.30	1.43	
CH_4 and CO_2 Potential	75% Sat.		100% Sat.		100% Sat.		75% Sat		100% Sat.		100% Sat.	
	CH_4 Gas Content (d.a.f.)				CO_2 Content (daf)		CBM Resources				CO_2 Storage Capacity	
	m^3/t	scf/ton	m^3/t	scf/ton	m^3/t	scf/ton	MM m^3	Bcf	MM m^3	Bcf	MM m^3	MM tonnes
Total Centralia Syncline Prospect	4.16	133	5.54	178	21.70	695	7.19	254	9.59	339	37.56	69.82
Adjusted Net 75% Area	4.16	133	5.54	178	21.70	695	5.39	191	7.19	254	28.17	**52.36**
Centralia CO2 Emissions 100%	8.00	million t/yr		6.5	Years storage capacity							
Centralia CO2 Emissions 50%	4.00	million t/yr		**13.1**	**Years storage capacity**							
Sorption Isotherms:	CH4 VL	300	scf/ton daf		CO2 VL	1175	scf/ton					
	CH4 PL	500	/psi		CO2 PL	500	/psi					

Based on the carbon dioxide sorption isotherm, coal seams in the Centralia syncline could store about 21.7 m^3/t of CO_2 (dry, ash-free basis) at 100% gas saturation. CO_2 storage in deep coal seams within the net (again, 75%) prospective Centralia syncline area could total an estimated 52.36 million t. (However, as shown by reservoir simulation in Section 5, actual CO_2 storage may be somewhat less than the total capacity due to permeability and well spacing issues.) That equates to approximately 13.1 years of emissions from Centralia, assuming 50% capture. Again, there are likely to be significant additional CO_2-prospective resources outside of the Centralia syncline in the Centralia-Chehalis region, which was selected for detailed study due to its close proximity to the power station.

Scoping CO_2-ECBM Reservoir Simulation

Scoping reservoir simulation was used to examine the likely range of CO_2 storage behavior in deep coal seams at the Centralia syncline area. The reservoir simulator used for the study was the Advanced Resources International COMET3 (binary isotherm – CH_4 and CO_2) model. COMET3 is a finite-difference, fully implicit simulator that is widely used for coalbed methane, enhanced coalbed methane, and CO_2 storage in coals.[56,57]

Given the relative lack of data, a simple five-well injection pattern was constructed for the purpose of scoping reservoir simulation. The model consists of a dual-porosity, single-permeability system where the simulated well is fully bounded, behaving as if it is one well within an infinite field of wells. We assumed 0.16-km^2 (40-acre) well spacing, for both injection and production wells, because permeability at Centralia is probably low (~1 mD). We also modeled tight spacing to maximize the efficiency of injection and storage in what is a fairly small area near the power plant. A five-spot injection pattern was implemented, taking advantage of the pattern's elements of symmetry for efficient model design (10-acre quarter-well model; **Figure 39**).

Figure 40 tabulates input parameters for the simulation model. Average ash (12%) and moisture content (20%) values were assumed (**Table 1**), as well as the methane and CO_2 sorption isotherms previously discussed. The simulated well was assumed to complete the three thickest lower seams, modeled as a single layer, for 18 m of total coal thickness (Big Dirty, Smith, Mendota). Depth to the 18-m single-layer coal reservoir was assumed to be 500 m. For illustrative purposes only, **Figure 41** shows a conceptual pattern of CO_2 injection wells on 40-acre spacing overlain on the Tono coal pit (the best-controlled structure at Centralia), although the model actually used geologic conditions in the less well-controlled Centralia syncline.

Other reservoir parameters, such as coal compressibility and relative permeability, are not known for Centralia, thus were assumed to be similar to those in the better-studied San Juan basin.[58] A standard value of 2 was assumed for differential CO_2 swelling factor. CO_2 solubility in coal seam formation water was assumed to be small and not considered for the purpose of this study.

The simulation model was run for 20 years with CO_2 injection starting on day one. The production well was shut down when produced gas composition reached 50% of CO_2, on the assumption that gas processing costs would no longer be justified by natural gas revenues. The producing well was run at a minimum bottom-hole pressure of 100 psia. Instead of limiting the gas injection rate, injection was conducted on pressure to maximize injected CO_2 volumes. Maximum injection pressure was assumed equal to frac pressure, calculated using a frac gradient of 0.6 psi/ft.

A total of six simulation runs were modeled, with sensitivities to permeability (0.1, 1.0, 10 mD) and initial methane saturation (75%, 100%). Future work might consider other sensitivities, such as well spacing, coal thickness, CO_2 injection rates, etc., but the six runs give a general indication of potential CO_2 behavior in the reservoir. The six cases are summarized as follows:

- **Case 1: 0.1 mD; 75% saturation (Figures 42, 43).** The first sensitivity modeled unfavorably low permeability and initial methane saturation. Very little methane 8,500 m^3 (0.3 MMcf) and little formation water is recovered at the production well. Injected CO_2 totals only 3.7 million m^3 (6,800 t; 130 MMcf) and remains close to the injection well over the 20-year injection period. Clearly, this case would not be economically feasible.

- **Case 2: 0.1 mD; 100% saturation (Figures 44, 45).** Initial methane saturation is more favorable but permeability remains very low. Methane recovery is slightly improved at 140,000 m^3 (5 MMcf) but remains very poor. CO_2 injection totals (4,600 t; 88 MMcf), actually less than for Case 1, which had 25% more initial storage capacity free prior to CH_4 displacement. This case would also be uneconomic.

- **Case 3: 1.0 mD; 75% saturation (Figures 46, 47).** Performance improves markedly with medium permeability. Although delayed for 6 years due to undersaturation, methane recovery rises to 7.1 million m^3 (0.25 Bcf), about comparable to a below-average Powder River basin well. CO_2 injection increases dramatically to 38 million m^3 (70,000 t; 1.33 Bcf) with the higher permeability. After 20 years CO_2 becomes more evenly distributed throughout the reservoir but does not break through to the production well.

- **Case 4: 1.0 mD; 100% saturation (Figures 48, 49).** Considered the most likely case, with medium permeability and full initial methane saturation. CO_2 does not break through over the 20-year period. Methane recovery totals 9.7 million m^3 (0.34 Bcf), similar to an average Powder River basin well. CO_2 storage is distributed quite uniformly throughout the reservoir, totaling 34 million m^3 (63,000 t; 1.19 Bcf).

- **Case 5: 10 mD; 75% saturation (Figures 50, 51).** High permeability markedly increases injectivity and flow but also causes rapid breakthrough to the production well, only about 2.7 years in this scenario. The production well reaches the 50% CO_2 level after 3 years and is shut in. Even with the higher permeability conditions methane recovery is fairly good (10 million m^3; 0.35 Bcf). CO_2 production continues until year 8, when injection pressure approaches the fracture gradient and coal matrix swelling becomes more severe. Even ceasing injection at year 7.6, the injected CO_2 volume totals 64 million m^3 (120,000 t; 2.25 Bcf), the highest of the six cases. Wider well spacing would probably better suit this high level of permeability.

- **Case 6: 10 mD; 100% saturation (Figures 52, 53).** CO_2 takes slightly longer to break through (3.1 years), after which the production well is shut in. Injection pressure approaches the frac gradient and injection ceases at year 8. High permeability and initial methane saturation allows excellent ECBM recovery (10 million m^3; 0.47 Bcf). CO_2 storage is essentially the same as for Case 5 at 64 million m^3 (120,000 t; 2.25 Bcf). This case also would improve with wider well spacing.

The reservoir simulation helps define the possible outcomes of CO_2 injection at Centralia. However, an injection test pilot ultimately would be needed to establish initial conditions and allow a more confident assessment of the feasibility.

Saline Aquifer CO_2 Storage Capacity

One recently developed concept that may have application at Centralia is the “Stacked Storage” model. The Southeast Regional Carbon Sequestration Partnership (SECARB) is employing this strategy in the Central Appalachian region.[59] Coal seams here are relatively thin while the adjacent sandstones are low in permeability. However, defining a stack of multiple injection targets makes CO_2 storage more feasible. It also helps to increase the surface area available for chemical reactions and permanent storage of CO_2 through mineralization within the thin intervals. This approach seems very relevant to Centralia.

There are four main storage mechanisms for CO_2 operate in saline aquifer rocks.[60] These are:

- **Structural and Stratigraphic Trapping.** Migration of CO_2 in response to its buoyancy and/or pressure gradients within the reservoir is prevented by low-permeability barriers (caprocks) such as shale.

- **Residual saturation trapping.** Capillary forces and adsorption onto the surfaces of mineral grains within the rock matrix trap some of the injected CO_2 along its migration path.

- **Dissolution Trapping.** Injected CO_2 dissolves and becomes trapped within the reservoir brine.

- **Geochemical Trapping.** Dissolved CO_2 reacts with pore fluids and minerals in the rock matrix of the reservoir, slowly forming reaction products as solid carbonate minerals over hundreds to thousands of years.

For the purposes of a first-order capacity estimate, we calculated structural and stratigraphic trapping in the estimated pore space. Residual saturation and dissolution trapping were not considered, due to lack of reservoir data at this early stage. Geochemical trapping was considered to be too slow to be significant over the time frame of an injection project (20-40 years) but would be significant over a much longer period.

Compared with the deep coal seams, reservoir data for the potential saline aquifer sandstones at Centralia are much less available. Data are limited to detailed petrographic descriptions including texture and mineralogy for core and outcrop samples from the Eocene Skookumchuck and Oligocene Lincoln Creek Formations. These two units, which comprise the injection and storage reservoirs at the Jackson Prairie underground gas storage field, also appear to be the most promising candidates at Centralia. The Skookumchuck and Lincoln Creek sandstones are stratigraphically adjacent to the coal targets and thus could be efficiently targeted under a “Stacked Storage” type of injection strategy.

Up to 1 km thick, the Skookumchuck generally includes a lower and upper sandstone units separated by a westward-thickening siltstone unit in between. **Figure 28** shows a typical stratigraphic interval of well-developed sandstone totaling about 45 m thick in several beds within the Skookumchuck coal section at Centralia. As discussed in Section 3, these sandstones generally are massive cross-bedded and thinly laminated sandstones which, along with interbedded siltstones, reflect shallow-water deposition. They are inter-tongued with marine, fine-grained sandstones and siltstones. The sandstone is fine- to medium-grained, micaceous and carbonaceous (coaly), basaltic and andesitic, and locally contains fine tuff. Poorly sorted generally, the more massive beds (such as the 25-m thick sand beneath the Lower Thompson and Big Dirty seams) can be better sorted.

The sandstone beds have lenticular geometry but some may be traced out for several kilometers. Mostly friable, they are cemented with calcite, iron oxide, and silica derived from volcanic glass. They consist mainly of feldspar, quartz, muscovite, biotite, and lithic fragments. Clastic grains account for 50-80% of the rock. Matrix and cement comprise the remaining 20-50%, consisting of calcite, clay minerals, chlorite, and altered volcanic glass.

Laboratory analysis shows Skookumchuck sandstones range from 5.3 to 35.2% porosity, while permeability ranges from 1.42 to 3,506 mD. The thicker, more massive beds generally have better reservoir characteristics. For a base case, we assumed average 20% porosity for the 45-m thick sandstone column shown in Figure 28. We further assumed that CO_2 saturation could reach 40%, with the remaining pore space filled with residual water and/or natural gas.

For a high case, we increased sandstone thickness 5-fold to 225 m, based on a reasonable extrapolation of sandstone occurrence in the 1,000-m thick Skookumchuck and 600-m thick Lincoln Creek Formations. We also increased porosity to 25%, assuming the massive, better-sorted sandstones with better-than-average porosity are the main target. Finally, we increased CO_2 saturation to 50%.

Table 3 shows potential storage capacity in saline aquifer sandstones at the Centralia syncline. The base case CO_2 storage calculation totals 37.5 million t, equivalent to 9.4 years of power plant emissions (50% capture). The high case would total 293 million t, equivalent to 73 years of emissions (at 50%). Adding together the deep coal and saline aquifer potential give a total storage capacity of 90 to 346 million t, equivalent to 22 to 86 years of emissions at 50% capture. This assumes that all of the volume could be contacted, which is probably optimistic.[61]

Table 3: Estimated Deep Coal and Saline Aquifer Storage Capacity at the Centralia Prospect

Coal Mass	Prospective Area		Depth	Press.	Coal Thickness		Ash	Moisture	Density	Coal Mass Billion daf	
	km^2	acres	m	psi	m	ft	%	%	ton/ac-ft	t	tons
Total Centralia Syncline Prospect	107	26400	500	725	18	59	12	20	1800	1.73	1.91
Adjusted Net 75% Area	80	19800	500	725	18	59	12	20	1800	1.30	1.43

CH_4 and CO_2 Potential	75% Sat.		100% Sat.		100% Sat.		75% Sat		100% Sat.		100% Sat.	
Deep Coal Storage Potential	CH_4 Gas Content (d.a.f.)				CO_2 Content (daf)		CBM Resources				CO_2 Storage Capacity	
	m^3/t	scf/ton	m^3/t	scf/ton	m^3/t	scf/ton	MM m^3	Bcf	MM m^3	Bcf	MM m^3	MM tonnes
Total Centralia Syncline Prospect	4.16	133	5.54	178	21.70	695	7.19	254	9.59	339	37.56	69.82
Adjusted Net 75% Area	4.16	133	5.54	178	21.70	695	5.39	191	7.19	254	28.17	**52.36**

Centralia CO2 Emissions 100%	8.00	million t/yr	6.5	Years storage capacity
Centralia CO2 Emissions 50%	4.00	million t/yr	**13.1**	**Years storage capacity**

Sorption Isotherms:	CH4 VL	300 scf/ton daf	CO2 VL	1175 scf/ton	
	CH4 PL	500 /psi	CO2 PL	500 /psi	

Saline Aquifer Storage Potential	Prospective Area		Depth	Press.	Sand Thickness		Rock Volume	Por-osity	Pore Volume	CO2 Sat.	CO2 Density	CO2 Capacity
	km^2	acres	m	psi	m	ft	km3		km3		kg/m^3	MM t
Base Case	80	19800	500	725	45	148	3.61	20%	0.72	40%	130	37.50
High Case (5 * h)	80	19800	500	725	225	738	18.03	25%	4.51	50%	130	292.97

Centralia CO2 Emissions 100%	8.00	million t/yr	4.7	Years storage capacity	Base Case
Centralia CO2 Emissions 50%	4.00	million t/yr	**9.4**	**Years storage capacity**	Base Case
Centralia CO2 Emissions 100%	8.00	million t/yr	36.6	Years storage capacity	High Case
Centralia CO2 Emissions 50%	4.00	million t/yr	**73.2**	**Years storage capacity**	High Case

Total Coal and Saline Aquifer Potential						CO2 Capacity MM t
Centralia CO2 Emissions 100%	8.00	million t/yr	11.2	Years storage capacity	Base Case	89.86
Centralia CO2 Emissions 50%	4.00	million t/yr	**22.5**	**Years storage capacity**	Base Case	89.86
Centralia CO2 Emissions 100%	8.00	million t/yr	43.2	Years storage capacity	High Case	345.34
Centralia CO2 Emissions 50%	4.00	million t/yr	**86.3**	**Years storage capacity**	High Case	345.34

CO_2 Storage Test Corehole Program

The next step for a potential CO_2 capture and storage project at Centralia would be to design and implement a reservoir testing program consisting of approximately 3 to 5 coreholes in the targeted Centralia syncline. Other high-potential deep coal and sandstone targets in the area that subsequently may be identified could also be tested. This section outlines the basic strategy for such a well test program. Should the project move forward, there would need to be a more detailed site selection, drilling design and cost estimation, and reservoir testing program performed for each of the selected locations.

The main objectives of the drilling program would be to confirm the presence of thick coals and reservoir-quality sandstone saline aquifers in the Centralia Syncline. The coal reservoir characterization would need to measure the following parameters: coal thickness, depth, quality, maceral composition, rank, gas content and composition, sorption isotherm (both methane and CO_2), and absolute permeability. The main techniques would be on-site desorption for gas content and composition; injection/falloff well testing for in-situ permeability and stress; and laboratory measurement of sorption isotherm, coal proximate analysis, vitrinite reflectance, and coal petrography for maceral composition.

The saline aquifer characterization would need to measure the following parameters: sandstone stratigraphy, geometry, porosity, permeability, mineralogy, texture, natural fracturing, fluid composition, pressure, and temperature. The main techniques would be coring, logging (porosity, permeability; mineralogy), and laboratory analysis (gas composition, permeability, porosity).

Once the data from the coreholes has been collected, it would be necessary to perform a comprehensive reassessment of the storage potential and reservoir properties at Centralia. This would involve more detailed GIS geologic mapping, including construction of cross-sections, detailed structure and depth mapping, and 3D analysis of individual coal seams and sandstones. Following the mapping, a more detailed reservoir simulation analysis would be needed to evaluate the deep coal and saline aquifer reservoirs (preferably within one model).

The costs for such a test program would depend on a number of variables, such as permitting requirements, total depth, hole diameter, casing program (fewer the better at this stage), core lengths, logging program, number of laboratory analyses, as well as the number of coreholes (there are certain economies of scale). We assume that seismic reflection data would not be needed for the corehole program, but would be essential for a CO_2 injection pilot.

Based on the somewhat elevated drilling and operations costs in the Pacific Northwest, we estimated the costs of the corehole delineation program (**Table 4**). The corehole test program as defined would provide the necessary data to permit a more complete evaluation of the CO_2 storage capacity and reservoir properties at Centralia, sufficient to reach a decision on whether to proceed with an injection pilot demonstration.

Geologic and Manmade Hazards

Injecting and storing CO_2 in deep coal seams at Centralia, like any underground storage project, would involve risks of unplanned leakage out of the injection zone or to the surface. During the past decade, methodologies and technologies have been developed to quantify and mitigate such risks.[62] Prior to conducting a CO_2 storage project at Centralia, there should be a more formal evaluation of the geologic and manmade risks, including their consequences and probability. Briefly, there appear to be two major risks: seismicity in the tectonically active Pacific Northwest region, and leakage to surface caused by poorly completed or abandoned wellbores in the injection area at Centralia.

Table 4: Estimated Costs for Reservoir Testing Corehole Program at Centralia

Activity	Corehole	No.	Total
Permitting	5000	3	15000
Drilling	150000	3	450000
Coring	30000	3	90000
Supervision	20000	3	60000
Well Testing	30000	3	90000
Lab Work	25000	3	75000
Geology	20000	3	60000
Simulation	20000	3	60000
Management	20000	3	60000
Total			**$960,000**

Seismicity. The Centralia area is located within the seismically active Pacific Northwest region, where earthquakes occur related to active subduction of the Kula plate beneath North America. However, the subduction rate here is relatively slow and large earthquakes in onshore western Washington are thought to be infrequent. The modern seismic record shows that the largest earthquakes recorded in this region been in the range of 4.0 to 5.0 magnitude.

No earthquakes larger than 4.0 magnitude have occurred during the past 100 years in the central Washington area near Centralia (**Figure 25**). There have been a few recent events within the Centralia coal mine area, but these have been smaller than 3.0 magnitude (**Figure 26**). It is possible that some of the identified faults at Centralia are seismically active, such as the Doty fault, which may represent a transform-type fault related to active subduction.[63]

Earthquakes are unlikely to cause release of CO_2 stored in deep coal seams. This is because the storage mechanism is adsorption of CO_2 onto the coal under pressure, with is transmitted by hydrostatic forces. Fault slip of several meters would not change the reservoir pressure conditions at depth and thus cannot cause CO_2 to escape. Only a sudden drop in hydrostatic pressure could cause that, but it is unlikely that seismicity could be such a cause.

Wellbore Leakage. A more likely potential source for leakage would be poorly completed or poorly abandoned wellbores in the Centralia syncline area. Fortunately, there are few petroleum wells in the area. Most of the water wells were shallow and did not penetrate the Big Dirty, Smith, and Mendota coal seams; these wells would not be at risk of contacting the CO_2 injection zone. **Figure 37** shows that only a handful of water wells in the Centralia syncline penetrated the Big Dirty seam; none of these are known to have penetrated the deeper Smith and Mendota seams. However, any wellbore that penetrates the target seams would need to be protected with cemented casing or properly abandoned (cement to surface).

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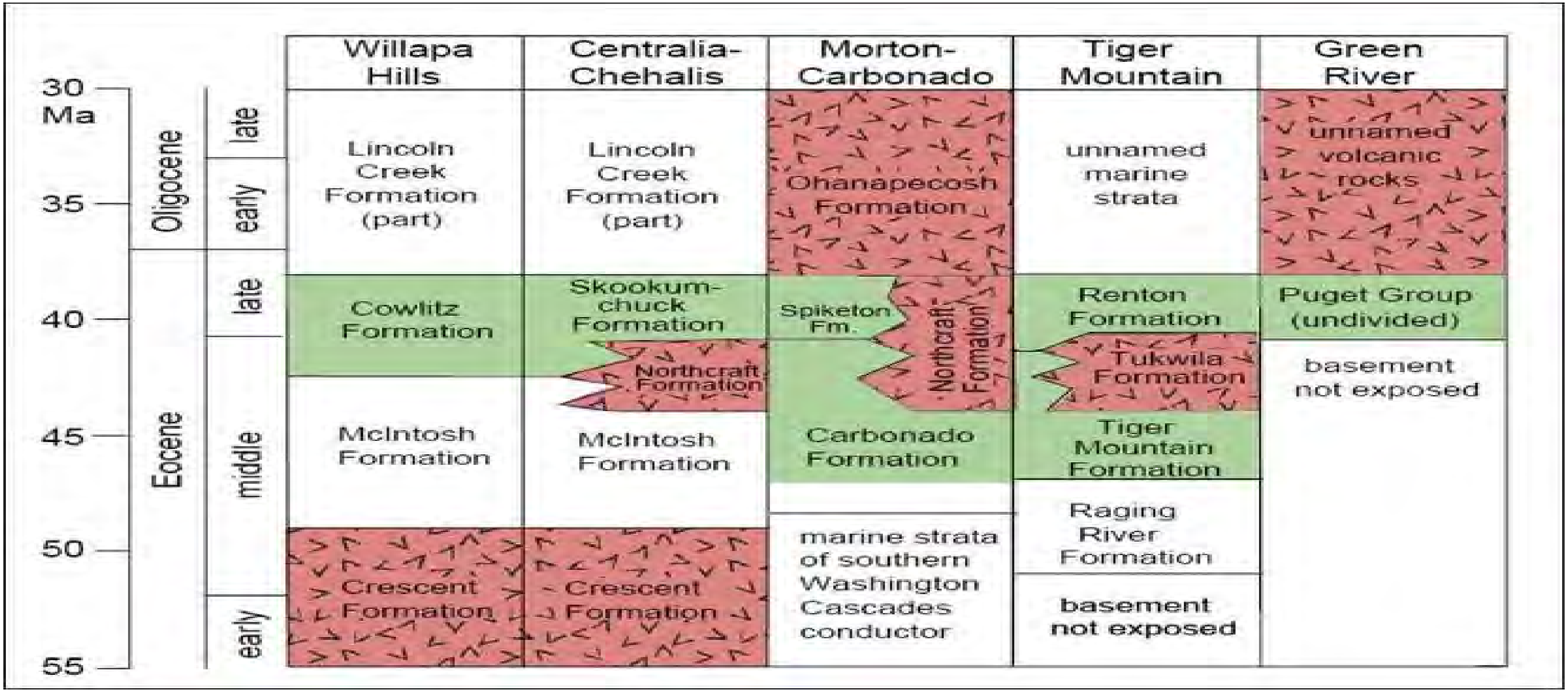
CENTRALIA (WASHINGTON STATE) GEOLOGIC FORMATION CO_2 STORAGE ASSESSMENT FIGURES

Scott Stevens
Advanced Resources International, Inc.

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Figure 1 : Generalized stratigraphic chart for coal fields in the state of Washington.



Source : From Brownfield, et al, 1994
(Tertiary Coals of Western Washington)

Figure 2 : Coal areas in Oregon and Washington with CO_2 storage potential include the Bellingham, Puget Sound (including Centralia), and Coos Bay region.

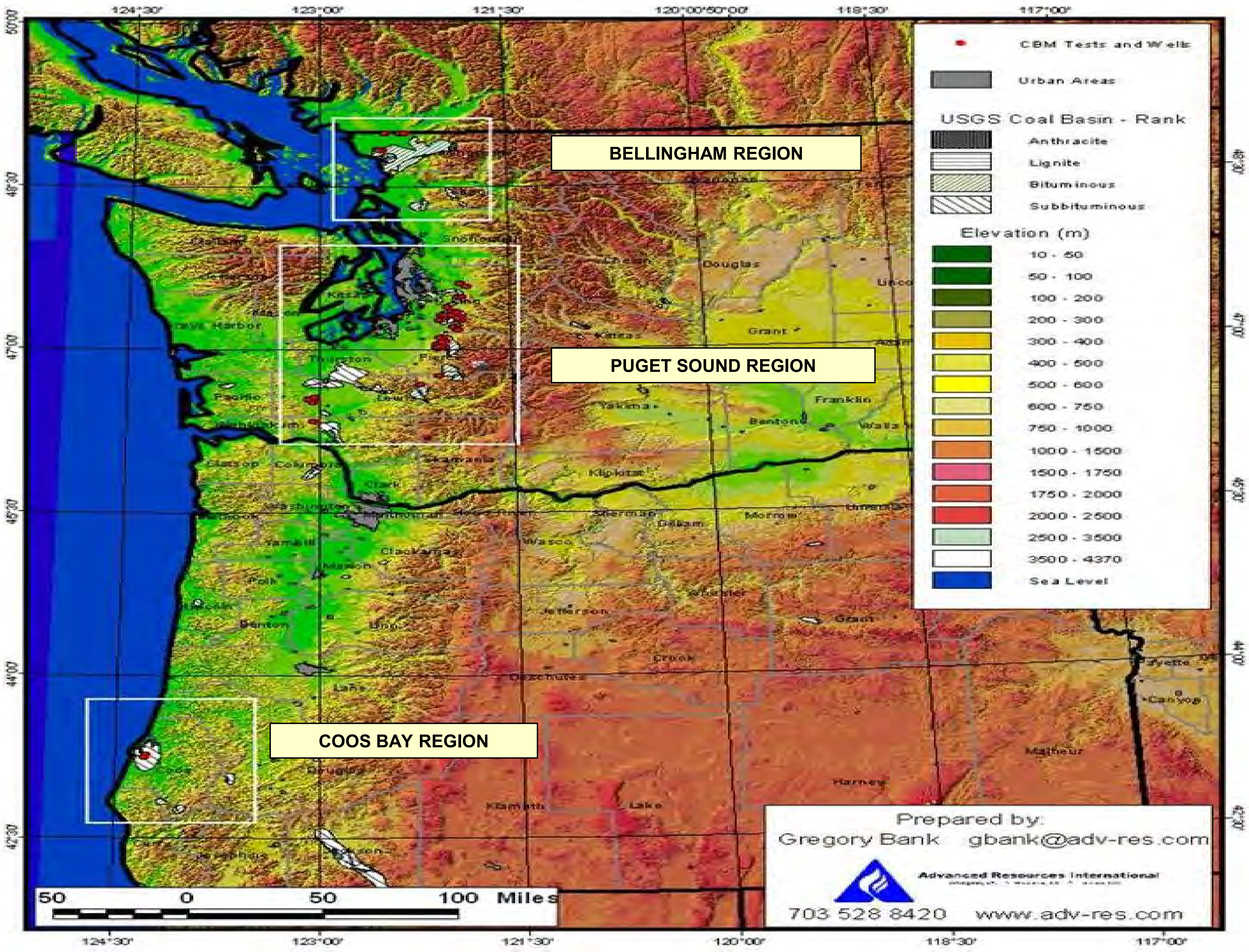


Figure 3 : TransAlta's 1,404-MW thermal power plant at Centralia is equipped with advanced SO_2 and NO_x scrubbers, making it one of the cleanest coal-fired plants in the US.

Figure 4 : Wireline coring rig (800-ft max) targeting the Big Dirty Seam at the Centralia mine.

Figure 5 : Mining operations in the Smith seam, central Packwood pit, Centralia coal mine.

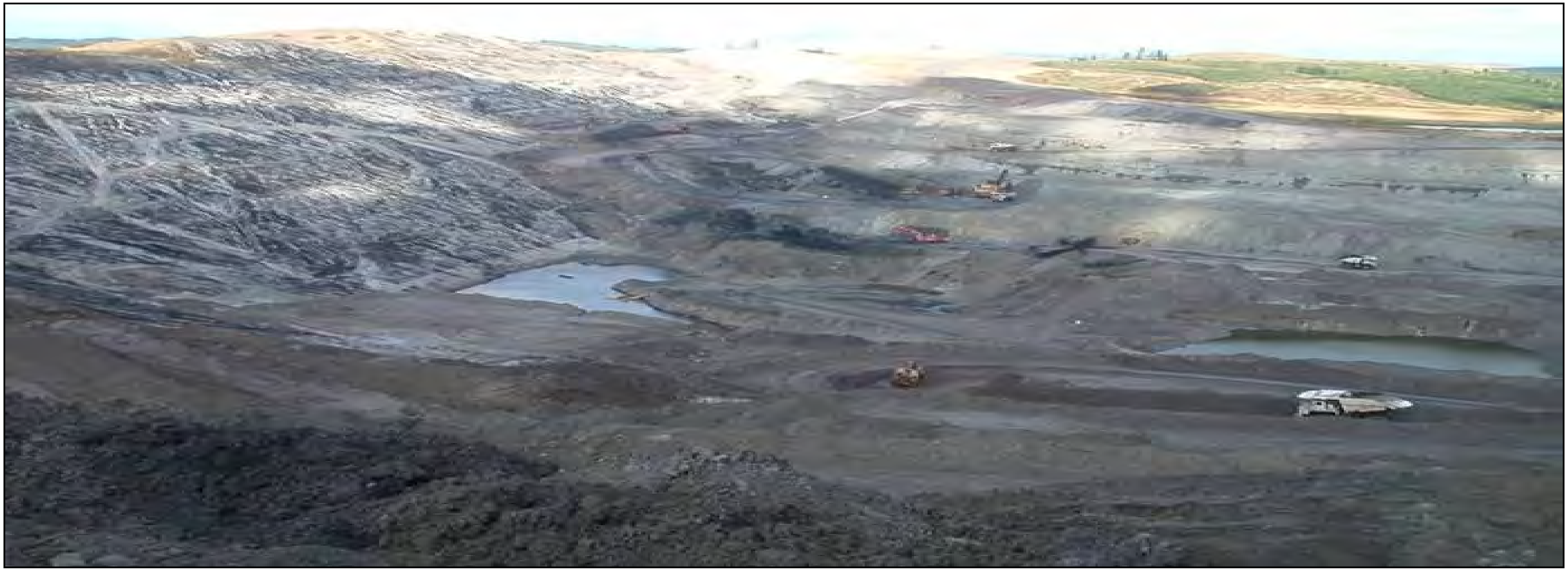


Figure 6 : Reclaimed hillside after mining and prior to reforestation, Centralia coal mine.

Figure 7 : Regional map of southwestern Washington State showing the Centralia coal mine, Jackson Prairie gas storage field, Mist gas field, CBM wells, and deep Shell well

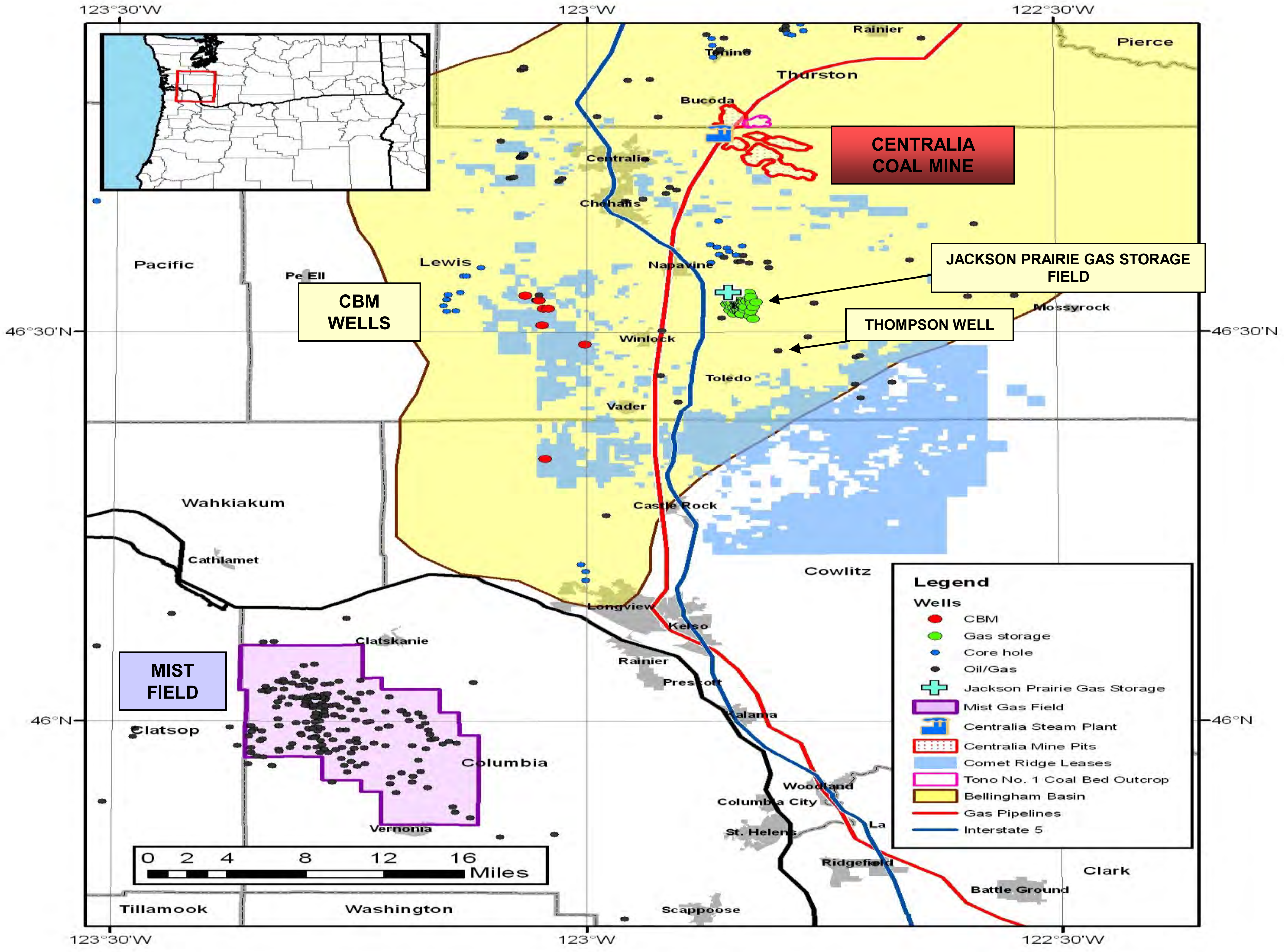


Figure 8 : Geomorphic map of Centralia-Chehalis basin showing Centralia coal mine, cities, power plant, major structural features, and significant petroleum wells.

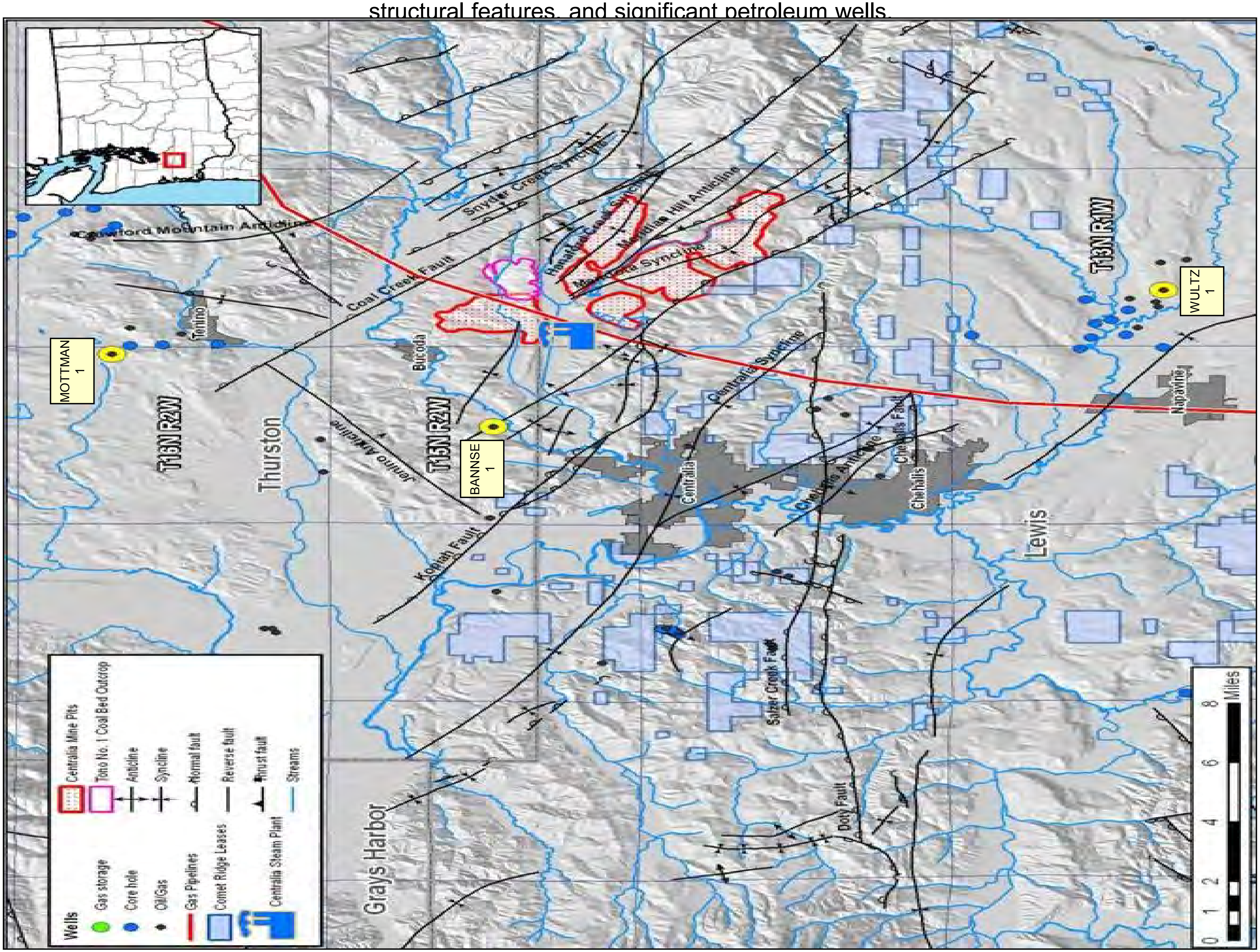


Figure 9 : Coalbed methane exploration wells in west-central Washington State.

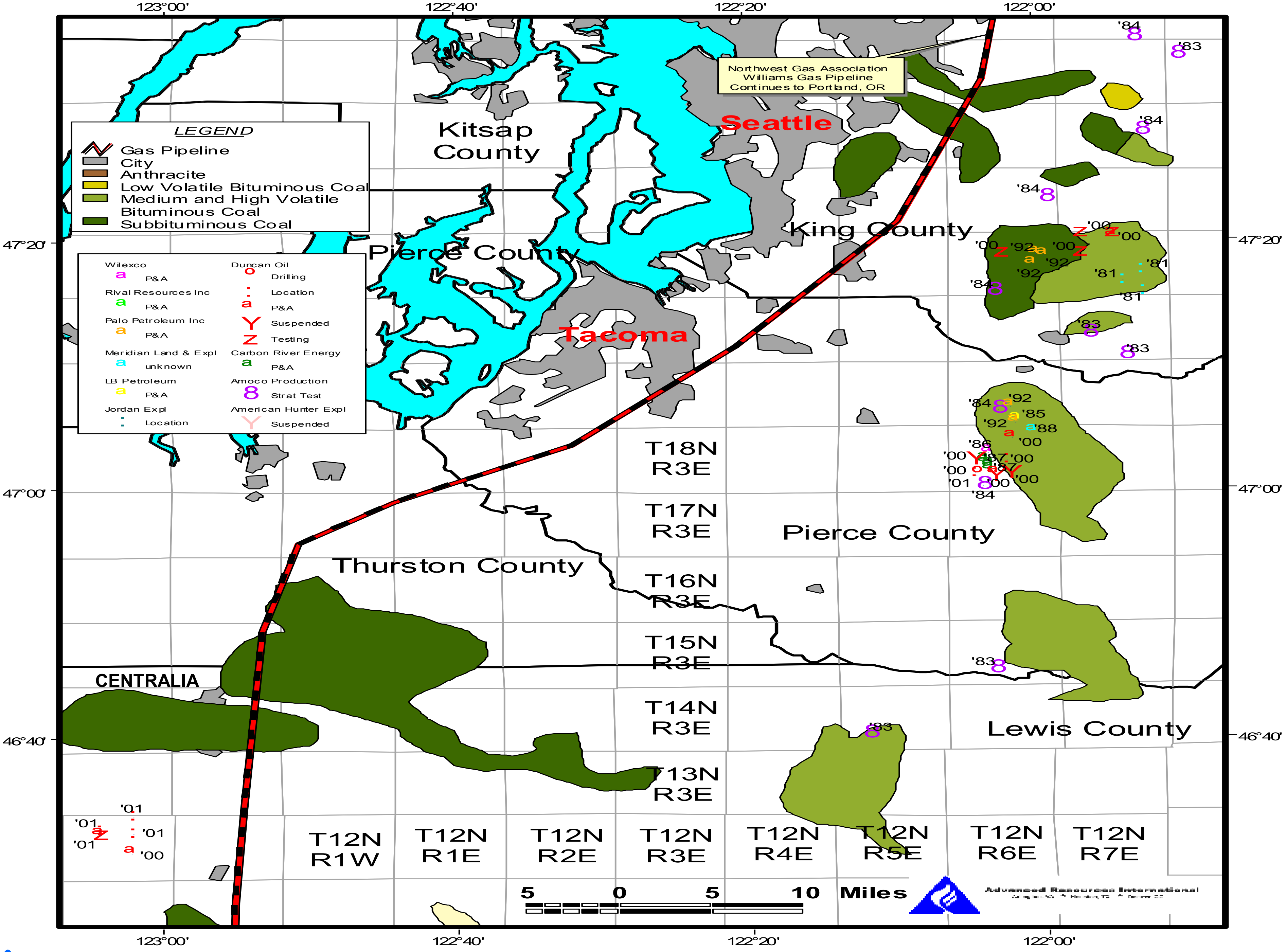


Figure 10a : Well log from Duncan Oil #3 coalbed methane exploration well (28-18N-6E, Pierce County, Washington). A total of 19 seam were penetrated for nominal 37 m (120 ft) of coal. Coal seam dips ranged from 15-80º (avg 34º), making true coal thickness 30 m (99 ft).

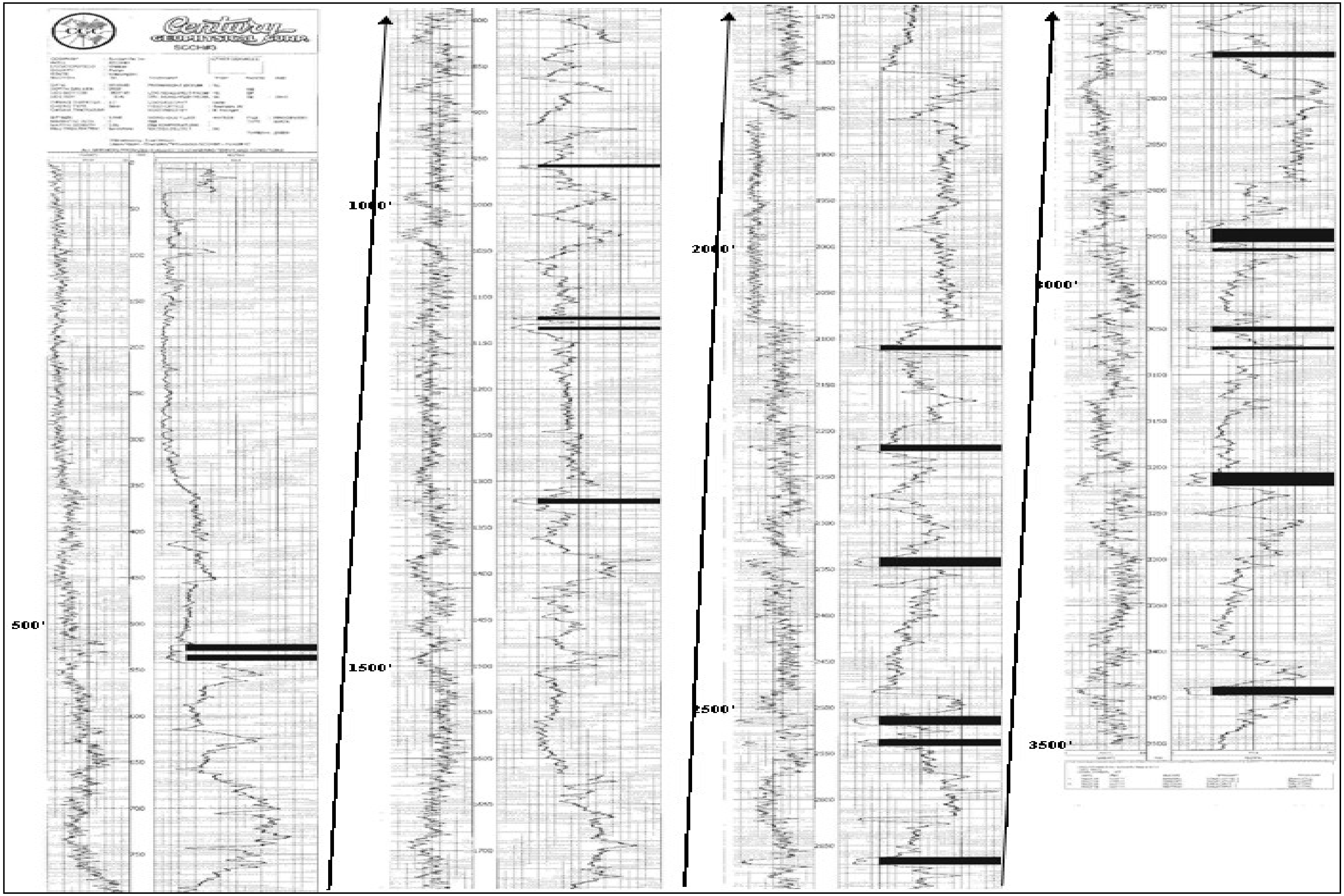


Figure 10b : Well log from Duncan Oil #3 coalbed methane exploration well (28-18N-6E, Pierce County, Washington). A total of 19 seam were penetrated for nominal 37 m (120 ft) of coal. Coal seam dips ranged from 15-80º (avg 34º), making true coal thickness 30 m (99 ft).

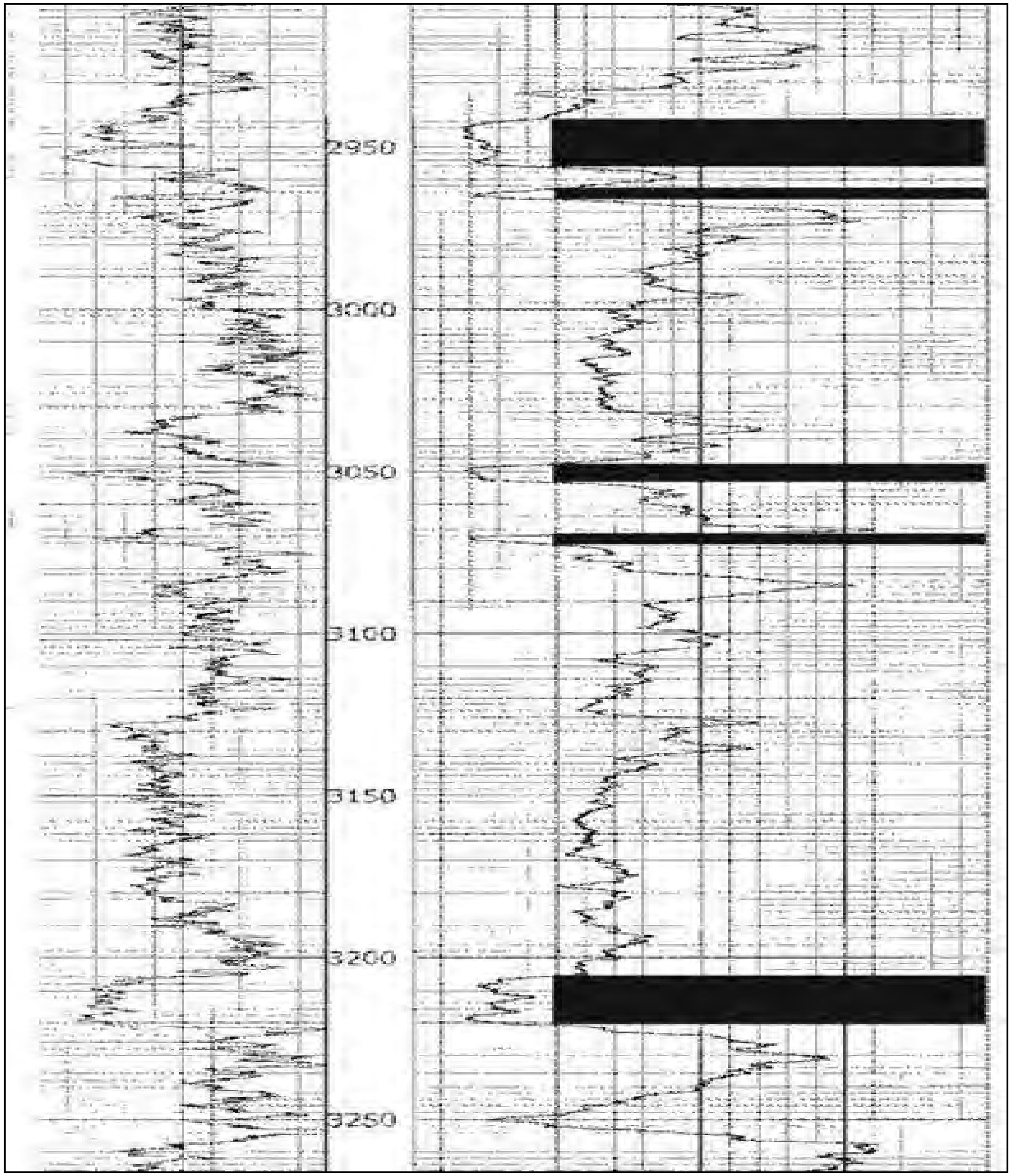


Figure 11 : Coalbed methane well operations, El Paso Inc. Carbonado pilot area.

Source : McHenry et al., 2003

Figure 12 : Coalbed methane completed wellhead, El Paso Inc. Carbonado pilot area.

Source : McHenry et al., 2003

Figure 13 : Coalbed methane wells in Coos Bay basin, Oregon

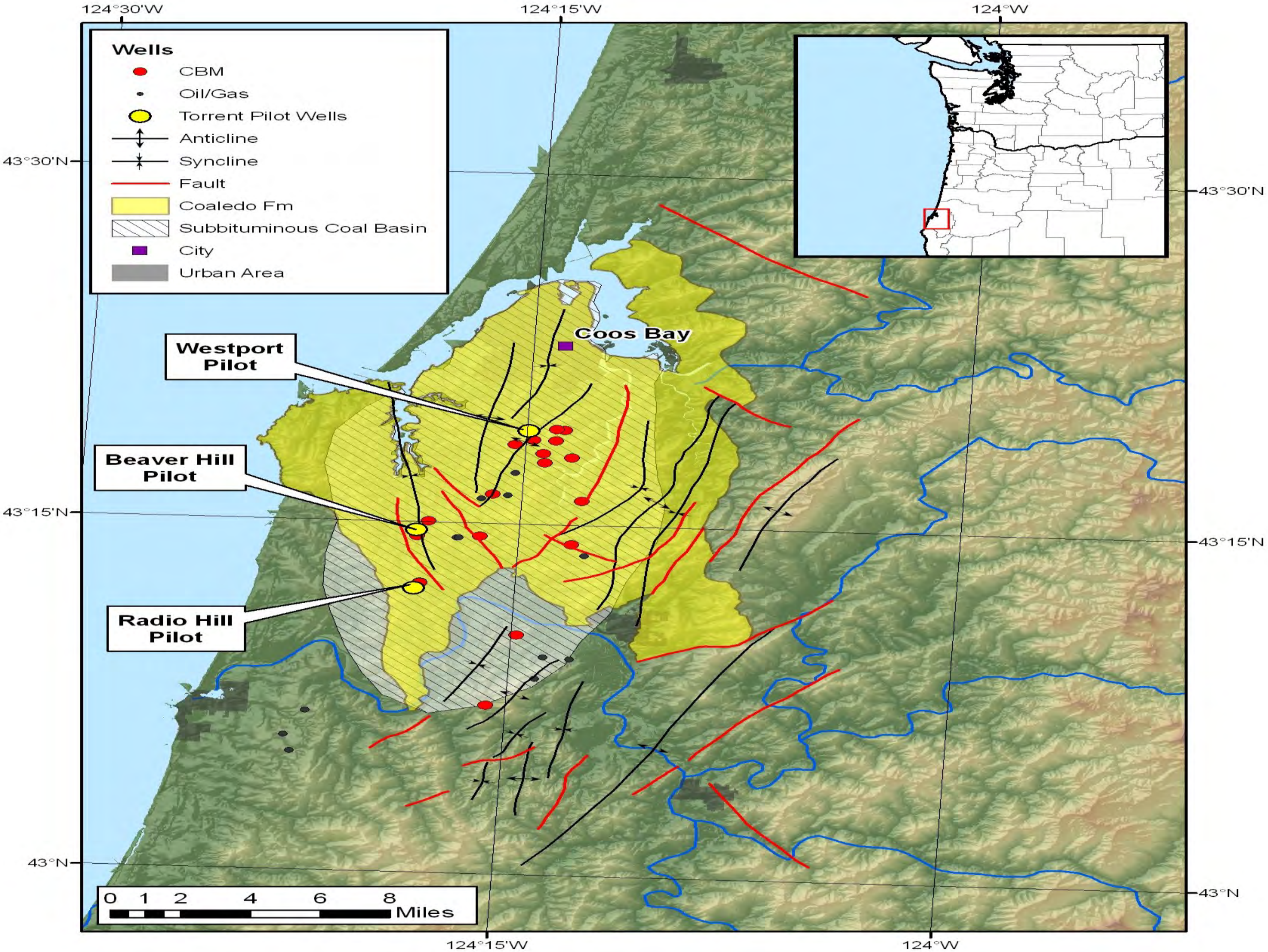
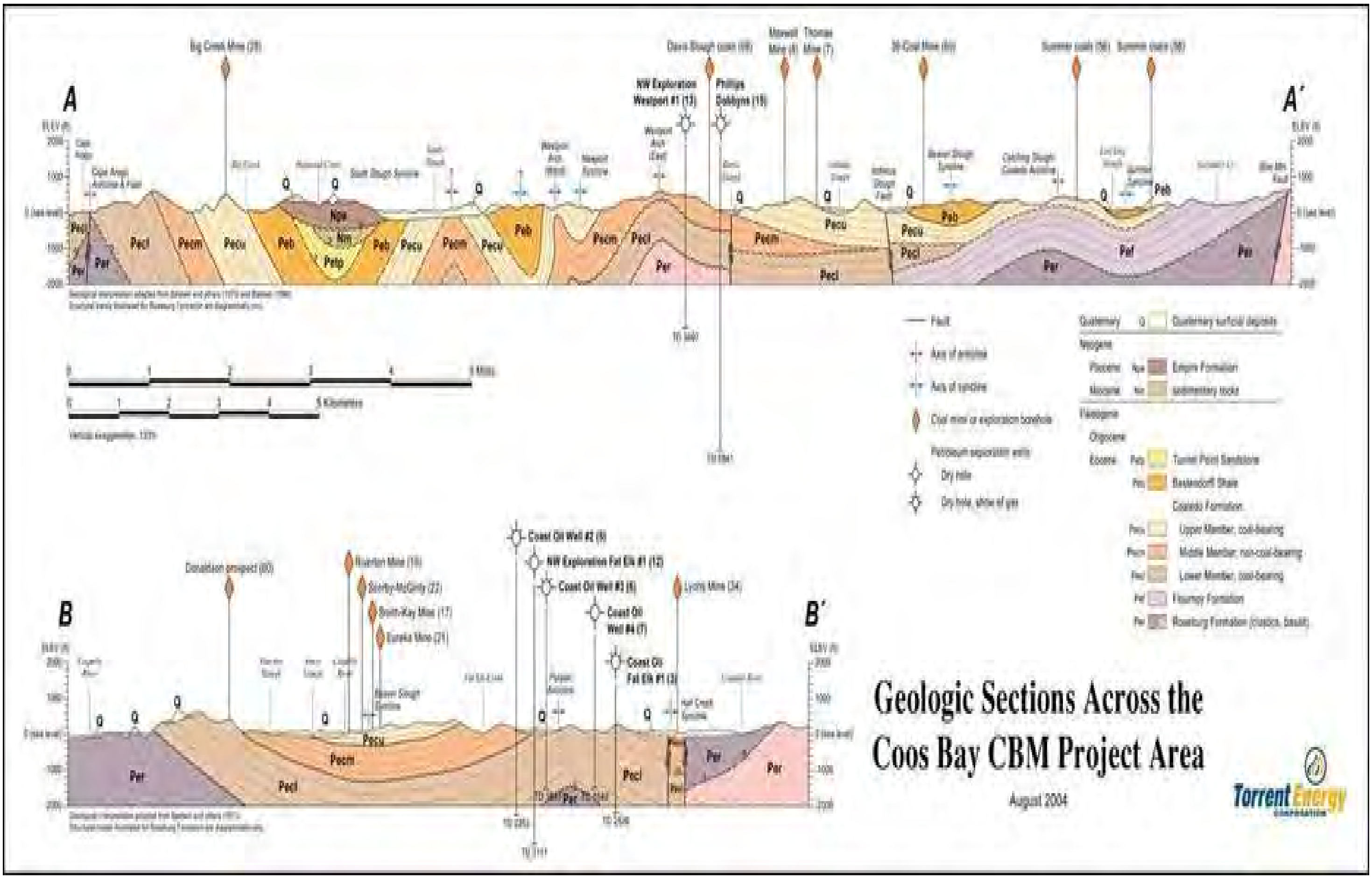
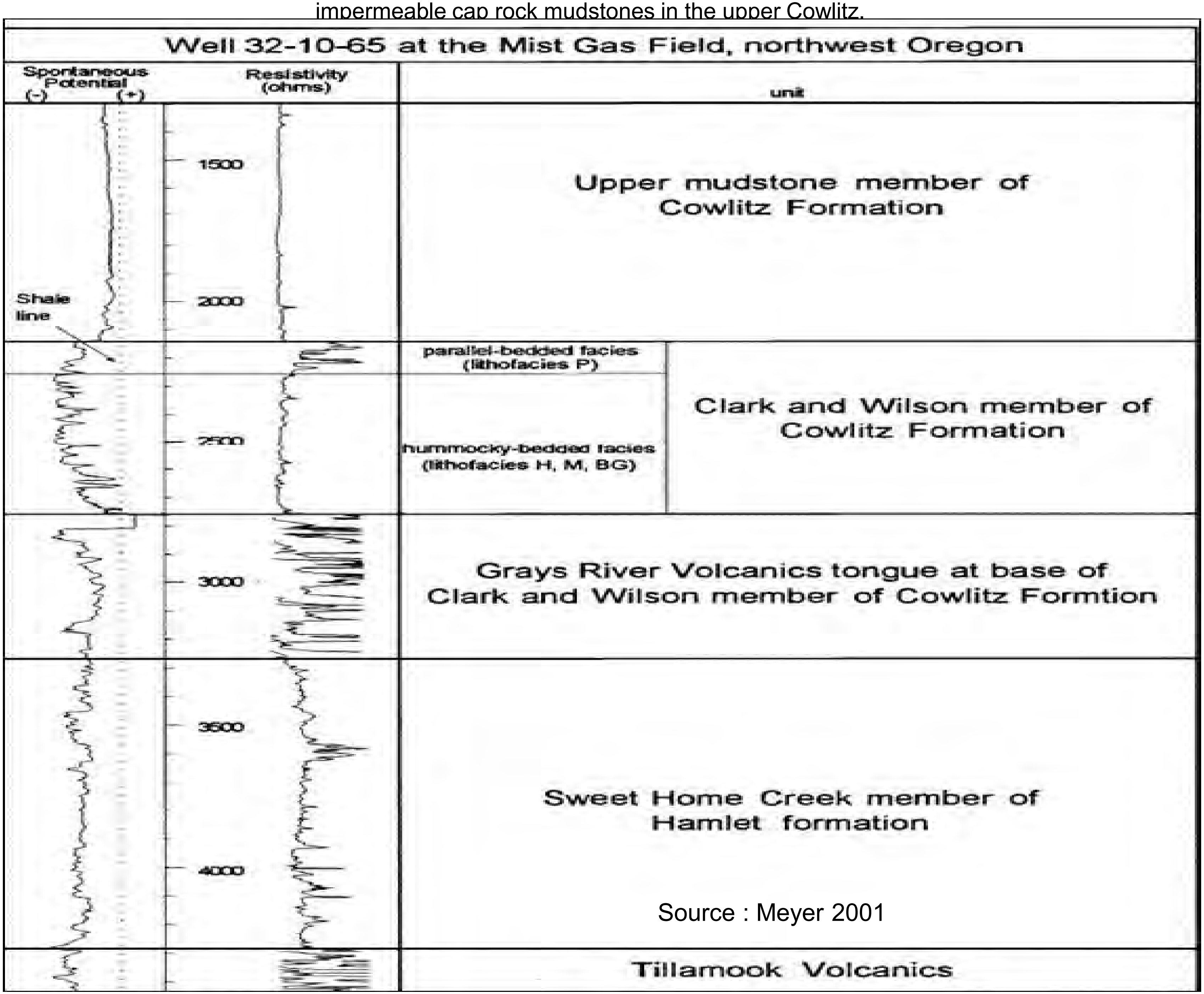


Figure 14 : Geologic cross-section across Torrent Energy's Coos Bay CBM project, Oregon.



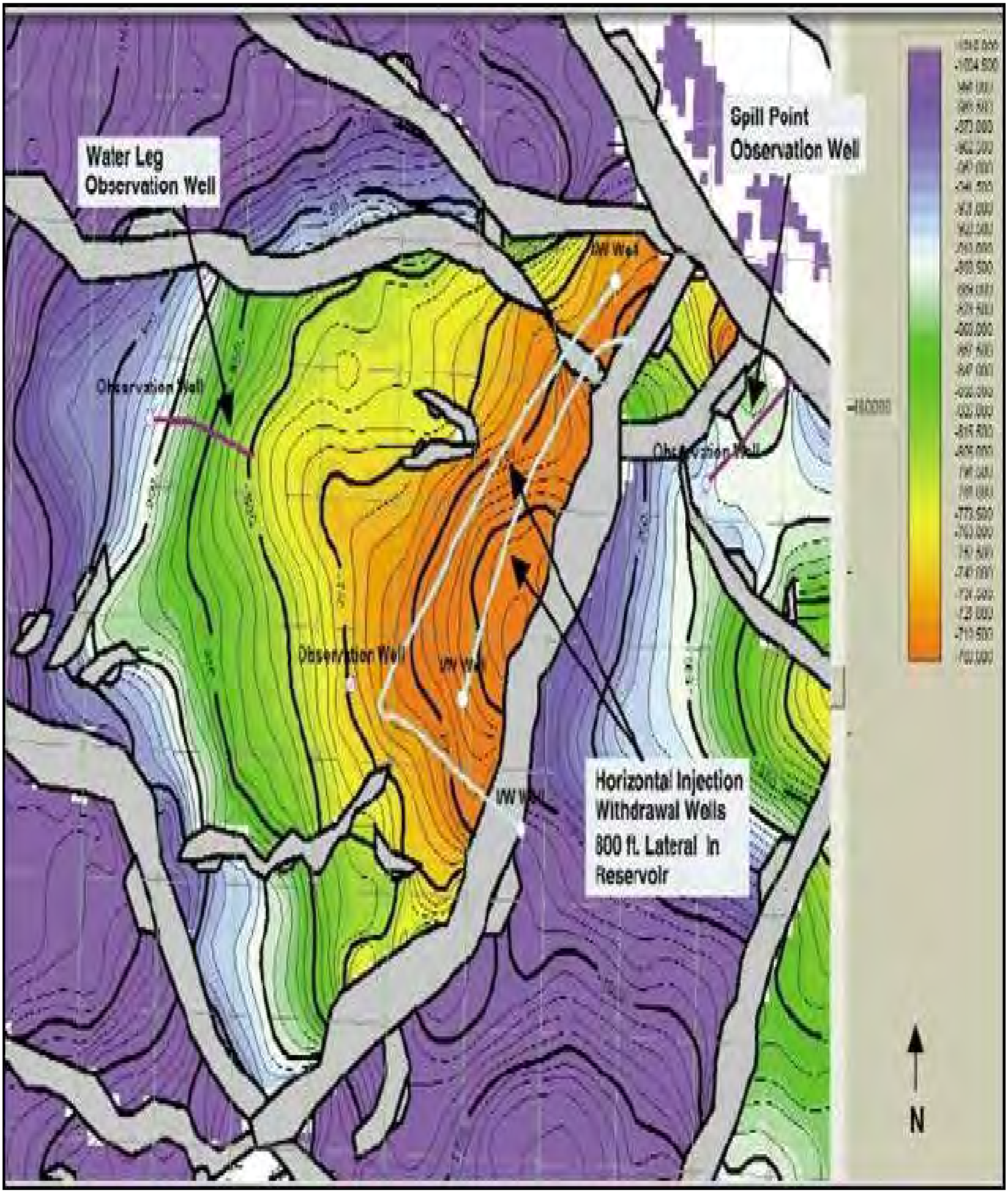
Source : Torrent Energy

Figure 15 : Well log from Mist gas field, Oregon, showing porous Clark/Wilson reservoir sandstones, Eocene Cowlitz Fm, overlain by impermeable cap rock mudstones in the upper Cowlitz.



Source : Meyer 2001

Figure 16 : Structural contour map on the structurally complex reservoir sandstone in the Eocene Cowlitz Formation at Mist gas storage field, Oregon. Storage targets in sandstones and coal seams at Centralia are expected to have comparable structural complexity.



Source : Meyer 2001

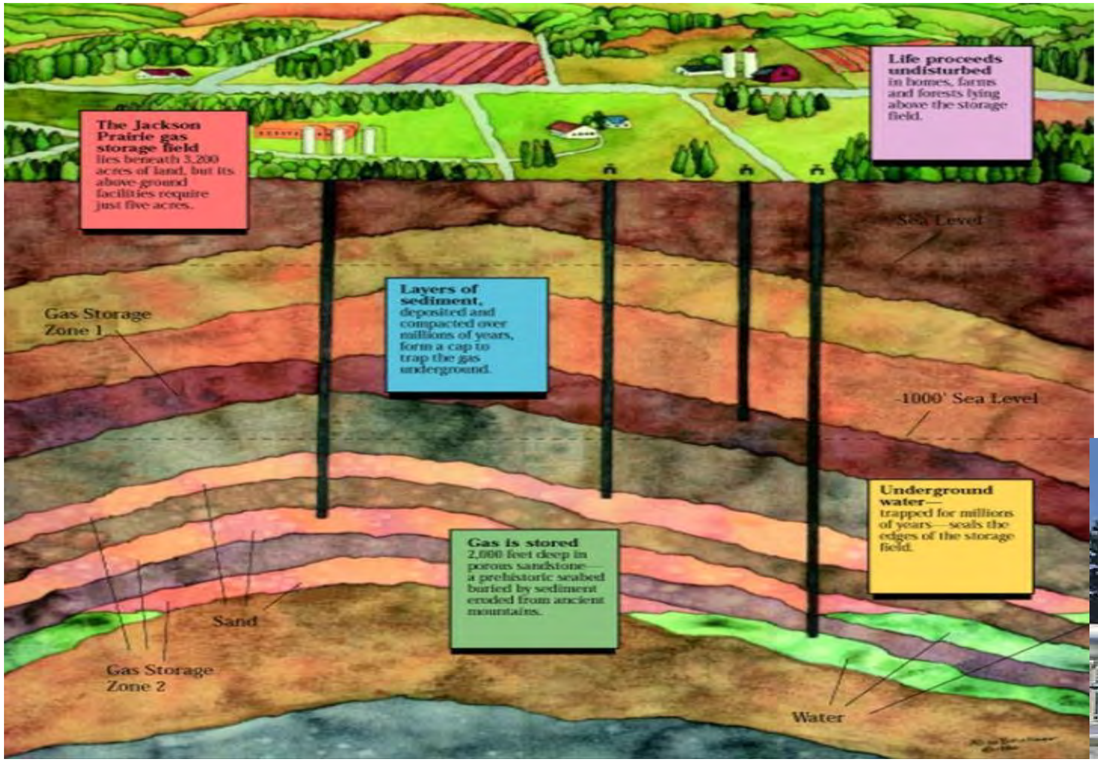


Figure 17 : Jackson Prairie underground gas storage field :

a) diagrammatic cross section

b) Aerial view of the field

c) Natural gas facilities

Source : Puget Sound Energy, 2008

Figure 18 : Detailed structure map of Tono basin, Centralia coal mine, showing surface geology, many small faults, and underground coal gasification coreholes (yellow).

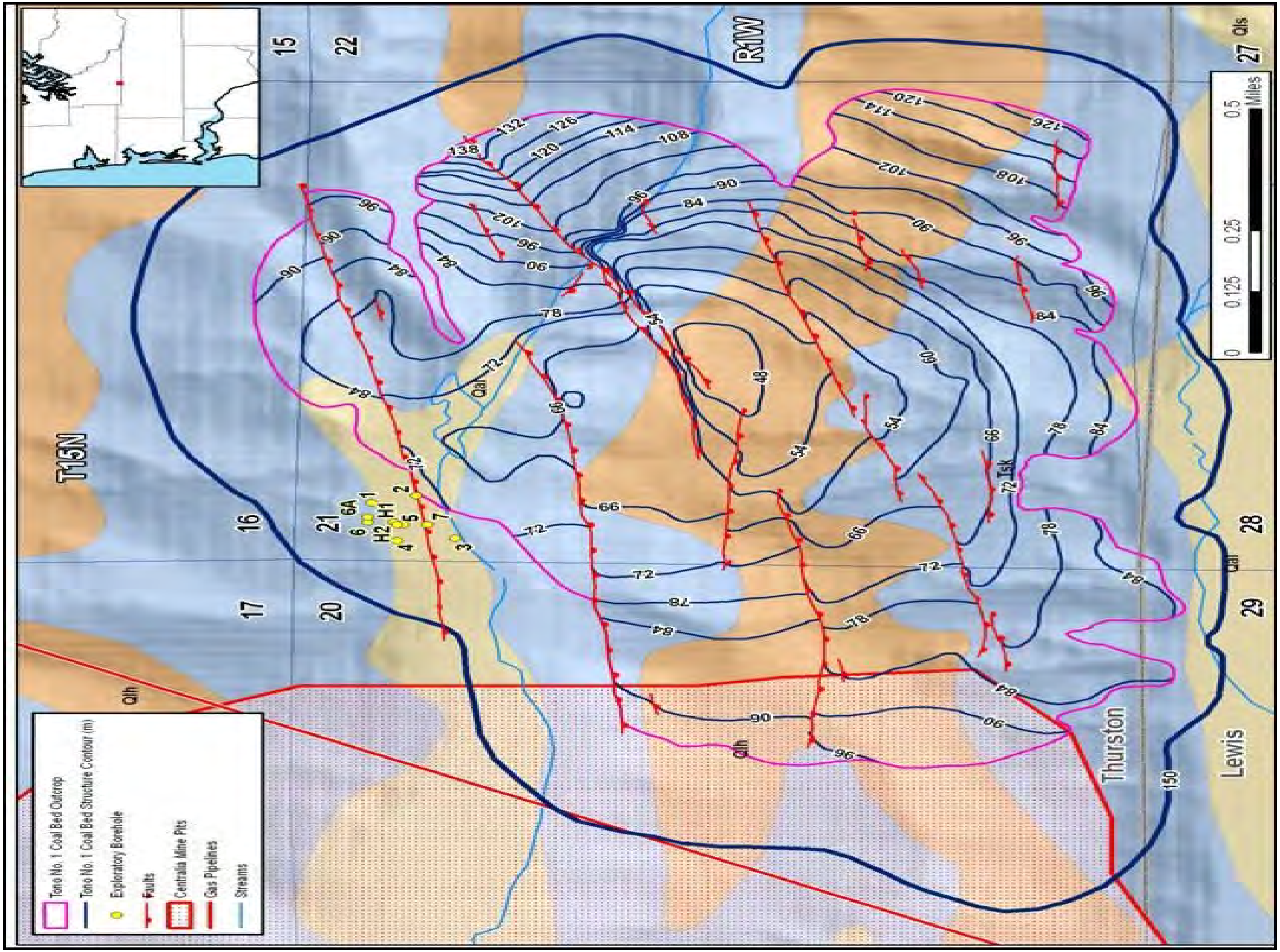


Figure 19 : Surface geology, structure, wells in the Centralia-Chehalis coal basin

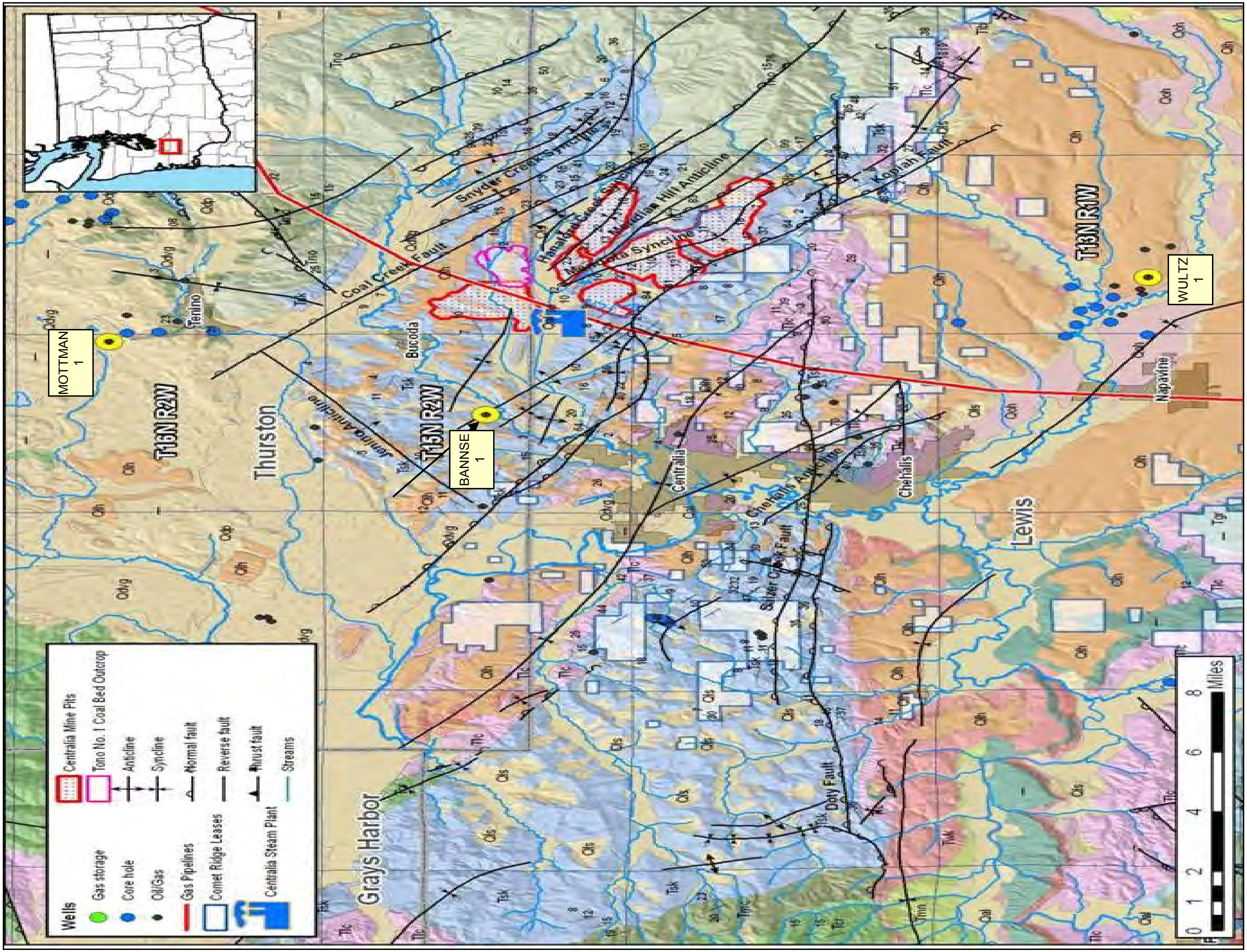
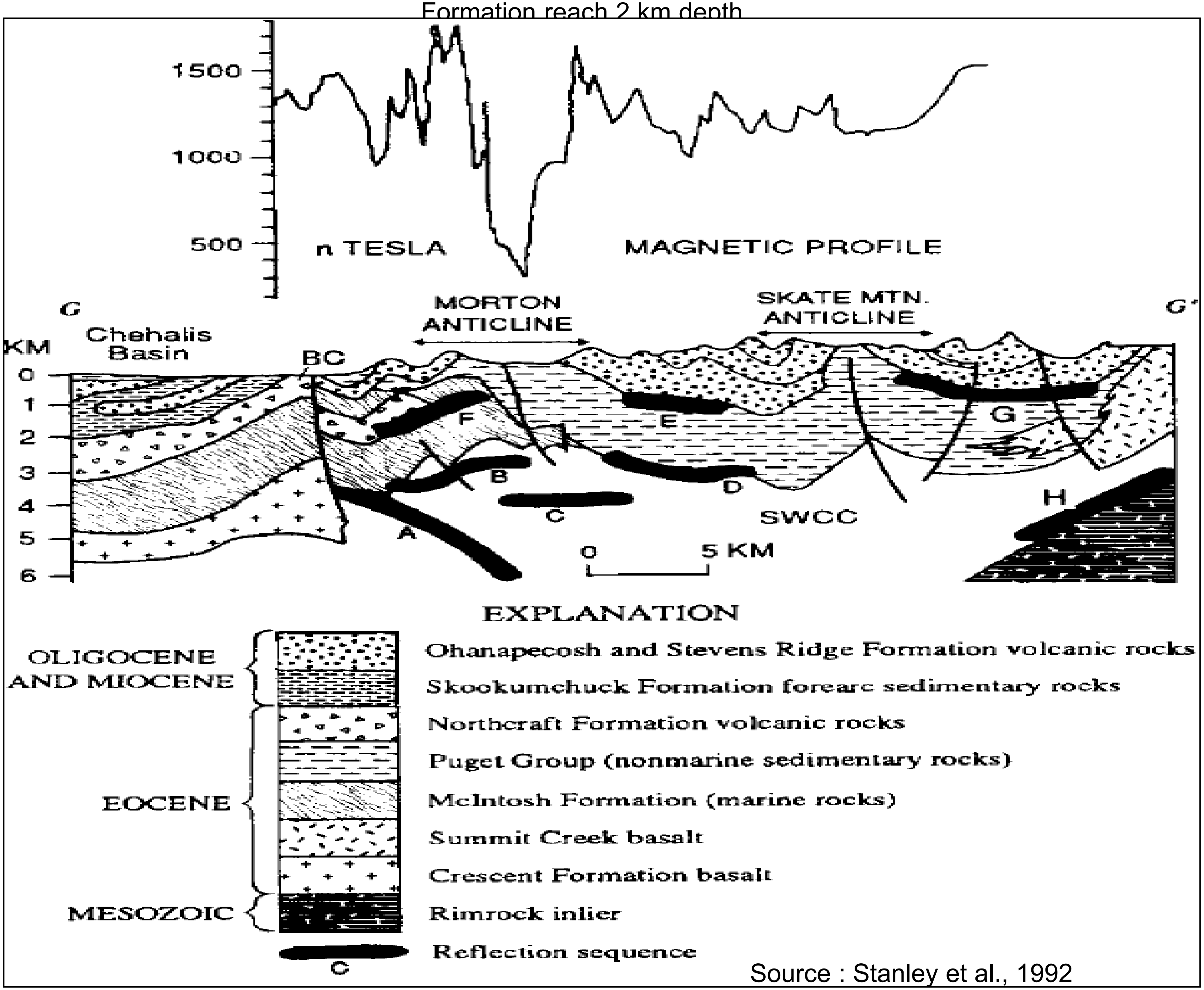
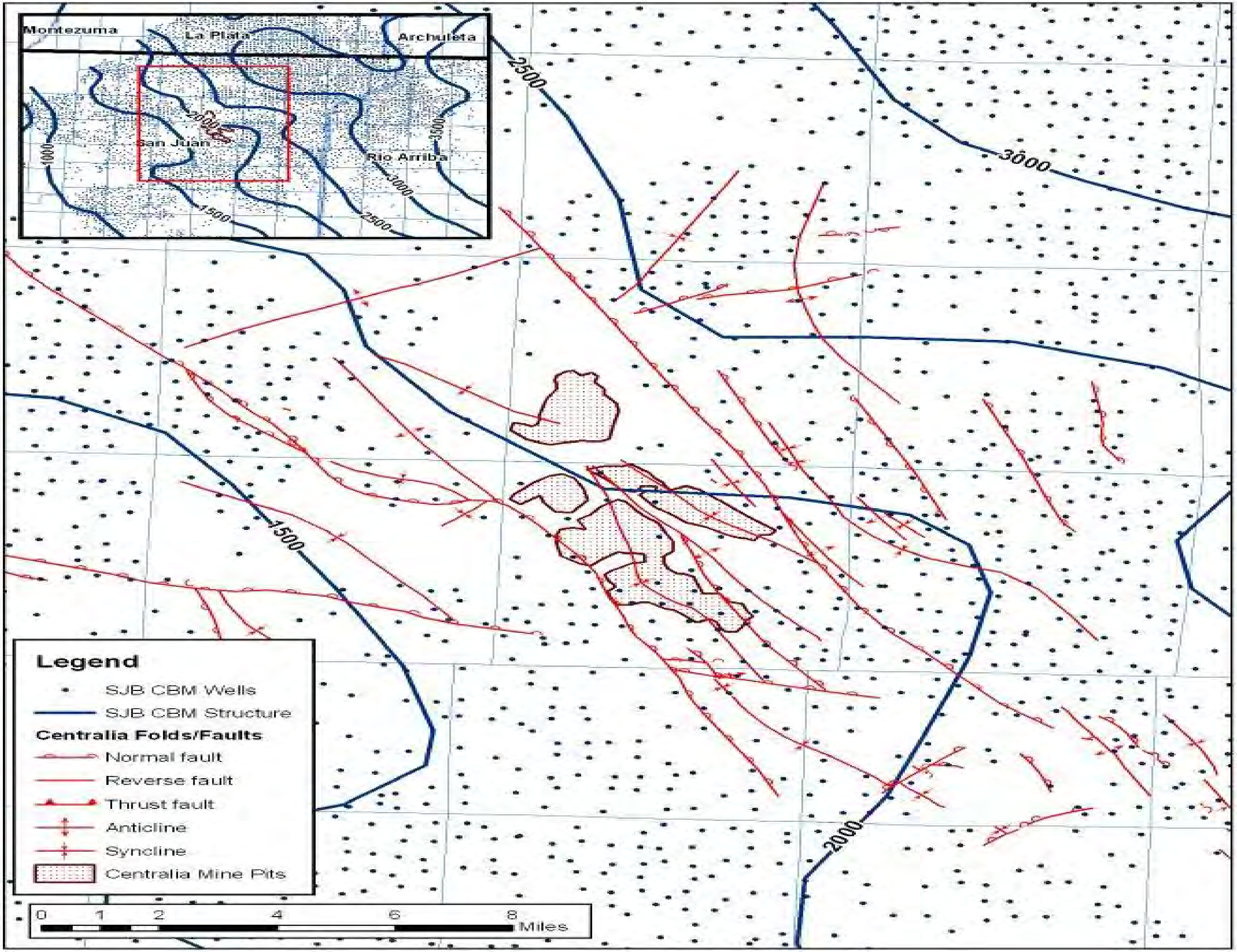


Figure 20 : Regional cross section interpretation based on electromagnetics, showing a total 3-5 km of sedimentary rocks resting on basaltic basement in the Chehalis basin. Coal seams and saline aquifers in the Skookumchuck Formation reach 2 km depth



Source : Stanley et al., 1992

Figure 21 : Comparison of Centralia (red) with a typical developed CBM basin (San Juan basin; blue), illustrating Centralia's smaller relative size and greater structural complexity.



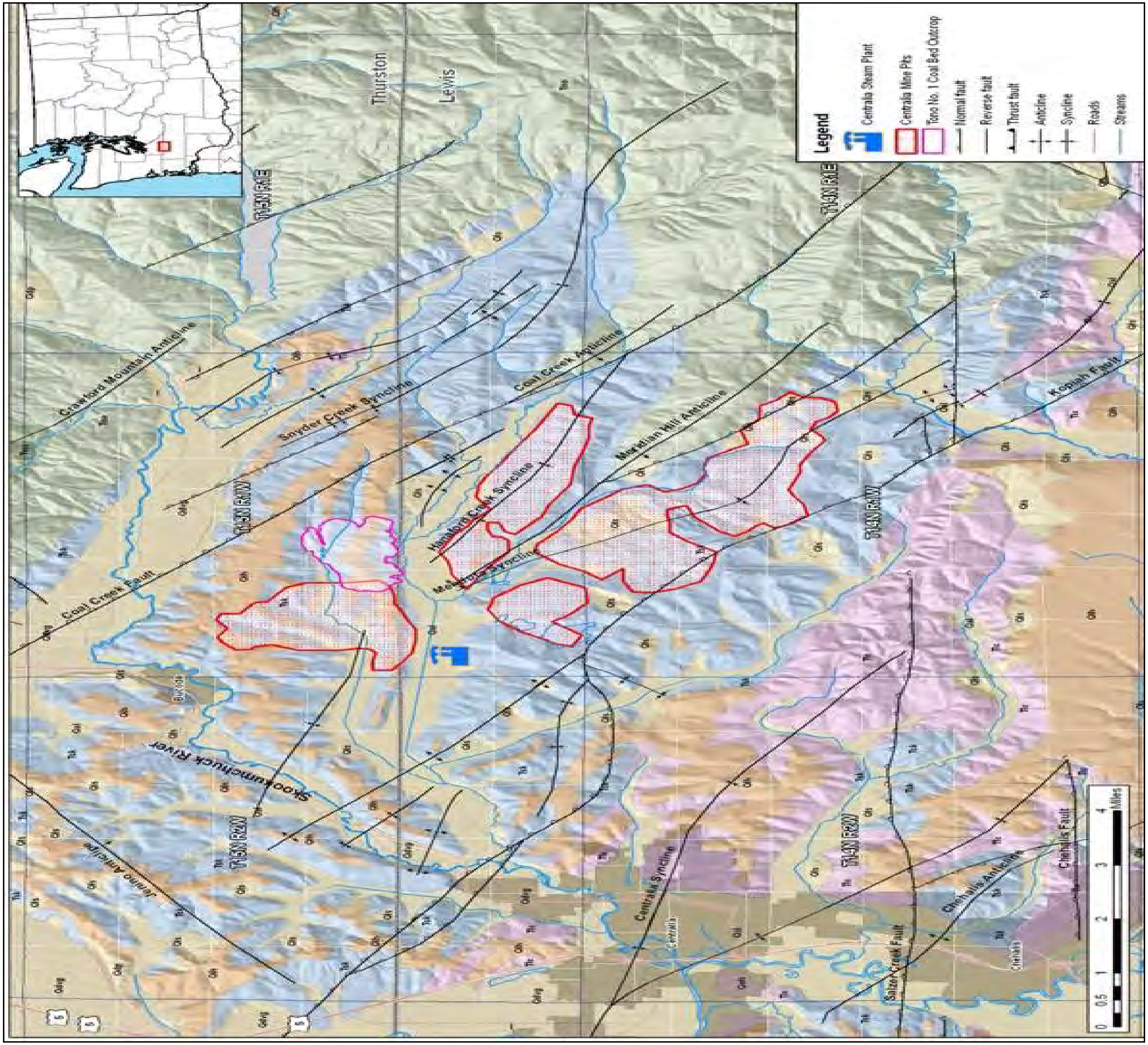
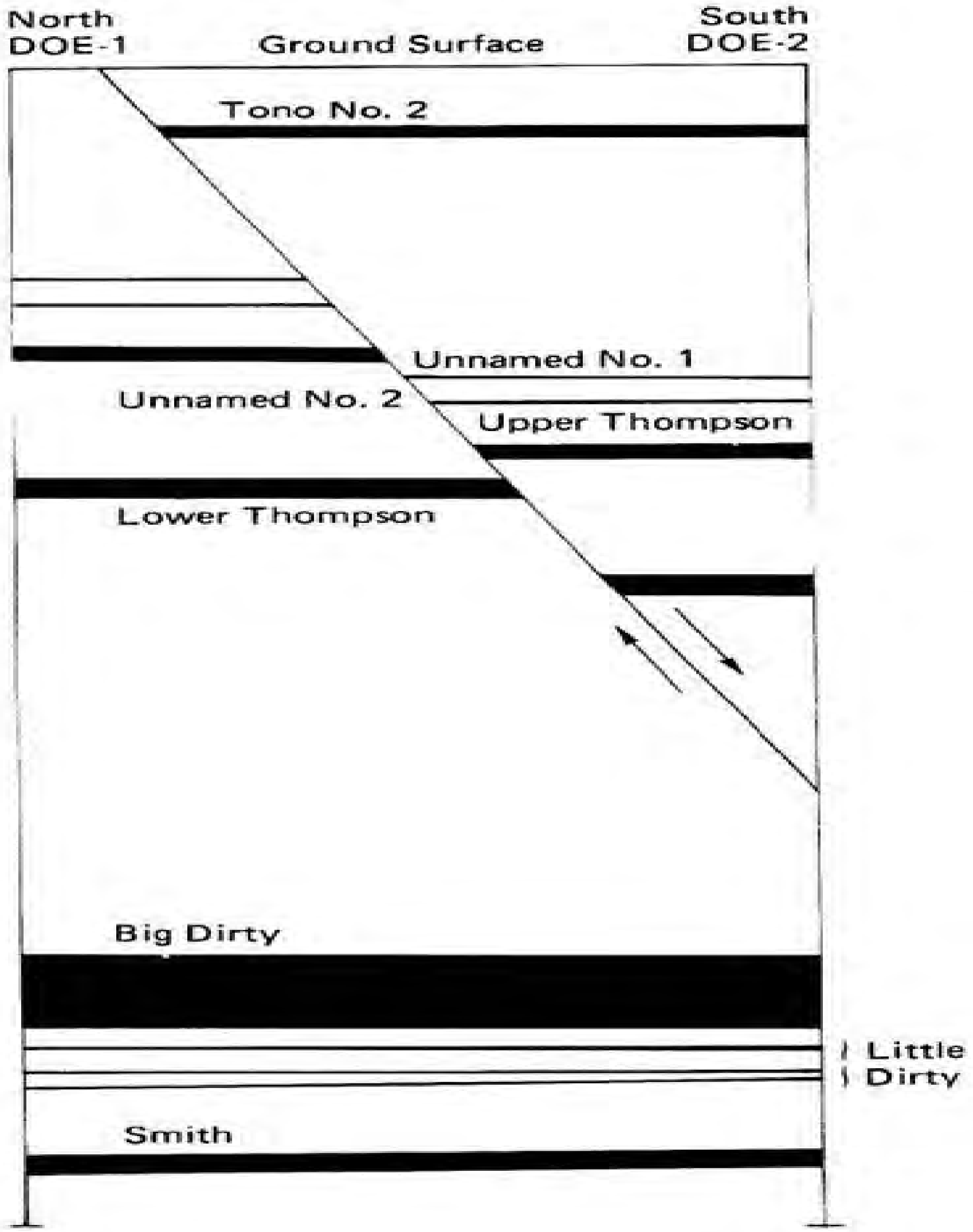


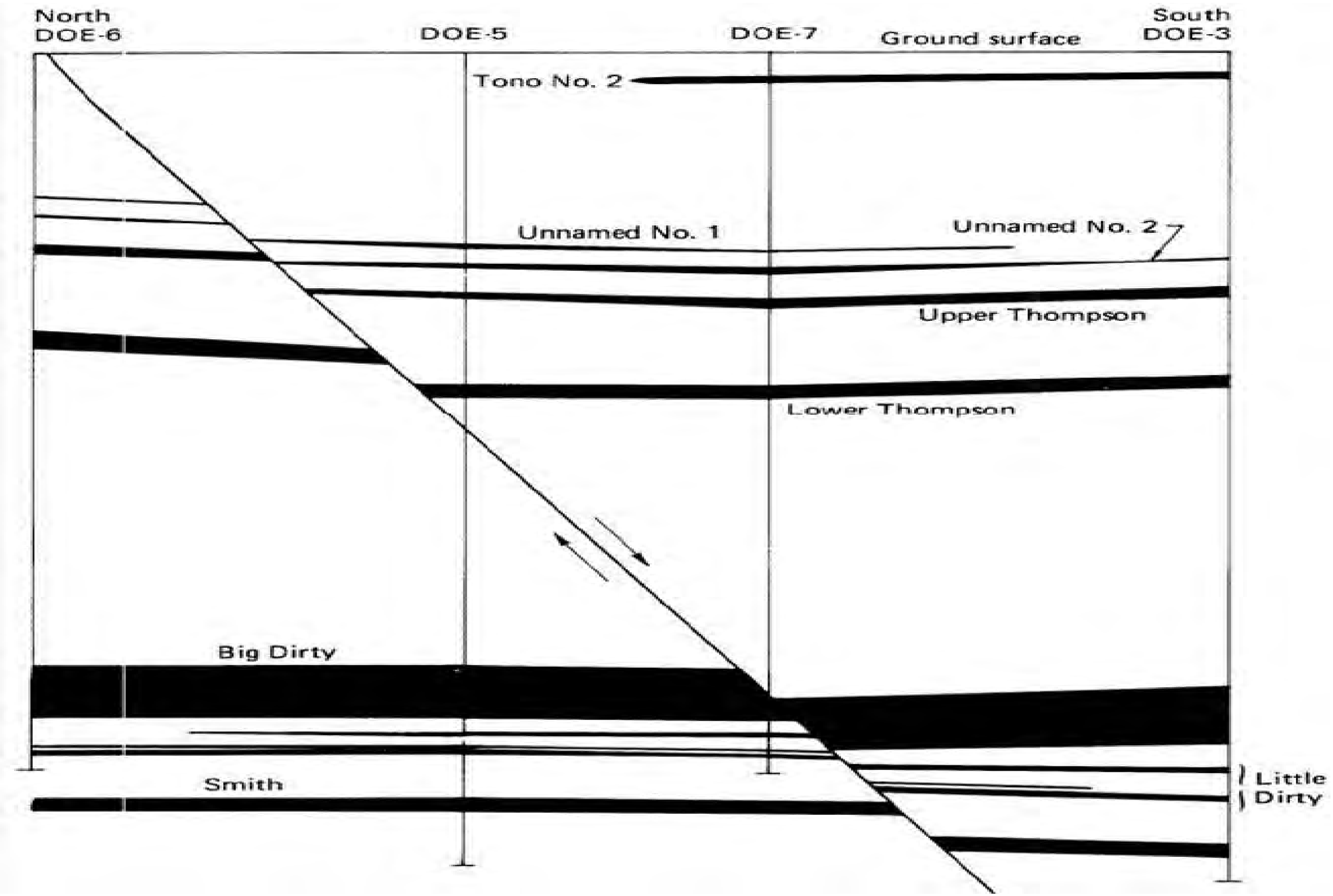
Figure 22 : Surface geology and structural features of the Centralia coal mine area.

Figure 23 : Normal fault between boreholes DOE-1 and -2 at the Tono pit, Centralia coal mine. The fault was not identified by surface seismic or other geophysical methods.



Source : Bartel and Love, 1981

Figure 24 : Normal fault through boreholes DOE-6, -5, -7, and -3 at the Tono pit, Centralia coal mine. The fault was not identified by surface seismic or other geophysical methods.



Source : Bartel and Love, 1981

Figure 25 : Earthquake distribution map of Washington. Centralia is a fairly inactive area.

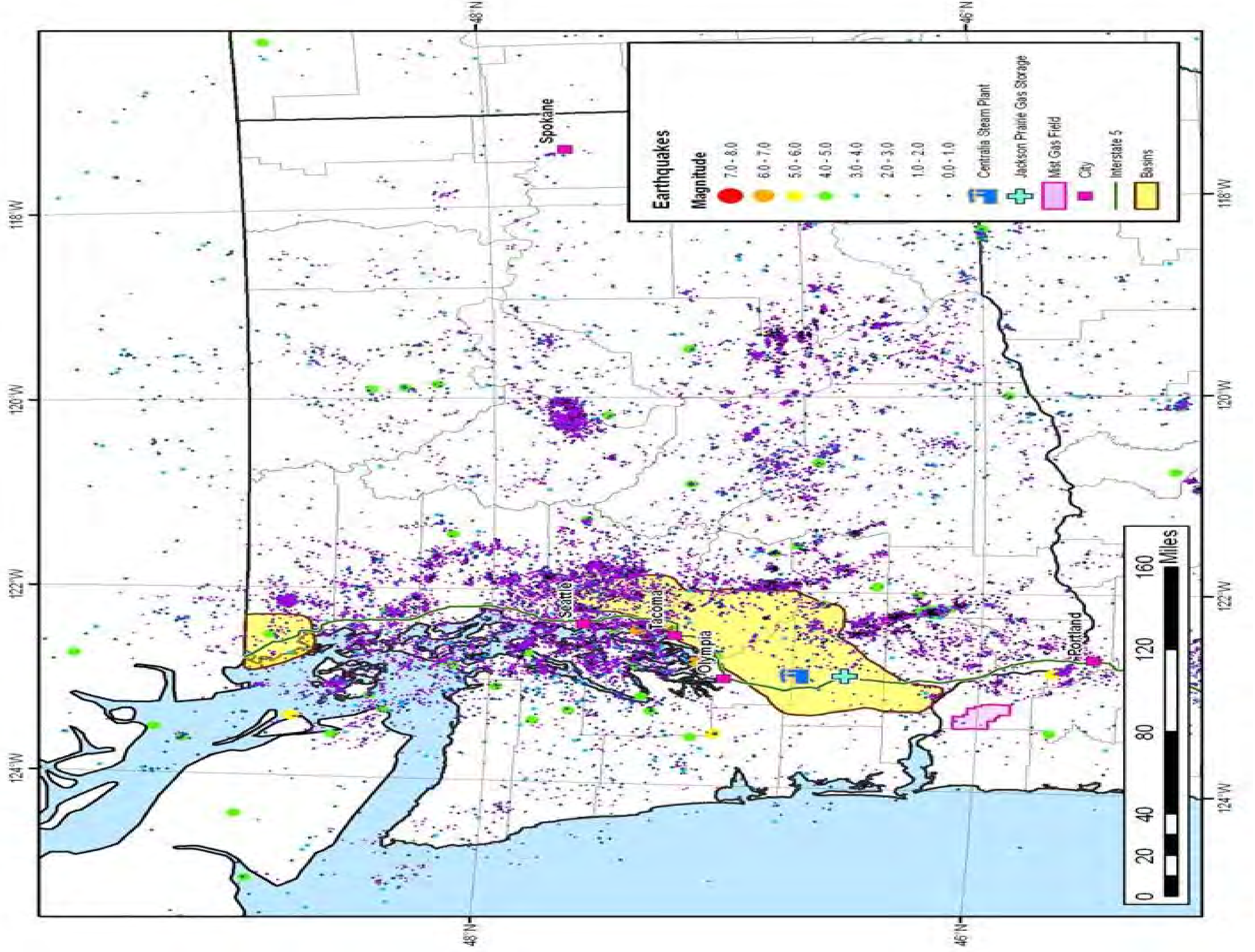


Figure 26 : Earthquake distribution map of central Washington. A few small (mag 2-3) events have occurred near the Centralia coal mine, with more activity 30 km SE near the Cascades.

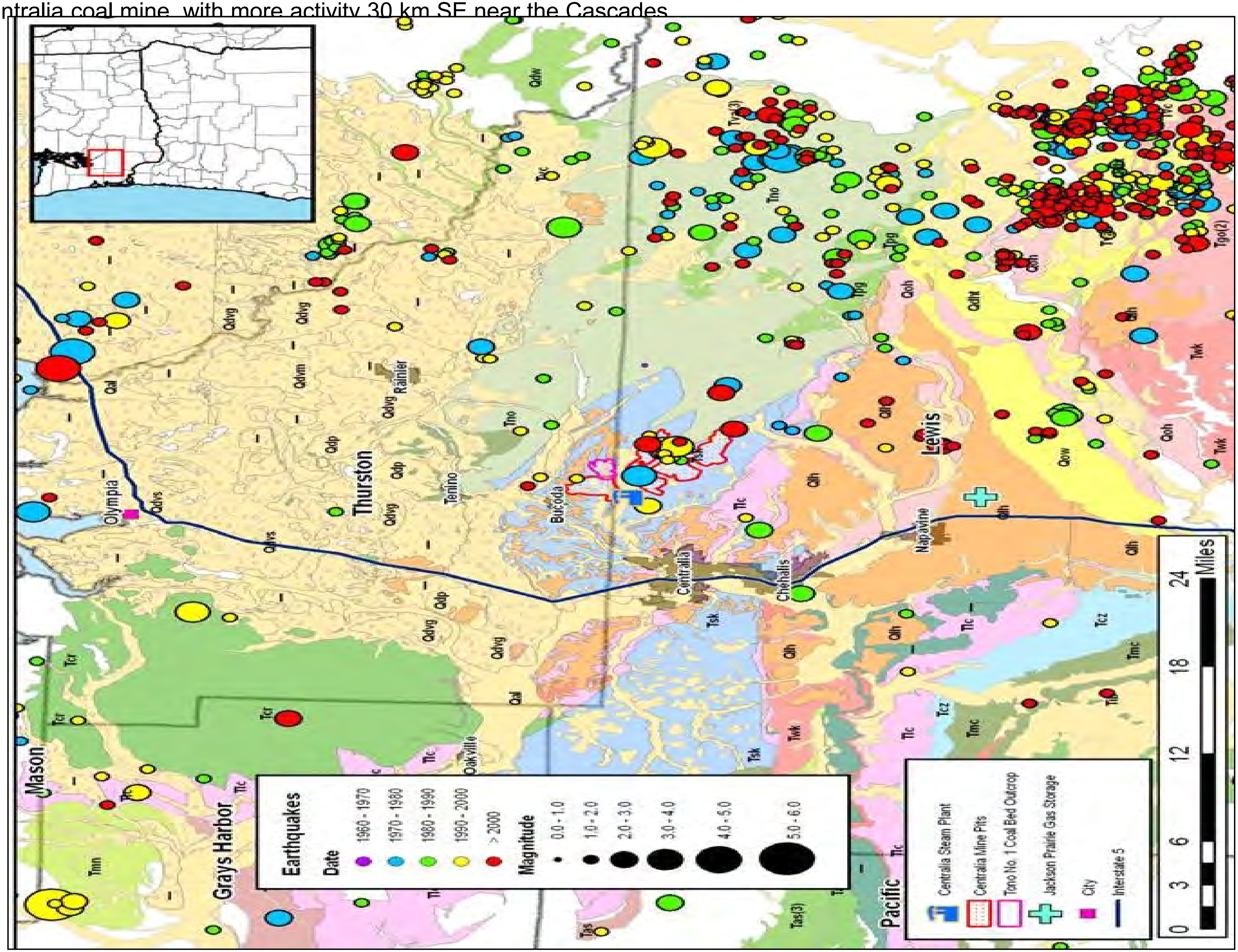


Figure 27 : Generalized tratigraphic chart for coal fields in the state of Washington, showing the primary target for CO_2 storage – the Big Dirty seam.

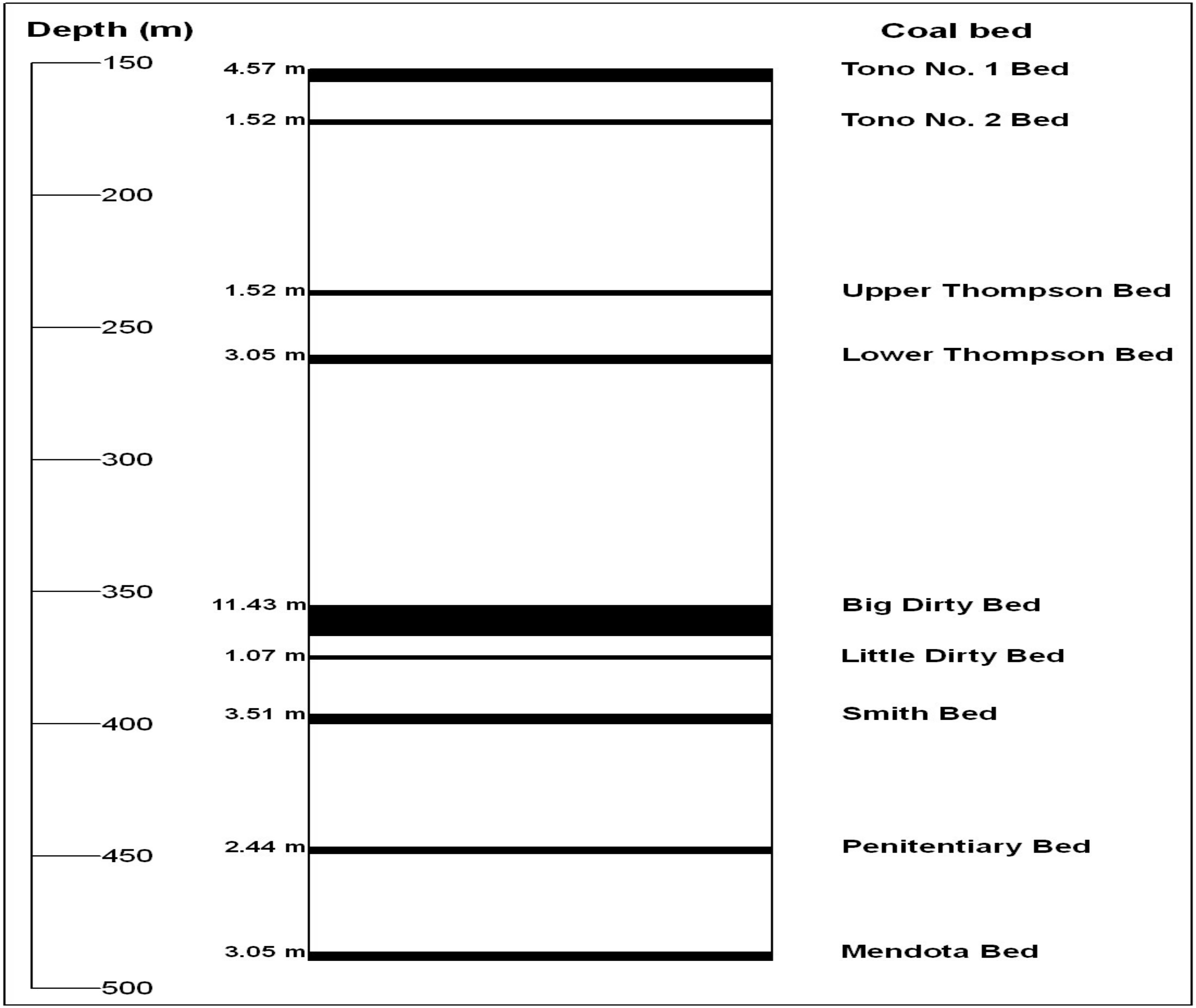
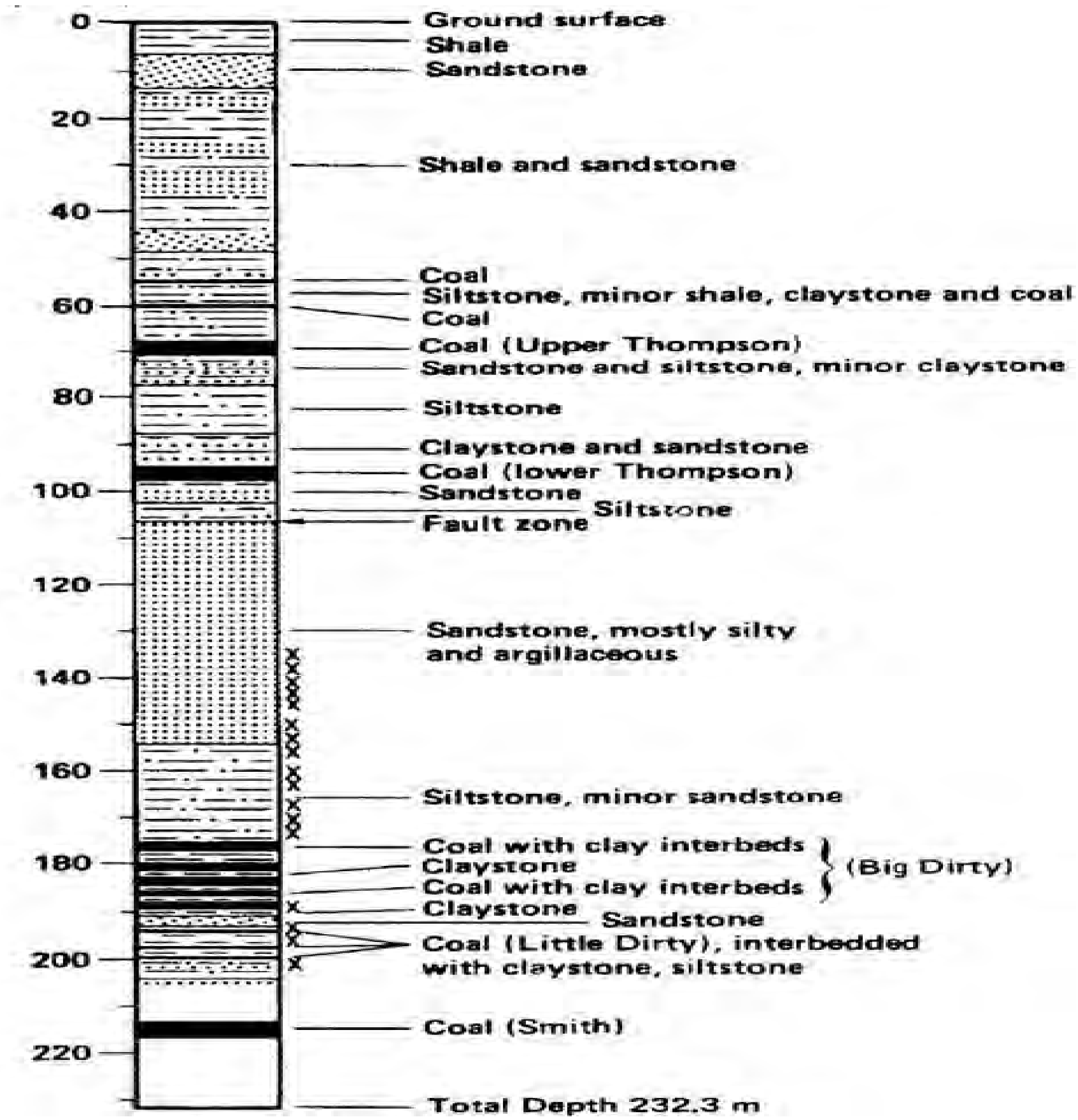
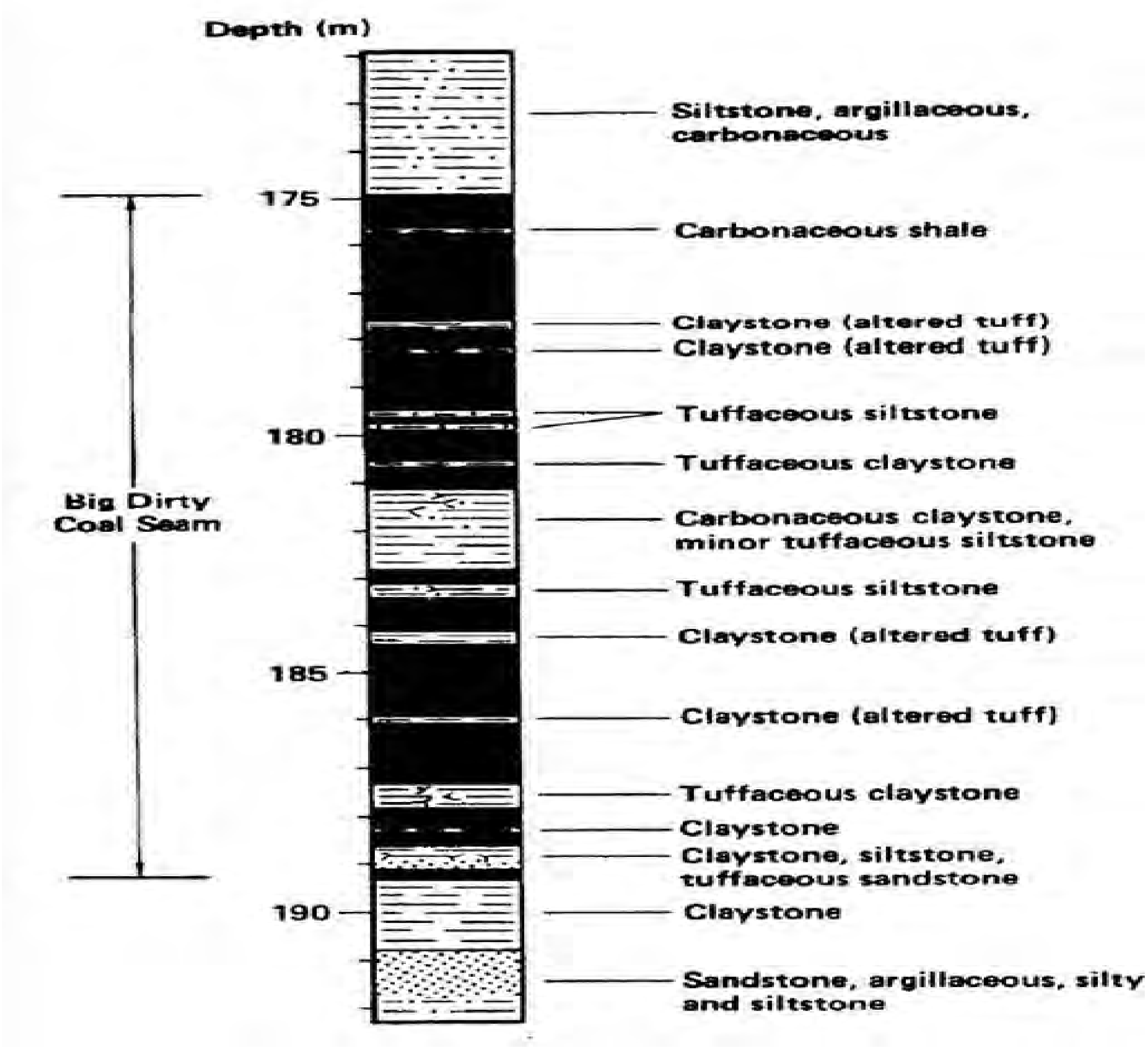


Figure 28 : Stratigraphic section for borehole DOE-5 at the Tono pit, Centralia coal mine.



Source : Bartel and Love, 1981

Figure 29 : Detailed stratigraphy of the Big Dirty seam, borehole DOE-5, Tono pit, Centralia coal mine.



Source : Bartel and Love, 1981

Figure 30 : 3-m thick Lower Thompson Seam at the Centralia mine.

Figure 31 : 15-m thick Big Dirty Seam at the Centralia mine, with white bentonite tuff parting.

Figure 32 : Aerial photo of Centralia coal mine showing the extent of surface mining and individual seam outcrops. The mine is currently being refilled and reforested.

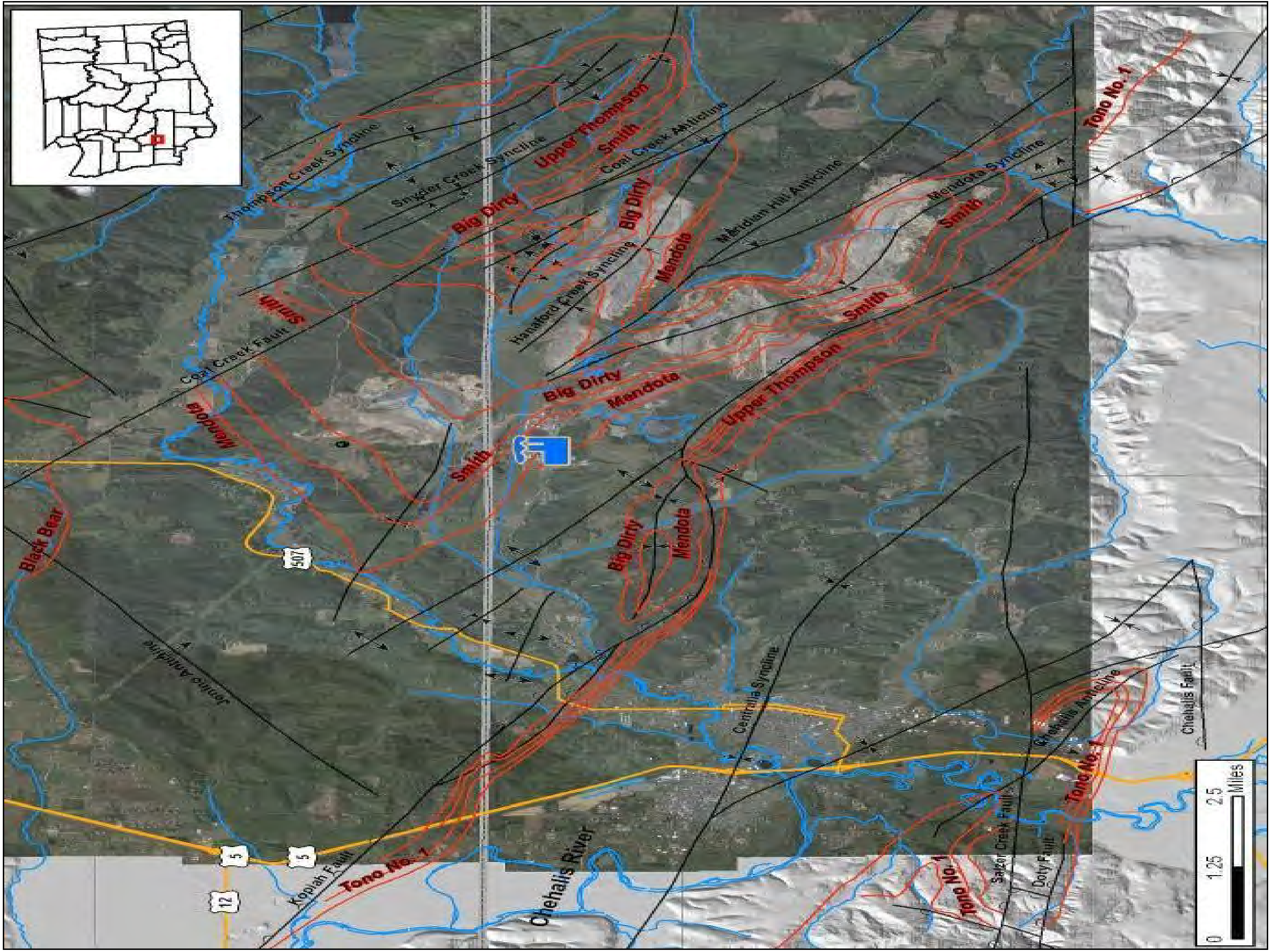
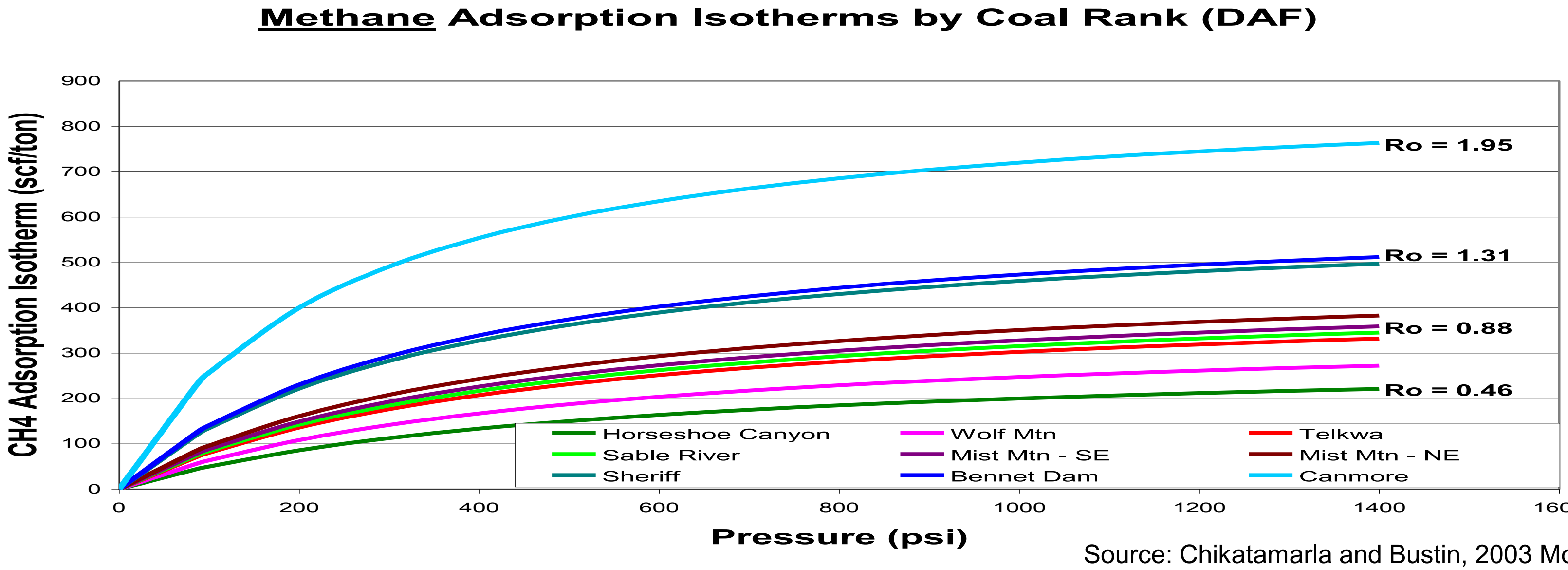
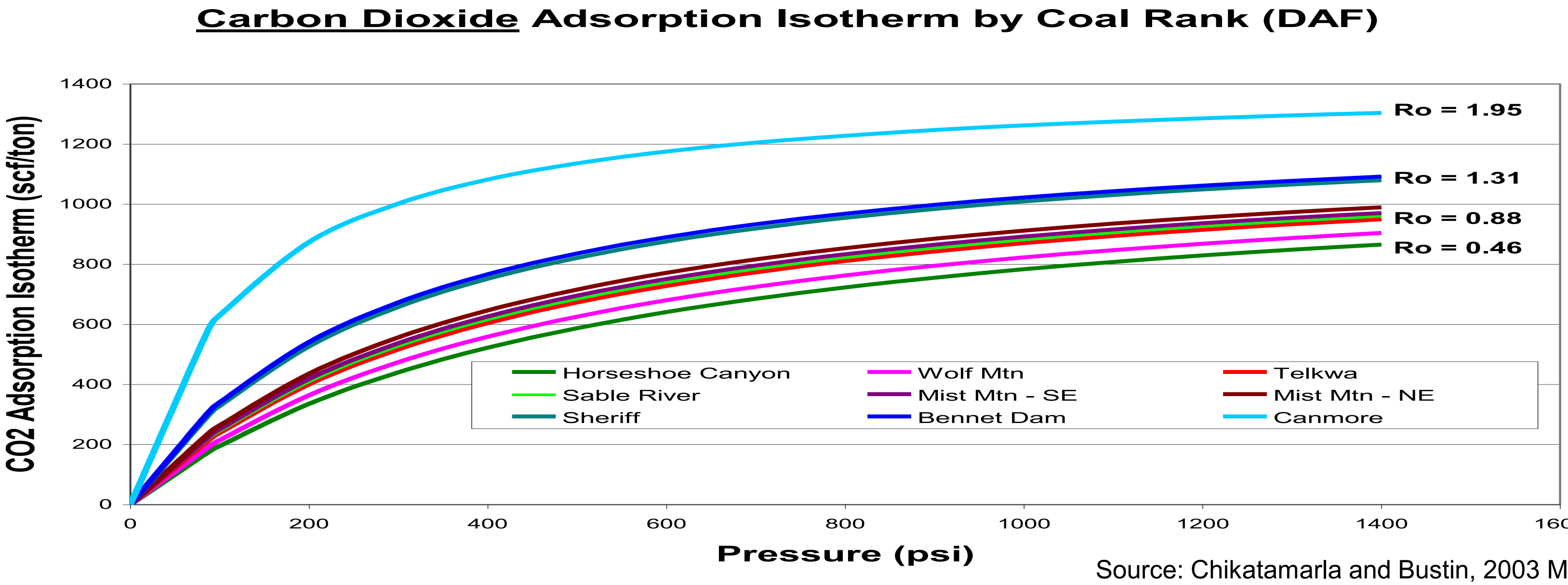


Figure 33 : Methane adsorption isotherms for coals in Washington state and British Columbia. The low-rank (R_o=0.46%) Horseshoe Canyon coal is the closest analog to the Big Dirty seam at Centralia.



Source: Chikatamarla and Bustin, 2003 McHenry et al., 2003.

Figure 34 : Methane adsorption isotherms for coals in Washington state and British Columbia. The low-rank (R_o=0.46%) Horseshoe Canyon coal is the closest analog to the Big Dirty seam at Centralia.



Source: Chikatamarla and Bustin, 2003 McHenry et al., 2003.

Figure 35 : Methane adsorption increases with rank for coals in Washington state and British Columbia. Both Langmuir Volume (V_L) and Langmuir Pressure (P_L) vary linearly with vitrinite reflectance (R_o).

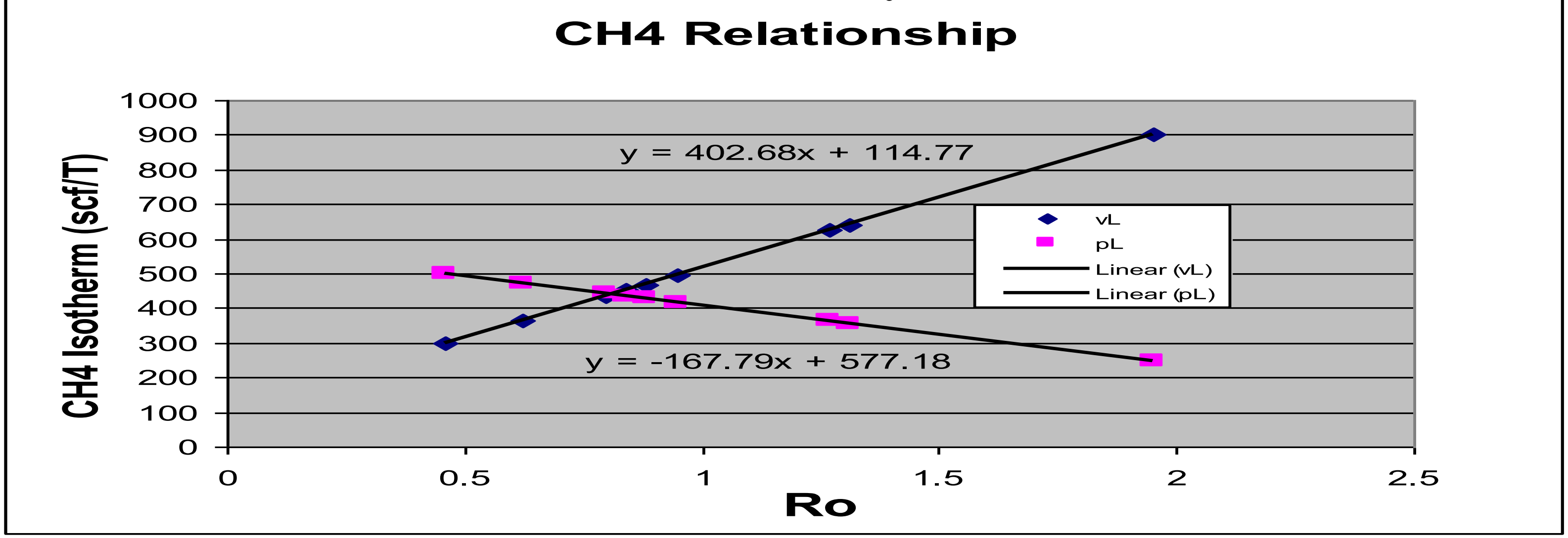


Figure 36 : CO_2 adsorption increases with rank for coals in Washington state and British Columbia. Both Langmuir Volume (V_L) and Langmuir Pressure (P_L) vary linearly with vitrinite reflectance (R_o).

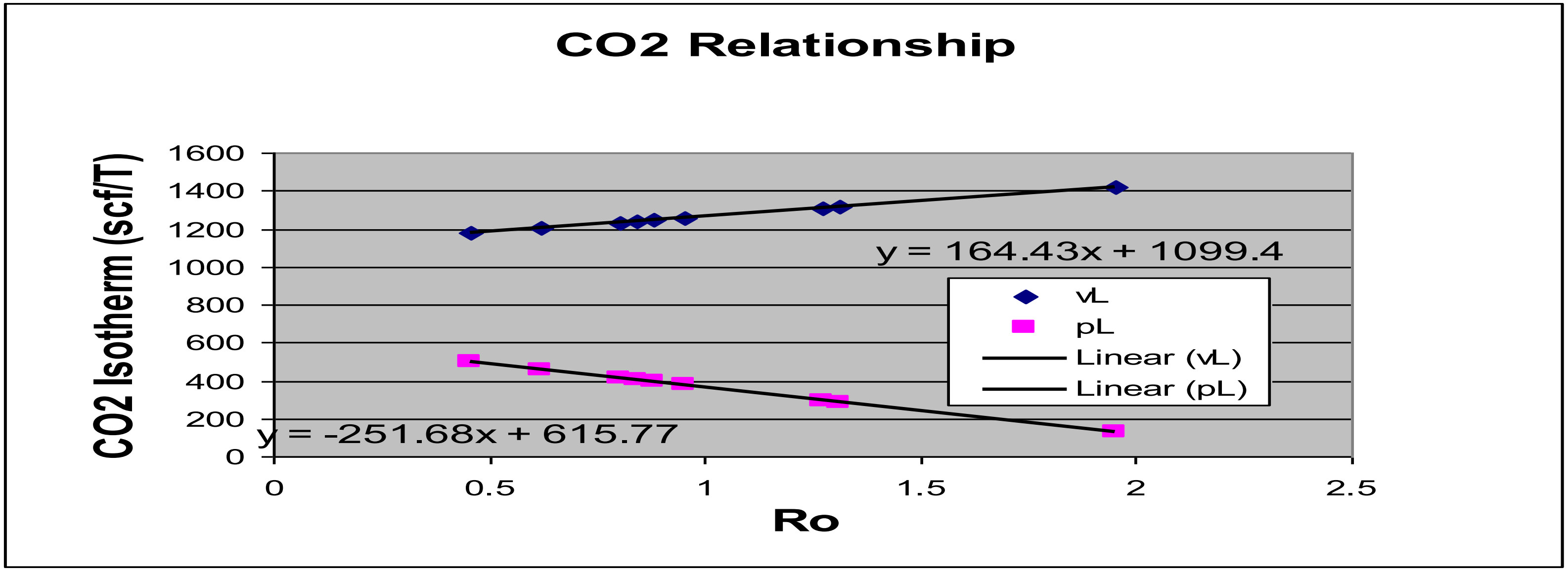


Figure 37 : Thickness and depth of Big Dirty seam near Centralia coal mine based on water well logs. The Big Dirty seam is deeper than 150 m (500 ft) and about 10 m (33 ft) thick in the Centralia syncline west of the coal mine.

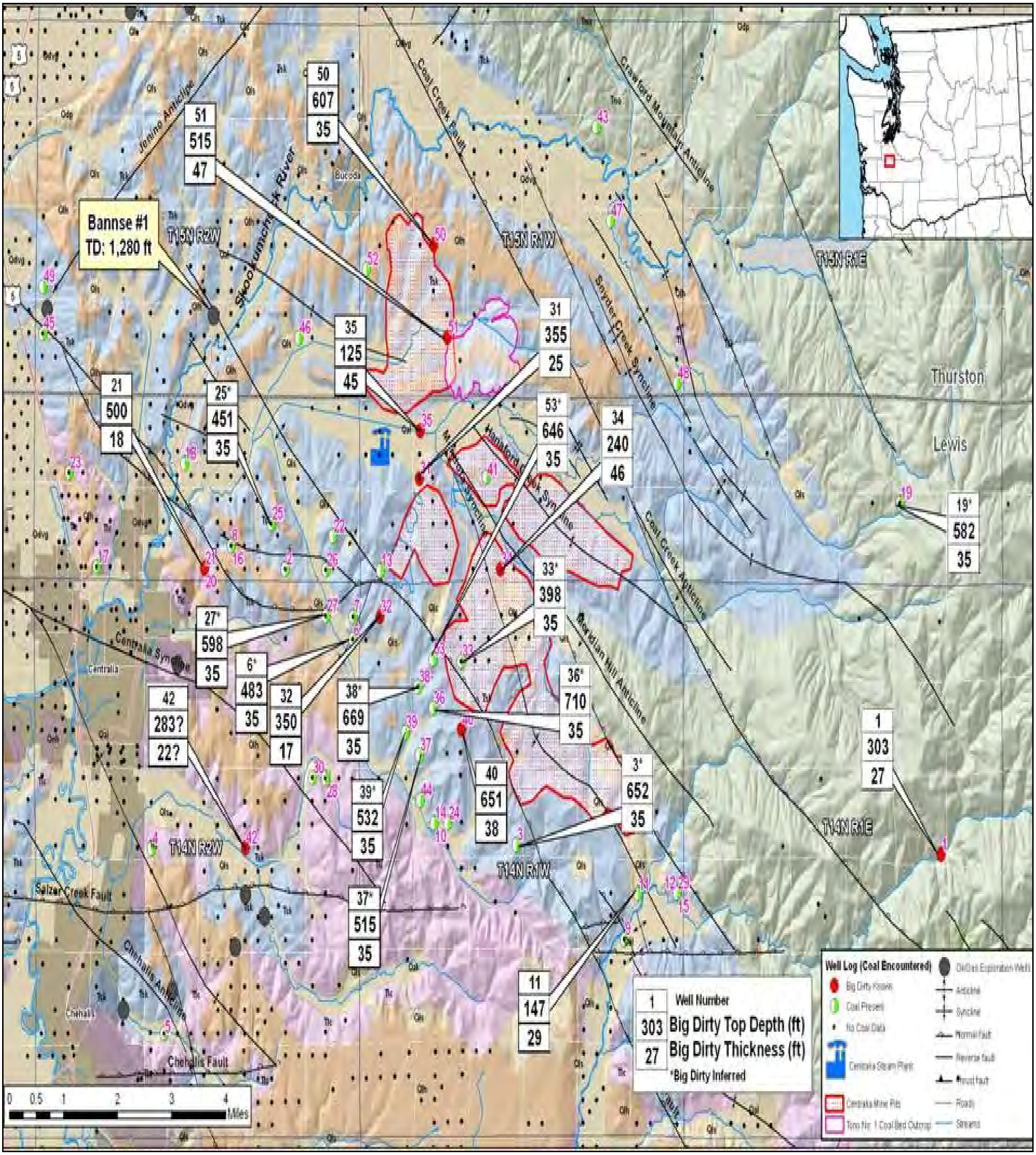


Figure 38 : Centralia coal field and adjacent areas (green) where the Big Dirty seam may be deeper than 150 m (500 feet), based on water well logs, and prospective for CO_2 storage.

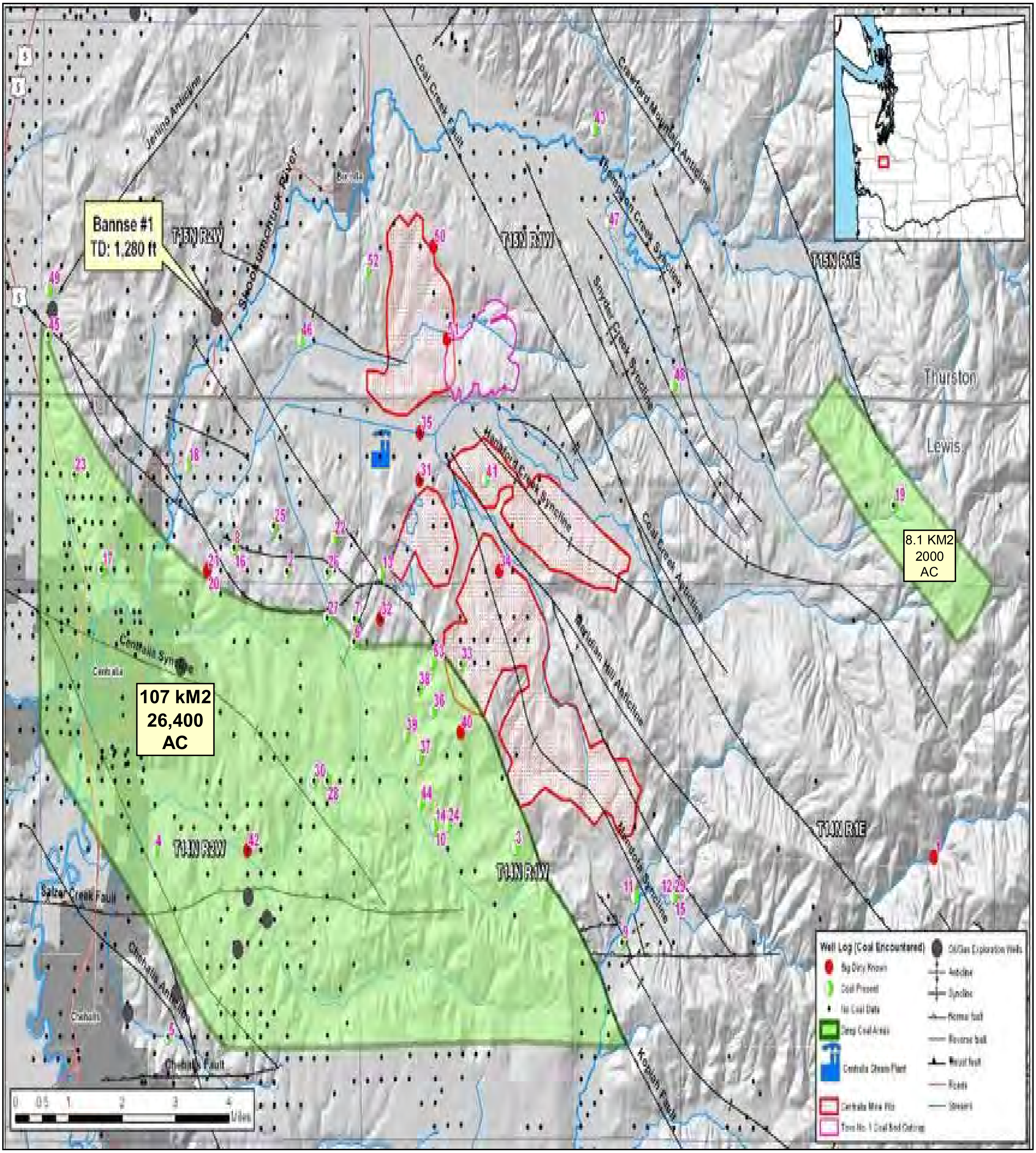


Figure 39 : Reservoir simulation grid of 5-well injection pattern, showing one-quarter 10-acre spaced model, employing one CO_2 injection well and one methane production well.

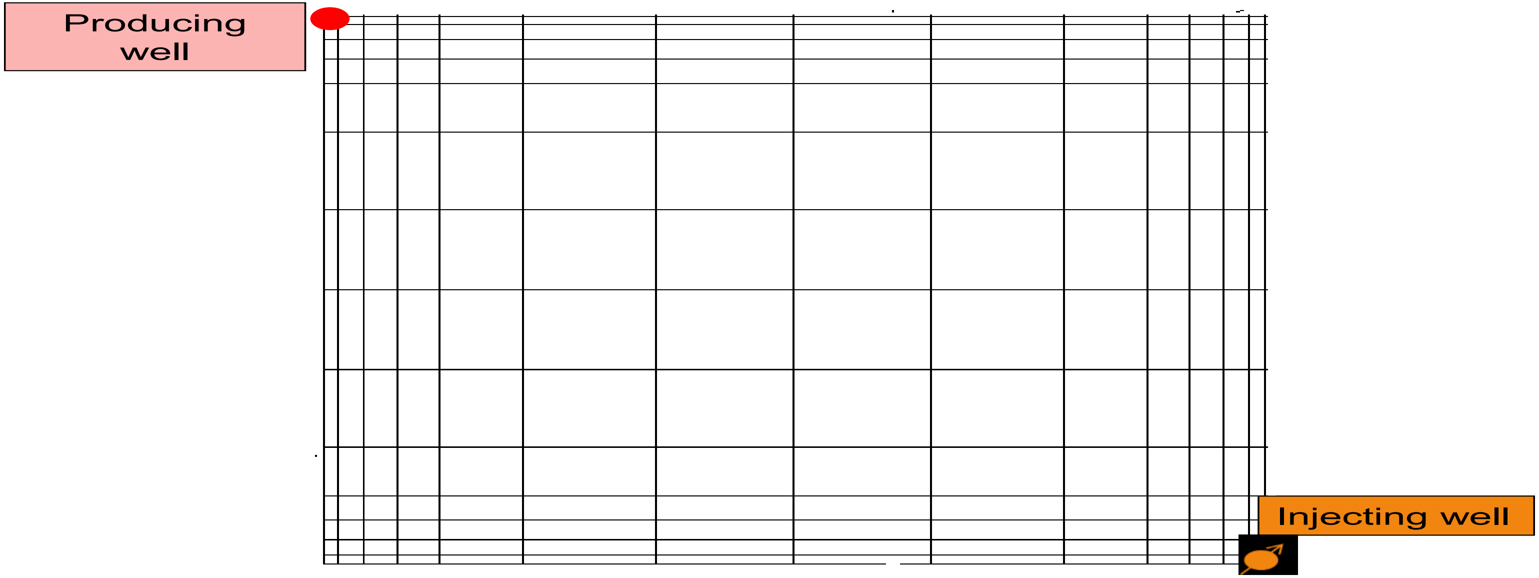


Figure 40 : Input parameters for reservoir simulation model of Centralia 5-spot.

Parameter	**Units**	**Value**	**Comments**
		Reservoir Paramaters	
Top Coal Elevation	ft	1640	
Net Coal Thickness	ft	60	
Initial Reservoir Pressure	psia	725	hydrostatic gradient assumed
Reservoir Temperature	F	85	assumed
Initial Water Saturation	%	100	
Coal Rank - Ro	%	0.46	
Coal Density	g/cc	1.3	calculated from ash and moisture. Ash density of 2.49g/cc and organic matter density of 1.3 assumed
Coal ash	%	12	
Coal moisture	%	20	
CH4 DAF Langmuir Volume	scf/t	1175	
CH4 Langmuir Pressure	psia	500	
CO2 DAF Langmuir Volume	scf/t	300	
CO2 Langmuir Pressure	psia	500	
Cleat Spacing	in	1	
Pore compressibility	1/psi	3.00E-04	
Matrix compressibility	1/psi	1.00E-06	
		Fluid Parameters	
Initial CH4 composition	%	100	
Gas gravity	-	0.6	
Water density	lbm/cuft	62.4	
Water viscosity	cp	0.45	
Water FVF	RB/STB	1.01	
CO2 differential swelling factor	v/v	2	

Figure 41 : Detailed structure map of Tono basin, Centralia coal mine, showing small faults, UCG coreholes (yellow), and conceptual CO_2 injection wells on 40-acre spacing (green).

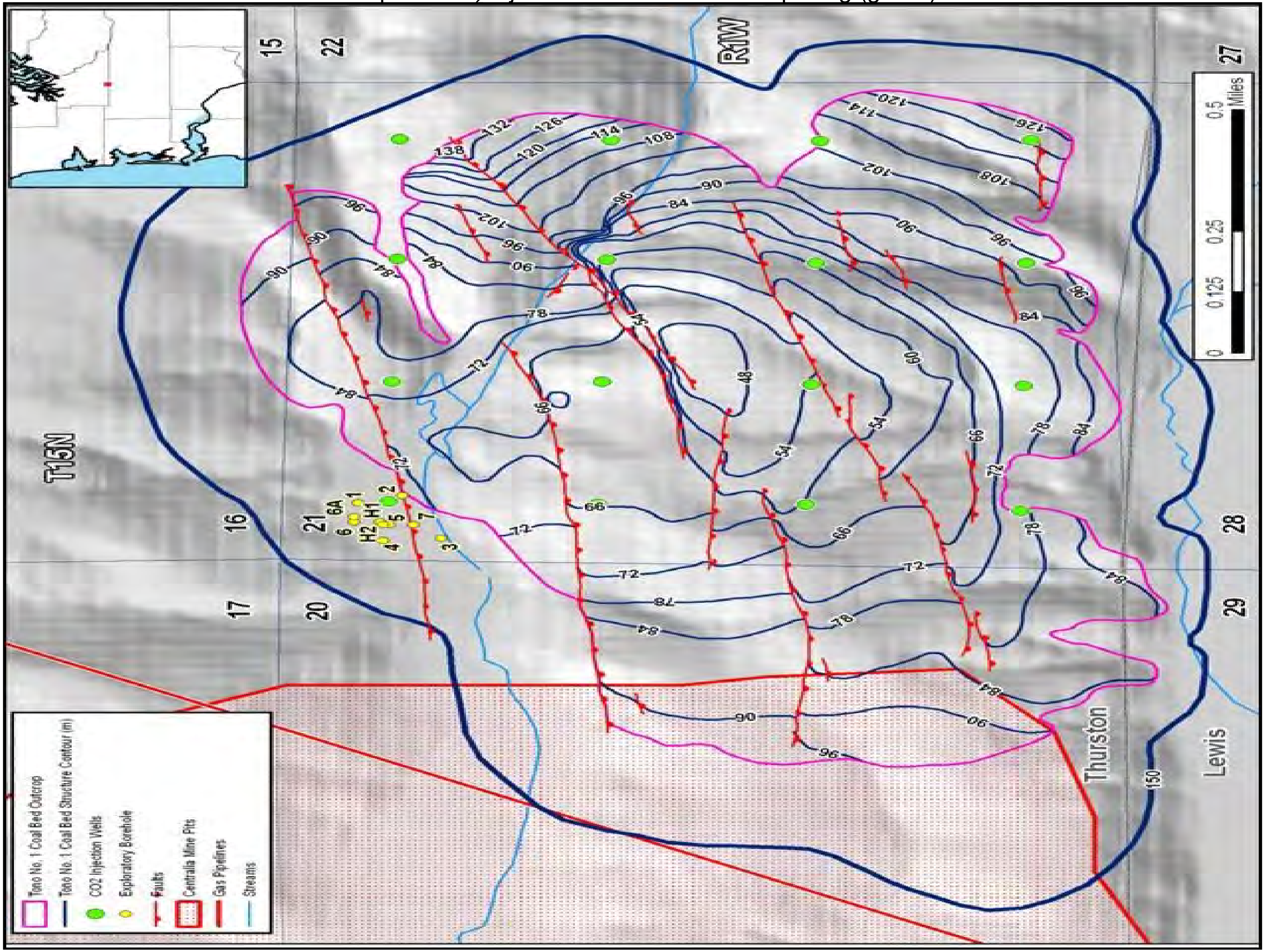


Figure 42 : Methane production for 0.1 mD / 75% gas saturation case. Low permeability results in low and declining gas and water production under this scenario.

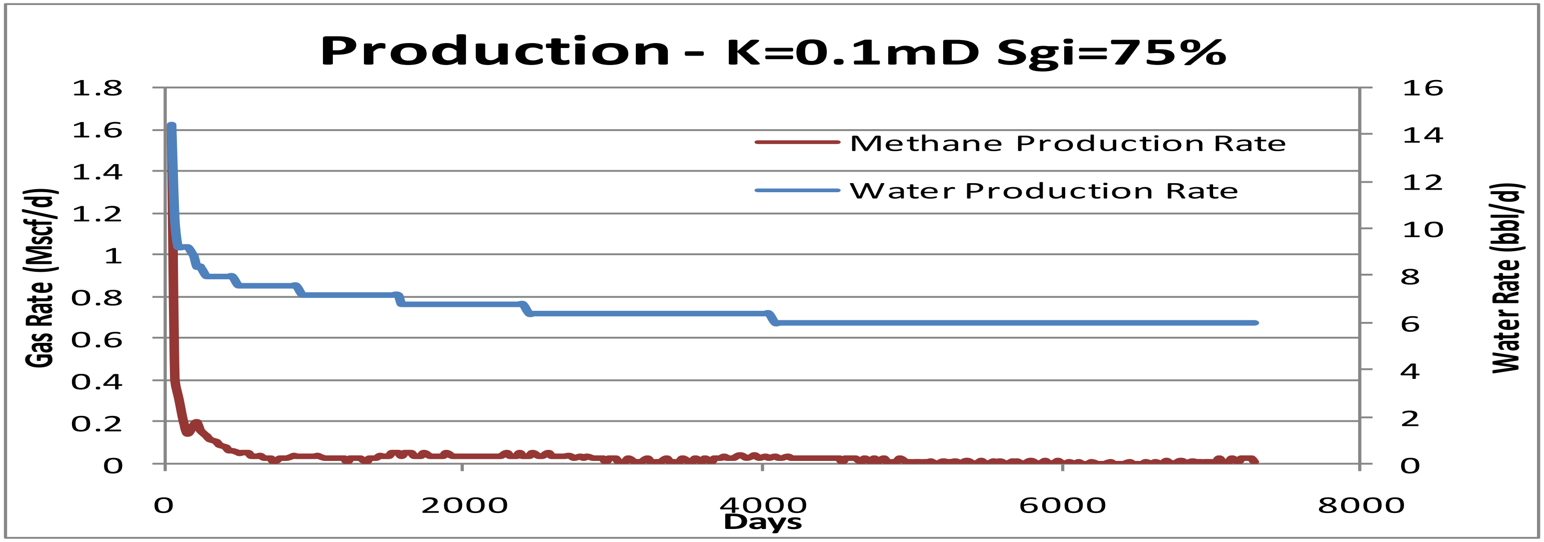
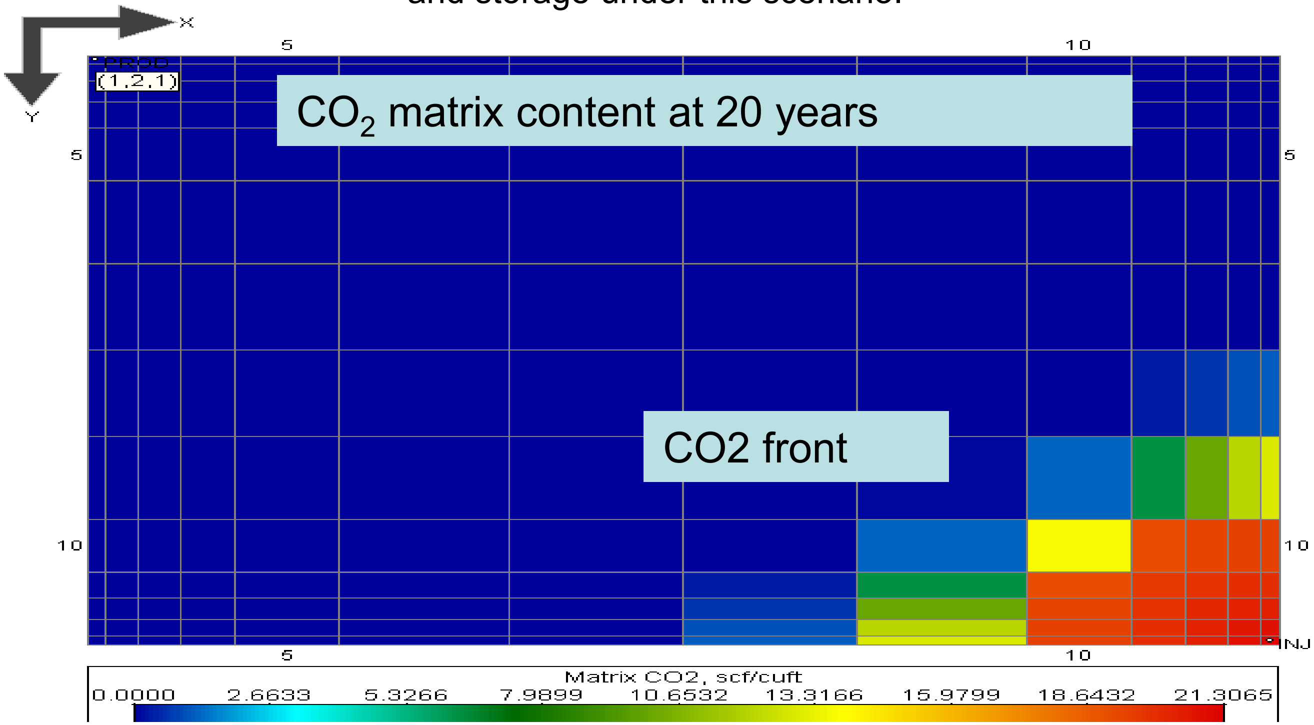


Figure 43 : CO$_2$ storage for 0.1 mD / 75% gas saturation case. Low permeability results in minimal CO$_2$ movement and storage under this scenario.



CO$_2$ matrix content at 20 years

CO2 front

Figure 44 : Methane production for 0.1 mD / 100% gas saturation case. Low permeability results in low and declining gas and water production under this scenario.

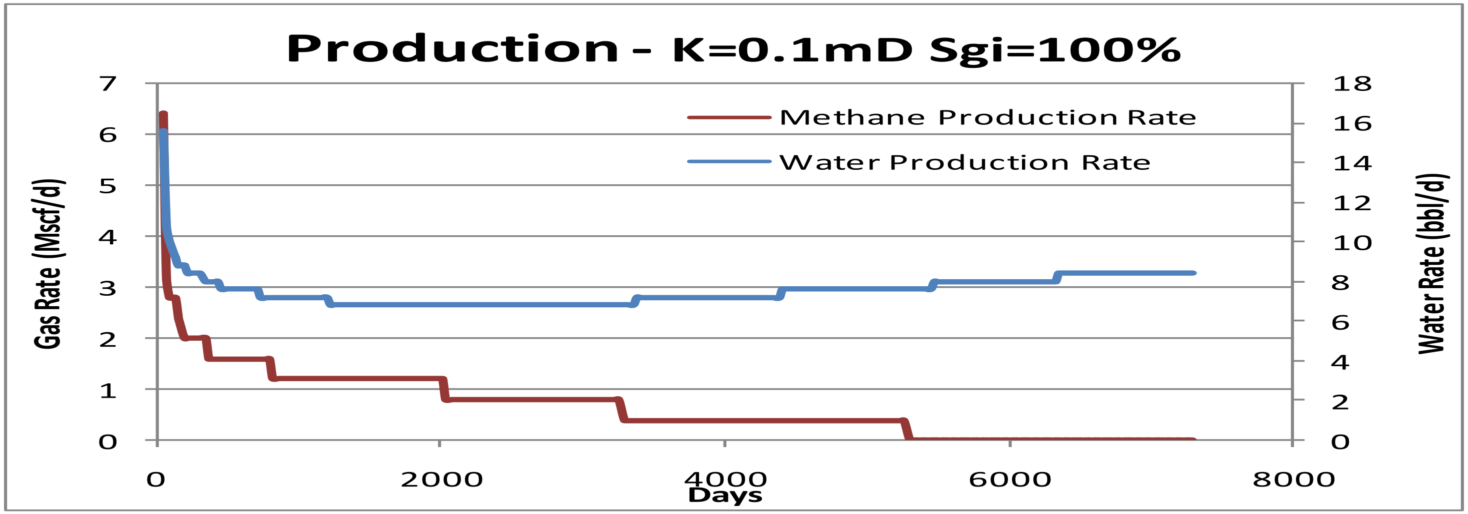
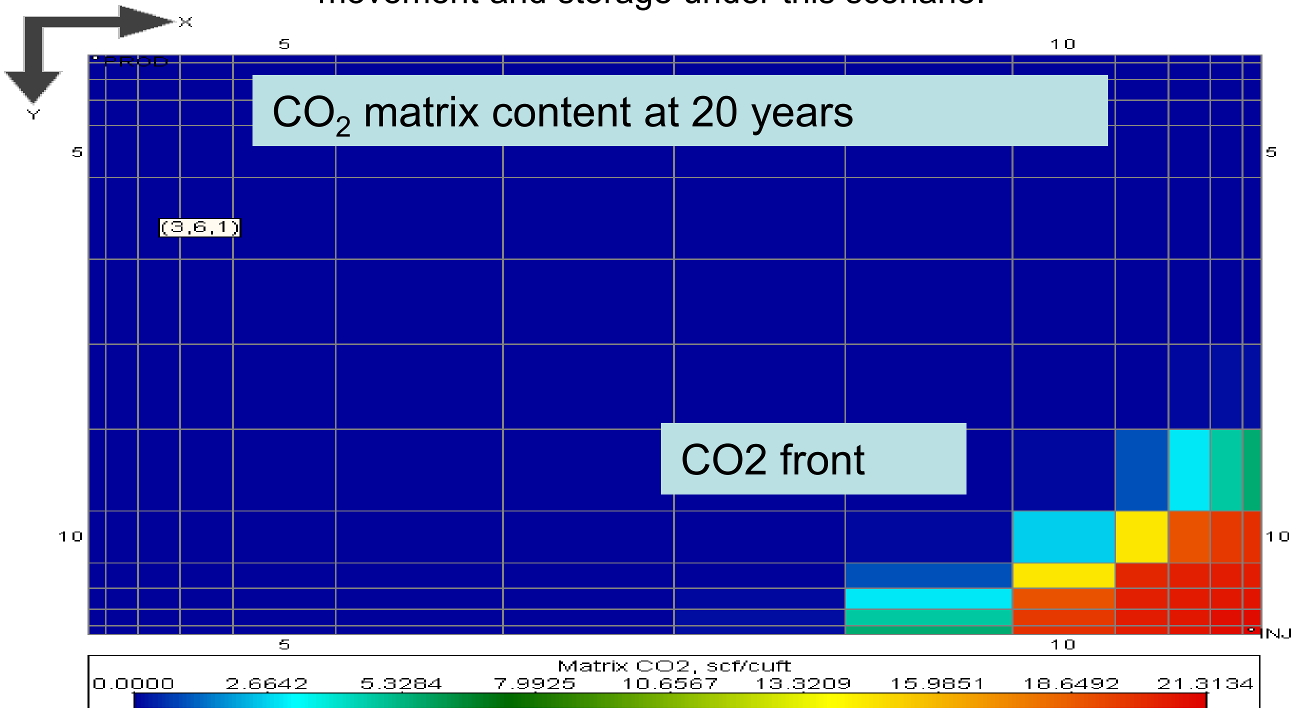


Figure 45 : CO_2 storage for 0.1 mD / 100% gas saturation case. Low permeability results in minimal CO_2 movement and storage under this scenario.



CO_2 matrix content at 20 years

CO2 front

Figure 46 : Methane production for 1.0 mD / 75% gas saturation case. Undersaturation delays gas production but medium permeability eventually allows gas to exceed 50 Mcfd (1500 m^3/day) at year 10.

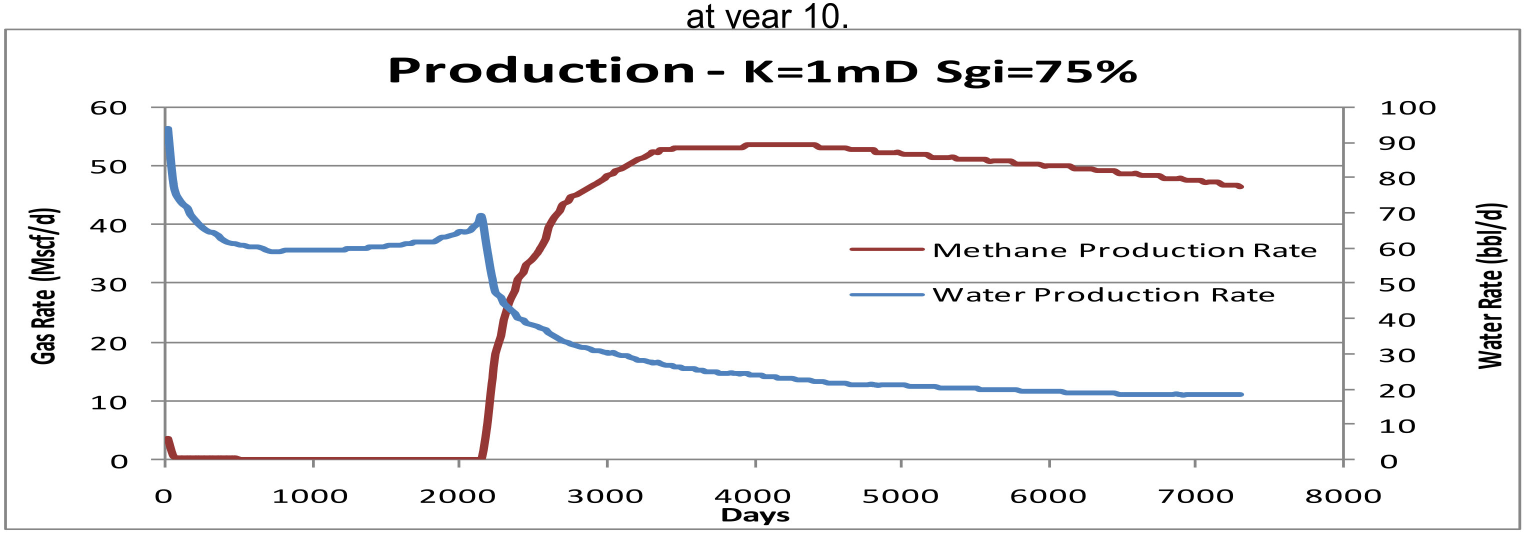
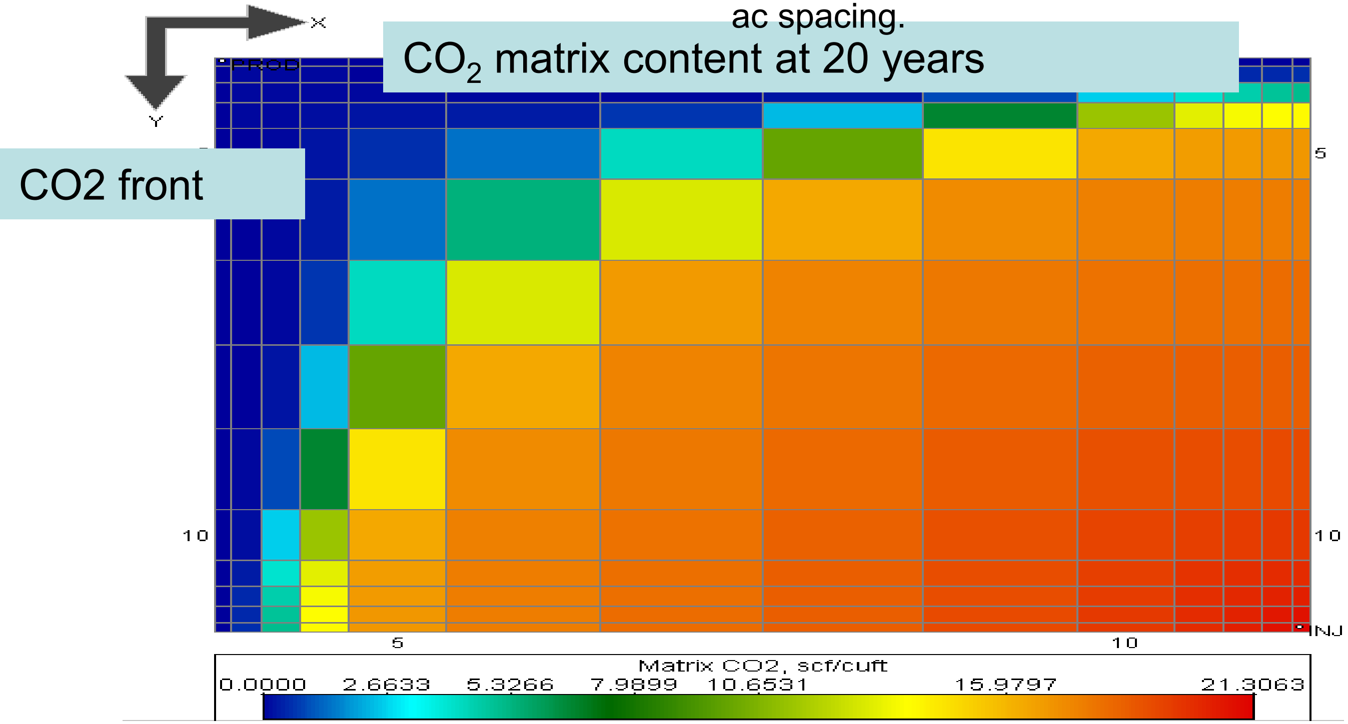


Figure 47 : CO_2 storage for 1.0 mD / 75% gas saturation case. Undersaturation and medium permeability aids CO2 storage, resulting in efficient CO_2 movement and storage under this scenario appropriate for 40-ac spacing.



CO_2 matrix content at 20 years

CO2 front

Figure 48 : Methane production for 1.0 mD / 100% gas saturation case. Medium permeability results in fairly slow dewatering and peak gas production of 65 Mcfd (1800 m^3/day) at year 6.

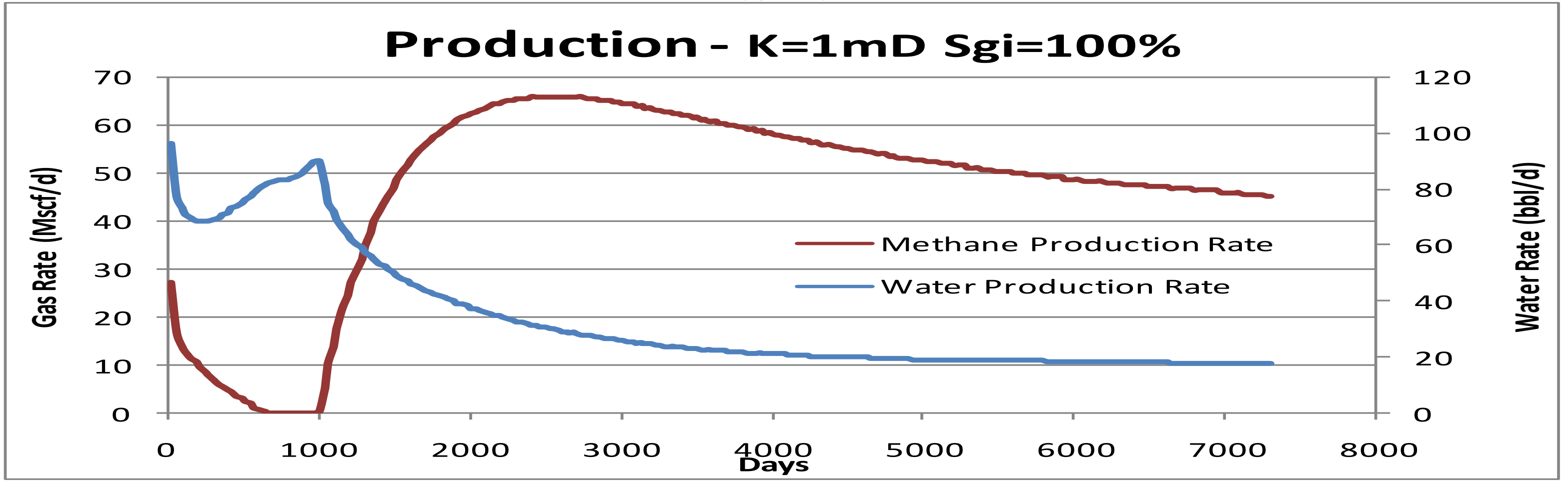
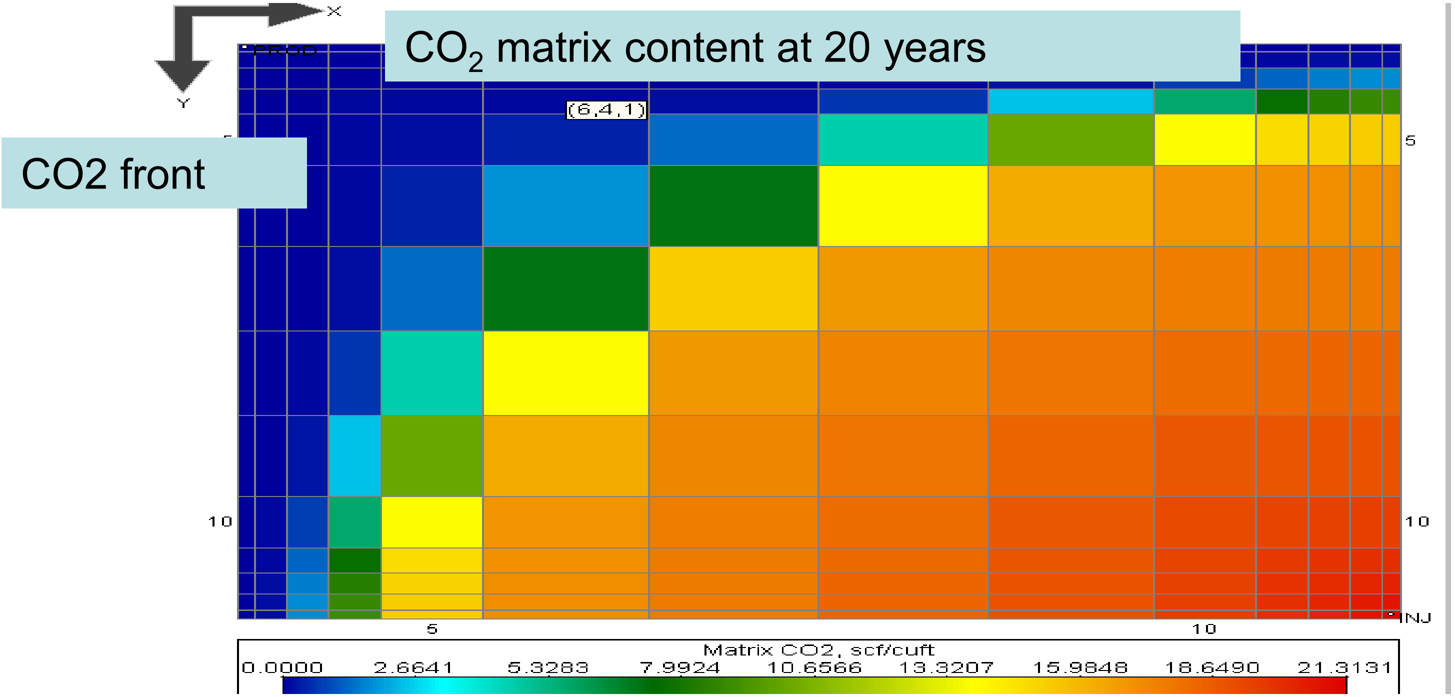


Figure 49 : CO_2 storage for 1.0 mD / 100% gas saturation case. Medium permeability results in efficient CO_2 movement and storage under this scenario appropriate for 40-ac spacing.


CO_2 matrix content at 20 years

CO2 front

Figure 50 : Methane production for 10 mD / 75% gas saturation case. High permeability causes rapid breakthrough of CO_2 to the methane production well, which is shut in after 3 years.

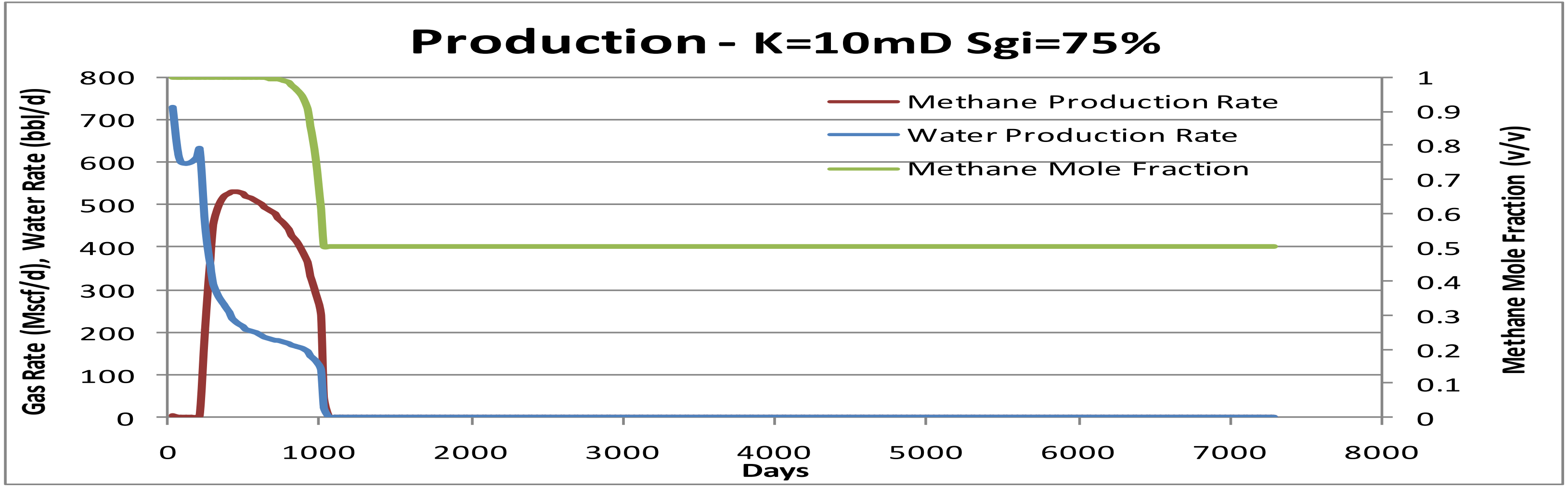
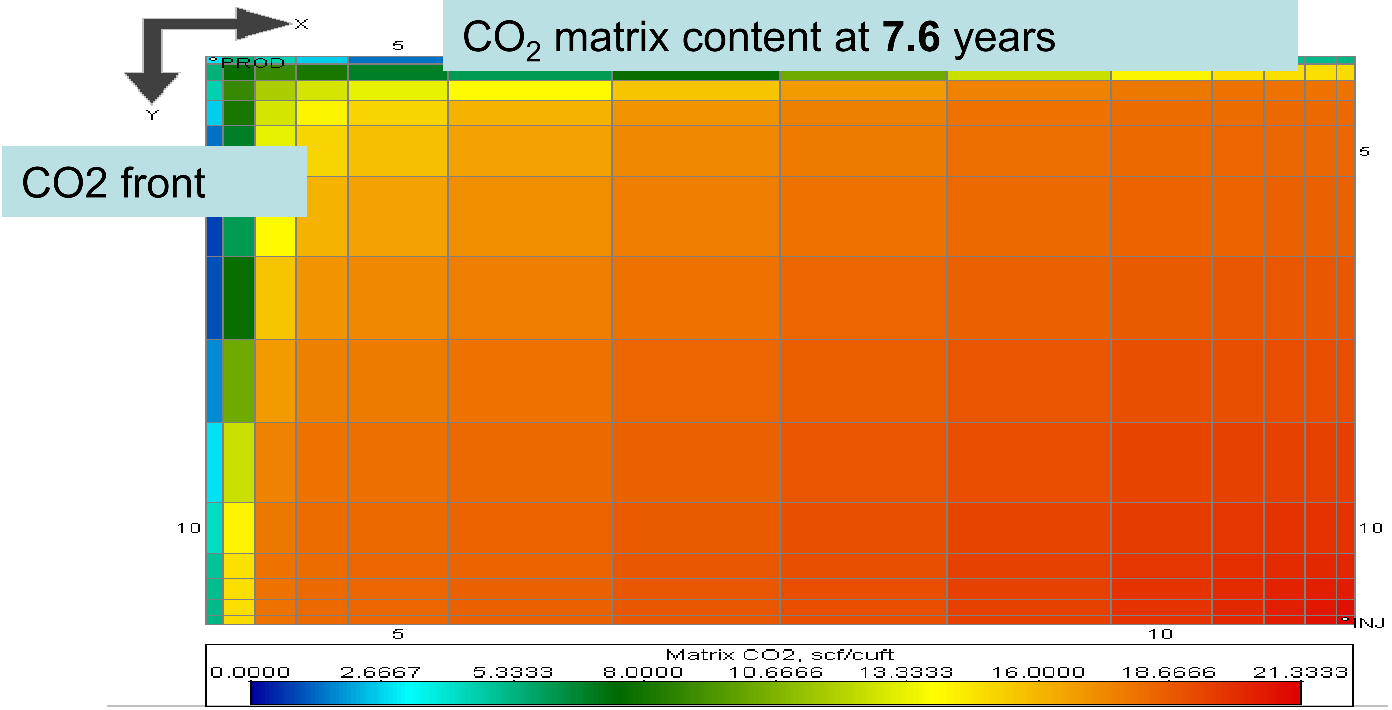


Figure 51 : CO_2 storage for 10 mD / 75% gas saturation case. CO_2 rapidly saturates the small 40-acre area around the injection well and injection pressure exceeds fracture pressure in year 7.6, shutting down the injection well, indicating spacing is too tight for such high permeability.



CO_2 matrix content at **7.6** years

CO2 front

Figure 51 : Methane production for 10 mD / 100% gas saturation case. High permeability causes rapid breakthrough of CO_2 to the methane production well, which is shut in after 3 years.

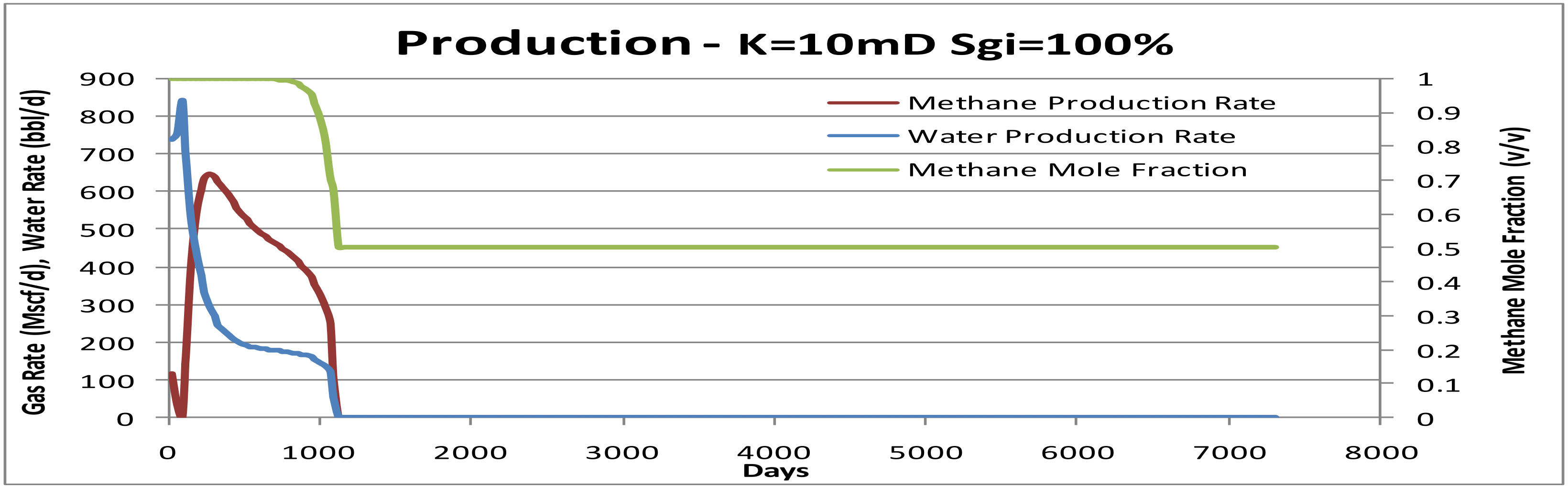
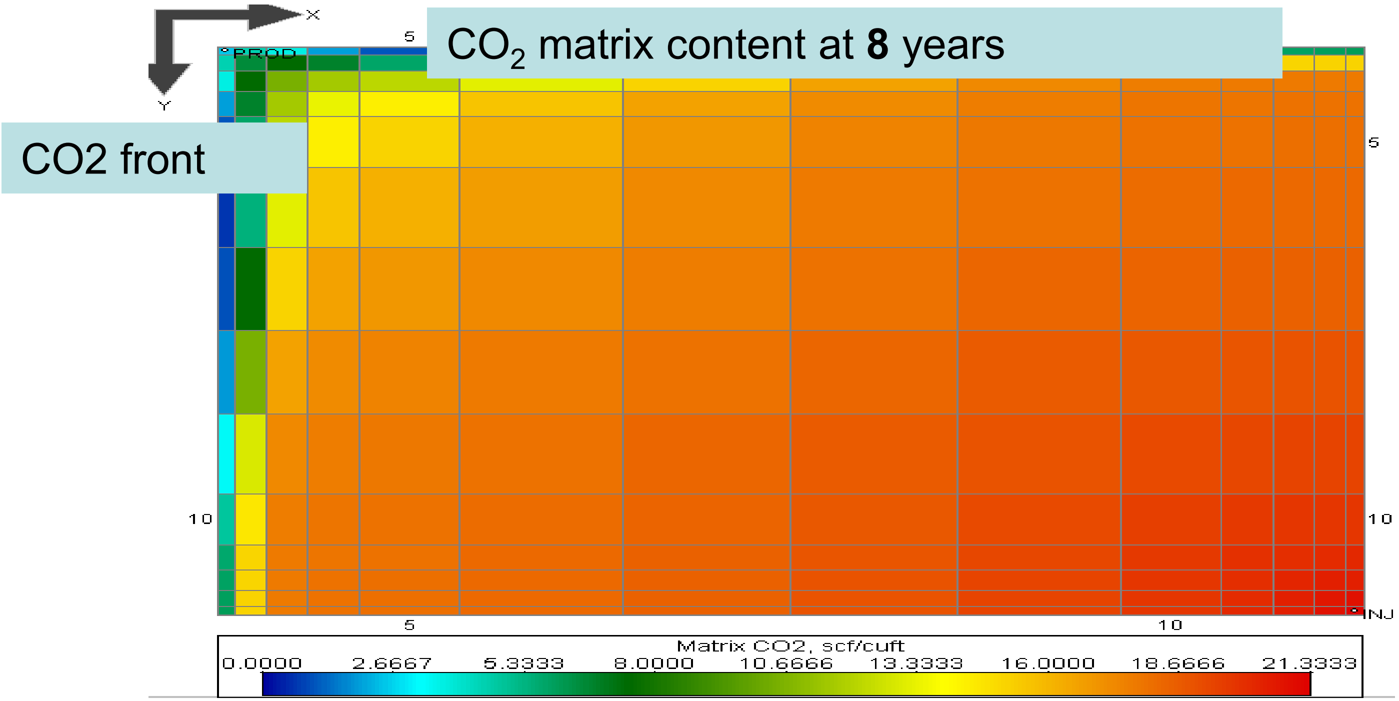


Figure 53 : CO_2 storage for 10 mD / 100% gas saturation case. CO_2 rapidly saturates the small 40-acre area around the injection well. Injection pressure exceeds fracture press in year 8, shutting down the injection well and indicating spacing is too tight for such high permeability.


CO_2 matrix content at **8** years

CO2 front

Figure 53 : CO_2 storage and methane production for deep coal project at Centralia, with sensitivity to initial methane saturation and permeability.

	Permeability (mD)					
	0.1		1		10	
	Saturation (%)		Saturation (%)		Saturation (%)	
	75	100	75	100	75	100
Cumulative Methane Production (MMcf)	0.3	5	250	341	353	470
Cumulative CO2 injected (MMcf)	130	88	1,333	1,192	2,252	2,247
Cumulative CO2 produced (MMcf)	0	0	0.1	0.02	14	11
Cumulative Water produced (MSTB)	48	55	262	247	304	301
Methane Recovery Factor (%)	0.1	1	66	69	93	95