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CO_2 sequestration potential beneath large power plants in the Colorado Plateau-Southern Rocky Mountain region, USA.

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Abstract

Six coal-fired power plant sites in the Colorado Plateau-Southern Rocky Mountains region generate close to 13,000 MW of electricity and represent point sources for 100 million tons of CO_2 per year. The geologic settings of these sites are investigated for potential sequestration of CO_2 separated from flue gas. Five of the sites are located on thick (~ 3 km) sedimentary sequences with simple, near-horizontal, layer-cake stratigraphy and few faults. Multiple potential reservoir and overlying seal units exist at these five sites. Because of the broad, low-amplitude structures, large storage potential exists. Nearby oil and gas fields offer both opportunities for enhanced recovery and challenges from unwanted invasion of migrating CO_2.

Introduction

The sedimentary basins of the Colorado Plateau and Southern Rocky Mountains region contain large resources of natural gas, oil and coal. Some of the coal is used locally to generate electricity, and these power plants dominate the point sources of CO_2 in the region (Fig. 1). The six largest power plant sites are the basis of this study (Table 1). Two sites (Hunter/Huntington and Four Corners/San Juan) have two power plants in close proximity and are treated as one site. The six power plant sites generate 13,000 MW of electricity and emit 100 million tons/year of CO_2. Natural CO_2 fields in the same region produce close to 30 million tons/year of CO_2 (Fig. 1). Most of this is piped to enhanced oil recovery projects in West Texas (Permian Basin), Rangely oil field (Piceance Basin, Colorado), and Lost Soldier-Wertz oil field (Southern Wyoming). At the moment, 4 million tons/year of CO_2 is vented from the La Barge CO_2 field in southwest Wyoming, but a proposed pipeline extension into the Powder River Basin (northeast Wyoming) for enhanced oil recovery is expected to use most of this surplus production.

This study investigates the possibilities and issues associated with geologic sequestration of CO_2 near the largest power plant sites, assuming the CO_2 can be separated from the flue gas. At least two of these are close to existing CO_2 pipelines, so alternative scenarios such as using the CO_2 for other sequestration projects remote from the site are possible. The Jim Bridger plant is 25 km from the southern Wyoming pipeline, and the Four Corners/San Juan plants are 30 - 40 km from the McElmo Dome – West Texas pipeline. This paper reviews only subsurface sequestration possibilities close to the plant (e.g. < 10 km).

The geological section beneath each power plant site is examined for the presence of high permeability formations ("reservoirs") potentially capable of receiving large volumes of CO_2, the adequacy of overlying, low permeability units ("seals") that will prevent vertical migration of the CO_2 plume, and the structural trends which will influence lateral plume migration directions. The presence of major faults that could be leakage zones will be noted, as will the existence of nearby oil and gas reservoirs or coal seams. CO_2 can be used for enhanced oil recovery, enhanced gas recovery through pressure support, enhanced coal bed gas recovery, or could also be considered an undesirable diluent of a gas reservoir.

Although saline aquifers are relatively common at 2 – 3 km depth beneath this region (Freethy and Cordy, 1991, Allis et al., 2001), water quality issues may be important where minimum injection depths are considered. Because of the likelihood of injection pressures of at least 80 bar (8 MPa, 1160 psi) to keep the CO_2 as a relatively dense, supercritical fluid (700 kg/m^3) for efficient transport, injection pressure safety margins mean that the depth will have to be at least 1 km. The injection depth is unlikely to be greater than 2 km depth because of the economic implications for added wellhead pressure needed for injection, and the additional well drilling costs. Migration of injected CO_2 to much shallower depths would raise serious environmental issues from both a safety perspective and if potable aquifers are present. In this paper we focus on the geological characteristics in the likely injection depth window of 1 – 2 km, close to these six power plant sites.

The following section of the paper is divided according to power plant. Each power plant is reviewed under the headings Geologic Setting, Opportunities for CO_2 Sequestration, and Potential Problems or Issues Needing Study. A bulleted format is used for the sake of brevity. In each case the material represents an overview of the main characteristics of the site, and it is designed to be a starting point if geologic sequestration of flue gas CO_2 considered for a particular plant site. In such cases a more thorough geologic investigation is recommended.

Power Plant Name	Approx. Capacity (MW)	2001 Generation (million MW-h)	2001- 02 Coal Consumption (mill. tons/y)	2001 CO_2 Emissions (mill. tons/y)
Hunter/Huntington (Utah)	2000	14.5	6.7	14.7
Intermountain Power Project (Utah)	1500	13.4	5.4	15.2
Jim Bridger (Wyoming)	2034	15.3	8.5	18.5
Navajo (Arizona)	2400	17.4	8.1	19.7
Four Corners/San Juan (New Mexico)	3650	26.8	15	31.0
Craig (Colorado)	1200	9.4	4.8	10.7

Table 1. Generation and emission characteristics for the six power plant sites considered in this paper. The sites are located on Figure 1.

Hunter/Huntington site

Two power plants, Hunter (1200 MW capacity) and Huntington (800 MW) are located about 15 km apart in Emery County, central Utah (Fig. 2a). Both are operated by Pacificorp (Scottish Power). The power plants are adjacent to the eastern margin of the Wasatch Plateau and the western periphery of the San Rafael Swell. This geologic structure has been used for numerical simulation of the reactive fate of injected CO_2 (White et al., 2003).

Geological Setting (Fig 2b)

- The San Rafael Swell is a major physiographic feature in east-central Utah. It represents a broad, basement-involved, asymmetrical anticline that trends north-northeast to south-southwest. The San Rafael Swell is one of numerous Laramide-age (middle to late Paleocene to early Oligocene) uplifts on the Colorado Plateau. The west flank is a gently dipping cuesta while the east flank is steeply dipping to near vertical in some locations. There are numerous subsidiary structures along the San Rafael Swell. Many of these structures have been drilled for and produced oil and gas including CO_2. Examples are Farnham dome, Woodside dome, Last Chance anticline, Salt Wash anticline, and

Ferron anticline. Rocks exposed on the uplift include the Cretaceous Mancos through Permian Pakoon Dolomite. The region also includes extensive Tertiary sandstone and Quaternary surficial deposits. Tertiary dikes and sills cut the sedimentary rocks in the southwest corner of the Swell. Minor high-angle, generally east-west-trending, normal faults are also mapped on the crest of the structure; extensive fracturing and joints are present in the White Rim Sandstone and other sandstone formations.

- Over 3,600 m of sedimentary rock ranging in age from Cretaceous to Cambrian including marine, fluvial, eolian, and continental deposits are in the San Rafael Swell. Precambrian granite and schist underlie the basal Cambrian Tintic Quartzite.

- ***Potential reservoirs***: (1) **Jurassic Navajo Sandstone** is 137 to 183 m thick, and is a classic example of an eolian deposit containing large-scale cross-beds, frosted quartz grains, and other diagnostic sedimentary eolian features. The Navajo generally has excellent porosity and permeability. It has produced CO_2 at Farnham Dome on the north plunging nose of the San Rafael uplift. (2) **Jurassic Wingate Sandstone** is 91 to 122 m thick in the uplift and relatively homogeneous. It was also deposited in an eolian environment and although little petrophysical work is available, it likely has good porosity and permeability. (3) **Permian White Rim Sandstone** is 61 to 244 m thick, and contains cross-beds in clean, fine-grained sandstone. The eolian White Rim may be the best candidate for CO_2 injection. It has excellent porosity and permeability, and is the main CO_2 reservoir at Gordon Creek field. (4) **Mississippian Redwall Limestone** is 183 to 305 m thick, and was deposited in a shallow marine environment. The Redwall is the deepest candidate for CO_2 injection and is not exposed in the San Rafael Swell. It has moderate porosity and permeability, and is a major producer of oil and gas in structural traps (faulted anticlines) to the southeast in the Paradox Basin. It has also tested significant flow rates of CO_2 from several wells in the basin though never produced. The Redwall in the San Rafael uplift likely has a fair amount of heterogeneity due to changes in depositional facies and carbonate diagenetic effects.

- ***Potential shale seals***: (1) **Cretaceous Mancos Shale** is greater than 700 m in thickness, consisting mostly of marine shales deposited in the Cretaceous Interior Seaway. It is divided into several members (Blue Gate Shale, Ferron Sandstone, Tununk Shale) and is exposed on the periphery of the San Rafael Swell forming strike valleys. (2) **Triassic Chinle Formation** is 100 m thick, consisting mostly of varicolored, bentonitic, and non-resistant mudstone and claystone with some locally interbedded resistant channel sandstone. The Chinle Formation was deposited under continental conditions by streams and in lakes. (3) **Triassic Moenkopi Formation** is 288 m thick, consisting mostly of siltstone, sandstone, and mudstone. However, the Sinbad Limestone Member of the Moenkopi has tested significant amounts of CO_2 at the Gordon Creek field to the northwest of the Swell. It is not considered a candidate because it is relatively thin, 15 to 46 m, with low permeability and porosity. What permeability and porosity are present in the Sinbad is the result of fracturing. The Moenkopi was deposited on a broad continental plain that was periodically flooded by an ocean during Early Triassic time. (4) **Permian Black Box Dolomite** ranges in thickness from 0 to 61 m in thickness, and was deposited in a shallow sea. Flow paths would likely be along major fracture or joint systems and minor high angle normal faults present in the region. (5) **Devonian Elbert Formation** is about 100 m thick, and contains dolomite and shale deposited in environments ranging from shallow marine/intertidal to delta front. (6) **Cambrian Ophir Formation** is about 60 m thick, consisting of mainly shale with a few limestone units. The Ophir was deposited in the deeper water environments of the Middle Cambrian epi-continental sea.

- ***Potential evaporite seals***: (1) **Jurassic Carmel Formation** is 73 to 91 m thick and consists of marine shale, limestone and anhydrite beds unconformably overlying Navajo Sandstone. (2) **Pennsylvanian Honaker Trail/Paradox Formations** are 30 to152 m and 91 to 305 m thick, respectively, composed of marine shale and anhydrite deposited in a restricted shallow sea of the Paradox Basin.

Opportunities for CO2 Sequestration

+ Numerous thick shale and anhydrite deposits provide excellent seals.

- + Thick sandstone and carbonate deposits with good porosity provide excellent reservoir potential.
- + The San Rafael Swell represents a huge area for potential storage and includes numerous subsidiary structures that have both reservoirs and seals as well.
- + Injection targets are relatively shallow in the vicinity of the power plants (about 2,000 meters to the Redwall Limestone).
- + Fractures and jointing in sandstone-dominated formations appear not to continue into overlying shales (seals).

Potential Problems or Issues Needing Study

- – The potential reservoirs in the Navajo, Wingate, and White Rim Sandstones are exposed and deeply incised by canyons on the flanks or crest of the San Rafael Swell. If the CO_2 plume moves quickly to the east from the injection points at the power plants, leakage to atmosphere may occur.
- – Flow paths would likely be along major fracture or joint systems. Minor high angle normal faults present in the region may contribute to CO_2 leakage.
- – The presence of tufa deposits east of the region (Doelling, 1994; Shipton et al., 2003) suggests surface leakage of CO_2-rich deep basin fluids has occurred.
- – Constructing CO_2 pipelines to subsidiary structures would involve distances of tens of kilometers and significant financial investments.
- – The Redwall Limestone may potentially already contain significant quantities of CO_2, hence storage capacity is uncertain.

Navajo Power Plant site

This 2400 MW coal-fired plant is located near to Page, near the Arizona-Utah state line (Coconino County and Navajo Nation (Fig. 3a). It is operated by the Salt River Project Ag. I & P District and is the largest coal-fired power plant in the study region. The following references have been used to assist the geologic setting discussion: Chidsey (1997), Chidsey et al. (1998), Doelling (1997), Hintze (1993), Utah Geological Survey (1998), Wilson and Moore (1969).

Geological Setting (Fig. 3b)

- Boundary between the Monument upwarp and the Kaiparowits basin, both Laramide features. Gentle north- to northwest-trending anticlines and synclines, secondary folds of the Kaiparowits basin extend into the area and are recognized best along Lake Powell where the lake surface serves as a perfect datum. The folds developed over deep faults in Precambrian basement rocks. Jurassic strata are the oldest rocks exposed on the crests of anticlines. Dips on the flanks of the structures are up to 7°, and plunge is generally to the north. These folds are tens of kilometers in length and many have been targets for petroleum exploration. A few minor normal faults developed parallel to the axes of some of the structures. These faults are typically high angle, down to the west, and have less than 30 meters of displacement.

- Over 4,000 m of sedimentary rock ranging in age from Cretaceous to Cambrian including marine, fluvial, eolian, and continental deposits in the Glen Canyon National Recreation Area and Navajo Nation, Utah and Arizona.

- Potential reservoirs: (1) **Permian Cedar Mesa Sandstone** is 350 m thick, and contains large-scale cross-beds, frosted quartz grains, and other sedimentary features that are typical of eolian deposits. However, the Cedar Mesa also contains some horizontal bedding and algal limestone and gypsum beds that suggest deposition in a sabkha. Thus, the Cedar Mesa Sandstone was deposited in eolian to coastal environment. Porosity ranges from 12 to 16 % (permeability is unknown), and includes intergranular and fracture porosity. The Cedar Mesa tested 96.1 to 93.1% CO_2 in 1983, from the

Mid-Continent Oil and Gas Reserves, Inc. Charger No. 1 well (section 29, T. 32 S. R. 3 E., SLBL&M) 130 kilometers to the northwest on the Escalante anticline. The well test had a total open flow gauged at 3.5 million cubic meters (124 million cubic feet [mmcf]) of gas per day from a net productive Permian and Triassic section of 600 m. (2) **Mississippian Redwall Limestone** is about 200 m thick, and was deposited in a shallow marine environment. Variations in depositional facies and carbonate diagenetic effects likely result in significant reservoir heterogeneity. It is cavernous where exposed in the Grand Canyon. The Redwall has produced oil in the Upper Valley field to the northwest (the only oil field in the Kaiparowits Basin) and tested CO_2 in the southern Paradox Basin to the east. (3) **Cambrian Tapeats Sandstone** is about 100 m thick, and contains fine- to coarse-grained dolomitic and glauconitic sandstone. These sands were deposited initially in a braided stream setting. Later widespread progradation of the sea resulted in shallow marine to shoreface deposition of blanket sands over the underlying coastal plain. Porosity ranges from 7 to 13 % (permeability is unknown), primary intergranular and some solution-enhanced porosity. The Tapeats tested 98 percent CO_2 in 1994 from the BHP Petroleum No. 28-1 well (section 28, T. 33 S. R. 7 E., SLBL&M) 120 km to the north on the giant Circle Cliffs anticline. The drill-stem test had a flow gauged at 141,600 cubic meters (5 mmcf) of gas per day.

- Potential seals: (1) **Triassic Chinle Formation** is 242 m thick, consisting mostly of varicolored, bentonitic and non-resistant mudstone and claystone with some locally interbedded resistant channel sandstone. The Chinle Formation was deposited under continental conditions by streams and in lakes. (2) **Triassic Moenkopi Formation** is 76 m thick, consisting mostly of siltstone, sandstone, and mudstone. The Moenkopi was deposited on a broad continental plain that was periodically flooded by an ocean during Early Triassic time. (3) **Permian Organ Rock Formation** is about 140 m thick, consisting of siltstone, sandstone, and shale. The Organ Rock was deposited in a marginal to shallow marine environment on the edge of a large coastal dune field. (4) **Cambrian Bright Angel Shale** is about 200 m thick, consisting of shale with a few siltstone and limestone units. The Bright Angel was deposited in the deeper water environments of the Middle Cambrian epi-continental sea.

- Carbon dioxide is present in many large anticlines to the north and northwest (Circle Cliffs, Escalante, Upper Valley, and Reese Canyon). The thick sections of Paleozoic carbonate rocks in the region (Cambrian Muav Limestone, Mississippian Redwall Limestone, and Permian Kaibab Limestone) are the probable CO_2 source rocks. One explanation is metamorphism of these marine carbonates by the heat of nearby igneous intrusive rocks including the laccoliths that form Navajo Mountain and the Henry Mountains to the north, and those associated with the volcanic flows of the High Plateaus to the northwest likely generated CO_2. This would require the CO_2 to be trapped for about 30 million years. An alternative explanation is that the CO_2 is more recent and is a product of prograde metamorphism in the lower crust, perhaps related to the uplift of the Colorado Plateau. This implies the CO_2 source to be regional in extent.

Opportunities for CO_2 Sequestration

+ Thick shale deposits provide excellent seals with few mapped faults and no tufa deposits identified
+ Thick sandstone and carbonate deposits with good porosity provide excellent reservoir potential
+ Injection targets are relatively shallow (about 1,500 m to the Cedar Mesa Sandstone; 2400 m to Redwall Limestone, and > 3,000 m to the Tapeats Sandstone)
+ Several large (tens of km), subtle, elongate structures in close proximity to the power plant; some have four-way closure, and storage potential could be large

Potential Problems or Issues Needing Study

− Structures potentially already contain significant quantities of CO_2, hence storage capacity is uncertain; none of the nearby structures has been targets of exploratory drilling

− CO_2 injection pipeline may have to cross lands belonging to the Navajo Nation requiring special permits and significant right-of-way fees

- CO_2 may be injected into rocks that underlie the Glen Canyon National Recreation Area raising environmental concerns

Four Corners/San Juan Power Plant site

Two coal-fired power plants are 15 km apart near Farmington, San Juan County, Arizona (Fig. 4a). The Four Corners plant has 2000 MW capacity (operated by Arizona Public Service Company), and the San Juan plant has a capacity of 1650 MW (operated by Public Service Company of New Mexico). The combined CO_2 emissions from these plants is 15 million tons/year – similar to the capacity of the McElmo Dome to West Texas CO_2 pipeline 35 km to the east. The following references have been used to assist the geologic setting discussion: Fassett (1978, 1983), Molenaar (1977), Ward (1990), Whitehead (1993a, b, c), Woodward and Callender (1977).

Geological Setting (Figs. 4b)

- The Four Corners area of northwest New Mexico consists of the Laramide-age (middle to late Paleocene to early Oligocene) San Juan structural basin and the Four Corners platform. The boundary between the Four Corners platform and the San Juan Basin is defined by a prominent monoclinal feature called "The Hogback" where the Cretaceous Cliff House Sandstone dips gently southeast into the basin. The San Juan Basin and Four Corners platform includes part of southwestern Colorado.

  The San Juan Basin is a major producer of gas in the United States with cumulative production over 17 trillion cubic feet (TCF) of gas from over 21,000 wells. Gas is produced primarily from: (1) a giant basin-centered stratigraphic trap; (2) fluvial, deltaic, and shallow-marine sandstones in stratigraphic traps; and (3) minor structural traps. Major reservoirs are the Fruitland Formation, Pictured Cliff Sandstone, Point Lookout Sandstone, Cliff House Sandstone, Mancos Shale, and Dakota Sandstone; all are Cretaceous in age. Unconventional gas production includes fractured tight sands in the Mancos and coalbed methane in the Fruitland.

  Rocks deposited in the Pennsylvanian-age Paradox Basin extend from Utah, Colorado, and Arizona into the Four Corners platform. Both oil and gas are produced from carbonate-buildup-type (phylloid-algal mounds) reservoirs in the Alkali Gultch and Barker Creek zones of the Pennsylvanian Paradox Formation. Unlike the fields in the San Juan Basin, hydrocarbons on the Four Corners platform are trapped in both structural (anticlines) and stratigraphic traps. The axes of these anticlines strike parallel with the northeast trend of the Four Corners platform and The Hogback monocline. These structures formed at the same time as the San Juan Basin.

  Rocks exposed on the surface of the region include the Cretaceous Mancos through Kirkland Shales. The Fruitland Formation outcrops just east of The Hogback where its coal beds are extensively mined in open pits to supply coal to the nearby Four Corners and San Juan power plants. The region also includes extensive Tertiary sandstone and Quaternary surficial deposits. Pliocene basaltic dikes and volcanic necks, including the famous landmark "Ship Rock," are exposed locally in the western part of the region on the Four Corners platform. Minor high-angle normal faults are also mapped on the surface in the Four Corners platform area.

- Over 4,500 m of sedimentary rock ranging in age from Cretaceous to Cambrian including marine, fluvial, deltaic, eolian and continental deposits in the San Juan Basin and Four Corners platform, New Mexico and Colorado.

- Potential **coal** reservoirs: (1) **Cretaceous Fruitland Formation** is 80 to 120 meters thick and contains shale, cross-bedded sandstone, and coal deposited in coastal swamps. It is the largest producer of coalbed methane in the United States (over 1,000 wells from three coal zones) with proved and undeveloped reserves of over 10 TCF of gas. (2) **Cretaceous Menefee Formation** is 250 to 300 m thick and contains fine- to coarse-grained sandstone, shale, and coal deposited in coastal swamps. It may contain between 22 and 34 TCF of coalbed methane.

- Potential **sandstone** reservoirs: (1) **Devonian McCracken Sandstone Member** of the Elbert Formation is less than 75 m thick and is present in the subsurface only in the Four Corners platform area. It consists of fine-grained dolomitic sandstone deposited in environments ranging from intertidal to delta front. (2) **Permian Cutler Sandstone** is 120 to 600 m thick and contains coarse arkosic sandstones that were shed off the Uncompahgre Highlands to the north-northwest. (3) **Jurassic Wingate and Entrada Sandstones** are as much as 270 m thick and contain fine- to medium-grained cross-bedded sandstone. These sands were deposited initially in an eolian setting. (4) **Cretaceous Dakota Sandstone** is 50 to 70 m thick, and contains sandstone, conglomeratic sandstone, shale and lenses of coal. These rocks were deposited in fluvial, deltaic and shallow-marine shoreline environments.

- Potential **shale** seals: (1) **Triassic Chinle Formation** is 200 to 450 m thick, consisting mostly of varicolored, bentonitic, and non-resistant mudstone and claystone with some locally interbedded resistant channel sandstone. The Chinle Formation was deposited under continental conditions by streams and in lakes. (2) **Cretaceous Mancos Shale** is greater than 600 meters in thickness, consisting mostly of marine shales deposited in the Cretaceous Interior Seaway. It is divided into to upper and lower parts separated by the Gallup Sandstone. (3) **Cretaceous Lewis Shale** is about 150 m thick, but locally it is as thick as 440 m and consists of marine shale with some limestone and sandstone beds deposited in the Cretaceous Interior Seaway. (4) **Cretaceous Kirkland Shale** is about 450 m thick and is divided into three members each being exposed on the surface. They consist of carbonaceous shale and fluvial sandstone.

- Potential **evaporite** seals: **Pennsylvanian Paradox Formation** within the Hermosa Group is about 300 m thick and is present in the subsurface only in the Four Corners platform area. It contains cyclic beds of penesaline and hypersaline anhydrite and halite deposited in the restricted shallow sea of the Paradox Basin.

- Carbon dioxide and other low-BTU gases are present in Pennsylvanian and Mississippian rocks of anticlines on the Four Corners platform (Tocito Dome, Ute Dome, and Hogback fields, for example). The thick sections of Paleozoic carbonate rocks in the region (Devonian Ouray Limestone, Mississippian Leadville Limestone, and Honaker Trail Formation) are the probable CO_2 source rocks. Metamorphism of these marine carbonates by the heat of nearby igneous intrusive rocks (including the laccoliths that form Sleeping Ute Mountain in southwestern most Colorado, the Carrizo Mountains in extreme northeastern Arizona, and Ship Rock on the Four Corners platform of New Mexico) generated CO_2. Alternatively, the CO_2 could be more recent and associated with lower crustal metamorphism as discussed earlier.

Opportunities for CO_2 Sequestration

+ Numerous unmineable coal seams provide an excellent location for CO_2 sequestration and enhancing coalbed methane production
+ Thick sandstone deposits with good porosity provide excellent reservoir potential
+ Thick shale, anhydrite and halite deposits provide excellent seals with few faults
+ Injection targets are relatively shallow
+ A CO_2 pipeline lies about 35 km to the east of the Four Corners and San Juan power plants
+ Tertiary CO_2 enhanced oil recovery programs could be conducted in nearby mature oil fields of the Four Corners platform.

Potential Problems or Issues Needing Study

– The Fruita and Menefee Formations (coal seams) are exposed at the surface nearby and may not be deep enough for efficient injection; surface leakage of CO_2 is a possibility; the Dakota and older formations are exposed farther west along the east flank of the Defiance uplift and the Red Rock monocline, and could also leak.

- – Some structures in the Four Corners platform area already contain significant quantities of CO_2 and other low-BTU gases
- – Benefits of CO_2 enhanced oil recovery unproven for mature oil fields in the Four Corners platform
- – A 35-kilometer-long CO_2 pipeline(s) is needed to access McElmo CO_2 pipeline to west Texas. This may have to cross tribal lands

Jim Bridger Power Plant Site

The coal-fired Jim Bridger plant has a capacity of 2034 MW and is situated on the eastern flank of the Rock Springs Uplift, 35 km east of Rock Springs, Sweetwater County, south Wyoming (Fig. 5a). It is operated by Pacificorp (Scottish Power).

Geological Setting (Fig. 5b; derived from DeBruin, 1997, Lickus and Law, 1988)

- South-to-north trending basement involved anticline.
- 1,800 m (6000 feet) structural closure encompassing about 3,000 km^2 (1,200 square miles) at the Cretaceous Baxter Shale datum (Lickus and Law, 1988).
- Surface exposures range from Tertiary Green River Formation on the flanks to Baxter Shale on the crest of the anticline.
- Normal faults have been mapped on the surface and drilling has identified many more that are not visible on the surface.
- Potential reservoirs for CO_2 injection are the Jurassic-Triassic Nugget Sandstone with an overlying seal formed by the Gypsum Springs Formation and the Pennsylvanian Weber Sandstone with the Permian Phosphoria Formation possibly forming an overlying seal.
- Baxter Shale is a secondary seal.
- Numerous oil and gas fields produce from secondary structures, fault traps and stratigraphic traps. Most of the hydrocarbon production is from Cretaceous-aged sandstone with minor production from the Nugget Sandstone and Phosphoria Formation. The Mississippian Madison contains CO_2 and water.

Opportunities for CO_2 Sequestration

- + Large trap, 3,000 km^2 of four-way closure.
- + Laterally extensive sandstone reservoirs (Nugget Sandstone and Weber Sandstone).
- + Primary seals directly overlying the potential reservoirs (Gypsum Springs overlying the Nugget and Phosphoria overlying the Weber) and a thick secondary seal (Baxter Shale).

Potential Problems or Issues Needing Study

- – Oil and gas operators who own production and leases in the area may fear contamination of proven and undiscovered hydrocarbon resources from injected CO_2.
- – Uncertainties where normal faults in region may allow upward leakage of injected CO_2.
- – The quality of the primary seals is questionable, the Phosphoria is a porous reservoir in some locations and the Gypsum Springs is thin (17 m) in the Rock Springs Uplift area.

Craig Power Plant Site

The Craig coal-fired power plant is located near the southern boundary of Craig, Moffat County, Colorado. The site is on the north-dipping flank of the Axial Basin Uplift formed by the Cretaceous Lewis Shale and Mesaverde Group (Fig. 6a). The plant is operated by The Tri-State G & T Association Inc. and it has a capacity of 1200 MW.

Geological Setting (Fig. 6b; Tweto, 1987)

- Flank of the Axial Basin Uplift, a regional structure formed by the plunge of the Uinta arch.
- Several smaller structures superimposed on the larger structure.
- Moffat Dome has fault-related structural closure 14 km south of the plant.
- Surface exposures range from Cretaceous Lewis Shale at the plant site to Mancos Shale at the crest of the Moffat Dome.
- Potential reservoirs for CO_2 injection are the Jurassic Entrada/Glen Canyon Group, and the Permian Weber Sandstone with overlying seals formed by the Mancos Shale and Chinle/State Bridge Formations, respectively.
- Moffat Dome is a producing oil field that is very near depletion. Oil has been produced from the Cretaceous Mancos Shale, Mesaverde Group, Dakota Sandstone and the Permian Weber Sandstone.

Opportunities for CO_2 Sequestration

+ Moffat Dome is a moderate size asymmetrical trap with about 700 meters of closure at the Permian horizon over perhaps 3.5 km^2.
+ Laterally extensive sandstone reservoirs (Entrada/Glen Canyon Group and Weber Sandstone) with potential reservoir in the Mississippian carbonate.
+ Thick Mancos Shale provides an excellent seal between the reservoirs and surface.
+ Possibility of using CO_2 for enhanced oil recovery

Potential Problems or Issues Needing Study

– More geologic detail is needed. Subtle structural features between the plant and Moffat Dome could result in gas migration pathways not currently considered.

– Formations directly overlying the potential reservoirs (Chinle/State Bridge and Dakota/Morrison/Curtis/Summerville) are mixed seal and reservoir so upward migration of gas could occur along the path from the plant to Moffat Dome.

– Moffat Dome and other neighboring structures are oil productive. It is not known whether the oil and gas operators would welcome the opportunities for enhanced oil recovery through CO2 injection, or fear contamination and degradation.

IPP-Delta Power Plant Site

The Intermountain Power Agency power plant near Delta, Millard County, Utah is coal-fired and has a capacity of 1600 MW (Fig. 7a; after Hintze and Davis, 2002). The plant is owned by the City of Los Angeles.

Geological Setting (Fig 7b; from Hintze and Davis, 2002***)***

- Situated in the Basin and Range physiographic province (normal faulting) and also overlies a low-angle Cretaceous thrust zone at depth
- 77.2 m of Pliocene - Miocene basin deposits
- Sand, silt, clay, and gravel, with traces of volcanic material.
- 1570.4 m of Miocene - upper Oligocene halite with some anhydrite.
- 9.7 m of Tertiary conglomerate.
- Unknown thickness (1076.6 m drilled thickness) of Cambrian (?) carbonates consisting of white, light-gray and gray, fine- to medium-crystalline dolomite and dark-gray to black, argillaceous dolomite; some minor light-gray green shale is present, pyrite is common throughout the carbonate section. H. J. Bissell interpreted the carbonates as Tertiary, G. C. Mitchell interpreted the carbonates as Ordovician through Devonian in age.
- Structural dip of the Cambrian carbonates is not known.

Opportunities for CO_2 Sequestration

+ Thick salt deposit provides an excellent seal.
+ Potential injection into salt, combination seal and reservoir.
+ Carbonate reservoirs below salt, porosity zones identified by drilling, 3012.0 - 3013.3 m has 12.5% density/neutron, 3079.7 to 3084.6 m appears to be fracture zone, 3099.8 to 3102.3 m has 12.5% density/neutron; several other zones with 4 to 6 % porosity.

Potential Problems or Issues Needing Study

– Salt reservoir (cavern) would be of limited volume.

– Carbonate porosity zones are thin and lateral extent unknown.

– Structure below the salt is unknown, beds could be horizontal, steeply dipping, or overturned.

– Carbonate stratigraphy is still highly questionable.

Discussion and Conclusions

Five of the six power plants sites were sited because of proximity to coal outcrop and seams suitable as a long-term feedstock for the plants. These five plants are situated on the Colorado Plateau and southern Rocky Mountains physiographic provinces and have similar geologic settings. The exception is the Intermountain Power Plant, Delta, Utah, where coal is brought by truck and rail from the east side of the Wasatch Plateau about 100 km away. With this site, other factors such as proximity to major power transmission corridors were important. This site is in the Basin and Range physiographic province which has been affected by tensional faulting since mid –Tertiary time. With the other five projects, the occurrence of near-surface coal is a consequence of a gentle local dip (< 5°) of the Cretaceous and early Tertiary sediments in combination with differential erosion. Despite the near-horizontal layer-cake stratigraphy characteristic of much of the Colorado Plateau, the dipping structures near these power plant sites mean that lateral migration of a subsurface CO_2 plume is possible if injection occurs close to the power plant. This need not be considered a negative factor, depending on the continuity of overlying sealing units, and an absence of major faults disrupting seal competency. White et al., (2003) show that slow lateral migration of a plume of injected CO_2 increases the opportunity for rock-fluid interactions, and this increases the potential for sequestration of CO_2 in minerals and as dissolved species.

Both the Jim Bridger (Wyoming) and the Craig (Colorado) power plants are situated on the flanks of large domal features with four-way closure that are also sites of oil and gas fields (Rock Springs Uplift and Moffat Dome respectively). In both cases, injection of CO_2 to 1 - 2 km depth near the power plants would target potential reservoirs that are stratigraphically below the proven petroleum fields. The presence of trapped oil and gas suggests that adequate seals are present over these domes, at least higher in the stratigraphic section. An issue in both areas is whether operating oil and gas lease-holders would welcome or oppose nearby CO_2 injection. Some CO_2 could be used for enhanced oil recovery in the mature oil fields, but without further investigation of likely flow paths of the injected CO_2, some CO_2 may be perceived as diluting or displacing natural gas resources. An additional strategic factor with the Jim Bridger plant is its location within 30 km of a major CO_2 pipeline through southern Wyoming, northeast Utah and northwest Colorado. There is a possibility for power plant CO_2 to displace natural CO_2 production from LaBarge field, resulting in a net CO_2 offset of emissions.

The Hunter-Huntington power plants site in central Utah is also situated on the flanks large monoclinal structure, the San Rafael Swell. Here erosion of the Swell has breached many of the potential Mesozoic reservoir and seal units, although in the case of the Permian White Rim sandstone, the outcrop area is small and displaced about 30 km east of the nearest power plant. The dip on the formations in the vicinity of the power plants is 1° to the west. This site is used by White et al. (2003) to simulate the fate of injected CO_2 based on the predicted CO_2 plume flow at depth and likely fluid-rock interactions. The study shows that on a 1000-year timescale, most of the CO_2 is sequestered.

The Navajo power plant in northern Arizona is also on a monoclinal structure that dips at about 2° to the northwest. Immediately south of the power plant there is little regional dip and a gently undulating structure. A regionally extensive reservoir-seal combination in the Permian at about 1,500 m depth appears ideal for sequestration. There are few faults and those that are present have minor displacements and are unlikely to provide high permeability channels through the seal rocks.

The Four-Corners/San Juan power plants are adjacent to a northeast-trending monocline known as The Hogback. This feature raises the sedimentary section to the northwest about 1 km in elevation, and this would be the direction that injected CO_2 would migrate. Suitable reservoir and seal units are present at appropriate depth, with 500 m of Mancos Shale immediately beneath the surface being the primary seal. These two power plants are 35 km from the McElmo-West Texas CO_2 pipeline, so like the Jim Bridger plant, opportunities exist for offsetting natural CO_2 production for enhanced oil recovery.

The geology of the Intermountain power plant near Delta, Utah is the least well-determined of all six sites considered in this paper. A nearby well intersected a thrust zone at 2.5 km depth with Cambrian carbonate rocks lying beneath the thrust, and upper Tertiary sediments above the thrust plane. The Basin and Range history of upper Tertiary faulting probably means that this region has more faults, and potential leakage of CO_2 to the surface may be more of a problem than with the other five sites. A buried salt/gypsum deposit near the plant may provide a secure location for gas storage, but whether it is large enough to store CO_2 emissions from 10 – 20 years of power plant operation is unknown.

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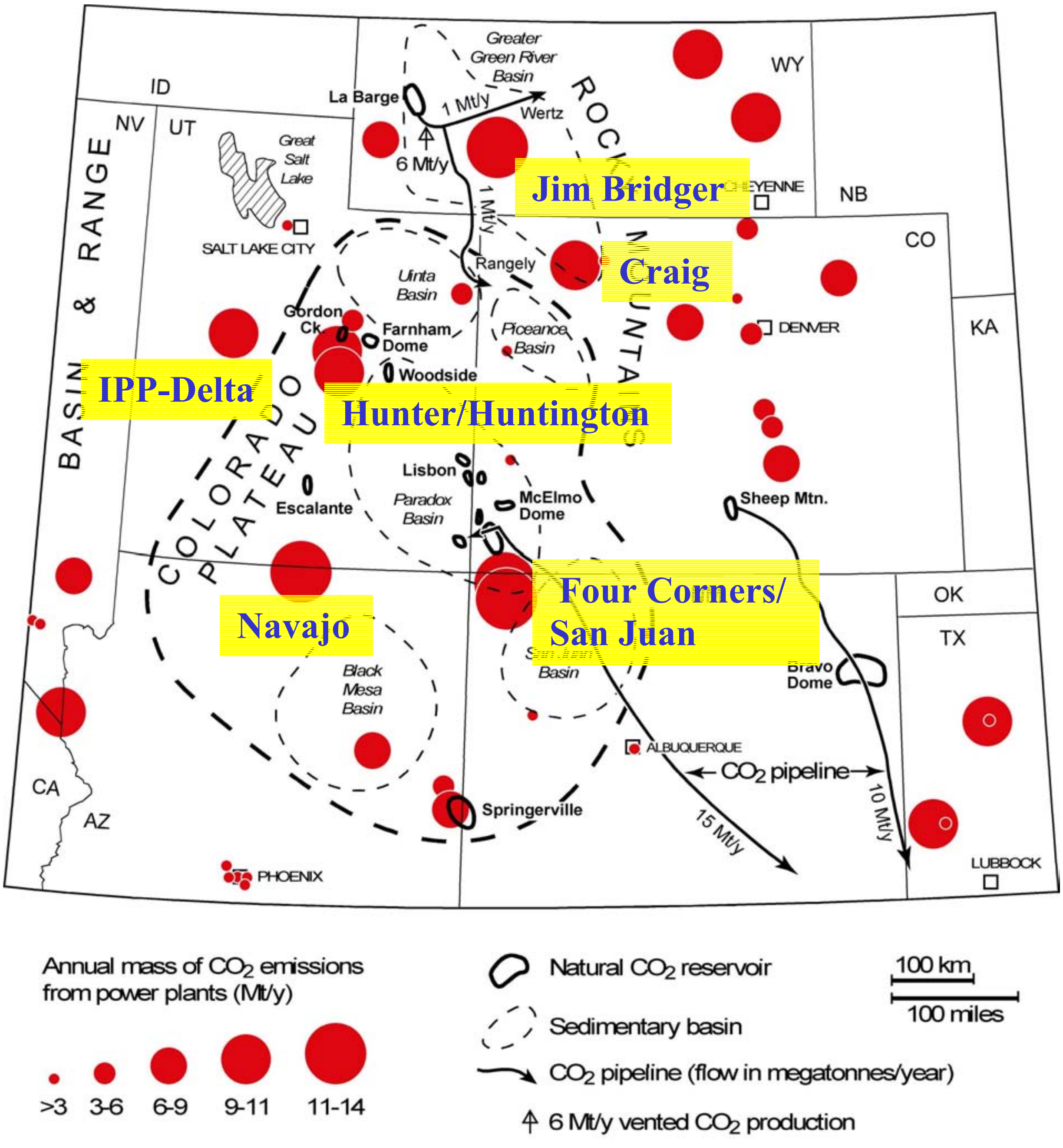


Figure 1. Location of major sources of CO_2 emissions from fossil fuel power plants in the Southern Rocky Mountains-Colorado Plateau, with size of the red dots proportional to emissions (in millions tons/year, after Hovorka, 1999). The six largest power plant sites are labeled, and are the subject of this paper.

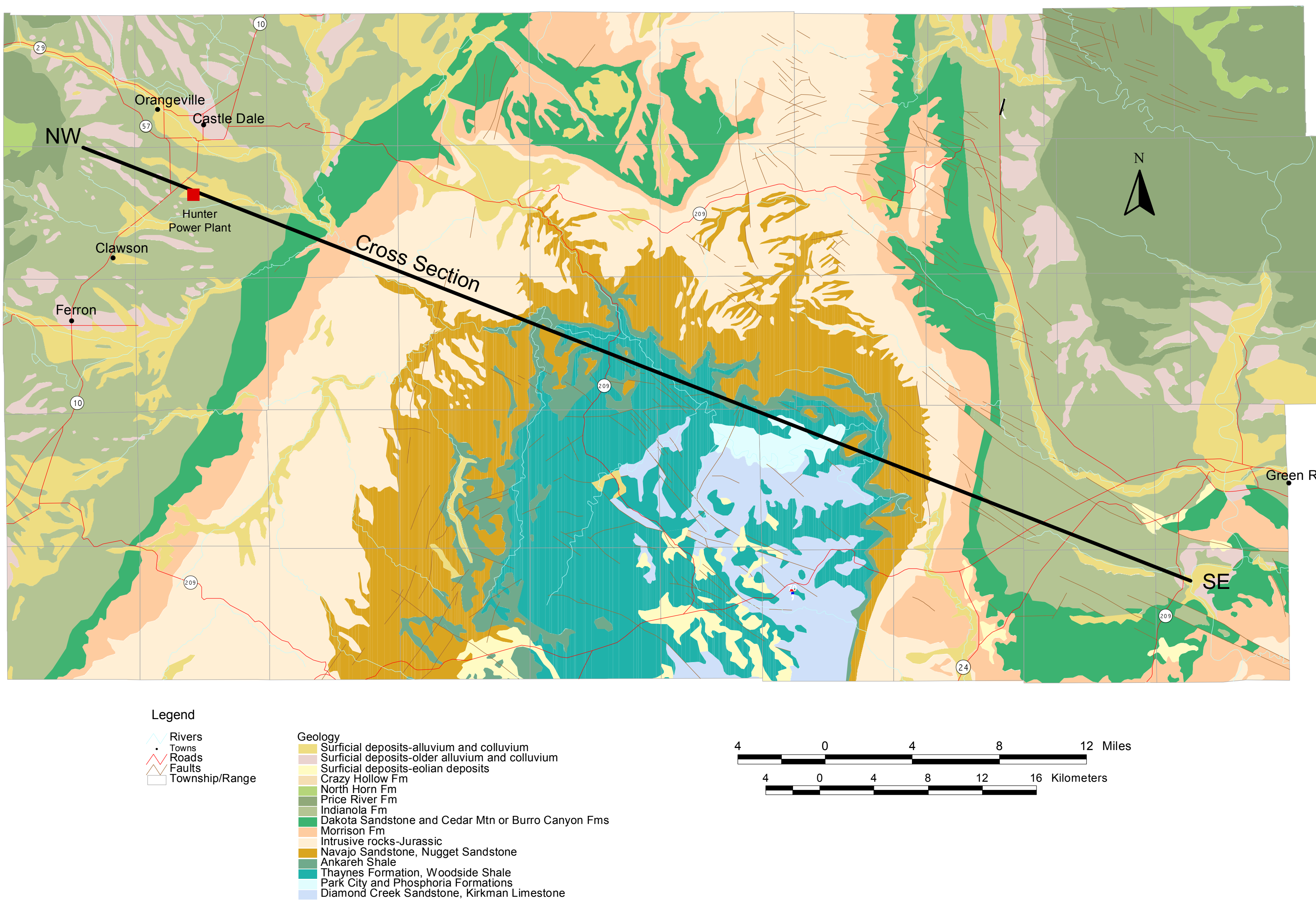
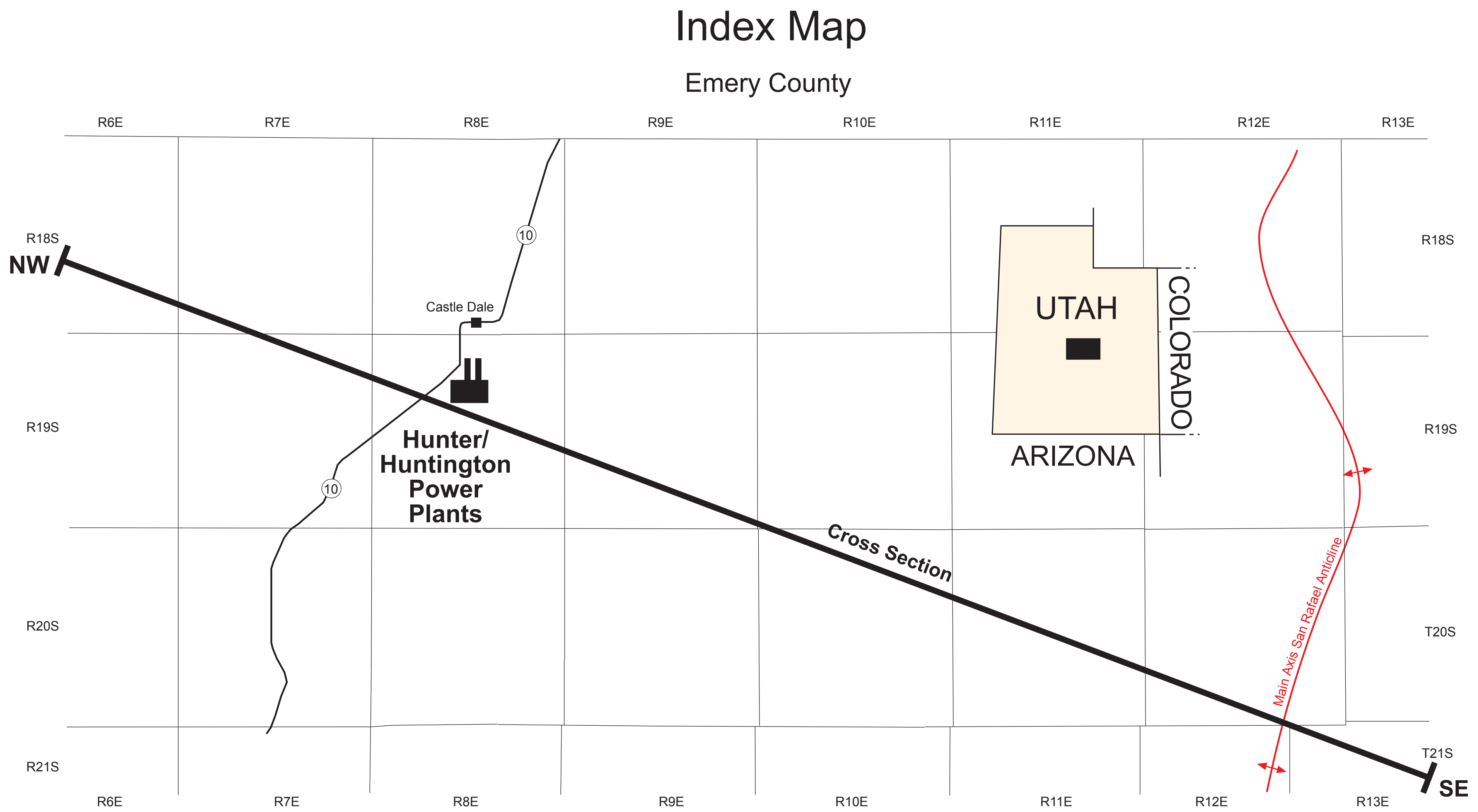
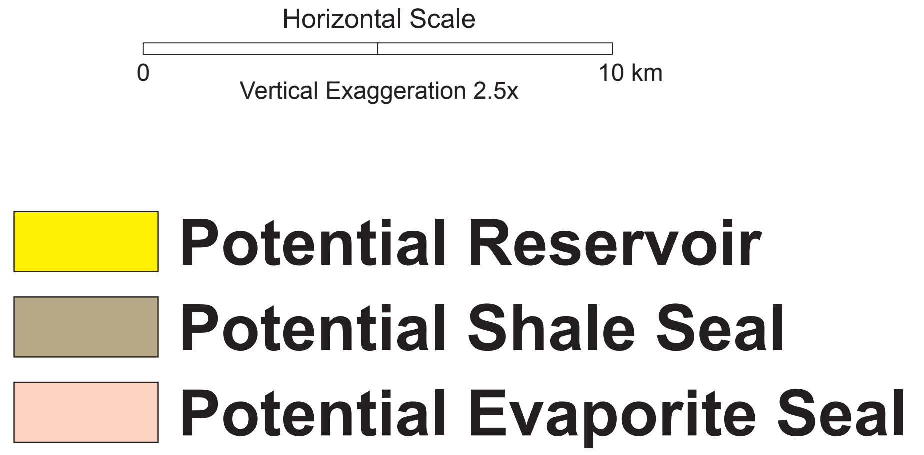


Figure 2a: Geologic map of the vicinity of the Hunter power plant, central Utah, and the location of the cross-section shown in Fig. 2b. Geology is taken from Hintze et al., (2000). The Huntington power plant is north of the map edge, about 15 km north of Orangeville.





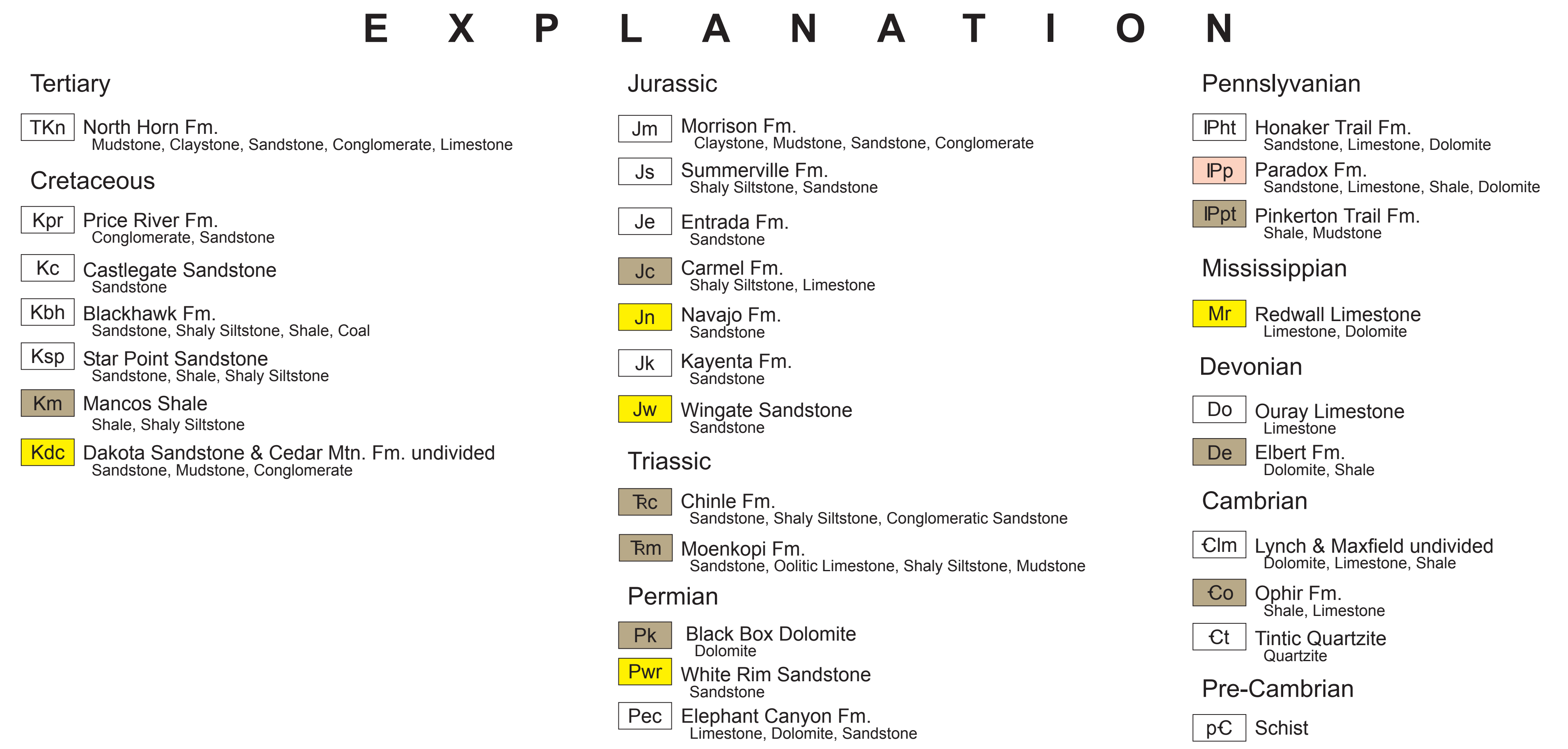
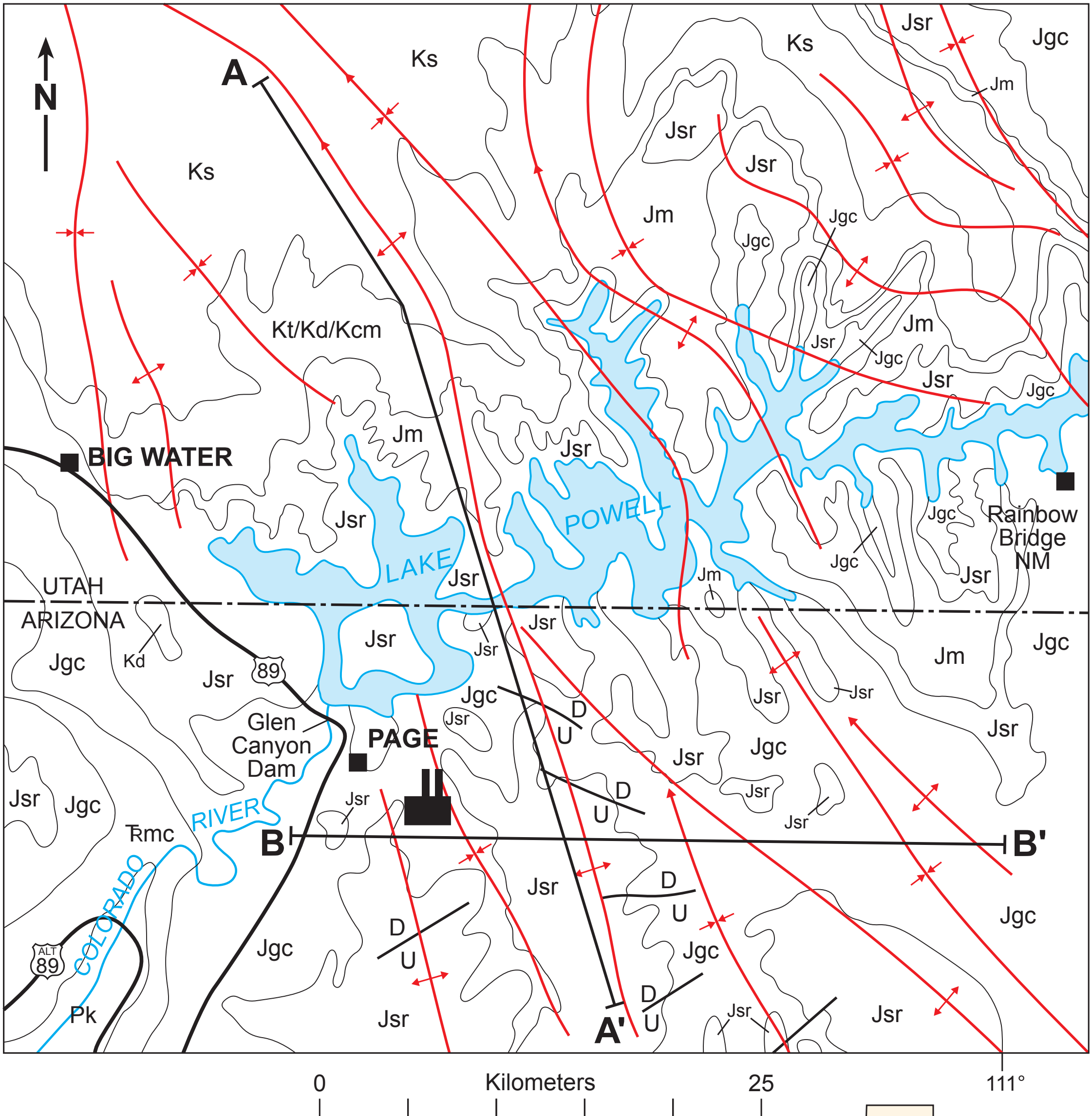


Figure 2b. Northwest-southeast cross-section through the Hunter power plant and across the San Rafael Swell. See Fig. 2a for map.



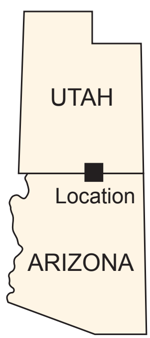


Figure 3a. Map showing location of cross-sections (lines A-A' and B-B') through Navajo power plant, northern Arizona in Fig. 3b, and generalized geology of the area.

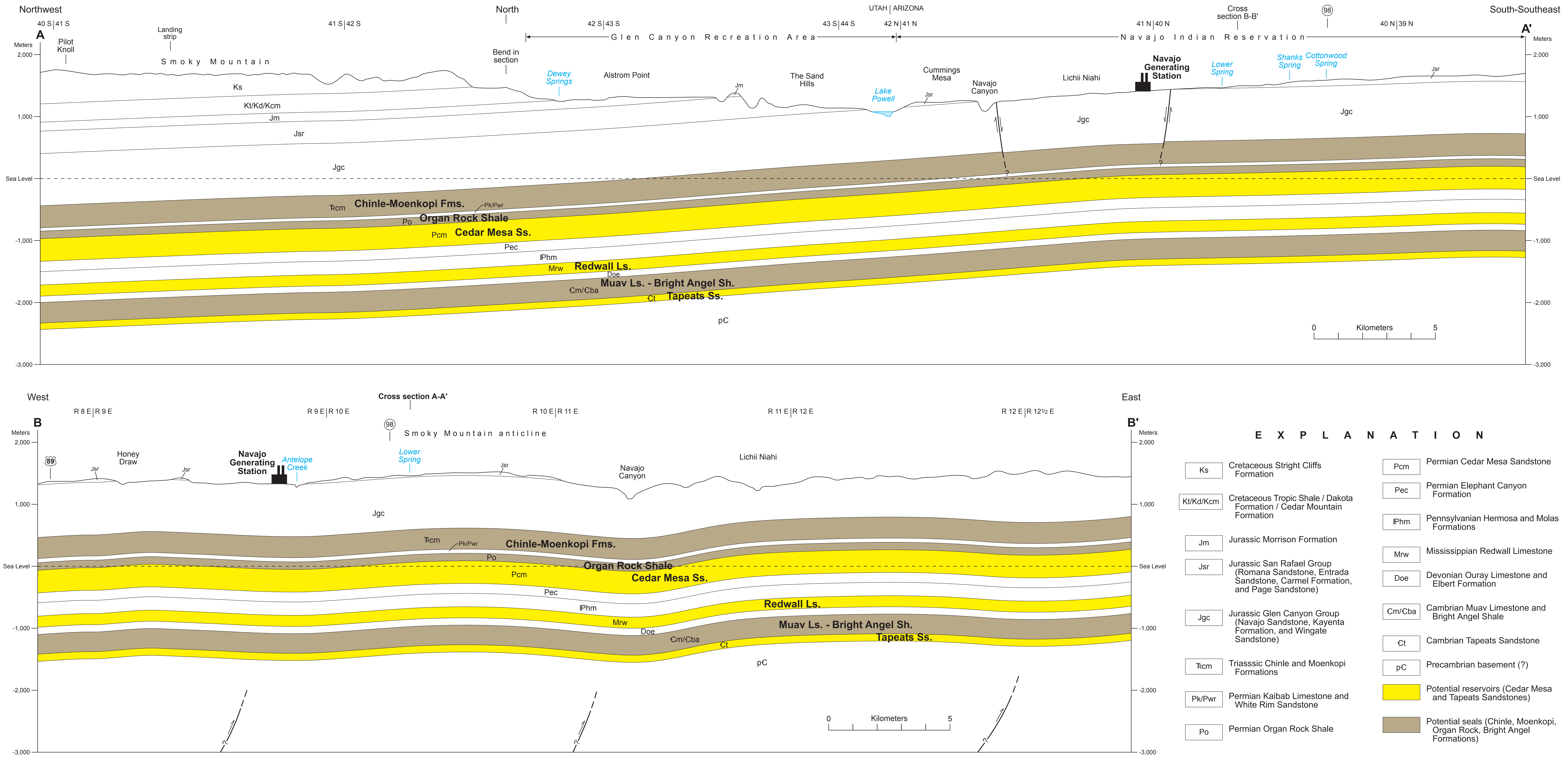


Figure 3b. Geologic cross-sections through Navajo power plant site. Refer to Fig. 3a for location.

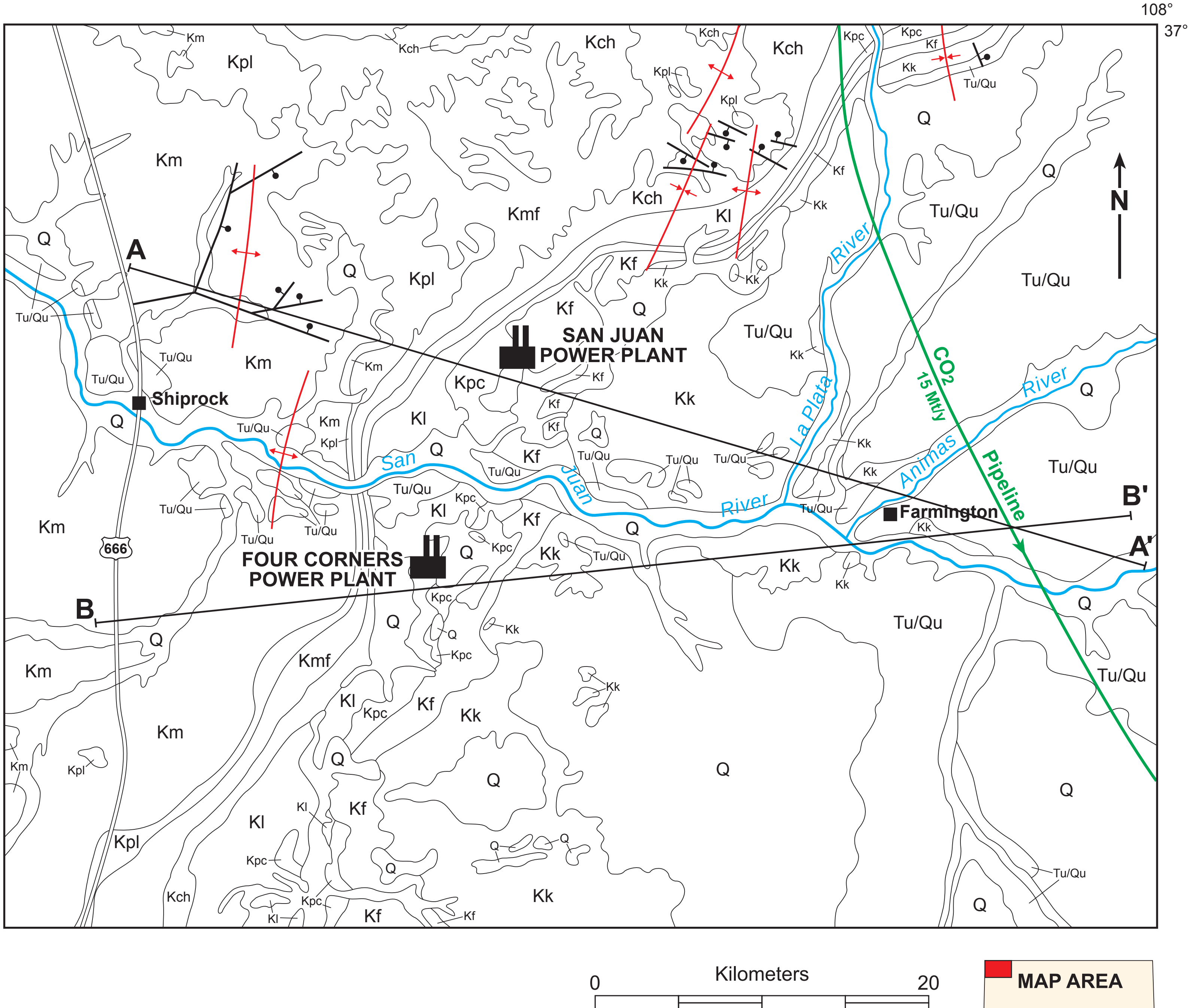


Figure 4a. Simplified geologic map of the region around the Four Corners and San Juan power plants. The location of the two cross-sections shown in Fig. 4b are shown as lines A-A' and B-B'.

E X P L A N A T I O N

Quaternary/Tertiary	Q	Quaternary surficial deposits
	Tu/Qu	Tertiary/Quaternary undivided
Cretaceous	Kk	Kirtland Shale
	Kf	Fruitland Formation
	Kpc	Pictured Cliff Sandstone
	Kl	Lewis Shale
	Kch	Cliff House Sandstone
	Kmf	Menefee Formation
	Kpl	Point Lookout Sandstone
	Km	Mancos Shale
	Kd	Dakota Sandstone
Jurassic	Jm	Morrison Formation
	Jwk	Wanakah Formation
	Je	Entrada Sandstone
	Jw	Wingate Sandstone
Triassic	TRc	Chinle Formation
Permian	Pc	Cutler Sandstone
Pennsylvanian	IPh	Hermosa Group
Mississippian	Ml	Leadville Limestone
Devonian	D	Devonian undivided
Cambrian	Ci	Ignacio Quartzite
Precambrian	pC	Precambrian basement

Potential Reservoirs

Sandstone (Dakota, Entrada, Wingate, Cutler, McCracken Sandstone Member of the Elbert Formation [Devonian] in northwest area of San Juan Basin)

Coal (Fruitland, Menefee)

Potential Seals

Shale (Kirtland [lower member], Lewis, Mancos, Chinle)

Evaporite (Paradox Formation in Hermosa Group, northwest area of San Juan Basin)

Figure 4b. Geologic cross-sections through the Four Corners and San Juan power plants. Refer to Fig 4a for location.

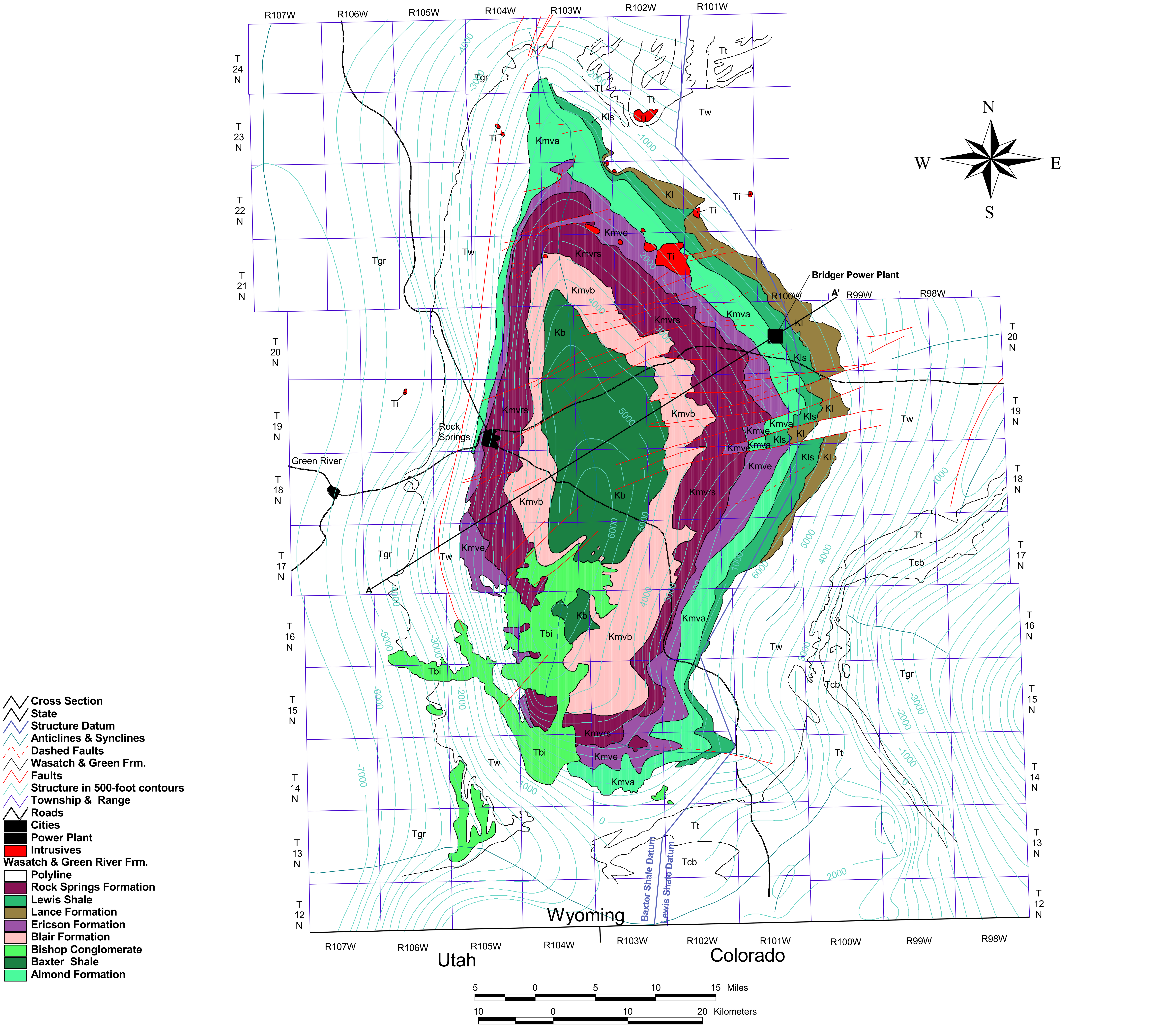


Figure 5a. Simplified geologic map of the region around the Jim Bridger power plant and Rock Springs Uplift, southern Wyoming. Location of cross-section in Fig. 5b shown as heavy line.

Structure contours drawn on Baxter Shale for west half of map and on the Lewis Shale for the east half of the map.

Figure 5b. Geologic cross-section through the Jim Bridger power plant and Rock Springs uplift. Refer to Fig. 5a for location.

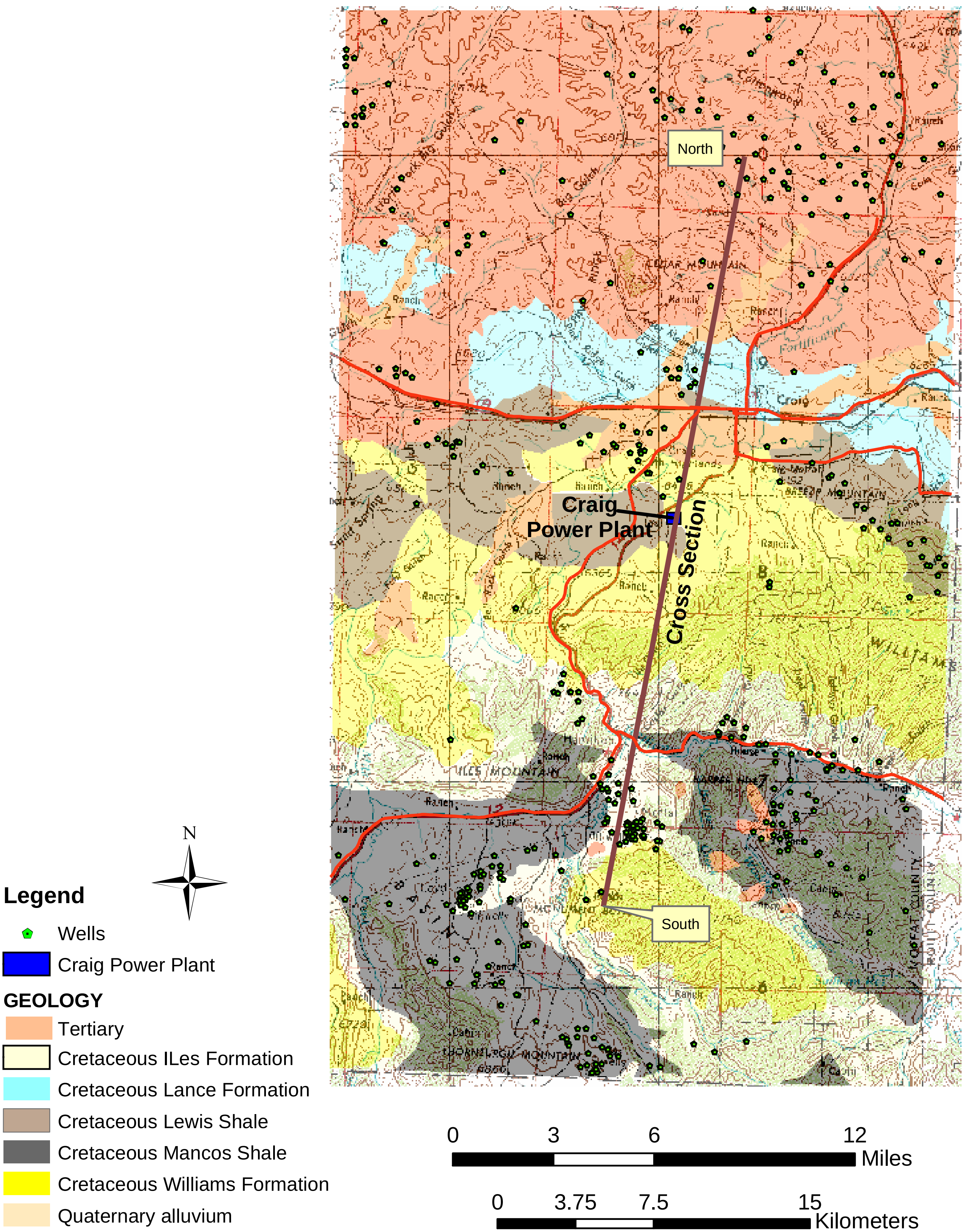


Figure 6a. Simplified geologic map of the region around Craig power plant and Moffat Dome, northwest Colorado. Location of cross-section in fig. 6b shown as heavy line.

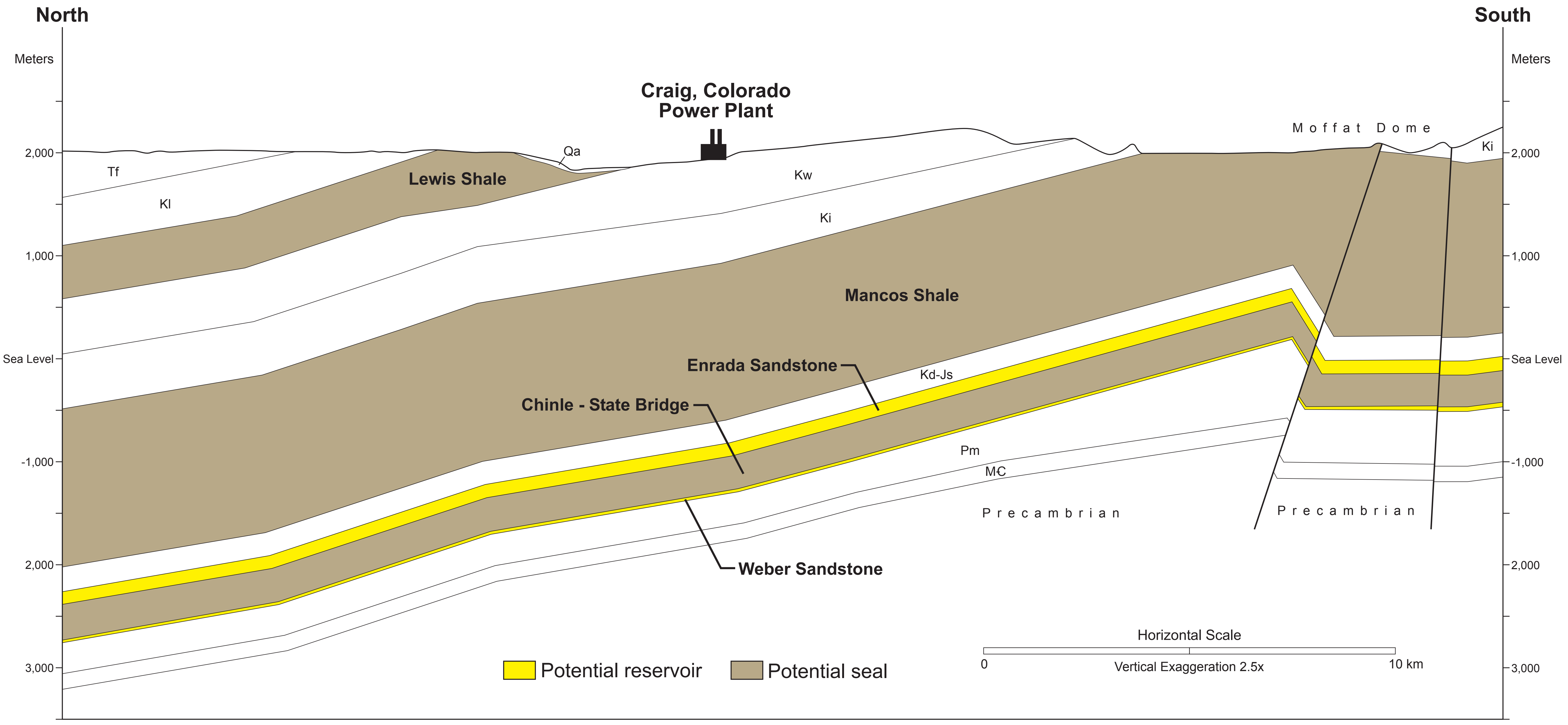


Figure 6b. Geologic cross-section through the Craig power plant. Refer to Fig. 6a for location.

Intermountain Power Plant

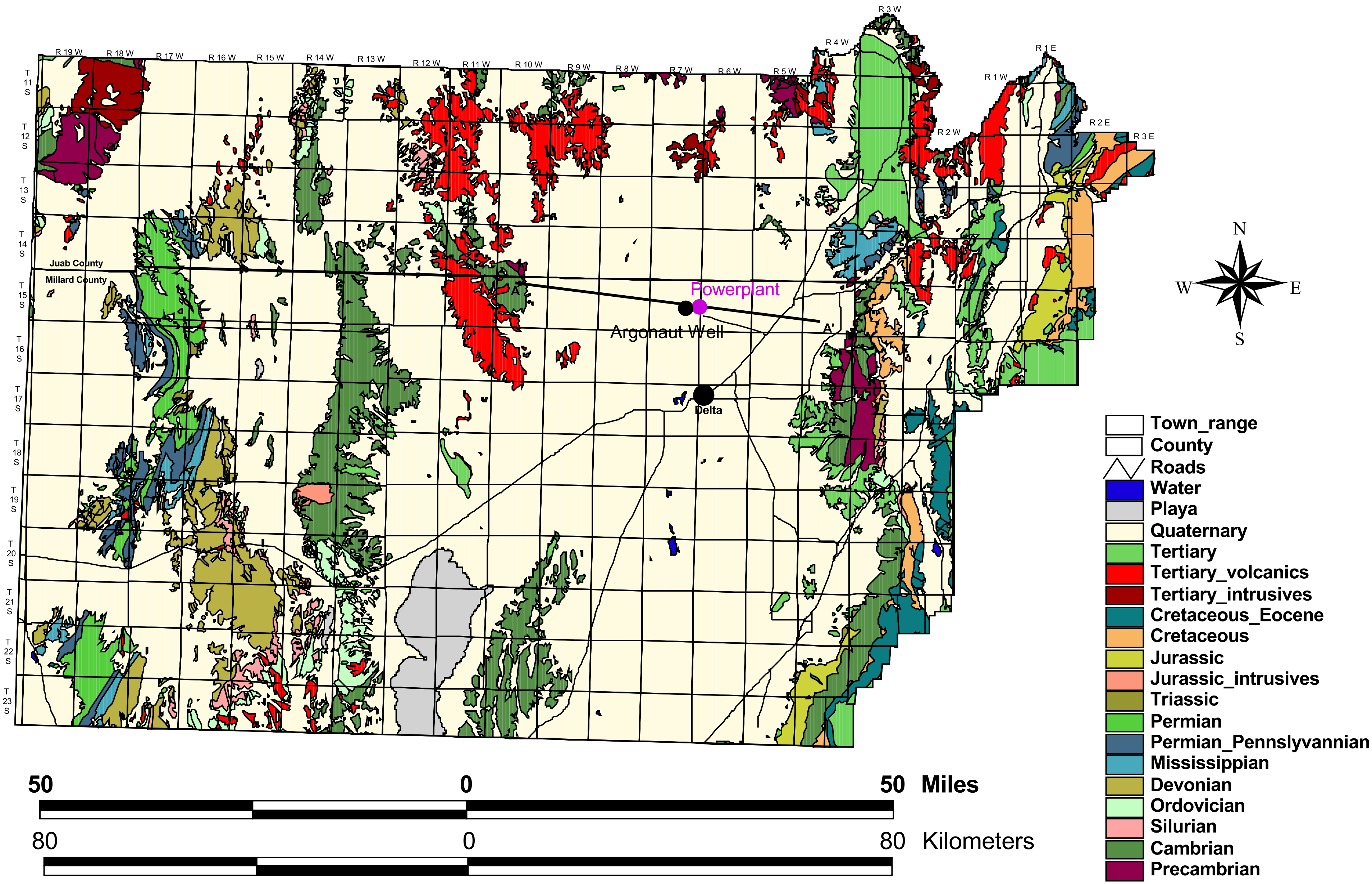


Figure 7a. Simplified geologic map of the region around the Intermountain Power Agency plant near Delta, central Utah. Location of cross-section in Fig. 7b shown as heavy line.

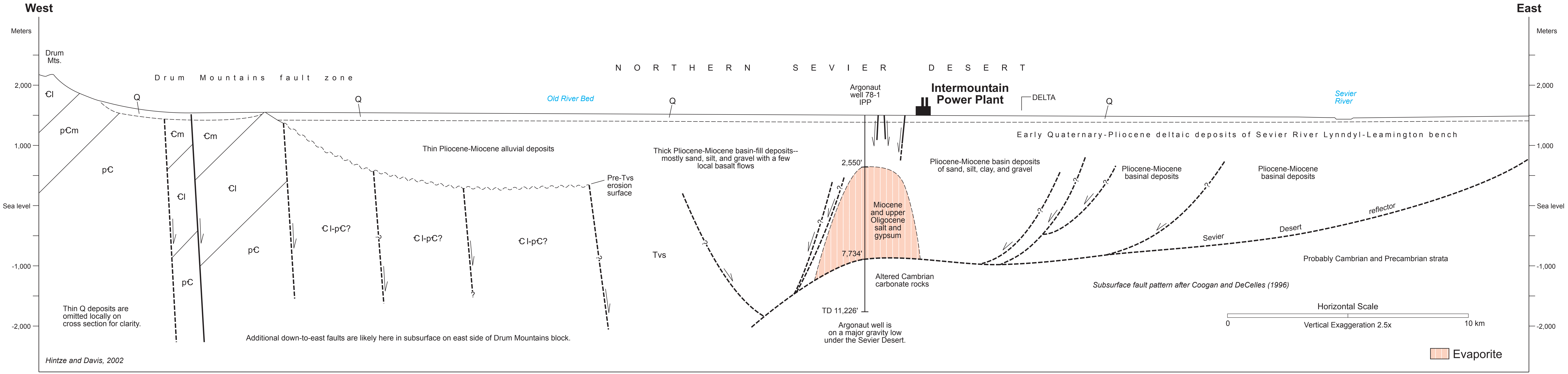


Figure 7b. Geologic cross-section through the Intermountain Power Agency plant. Refer to Fig. 7a for location.