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Technical Memorandum No. 86-68330-2012-27

Review of Geologic Investigations and Injection Well Site Selection, Paradox Valley Unit, Colorado

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center

November 2012

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Bureau of Reclamation
Technical Service Center
Seismotectonics and Geophysics Group

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1.0 Introduction

The Bureau of Reclamation (Reclamation) operates a deep injection well at Paradox Valley in western Colorado (Figure 1), as part of the Paradox Valley Unit (PVU) of the Colorado River Basin Salinity Control Program (CRBSCP). Paradox Valley, overlying a salt anticline, is a major contributor to the salt load of the Colorado River. The Dolores River, a tributary of the Colorado, picks up about 205,000 short tons (185,000 metric tons) of salt annually from natural brine inflows as it crosses Paradox Valley. PVU was authorized for construction by the Colorado River Basin Salinity Control Act of 1974 (Public Law 93-320; amended in 1984 as Public Law 98-569).

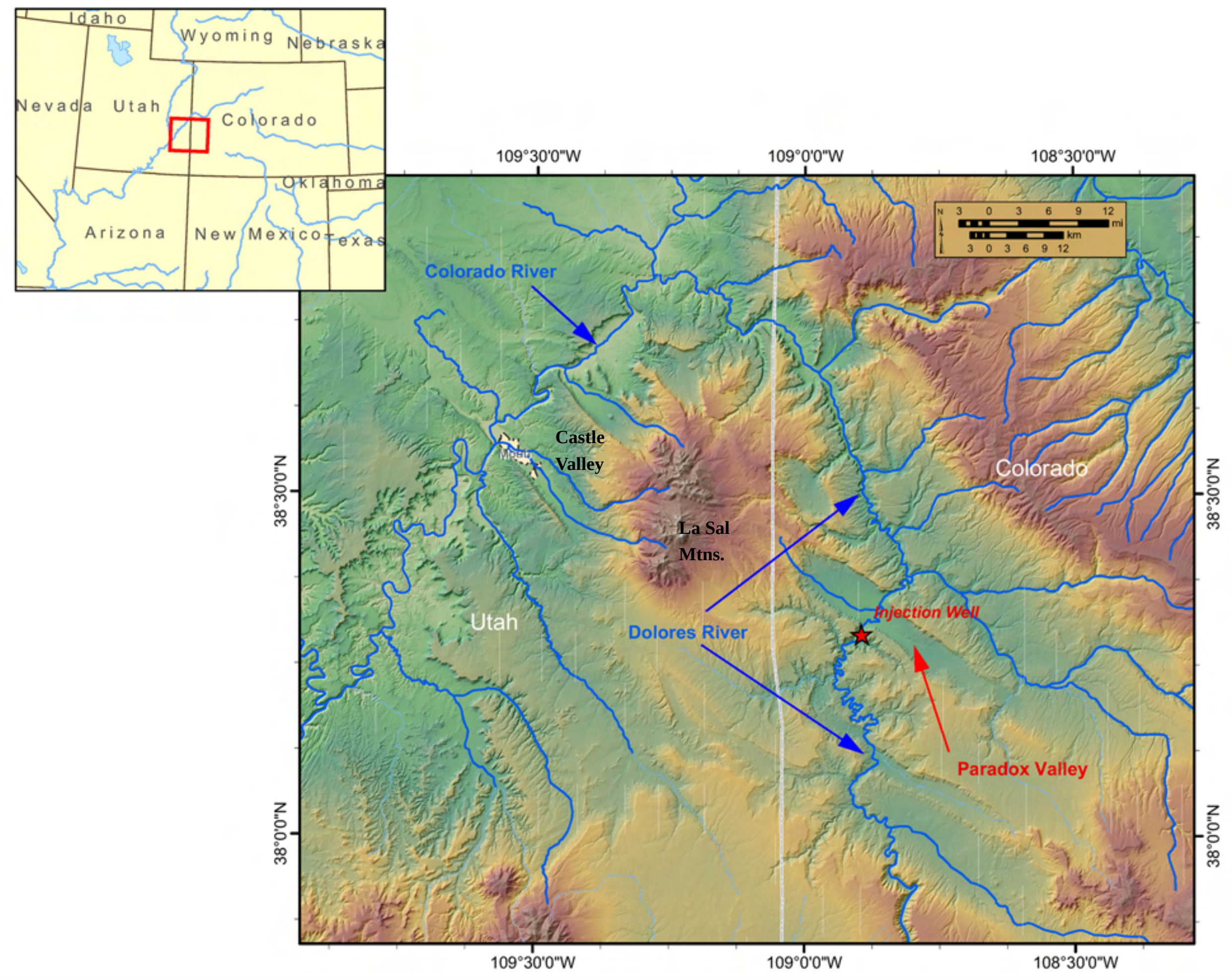


Figure 1: Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado.

The purpose of PVU is to divert up to 90 percent of the Paradox Valley brine inflows from entering the Dolores River, where they would substantially degrade water quality. Subsurface brine flows are intercepted by long-term pumping from a field of shallow extraction wells located along the river (Figure 2). The extracted brine is then collected and filtered at a surface-treatment facility, piped about 3.6 miles (6 km) to an injection facility at the edge of the valley, and finally injected into a 15,900-ft (4.8-km) deep injection well for long-term disposal. The injection well is designed to dispose of brine deep underground, confined to a narrow target zone extending over only the lowest 1,700 ft (500 m) of the borehole. Within this target zone, most of the injected brine is taken up by a subhorizontal formation of Mississippian-age limestone. The in-situ formation water in the injection zone is already brine, and therefore is not considered to be a potential source of potable water.

Deep-well brine injection at PVU has occurred more or less continuously since 1996, a duration of more than 16 years. Over this period, the maximum injection pressures required to dispose of the annual volume of diverted brine have gradually increased and within the next several years are

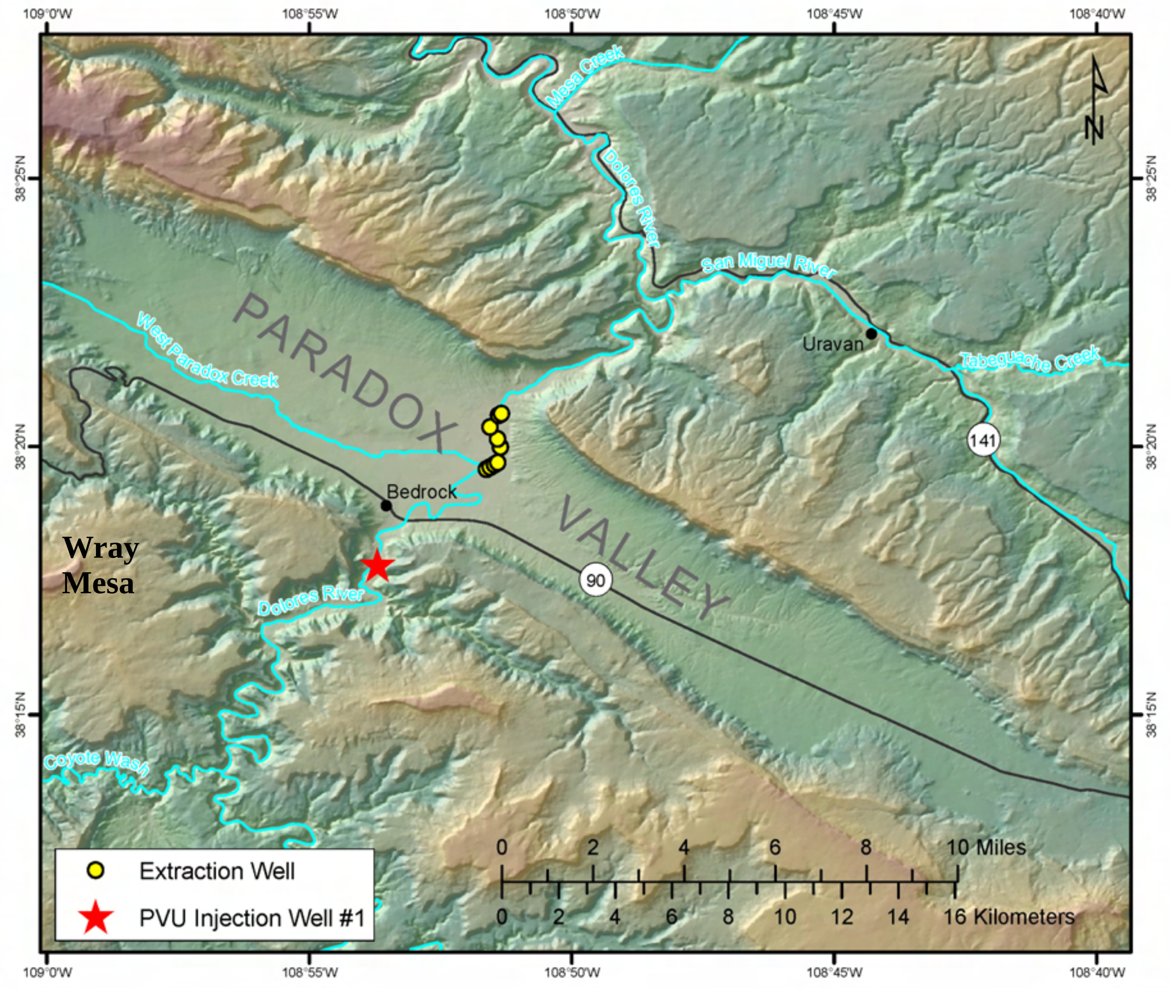


Figure 2: Location of the Paradox Valley Unit brine extraction wells and PVU Injection Well #1.

projected to reach the maximum allowable surface injection pressure (MASIP) specified in Reclamation's operating permit from the U. S. Environmental Protection Agency (EPA). The MASIP limit is designed to prevent injected brine from breaching a confining layer of salt that lies above the injection target zone, thus preventing contamination of shallow, potentially potable groundwater. Should the MASIP limit be reached, shut-ins of the injection well would be required to allow time for near-well pressures to dissipate, which reduces the operational efficiency and benefits of the project.

One of the long-term options under consideration for addressing the problem of increasing injection pressures is to drill a second injection well in the same general area, which would prolong the operational life of the existing well by allowing a reduction in the average annual injected volume of brine for each well. In order to fully evaluate this option, the most promising site locations for a potential second injection well must be identified, and feasibility and costs determined.

This report reviews existing geologic and geophysical studies that are relevant to site selection for a second injection well. Much of this work was done in the 1980's, prior to siting the first injection well, although some studies are more recent. This report is intended to provide a roadmap to these early PVU investigations, and to lay the foundation for determining what additional studies, if any, are now needed to identify and characterize suitable sites for a second injection well.

2.0 Project Background

2.1 Paradox Valley Unit

The Paradox Valley Unit (PVU) is located in western Montrose County approximately 55 miles (89 km) southwest of Grand Junction, CO and 10 miles (16 km) east of the Colorado-Utah border (Figure 1). The Dolores River, a tributary of the Colorado River, flows from the southwest to the northeast across Paradox Valley. The valley was formed by the collapse of a salt-cored anticline (Cater, 1970). Due to the presence of the salt diapir underlying Paradox Valley, and groundwater inflow from the La Sal Mountains at the northwest end of Paradox Valley, there are a series of diffuse brine springs which discharge highly saline water (0.26 kg/l of dissolved solids - more than seven times the 0.035 kg/l salinity of ocean water) into the Dolores River. PVU is designed to divert highly saline groundwater flows from entering the Dolores River and degrading water quality downstream. To do this, brine is extracted from nine shallow wells located within the valley along the river (Figure 2). The extracted brine is collected and filtered at a surface treatment facility, piped southwest about 3.6 miles (6 km), and then injected at high pressure into a deep disposal well located along the Dolores River, approximately 0.9 miles (1.5 km) southwest from the margin of Paradox Valley, near the town of Bedrock, Colorado (Figure 2). Details on the PVU project background, purpose, and benefits are provided in Reclamation's environmental assessment (USBR, 1997) as well as the EPA injection well permit fact sheet (EPA, 1997).

2.2 Feasibility Studies

An initial study to assess the feasibility of deep well injection for brine disposal was made in 1975 by Turner, who identified the Mississippian-age limestone formations present in the area, specifically the Leadville formation, as having the best reservoir and aquifer characteristics of the formations considered. Turner recommended that consideration be given to rehabilitating existing, abandoned oil and gas exploration wells as brine disposal wells, and he identified several candidate wells in the area. Additional feasibility and environmental studies were completed in 1978 by Reclamation (USBR, 1978), with recommendations made to further refine the feasibility of disposal by deep-well injection, and make preliminary cost estimates. A report by Williams Brothers Engineering (Williams Brothers, 1982) evaluated available geologic, geophysical, hydrogeologic, and engineering data for the area, assessed potential reservoir properties, evaluated the potential for re-use of existing petroleum wells for deep-well injection, prepared an initial design for a complete brine diversion system, assessed the impact of deep well injection, and made preliminary cost estimates. The Williams Brothers (1982) report recommended re-entry and completion of the Continental Scorup No. 1 well, located within Paradox Valley, as the primary injection well, and the Chicago No. 1 Ayers well (located about 1.9 miles (3 km) southwest of Paradox Valley) as a potential second well (see Figure 3 for locations of these wells). The report discussed available seismic reflection data from several geophysical data brokers, but based on a review of sample data decided that the data quality was inadequate to provide a good isopach map of either the Mississippian- or Devonian-age formations. The sample and reconnaissance data provided by the geophysical brokers apparently was sufficient to verify the existence of a major northwest-striking fault between the Chicago No. 1 Ayers and Union No. 1-0-30 Ayers wells that vertically offset the Leadville formation with about 6,000 ft (1,800 m) of throw.

The Scorup No. 1 well apparently was deemed to be impractical for re-use as an injection well, and preliminary technical specifications were developed in 1982 or 1983 to drill a 15,500-ft (4.7 -km) deep new well for deep injection at a nearby location within Paradox Valley. This well would have required drilling through nearly 15,000 ft (4.6 km ft) of salt. Two reports reviewing these plans were prepared in 1983. The first, by the consulting firm OGS Associates (Goins and Flak, 1983) recommended against using an injection well location that would require drilling through more than about 9,000 ft (3,000 m) of salt due to salt collapse and other completion problems. Goins and Flak (1983) also noted several criteria that should be considered, including reservoir size and permeability, proximity to the brine extraction field, and injecting at sufficiently high pressures to cause fracturing and avoid plugging of formation permeability by suspended solids and precipitates. A second review report by the firm OTS, Inc. (Klementich, 1983) noted the difficulty and cost of drilling through massive salt formations, and instead recommended drilling in a location where no more than 500 ft (150 m) of salt would be encountered.

By 1985, plans had focused on drilling a new well within the immediate vicinity of the Union Otho Ayers No. 1 well (Figure 3), which would have the benefits of having a known lithology, having a relatively thin (250 to 500 ft; 76 to 152 m) confining layer of salt over the injection zone, and avoiding the problems of drilling through deep salt. These plans were reviewed by the consulting firm of Ken E. Davis Associates (Davis, 1995), who noted the variable and relatively low matrix permeability of the Leadville formation, and that more than one disposal well might be required. Davis (1985) also deemed it essential that the disposal well be hydraulically fractured.

PVU Salinity Control Well No. 1 (originally, Paradox Valley Injection Test Well #1) was completed in 1987 to a total depth of 15,900 ft (4.8 km). A schematic diagram of the well is shown in Figure 4.The well was built to EPA Underground Injection Code (UIC) Class I standards ("Isolate hazardous, industrial and municipal wastes through deep injection"), but was permitted by EPA as a Class V disposal well ("Manage the shallow injection of non-hazardous fluids"). The well pene-

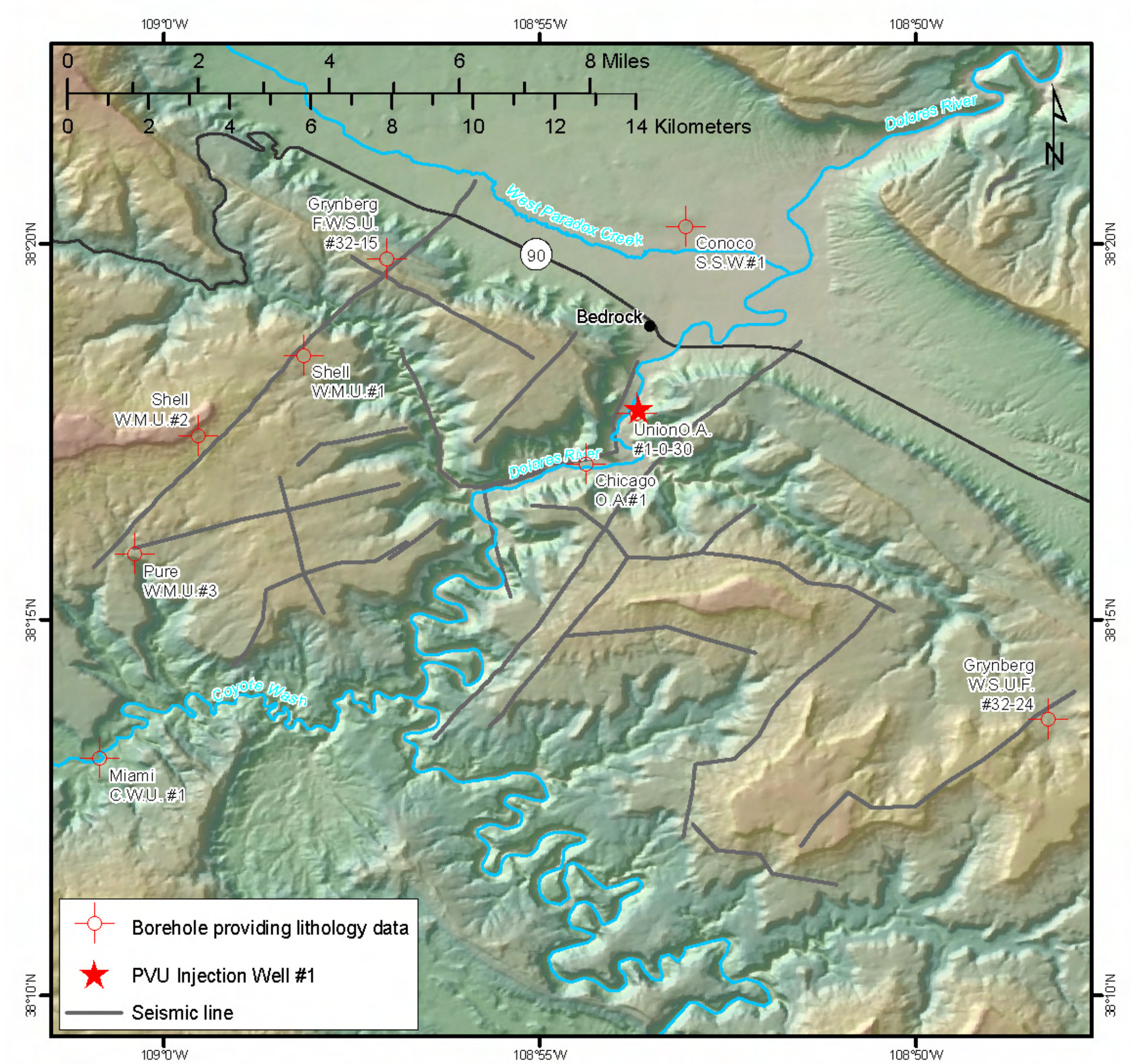
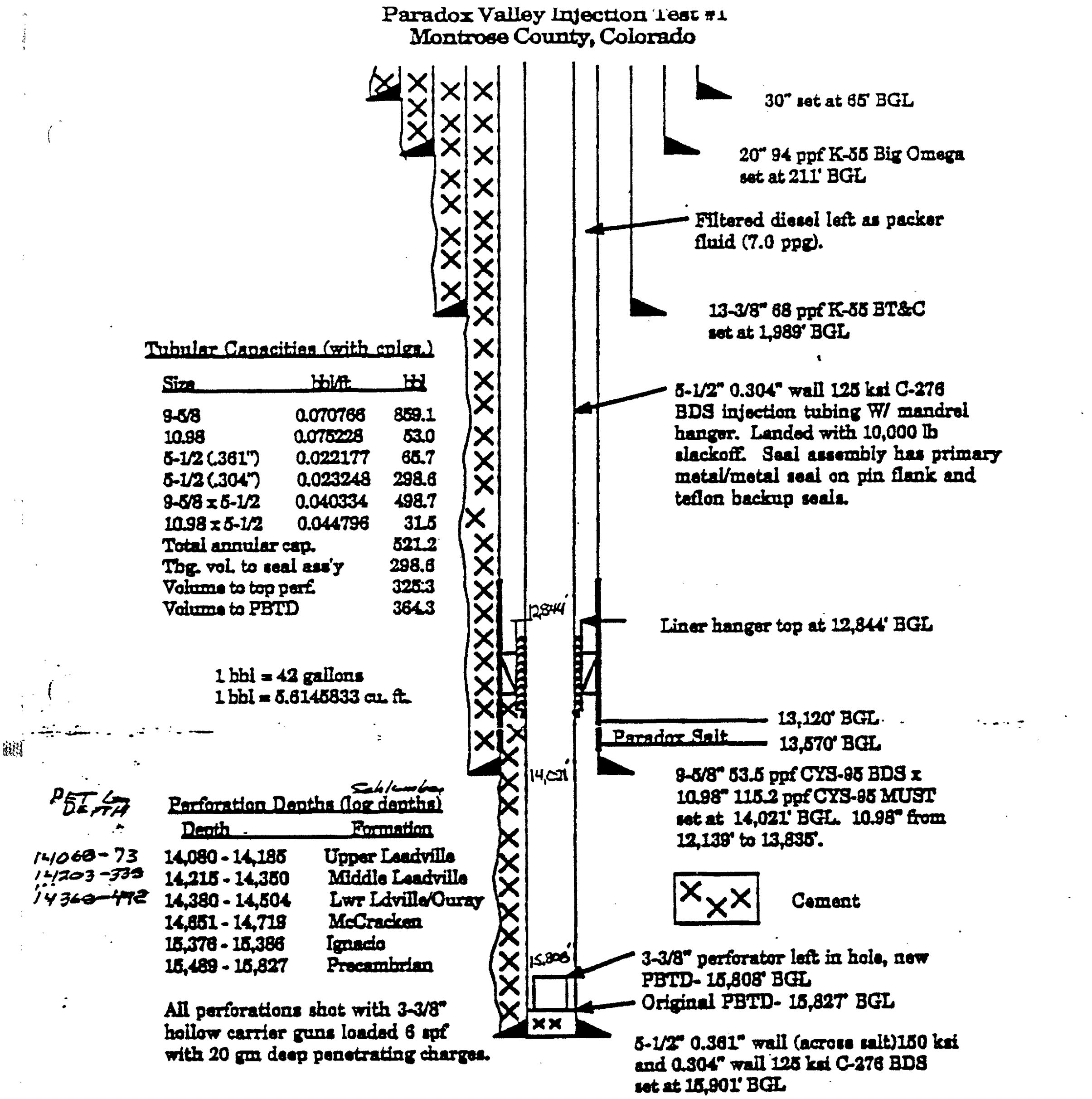


Figure 3: Locations of existing deep petroleum exploration wells in the Paradox Valley area.

trates Triassic- through Cambrian-age sedimentary rock layers and metamorphic Precambrian basement. Based on interpretation of core and log data, the Mississippian Leadville carbonate was selected as the primary injection zone and the upper Precambrian as a secondary zone (Bremkamp and Harr, 1988).

2.3 PVU Injection History

Between 1991 and 1995, PVU conducted a series of 7 injection tests, an acid stimulation test, and a reservoir integrity test. The purpose of these tests was to qualify for a permit for long-term injection from EPA. Continuous injection of brine began in July, 1996, after EPA granted the permit. Since continuous injection began, PVU has instituted and maintained three major changes in



*Tubular Ratings

Size (in.)	Weight (ppf)	ID (in.)	Drift (in.)	Burst (psi.)	Collapse (psi.)	Tensile (klb.)
9-5/8**	53.5	8.535	8.500	9410**	7330	1477
10.98	115.2	8.800	8.500	16,500	16,990	2091
5-1/2	23.1	4.778	4.653	17,230	13,480	874
5-1/2	19.2	4.892	4.767	12,440	7890	620

* The 20", 13-3/8", 9-5/8", and 10.98" were made by Mannesman of West Germany. The 5-1/2" C-276 was made by INCO Alloys of Huntington, West Virginia. The wellhead equipment was made by Cameron Iron Works of Houston, Texas. The liner hanger/ seal assembly were made by Texas Iron Works of Houston, Texas.

Figure 4: Schematic diagram of Paradox Valley Injection Test Well No. 1.

injection operations. Each change was invoked to mitigate the potential for unacceptable seismicity or to improve injection economics. These injection phases are described below. Plots of the daily average injection flow rate, surface injection pressure, and downhole pressure (at a depth of 14,100 ft (4.3 km)) throughout the history of PVU injection operations are shown in Figure 5.

2.3.1 Phase I (July 22, 1996 - July 25, 1999)

During this initial phase of continuous injection, PVU injected at a nominal flow rate of 345 gpm (~1306 l/min), at about 4,950 psi (~34.1 MPa) average surface pressure. This corresponds to approximately 11,800 psi (~81.4 MPa) downhole pressure at 14,100 ft (4.3 km) depth. To maintain this flow rate, 3 constant-rate pumps were used with each operating at 115 gpm. The surface pressure on occasion approached the wellhead pressure safety limit of 5,000 psi. At these times PVU would shut down one or two injection pumps, reducing the injection rate and allowing the pressure to drop a few hundred psi, before returning to three-pump injection. These shutdowns occurred frequently and lasted for minutes, hours, or a few days. Maintenance shutdowns lasted for one to two weeks and, in mid-1997, a 71-day shutdown was needed when replacing the operations contractor. The shutdowns resulted in an overall average injection rate for phase I of ~300 gpm (1136 l/min). The injectate during phase I was 70% Paradox Valley Brine (PVB) and 30% fresh water.

2.3.2 Phase II (July 26, 1999 - June 22, 2000)

Following two magnitude **M** 3.5 induced earthquakes in June and July, 1999, PVU augmented injection to include a 20-day shutdown (i.e., a “shut-in”) every six months. Prior to these events, it was noted that the rate of seismicity in the near-wellbore region (i.e., within about a 2-km radius from the wellbore) decreased during and following unscheduled maintenance shutdowns and during the shutdowns following the injection tests of 1991 through 1995. It was thought that the biannual shutdowns might reduce the potential for inducing large-magnitude earthquakes by allowing extra time for the injectate to diffuse from the pressurized fractures and faults into the formation rock matrix. When injecting during this phase, the injection pressure and flow rate were the same as during phase I.

2.3.3 Phase III (June 23, 2000 - January 6, 2002)

Immediately following a **M** 4.3 earthquake on May 27, 2000, PVU shut down injection operations for 28 days. During this shutdown period, PVU evaluated the existing injection strategy and its relationship to induced seismicity. PVU decided to reduce the injection flow rate in order to reduce the potential for inducing large-magnitude earthquakes. On June 23, 2000, PVU resumed injection using two pumps rather than three. This change decreased the injection flow rate by 33% compared to earlier phases, to 230 gpm (~871 l/min). The 70:30 ratio of brine to fresh water and the biannual 20-day shutdowns were maintained.

2.3.4 Phase IV (January 7, 2002 - present)

Beginning with continuous injection operations in 1996, PVU diluted the injectate to 70% PVB and 30% Dolores River fresh water. A geochemical study had predicted that if 100% PVB were injected, it would interact with connate fluids and the dolomitized Leadville limestone at down-

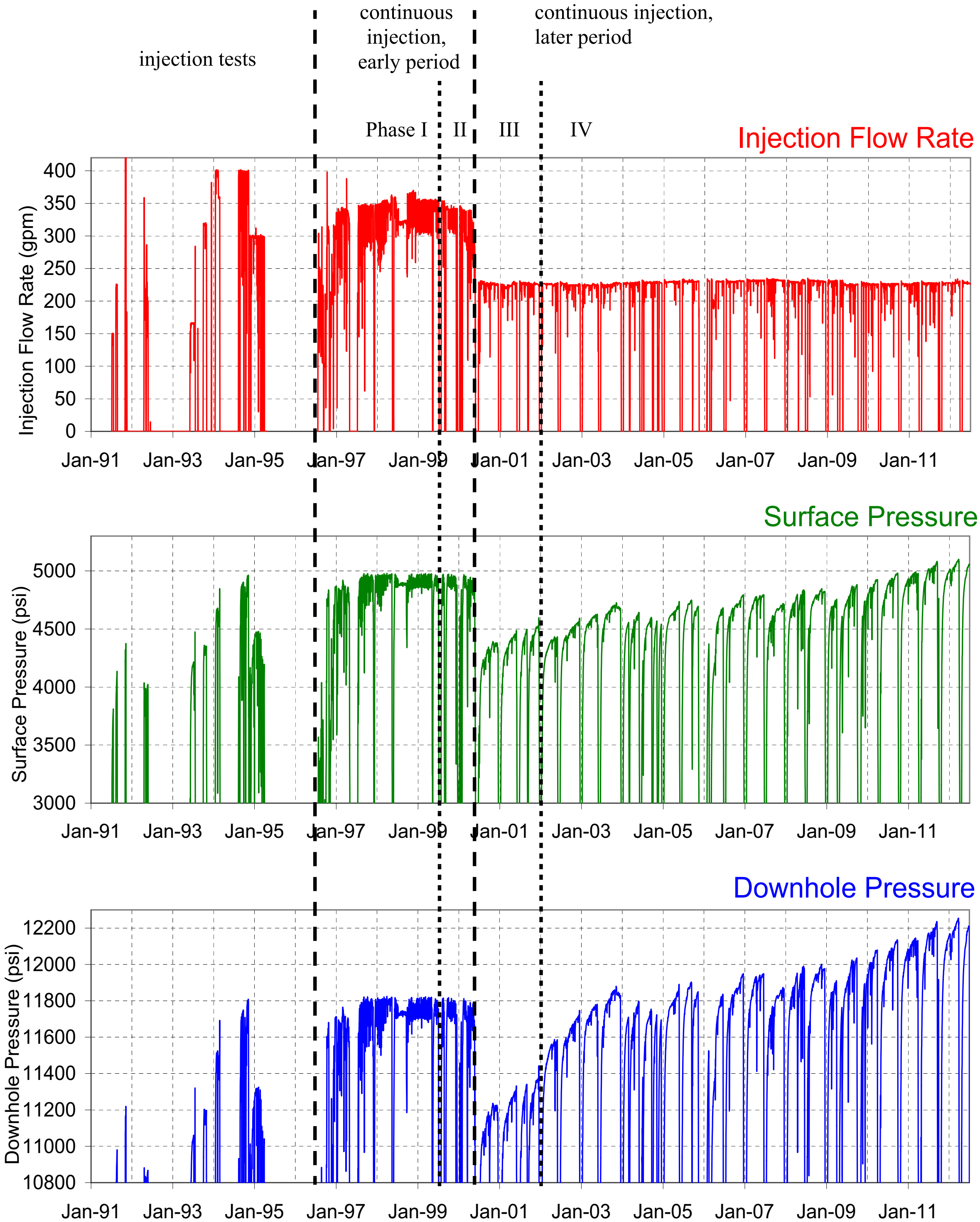


Figure 5: Daily average injection flow rate (top), daily average surface injection pressure (middle), and daily average downhole pressure at 14,100 ft (4.3 km) depth (bottom) during PVU injection operations.

hole (initial) temperatures and pressures, and that PVB would then precipitate calcium sulfate, which in turn would lead to restricted permeability (Kharaka, 1997). During October 2001, with the decreased injection volume discussed above, the injectate concentration question was reconsidered. Temperature logging in the injection interval recorded substantial near-wellbore cooling, indicating that if precipitation occurred, it would not be near the wellbore perforations where clogging would be a concern. Further discussions indicated that, if precipitation occurs, its maximum expected rate is ~8 tons of calcium sulfate per day. To put this amount into perspective, injecting at ~230 gpm, assuming a density of 8.33 lbs/gal, results in a daily injection of ~1380 tons. The maximum expected precipitate is ~0.6% of the daily injection mass.

After considering this new information, the decision was made to begin injecting 100% PVB, in order to increase the amount of salt disposed of with the reduced injection rate initialized in phase III. Injecting 100% PVB began on January 7, 2002, following the December-January 20-day shutdown, and has been maintained since. The same reduced injection rate as in phase III (230 gpm) and biannual 20-day shutdowns have been maintained. The only noticeable affect of the change to 100% PVB injectate has been increasing bottom hole pressure because of the increased density of 100% PVB (by about 5%) over the 70% PVB : 30% fresh water mix.

2.4 Injection Pressures

The surface and downhole injection pressures at PVU Well #1 have varied considerably over time (Figure 5). After the injection flow rate was decreased by one-third in mid-2000, both the surface and downhole injection pressures dropped by approximately 800 psi and then began to slowly recover. In January, 2002, the injectate was changed from a 70% brine : 30% fresh water mix to 100% brine. The increased density of the 100% brine injectate compared to the former mix resulted in an immediate increase in the downhole pressure of about 300 psi (Figure 5, lower plot). By mid-2003, the downhole pressure had reached the same value it was prior to the mid-2000 decrease in injection flow rate (about 11,800 psi). The surface injection pressure, in contrast, did not reach it's pre-2000 value of just under 5000 psi until mid-2010 (Figure 5, middle plot).

Since 2002, the daily average injection flow rate and composition of the injectate have remained nearly constant. There have, however, been significant variations in the frequency and length of injection well shut-ins. Since mid-1999, the injection well has operated under an official schedule of two 20-day shut-ins (or shut-downs) each year, when injection ceases, and continuous injection otherwise. However, several additional shut-ins of varying lengths have occurred over the years, usually for required equipment maintenance or repairs. While many of these extra shut-ins were short, some were of significant duration. For example, a prolonged shut-in of more than two months occurred in late 2005 to early 2006 after a tank explosion. Between mid-December, 2008, and mid-December, 2009, approximately 75 shut-down days occurred rather than the nominal 40 days per year. These additional days were due to a change from a winter-summer shut-in schedule to a spring-fall schedule and to additional shut-down time required when upgrading surface equipment at the injection wellhead. When significant extra injection well shut-downs occur, the maximum injection pressures tend to fluctuate. In contrast, when the official injection schedule is maintained for a sufficient period of time, the maximum injection pressures tend to increase consistently during each successive injection cycle (such as in 2002-2003 and 2010-2012).

2.5 Consideration of a Second Injection Well

The maximum allowable surface injection pressure (MASIP) currently permitted for PVU Injection Well #1 is 5,350 psi. The highest daily average surface injection pressure recorded to date for this well is 5,100 psi, reached in March, 2012. Since 2009, the maximum surface injection pressure has been increasing at a rate of roughly 100 psi per year. If the current rate of pressure increase continues, the MASIP will be reached in 2014 or early 2015. To prevent the injection pressure from exceeding the current MASIP, the volume of brine injected annually would need to be reduced. This could be accomplished by either decreasing the daily average injection flow rate or increasing the annual number of injection well shut-down days. In either case, the efficiency of injection operations would decline and PVU would become less economically viable.

Reclamation is considering whether to request an increase in the MASIP for PVU Injection Well #1 from EPA. However, even if such an increase is pursued and granted, it will only postpone the need to address the increasing injection pressures for a few additional years. A longer-term solution is required. The installation of a second injection well is among the solutions being considered. While other options are being evaluated, Reclamation has decided to move forward with the analysis required to determine the optimal location of a potential second injection well.

3.0 Geology

3.1 Regional Geology

3.1.1 Geologic Setting

Paradox Valley is located in the northeastern part of Paradox Basin—an elongate northwest-southeast trending structural basin which extends from eastern Utah into western Colorado, within the Colorado Plateau region (Figure 6). Rapid subsidence of Paradox Basin during the Mississippian, Pennsylvanian, and Permian Periods (~350 - 250 Ma) accommodated marine intrusion and resulted in the interfingering of marine deposits, including evaporates, and terrestrial material shed from the nearby (Uncompahgre) uplifted areas to the northeast (McClure et al., 2003).

The northern part of Paradox Basin, known as the Paradox fold and fault belt, contains several northwest-striking diapiric salt-cored anticlines. These salt-cored anticlines developed as a result of plastic flow of the Pennsylvanian-age Paradox stratigraphic unit. The Paradox unit consists of as much as 85% halite and is best imagined as a viscous liquid (Huntoon, 1988). Subsequent dissolution of salt beneath the crests of some of the anticlines resulted in downfaulting and the development of grabens, or salt valleys (Nuccio and Condon, 1996; Gutierrez, 2004). Paradox Valley developed as a result of structural collapse along the crest of one of these salt-cored anticlines and is bounded by nearly vertical normal faults.

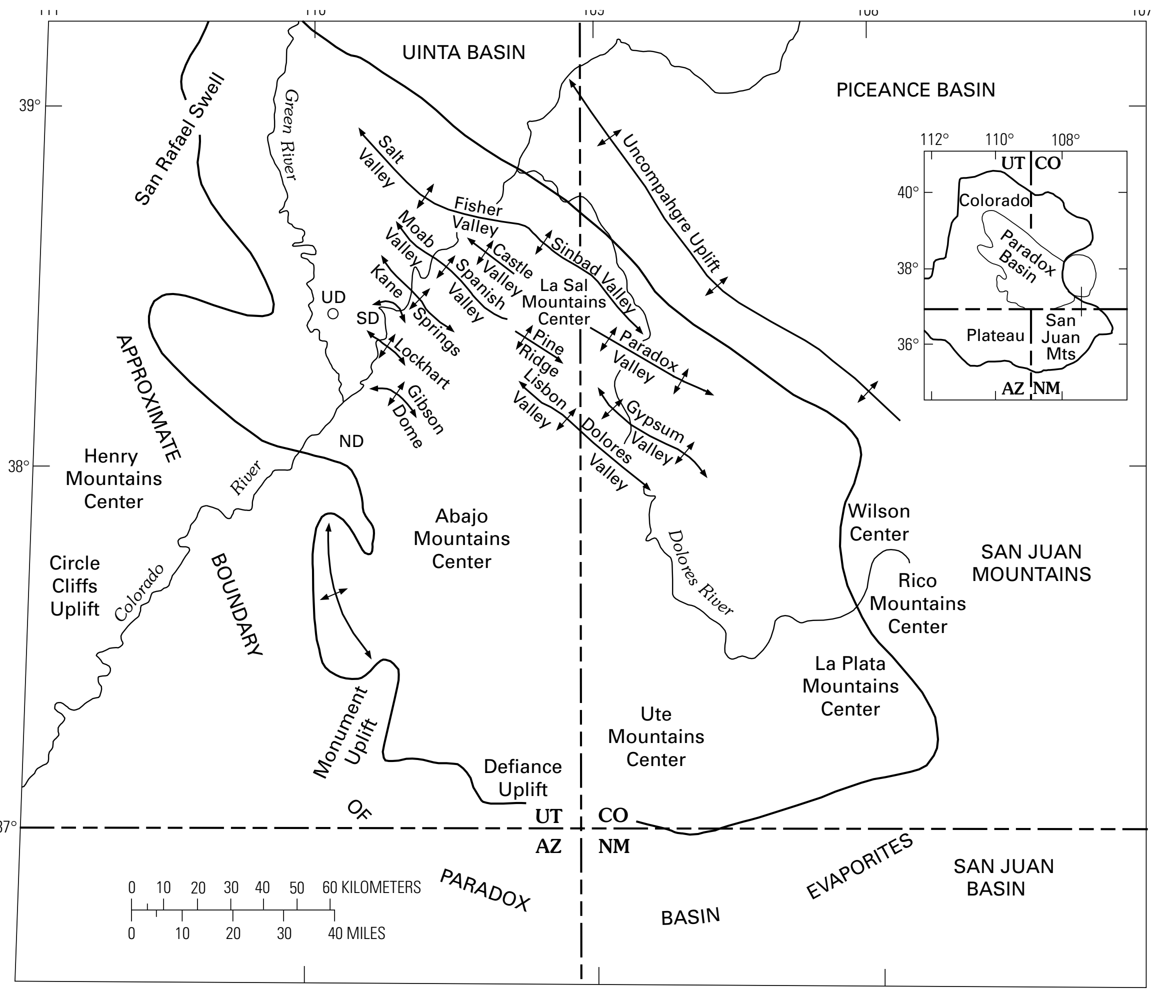


Figure 6: Map showing the location and major features of Paradox Basin. Paradox Valley is located near the northeastern edge of Paradox Basin. Figure taken from Grout and Verbeek, 1998.

3.1.2 Faults and Joints

The tectonic history of northern Paradox Basin is complex, as are the resulting fault and joint patterns. This region contains both deep basement faults, possibly originating as long ago as the Precambrian (> 540 Ma) (Baars and Stevenson, 1981), and as recent as Tertiary (65 - 2 Ma) surface faults. Sets of joints or fractures are present in both the older and younger rock units. Although these joints are often sub-parallel to the faults, the developmental relationship of the fault and joint patterns is not always clear (Grout and Verbeek, 1998). Varying and sometimes conflicting interpretations of the tectonic development and relationships of the observed structural features of the Paradox fold and fault belt have been published. Here we present an overview of the major regional fault and joint patterns observed rather than a detailed tectonic history.

Buried Faults

Parallel, northwest-trending, steeply-dipping normal faults are present in the basement and buried Paleozoic rock units of the Paradox fold and fault belt. The presence of these basement faults contributed to the formation of the northwest-trending diapiric salt anticlines (Baars and Stevenson, 1981; Friedman et al., 1994; Grout and Verbeek, 1998). Although some vertical movement occurred on these faults during the early Paleozoic (Baars and Stevenson, 1981), activity along the faults greatly increased during the Mississippian Period, when Paradox Basin began rapidly subsiding. Significant activity continued on these faults into the Permian Period, and possibly into the Triassic Period. The faults may have been reactivated as late as the Tertiary (Verbeek and Grout, 1998; Doelling et al., 1988). The faults having the largest vertical displacements generally have their downthrown sides to the northeast, resulting in a deepening of Paradox Basin toward the northeast (Doelling et al., 1988). In the vicinity of Paradox Valley, these northwest-trending basement faults occur on the northeast flank of the Wray Mesa-Sneffels structural high trend and are referred to in early PVU geology reports as the Wray Mesa fault system (Bremkamp and Harr, 1988).

Northeast-trending fault zones are also present in the basement and buried Paleozoic rocks of northern Paradox Basin. According to Barrs and Stevenson (1981), these features, along with the northwest-trending basement faults described above, originated as conjugate shear zones during the Precambrian. While significant vertical movement occurred on the northwest-trending faults during the late Paleozoic (described above), the northeast-trending faults appear to have accomodated mainly strike-slip movement. These northeast-trending, subsurface basement lineaments are not as well-mapped or as well-understood as the northwest-trending faults. It is not known whether each of these features consists of a wide shear zone, a single wrench fault, or a series of en echelon strike-slip faults (Hite, 1975). Some of the northwest-trending basement faults are offset by northeast displacement (Hite, 1975), indicating activity along the northeast features at least subsequent to the late Paleozoic. The laccolith complex of the La Sal Mountains, which is located just northwest of Paradox Valley and divides the Paradox Valley - Castle Valley anticlinal structure in two (Figures 1 and 4), may be located at the intersection of the anticline with one of these northeast-trending fault zones (Friedman et al., 1994).

Surface Faults

Many relatively young normal faults are present at the surface in Paradox Basin. Some of these faults may be the result of tectonic extension during the Tertiary, while others are clearly related to salt dissolution and collapse of overlying strata (Doelling et al, 1988). Regardless of the cause of the fault formation, the faults generally trend northwest-southeast, parallel to the salt anticlines and underlying basement normal faults. Salt diapiric movement, salt dissolution, and the lowering of salt valley floors is ongoing (Friedman et al., 1994).

Extensional, northeast-trending, high-angle faults with predominantly vertical offset have also been mapped at the surface in northern Paradox Basin. According to formation cutting relations, these faults were active sometime from Jurassic to Pleistocene time, in strata between the salt section and the surface (Friedman et al., 1994).

Joints

Several widespread, extensional joint sets are present across central Paradox Basin. Grout and Verbeek (1998) classify these joint sets into two major systems, one that evolved during the Permian Period (300 - 255 Ma) and another system of Tertiary and younger age (< 65 Ma). In addition, a system of Carboniferous-age joint sets is present in Mississippian and older rocks along the eastern margin of Paradox Basin. Regardless of age, each system consists of joint sets striking from northwest to northeast. Strikes of the Paleozoic-age joint sets, which are likely to be present in the sub-salt rock units in the vicinity of Paradox Valley, are reported as: N62W, N27W, N19W, N18E, and N64E (measured from outcrops near Telluride, Colorado, approximately 75 miles southeast of PVU; Grout and Verbeek, 1998). In the Lisbon Valley area in eastern Utah (Figure 6), these joint sets are perpendicular to bedding, indicating that they formed prior to the major anticline-building episode in the late Permian to early Triassic (Grout and Verbeek, 1998). Strikes of the Tertiary-age joints range from N85W to N62E. The majority of these joint sets are vertical, regardless of bedding dip.

3.2 Local Geology

3.2.1 Paradox Valley Morphology

Paradox Valley is approximately 25 miles (40 km) long and generally 2.5 to 4.5 miles (4.0 to 7.2 km) wide. The valley has a relatively flat floor enclosed by steep sandstone walls. Elevations within the valley vary from approximately 4900 to 5600 ft (1500 to 1700 m) above mean sea level (amsl). Elevations along the valley rim are approximately 6200 to 6900 ft (1900 to 2100 m) amsl, while elevations rise to over 11,800 ft (3600 m) in the La Sal Mountains just northwest of Paradox Valley.

Rivers in the Paradox Basin flow parallel and perpendicular to the northwest-trending salt anticlines. In Paradox Valley, the Dolores River flows across strike near the town of Bedrock, Colorado (Figure 2). West Paradox Creek, a small tributary, enters the Dolores River within the valley from the northwest.

3.2.2 Stratigraphy

Paradox Valley and the surrounding mesas contain rocks spanning Precambrian to mid-Cretaceous time (>570 to approximately 90 Ma). The Precambrian basement rock consists of granite, schist, gneiss, and pegmatite. Overlying the Precambrian rock is a series of sedimentary units deposited primarily in marine or near shore environments. These layers include sandstones, siltstones, shales, conglomerates, limestones, dolomites, and evaporites.

A stratigraphic column of the Paradox Valley area is presented in Table 1. PVU Injection Well #1 is sited on the Triassic-age Chinle Formation. The stratigraphy of the underlying formations shown in Table 1, down to the Precambrian basement rock, is taken from the geologic well log of this borehole (Harr, 1988). Depths of geologic units encountered in this well are included in the table and are relative to the local ground surface elevation of 4996 ft (1523 m). Descriptions of the rock units are taken from several sources (see footnote no. 2 in the table). The overlying stratigraphy, including the Triassic-age Wingate sandstone to the Cretaceous-age Mancos shale, was taken from a geologic map of the Moab Quadrangle produced by the U.S. Geological Survey (Williams, 1964). Not all rock units may be present in the immediate vicinity of Paradox Valley. The Jurassic-age Morrison Formation generally tops the cliffs surrounding Paradox Valley, while the Cretaceous-age Burro Canyon and Dakota Formations are present at the higher elevations of the mesas. A remnant of the Mancos shale is present just beyond the southeastern end of the valley. The floor of Paradox Valley consists of Quaternary alluvial and eolian deposits overlying the diapiric Paradox (salt) formation.

The Mississippian Leadville formation is the primary target reservoir for PVU brine injection, due to its sedimentary and structural characteristics. The Leadville formation consists of limestone and dolomite layers that are fractured, faulted, and contain karst features. The lower Leadville formation (Kinderhookian-age) is stromatilitic dolomite, lime mudstones, and pelletal lime mudstone deposited in intertidal to subtidal environments. The upper Leadville formation (Osagean-age) contains fossiliferous pelletal and oolitic limestone, and lime and dolomitic mudstone (Doelling et al., 1988). The upper Leadville underwent uplift and erosion after deposition, resulting in karst-type weathering and the formation of a *terra rossa* type regolith on the surface. *Terra rossa* is a red clay soil that forms on the surface of limestone bedrock. Under oxidizing conditions, iron oxide forms in the clay, giving the soil a red-orange color. This karstic portion of the Leadville is not considered a potential reservoir due to the concentration of fines infilling the karst features (Bremkamp et al., 1984).

3.3 Early PVU Geologic Investigations

Early in the PVU project, geologic and geophysical studies were performed to better understand the local geologic structure and stratigraphy, to characterize potential reservoir formations, and to determine optimal sites for proposed injection wells. The most detailed of these studies were performed in the 1980’s. Very little geologic or geophysical investigation has been performed by PVU since that time, and therefore the results from these early studies still comprise the most comprehensive geologic interpretation currently available to Reclamation.

3.3.1 Development of Structural Geologic Models

Prior to the selection of the site for the current PVU injection well, geophysical interpretations were performed for Reclamation by two groups of consultants using deep seismic reflection and well log data (Katz and Carroll, 1984; Bremkamp et al. 1984). The study area was located southwest of central Paradox Valley, where the Dolores River enters the valley. These investigations utilized 15 single-fold seismic reflection lines recorded in 1961 by Empire Geophysical (lines

Table 1: Paradox Valley Stratigraphy.

Stratigraphic Unit	Vertical Depth to Top of Unit In PVU Well #1 (ft)[1]	Description[2]
CRETACEOUS		
Mancos Shale	above elevation of wellhead	Dark gray to black, soft, fissile marine shale with thin sandstone beds at various horizons
Dakota Sandstone		Yellowish-brown and gray friable to quartzitic fluvial sandstone and conglomeratic sandstone with interbedded gray to black carbonaceous nonmarine shale
Burro Canyon Fm.		White, gray, and light-brown fluvial sandstone and comglomerate interbedded with green and purplish lacustrine siltstone, shale, and mudstone, and thin beds of impure limestone
JURASSIC		
Morrison Fm.	above elevation of wellhead	Fluvial and lacustrine shale, mudstone, and sandstone; local thin limestone beds
Summerville Fm.		Red, gray, green, and brown sandy shale and mudstone of terrestrial origin
Entrada Fm.		Orange, buff, and white, fine- to medium-grained, massive, and cross-bedded eolian sandstone; basal few feet may consist of red siltstone and fine-grained sandstone and is sometimes referred to as the Carmel Formation.
Navajo Sandstone		White, grayish-yellow, gray, and pale orange-pink, fine-grained, cross-bedded eolian sandstone
TRIASSIC		
Kayenta Fm.	above elevation of wellhead	Irregularly interbedded fluvial red, buff, gray, and lavender shale, siltstone, and fine- to coarse-grained sandstone
Wingate Sandstone		Reddish-brown, buff, and grayish-orange, fine-grained, massive, thick-bedded, and prominently cross-bedded eolian sandstone
Chinle Fm.	0 (at surface)	Siltstone- red to orange-red, with interbedded red fine-grained sandstone, shale, clay-pellet conglomerate containing limestone pebbles; conglomerate, and few thin beds of gypsum occur locally at base; terrestrial depositional environment.
Moenkopi Fm.	390	Sandy shale/silty sandstone- brown, bedded, often ripple marked, some conglomerate present. Marine and terrestrial depositional environment.

Stratigraphic Unit	Vertical Depth to Top of Unit In PVU Well #1 (ft)[1]	Description[2]
PERMIAN		
Cutler Fm.	1140	Sandstone/conglomerate- red to purple arkose, fluvial, with some sandy shales; deposited in alluvial fans
PENNSYLVANIAN		
Hermosa Group - Honaker Trail Fm.:		
Upper Honaker Trail	8313	Limestone/sandstone/siltstone- deposited in marine conditions
LaSal	12006	Limestone/dolomite- some silty limestone, oolitic limestone, and algal limestone present
Lower Honaker Trail	12082	Limestone/sandstone/siltstone- deposited in marine conditions
Hermosa Group - Paradox Fm.:	12350	Resulted from intermittently closed marine environment
Ismay	12839	Limestone- stacked algal carbonate mounds, and other shallow-water carbonates and dolomites.
1st Main Salt	13104	Dolomite/salt- intermittently closed marine depositional environment
2nd Main Salt	13497	Salt/anhydrite/shale- intermittently closed marine depositional environment
Base Salt - Lower Paradox	13566	Shale/anhydrite/(minor) limestone- intermittently closed marine depositional environment
Hermosa Group - Pinkerton Trail Fm.	13693	Shales/anhydrite/siltstone/(minor) limestones- dark colored shales, limestone formed by marine invasion
Molas Fm.	13944	Shale/siltstone/claystone- regolith/soil (*terra rosa*) developed on the karst surface of the Leadville formation after a period of extensive weathering and erosion.
MISSISSIPPIAN		
Leadville Fm.	13984	Limestone/dolomite- lower unit (Kinderhookian -age) stromatilitic dolomite, lime mudstones, pelletal lime mudstones; deposited in intertidal to subtidal enviroments. Upper unit (Osagean-age) fossiliferous pelletal and oolitic limestone, and lime and dolomitic mudstone.

Stratigraphic Unit	Vertical Depth to Top of Unit In PVU Well #1 (ft)[1]	Description[2]
DEVONIAN		
Ouray Fm.	14400	Limestone- lime mudstone, pelletal lime mudstone and skeletal limestone that is locally dolomitized; formed in quiet-water marine environment
Elbert Fm.	14440	Sandstone/shales/sandy dolomites
McCracken Fm.	14607	Sandstone- with occasional interbeds of sandy dolomite, product of marine transgression
Aneth Fm.	14681	Dolomite/shale- dark colored, dense, argillaceous sequence
CAMBRIAN		
Lynch Fm.:		
Upper Lynch Shale	14763	Sandstone/interbedded shale, dolomite, limestone
Lynch Limestone	14835	Limestone
Lower Lynch Shale	14928	Shale
Muav Fm.	14988	Limestone
Bright Angel Fm.	15103	Shale
Ignacio Fm.	15246	Sandstone, sometimes referred to as quartzite; transgressive depositional environment
PRECAMBRIAN		
Precambrian	15446	Described regionally as granitic rock with well-developed northwest and northeast orthogonal fracture systems; identified in PVU Injection Well #1 as moderately metamorphosed diorite-gabbro schist (Bremkamp 1988)

[1] Depths were taken from the geologic drill log of PVU Salinity Control Well #1, by C. L. Harr. Depths are relative to the ground surface elevation (4996 ft) and have been corrected for borehole deviation.

[2] Descriptions were taken from: Bremkamp et al., 1988; Campbell, 1981; Doelling et al., 1988; Williams, 1964; and Nuccio and Condon, 1996.

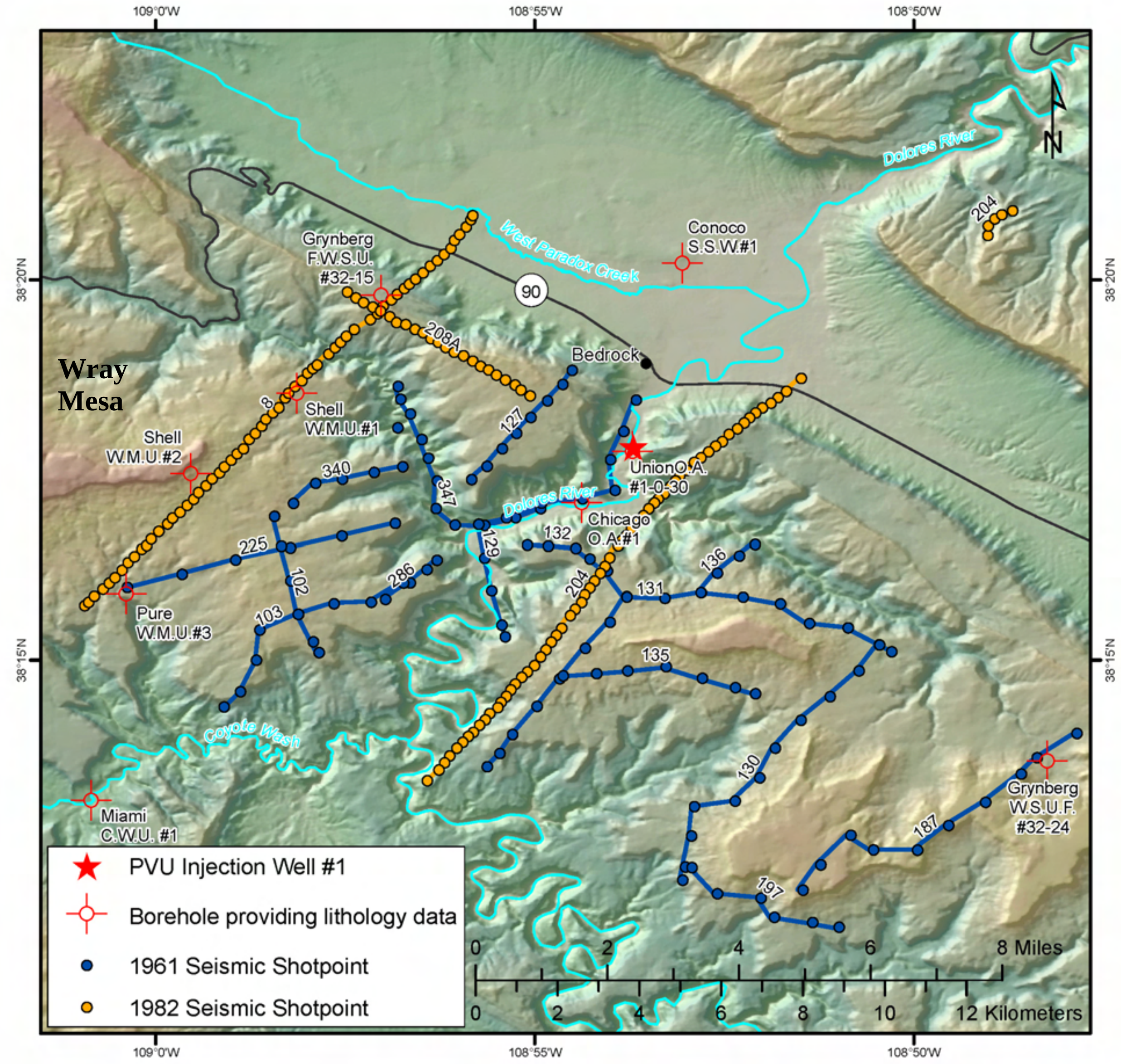


Figure 7: Locations of seismic reflection lines and deep wells used in early PVU geophysical studies.

136, 131, 103, 340, 135, 102, 347, 197, 225, 127, 286, 132, 130, 137, and 139) (Figure 7). These data were reprocessed for Reclamation by Western Geophysical in 1984. Additionally, three 12-fold seismic lines recorded in 1982 by Seisport Exploration were acquired by Reclamation and used in the studies (Lines 8, 204, and 208A, Figure 7). In both data vintages, the quality decreases greatly in thick salt sections. Data quality also decreases in areas overlain by unconsolidated material such as in valley bottoms. Logs from nine wells were used as control points for formation depth and velocity (Figure 7). Only six of the wells, however, penetrated the Paradox salt member and Leadville formation (Table 2).

Table 2: Wells providing data for original PVU geophysical interpretations

OPERATOR	YEAR DRILLED	OFFICIAL WELL NAME[1]	NAME USED IN EARLY PVU REPORTS	TOTAL DEPTH (ft)	DEEPEST FORMATION REACHED
Chicago Corp.	1950	Otho Ayers #1	none	6,860	Penn.-Upper Hermosa
Continental Oil Co.	1958	Scorup Somerville Wilcox #1	Conoco No. 1	~15,000	Miss.-Leadville (did not penetrate entire formation)
Shell Oil Co.	1961	Wray Mesa Unit #1	Shell No. 1	11,268	Precambrian
Shell Oil Co.	1961	Wray Mesa Unit #2	Shell No. 2	11,593	Cambrian
Miami Oil Co.	1962	Coyote Wash Unit #1	Miami	10,650	Miss.-Leadville (did not penetrate entire formation)
Pure Oil Co.	1963	Wray Mesa Unit #3	Pure No. 3	11,301	Devonian?
Union Oil Co.	1971	Otho Ayers #1-0-30	Union or Unocal	14,400	Devonian-Ouray
Grynberg Petroleum Co.	1975	Wild Steer Unit Federal #32-24	Grynberg	9,533	Penn.-Upper Hermosa
Grynberg Petroleum Co.	1975	Federal Wild Steer Unit #32-15	Grynberg	7,814	Penn.-Upper Hermosa

[1] Official name is the name listed in the Colorado Oil and Gas Commission Database

The investigators created structural contour maps of the top of the Cutler formation, massive salt member of the Paradox formation, and Leadville formation, and isopach maps for the Paradox salt member (including the underlying Pinkerton Trail and Molas formations) and Leadville formation. Contours from the maps of Katz and Carroll (1984) and Bremkamp et al. (1984) were digitized and are overlaid on the local topography and other geographical features in Figures 8 to 12. Fault traces and well locations were also digitized from the drawings and are included in the figures.

In comparing the geophysical interpretations from the two groups of investigators, we found not only significant differences in the interpreted contours, but also some significant differences in the elevations of the geologic formations reported for the wells. In order to investigate these discrepancies, we compared the geologic well data from the contour maps to well log data available from the Colorado Oil and Gas Conservation Commission online database (http://cogcc.state.co.us/

cogis, data retrieved Sept. 25, 2012). Depths to the geologic formations of interest were found in the database for all wells except for the Pure Oil Wray Mesa Unit #3 well, although in some cases only partial information is available. Tables comparing the elevations and thicknesses of the geologic units of interest in the wells, as reported by Katz and Carroll (1984), Bremkamp et al. (1984), and the Colorado Oil and Gas Commission database are included in Appendix A. The major findings are summarized in the discussions of the contour maps below.

A seismic reflector for the Cutler formation was not discernible and therefore the structure of the Cutler formation was interpreted from the limited well data alone. Both groups interpreted the Cutler formation as generally dipping toward the southwest, although inferred details of the structure are different (Figure 8). The well data used by Katz and Carroll match that listed in the Colorado Oil and Gas Commission database much better than the data used by Bremkamp et al. The differences between the Katz and Carroll Cutler formation well elevation data and the Colorado Oil and Gas Commission database range from 0 to 189 ft; the median absolute difference for the five wells compared is 12 ft. The differences between the Bremkamp et al. well data and the Colorado database range from 10 to 434 ft; the median absolute difference for the seven wells compared is 243 ft. Neither interpretation, however, takes into account the 426-ft elevation difference in the top of the Cutler formation between the Chicago Corp. Otho Ayers #1 and Union Otho Ayers #1-0-30 wells reported to the Colorado Oil and Gas Commission (Appendix A). (These two wells are located approximately 1.6 km apart along the Dolores River, slightly southwest of PVU Injection Well #1.)

Significant problems were found with the top-of-salt contour map produced by Katz and Carroll (Figure 9, lower map). They report an elevation of 1628 ft for the top of the Paradox salt member in the Conoco Scorup #1 well in the center of Paradox Valley, whereas Bremkamp et al. used a value of 4414 ft. These elevations correspond to depths of 3416 and 630 ft below local ground surface, respectively. The elevation of the top of the salt in this well is not reported in the Colorado Oil and Gas Commission online database. However, the geologic map of the area indicates a thin layer of Quaternary alluvial and eolian deposits underlain by the Paradox member of the Hermosa formation at this site (Williams, 1964). In PVU Injection Well #1, there is about 750 ft from the top of the Paradox formation to the top of the main salt member. Hence, the depth of the Paradox salt member at the location of the Conoco Scorup #1 well very likely should be only a few hundred ft, as indicated by Bremkamp et al., not the 3400 ft used by Katz and Carroll. Another elevation value used by Katz and Carroll for their interpretation of the top of the salt also appears to be grossly incorrect. They used an elevation of -4049 ft for the Shell Wray Mesa Unit #1 well. Bremkamp et al. apparently did not have elevation data for the top of the salt in this well, and neither is any value reported in the Colorado online database. However, extrapolating from the elevation for the top of the Hermosa group reported in the online database and assuming that the thickness of the upper Hermosa group is similar to that reported in PVU Injection Well #1 gives an estimated elevation of the top of the salt of -7148 ft in the Wray Mesa Unit #1 well. This is more than 3000 ft deeper than the value used by Katz and Carroll. It is possible that Katz and Carroll applied the elevation data of -4049 ft to the incorrect well, since a similar value (-4149 ft) was used by Bremkamp et al. for the Pure Oil Wray Mesa Unit #3 well to the southwest. In any case, the discrepancies apparent in the Katz and Carroll well data used in their geophysical interpretation leads us to discount their contour map for the top of the Paradox salt member and rely instead on that produced by Bremkamp et al. Besides the major salt diapir underlying Paradox Valley,

Structural Maps of the Top of the Cutler Formation

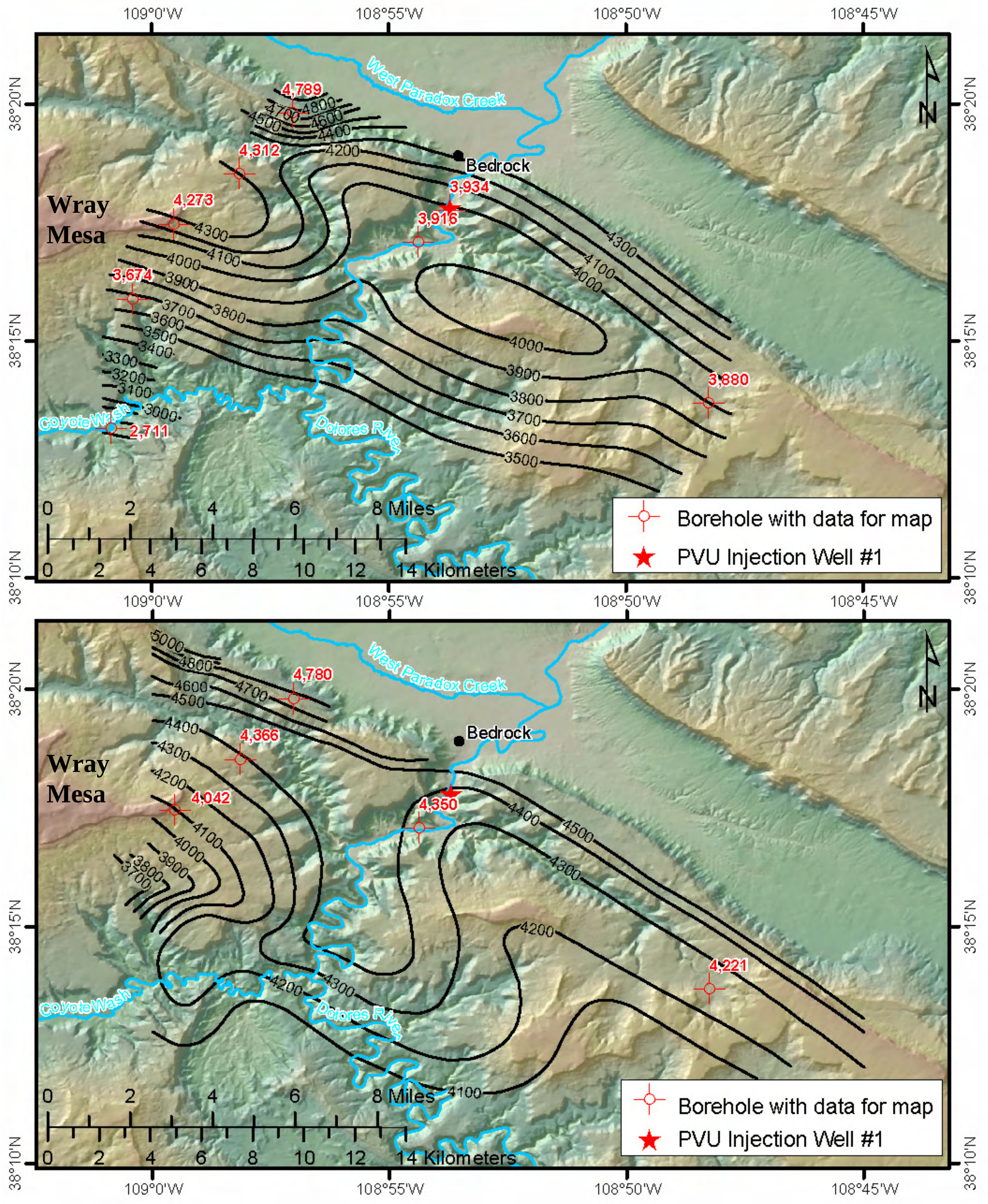


Figure 8: Structural contour maps of the top of the Cutler formation. Contour values are elevations in feet relative to mean sea level. Contour interval is 100 ft. Two interpretations are shown, from Bremkamp et al. (1984) (top) and Katz and Carroll (1984) (bottom).

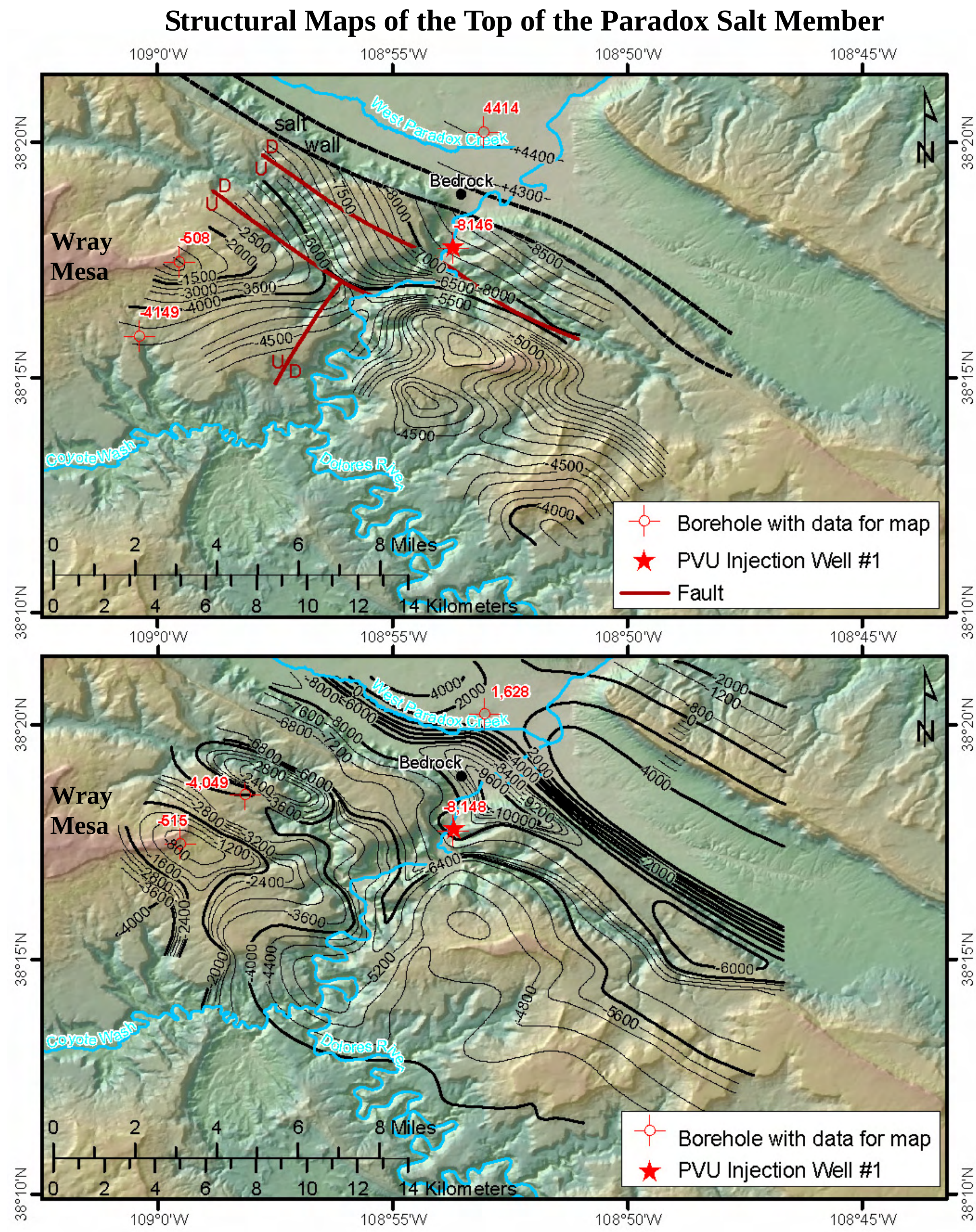


Figure 9: Structural contour maps of the top of the Paradox formation. Contour values are elevations in feet relative to mean sea level. Contour interval is variable. Two interpretations are shown, from Bremkamp et al. (1984) (top) and Katz and Carroll (1984) (bottom).

Bremkamp et al. mapped two other distinct salt features: a diapiric feature centered at the Shell Wray Mesa Unit #2 well and a pillow-type feature to the southeast which does not pierce the overlying geologic units (Figure 9, upper map).

The well control data used by the two groups of investigators for mapping the top of the Leadville formation are consistent with each other and with data from the Colorado Oil and Gas Commission database (where available), with the exception of the elevation of the top of the Leadville formation indicated for the Conoco Scorup #1 well in the center of the valley. The value used by Katz and Carroll (-9698 ft) differs from the value indicated by the online database (-9682 ft) by only 16 ft, whereas the value used by Bremkamp et al. (-9946 ft) differs by 264 ft. This discrepancy does not cause a significant flaw in Bremkamp et al.'s structural interpretation of the top of the Leadville formation, however. It does indicate that the throw across the fault interpreted by Bremkamp's group to lie just southwest of the Conoco Scorup #1 well to be greater than indicated on their map and correspondingly the dip of the Leadville formation in the fault block containing the Conoco Scorup well to be somewhat steeper than indicated (Figure 10, upper map). (No seismic reflection data were available across Paradox Valley, and Bremkamp et al. inferred the location and throw across this fault based on seismic reflection data southwest and northeast of the valley and on the depth of the Leadville formation in the Conoco Scorup #1 well.)

Despite the fact that the two groups of investigators interpreted the same seismic reflection data and used nearly the same well control data, their structural interpretations of the top of the Leadville formation have significant differences. Both interpretations indicate a structural high on Wray Mesa where the Leadville formation was eroded, as indicated by the absence of the Leadville formation in the Shell Wray Mesa Unit #1 and #2 wells. They also both indicate a structural high to the southeast, across the Dolores River canyon from Wray Mesa. However, Bremkamp's group indicates an elevation of approximately -5100 ft for this structural high (Figure 10, upper map), whereas Katz and Carroll indicate an elevation of about -4400 ft (Figure 10, lower map), a difference of 700 ft. In general, Bremkamp et al. indicate that, on the northeast side of the two structural highs mentioned above, the Leadville formation dips toward the northeast. Katz and Carroll's structural interpretation is more convoluted. For example, just northeast of the area where the Leadville formation is eroded on Wray Mesa, Katz and Carroll show the Leadville dipping toward the southwest rather than toward the northeast as in Bremkamp et al.'s interpretation. Significant differences are seen in the interpreted dip of the Leadville formation in the immediate vicinity of PVU Injection Well #1 also. For example, Bremkamp et al. show no significant change in depth of the Leadville formation immediately southeast of the well (where you can follow the -9000-ft elevation contour). In contrast, Katz and Carroll show the Leadville formation shallowing substantially in the same area southeast of the well, to an elevation of less than -8000 ft. Similar differences can be seen to the northwest of the injection well; Katz and Carroll show the Leadville shallowing by more than 1000 ft along the same path where Bremkamp et al. indicate a constant elevation of -9000 ft. While both groups of investigators show northwest-trending faults downthrown to the northeast, there are non-trivial differences in the locations, trends, and throws of the faults. In addition, Bremkamp et al. indicate a northeast-trending fault that is absent in Katz and Carroll's interpretation. Katz and Carroll indicate an additional northwest-trending fault in this location instead, downthrown to the southwest rather than to the northeast. Bremkamp's group also indicates a fault in the center of Paradox Valley that is absent from Katz and Carroll's

Structural Maps of the Top of the Leadville Formation

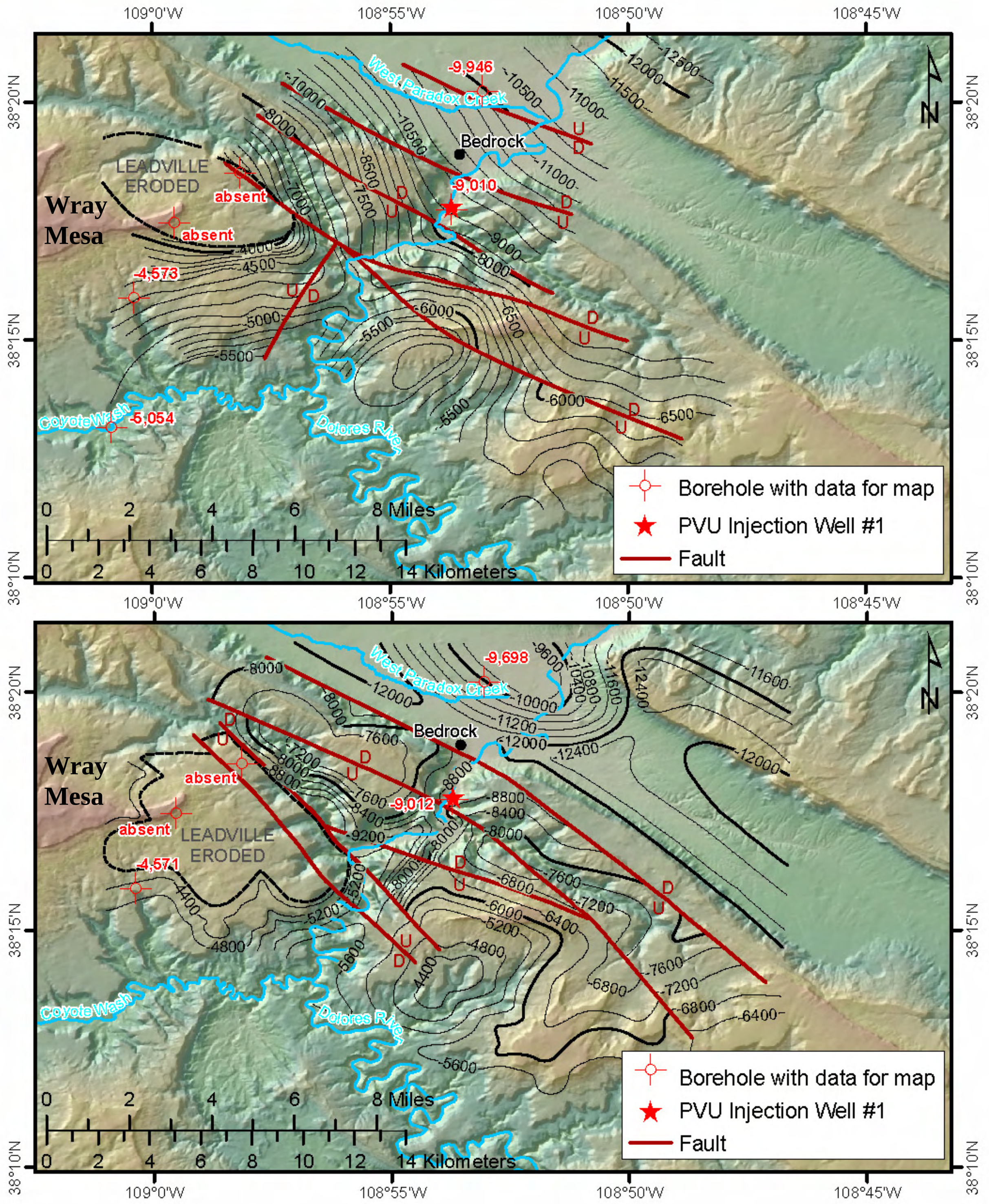


Figure 10: Structural contour maps of the top of the Leadville formation. Contour values are elevations in feet relative to mean sea level. Contour interval is variable. Two interpretations are shown, from Bremkamp et al. (1984) (top) and Katz and Carroll (1984) (bottom).

interpretation. Such significant differences between two independent interpretations of the same data suggest that the data were of marginal quality.

Bremkamp et al.'s Paradox salt member isopach map indicates that salt thickness locally ranges from over 14,000 ft in the center of Paradox Valley to less than 500 ft (Figure 11, upper map). Variations in salt thickness are mainly due to the presence of the main salt diapir underlying Paradox Valley and the two smaller features discussed previously. Because of the incorrect well data incorporated into Katz and Carroll's interpretation of the top of the Paradox salt member, discussed above, their salt isopach map is also flawed (Figure 11, lower map).

The thickness of the Leadville formation was not resolvable through the seismic reflection data and was interpreted from well data and structural elevation changes of the top of the Leadville formation. (Katz and Carroll assumed that the Leadville formation was eroded at an elevation of -4200 ft, based on information from well logs.) Data from two local wells that penetrated the entire Leadville formation, two wells that partially penetrated the Leadville formation, and two wells that indicated the absence of the Leadville suggest that the thickness of the Leadville formation ranges from 0 ft (completely eroded) to about 340 ft. However, the two groups of investigators infer very different trends of Leadville thickness in areas without well control (Figure 12). Bremkamp et al. (1984) show a thinning of the Leadville formation along an inferred northwest-trending post-Leadville horst (Figure 12, upper map), while Katz and Carroll show only local thinning and erosion on Wray Mesa. We consider the well data to be too sparse to make a reliable isopach map for the study area and therefore do not give much credence to either interpretation.

In additional to the structural maps discussed above, Bremkamp et al. (1984) also created an isopach map of the thickness of Leadville formation with greater than 5% porosity (Figure 13). The porosity values were computed solely from sonic logs from 3 boreholes and a neutron well log from an additional hole. Two of these boreholes, the Conoco Scorup #1 well and the Miami Oil Coyote Wash Unit #1 well, only partially penetrated the Leadville formation and therefore only provide a lower limit on the Leadville thickness with greater than 5% porosity. Two other boreholes indicate an absence of the Leadville formation.

With the exception of the results from the Conoco Scorup #1 well in the center of Paradox Valley, the thickness of the Leadville exhibiting greater than 5% porosity ranges from 0 ft (where the Leadville is eroded) to 31 ft (Figure 13). In contrast, the porosity values computed from the Conoco Scorup #1 well indicate 86 ft of 5% or greater Leadville porosity (and this is a lower limit, since the entire Leadville formation was not penetrated by this well). Bremkamp et al. (1984) attribute this variability to the thinning and weathering of the Leadville along their inferred horst southwest of Paradox Valley. Karst-type weathering along such an elevated feature would result in infilling of voids in the Leadville formation with shale and clay, reducing porosity. It is a little disconcerting that the single well showing an anomalously thick section of 5% or greater porosity within the Leadville formation in this analysis is also the single well for which porosities were computed from a neutron geophysical well log rather than a sonic log. It is not known whether differences in the two log analysis methods used could have contributed to the difference in the porosity results. However, according to a later report (Harr, 1989), the higher porosity values computed for the Conoco Scorup #1 well are supported by core and drill stem testing data from that well. Porosity values later derived from analysis of the sonic log acquired in PVU Injec-

Isopach Maps of the Paradox Salt Member

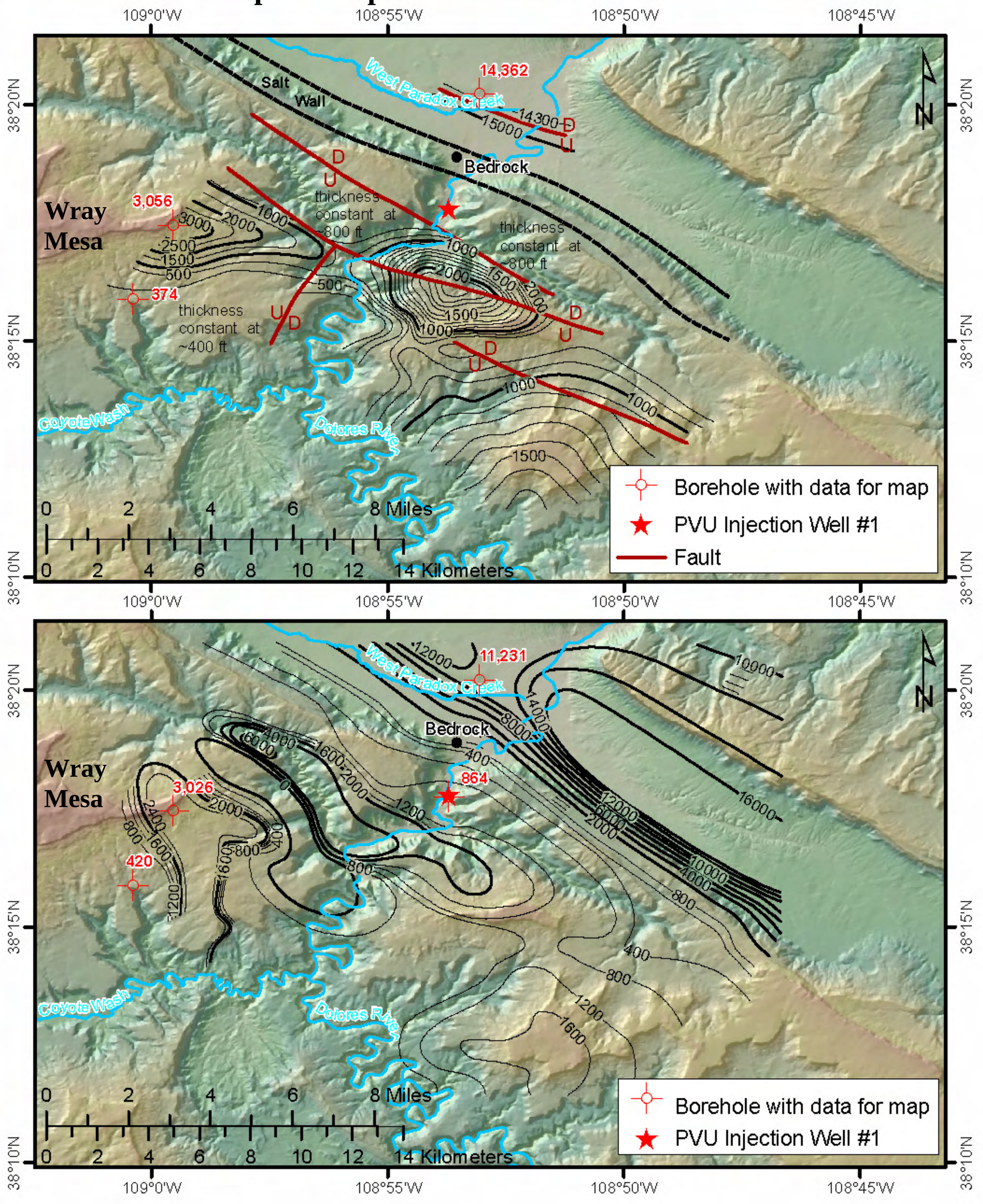


Figure 11: Isopach maps of the Paradox formation massive salt member. The mapped interval also includes the underlying Pinkerton Trail and Molas formations, which are approximately 420 ft thick at the PVU Injection Well #1. Contour values are thicknesses in feet. Contour interval is variable. Two interpretations are shown, from Bremkamp et al. (1984) (top) and Katz and Carroll (1984) (bottom).

Isopach Maps of the Leadville Formation

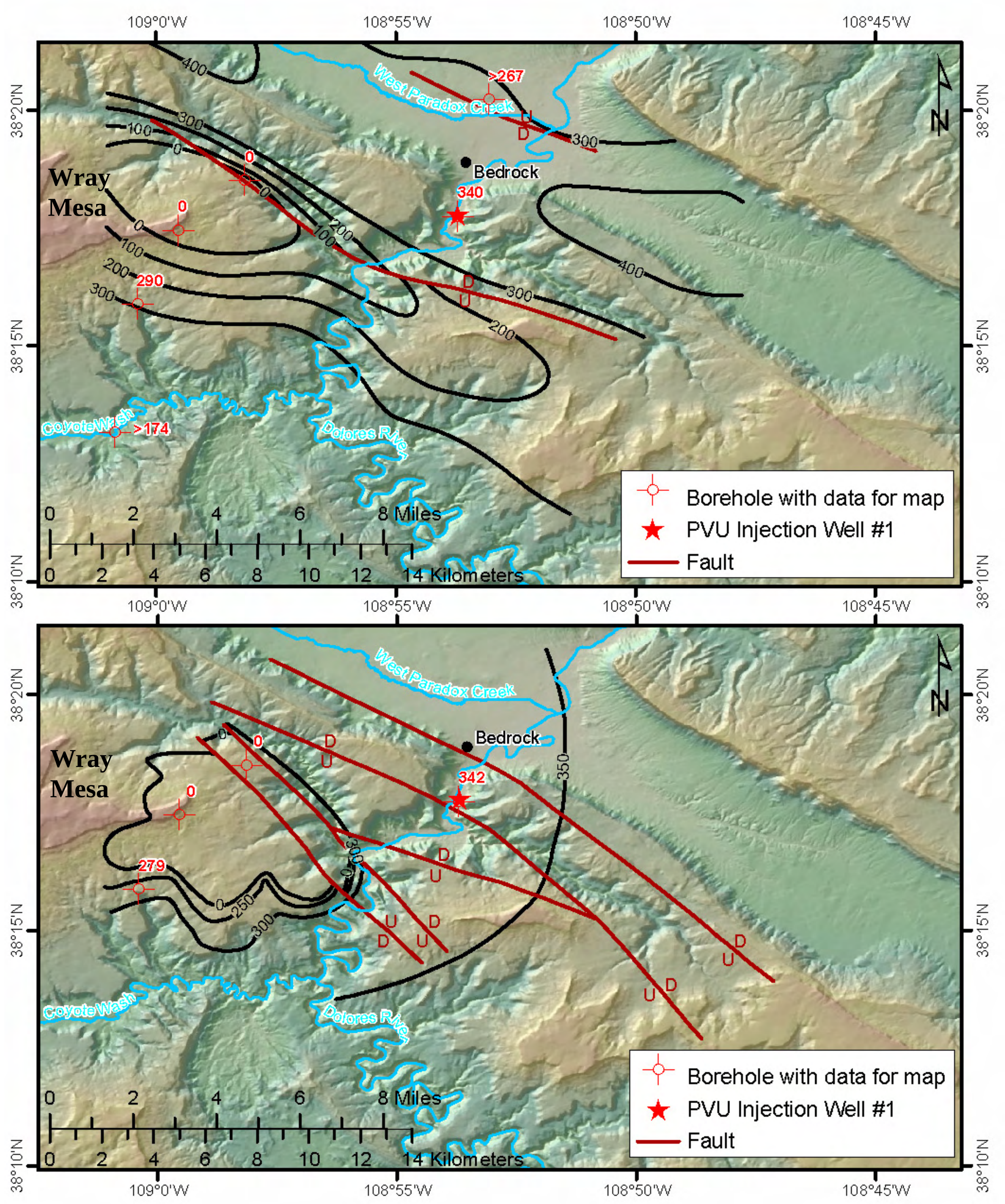


Figure 12: Isopach maps of the Leadville formation. Contour values are thicknesses in feet. Two interpretations are shown, from Bremkamp et al. (1984) (top) and Katz and Carroll (1984) (bottom).

tion Well #1 also show anomalously high values, indicating 86 ft of 5% or greater porosity (Bremkamp and Harr, 1988).

In addition to the maps shown above, Katz and Carroll (1984) and Bremkamp et al. (1984) each included two cross sections in their reports. The locations of these cross sections are shown on the map in Figure 14. Cross sections X-X' and Y-Y', from Bremkamp et al. (1984), are shown in Figures 15 and 16, respectively. Cross sections A-B and A-C, from Katz and Carroll (1984), are presented in Figures 17 and 18. As with the structural contour and isopach maps, significant differences in the geologic models constructed by the two groups of investigators are apparent in the cross sections. For example, the crest of the Paradox Valley salt anticline is much deeper on Katz and Carroll's cross sections than on Bremkamp et al.'s cross sections. As discussed previously, we believe that Katz and Carroll used incorrect elevation data for the top of the Paradox salt member in the Conoco Scorup #1 well in the center of Paradox Valley. Additional striking differences between the two interpretations are seen by comparing cross sections X-X' and A-B. These cross sections both transect the Conoco Scorup #1 and Union Otho Ayers #1-0-30 wells (Figure 14) but show significantly different structural interpretations between the wells. On cross section A-B, Katz and Carroll indicate that the fault bounding Paradox Valley to the southwest extends to the ground surface (Figure 17) whereas Bremkamp et al. show the fault terminating in the salt layer (cross section X-X', Figure 15). Katz and Carroll interpret approximately 3200 ft of throw across this fault (at the depth of the Leadville formation), whereas Bremkamp et al. indicate about 1400 ft of vertical offset across the fault. As mentioned previously, Bremkamp et al. infer the existence of a fault beneath the Paradox Valley salt anticline (Figure 15). Katz and Carroll do not show a fault beneath Paradox Valley, but rather show the deep rock units dipping toward the southwest (Figure 17). Hence, the two groups of investigators constructed very different geologic models to satisfy the limited well data and (apparently marginal) seismic reflection data available.

After drilling PVU Injection Well #1, William Bremkamp and Clarence Harr prepared a second report titled 'Area of Least Resistance to Fluid Movement and Pressure Rise' (Bremkamp and Harr, 1988). This report contains a regional map of the structure of the top of the Leadville formation, which covers a much greater area than the map from their 1984 report (Figure 19). The report also contains three interpreted cross sections (Figure 20). The Leadville formation structural map was created using the previously obtained seismic data, all well data available at the time, and Bremkamp's 'recall memory' of the area.

By assuming a vertical pressure gradient of 0.44 psi/ft within the Leadville formation (based on drill stem testing in PVU Injection Well #1 and the nearby Union well) and assuming that fluid could not pass faults where the fracture zones (i.e. Leadville and upper Precambrian) are not juxtaposed, a map showing contours of hydrostatic pressure within the Leadville formation and the area of least resistance to fluid movement and pressure rise within the Leadville formation from fluid injection into PVU Injection Well #1 was created (Figure 21). Pressure changes due to variations in topography were not accounted for in this analysis, and the hydrostatic pressure contours simply conform to elevation changes in the mapped top of the Leadville formation (from Figure 19).

Fluid was projected to travel to the northwest and southeast, bounded within a two-mile-wide corridor between northwest-trending impermeable faults. Bremkamp and Harr believed that the

Isopach Map of Leadville Intervals Having Greater Than 5% Porosity

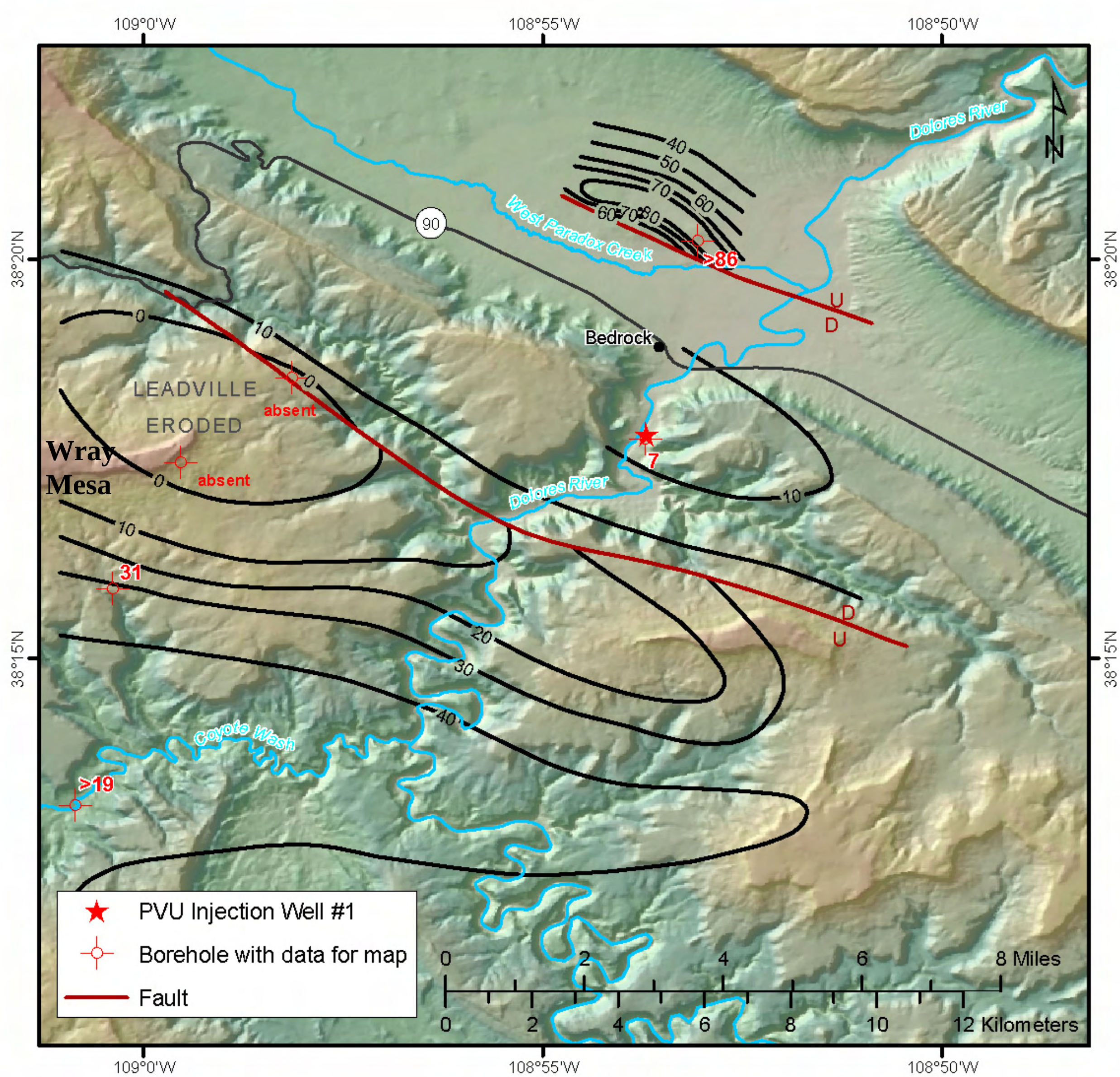


Figure 13: Isopach map of Leadville intervals having greater than 5% porosity. Contour values are thicknesses in feet. Contour interval is 10 ft. Contours and fault traces were digitized from drawing no. 8, Bremkamp et al., 1984.

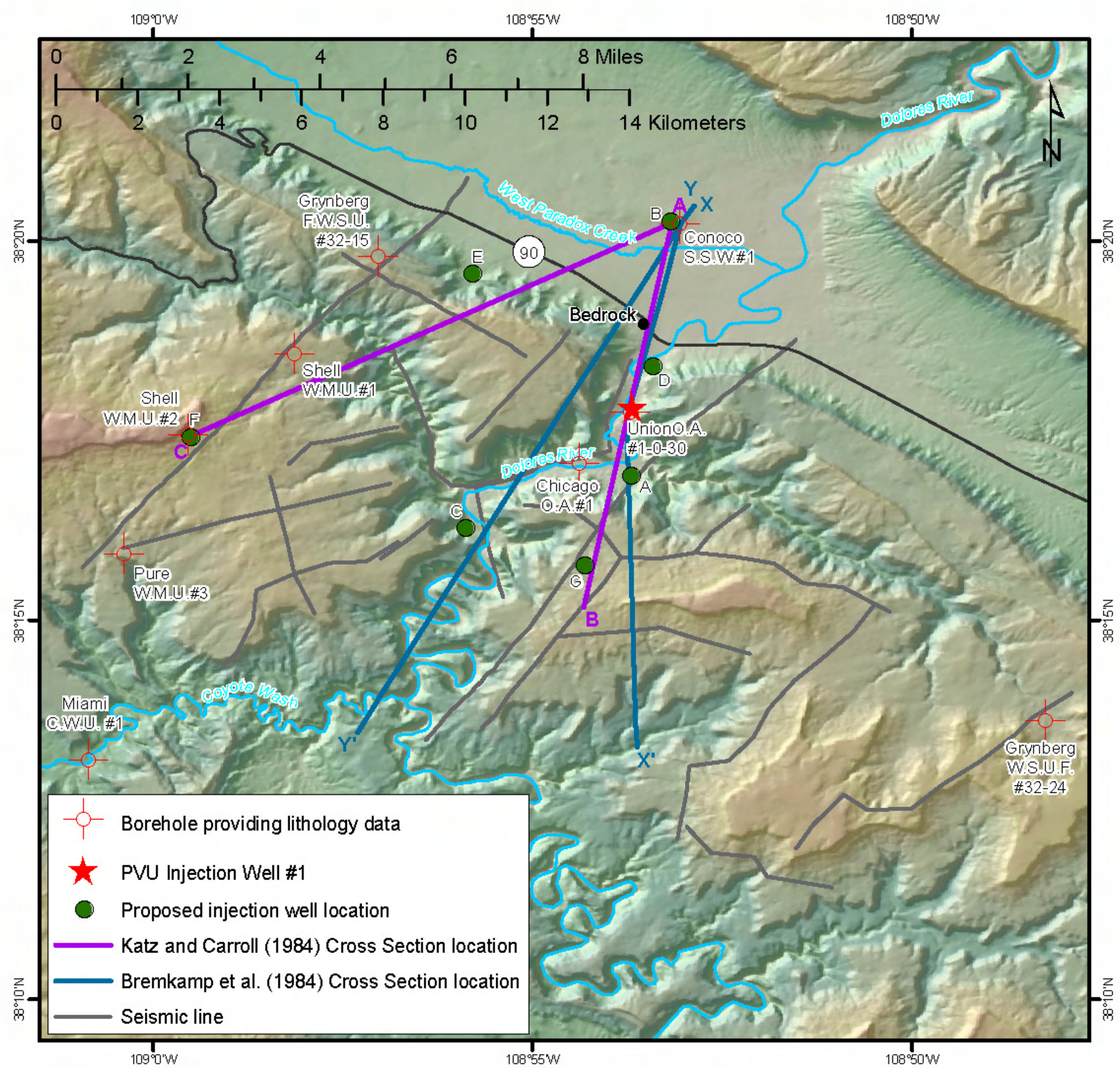


Figure 14: Locations of cross sections A-B and A-C from Katz and Carroll (1984) and cross sections X-X' and Y-Y' from Bremkamp et al. (1984). The locations of the seismic reflection lines and well control used in the geophysical interpretations are included for reference. See section 4.2 for descriptions of proposed injection well locations A through G.

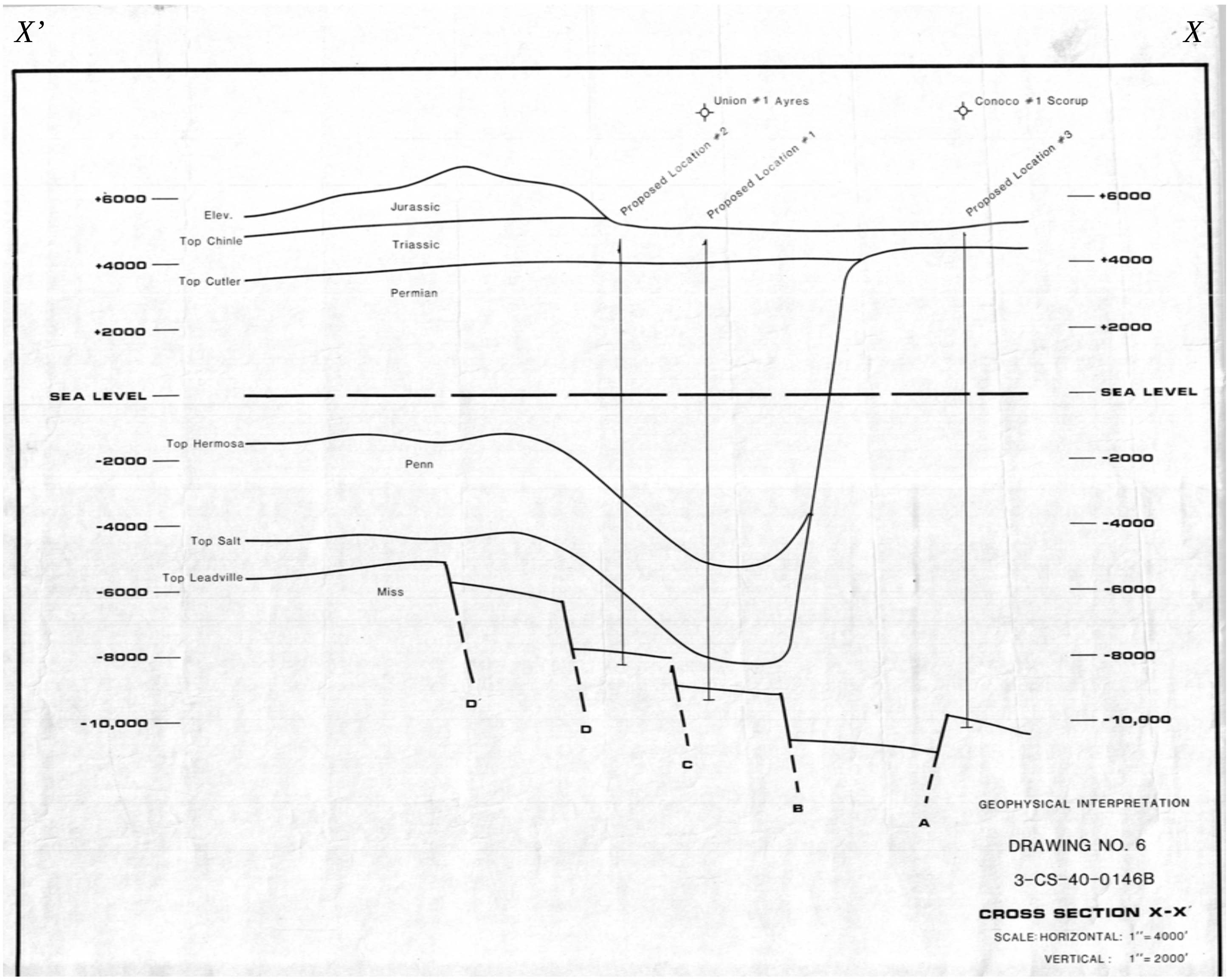


Figure 15: Cross section X-X' from Bremkamp et al. (1984). The location of the cross section is shown on the map in Figure 14.

Y'   Y

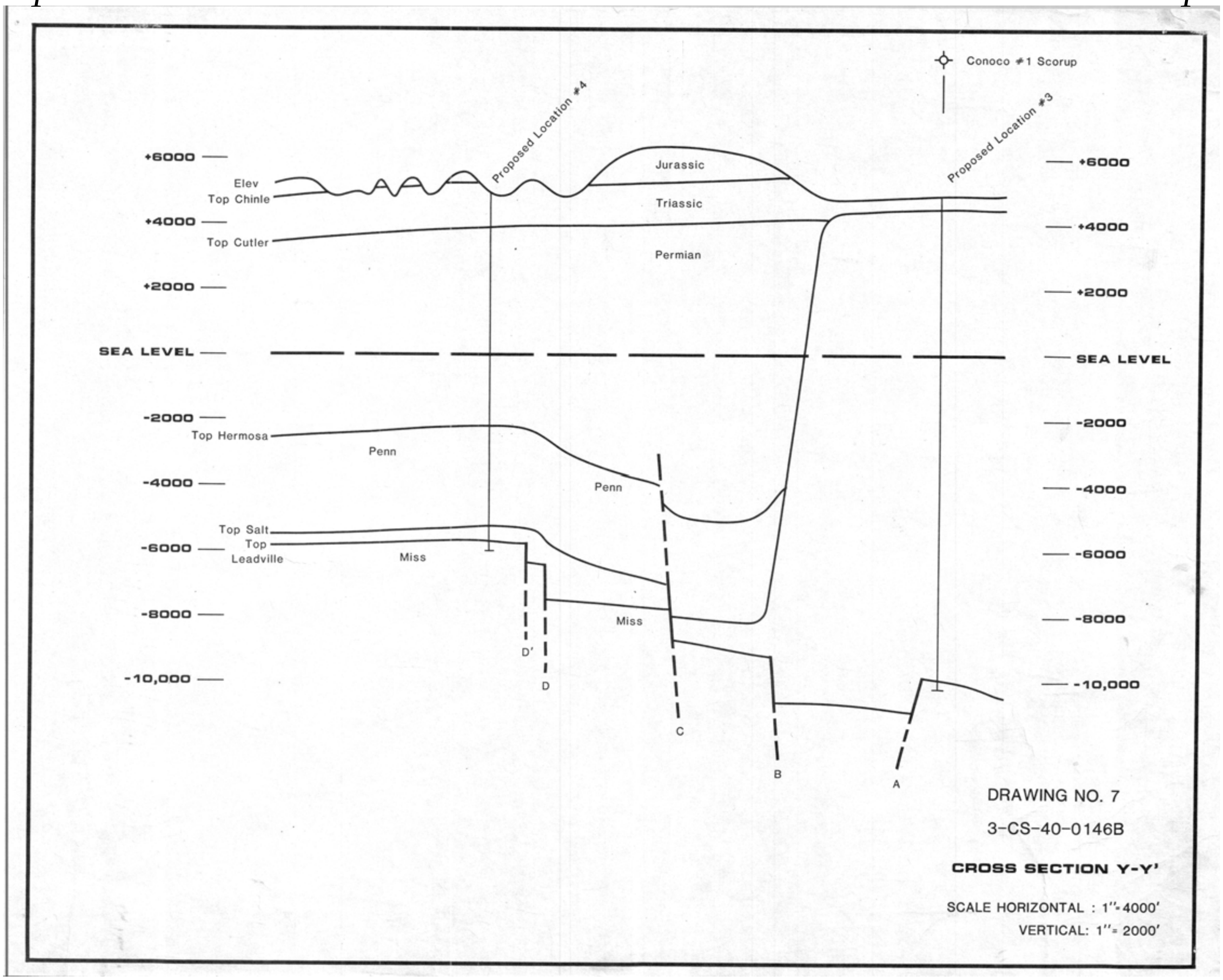


Figure 16: Cross section Y-Y' from Bremkamp et al. (1984). The location of the cross section is shown on the map in Figure 14.

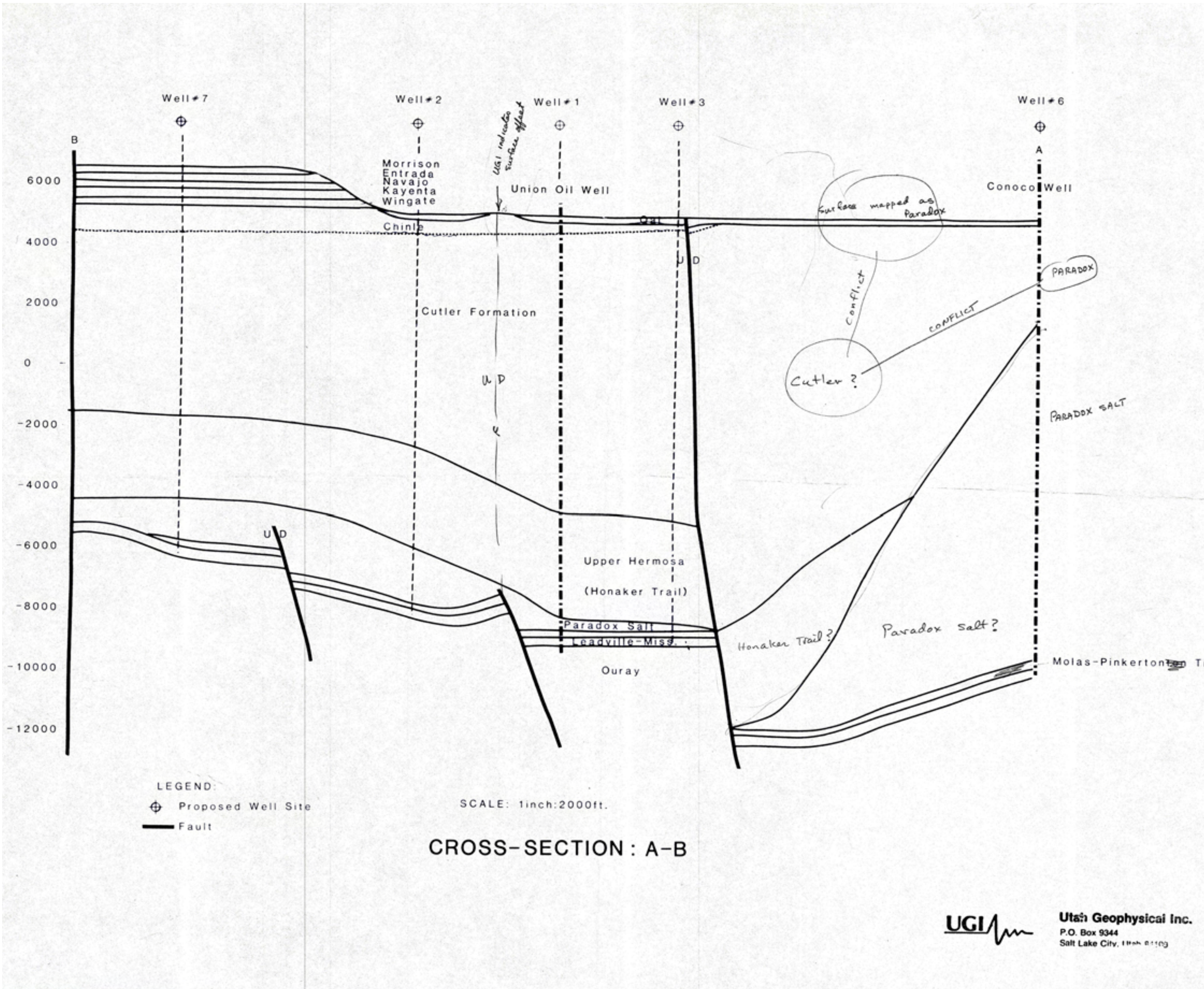


Figure 17: Cross section A-B from Katz and Carroll (1984). The location of the cross section is shown on the map in Figure 14.

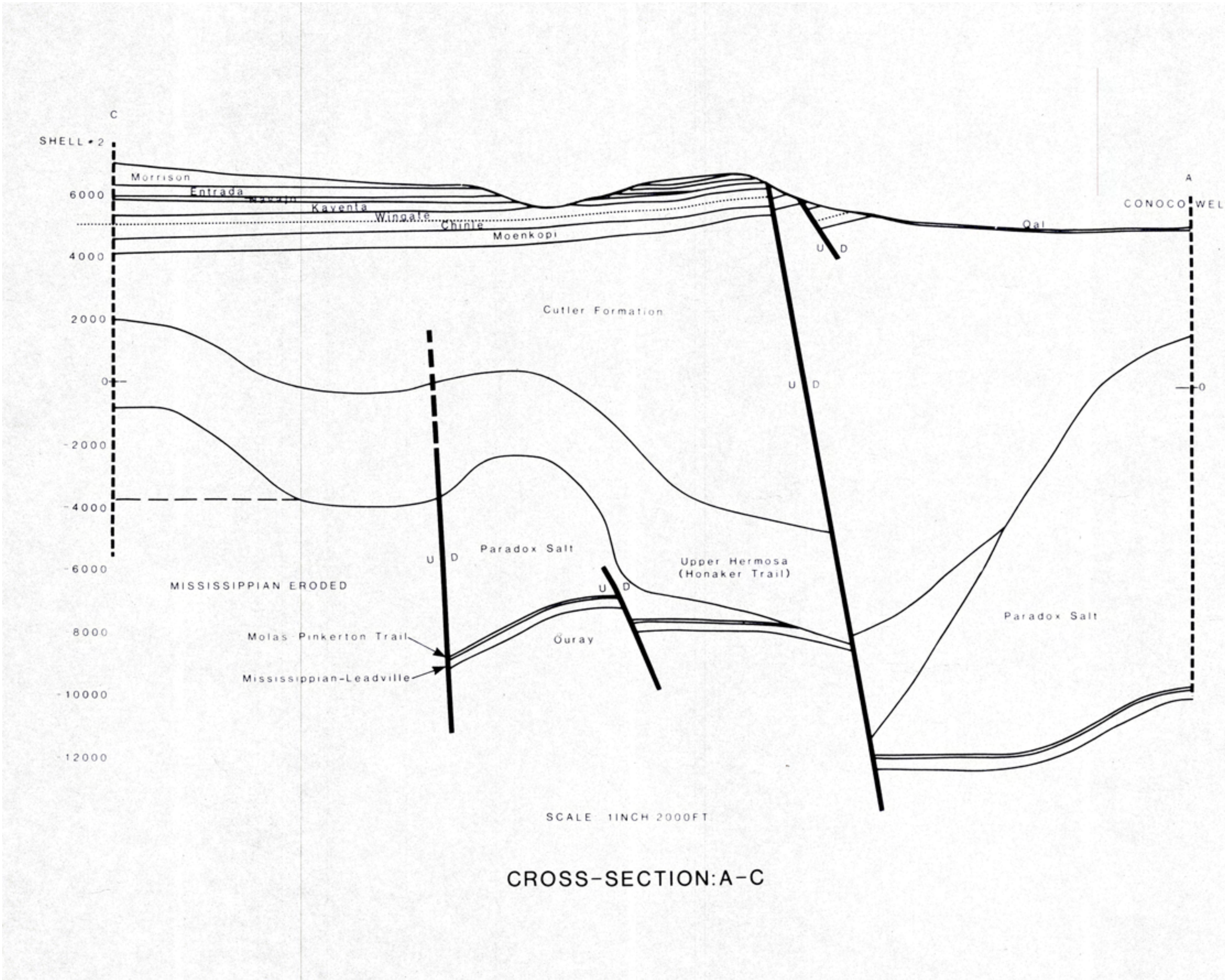


Figure 18: Cross section A-C from Katz and Carroll (1984). The location of the cross section is shown on the map in Figure 14.

Regional Structural Map of the Top of the Leadville Formation

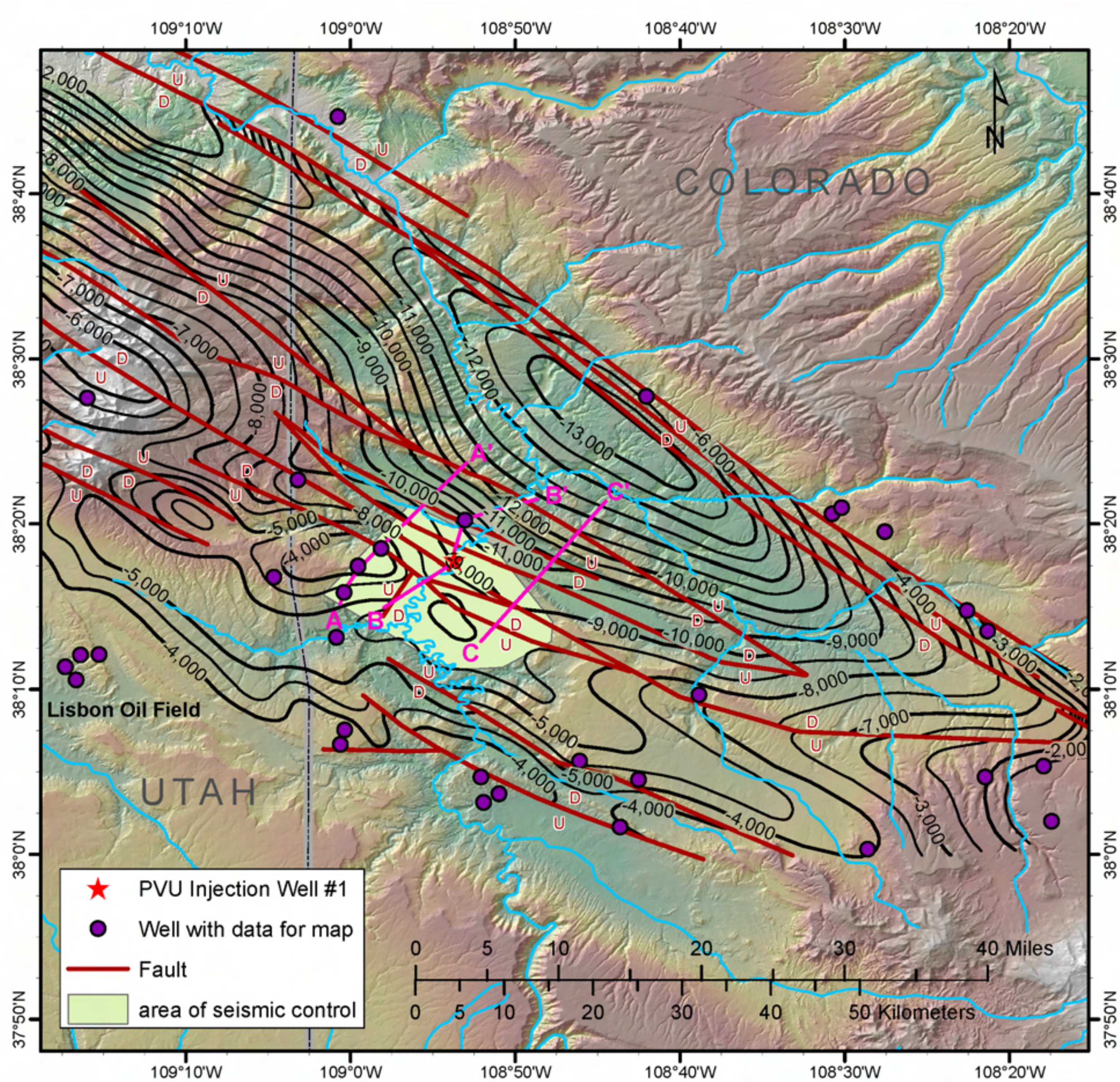


Figure 19: Regional structural contour map of the top of the Leadville Formation. Contour values are elevations in feet relative to mean sea level. Contour interval is 500 ft. Contours, and fault traces were digitized from drawing no. 1, Bremkamp and Harr (1988).

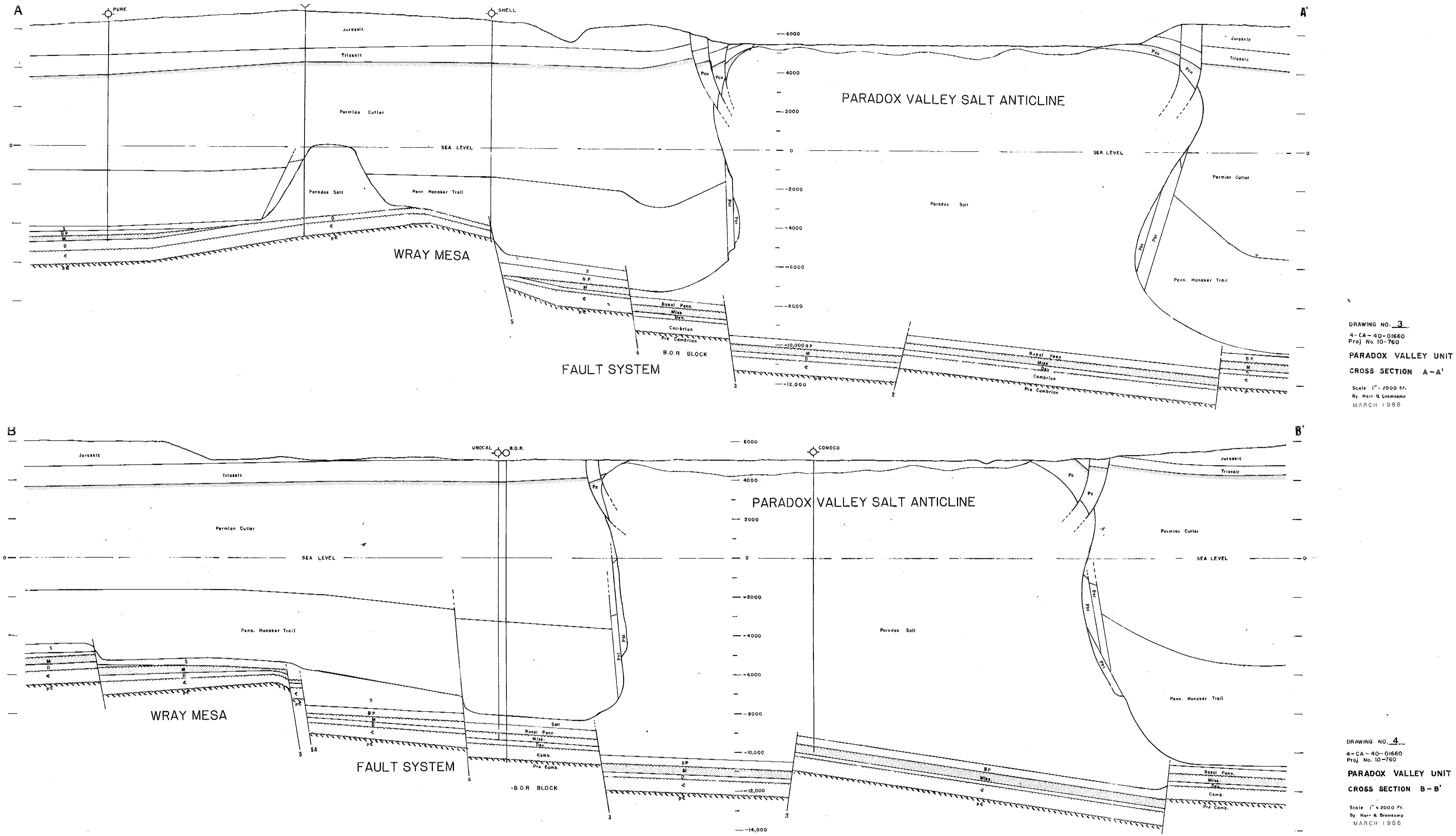


Figure 20: Cross sections A-A', B-B', and C-C' from Bremkamp and Harr (1988). The locations of the cross sections are shown in Figure 17.

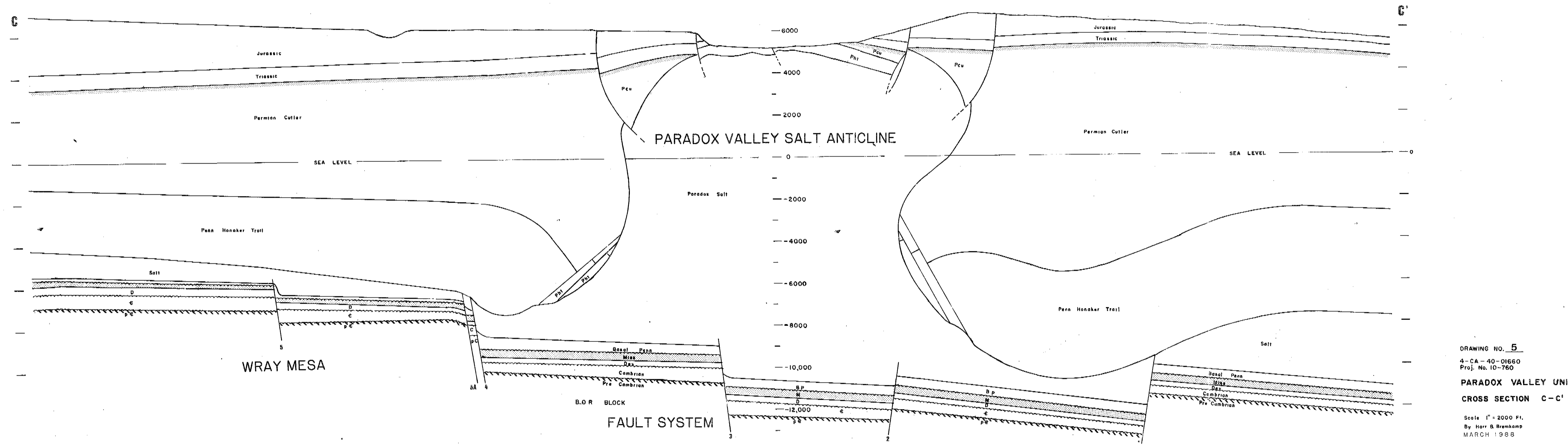


Figure 20, continued.

Hydrostatic Pressure within the Leadville Formation

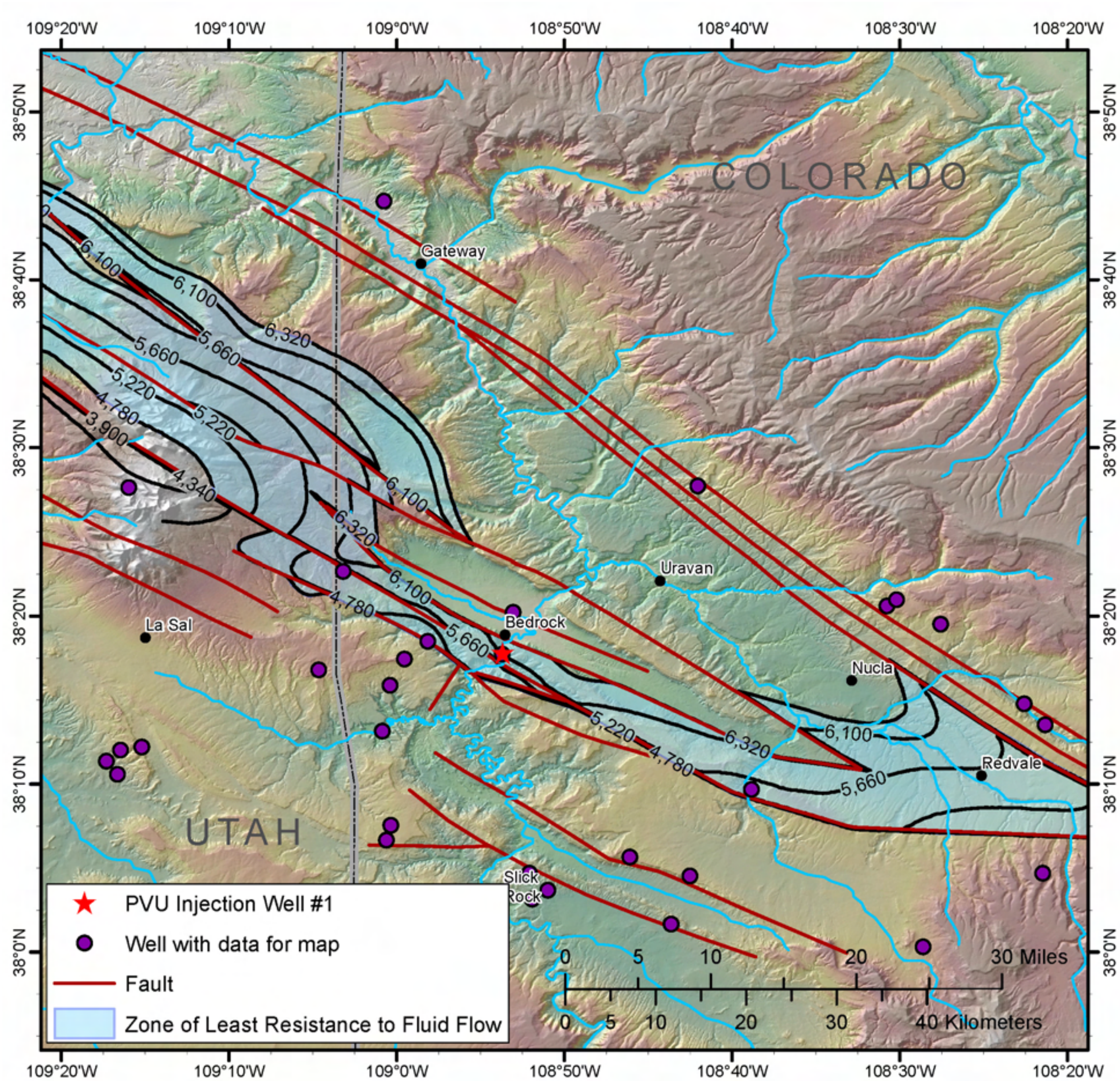


Figure 21: Regional contour map of hydrostatic pressure within the Leadville Formation. Contour values are pressures in pounds-per-square-inch (psi). Contour interval is 440 psi, except for the 6,320 psi contour. Pressure contours were digitized from drawing no. 2, Bremkamp and Harr (1988). Fault traces were digitized from drawing no. 1, Bremkamp and Harr (1988).

injectate would remain within this corridor during an estimated 100-year lifetime of the injection well. The authors noted that although injected fluid would be contained within this corridor, the pressure rise would extend past the corridor into the northwest and southeast “fan shaped” areas beyond Paradox Valley. The limit of the zone of least resistance to pressure rise associated with injection into the Leadville formation is defined to the northeast by the hydrostatic pressure contour of 6,320 psi (Figure 21). Bremkamp and Harr (1988) do not explain why a value of 6,320 psi was chosen to define the extent of the zone of least resistance to fluid flow and pressure rise. According to the map, the hydrostatic pressure within the Leadville formation at PVU Injection Well #1 was approximately 6,100 psi (prior to injection). Given the hydrostatic pressure gradient of 0.44 psi/ft, the 6,320 psi contour represents a difference of 500 ft in the elevation of the Leadville formation.

While a corresponding map was not constructed for injection into the upper Precambrian, Bremkamp and Harr (1988) indicate that the pattern of fluid flow and pressure rise in the Precambrian would be similar to that in the Leadville.

3.3.2 Reservoir Characterization

The characteristics of potential reservoir formations in the Paradox Valley area were examined through the use of well log data, drill stem testing (DST), and the examination and testing of cores. Early investigations utilizing information from preexisting wells considered the Mississippian (Leadville) formation as the most likely target reservoir for brine disposal, but also considered the Devonian (Elbert, McCracken, Ouray) and Permian (Cutler) formations as potential targets (Turner, 1975; Williams Brothers, 1982). The Mississippian Leadville formation demonstrated the best reservoir characteristics during the initial testing of PVU Injection Well #1 (Bremkamp and Harr, 1988). Bremkamp and Harr (1988) also classified the Precambrian as a target reservoir, based on the porosity and fracturing observed in that formation in PVU Injection Well #1. Bremkamp and Harr’s (1988) descriptions of potential reservoir formations, based largely on observations in PVU Injection Well #1, are summarized below.

Mississippian Leadville

Throughout most of Paradox Basin, the Leadville formation has excellent reservoir characteristics. In the Paradox Valley area, however, portions of the Leadville were severely eroded during Pennsylvanian uplift (such as under Wray Mesa, Figure 10). Not only was the thickness of the Leadville decreased along the structural highs, but the porosity was also reduced when solution cavities that formed during uplift filled with shales and clays. Areas of dolomitization directly below these weathered sections generally have the best reservoir characteristics. Effective porosity improves with the degree of dolomitization. The complexity of structural relief present during weathering and dolomitization make the reservoir characteristics of the Leadville formation in the Paradox Valley area variable and difficult to predict.

Bremkamp and Harr (1988) compiled log-derived porosity data from eight wells to characterize the regional porosity of the Leadville formation. Bremkamp et al. (1984) includes porosity values from one additional well (from the map in Figure 13). The combined data are presented in Table 3. (The Lisbon Oil Field wells included in the table are located approximately 27 miles southwest of PVU Injection Well #1.) The variation of Leadville porosity is apparent from the table, espe-

Table 3: Porosity of the Leadville Formation measured in local and regional wells, taken from Bremkamp et al. (1984) and Bremkamp and Harr (1988).

Well Name	Thickness of Leadville (ft)	Distance from PVU Inj. Well #1 (km)	Feet of 3% or greater porosity	Feet of 5% or greater porosity	Feet of 10% or greater porosity
PVU Injection Well #1	416	0	164	86	2
Union Otho Ayers No 1-0-30	340	0.12	33	7	0
Conoco-Scorup Somerville Wilcox #1	264+	4.6	118	86	31
Pure Oil -Wray Mesa Unit #3	279	10.4	not reported	31	not reported
Pure No. C-92 Lisbon	459	43.5	67	4	0
Union No. B-624 Lisbon	430	43.5	250	98	0
Union No. C-93 Lisbon	404	43.5	163	107	11
Union No. B-815 Lisbon	460	43.5	247	99	37
Union No. D-89 Lisbon	508	43.5	313	187	33

cially when comparing porosity values at PVU Injection Well #1 with those from the Union-Ayers well, located only 400 ft (0.12 km) away. The Leadville interval in PVU Injection Well #1 has 164 ft with 3% or greater porosity while the Leadville interval encountered in the Union well contains only 33 ft of the same. Leadville porosity in PVU Injection Well #1 is intermittent throughout the Leadville formation, which is considered atypical (Bremkamp and Harr, 1988).

The low porosity of the Leadville makes it an inadequate reservoir when considering intermatrix porosity alone. Hydrologic permeability is greatly increased due to the presence of an extensive fracture field related to the Wray-Mesa fault system. At PVU Injection Well #1, 182 ft of Leadville core was recovered. Twenty-seven percent of the core contained open fractures, and hairline fractures were present throughout the recovered core. Dominant fracture inclinations ranged from 65 to 85 degrees. Analysis of microscanner image, fracture identification, and sonic waveform borehole logs also indicate significant intervals of fracturing within the Leadville formation.

Precambrian Schist
The permeability of the Precambrian schist penetrated by PVU Injection Well #1 is controlled by both the porosity and the presence of fractures. Based on analysis of sonic log data, the upper Precambrian schist at this site was estimated to have 42 ft with 3% or greater porosity and 30 ft with 5% or greater porosity. Fractures observed in 30 ft of recovered core show dips ranging from 22 to 65 degrees. Those with 55 degrees dip and near common azimuth were dominant. The microscanner image, fracture identification, and sonic waveform borehole logs indicate fracturing over a 150-ft interval of the upper Precambrian. (15,500 - 15,650 ft depth). Bremkamp and Harr (1988) considered the upper 191 ft of Precambrian as a viable injection zone.

Devonian-Cambrian
Reservoir characteristics of the Devonian and Cambrian formations in northeastern Paradox Basin are generally poor. However, due to the presence of fractures in the Devonian Ouray formation and the top of the Devonian Elbert formation in PVU Injection Well #1, Bremkamp and Harr (1988) considered these formations to be potential reservoirs locally. Combined they contain 14 ft of 5% or greater porosity in PVU Injection Well #1. The Devonian McCracken and Cambrian Ignacio formations do have some favorable porosity and fracture characteristics, but they were considered to have low storage volume potential.

3.4 Additional Information

Little additional geologic or geophysical information has been gathered by Reclamation since the early PVU studies were performed. The limited additional well data and seismic reflection data that have been obtained are discussed briefly below. In addition, the spatial pattern of seismicity induced by injection into PVU Injection Well #1 is presented, for comparison to Bremkamp and Harr’s (1988) predicted pattern of fluid flow and pressure rise.

3.4.1 Well Data

A search of the Colorado Oil and Gas Commission well database (http://cogcc.state.co.us/cogis, June, 2012) revealed only one borehole that has been drilled to the depth of the Leadville formation in the vicinity of Paradox Valley since the initial PVU geologic investigations were performed in the 1980's. The location of this borehole is shown in Figure 22. The well was completed in 2008, to a total depth of 14,421 ft. The reported depth at which the hole encountered the top of the Leadville formation has been converted to elevation with respect to sea level for comparison to Bremkamp and Harr's (1988) interpreted top-of-Leadville contours. The interpreted contours and observed Leadville elevation in the new borehole are shown in Figure 22. The 2008 well encountered the Leadville formation at an elevation of 8501 ft below sea level. This strongly suggests that the buried fault which Bremkamp and Harr extrapolated to lie just west of this borehole should actually locate east of the well, so that the borehole lies on the upthrown side of the fault. The thickness of the Leadville formation encountered in this well is not reported in the Colorado Oil and Gas Commission online database. However, the depth interval between the top of the Leadville formation and the top of the McCracken formation is reported as 554 ft. Assuming that the Devonian Ouray and Elbert formations have the same thickness here as in PVU Injection Well #1 (207 ft) gives an estimated thickness of the Leadville formation of 347 ft. This is a little less than the ~400-ft thickness estimated by Bremkamp et al. (1984), but the trend is consistent with their interpreted thickening of the Leadville formation along the edge of the valley (Figure 12, upper plot).

3.4.2 Seismic Reflection Data

The rights to two additional seismic reflection lines were purchased by Reclamation in 2004 (Figure 22). These lines have been processed but no geologic interpretation of them has been documented. We have not found any evidence that they have been tied to the lithology, or that the locations and throws of faults have been interpreted from them. Interpretation of these lines would help evaluate the accuracy of Bremkamp and Harr's (1988) interpreted top-of-Leadville contours and faults in the areas the lines transect. They are available for further studies if the additional information they may provide is deemed useful for siting a second injection well.

A preliminary search of seismic reflection data available for purchase has shown that there are many existing 2-D seismic reflection datasets in the Paradox Valley area, both across the valley itself and on the surrounding mesas. These data were acquired between the early 1960's and mid-1980s. Folds range from single- to 24-fold. Data acquired with either dynamite or vibroseis sources are available. To date, none of the available reflection lines have been reviewed by Reclamation for data quality.

3.4.3 Induced seismicity

More than 5,800 shallow earthquakes (locating less than 8.5 km (27,900 ft) deep with respect to the ground surface elevation at PVU Injection Well #1) have been recorded in the vicinity of Paradox Valley since PVU injection operations began in 1991. No such shallow earthquakes were detected in six years of seismic monitoring prior to the start of injection operations.

Earthquakes were first detected 4 days after the start of the initial injection test into PVU Injection Well #1 in July, 1991. The first earthquakes occurred very close to the injection well. As injection continued, earthquakes continued to occur close to the well but also began occurring at greater and greater distances from the well. The expansion of seismicity away from the well over time is seen in the upper plot of Figure 23. This graph shows the recorded earthquakes with computed

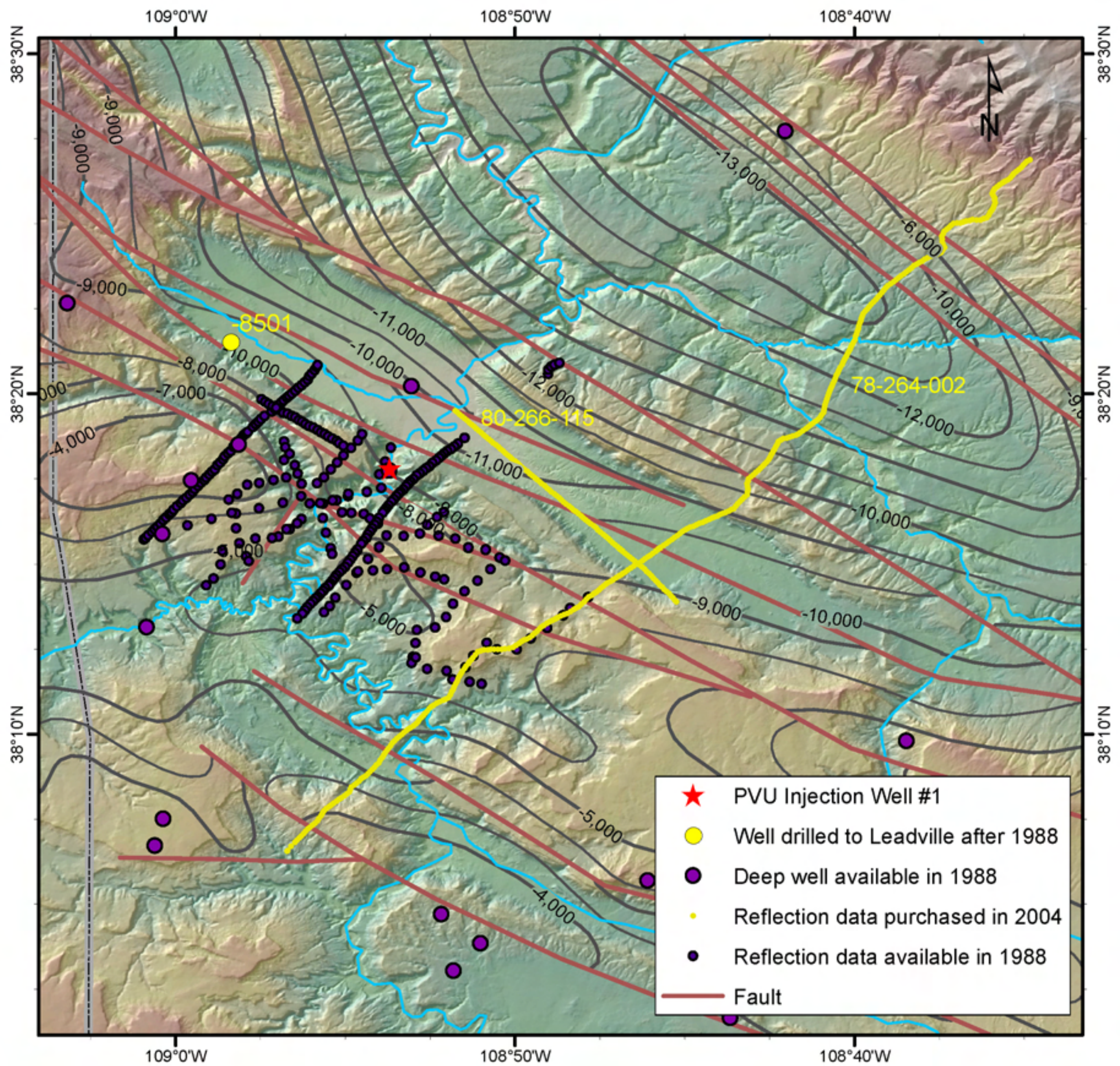


Figure 22: Location of a local well that has been drilled to the depth of the Leadville formation since the 1980's (yellow circle), and the locations of two additional seismic reflection lines that were purchased by Reclamation in 2004 (yellow lines). The elevation, relative to mean sea level, at which the well reached the top of the Leadville formation is plotted next to the well symbol, for comparison to the interpreted top-of-Leadville contours of Bremkamp and Harr (1988).

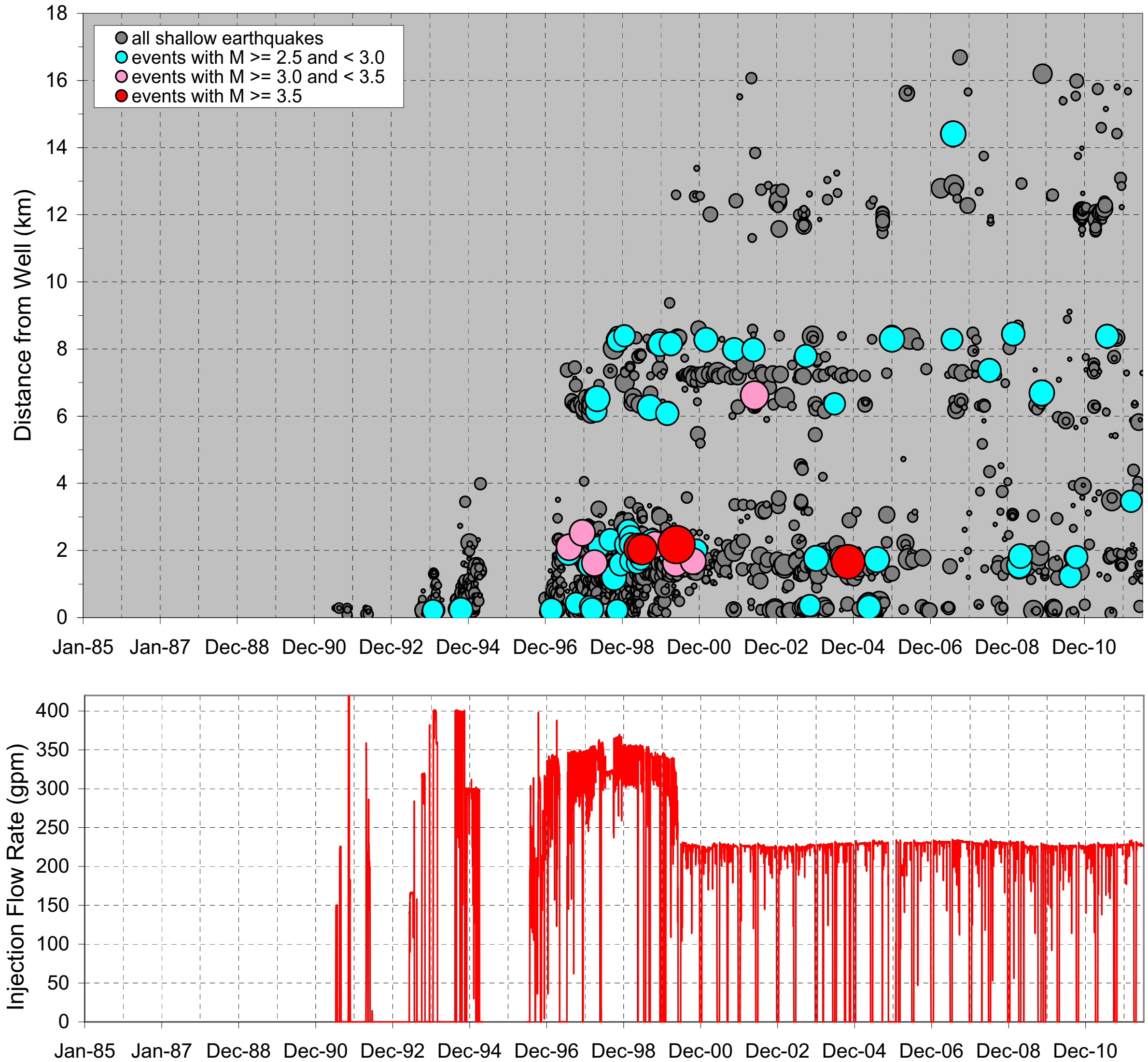


Figure 23: Upper plot - scatter plot of earthquakes having magnitude ≥ 0.5 *and locating less than 8.5 km deep (relative to the ground surface elevation at the injection wellhead), plotted as a function of date and distance from PVU Injection Well #1. Each circle represents a single earthquake, with the width of the circle scaled by the event magnitude. The lower plot shows the daily average injection flow rate.*

duration magnitude of **M** 0.5 or greater, locating less than 8.5 km (27,900 ft) deep, plotted as a function of date and distance from the injection well. Each circle on the graph represents one earthquake, and the width of the circle is scaled by relative earthquake magnitude. The lack of shallow seismicity detected during six years of pre-injection seismic monitoring and the temporal-spatial evolution of shallow seismicity since the start of injection operations demonstrated in Figure 23 strongly suggest that these shallow earthquakes have been induced by PVU fluid injection.

The spatial distribution of induced seismicity is presented in more detail in the series of maps shown in Figure 24. By the end of the injection tests in 1995, earthquakes were occurring 3 to 4 km (1.9 to 2.5 miles) from the injection well (Figure 24a). This area of induced seismicity immediately surrounding the injection well has historically been called the "primary zone" of induced seismicity, but is also referred to as the "near-well" region. In 1997, a few months after the start of continuous injection, earthquakes began occurring 6 to 8 km (3.7 to 5.0 miles) northwest of the injection well (Figure 24b). This cluster of induced seismicity is called the "secondary zone" of induced seismicity, or the "northwest (NW) cluster". In mid-2000, earthquakes were first detected 12 to 14 km (7.5 to 8.7 miles) from the injection well, along the northern edge of Paradox Valley (Figure 24b). Several distinct clusters of earthquakes have occurred along the northern edges of the valley since 2000 (Figure 24c,d). The earthquakes occurring in all of these clusters are referred to as "northern valley events". An earthquake was first detected about 6 km (3.7 miles) southeast of the injection well in 2004 (Figure 24c), but the seismicity rate in this area markedly increased beginning in 2010 (Figure 24d). This tight group of earthquakes is referred to as the "southeast (SE) cluster". In recent years, a few isolated earthquakes have been detected in previously aseismic areas, including in the center of Paradox Valley (Figure 24d).

The spatial distribution of induced seismicity does not necessarily indicate the pattern of flow of injected fluids. As suggested by Bremkamp and Harr (1988), an increase in pore pressure may occur far from the location of the injectate, as in-situ groundwater is displaced. Furthermore, the emplacement of large quantities of injectate can cause local subsurface stress conditions to change, and such changes may induce earthquakes in areas that are not necessarily experiencing direct changes in pore pressures from fluid injection.

Although the relationship between the flow of injected fluids and associated pressure rise of in-situ groundwater and the occurrence of induced seismicity is complex, the pattern of induced seismicity is the only indication we currently have for where subsurface conditions have been affected by fluid injection. A comparison of the pattern of induced seismicity and the predicted "area of least resistance to fluid movement and pressure rise" in the Leadville formation, from Bremkamp and Harr (1988), may shed some light on the consistency of the seismicity and the geologic/hydrologic model. Such a comparison is presented in Figure 25, which shows the seismicity superimposed on Bremkamp and Harr's contours of Leadville hydrostatic pressure and zone of predicted fluid flow and pressure rise. Bremkamp and Harr did not make a comparable map of predicted fluid flow and pressure rise from injection into the Precambrian, but they stated that the pattern would be similar to that mapped for the Leadville formation.

Bremkamp and Harr (1988) predicted that the fluid injected into the Leadville formation from PVU Injection Well #1 would be confined to a two-mile-wide, northwest-southeast-trending cor-

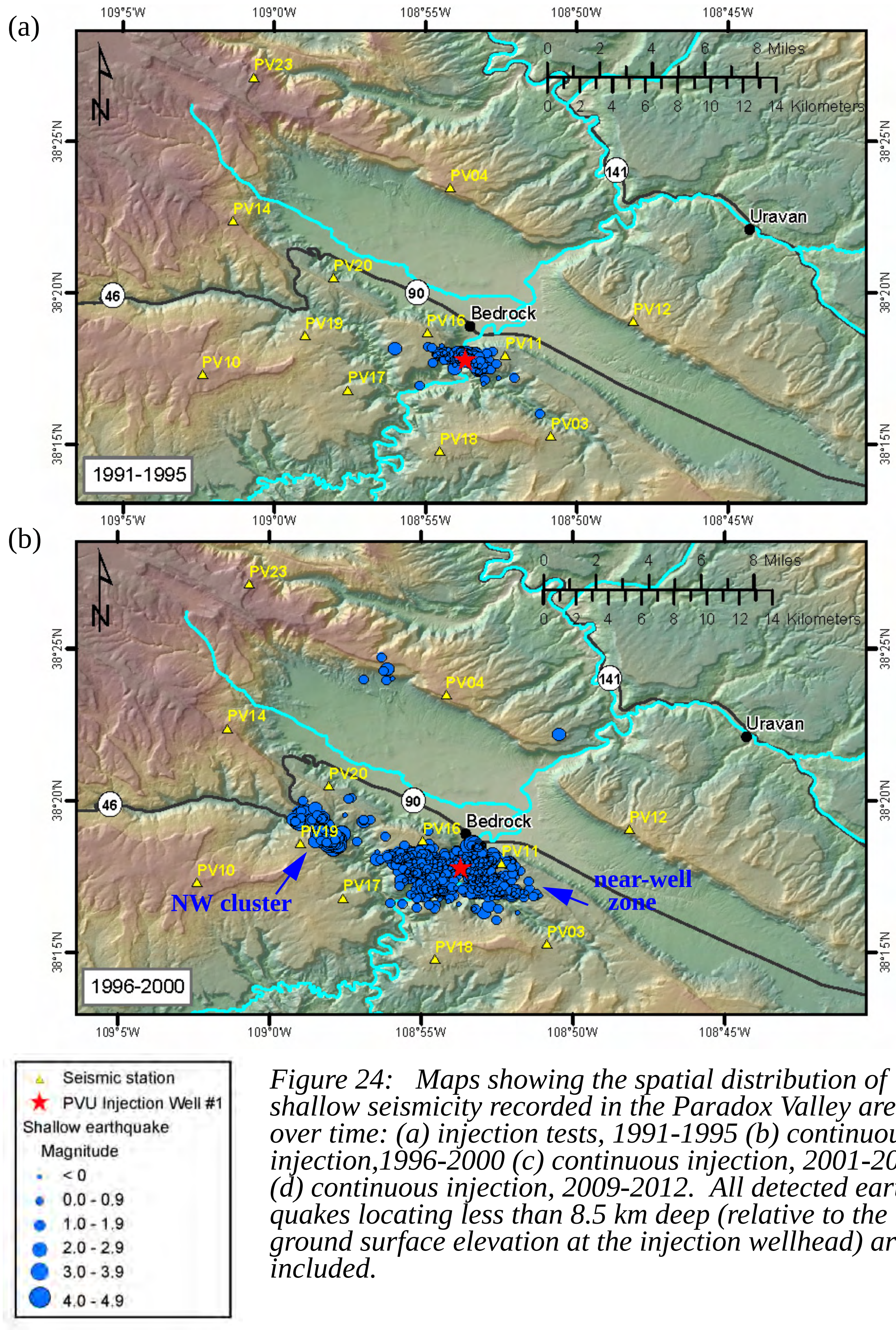
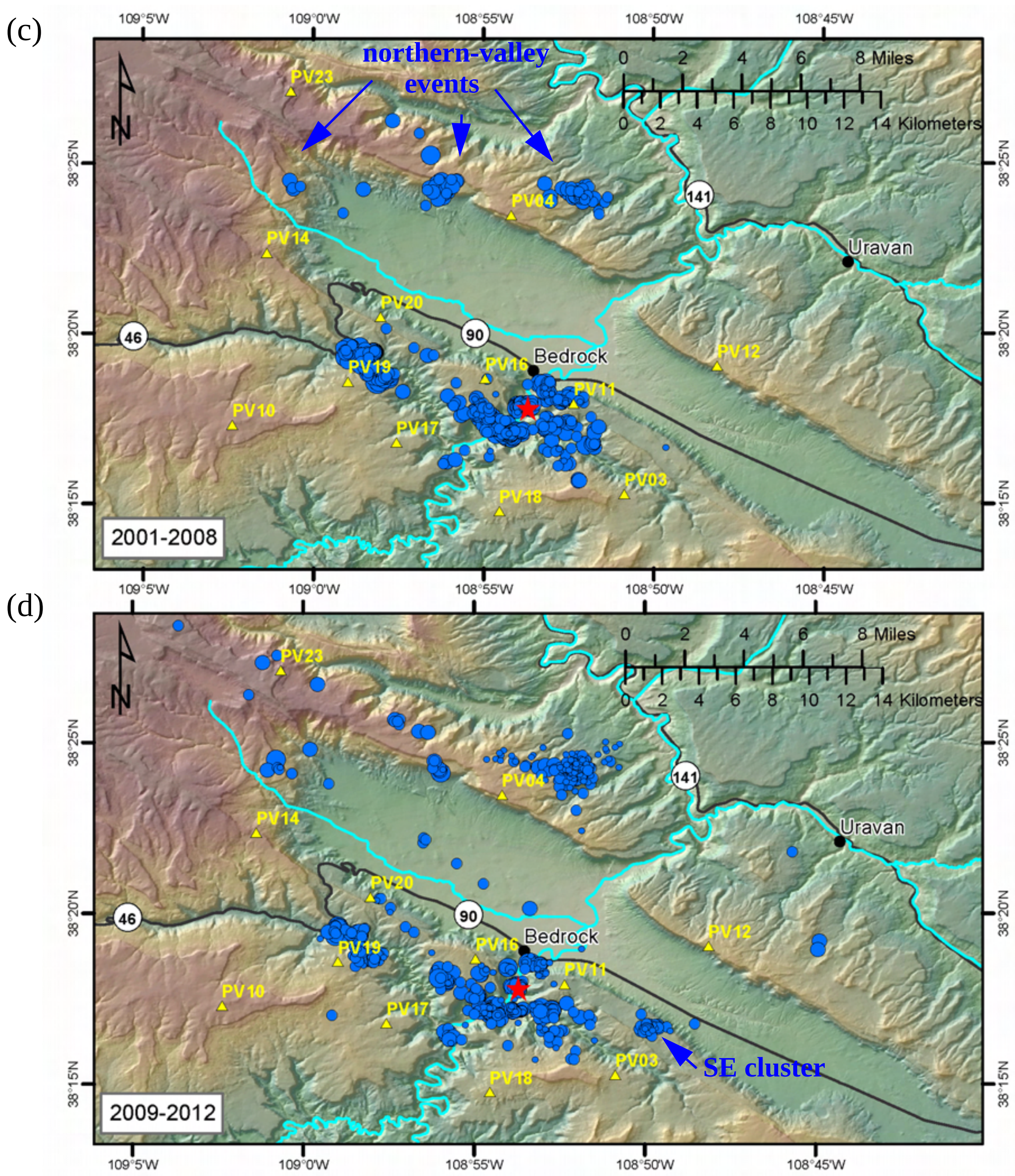


Figure 24: Maps showing the spatial distribution of shallow seismicity recorded in the Paradox Valley area over time: (a) injection tests, 1991-1995 (b) continuous injection,1996-2000 (c) continuous injection, 2001-2008 (d) continuous injection, 2009-2012. All detected earth-quakes locating less than 8.5 km deep (relative to the ground surface elevation at the injection wellhead) are included.



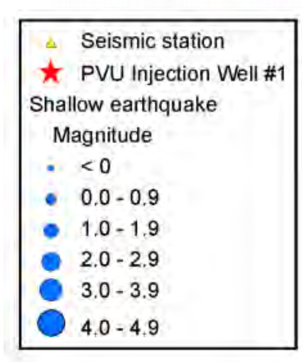


Figure 24, continued.

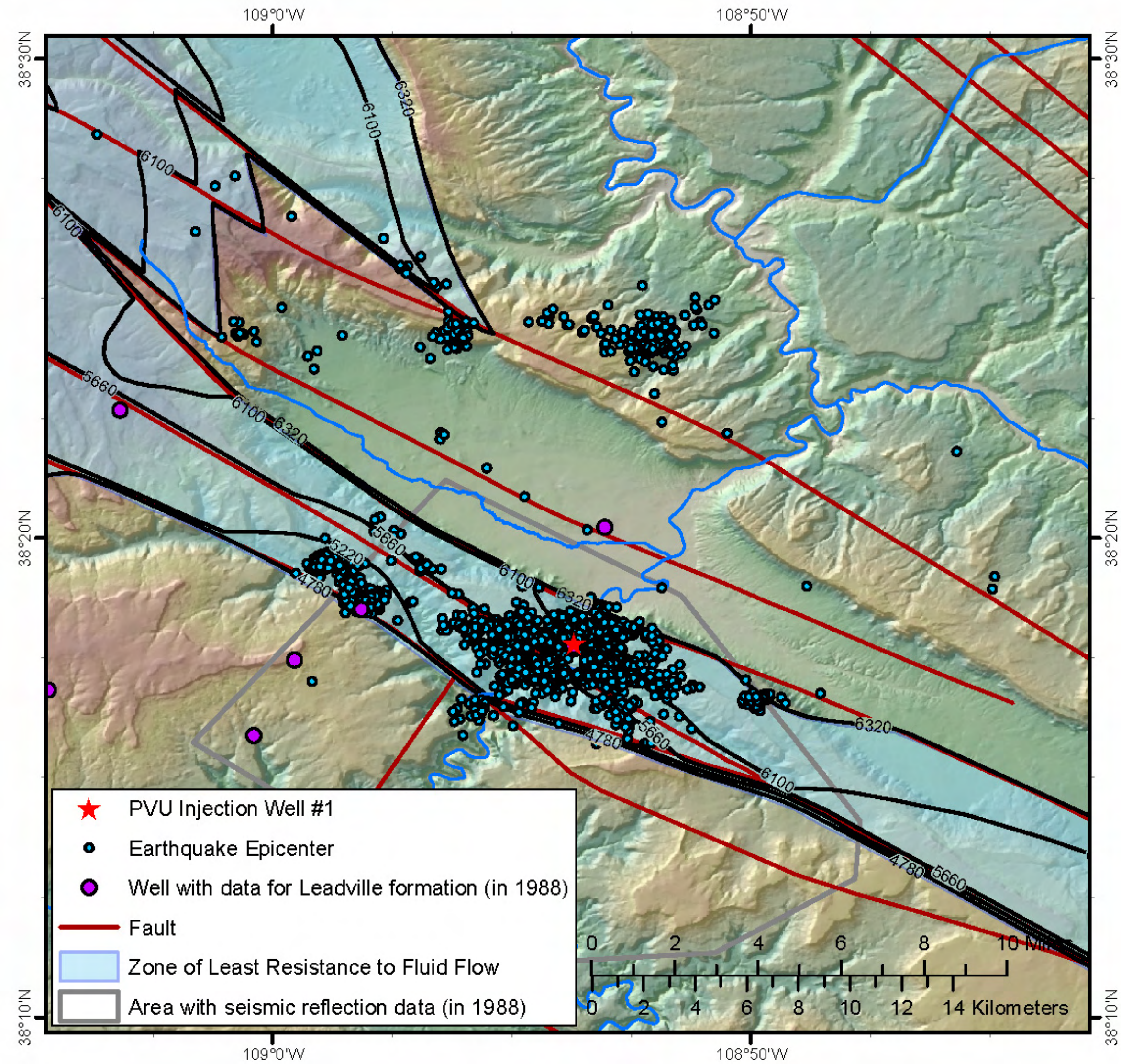


Figure 25: Contour map of hydrostatic pressure within the Leadville formation and predicted area of least resistance to fluid movement and pressure rise from injection into PVU Injection Well #1, from Bremkamp and Harr (1988) (drawing no. 2), and epicenters of shallow earthquakes interpreted to be induced by fluid injection into PVU Injection Well #1. (Fault traces were digitized from drawing no. 1, Bremkamp and Harr, 1988).

ridor bounded by impermeable faults. The majority of the seismicity occurring on the southern side of Paradox Valley lies within these fault boundaries, with the exception of a cluster of earthquakes occurring near the complex intersection of faults located 3.4 km southwest of the injection well (Figure 25). The general lack of seismicity outside of these fault boundaries supports Bremkamp and Harr's interpretation that these faults are impermeable to fluid flow through the Leadville formation, although details of the intersection of faults to the southwest of the well may not be correct.

Bremkamp and Harr also predicted that the pressure rise associated with fluid injection would extend into the "fan-shaped" areas wrapping around the northwestern and southeastern ends of Paradox Valley (Figure 21). There is less resistance to fluid flow and pressure rise toward the northwest, since the Leadville formation becomes shallower in that direction and therefore the hydrostatic pressure decreases. Based on this prediction, the occurrence of seismicity at the northwestern end of Paradox Valley is not unexpected. However, most of the shallow earthquakes occurring along the northern edges of Paradox Valley lie outside the boundaries of Bremkamp and Harr's "area of least resistance to fluid flow and pressure rise" (Figure 25). The outline of this region of least resistance to pressure rise is based on the depth and dip of the Leadville formation, the locations and throws of faults, and a hydrostatic pressure boundary value of 6,320 psi (see section 3.3.1). The geologic model was extrapolated by Bremkamp and Harr from limited well and seismic reflection data. The available seismic reflection data did not extend to the areas of seismicity occurring around the northern edges of Paradox Valley, and there are no known wells that penetrate the Leadville formation in the vicinity of the northern-valley seismic zones (Figure 25). Hence, there are no apparent data points to constrain the geologic model at the northern end of Paradox Valley. Furthermore, Bremkamp and Harr (1988) do not explain why the hydrostatic pressure contour of 6,320 psi was chosen to define the extent of the zone of least resistance to pressure rise, and therefore the value appears to be somewhat arbitrary. Based on the limited geologic data available, it is possible that an equally acceptable geologic/hydrologic model could be constructed that would include the northern valley seismicity within the area of Leadville (and Precambrian) pressure rise from fluid injection into PVU Well #1. Additional deep seismic reflection data and/or well data at the northern end of Paradox Valley would be needed to better constrain the hydrologic model in this area.

Several earthquakes that have occurred beneath central Paradox Valley since 2010 coincide with the location of the mid-valley fault mapped by Bremkamp and Harr (Figure 25). These earthquakes locate within the Precambrian basement. (Most occur at elevations between -3.6 and -6.5 km (-11,800 to -21,300 ft), although the largest earthquake recorded to date, a M 1.4 event, locates somewhat deeper at -8.2 km (-26,900 ft) elevation.) While it is possible that changing conditions related to PVU fluid injection has caused slip on this basement fault, the earthquakes recorded to date do not provide sufficient-quality data to compute focal mechanisms and determine the orientation of the source fault(s).

4.0 Injection Well Site Selection

4.1 Criteria for Site Selection

Site selection for a second well is dependent on several criteria, both geological and logistical. Geological criteria include the characteristics of the reservoir formation (e.g., thickness, spatial extent, depth, porosity, permeability, chemical composition, and fracture gradient), the characteristics of the confining layer (e.g., thickness, fracture gradient, composition, and integrity), anticipated flow paths and barriers for the injected fluid, the estimated reservoir capacity, and the degree of confidence in the geophysical and geological interpretations for the site. Logistical considerations include the distance and elevation difference between the extraction field and the injection well, drilling difficulty level, the anticipated longevity of the well, and access issues. Additional constraints include the hydrologic and stress/pore-pressure isolation from the existing injection well.

Reservoir Properties

The Mississippian Leadville formation has been identified as the primary objective reservoir in the region (e.g., Bremkamp and Harr, 1988; Harr, 1989). The porosity of the formation is regionally variable, and the amount of Leadville porosity data in the immediate vicinity of Paradox Valley is limited (Table 3). Furthermore, Leadville porosity can vary over very short distances (such as between PVU Injection Well #1 and the Union Otho Ayers No 1-0-30 well, Table 3). Bremkamp et al. (1984) considered it necessary for a portion of the Leadville formation to have a porosity of 5% or greater in order to initiate injection and allow fluid to reach fractures not directly connected to the borehole. While proximity to well data can provide some information on the potential porosity characteristics at a proposed second well site, the possibility of significant variation in characteristics over short distances means that Leadville porosity characteristics may not be known confidently prior to drilling a well.

As intermatrix porosity of the Leadville is low, much of the rock's permeability is supported through the presence of fractures. The Leadville formation contains a fracture field associated with the northwest-trending Wray-Mesa Fault system. Cores from PVU Injection Well #1 show extensive fracturing while the fracture system is less pronounced at the Conoco Scorup #1 well. The permeability at each site was interpreted to be nearly equal (Harr 1989), illustrating the importance of both fractures and porosity in creating an adequate reservoir.

The underlying Precambrian schist also may act as a reservoir. The upper 65 ft of schist at Injection Well #1 had 42 ft of 3% or greater porosity. Fractures were also present in the cores but to a lesser extent than in the Leadville formation.

In choosing a site for a second injection well, it will be essential that the proposed reservoir can sustain injection over its lifetime (at least 25 years). To accurately estimate the capacity of the reservoir, it likely will be necessary to evaluate fundamental reservoir characteristics such as the intermatrix porosity of the rock, the degree of fracturing, the reservoir layer thickness, and the location and offsets of faults. While the total storage space available is largely determined by porosity, fractures, and the volume of the formation, the geometry of the subsurface rock units and buried faults will likely control the pattern of fluid flow. Accurate measurement of the porosity, degree of fracturing, and thickness of the Leadville formation likely can be determined only from well data, while the depth and dip of formations and location and offsets of faults possibly can be interpreted from high-quality deep seismic reflection data.

Confining Layer Thickness and Integrity

A crucial aspect in choosing an injection site is the assurance that the injected brine will remain confined at depth. The impermeability and plastic behavior of the Paradox formation salt makes it an excellent confining layer. At least 250 ft of salt is necessary in order to safely confine the injected brine (Bremkamp et al. 1984, Katz and Carroll, 1984). While a thicker layer of salt is a better barrier, the difficulties in drilling and maintaining a well increase in thick salt sections. An extremely thick salt section has the potential for damage or collapse of the well over time.

Hydrologic and Pore-Pressure Separation from Injection Well #1

As the main goal in drilling a second injection well is to allow for the further injection of brine without exceeding the maximum allowable surface injection pressure, it is necessary that the reservoir accessed by the second well be hydrologically separated from that of PVU Injection Well #1. Control of induced seismicity, which is related to incremental changes in pore pressure, also requires separation from the effects of the existing well and reservoir. The local subsurface geology and hydrology (e.g., as mapped from well logs and deep seismic reflection data in Bremkamp and Harr, 1988) and the spatial distribution of earthquakes induced by fluid injection to date will both need to be considered when evaluating the separation of proposed well sites from the previously-injected reservoir.

Confidence in Subsurface Geologic Interpretation

Site selection depends on our understanding of the subsurface geologic structure and reservoir characteristics. Confidence in subsurface geologic and geophysical interpretations largely relies on the proximity of direct measurements (wells) and the availability of good-quality deep seismic reflection data. Unfortunately, the number of existing wells that penetrate the Leadville formation in the vicinity of Paradox Valley is very limited. The quality of available seismic reflection data is highly variable, with the better-quality data often acquired on the surrounding mesas, at higher, less-desirable elevations for an injection well site. Hence, limiting site selection to areas with existing high-quality subsurface data significantly reduces the flexibility in locating a second injection well. Acquiring additional subsurface information, such as from deep seismic reflection data recorded with modern acquisition techniques, may increase the flexibility of the site selection process, but at a significant cost.

Logistics and Cost Concerns

Many factors contribute to the logistics involved in drilling and operating a new brine disposal well. For example, the elevation of a selected site relative to the extraction wells and the distance from the extraction wells play a large role in the cost involved in injecting waste water over the well's lifetime. A second injection well site ideally would be located close to the extraction wells, with a minimum elevation difference. If directional drilling allows access to new reservoirs from existing surface facilities, then costs could be reduced by using preexisting infrastructure (e.g. pipelines and roads).

The depth to the reservoir formation and the thickness of the overlying confining layer also play a large role in the logistics of drilling and the longevity of the well. The cost of drilling and completing the well increases with total well depth. Thick salt layers can cause difficulties in both drilling and maintaining a well. The plastic nature of salt may cause a well to collapse.

4.2 Proposed Sites from Previous Studies

Several potential injection well sites were proposed during early PVU studies (Bremkamp et al., 1984; Katz and Carroll, 1984). Investigators largely relied on existing well data when evaluating sites, both because of the variable and often marginal quality of the available seismic reflection data and because of the variability of the reservoir characteristics of the Leadville formation. The location of PVU Injection Well #1 was selected largely due to its proximity to the Union Oil Co. #1 well, which allowed for accurate interpretation of the subsurface geology and eased logistics of creating a new well. The Union well showed adequate salt thickness to confine injected brine (270 ft) and demonstrated favorable reservoir qualities. (See Davis (1985) for an engineering review of PVU Injection Well #1 site selection.)

Most of the potential injection well site locations documented in early PVU reports were proposed prior to the site selection and drilling of PVU Injection Well #1 (Bremkamp et al., 1984; Katz and Carroll, 1984). One report, written after the completion of PVU Injection Well #1, specifically details the benefits of a site proposed for the location of a second injection well (Harr, 1989). This latter study employed similar criteria for site selection as the earlier studies, with the exception of the additional criterion of hydrologic isolation from the target reservoir of the first injection well. Besides the location chosen for PVU Injection Well #1, seven additional sites were suggested in these reports. The same location was sometimes proposed by more than one group of authors. A combined list of the proposed sites documented in three cited PVU reports is given below; site locations are shown in (Figure 26).

Site A

(Bremkamp et al., 1984 - location #2; Katz and Carroll, 1984 - well #2)

Latitude and Longitude: 38.282 N, 108.895 W
Elevation: 5020 ft
Salt Thickness: 1400 - 1500 ft
Depth to Leadville: 12,450 ft
Leadville Thickness: ~ 300 - 325 ft

Two groups of consultants recommended this site as a potential location for the initial PVU injection well. The site is located approximately 3/4 mile (1.2 km) south of PVU Injection Well #1. It has a thicker salt layer and a shallower depth to the Leadville formation than PVU Well #1. A

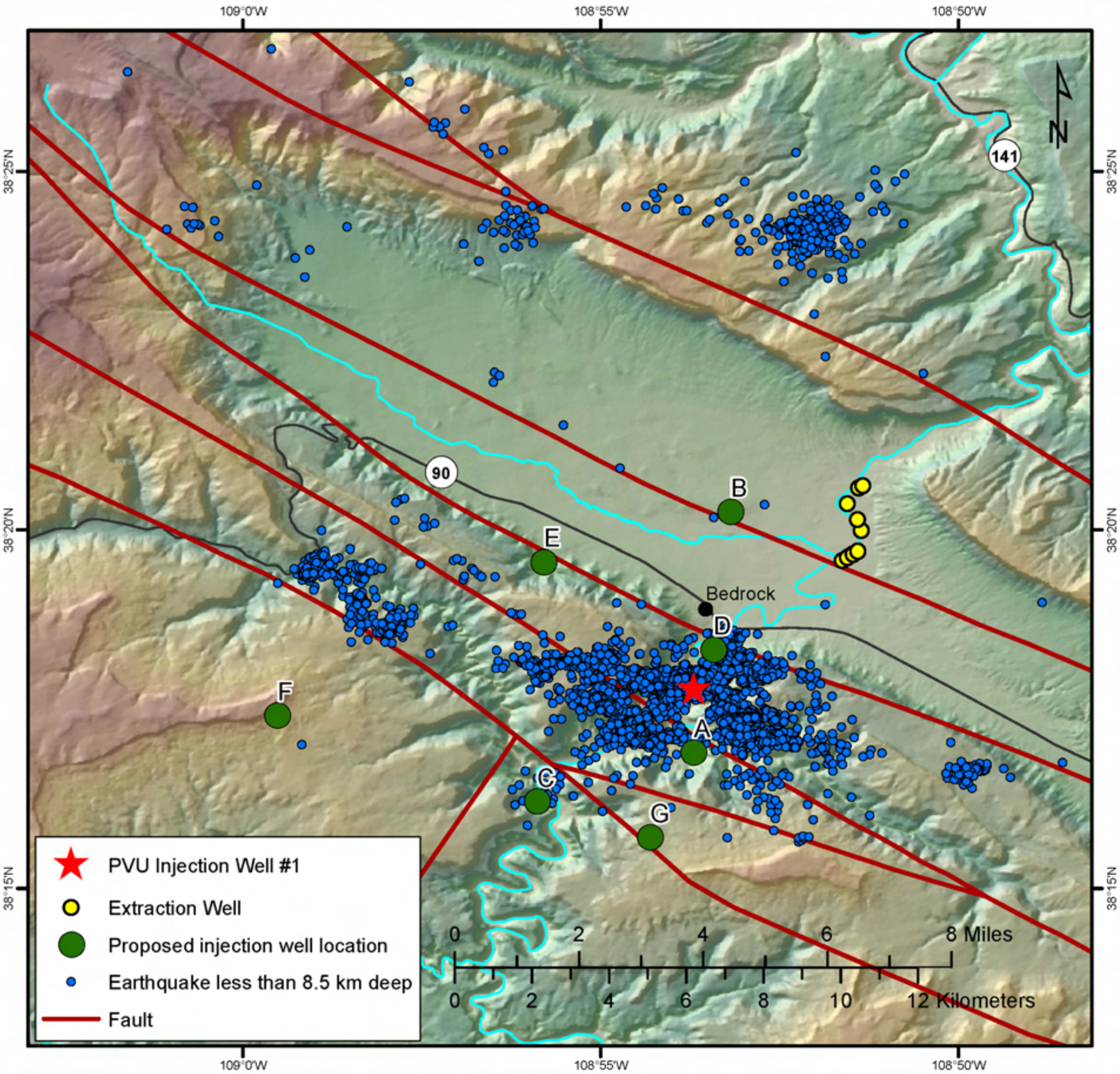


Figure 26: Locations of potential sites for an injection well, proposed by Katz and Carroll (1984), Bremkamp et al. (1984), and Harr (1989). See text for a description of each proposed location.

normal fault in the basement and Paleozoic rocks with between 1000 and 2600 ft of throw (down-faulted toward PVU Well #1) lies between this site and PVU Injection Well #1 (Bremkamp et al., 1984; Katz and Carroll, 1984). While Bremkamp et al. (1984) considered it unlikely that fluids would migrate through the Leadville formation across this fault, seismicity induced by injection into PVU Well #1 routinely occurs at this site. Hence, it must be considered highly unlikely that this site is hydrologically isolated from PVU Well #1.

Site B

(Bremkamp et al., 1984 - location #3; Harr, 1989; Katz and Carroll, 1984 - well #6)
Latitude and Longitude: 38.337 N, 108.877 W
Elevation: 5040 ft
Salt Thickness: 13,750 ft
Depth to Leadville: ~ 14,760 ft (Katz and Carroll 1984)
Leadville Thickness: ~250 ft (Katz and Carroll 1984)

This site lies in the center of the Paradox Valley salt anticline, near the Conoco Scorup Somerville Wilcox #1 well. This location was proposed in all reports detailing potential injection well sites, including a report specifically promoting it as a second injection site (Harr, 1989). The site was considered to have the best reservoir characteristics of all of the proposed sites based on gamma-ray neutron logs, drill stem test (DST) data, and limited core data from the Conoco well. Prior to the drilling and testing of PVU Injection Well #1, the porosity of the Leadville formation observed from the Conoco well was much higher than that seen in the rest of the area. This site would have been considered the preferred choice for the initial PVU injection well if it were not for the difficulties in drilling and maintaining a well in a 14,000-ft section of salt. The report by Harr (1989) details the reservoir characteristics of this site, as well as suggested procedures to successfully drill the well through the salt section.

Site B is separated from PVU Injection Well #1 by a salt-filled graben (cross section B-B’, Figure 20) and is removed from most of the seismicity induced by injection into PVU Well #1. However, clusters of shallow seismicity that are likely related to fluid injection into PVU Well #1 (based on spatial and temporal seismicity patterns) occur roughly 8 to 13 km northwest of this location within the same fault block, as interpreted by Harr and Bremkamp (1988) (Figure 26). (Isolated earthquakes within Paradox Valley, most of which have occurred within the last two years, locate at much closer distances.) There are no apparent deep seismic reflection or well data to constrain Harr and Bremkamp’s interpreted locations of faults and depths to the Leadville formation at the northwest end of Paradox Valley. Given the uncertainty in the geologic interpretations, it is not possible to state definitively whether site B is hydrologically isolated from the seismicity occurring at the northwest end of Paradox Valley. Based on the interpreted shallowing of the Leadville formation to the northwest, fluid injected into the Leadville formation at site B would be expected to migrate toward the induced seismicity at the northwest end of Paradox Valley.

Site C

(Bremkamp et al., 1984 - location #4)
Latitude and Longitude: 38.270 N, 108.932 W
Elevation: 5060 ft

Salt Thickness: 250 ft
Depth to Leadville: ~ 12,500 ft
Leadville Thickness: 100 - 250 ft?

This site is located along the Dolores River, about 4.8 km southwest of PVU Injection Well #1. Prior to the completion of PVU Well #1, Bremkamp et al. (1984) suggested this site as a potential location for a second injection well to increase the total reservoir capacity of PVU. Site C lies to the west of a fault that Bremkamp et al. interpreted as being impermeable to fluid flow within the Leadville formation. Hence, the geologic interpretation indicates that the Leadville formation at site C is hydrologically isolated from injection into the Leadville at PVU Injection Well #1. A small number of earthquakes induced by fluid injection into PVU Well #1 locate at this site.

Unfortunately, the thickness of the Leadville formation at this site is not well constrained. Bremkamp et al. (1984) report a conservative estimate of 100 ft for the thickness of the Leadville formation at this site, but the Leadville isopach map of Katz and Carroll (1984) indicates a thickness of 250 ft at this location. According to the geophysical interpretation of Bremkamp et al. (1984), the thickness and reservoir quality of the Leadville formation was decreased along a structural high in this area, due to erosion, karst weathering, and infill of voids with shale and clay.

Site D
(Katz and Carroll, 1984 - well #3)
Latitude and Longitude: 38.304 N, 108.891 W
Elevation: 5050 ft
Salt Thickness: 250 ft
Depth to Leadville: 13,850 ft
Leadville Thickness: 300 ft

This site lies on the southern boundary of Paradox Valley along the Dolores River, approximately 3/4 mile (1.2 km) north of PVU Injection Well #1. The thickness of the salt section here is uncertain. The salt section is likely thinner here than at PVU Injection Well #1, but Katz and Carroll (1984) state that the overlying Hermosa shale would likely form an adequate seal for injection into the Leadville formation. They also suggest that faulting occurring 1/4 mile (0.4 km) to the northeast may enhance reservoir quality by “fault-associated fracturing”. If the geologic interpretation of Harr and Bremkamp (1988) is correct, this location lies in the same fault block as PVU Well #1, and therefore the Leadville formation at this location is not hydrologically isolated from fluids injected into PVU Well #1. The occurrence of seismicity induced by injection into PVU Injection Well #1 at site D supports this geologic interpretation.

Site E
(Katz and Carroll, 1984 - well #4)
Latitude and Longitude: 38.326 N, 108.932 W
Elevation: 5350 ft
Salt Thickness: 200 ft
Depth to Leadville: 13,350 ft

Leadville Thickness: 300 ft

This site lies on the southern boundary of Paradox Valley, about 4.5 km northwest of PVU Injection Well #1. As with site D, the thickness of the salt layer here is uncertain but likely to be inadequate, and Katz and Carroll (1984) argue that the lower Hermosa shale would form an adequate seal. The depth to the Leadville formation is expected to be a few hundred ft less here than at site D. Although Wray Mesa faults may enhance reservoir characteristics at this location (Katz and Carroll, 1984), the geologic interpretation is less well-constrained here than at most other proposed sites because of greater distances to seismic reflection and well control points. According to the geologic interpretation of Bremkamp and Harr (1988), this proposed location lies in the same fault block as PVU Injection Well #1 and is not hydrologically isolated from it. However, induced seismicity has not been observed at site E; the nearest induced earthquakes locate about 1 km away.

Site F
(Katz and Carroll, 1984 - well #5)
Latitude and Longitude: 38.290 N, 108.992 W
Elevation: 6982 ft
Salt Thickness: 3,026 ft

This site is located near the Shell Oil Wray Mesa Unit #2 well, 8.6 km west of PVU Injection Well #1. The Leadville formation is fully eroded at this location. Katz and Carroll (1984) propose considering an injection well at this site utilizing the lower Cutler and upper Hermosa formations as the target reservoir. Logs from the Wray Mesa Unit #2 well show 300 ft of clean sand with likely high permeability. The proposed target reservoir lies above the Paradox salt. Katz and Carroll (1984) do not mention what the proposed confining layer would be, although an earlier report indicates that the overlying Moenkopi and Chinle formations may act as sufficient confining layers (Williams Brothers, 1982). The distance of this site from the extraction wells and the site's high elevation would make the logistics of developing an injection well at this location difficult.

Site G
(Katz and Carroll, 1984 - well #7)
Latitude and Longitude: 38.262 N, 108.905 W
Elevation: 6500 ft
Salt Thickness: 1000 ft
Depth to Leadville: 12,200 ft (Katz and Carroll 1984)
Leadville Thickness: 350 ft

This site is located about 3.9 km south of PVU Injection Well #1. The thickness of the salt layer and depth to the Leadville formation make this site a potential candidate. Katz and Carroll (1984) claim that the seismic reflection data are good in this area, lending increased reliability to the subsurface geologic interpretation. However, there is no well control for the interpreted thickness of the Leadville formation in this area. Katz and Carroll (1984) estimated a thickness of 325 to 350 ft for the Leadville formation at this location, but Bremkamp et al. (1984) interpreted a thickness of only ~150 ft at this site (Figure 12). Furthermore, the high elevation of the site and the distance from the extraction wells makes this site logistically undesirable. For this reason, it was Katz and Carroll's (1984) last choice of their seven proposed locations for an initial PVU injection well. Site G lies just outside the zone of seismicity induced in the vicinity of PVU Injection Well #1. It locates in a small fault block, as interpreted by Harr and Bremkamp (1988) (Figure 26). The hydrologic connectivity of the Leadville formation between this fault block and adjoining blocks has not been evaluated.

5.0 Discussion

The majority of the injection well site locations proposed in the 1980's are not favorable for the location of a second PVU injection well. Sites A, D, and E lie within the northwest-southeast-trending fault-bounded corridor of fluid flow from PVU Injection Well #1, as predicted by Bremkamp and Harr (1988) and corroborated by the pattern of induced seismicity (Figure 25). Hence, fluid injected into the Leadville or Precambrian formations at these locations would almost certainly not be hydrologically isolated from the reservoirs accessed by PVU Injection Well #1.

Sites F, C, and G lie along an inferred old structural high where the Leadville formation was eroded and weathered, according to Bremkamp et al. (1984). The Leadville formation is completely eroded at site F and is of unknown thickness and porosity characteristics at sites C and G. The unknown lateral extent of the proposed Cutler formation reservoir at site F, as well as the site's high elevation, lead us to discount this proposed location. The potential thinning and weathering-related reduced porosity of the Leadville formation at sites C and G, along with the lack of well data to provide reliable reservoir characterization data, make drilling at these locations a considerable risk. The complex, and perhaps not correctly understood, fault geometries in this area also raise the question of the spatial extent of potential reservoirs. Further investigations would need to be performed before choosing to drill a deep injection well at sites C or G.

Site B, located in the center of Paradox Valley close to the Conoco Scorup No. 1 well, remains a potentially viable option. Reservoir characteristics in this area are favorable and it is close to the extraction well field. Two issues should be addressed, however, before a decision is made to install a second PVU injection well at this proposed location. First, the long-term stability of the wellbore in the 14,000-ft section of salt must be thoroughly evaluated. A high degree of confidence in the long-term stability of the wellbore must be obtained before proposing the costly installation of an injection well at this location. Second, the hydrologic isolation of this location relative to clusters of seismicity located 8 or more km to the northwest should be considered.

Documented opinions on the feasibility of drilling and maintaining an injection well through the thick salt diapir within Paradox Valley vary. Goins and Flak (1983) state that installing a 15,500-ft disposal well within Paradox Valley is "impractical due to problems completing thru deep salt, high fracturing pressures, and excessive well cost". They further state that, "The deepest salt can be completed thru with good well life is approximately 11,000 ft" and, "Ideally, a location should be picked so that salt is no deeper than 9000' to further reduce the risk of salt collapse and well cost." Klementich (1983) provides similar comments, "It is possible, but extremely difficult and very costly, to drill nearly 15,000' of massive, laterally loaded, salt beds, equip the well for permanent injection and expect a useful life of twenty plus (20+) years. ... It would be more logical to drill a well "off structure" where only approximately 500' (plus or minus) of salt would be encountered." Despite these initial arguments against locating an injection well within Paradox Valley, by 1988, preliminary designs were made for a second injection well at site B. Flak and Ables (1988) present a well design and cost estimate for installation of an injection well at this location, with an expected project life of "100 years minimum". In 2003, Reclamation hired Subsurface Technology, Inc. to review plans for installation of an injection well at or near site B, including the Flak and Ables (1988) report. This review resulted in a letter from Subsurface Technology stating that, "the technology is available to successfully drill, complete, and operate a second well below 14,000 ft of salt" and that "Subsurface generally agrees with the basic design considerations that were proposed in 1988 ... It would appear that we have a good basis for the design and implementation of a second well to penetrate the fault block below the salt diapir" (Bundy, 2003). The engineering considerations of installing an injection well through the salt diapir have not been revisited since this 2003 review.

The hydrologic isolation of site B relative to clusters of seismicity located 8 or more km to the northwest is not well understood. Based on the interpreted shallowing of the Leadville formation to the northwest, however, fluid injected into the Leadville formation at site B would be expected to migrate toward the seismicity at the northwest end of Paradox Valley. Although the northern-valley seismicity appears to be related to injection of fluid into PVU Injection Well #1, based on temporal and spatial seismicity patterns (Figure 23), it is not consistent with the geologic and hydrologic model constructed by Bremkamp and Harr (1988). As discussed in section 3.4.3, no apparent data were available to constrain the original geologic model at the far northwest end of the valley. It may be advisable to obtain additional deep seismic reflection data between site B and the northwest end of Paradox Valley. This would allow a better understanding of the geologic structure along the potential flow path of fluid injected at site B (allowing for an estimate of the reservoir capacity), and may shed light on the hydrologic connectivity of site B to the seismically-active areas at the northwest end of the valley.

Recent informal discussions within Reclamation have included considering drilling a second injection well into the deepest fault block beneath Paradox Valley, located immediately northeast of the fault block containing PVU Injection Well #1 (see cross sections, Figure 20). Early investigators did not recommend installing an injection well in this deep fault block, presumably because of the increased cost associated with drilling to the additional depth that would be required. The scarcity of optimum site locations for a second injection well, however, has raised the question of whether drilling into the deep fault block should be reconsidered. Extremely little induced seismicity has located within this block, suggesting that the Leadville and Precambrian target reservoirs within this block are hydrologically isolated from those being utilized by PVU Well #1. If modern directional drilling techniques could be used, the wellhead for the second injection well could potentially be located close to PVU Injection Well #1. This would allow many of the surface facilities already in place to service the first injection well to also be used to support the second well, thereby reducing the cost of the project. In addition, directional drilling would greatly decrease the thickness of salt that the well would penetrate, compared to drilling a vertical well within the salt anticline underlying Paradox Valley. To date, no engineering evaluation has been performed to determine the feasibility of the directional drilling. If the directional drilling were deemed feasible and this proposed location were to be pursued, it may be advisable to acquire additional high-resolution deep seismic reflection data to better define the deep geologic structure at the boundary between the fault blocks.

Alternative sites that may be considered are on the northern side of Paradox Valley, where the Dolores River exits the valley, or within the Dolores River valley slightly farther downstream. An injection well in this area would be close to the extraction well field, with a minimal elevation difference. A well in this vicinity could penetrate either the upthrown fault block on the northern side of Paradox Valley or the northern-most fault block underlying Paradox Valley (see cross section B-B', Figure 20). Based on the very limited seismic reflection data available to early investigators in this vicinity (small segment of line 204, Figure 7), Bremkamp and Harr (1988) estimated an elevation of about -11,000 to -12,000 ft for the top of the Leadville formation in this area (see contours on Figure 22). This interpretation corresponds to a depth of approximately 16,000 to 17,000 ft, relative to the local ground surface within the Dolores river valley. Bremkamp and Harr (1988) show an anomalously thin layer of salt in the upthrown fault block on this side of Paradox Valley (section B-B', Figure 20), but given the very limited data available at the time, it is doubtful that this thickness is well-constrained. No deep well data are available in this area to constrain the thickness of the salt, the thickness of the Leadville formation, or the reservoir characteristics (porosity and fracturing) of the Leadville or Precambrian formations. The acquisition of additional deep seismic reflection data, either through purchase or field acquisition, is highly recommended prior to proposing an injection well in this area. Also, a well is this area would be located less than 5 km away from an active cluster of northern valley seismicity (Figure 25). A better geologic/hydrologic model between the areas of northern valley seismicity and PVU Injection Well #1 and between the northern valley seismicity and any proposed well sites in this vicinity would be desirable.

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Appendix A
Paradox Valley Geologic Well Data

The following tables present a comparison of geologic data for nine wells located in and near Paradox Valley, Colorado. Data from these wells were used for the geophysical interpretations discussed in the main body of this report (section 3.3.1). The data included in the tables were taken from three sources: the online database maintained by the Colorado Oil and Gas Conservation Commission (COGIS: Colorado Oil and Gas Information System at http://cogcc.state.co.us/cogis), Bremkamp et al. (1984), and Katz and Carroll (1984).

Table A-1 contains a comparison of geologic elevation well data from the three sources. Elevations are given for the top of the Cutler formation, top of the Paradox formation salt member, and top of the Leadville formation. Table A-2 contains a similar comparison for geologic unit thickness values. This table contains data for the thickness from the top of the Paradox salt member to the top of the Leadville formation and the thickness of the Leadville formation. Not all wells penetrated all formations, and not all sources provided data for each item in the tables. However, for most of the items, a comparison can be made between at least two of the sources. Since the online Colorado Oil and Gas Commission database (COGIS) is considered to be the most reliable source of data, the differences between the data from Bremkamp et al. (1984) and Katz and Carroll (1984) and the online database are listed when possible.

The values printed in bold face - two values for the top of the Paradox salt member in Table A-1 and one value for the salt thickness in Table A-2 - indicate data that appear to be grossly incorrect. These data are discussed in section 3.3.1. All of the grossly incorrect values came from Katz and Carroll (1984).

Well Name	Source	Top of Formation					
		Cutler		Paradox Salt Member		Leadville	
		Elev. (ft)	Difference from COGIS Database	Elev. (ft)	Difference from COGIS Database	Elev. (ft)	Difference from COGIS Database
Otho Ayers #1 (Chicago Corp.)	CO Oil &Gas Commission (COGIS)	4350		hole too shallow			
	Bremkamp et al. (1984)	3916	-434				
	Katz and Carroll (1984)	4350	0				
Scorup Somerville Wilcox #1 (Conoco #1)	CO Oil &Gas Commission (COGIS)	not present				-9682	
	Bremkamp et al. (1984)			4414		-9946	-264
	Katz and Carroll (1984)			**1628**	not consistent with geologic map	-9698	-16
Wray Mesa Unit #1 (Shell #1)	CO Oil &Gas Commission (COGIS)	4177		-7148	estimated from Hermosa depth	Leadville eroded	
	Bremkamp et al. (1984)	4312	135				
	Katz and Carroll (1984)	4366	189	**-4049**	3099		
Wray Mesa Unit #2 (Shell #2)	CO Oil &Gas Commission (COGIS)	4030		-555			
	Bremkamp et al. (1984)	4273	243	-508	47		
	Katz and Carroll (1984)	4042	12	-515	40		
Coyote Wash Unit #1 (Miami Oil)	CO Oil &Gas Commission (COGIS)	3014		-4073		-5052	
	Bremkamp et al. (1984)	2711	-303			-5054	-2
	Katz and Carroll (1984)						
Wray Mesa Unit #3 (Pure Oil)	CO Oil &Gas Commission (COGIS)	geologic well log not available					
	Bremkamp et al. (1984)	-3674		-4149		-4573	
	Katz and Carroll (1984)					-4571	
Otho Ayers #1-0-30 (Union Oil)	CO Oil &Gas Commission (COGIS)	3924		-8158		-9022	
	Bremkamp et al. (1984)	3934	10	-8146	12	-9010	12
	Katz and Carroll (1984)			-8148	-2	-9012	10
Wild Steer Unit Fed. #32-24 (Grynberg 32-24)	CO Oil &Gas Commission (COGIS)	4209		hole too shallow			
	Bremkamp et al. (1984)	3880	-329				
	Katz and Carroll (1984)	4221	12				
Fed. Wild Steer Unit #32-15 (Grynberg 32-15)	CO Oil &Gas Commission (COGIS)	4775					
	Bremkamp et al. (1984)	4789	14				
	Katz and Carroll (1984)	4780	5				

Table A-1: Elevations for the top of the Cutler formation, Paradox formation salt member, and Leadville formation in wells drilled in and near Paradox Valley, Colorado.

Well Name	Source	Top-of-Salt to Top-of-Leadville Thickness		Leadville Thickness	
		Thickness (ft)	Difference from COGIS Database	Thickness (ft)	Difference from COGIS Database
Scorup Somerville Wilcox #1 (Conoco #1)	CO Oil &Gas Commission (COGIS)	not available		> 274	
	Bremkamp et al. (1984)	14362		> 267	-7
	Katz and Carroll (1984)	**11231**		not used	
Wray Mesa Unit #2 (Shell #2)	CO Oil &Gas Commission (COGIS)	3052	top salt to top Elbert	Leadville eroded	
	Bremkamp et al. (1984)	3056	4		
	Katz and Carroll (1984)	3026	-26		
Coyote Wash Unit #1 (Miami Oil)	CO Oil &Gas Commission (COGIS)	979		>174	
	Bremkamp et al. (1984)	not used		>174	0
	Katz and Carroll (1984)	not used		not used	
Wray Mesa Unit #3 (Pure Oil)	CO Oil &Gas Commission (COGIS)	geologic well log not available			
	Bremkamp et al. (1984)	374		290	
	Katz and Carroll (1984)	420		279	
Otho Ayers #1-0-30 (Union Oil)	CO Oil &Gas Commission (COGIS)	864		342	
	Bremkamp et al. (1984)	~800	-64	340	-2
	Katz and Carroll (1984)	864	0	342	0

Table A-2: Thicknesses for the top-of-salt to top-of-Leadville interval and Leadville formation, in wells drilled in and near Paradox Valley, Colorado.