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Key Points:

- Paradox Valley is the site of significant seismicity induced by deep injection
- Models of the deep geologic structure are presented
- The geologic models have large uncertainty but are consistent with seismicity

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Geological structure of the Paradox Valley Region, Colorado, and relationship to seismicity induced by deep well injection

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Abstract The Bureau of Reclamation (Reclamation) operates a deep injection well at Paradox Valley in western Colorado. Seismicity has been recorded since 1985, with more than 5900 likely induced earthquakes detected since injection operations began in 1991, making this project a unique and valuable case study in the long-term development of injection-induced seismicity. Likely induced earthquakes occur in a complex pattern with clusters separated by aseismic gaps of 2 km or more, and have been observed up to 16 km from the injection well. To evaluate how the subsurface geologic structure may control the occurrence of induced seismicity, we compare the earthquake locations to a set of geologic models that Reclamation commissioned prior to drilling the injection well. Our analysis indicates that many aspects of the observed seismicity pattern can be attributed to the complex geologic structure. The earthquake depths and locations are generally consistent with the structural trends of the primary injection target formation, within the uncertainty of the models, and some of the mapped basement faults appear to serve as boundaries in the earthquake locations, suggesting that they are barriers to flow. Additionally, the majority of events follow the predicted fluid flow pattern, which trends northwest–southeast and wraps around Paradox Valley. Some features of the seismicity pattern, such as the early onset of seismicity to the northwest of the injection well and the distinct clustering, are not explained by the current geologic models and may be related to unmapped geologic features or local variations in the stress field.

1. Introduction

The Bureau of Reclamation (Reclamation), U.S. Department of the Interior, operates a 4.8 km deep injection well at Paradox Valley in western Colorado, as part of the Paradox Valley Unit (PVU) of the Colorado River Basin Salinity Control Program (CRBSCP). The Paradox Valley Unit is in western Montrose County approximately 89 km southwest of Grand Junction, Colorado, and 16 km east of the Colorado-Utah border (Figure 1). 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).

Paradox Valley is a major contributor to the salt load of the Colorado River. Prior to the initiation of injection, the Dolores River, a tributary of the Colorado River, picked up roughly 185,000 metric tons of salt annually from natural brine inflows as it flowed 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 both 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 that discharge highly saline water (0.26 kg/L of dissolved solids, which is more than seven times the 0.035 kg/L salinity of ocean water) into the Dolores River.

PVU is designed to improve water quality in the Dolores River by preventing highly saline groundwater flows from entering the river. To accomplish this, brine is extracted from nine shallow wells located within Paradox Valley along the river. The extracted brine is collected and filtered at a surface treatment facility, piped southwest about 6 km, and then injected at high pressure into a deep disposal well known as PVU Injection Well #1 and located along the Dolores River, approximately 1.5 km southwest of the margin of Paradox Valley (Figure 1). The injection well is designed to dispose of brine deep underground within a target zone extending over the lowest 500 m of the borehole.

Reclamation has injected brine nearly continuously at PVU since 1996. A series of injection tests conducted between 1991 and 1995 preceded continuous injection. The injection rate has varied during different phases of the project, but from 2008 to 2012, the average injection rate was 719 L/min

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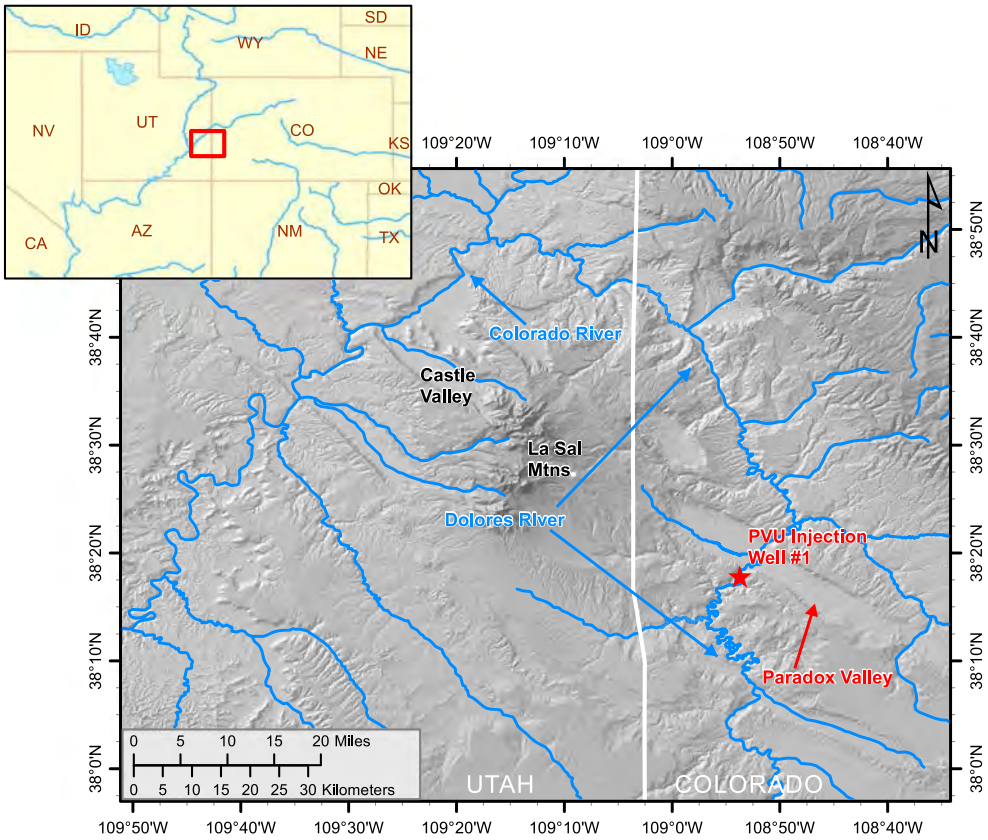

Figure 1. Location of Reclamation's PVU Injection Well #1 in western Colorado.

(190 gallons per minute), with wellhead pressures up to 35 MPa, equivalent to 5076 pounds per square inch (psi), and estimated downhole pressures exceeding 83 MPa (12,038 psi) (Figures 2a and 2b). To date, approximately 7.7 million m^3 of fluid has been injected, corresponding to approximately 1.8 million metric tons of salt (A. Nicholas, personal communication, 2014).

Seismic monitoring has been an integral part of PVU throughout its history. In conjunction with the PVU deep injection well, Reclamation operates the local Paradox Valley Seismic Network (PVSN). PVSN was installed prior to the initiation of injection to record the local background seismicity and subsequently monitor any earthquakes that might be induced by injection operations. Installation of what was originally a 10-station short-period network began in 1983. The network was continuously operational by 1985. Reclamation has expanded and updated PVSN over the years, and the network currently consists of 20 continuously telemetered, three-component broadband digital seismometers.

The pattern of PVU-induced seismicity is complex. Since injection began in 1991, PVSN has recorded more than 5900 shallow earthquakes believed to be related to PVU injection. These earthquakes have been observed at increasing distance from PVU Injection Well #1 over time (Figure 2c). Likely induced earthquakes have been detected as far as 16 km from the injection well. The vast majority of the earthquakes occur in distinct clusters, with aseismic gaps of 2 km or more between the clusters. The earthquakes do not extend to equal radial distances at all azimuths, but rather the spatial distribution of the seismicity around the injection well is strongly asymmetric.

In this paper, we review the existing geologic and geophysical studies that provide constraints on the deep geologic structure in the vicinity of the PVU injection well. We then compare the observed spatial distribution of induced seismicity to the geologic models and evaluate how the geologic structure influences the pattern of PVU-induced seismicity. While several factors may influence the spatial distribution of seismicity induced by deep well injection, the complex geologic structure of the Paradox Valley area likely has a major influence on the seismicity patterns observed at PVU.

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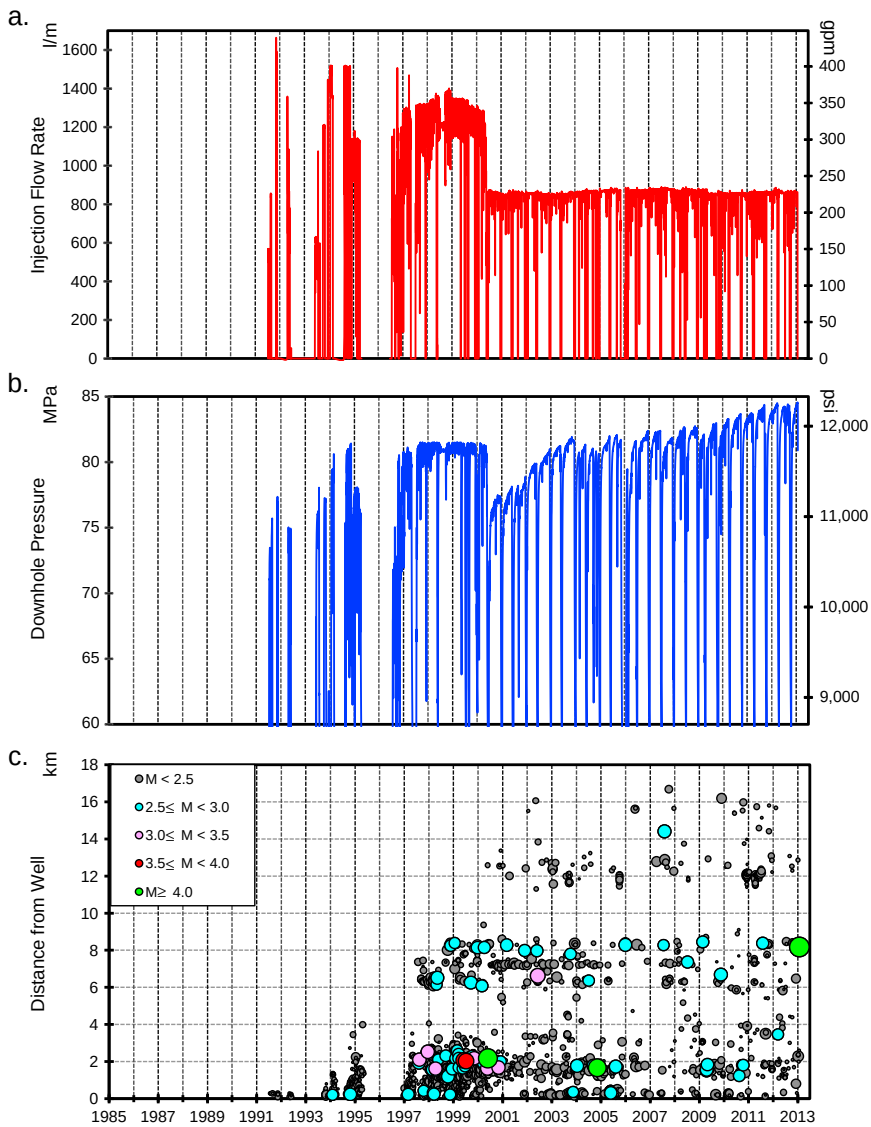

Figure 2. (a) Injection flow rate in liters per minute (left axis) and gallons per minute (right axis), (b) estimated downhole pressure in megapascals (left axis) and pounds per square inch (right axis), and (c) shallow earthquakes plotted as a function of distance from the PVU Injection Well #1 in kilometers since the start of seismic monitoring. Downhole pressure is estimated from measured wellhead pressure, and has been truncated on the lower end to better show details of the increase in recent years. The size of each circle on Figure 2c is scaled by the magnitude of the event.

2. Geology

Early in the PVU project, Reclamation contracted geologic and geophysical studies 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 occurred in the 1980s and are documented in a series of internal reports. Very little geologic or geophysical investigation has been performed by Reclamation since that time, and therefore, the results from these early studies still comprise the most comprehensive geologic interpretation currently available to Reclamation. In this paper, we integrate the data from these reports with published geologic information.

2.1. Regional Geology

2.1.1. Geologic Setting

Paradox Valley lies 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.

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Rapid subsidence of Paradox Basin during the Mississippian, Pennsylvanian, and Permian Periods accommodated marine intrusion and resulted in the interfingering of marine deposits, including evaporites, with terrestrial material shed from the nearby uplifted Uncompahgre Highlands 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 formation. The Paradox formation contains a thick salt section that 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; *Gutiérrez*, 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.

2.1.2. Buried Faults

Parallel, northwest trending, steeply dipping normal faults occur 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, when Paradox Basin began rapidly subsiding. Significant activity continued on these faults into the Permian Period, and possibly into the Triassic Period. These faults may have been reactivated as late as the Tertiary [*Grout and Verbeek*, 1998; *Doelling*, 1988]. The faults with the largest vertical displacements generally have their downthrown sides to the northeast, resulting in a deepening of Paradox Basin toward the northeast [*Doelling*, 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 here as the Wray Mesa fault system.

Northeast trending fault zones are also present in the basement and buried Paleozoic rocks of northern Paradox Basin. According to *Baars 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 (as described above), the northeast trending faults appear to have accommodated 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 (Figure 1), may be located at the intersection of the anticline with one of these northeast trending fault zones [*Friedman et al.*, 1994].

2.2. Stratigraphy and Characteristics of Injection Target Formations

Paradox Valley and the surrounding mesas contain rocks spanning Precambrian to mid-Cretaceous time. 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 nearshore 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). The overlying stratigraphy, including the Triassic-age Wingate sandstone to the Cretaceous-age Mancos shale, is taken from a geologic map of the Moab Quadrangle produced by the United States Geological Survey [*Williams*, 1964]. Descriptions of the rock units are taken from several sources (see Table 1 footnote).

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) consists of stromatolitic dolomite, lime mudstones, and pelletal lime mudstone deposited in intertidal to subtidal environments. The upper Leadville formation (Osagean-age) is separated by an unconformity and

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Table 1. Paradox Valley Stratigraphy

Stratigraphic Unit	Depth[a]	Description[b]
	Cretaceous[c] (145–65 Ma)	
Mancos Shale	Above elevation of wellhead	Dark gray to black, soft, fissile marine shale with thin sandstone beds at various horizons
Dakota Sandstone		Friable to quartzitic fluvial sandstone and conglomeratic sandstone with interbedded carbonaceous nonmarine shale
Burro Canyon Fm.		Fluvial sandstone and conglomerate interbedded with lacustrine siltstone, shale, and mudstone, and thin beds of impure limestone
	Jurassic (205–145 Ma)	
Morrison Fm.	Above elevation of wellhead	Fluvial and lacustrine shale, mudstone, and sandstone; local thin limestone beds
Summerville Fm.		Sandy shale and mudstone of terrestrial origin
Entrada Sandstone		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		Fine-grained, cross-bedded eolian sandstone
	Triassic (255–205 Ma)	
Kayenta Fm.	Above elevation of wellhead	Irregularly interbedded fluvial shale, siltstone, and fine- to coarse-grained sandstone
Wingate Sandstone		Fine-grained, massive, thick-bedded, and prominently cross-bedded eolian sandstone
Chinle Fm.	0 (at surface)	Siltstone interbedded with lenses of sandstone and shale, limestone-pebble, and shale-pellet conglomerate, with lenses of grit and quartz-pebble conglomerate near base; terrestrial depositional environment
Moenkopi Fm.	390	Sandy shale/silty sandstone with some conglomerate present; marine and terrestrial depositional environment
	Permian (298–255 Ma)	
Cutler Fm.	1,140	Fluvial arkose and arkosic conglomerate, with some sandy shales; deposited in alluvial fans
	Pennsylvanian (322–298 Ma)	
Hermosa Group–Honaker Trail Fm.: Upper Honaker Trail	8,313	Limestone/sandstone/siltstone; deposited in marine conditions
La Sal	12,006	Limestone/dolomite; some silty limestone, oolitic limestone, and algal limestone present
Lower Honaker Trail	12,082	Limestone/sandstone/siltstone; deposited in marine conditions
Hermosa Group–Paradox Fm.:	12,350	Resulted from intermittently closed marine environment
Ismay	12,839	Limestone, stacked algal carbonate mounds and other shallow-water carbonates and dolomites
1st Main Salt	13,104	Dolomite/salt; intermittently closed marine environment
2nd Main Salt	13,497	Salt/anhydrite/shale; intermittently closed marine environment
Base Salt–Lower Paradox	13,566	Shale/anhydrite/(minor) limestone; intermittently closed marine depositional environment
Hermosa Group–Pinkerton Trail Fm.	13,693	Shales/anhydrites/siltstone/(minor) limestones; dark colored shales, limestone formed by marine invasion
Molas Fm.	13,944	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 (355–322 Ma)	
Leadville Fm.	13,984	Limestone/dolomite; lower unit (Kinderhookian-age) stromatolitic dolomite, lime mudstones, pelletal lime mudstones; deposited in intertidal to subtidal environments; upper unit (Osagean-age) fossiliferous pelletal and oolitic limestone, and lime and dolomitic mudstone
	Devonian (416–355 Ma)	
Ouray Fm.	14,400	Limestone-lime mudstone, pelletal lime mudstone and skeletal limestone that is locally dolomitized; formed in quiet-water marine environment

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Table 1. (continued)

Stratigraphic Unit	Depth[a]	Description[b]
Elbert Fm.	14,440	Sandstone/shales/shaly dolomites
McCracken Fm.	14,607	Sandstone with occasional interbeds of sandy dolomite; transgressive depositional environment
Aneth Fm.	14,681	Dolomite/shale; dense, argillaceous sequence
		Cambrian (540–488 Ma)
Lynch Fm.:		
Upper Lynch Shale	14,763	Sandstone/interbedded shale, dolomite, limestone
Lynch Limestone	14,835	Limestone
Lower Lynch Shale	14,928	Shale
Muav Fm.	14,988	Limestone
Bright Angel Fm.	15,103	Shale
Ignacio Fm.	15,246	Sandstone, sometimes referred to as quartzite; transgressive depositional environment
		Precambrian (>540 Ma)
Precambrian	15,446	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

[a]Depths are taken from the geologic drill log of PVU Injection Well #1 by *Harr* [1988]. Depths are relative to the ground surface elevation (4996 ft) and have been corrected for borehole deviation.
[b]Descriptions are taken from *Bremkamp and Harr* [1988], *Campbell* [1981], *Doelling* [1988], *Williams* [1964], and *Nuccio and Condon* [1996].
[c]Ages from *Walker and Geissman* [2009].

contains fossiliferous pelletal and oolitic limestone, and lime and dolomitic mudstone [*Campbell*, 1981]. The upper Leadville underwent uplift and erosion after deposition, resulting in karst-type weathering and the formation of a *terra rosa*-type regolith on the surface. Hence, 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 [*Bremkamp and Harr*, 1988].

Porosities derived from analysis of the sonic log acquired in PVU Injection Well #1 indicate 86 ft of 5% or greater porosity [*Bremkamp and Harr*, 1988]. This is similar to the porosity found in the Conoco Scorup Somerville Wilcox #1 (hereinafter referred to as Conoco Scorup #1) well, located 4.6 km north-northeast of PVU Injection Well #1 (Figure 3), but significantly higher than the values in any other wells in the region, which range from 0 ft (where the Leadville is eroded) to 31 ft (9 m) of 5% or greater porosity. In addition, the hydrologic permeability within the Leadville formation at PVU Injection Well #1 is greatly increased by the presence of an extensive fracture field related to the Wray Mesa fault system, as evidenced by 27% of the 182 ft (56 m) of recovered Leadville core containing open fractures and by the presence of hairline fractures throughout the core [*Bremkamp and Harr*, 1988]. The Leadville formation shows very little fracturing in the nearby Union Otho Ayers #1-0-30 Well [*Bremkamp and Harr*, 1988], consistent with the lower porosity measured in that well. Core data from other nearby wells are not available, but given the low primary porosity of the Leadville, we expect the degree of fracturing to be strongly correlated with the porosities derived from logging.

Other formations that were considered viable injection zones in PVU Injection Well #1 include the Precambrian schist, the Devonian Ouray, Elbert, and McCracken formations, and the Cambrian Ignacio formation. The upper 191 ft (58 m) of Precambrian schist in PVU Injection Well #1 was estimated to contain 30 ft (9 m) of 5% or greater porosity. The Devonian and Cambrian formations showed some favorable porosity and fracture characteristics but were considered to have low storage volume potential. PVU Injection Well #1 contains perforated intervals in the Leadville formation, the Precambrian schist, and some intervening Devonian and Cambrian formations, although early flow profiles indicated that the Leadville formation accepts the majority of fluid [*Envircorp*, 1995].

2.3. PVU Geologic Investigations

Prior to the selection of the site for the current PVU injection well, Reclamation contracted two groups of consultants to perform geophysical interpretations of deep seismic reflection and well log data [*Bremkamp et al.*, 1984;

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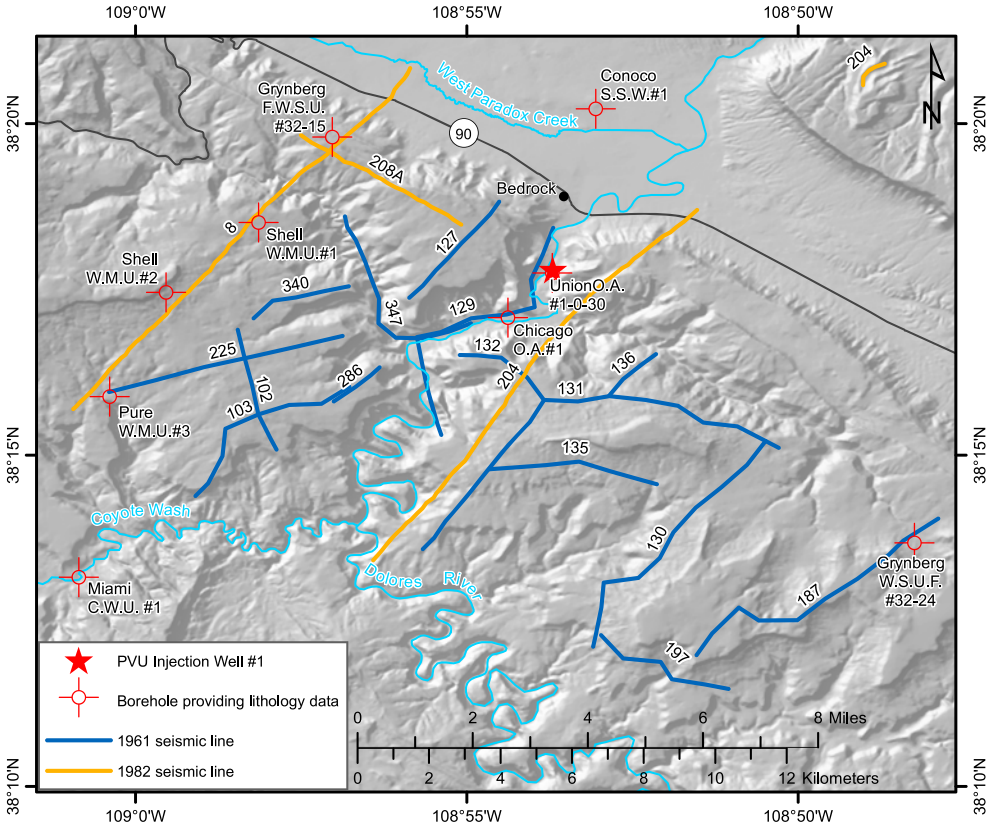

Figure 3. Locations of seismic reflection lines and deep wells used in early PVU geophysical studies.

Katz and Carroll, 1984]. The study area focused on the area 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 102, 103, 127, 130, 131, 132, 135, 136, 137, 139, 197, 225, 286, 340, and 347; Figure 3). These data were reprocessed for Reclamation by Western Geophysical in 1984. Additionally, Reclamation acquired three 12-fold seismic lines recorded in 1982 by Seisport Exploration (Lines 8, 204, and 208A; Figure 3). 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. The studies also used logs from nine wells as control points for formation depth and velocity (Figure 3). Only six of the wells, however, penetrated the Paradox salt member and Leadville formation (Table 2).

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. We digitized contours, fault

Table 2. Wells Providing Data for Original PVU Geophysical Interpretations

Operator	Year Drilled	Official Well Name[a]	Total Depth (ft)	Deepest Formation Reached
Chicago Corp.	1950	Otho Ayers #1	6,860	Penn. Upper Hermosa
Continental Oil Co. (Conoco)	1958	Scorup Somerville Wilcox #1	~15,000	Miss. Leadville (did not penetrate entire formation)
Shell Oil Co.	1961	Wray Mesa Unit #1	11,268	Precambrian
Shell Oil Co.	1961	Wray Mesa Unit #2	11,593	Cambrian
Miami Oil Co.	1962	Coyote Wash Unit #1	10,650	Miss. Leadville (did not penetrate entire formation)
Pure Oil Co.	1963	Wray Mesa Unit #3	11,301	Devonian?
Union Oil Co.	1971	Otho Ayers #1-0-30	14,400	Devonian Ouray
Grynberg Petroleum Co.	1975	Wild Steer Unit Federal #32-24	9,533	Penn. Upper Hermosa
Grynberg Petroleum Co.	1975	Federal Wild Steer Unit #32-15	7,814	Penn. Upper Hermosa

[a]Official name is the name listed in the COGIS.

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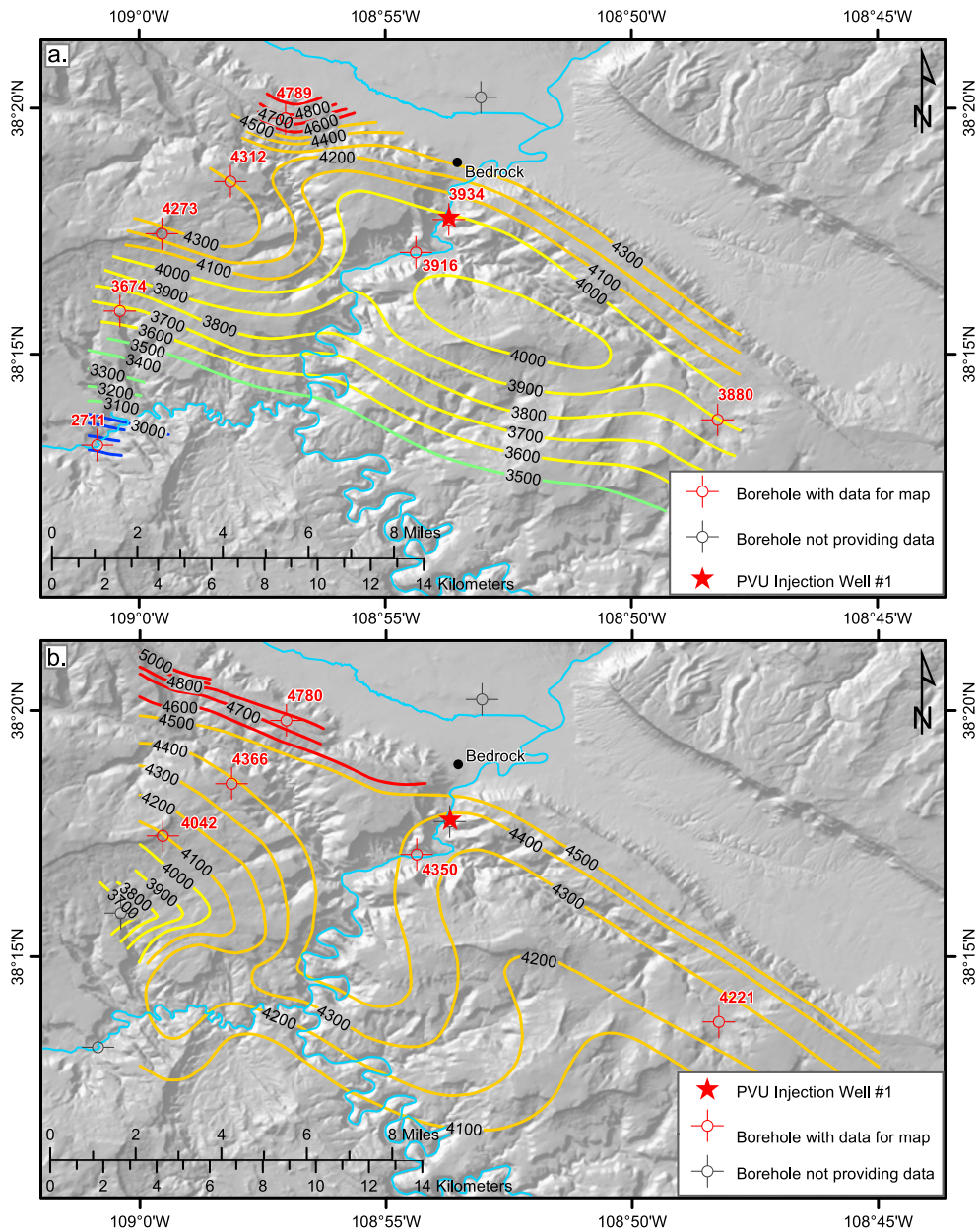

Figure 4. Structural contour maps of the top of the Cutler formation. Contour values are elevations in feet relative to sea level. Contour interval is 100 ft. Two interpretations are shown, from (a) *Bremkamp et al.* [1984] and (b) *Katz and Carroll* [1984]. Red labels indicate the elevation of the Cutler formation in the corresponding borehole.

traces, and well locations from the maps of Katz and Carroll and Bremkamp et al. and superimposed these on the local topography and other geographical features (Figures 4–8). The elevations or thicknesses of the layer in each borehole are also taken from the source maps and are labeled in red.

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 Information System (COGIS), an online database maintained by the Colorado Oil and Gas Conservation Commission that contains substantial information related to Colorado oil and gas wells (http://cogcc.state.co.us/cogis). Depths to the geologic formations of interest were found in the database for all wells except

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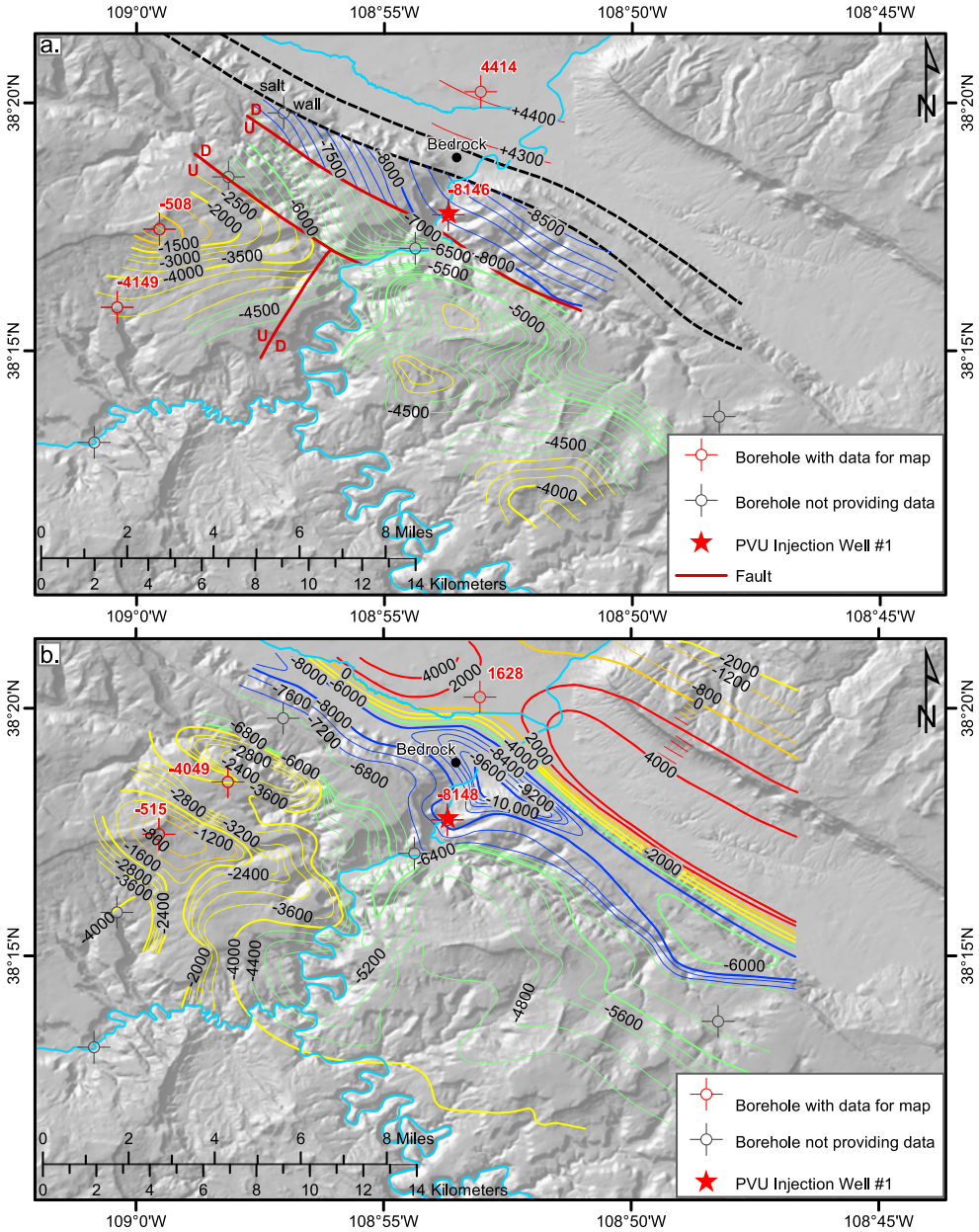

Figure 5. Structural contour maps of the top of the Paradox formation massive salt member. Contour values are elevations in feet relative to mean sea level. Contour interval is variable. U and D labels indicate the upthrown and downthrown sides of the faults, respectively. Two interpretations are shown, from (a) *Bremkamp et al.* [1984] and (b) *Katz and Carroll* [1984]. Red labels indicate the elevation of the Paradox massive salt member in the corresponding borehole.

for the Pure Oil Wray Mesa Unit #3 well, although in some cases only partial information was available. Table 3 shows a comparison of elevations of the geologic units of interest in the wells, as reported by Katz and Carroll, Bremkamp et al., and the COGIS. The major findings are summarized in the discussions of the contour maps below.

2.3.1. Local Structural Models

A seismic reflector for the Cutler formation was not discernible, and therefore, the structure of the Cutler formation was interpreted only from the limited well data and surface structure. Both groups interpreted the Cutler formation as generally dipping toward the southwest, although inferred details of the structure are different (Figure 4). The well data used by Katz and Carroll match that listed in the COGIS better than the data used by Bremkamp et al. The differences between the Katz and Carroll

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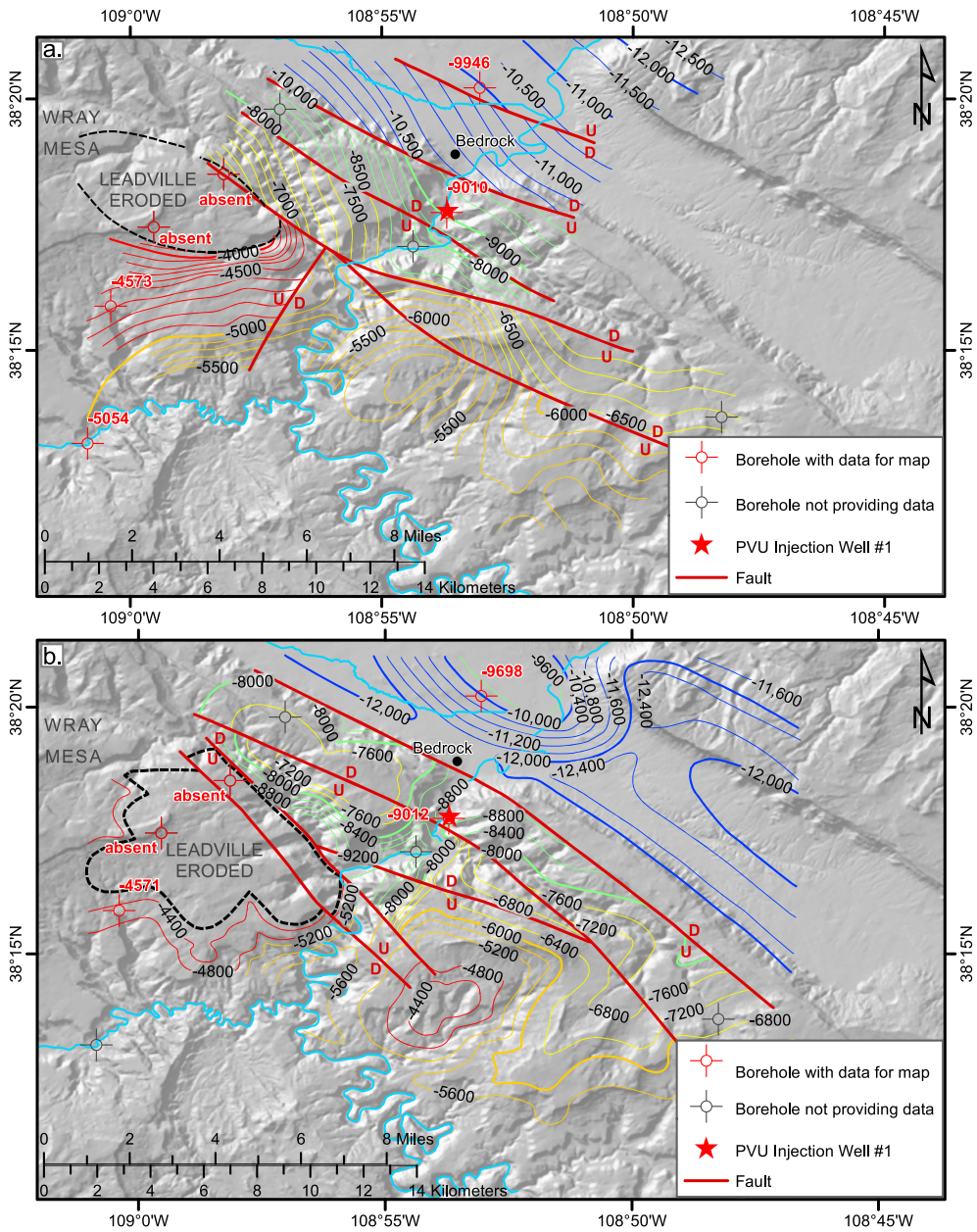

Figure 6. Structural contour maps of the top of the Leadville formation. Contour values are elevations in feet relative to mean sea level. Contour interval is variable. U and D labels indicate the upthrown and downthrown sides of the faults, respectively. Two interpretations are shown, from (a) *Bremkamp et al.* [1984] and (b) *Katz and Carroll* [1984]. Red labels indicate the elevation of the Leadville formation in the corresponding borehole.

Cutler formation well elevation data and the COGIS range from 0 to 189 ft (58 m); the median absolute difference for the five wells compared is 12 ft (4 m). The differences between the Bremkamp et al. well data and the COGIS range from 10 to 434 ft (3 to 132 m); the median absolute difference for the seven wells compared is 243 ft (74 m). Neither interpretation, however, takes into account the 426 ft (130 m) 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 in the COGIS, as Bremkamp et al. used a value for the Chicago Corp. Otho Ayers #1 well that differed significantly from the COGIS-reported value, and Katz and Carroll did not use the Union Otho Ayers #1-0-30 well in their interpretation of the Cutler formation. These two wells are located approximately 1.6 km apart along the Dolores River, slightly southwest of PVU Injection Well #1.

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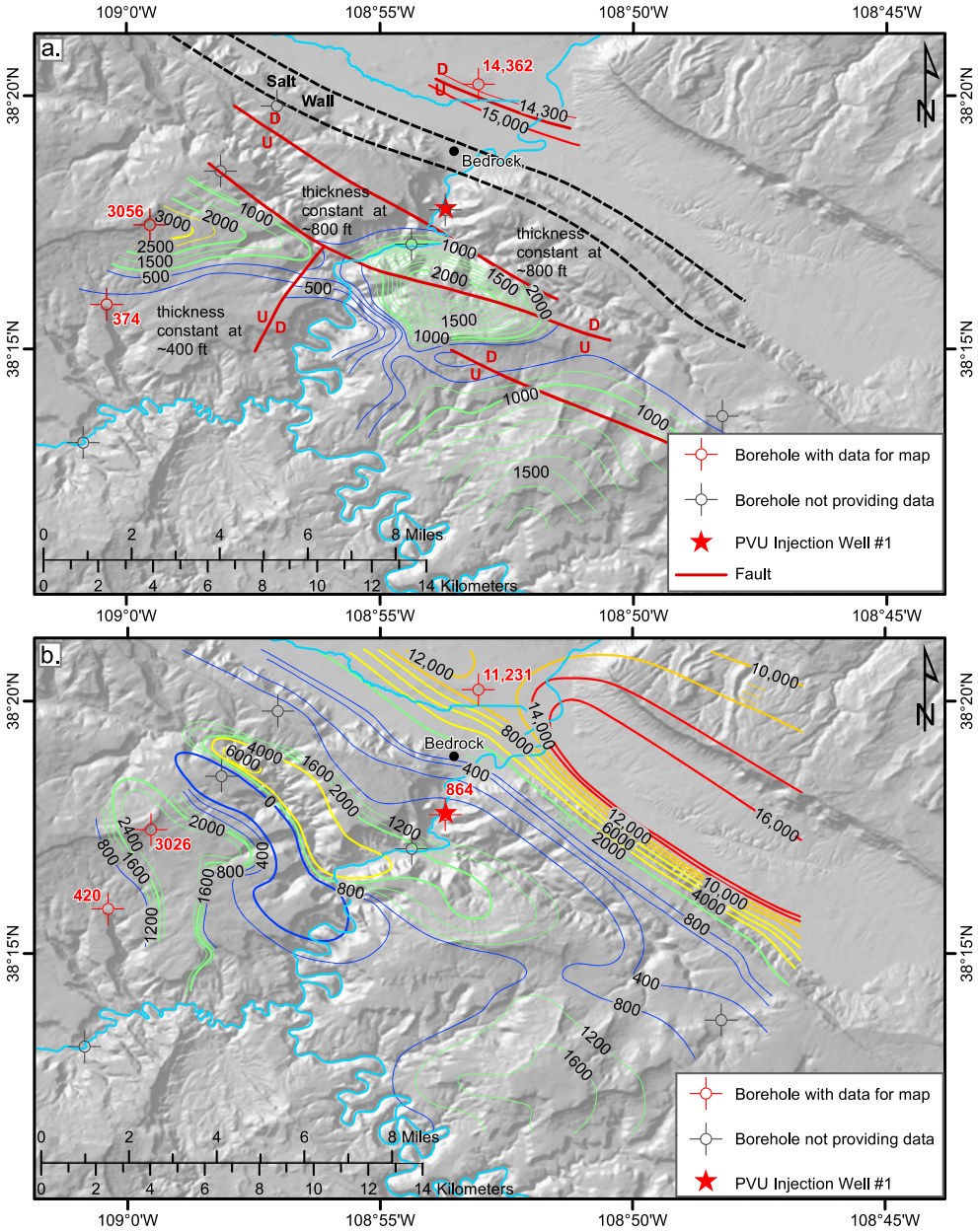

Figure 7. Isopach maps of the Paradox formation massive salt member. The mapped interval also includes the underlying Pinkerton Trail and Molas formations, which are approximately 420 ft thick at the PVU Injection Well #1. Contour values are thicknesses in feet. U and D labels indicate the upthrown and downthrown sides of the faults, respectively. Two interpretations are shown, from (a) *Bremkamp et al.* [1984] and (b) *Katz and Carroll* [1984]. Red labels indicate the thickness of the Paradox massive salt member in the corresponding borehole.

We found significant problems in the top-of-salt contour map produced by Katz and Carroll (Figure 5b). They report an elevation of 1628 ft (496 m) 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 (1345 m). These elevations correspond to depths of 3416 ft (1041 m) and 630 ft (192 m) below local ground surface, respectively. The elevation of the top of the salt in this well is not reported in the COGIS. 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]. (The Paradox layer has subsequently been redefined as a formation, following the definition of *Wengerd and Strickland* [1954].) In PVU Injection Well #1, there is about 750 ft (229 m) from the top of the Paradox formation to the top of the main salt member. Hence, the depth of

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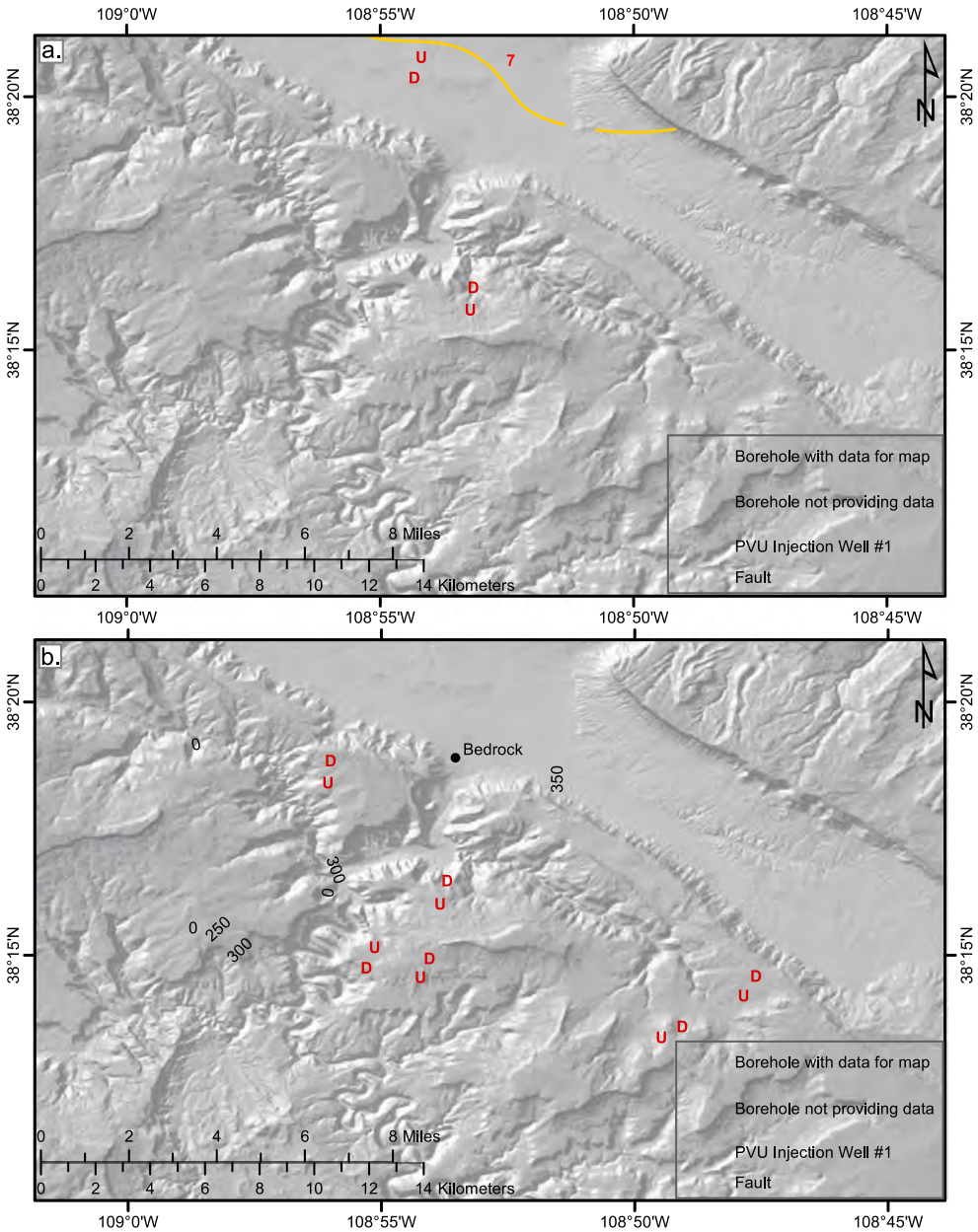

Figure 8. Isopach maps of the Leadville formation. Contour values are thicknesses in feet. U and D labels indicate the upthrown and downthrown sides of the faults, respectively. Two interpretations are shown, from (a) *Bremkamp et al.* [1984] and (b) *Katz and Carroll* [1984]. Red labels indicate the thickness of the Leadville formation in the corresponding borehole.

the Paradox salt member at the location of the Conoco Scorup #1 well very likely should be only a few hundred feet, as indicated by Bremkamp et al., not the ~3400 ft used by Katz and Carroll. Another elevation value that Katz and Carroll used in their interpretation of the top of the salt is questionable. They used an elevation of −4049 ft (−1234 m) 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 COGIS. However, the isopach map created by Katz and Carroll shows the salt to be eroded at this location (Figure 7b). Bremkamp et al.'s isopach map shows the salt to be less than 1000 ft (305 m) thick in this location, though the exact thickness cannot be determined from their contour map. In any case, the inconsistencies and probable errors in the Katz and Carroll well data used in their geophysical interpretation lead 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, Bremkamp et al. mapped two other distinct salt

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Table 3. Elevations for the Top of the Cutler Formation, Paradox Formation Salt Member, and Leadville Formation in Wells Drilled In and Near Paradox Valley, Colorado

		Top of Formation (Elevation in ft)[b]					
		Cutler		Paradox Salt Member		Leadville	
Well Name	Source[a]	Elev. (ft.)	Diff. from COGIS	Elev. (ft.)	Diff. from COGIS	Elev. (ft.)	Diff. from COGIS
Chicago Otho Ayers #1	COGIS	4350	N/A	Hole too shallow			
	Bremk.	3916	−434				
	Katz	4350	0				
Conoco Scorup Somerville Wilcox #1	COGIS	Not present				−9682	N/A
	Bremk.			4414		−9946	10
	Katz			1628[c]		−9698	258
Shell Wray Mesa Unit #1	COGIS	4177	N/A	No reliable data available[d]		Leadville eroded	
	Bremk.	4312	135				
	Katz	4366	189				
Shell Wray Mesa Unit #2	COGIS	4030	N/A	−555	N/A		
	Bremk.	4273	243	−508	47		
	Katz	4042	12	−515	40		
Miami Oil Coyote Wash Unit #1	COGIS	3014	N/A	−4073		−5052	N/A
	Bremk.	2711	−303			−5054	−2
	Katz						
Pure Oil Wray Mesa Unit #3	COGIS			Geologic well log not available			
	Bremk.	3674		−4149		−4573	
	Katz					−4571	
Union Otho Ayers #1-0-30	COGIS	3924	N/A	−8158	N/A	−9022	N/A
	Bremk.	3934	10	−8146	12	−9010	12
	Katz			−8148	10	−9012	10
Grynberg Wild Steer Unit Fed. #32-24	COGIS	4209	N/A	Hole too shallow			
	Bremk.	3880	−329				
	Katz	4221	12				
Grynberg Fed. Wild Steer Unit #32-15	COGIS	4775	N/A				
	Bremk.	4789	14				
	Katz	4780	5				

[a]COGIS = Colorado Oil and Gas Information System, maintained by the Colorado Oil and Gas Conservation Commission. Bremk. = *Bremkamp et al.* [1984]. Katz = *Katz and Carroll* [1984].
[b]In most cases, the COGIS database lists only a depth to each formation in the well. Elevations are calculated assuming a vertical well.
[c]Not consistent with geologic map.
[d]Katz and Carroll list an elevation of −4049 ft for the top of the Paradox salt member; however, this depth is questionable as it is inconsistent with their own isopach map.

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 5a).

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 COGIS (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 of −9698 ft (−2956 m) used by Katz and Carroll differs from the value reported in the COGIS of −9682 ft (−2957 m) by only 16 ft (5 m), whereas the value of −9946 ft (−3032 m) used by Bremkamp et al. differs by 264 ft (80 m). This discrepancy does not cause a significant flaw in Bremkamp et al.'s structural interpretation of the top of the Leadville formation. It does, however, indicate that the throw across the fault interpreted by Bremkamp et al. to lie just southwest of the Conoco Scorup #1 well may be greater than indicated on their map, and correspondingly, the dip of the Leadville formation in the fault block containing the Conoco Scorup #1 well may be somewhat steeper than indicated (Figure 6a).

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 is 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 second structural high about 9 km southeast of the eroded area. However, Bremkamp et al.'s interpretation indicates an elevation of approximately −5100 ft (−1554 m) for this

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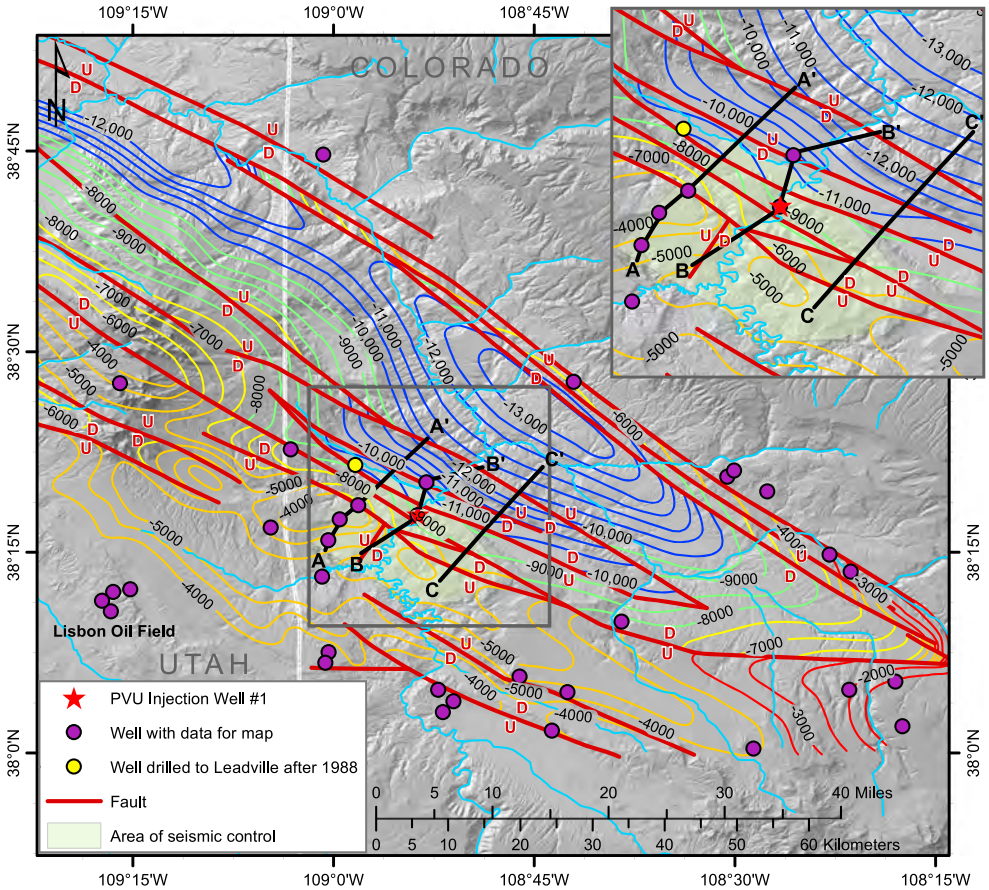

Figure 9. Regional structural contour map of the top of the Leadville formation. Contour values are elevations in feet relative to mean sea level. Contour interval is 500 ft. Black lines indicate the locations of the cross sections shown in Figure 10. U and D labels indicate the upthrown and downthrown sides of the faults, respectively. Contours and fault traces were digitized from *Bremkamp and Harr* [1988]. The maps depicts all wells drilled before 1988 and sufficiently deep to intersect the Leadville at the elevation drawn; it is not known whether Bremkamp and Harr had access to well logs from all of the depicted wells. The location of the inset map, which shows greater detail of the area surrounding Paradox Valley, is marked with a gray box.

structural high (Figure 6a), whereas Katz and Carroll's results indicate an elevation of about −4400 ft (−1341 m) (Figure 6b), a difference of 700 ft (214 m). 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.

The reports also have significant differences in the interpreted dip of the Leadville formation in the immediate vicinity of PVU Injection Well #1. For example, Bremkamp et al. show no significant change in depth of the Leadville formation immediately southeast of the well, along the azimuth of the −9000 ft (−2743 m) 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 (−2438 m). Similar differences can be seen to the northwest of the injection well; Katz and Carroll show the Leadville shallowing by more than 1000 ft (305 m) along the same path where Bremkamp et al. indicate a constant elevation of −9000 ft (−2743 m). To put these differences into perspective, the 1000 ft difference in the interpreted top-of-Leadville elevation is two and a half times the approximate 400 ft thickness of the formation.

Furthermore, while both groups of investigators show northwest trending faults downthrown to the northeast, their interpretations contain nontrivial differences in the locations, strikes, 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

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southwest rather than to the northeast. Bremkamp et al.'s interpretation also indicates a fault in the center of Paradox Valley that is absent from Katz and Carroll's interpretation. Such significant differences between two independent interpretations of the same data suggest that the seismic reflection data were of marginal quality.

The Paradox salt member isopach map from Bremkamp et al. indicates that salt thickness locally ranges from over 14,000 ft (4267 m) in the center of Paradox Valley to less than 500 ft (152 m) (Figure 7a). Variations in salt thickness primarily result from the presence of the main salt diapir underlying Paradox Valley and the two smaller features discussed previously. Because of the suspected 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 in doubt (Figure 7b).

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 (−1280 m), 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 (104 m). However, the two groups of investigators infer very different trends of Leadville thickness in areas without well control (Figure 8). Bremkamp et al. show a thinning of the Leadville formation along an inferred northwest trending post-Leadville horst (Figure 8a), while Katz and Carroll show only local thinning and erosion on Wray Mesa (Figure 8b). 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.

2.3.2. Regional Structural Models

After PVU Injection Well #1 was drilled, Bremkamp and Harr prepared a report titled "Area of least resistance to fluid movement and pressure rise" [1988]. This report contains a regional map of the structure of the top of the Leadville formation (Figure 9), which covers a much greater area than the map from their 1984 report. The Leadville formation structural map was created using the previously obtained seismic data and all well data available at the time. In addition, Bremkamp's knowledge of the area from many years of oil exploration work was reported to have influenced the interpretations. The report also contains three cross sections, which show their interpretation of the geologic structure in more detail than can be expressed in the contour maps (Figure 10).

Bremkamp and Harr also created 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 due to fluid injection into PVU Injection Well #1 (Figure 11). In order to create this map, they assumed a vertical pressure gradient of 0.44 psi/ft (9.95×10^{-3} MPa/m) within the Leadville formation (based on drill stem testing in PVU Injection Well #1 and the nearby Union Otho Ayers #1-0-30 well) and assumed that fluid could not pass faults where the injection target formations are not juxtaposed. 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 9).

Bremkamp and Harr projected fluid to travel from the injection well to the northwest and southeast, bounded within a 4 km wide corridor between northwest trending impermeable faults. Bremkamp and Harr believed that the 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 bounded to the northeast by the hydrostatic pressure contour of 6320 psi (44 MPa) (Figure 11). According to the map, the hydrostatic pressure within the Leadville formation at PVU Injection Well #1 prior to injection was approximately 6100 psi (42 MPa). Given the hydrostatic pressure gradient of 0.44 psi/ft (9.95×10^{-3} MPa/m), the 6320 psi (44 MPa) contour represents a difference of 500 ft (152 m) in the elevation of the Leadville formation.

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

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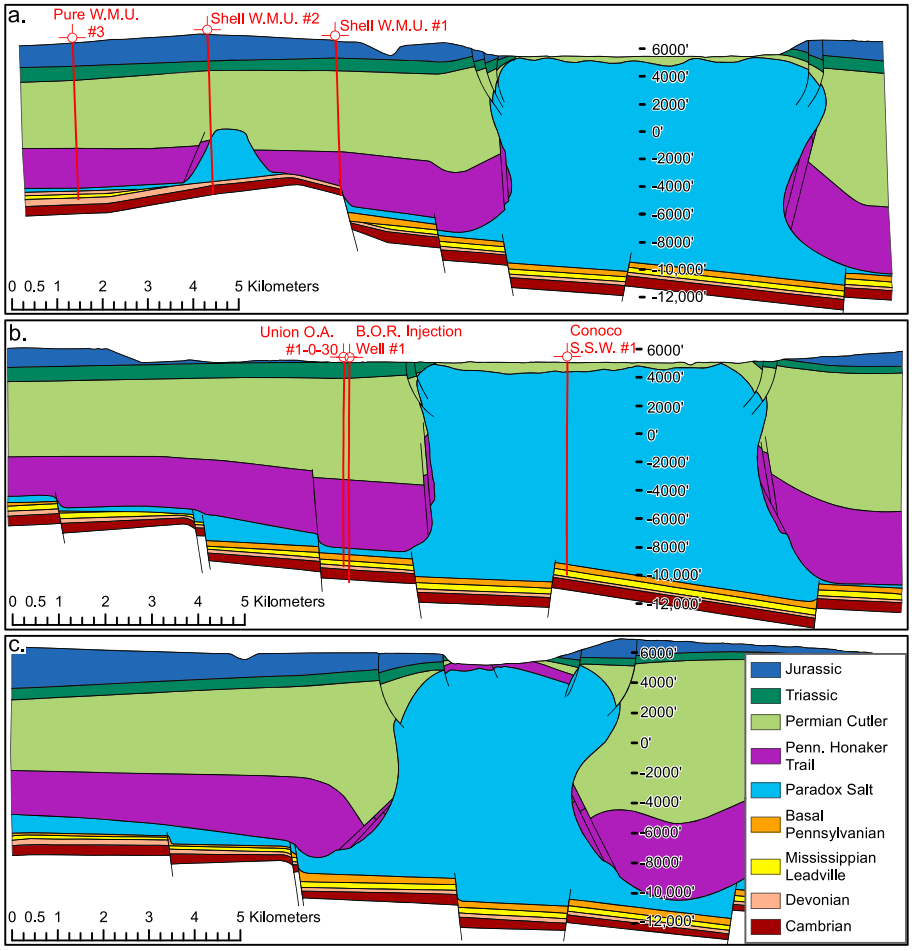

Figure 10. Cross sections (top) A-A′, (middle) B-B′, and (bottom) C-C′, digitized and modified from *Bremkamp and Harr* [1988]. The locations of the cross sections are shown in Figure 9. There is no vertical exaggeration. Elevations in feet relative to mean sea level are shown for comparison to the contour maps in Figures 4–9.

2.3.3. Comparison to Later Well Data

Reclamation has collected little additional geologic or geophysical information since the early PVU studies were performed. A search of the COGIS (http://cogcc.state.co.us/cogis, June 2013) revealed only one well drilled to the depth of the Leadville formation in the vicinity of Paradox Valley since the initial PVU geologic investigations were performed in the 1980s. The well, Cleary Bedrock Unit #6-4-47-19, was completed in 2008 to a total depth of 14,421 ft (4396 m) (Figure 9). We compared the well's reported top-of-Leadville depth to Bremkamp and Harr's interpreted top-of-Leadville contours. As with the other wells, we assumed a vertical well in converting the reported depth to an elevation. The 2008 well encountered the Leadville formation at an elevation of 8501 ft (2591 m) below sea level. This 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 COGIS. However, the depth interval between the top of the Leadville formation and the top of the McCracken formation is reported as 554 ft (169 m). Assuming that the Devonian Ouray and Elbert formations have the same thickness of 207 ft (63 m) here as in PVU Injection Well #1 gives an estimated thickness of the Leadville formation of 347 ft (106 m). This is a little less than the ~400 ft (122 m) thickness estimated by Bremkamp et al., but the trend is consistent with their interpreted thickening of the Leadville formation along the edge of the valley (Figure 8a).

3. Induced Seismicity

The Paradox Valley Seismic Network has recorded more than 5900 shallow earthquakes (less than 8.5 km deep) in the vicinity of Paradox Valley since PVU injection began in 1991. In contrast, a recent, comprehensive review

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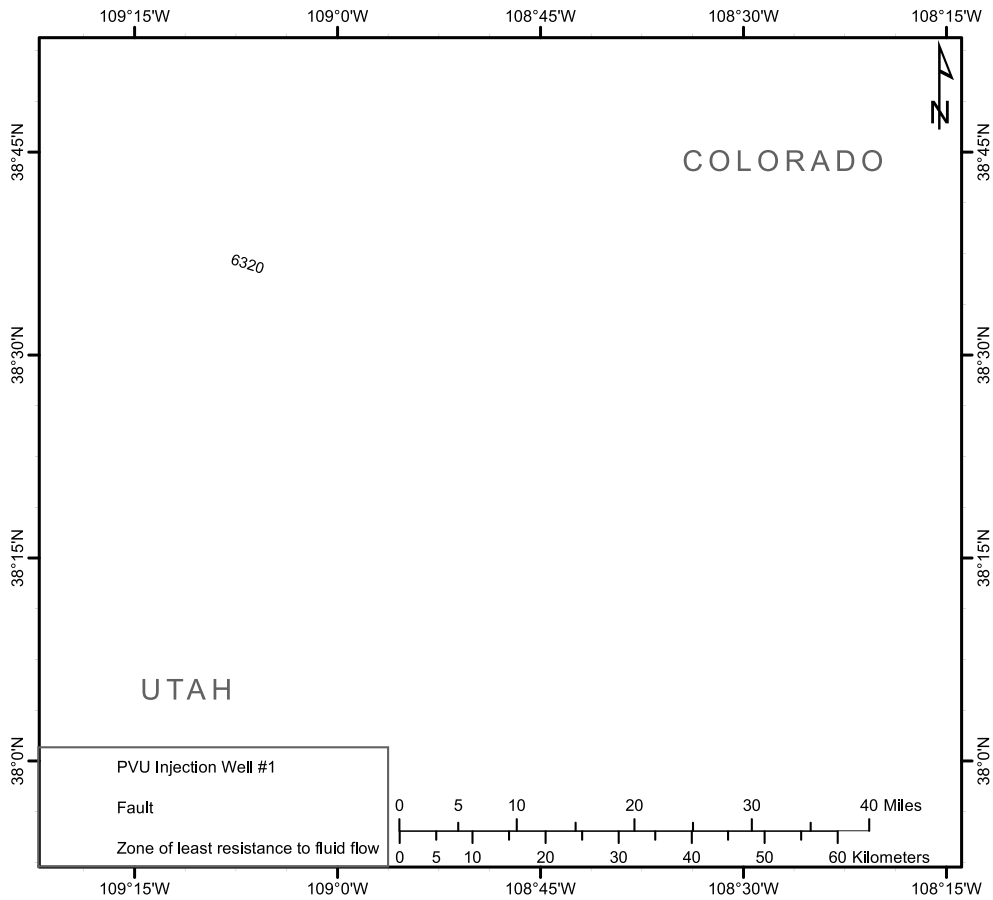

Figure 11. Regional contour map of hydrostatic pressure within the Leadville formation. Contour values are pressures in pounds per square inch (psi). Contour interval is 440 psi, except for the 6320 psi contour. Pressure contours and fault traces were digitized from *Bremkamp and Harr* [1988].

of the historical PVSN data files indicates only one local earthquake recorded during the 6 year pre-injection seismic monitoring period, and this earthquake occurred about 19 km from the well, at an estimated depth of 15 km [*Block et al.*, 2014]. PVSN first detected shallow earthquakes 4 days after the start of the initial injection test in July 1991. These earthquakes occurred very close to the injection well. As injection progressed, earthquakes continued to occur close to the well but also began occurring at increasing distances from the well. By 2002, earthquakes were occurring up to 16 km from the well (Figure 2c). The vast majority of the earthquakes occur at depths between approximately 2.5 and 6.5 km, with many occurring close to the depth of the injection interval (4.3 to 4.8 km). The lack of shallow seismicity during 6 years of pre-injection seismic monitoring, the general correlation of the depths of the earthquakes and the depth of injection, and the temporal-spatial evolution of the seismicity since the start of injection demonstrated in Figure 2c strongly suggest that these earthquakes have been induced by PVU fluid injection.

3.1. Event Location Methods

We calculate two sets of hypocenters for the local earthquakes recorded by PVSN. Initially, we compute absolute earthquake locations using manually determined *P* wave and *S* wave arrival times. These hypocenters are computed using local three-dimensional (3-D) *P* wave and *S* wave velocity models we have developed from hypocenter-velocity-station correction inversions of PVSN-recorded earthquake and explosion data. Both the hypocenter-velocity inversion and earthquake location software we use were developed in-house and represent an extension of the work of *Block* [1991]. Second, we compute precise relative event locations from inversion of arrival time differences obtained from cross correlations of windowed *P* wave and *S* wave arrivals extracted from filtered waveforms recorded at the same station for pairs of events. Because of the abundance of similar waveforms, time differences from manual arrival time picks are not included in the relative location

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procedure, with the exception of data for the five events with magnitude of 3.5 or greater. Because most of the waveforms for these events are clipped but many of the first breaks are clear, they are incorporated into the relative location using differences of high-quality manually determined arrival times. For the relative location inversion, we use a double-difference-type algorithm developed in-house. The 3-D velocity models described above are used and remain fixed during the inversion. No event clustering is performed; an event may tie to any other event in the database. However, because the absolute locations are not well constrained by the time-difference data alone, we keep the locations of eight widely spaced (~3 to 8 km apart) events with well-constrained absolute locations fixed during the relative location procedure. An earthquake must tie, either directly or indirectly (possibly through multiple event pairs), to an event with a fixed location to be retained in the relative location inversion. Approximately 87% percent of all local earthquakes and 93% of induced earthquakes with duration magnitude ≥ 0 occurring within 10 km of the PVU injection well are considered well constrained in the relative location inversion. These events are assigned a location quality factor of "a". For the remaining events, we use the absolute locations and assign a location quality factor of "b".

Both the absolute and relative location uncertainties affect the reliability of the seismicity patterns produced. When considering the relative locations of widely spaced earthquakes, the absolute location uncertainties of the events fixed during the hypocenter relative location are the most important factor. The standard errors of the absolute locations of these fixed events vary from 50 to 100 m horizontally and 70 to 150 m vertically. When considering the spatial distribution of more closely spaced events ($< \sim 3$ km apart), the relative location uncertainties are the dominating factor. Preliminary analysis of the relative relocation errors indicates that these errors are generally less than 50 m horizontally and 100 m vertically.

The b-quality events have significantly higher errors, with average errors of approximately 500 m horizontally and 800 m vertically.

3.2. Spatial Patterns of Induced Seismicity

Several distinct groups, or clusters, of induced seismicity have developed over the history of PVU injection (Figure 12). By the end of the injection tests in 1995, earthquakes were occurring 3 to 4 km from the injection well (Figure 12a). We refer to the area of induced seismicity immediately surrounding the injection well as both the "primary zone" of induced seismicity and the "near-well" region. In mid-1997, nearly 1 year after the start of continuous injection, earthquakes began occurring 6 to 8 km northwest of the injection well (Figure 12b). We identify this cluster of induced seismicity as the "northwest (NW) cluster." In mid-2000, PVSN first detected earthquakes 12 to 14 km from the injection well, along the northern edge of Paradox Valley (Figure 12b). Several distinct clusters of earthquakes have occurred along the northern edges of the valley since 2000 (Figures 12c and 12d). We refer to the earthquakes in these clusters as "northern-valley events." PVSN first detected an earthquake about 6 km southeast of the injection well in 2004 (Figure 12c), but the seismicity rate in this area markedly increased beginning in 2010 (Figure 12d). We refer to this tight group of earthquakes 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 12d).

Five PVU-induced earthquakes of local magnitude (M_L) 3.5 or greater have occurred (Figure 13). Four of these events locate in the near-well region, in a narrow band south and west of the injection well, at radial distances between 1.6 and 2.2 km. These four earthquakes range in magnitude from M_L 3.5 to M_L 4.3 and occurred between mid-1999 and late 2004. The remaining earthquake occurred in the NW cluster, at a distance of 8.2 km from the injection well. This earthquake occurred in January 2013 and had a magnitude of M_L 4.4, making it the largest PVU-induced earthquake to date.

3.3. Relationship of Induced Seismicity to Geologic Models

Because the two structural geologic models presented here have significant differences in their details, we only attempt to compare the gross features of the models to the general patterns of induced seismicity. A more detailed comparison of the induced seismicity to the geology would require that additional information be obtained to refine the structural geologic models. This is especially true in terms of comparing the earthquake depths to the stratigraphy, as it has already been shown that the differences in the interpreted depths to the primary injection target formation, the Leadville, exceed twice the thickness of the formation, even in the close vicinity of the injection well. Also, the earthquake depths have greater uncertainties than

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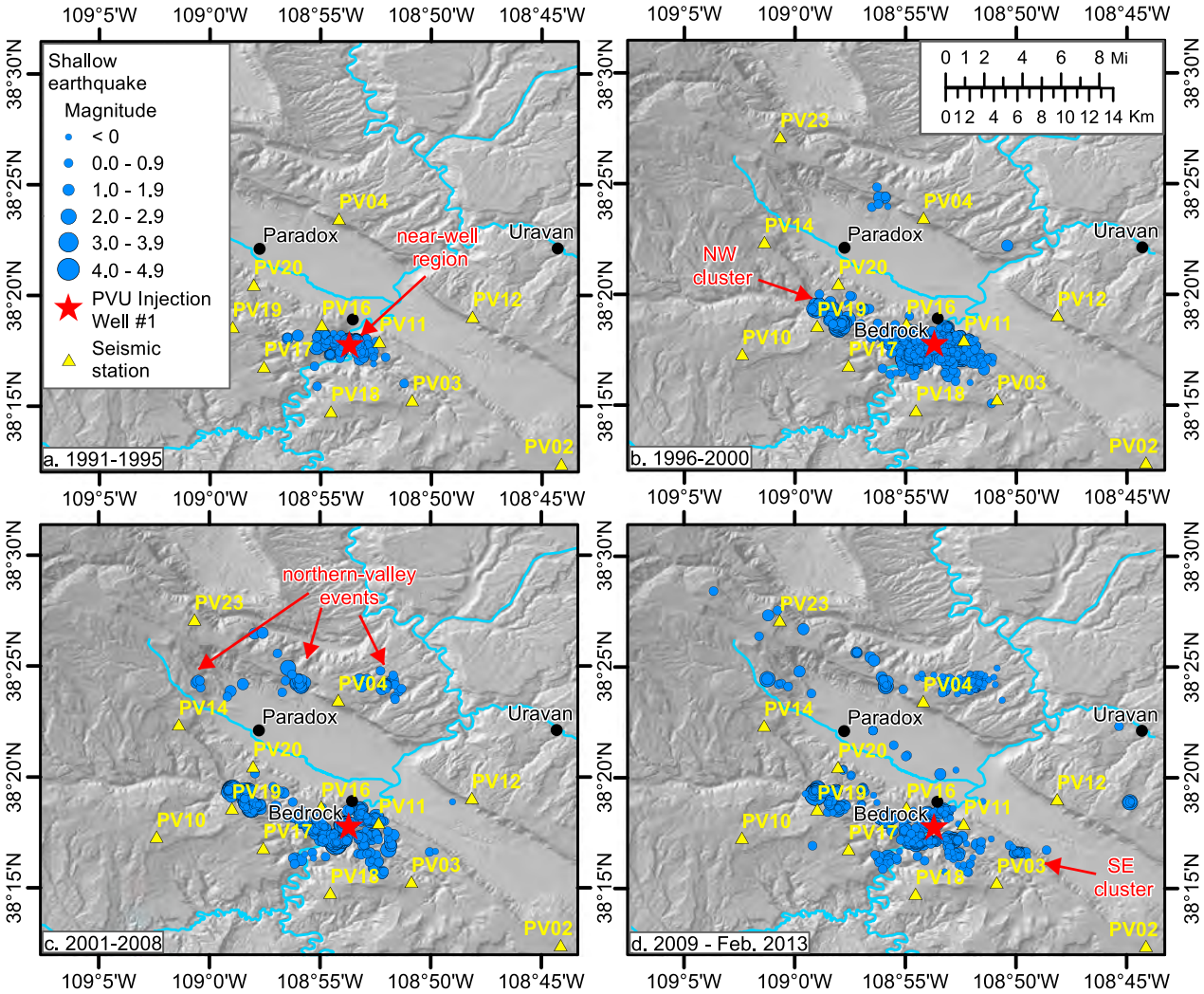

Figure 12. Maps showing the spatial distribution of shallow seismicity recorded in the Paradox Valley area over time: (a) injection tests, 1991–1995; (b) continuous injection, 1996–2000; (c) continuous injection, 2001–2008; and (d) continuous injection, 2009 to February 2013. All detected earthquakes locating less than 8.5 km deep (relative to the ground surface elevation at the injection wellhead) are included.

their epicenters, especially in areas distant from the injection well where the seismic station coverage, particularly in terms of horizontal components, has historically been significantly lower.

While we do not believe that the basement faults discussed in section 2.3 are active, our models indicate that they may serve as barriers to flow, bounding the seismicity within distinct fault blocks. The pattern of induced seismicity occurring southwest of Paradox Valley, in the near-well region, NW cluster, and SE cluster is consistent with the model of northwest trending impermeable faults lying a few km northeast and southwest of the injection well. The distribution of induced seismicity does not strictly fit either the Bremkamp and Harr or Katz and Carroll fault model but conforms better to a combination of faults from each model. The earthquakes are well constrained within the area between the fault lying about 2 km northeast of the injection well, along the edge of Paradox Valley, from the Bremkamp and Harr model (Figure 13a) and the fault lying about 5 km southwest of the injection well from the Katz and Carroll model (Figure 13b). These two faults are marked by black arrows in Figure 13. During the 4 years of injection tests (1991 to 1995) and the first 3.5 years of continuous injection (mid-1996 to early 2000), PVSN detected no induced earthquakes outside the corridor bounded by these faults.

Seismic activity in the NW cluster, located 6 to 8 km northwest of the injection well, began much earlier than in the SE cluster, located about 6 km southeast of the injection well. The NW cluster became active in

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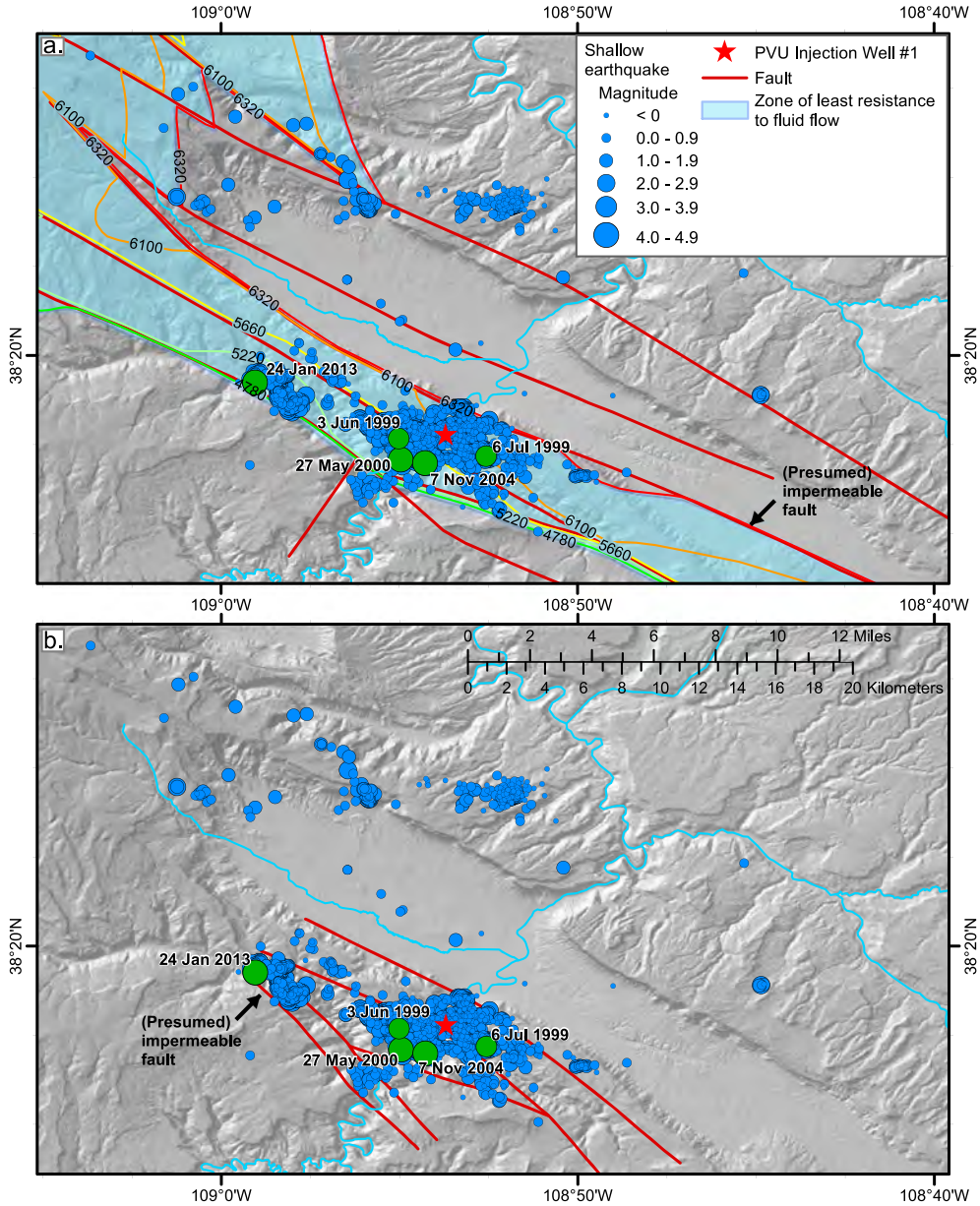

Figure 13. Epicenters of shallow earthquakes interpreted to be induced by fluid injection, superimposed (a) on a contour map of hydrostatic pressure within the Leadville and predicted area of least resistance to fluid movement and pressure rise from injection, from *Bremkamp and Harr* [1988] and (b) on a map of faults in the Leadville formation from *Katz and Carroll* [1984]. Black arrows denote the presumed impermeable faults discussed in section 3.3. The epicenters of the five largest events to date are shown in green and labeled with their dates.

mid-1997, only 1 year after the start of continuous injection, whereas no earthquakes occurred in the SE cluster until 2004 and very little activity occurred there prior to 2010. The much earlier onset of seismic activity in the NW cluster compared to the SE cluster could be due to either a shallowing of the injection target formations to the northwest and not to the southeast, or a higher-permeability pathway to the northwest (and possibly a partially impermeable barrier to the southeast, such as a sealed fault). Of course, both factors could also be present. The Bremkamp et al. structural model of the Leadville formation (Figure 6a) is consistent with the former possibility, but the Katz and Carroll model (Figure 6b), which shows a shallowing of the Leadville both to the northwest and southeast, is not. The Katz and Carroll model does show a fault in between the near-well and southeast clusters, which could serve as a semipermeable barrier, slowing down the migration of fluid to the southeast (Figure 13b).

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The occurrence of seismicity along the northern edges of Paradox Valley (in the "northern-valley" earthquake clusters) is not totally unexpected. Bremkamp and Harr 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 within their "area of least resistance to fluid flow and pressure rise" (Figure 13a). As discussed above, in their structural model, 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. However, most of the shallow earthquakes occurring along the northern edges of Paradox Valley lie outside the boundaries of the "area of least resistance to fluid flow and pressure rise" (Figure 13a). The boundaries of this region are based on the depth and dip of the Leadville formation, the locations and throws of faults, and a hydrostatic pressure boundary value of 6320 psi. 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. Hence, there are no apparent data points to constrain the geologic model at the northern end of Paradox Valley. Furthermore, Bremkamp and Harr do not explain why the hydrostatic pressure contour of 6320 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 Injection Well #1. Additional deep geophysical data at the northern end of Paradox Valley would be needed to better constrain the hydrologic model in this area and further investigate this issue.

The few earthquakes that have occurred beneath central Paradox Valley since 2010 roughly coincide with the location of the mid-valley fault mapped by Bremkamp and Harr (Figure 13a). These earthquakes are small, ranging in magnitude from duration magnitude (M_D) −0.7 to 1.4. The central valley earthquakes recorded to date do not provide sufficient data to determine robust focal mechanisms. Although these events align with the interpreted fault strike, it is unlikely that these earthquakes are due to slip of this mapped basement fault. As discussed by *Ake et al.* [2005], the maximum horizontal stress is aligned subparallel to the northwest trending basement faults, and therefore, these faults are not optimally oriented in the stress field for shear failure. The earthquake focal mechanisms and hypocenter alignments that have been analyzed to date indicate that most of the induced earthquakes tend to occur as a result of shear failure on faults oriented roughly 40° from the general strike of the mapped northwest trending faults [*Ake et al.*, 2005]. The mapped faults themselves may serve as relatively high-permeability, aseismic pathways for propagation of pore pressure. Hence, it is likely that the central valley earthquakes align along the strike of the mapped basement fault either because the fault zone serves as a relatively high-permeability pathway for pore pressure propagation or because the earthquakes are occurring in response to stress changes at the edge of the fault block. The long delay in onset of this seismicity indicates a relatively long time required to achieve either sufficiently high pore pressure perturbation along the fault zone or sufficiently high changes in the stress field. If the earthquakes occur in response to pore pressure perturbation, the pore pressures may have propagated southeast from the north end of Paradox Valley, more directly from the injection well through the Precambrian basement, or perhaps by both routes. The hypocenters of the first three central valley earthquakes, which occurred over a 3 week period in July and August of 2010, nearly collocate (within 30 m) and are the farthest to the northwest, supporting the first possibility. The subsequent earthquakes, however, do not show any clear spatial trend.

Based on earthquake hypocenters and focal mechanism analyses, none of the five largest-magnitude events to date coincide with the major basement faults mapped by early investigators (Figure 13). *Ake et al.* [2005] found that 89% of 1345 near-well events having well-constrained focal mechanisms have strike-slip mechanisms and that 86% of those events have a fault plane azimuth of N86°E, with most of the remaining events occurring on an azimuth of N49°W. All of the five largest events have focal mechanisms and epicenter lineations that are roughly consistent with strike-slip motion along the east–northeast azimuth, at an angle of approximately 40° to the mapped basement faults (the focal mechanism for the 27 May 2000 event was computed by the Saint Louis University Earthquake Center, while the other four focal mechanisms were determined by Reclamation from PVSN data).

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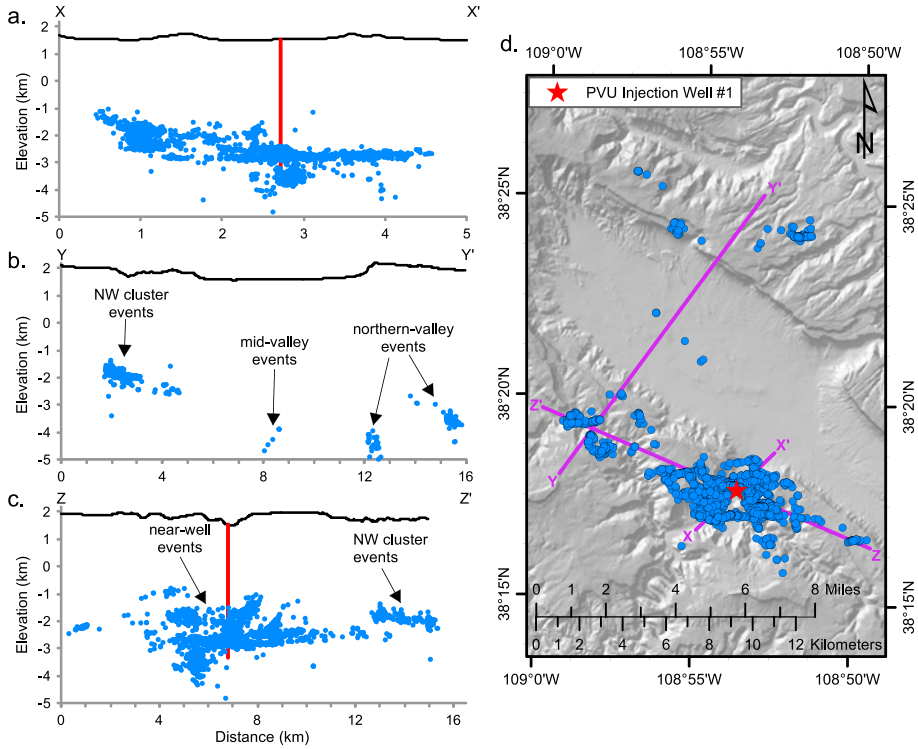

Figure 14. Cross sections (a) X-X′, (b) Y-Y′, and (c) Z-Z′. Blue dots indicate "a" quality earthquake hypocenters within 1.5 km of the cross-section line in Figure 14a and 3 km of the cross-section line in Figures 14b and 14c. The "a" quality hypocenters are determined using a relative location algorithm and precise time differences computed from waveform cross-correlations. Vertical exaggeration is variable. The red lines on Figures 14a and 14c show the projection of PVU Injection Well #1. (d) The locations of the cross-section lines (purple lines) and the "a" quality earthquake epicenters in map view (blue circles) are shown.

The relative earthquake depths are consistent with the general trends of the geologic models, especially with both the local and regional models developed by Bremkamp's group. As mentioned above, comparing the earthquake depths to the interpreted geologic models is more uncertain than comparing their epicenters, and therefore, we only examine the trends in depth in a broad sense. In the near-well region, earthquakes tend to occur shallower southwest of the well and deeper northeast of the well, consistent with the downfaulting of the Leadville formation to the northeast toward Paradox Valley interpreted by both groups of investigators (Figure 14a). In addition, earthquakes occurring in the two largest northern valley clusters, located near seismic station PV04 directly across Paradox Valley from the NW cluster, locate roughly 1.5 to 2.0 km (4900 to 6600 ft) deeper than events in the NW cluster (Figure 14b). This elevation difference is consistent with the several-thousand-foot elevation change interpreted by Bremkamp and Harr in their regional model (Figure 9). Finally, the relative earthquake depths are also consistent with Bremkamp et al.'s interpretation of uplift of the basement and overlying stratigraphy northwest of the injection well, as indicated by shallowing of the earthquake hypocenters toward the NW cluster (Figure 14c).

4. Discussion

While some of the large-scale features of the PVU-induced seismicity are consistent with the geologic models presented here, not all details of the complex seismicity patterns can be explained solely using the information currently available. For example, induced seismicity in the NW cluster began in 1997, only 1 year after the start of continuous injection operations, but the seismicity has not progressed any farther to the northwest during the subsequent 16 years of injection. If the seismicity is related to pore pressure increase, the lack of seisimicity progression suggests that there is an impermeable boundary just northwest of the NW cluster. This boundary could either be a northeast trending sealing fault zone, the absence of the primary injection horizon (the Leadville formation) due to erosion, or a significant decrease in effective permeability due to some other factor, such as weathering and clay infilling of pore space. Alternatively, the occurrence of

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seismicity could be strongly influenced by preexisting stress heterogeneities, and the NW cluster could be an area where faults were critically stressed prior to the initiation of injection, decreasing the amount of pore pressure increase necessary to cause seismicity. The northwestern edge of the NW cluster is beyond the area investigated by seismic reflection data, and therefore, those data provide no constraint on the geologic model at this boundary, nor do we have any measurements of the past or present in situ stress state in this area.

The current geologic investigations also shed no light on the reason behind the distinct clustering of the induced earthquakes and the sometimes large (up to 2 km) gaps between clusters. Previous studies indicate that the PVU-induced earthquakes are consistent with slip on preexisting fault surfaces due to a decrease in the effective normal stress [*Ake et al.*, 2005]. One explanation then for the clustering of the seismicity and the aseismic gaps between clusters is that the current seismicity pattern simply reflects the pattern of preexisting faults that are close to critical condition for shear failure to occur in the current stress field. Variations in the structure of salt bodies have been found to cause heterogeneity of the stress field in adjacent layers [*Luo et al.*, 2012], which may be influencing the distribution of seismicity.

As discussed above, the vast majority of the PVU-induced earthquakes analyzed to date do not appear to occur on the faults that were mapped with seismic reflection data. Because the fault segments on which many of the induced earthquakes occur may not be laterally extensive and may not have significant vertical offset, they may be difficult to detect with deep seismic reflection data, even with more modern data acquisition and processing methods. Furthermore, the pattern of induced seismicity indicates a complex network of numerous, closely spaced fault segments. The complexity of the geologic structure, coupled with the difficult data acquisition environment (from the presence of the thick salt layer, salt diapirs, and large topographical relief) makes acquiring seismic reflection data with sufficient quality and spatial resolution to detect the individual fault segments on which induced earthquakes occur challenging.

5. Conclusions

The spatial and temporal patterns of seismicity in the vicinity of Paradox Valley indicate that most, if not all, shallow earthquakes are induced by fluid injection at PVU Well #1. The majority of earthquakes lie within the area of least resistance to fluid flow postulated by *Bremkamp and Harr* [1988], providing general support for their model. However, many open questions related to the distribution of seismicity remain. In particular, it is unknown whether all earthquakes are induced by increased pore pressure due to fluid flow, or whether some events are induced by stress changes in the absence of pore pressure perturbation.

While the current models provide a basic framework in which to understand the evolution of seismicity, the variation in interpretations, as well as the sparseness and sometimes marginal quality of the data on which the interpretations are based, suggests that the ability of these models to uniquely resolve the relevant features is limited. In order to construct an accurate and well-constrained model relating the PVU-induced seismicity to the geology, additional refinement of the geologic model will be necessary, most likely through the acquisition of additional geologic and geophysical data.

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