RECLAMATION
Managing Water in the West

Technical Studies and Evaluations for the Second Injection Well Alternative at the Paradox Valley Unit

Report from the Consultant Review Board

Meeting, July 25-27, 2017
Denver Federal Center
Denver, Colorado

EMPSi
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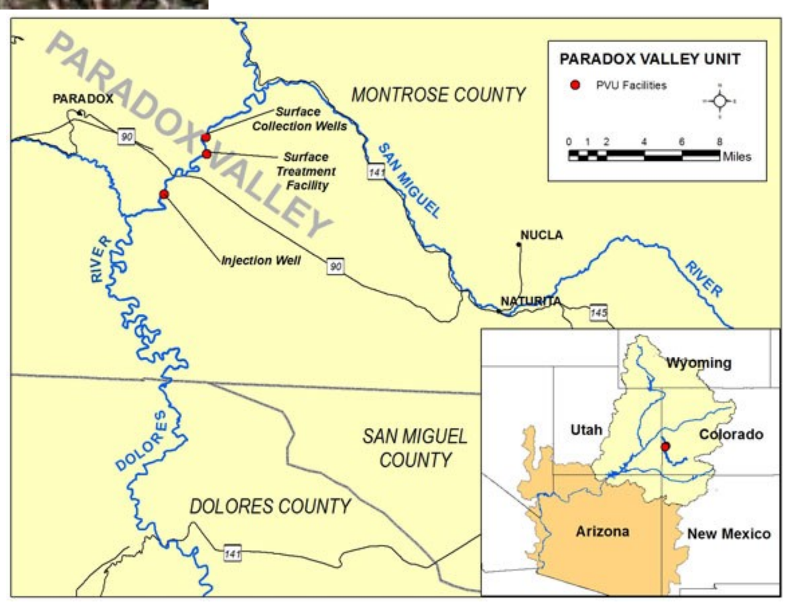

U.S. Department of the Interior
Bureau of Reclamation
Paradox Valley Unit
Western Colorado Area Office
Grand Junction, CO

September 2017

Mission Statements

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.

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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ACRONYMS AND ABBREVIATIONS

Acronyms and Abbreviations	Full Phrase
BIF	Brine Injection Facility
CRA	corrosion resistant alloys
CRB	Consultant Review Board
EIS	environmental impact statement
km	kilometer
m	meter
MWD	measurements while drilling
PVU	Paradox Valley Unit
Reclamation	United States Department of the Interior, Bureau of Reclamation
VSP	vertical seismic profiling

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EXECUTIVE SUMMARY

The United States Department of the Interior, Bureau of Reclamation (Reclamation) convened a formal, independent, external Consultant Review Board (CRB) to consider drilling a second injection well for brine disposal in Paradox Valley. A second injection well is one of several alternative brine disposal methods being considered if Paradox Valley Unit (PVU) well #1 (PVU #1) ceases to function, or if a substantial reduction in the current injection rate is required to reduce wellhead pressures or induced seismicity to acceptable levels. The identified alternative brine disposal methods will be compared in an environmental impact statement (EIS), which will be based on numerous technical studies and evaluations, including this report. In this report, drilling a second injection well is called the Second Injection Well Alternative, and its location (currently unspecified) is called PVU #2.

The CRB was charged with providing an independent peer review of the scientific and technical studies that form the basis for the Second Injection Well Alternative. The CRB members are listed in **Appendix A** and a list of materials provided by Reclamation is in **Appendix B; Appendix C** is a list of the presentations made at the Denver meeting of the CRB on July 25-27, 2017. Reclamation also provided a list of seven questions to be addressed by the CRB in this report.

The CRB commends Reclamation for their efforts to monitor and document the performance and effects of the PVU #1 well, and its relationship to regional geology. Particularly noteworthy is the number of peer-reviewed publications by Reclamation scientists that describe this scientifically valuable case history of induced seismicity. The breadth, thoroughness, and persistence over time of these efforts may well be superior to those at any other injection facility, worldwide. These efforts, and the scientific studies of contractors providing analysis to evaluate the Second Injection Well Alternative, are thorough and state-of-the-art.

After evaluating the available information, all members of the CRB agree that the Second Injection Well Alternative remains a viable alternative for brine disposal. The CRB also made 13 recommendations (many clearly anticipated by Reclamation and its contractors) concerning additional investigations that could provide critical information informing decisions concerning the siting and design of a second injection well, and improve the likelihood that the well will function successfully for many decades.

CHAPTER 1
RECOMMENDATIONS

1.1 RECOMMENDATION #1 – RANKING OF CANDIDATE WELL SITES

The proposed well sites along the Dolores River Valley and on Monogram Mesa are both appropriate for a second injection well (PVU #2). If additional analysis confirms a Dolores River Valley site is viable, it is more desirable because of infrastructure and access considerations.

Based on available information, there are two possibly viable locations where well sites should be evaluated further as candidate sites for PVU #2. These are (see **Figure 1**, Possible New Well Locations):

A. Sites in the Dolores River Valley 1 to 2 kilometers (km) south of the current PVU #1 site. These include so-called Brine Injection Facility (BIF) surface sites as described in the deep well feasibility study (Petrotek Engineering Corporation 2017). Although not investigated as a viable candidate in the feasibility study, the abandoned Chicago wellsite adjacent to the Dolores River should also be considered as a possible surface location for the future injection well. To avoid confusion, in this report when we refer to the "Dolores River Valley sites" we include both the BIF sites and the site near the abandoned Chicago well.

B. Sites on the Monogram Mesa, 25 to 30 km southeast of the current PVU #1 site. The deep-well feasibility study assessed two sites here, Monogram Mesa 1 and Monogram Mesa 2; however, subsequently because of environmental concerns Monogram Mesa 2 was removed from consideration as a viable site .

At both sites drilling can reach targets in the Leadville Formation, which provides an attractive reservoir for brine disposal. The target areas appear to be

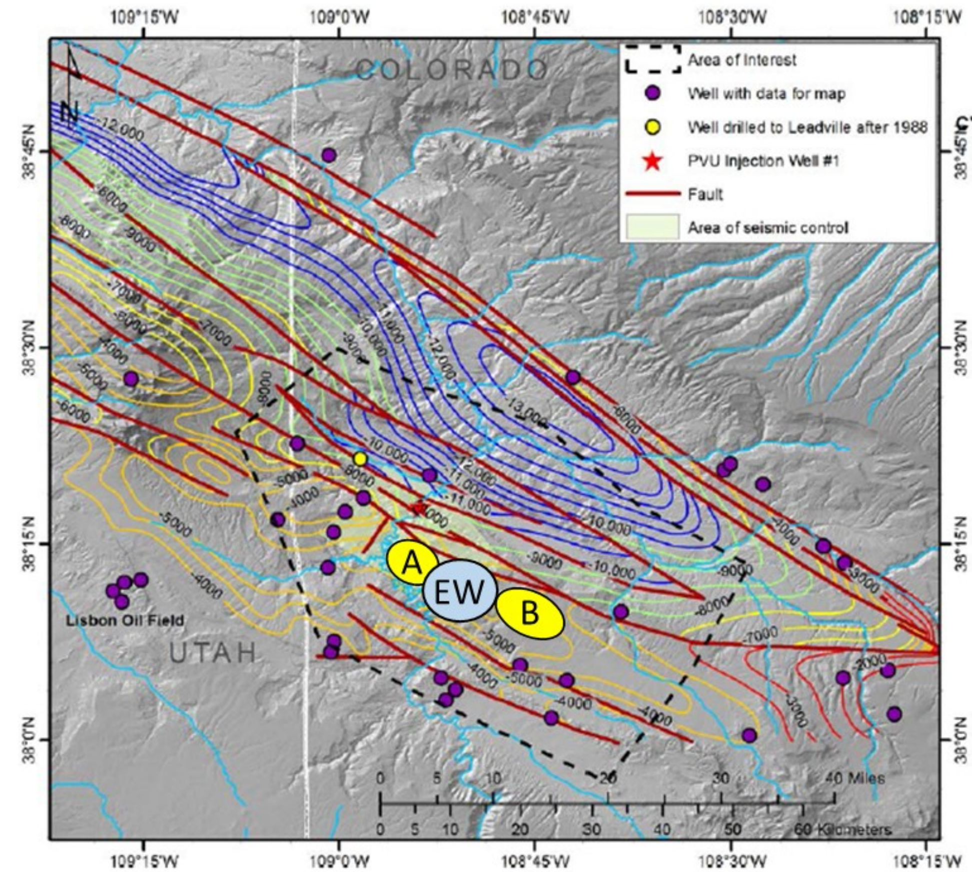


Figure 1. Possible New Well Locations.
Ellipses A and B indicate the two proposed subsurface target location areas for exploratory wells near possibly viable locations for the new injection well PVU #2. Location A is south of PVU #1 along the Dolores River Valley and location B is on Monogram Mesa. The blue ellipse (labeled EW, for "exploratory well") indicates a possible location for either an exploratory well or a monitoring well.

overlain with salt and lie within the same "new fault block" to the southwest of a through-going major boundary fault that seems to be a sealing fault, apparently preventing pressure and fluid diffusion from the reservoir associated with PVU #1. The Dolores River Valley surface sites will all require directional drilling to cross this boundary fault to access the new fault block; for the Monogram Mesa sites, a near-vertical well will penetrate the new fault block.

Other proposed sites are unacceptable based primarily on surface site considerations or inadequate reservoir compartment size (e.g., Pinon Ridge). Whether the Dolores River Valley or Monogram Mesa candidate sites for PVU #2 are ultimately acceptable depends on evaluating the properties (thickness, porosity, permeability, presence of smaller faults, and state of stress) of the Leadville Formation, as it is highly variable both laterally and stratigraphically. For the Dolores River Valley sites to be acceptable, it must be verified that the injection targets for PVU #2 and PVU #1 lie in separate reservoir compartments, i.e., that northern boundary fault of the new fault block is a sealing fault.

The Dolores River Valley sites are considered higher risk because their long offsets require drilling through the boundary fault and at an angle. These sites are also geographically close to clusters of earthquakes associated with the PVU #1 well. However, because of their proximity to the PVU #1 well site, the surface/logistical advantages of these sites are substantial. These advantages may mitigate the higher subsurface risks, which can be evaluated pending some additional modeling work to estimate pressurization near the boundary fault (see Recommendations #10 and #12), and by investigations assessing the impact of drilling horizontally farther away from the fault to reach a more desirable injection location (3D seismic survey; drilling exploratory wells; modeling salt rheology; see Recommendations #3, #4, and #7).

The Monogram Mesa 1 site is ranked highest with respect to drilling considerations (well-bore can be near-vertical) and subsurface characterization (site is far from the boundary fault, and far from PVU #1 and the associated pressurization of the Leadville Formation). Also, Monogram Mesa 1 is situated near the middle of the reservoir compartment, in a location that has been virtually aseismic up to the present. However, Monogram Mesa 1 has less desirable surface characteristics; surface access is difficult and developing the site requires installing a long pressurized pipeline from the brine production wells in Paradox Valley. It is also possible that the Monogram Mesa 1 site is close to a salt weld; this can be evaluated by a 3D seismic survey and by drilling an exploratory well (see Recommendations #3 and #4).

1.2 Recommendation #2 – Passive Seismic Monitoring

If the second injection well is on the Monogram Mesa, seismicity near the well site must be monitored beginning at least 2 years before injection begins.

Monitoring of earthquake activity prior to injection is essential, as it provides a basis for evaluating how/whether injection affects the locations, magnitudes, and rate of earthquakes occurring near the well. Stations near to and surrounding the well site make it possible to identify small-magnitude earthquakes and to determine reliable focal depths.

Seismologists who operate regional networks of seismograph stations and produce earthquake catalogs have learned several "rules of thumb" concerning what is required to determine accurate hypocentral locations from travel time picks:

- Obtaining an accurate location requires incorporating accurate time picks for both P and S arrivals. Locations determined with P picks only typically have smaller formal errors but much larger systematic errors than locations incorporating both P and S times.

- Picks for S tend to be inaccurate when determined using vertical-component records; this is why installing networks of three-component stations is essential.
- Obtaining an accurate epicenter (map location) requires stations that "surround" the earthquake, i.e., the earthquake lies within the polygonal footprint of the stations providing time picks. A statistic that measures this is "azimuthal gap angle," i.e., the largest angle separating two stations providing picks for the event, as viewed from the perspective at the epicenter. Typically, epicentral locations are considered unreliable if gap angle exceeds 180° (the epicenter lies outside the footprint of the network), somewhat reliable if the gap angle is 120° or less, and very reliable if the gap is 90° or less.
- Obtaining a highly accurate focal depth requires both P and S picks from a station situated within a distance approximately corresponding to the focal depth. If the nearest station reporting P and S is greater than about twice the focal depth, depth determinations are often inaccurate.
- Systematic errors in location are reduced if a very accurate velocity model is available for the region where the network detects earthquakes, especially within portions of the region where azimuthal gaps and station-epicentral distances are too large—this is why network operators are always striving to obtain better information about P and S velocities. This is exacerbated in situations where velocity structure is inhomogeneous; even if the structure is well defined and even when sophisticated location algorithms are used, inhomogeneity greatly increases systematic location errors.

Nevertheless, experience shows that for earthquakes with azimuthal gaps less than 90° and with nearest stations reporting P and S having event-station distances less than the focal depth, locations are highly accurate, even when determined using relatively simple location algorithms that utilize a 1D, often-somewhat-inaccurate velocity structure.

When the PVU #2 site is chosen, we presume it is desirable to locate nearby earthquakes with an accuracy comparable to that provided by the current PVU seismic network (**Figure 2**, Seismic Stations and Seismicity). If the second injection site is close to the PVU #1 well (within a few km; e.g., one of the Dolores River Valley sites), it may be unnecessary to install additional seismic stations prior to completing the new well (see **Figure 2**). However, if the second injection site is more than five km from the PVU #1 wellsite (e.g., on Monogram Mesa), installing at least three or more new seismic stations is essential, and even more are highly desirable.

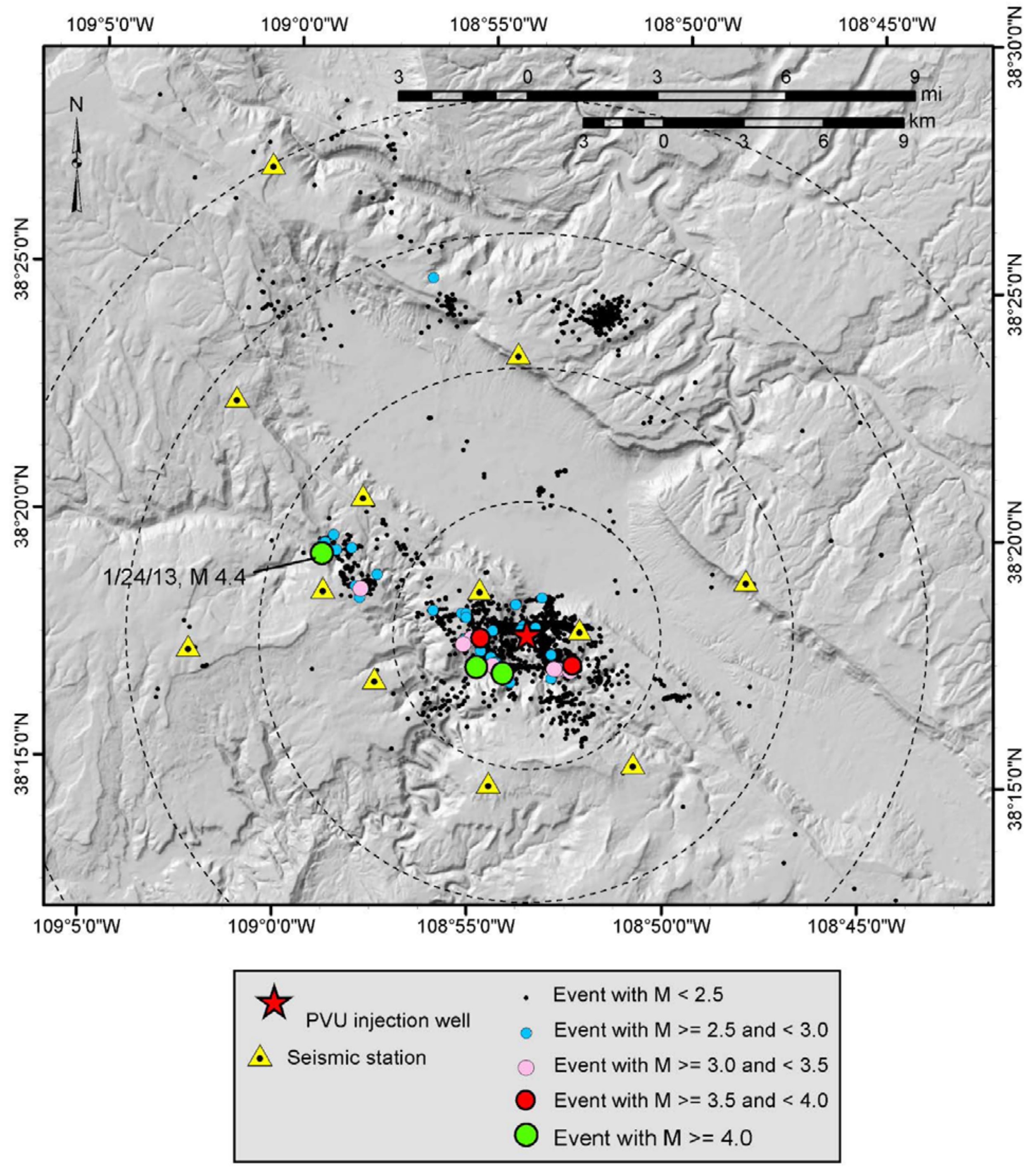


Figure 2. Seismic Stations and Seismicity.
Seismic monitoring stations (triangles) and earthquakes located since injection began at PVU #1 up through December 2016. Dashed circles mark distances of 5 km, 10 km, 15 km, and 20 km from PVU #1. If PVU #2 is at any of the Dolores River Valley sites (near "A" in **Figure 1**), this network of stations is adequate to monitor seismicity levels prior to when injection begins. If PVU #2 is on the Monogram Mesa ("B" in **Figure 1**), new stations near the site should be installed at least 2 years before injection begins. (Figure reproduced from Block 2017).

1.3 RECOMMENDATION #3 – 3D SEISMIC STUDY

A regional seismic survey covering viable candidate well sites should be completed and interpreted prior to making the tentative site choice; then, a more detailed 3D seismic survey should be undertaken at the site chosen.

Since the southern new fault block is large and there are two possibly viable sites within it (A and B in **Figure 1**), a "regional-scale" seismic survey should be performed even before drilling an exploratory well (see Recommendation #4). This regional-scale survey would need to cover 60 square miles or more to encompass both possibly viable sites. Such a 3D seismic survey would be costly, but could be designed with a sparse grid of shots and receivers appropriate for elucidating structural detail, although lacking the resolution necessary for detailed reservoir characterization.

These surveys are important because:

- They can assess whether or not the bounding faults have 500 feet (ft) or more of offset and are sealing;
- They can determine if the Leadville Formation and salt are of adequate thickness to serve as reservoir/seal;
- They may identify previously unknown sealing faults within the interior of the new fault block, leading to compartmentalization that might reduce well life for PVU #2; and
- Potentially they can identify smaller faults that may be critically stressed.

A logical path is to:

- Perform this regional-scale survey; then
- Select a location for an exploratory well; and finally
- Follow up by conducting a high-resolution 3D, three-component (3C) survey covering at least 15 square miles, suitable for detailed reservoir characterization. This high-resolution survey would require dense receiver coverage with sources wherever they can be placed within the grid.

There may be an executive decision to conduct a single seismic survey, either for reasons of cost, or because the site for PVU #2 has been chosen before any seismic survey begins. In this case seismic modeling can facilitate the survey design. We advocate conducting both surveys in a sequential manner but realize it may prove too costly to mobilize and demobilize a high-channel-count crew that can operate in the challenging terrain surrounding Paradox Valley.

1.4 RECOMMENDATION #4 – EXPLORATORY WELLS

An exploratory well at the candidate well site should be completed and interpreted prior to making the final site choice for the new well. Reclamation should also consider installing one or more monitoring wells at appropriate distances (e.g., 2 km and 5 km).

Drilling a single exploratory well or a set of low-cost exploratory wells will reduce siting and drilling risks for PVU #2. Exploratory wells can be "slim-hole" wells with reduced casing requirements, designed to have as small a diameter as is feasible, given coring and tool needs during drilling and post-drilling testing requirements. Exploratory wells cannot be converted to injection wells, but they could be equipped as long-term monitoring wells.

1.4.1 Well Location

As explained above, our current knowledge suggests that both the Dolores River Valley and Monogram Mesa sites are acceptable locations for a future injection well, but each has somewhat different characteristics. To reduce risk, further technical studies are needed to give a relative ranking of the siting options (see Recommendations #3, #5, #7, and #9). The exploratory well drilling should only begin after the additional modeling studies of the pressure-stress-time response of the new fault block to injection (see Recommendations #10, #11, and #12). Planning for the execution of the exploratory well can begin sooner so that action can be initiated quickly after the additional studies are complete.

The number and location of exploratory wells depend on the results of the technical studies and the realistic possibility that, because of various economic, environmental, and legal issues, siting locations for PVU #2 are further constrained. This leads to the following options:

- If one or the other of these general sites (A and B in **Figure 1**) is strongly favored as the site for PVU #2, a first exploratory well should be located near this favored site as a primary location.
    - In this case, we also recommend considering drilling a second exploratory well designed explicitly to become a monitoring well. The distance of this monitoring well from the site chosen for PVU #2 should be determined based on consideration of current knowledge concerning seismicity and subsurface pressure, and additional diffusional flow studies (see Recommendations #10 and #11).
- If both sites A and B remain as options for PVU #2 after the technical studies are complete, then we recommend drilling exploratory wells at both sites.

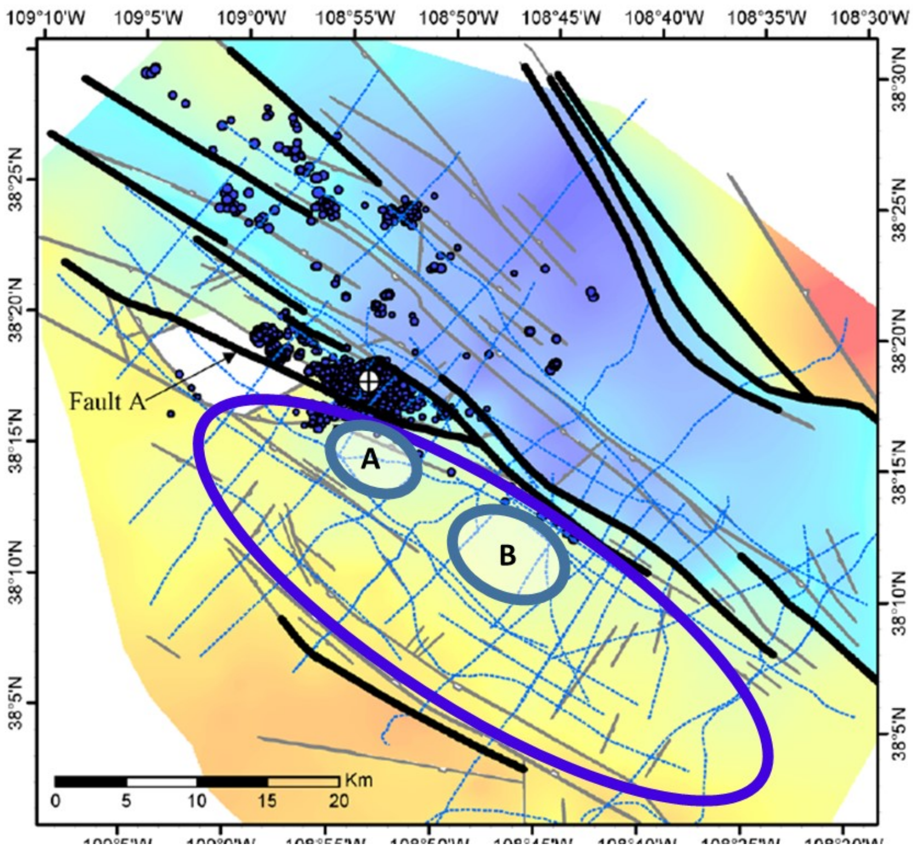
- In this case, if the first exploratory well indicates exceptionally favorable conditions, it may not be necessary to drill a second exploratory well.
- If the first exploratory well indicates marginal suitability as a long-term injection site, the second exploratory well should be drilled near to the site of the second option.
- In general, the CRB favors drilling the first well in the Dolores River Valley south of the existing PVU #1 site.

- Although the two options above are favored, there is an alternative option. The alternative is to drill the first exploratory well in a region intermediate between the two sites (e.g., at location EW in **Figure 1**), with the plan to convert this exploratory well to a monitoring well. Area EW was chosen because it lies between the proposed bottom-well target locations for the Dolores River Valley sites (A in **Figure 1**) and the Monogram Mesa sites (B in **Figure 1**). Other exploratory well locations closer to either A or B would be acceptable.

This exploratory well should penetrate to the base of the sediments. The proposed PVU #2 injection targets in the Leadville Formation are all situated within the large fault-bounded "new fault block" that has these characteristics (see **Figure 3**, Regional Faulting and Seismicity**.**):

- It appears not to have any internal faults with a significant vertical offset that could lead to a sealing condition (i.e., all have less than the 500 ft offset criterion mentioned by the geological experts; see Detournay and Dzik 2017). Internal compartmentalization of the new fault block could reduce the well life for PVU #2.
- The strata are generally flat-lying, having dips close to zero.
- The block appears to be separated by at least one sealing fault and one partially sealing fault from the current PVU #1 injection location in the Leadville Formation, and from the reservoir blocks that take the PVU #1 injection volumes.
- Within this new fault block there has been no detected induced seismicity associated with the current injection at PVU #1. This provides support for the assertion that the fault (or faults) to the northeast of areas A and B are truly sealing, or indicates that critically stressed faults are not present in this area.

Within this new fault block, if the petrophysical conditions (porosity and permeability) of the Leadville Formation are similar to those near the PVU #1 well, the new injection well PVU #2 should be even more effective than PVU #1 because the new location provides an adequate volume to accommodate long-term injection and dissipate pressure effectively.



The New Fault-Delineated Block Preferred for PVU #2 Injection

Figure 3. Regional Faulting and Seismicity.
A geological interpretation of the nature of the faults in the Paradox Valley region combined with the seismic hypocenters (black circles). Ellipses A and B indicate the two proposed general subsurface target areas for PVU #2: south of PVU #1 along the Dolores River Valley and on the Monogram Mesa, respectively. The large blue-bordered ellipse indicates that the area (hence volume) in the fault block available for unimpeded fluid flow is very much larger than the area accessed by the current PVU #1 well (indicated by + symbol).

1.4.2 Drilling Issues – Topography

The topography may be challenging in the proposed exploratory well area, but this will be a slim hole well, not the final injection well. Thus it can be drilled from a pad with a substantially smaller footprint than a full-scale injection well, and involve a somewhat smaller drilling rig.

1.4.3 Drilling Issues – Hole Size

A well intended only for exploration purposes can be drilled rapidly because it requires a relatively small-diameter hole. In general, the rate of advance is linearly proportional to the area of the bottom of a hole, so faster penetration is achieved for slimmer holes. In comparison with larger-diameter holes, smaller-diameter holes have lower mud volume requirements, easier hole cleaning, less time for borehole instability issues to develop, and better intrinsic stability. The risks affecting holes for an exploratory well are substantially less than those affecting a larger-diameter injection-well hole. In addition, it should be possible to eliminate one of the casing strings, reducing hardware and time costs.

Once decisions are made concerning the desired testing program, the diameter of the exploratory well is fixed by the minimum bottom-hole diameter required to perform the tests chosen. Some of these tests must be performed with the drill pipe, such as a double packer drill-stem flow test to determine flow properties (particularly for the intervals to be perforated) and MiniFrac™ stress measurements; others are performed on wireline tools.

1.4.4 Measurements in an Exploratory Well

The three major methods of measuring data in a well are:

- Drill-stem permeability tests or MiniFrac™ stress measurement tests performed at the bottom of the drill string;
- Geophysical logging tool measurements that are performed using wireline methods; and
- Vertical seismic profiling (VSP) or similar larger-scale seismic measurements that require that the borehole be instrumented with a set of geophones.

There are hybrid methods, such as small-scale stress or permeability testing, that use geophysical logging tools lowered with a wireline unit, but issues remain as to the representativeness of these methods. Conducting step-out VSP surveys from the exploratory well may require installation of a string of geophones on a wireline in the wellbore for a period of a week or two. During the actual drilling of the exploratory well, any method requiring withdrawing the bit and lowering a tool is time consuming and tends to slightly increase risk to the wellbore, whereas wireline logging is considered safer and is inherently more rapid.

1.4.5 Measurements while Drilling (MWD)

Use of MWD methods reduces the need for wireline logging when the well is completed, because collecting adequate geophysical data from the upper part of the sequence (above the Paradox Salt) provides stratigraphic control. Also, for the design and operation of PVU #2 the detailed petrophysical properties of the overlying strata are not relevant. MWD generally are viewed as being geophysical in nature, but here we include broader data needs, such as drilling parameters, drilling fluid, and circulation data, and other drilling data (e.g., kicks and mud loss zones) that will help reduce risk for future PVU #2 well siting and installation.

For example, in addition to geophysical logging while drilling, it is feasible to use the penetration data (WOB - weight on bit, RPM – rotation speed, ROP – rate of penetration, etc.) to establish first-order correlations to rock strength and other properties. To be useful, these data will need to be reviewed for quality control (precision and accuracy). Although penetration information is not generally included on the list of parameters of primary interest concerning the injectivity of the Leadville Formation, these correlations and relationships generally help to assess overall geomechanical conditions. All the information from the exploratory well should be reviewed to provide a firm basis for the design of the new injection well, and this will also substantially reduce risks for the drilling of the PVU #2 well.

1.4.6 Cuttings and Core

Continuous collection of cuttings samples is standard practice, but coring does increase costs and risks for an exploration well. For the proposed wells, the interval where core is of highest priority is in the permeable zone in the Leadville Formation, as it appears to be the dominant zone that accepts injected brine. If a core interval is collected, it should be analyzed for standard petrophysical properties (fractures, porosity, permeability, etc.). Cuttings should also be examined for lithology and texture, and it is possible to do fine-scale matrix fabric analysis on cuttings to quantify matrix porosity.

The key objective for these studies on cuttings and cores is to establish an estimate of matrix porosity and permeability over the entire vertical extent of the target injection zones. Given the small sampling volume and the vertical nature of an exploratory well, it is unlikely that the nature and distribution of natural fractures can be delineated, especially as the available data indicate that porosity is highly variable in the Leadville Formation. This is an important statement because fluid flow in the Leadville Formation appears to be fracture-dominated, but it is the matrix porosity that governs the fluid storativity of the strata in the new fault block.

Collection of a short core in the salt interval also may prove to be useful. This could provide essential information to constrain the proposed salt rheology modeling study (see Recommendation #7).

1.4.7 Stress Data

Stress measurements are needed at several depths below the base of the Paradox Salt in any exploratory well. At this time, we assume that once the salt is penetrated (and perhaps cased), adequate time will be available for testing programs. A MiniFrac™ tool on the drill string can be lowered into the hole to measure the value and orientation of the minimum principal stress (assumed to be horizontal).

There are no reliable stress measurements currently available. Thus, collecting these data will provide important baseline information for all geomechanical modeling, define the fracture gradient explicitly, and provide information about which faults might be critically stressed.

1.4.8 Permeability Data

The traditional method for obtaining realistic permeability data at an appropriate scale is to use a double-packer drill-stem test. These tests involve opening a packer-isolated interval of the formation and allowing flow into the drill string.

However, it is highly preferred to instead perform injection tests for the following reasons:

- Injecting additional fluid (increasing pressure) is more relevant than production to the goals of the PVU #2 well.
- Fracture flow sensitivity to pressure changes is high but poorly known, so to determine far-field properties there is merit in doing injection rather than depletion tests.
- Repeated and different injectivity tests can be performed without withdrawing the drill string.
- Injection tests at different relative pressures ΔP and for different times can be implemented to obtain data for different volumes.
- The injection tests can be followed by a step-rate injection test to assess the fracture pressure.

Injection tests can be performed at a constant pumping rate or at constant pressure; in both approaches, the data can be interpreted to estimate permeability. The longer the injection test is performed, the larger the volume evaluated.

There are wireline methods to estimate permeability, but all wireline methods access very small volumes of the formation because of the small contact area of the tool. If the dominant flow mechanism is fracture flow, the results will be of little use. Because we believe that flow along fractures dominates the permeability, we cannot recommend wireline formation-testing methods.

1.4.9 Wireline Geophysical Data

In addition to the conventional suite of wireline devices (natural gamma, resistivity, neutron porosity, caliper, sonic log, etc.), we recommend including the following geophysical wireline logs:

- FMI – Formation Micro-Imager log for fracture identification in the borehole wall;
- Multiple-receiver acoustic log with analysis of back-scattered waves to give some idea of the natural fracture frequency and orientations near the wellbore;
- Other geophysical logging tools deemed to provide useful information on the nature of the Leadville Formation injection interval.

We recommend that Reclamation consult a geophysical logging expert to develop a more-informed list of desired logs to meet specific data needs.

1.4.10 Vertical Seismic Profiling (VSP)

Once an exploration wellbore is available, it is feasible and relatively economical to carry out step-out VSP in several directions to more precisely delineate the seismic stratigraphy and acoustic properties of the region. The 3D VSP could be acquired in conjunction with the 3D, 3C seismic survey to optimize the processing and interpretation of both surveys. Collecting VSP data would certainly help enhance the resolution of the surface seismic data. The VSP would require 3C or 4-C receivers. Although the longer the array the better, it is especially important to stage the array near the bottom of the well and to straddle the Leadville Formation.

The VSP profile should be developed along a radius (or multiple radii) from the wellhead using seismic excitation sites at the surface, with a recording string of geophones within the borehole (**Figure 4**, Radial Step-out VSP Characteristics**.**). The surface excitation sites (if vibroseis is utilized) are stepped out from the wellhead at pre-designed spacings in a radial direction to create an aperture within which acoustic properties and seismic stratigraphy are determined. The multiple pathways and shorter travel distances associated with VSP profiling, combined with its precise constraints on depth, can greatly improve the interpretation of existing seismic data and any 3D seismic surveys taken in the future (see Recommendation #3). Better velocity information will also improve accuracy of past and future earthquake locations. Hence, the VSP data provide another method to reduce risk.

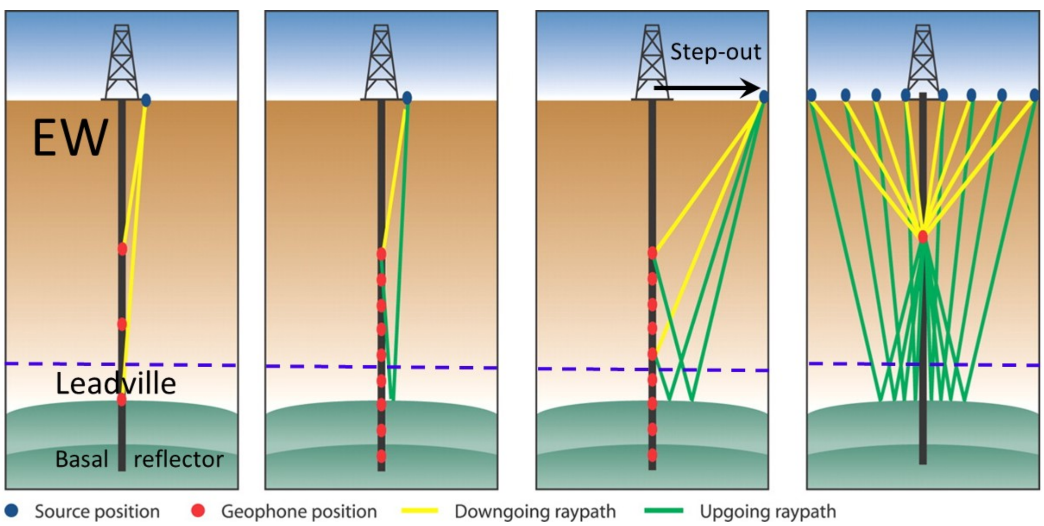


Figure 4. Radial Step-out VSP Characteristics.
(EW = Exploration Well; see **Figure 1**). Figure redrawn from Campbell et al. (2005).

1.4.11 An Exploratory Well as a Monitoring Well

The location of the exploratory well is an issue in the decision concerning whether to convert it to a monitoring well. If the well is too close to PVU #2 (for example, within 500 meters [m]), it will serve as a useful monitoring well for a few years, but then its usefulness will diminish over time when inferring what is happening at larger distances (e.g., 2 to 10 km) becomes important.

The CRB therefore recommends considering drilling an exploratory well explicitly designed as a monitoring well. This well would be placed at a distance of 3 to 6 km (depending on further analysis) to monitor changing conditions within the far-field; this would provide an important window into the subsurface for a considerable length of time. This monitoring well can serve multiple purposes, and the following is a list of methods to consider:

- Precision tiltmeter string installation in the upper 2 km of the well to determine ground deformation as injection proceeds.
- Placement of geophones at several locations in the well to collect microseismic data, greatly constraining the hypocenter location uncertainty for induced earthquakes (see Recommendation #2).
- Defining and installing pressure measurement devices to measure the pressure development in the strata behind the casing at several locations, including the most permeable zone in the Leadville Formation.

This list is not exhaustive; additional functions may be developed for a monitoring well based on ongoing and recommended Reclamation studies (see Recommendations #8 and #13). Design of this monitoring well can commence after completion of the first exploratory well near the preferred site.

1.5 RECOMMENDATION #5 – ENGINEERING DESIGN STUDY FOR DRILLING AT PROPOSED WELL SITES

A more thorough engineering design study would help make essential choices for drilling the proposed injection well PVU #2, and any exploratory or monitoring wells.

We recommend undertaking an engineering design study of specific surface and bottom hole locations for the two proposed sites for PVU #2 (A and B in **Figure 1**). This study would evaluate surface location issues as well as downhole trajectory concerns, i.e., how wellbore orientation relative to the tectonic stress field affects wellbore instability and directional drilling risk. Also, the study should consider wellbore trajectory shape, considering various types of slant, “S,” deep “J,” or even double-build horizontal geometries if completion techniques warrant this. The study should consider needs for specific wellbore orientations through any salt section as well as in the target formation.

For the final two sections of the injection well, a more engineered approach for construction is appropriate. The study should consider completion technique, well orientation, wellbore construction, directional planning, casing design, cementing plan, drilling fluid selection, and wellbore integrity (including well control and lost-circulation mitigation).

1.6 RECOMMENDATION #6 – CORROSION STUDY

An engineering study is needed to evaluate the most effective and economical corrosion mitigation for the new well.

The corrosion resistant alloys (CRA) used at PVU #1 have functioned well for more than 20 years, but they are exceptionally expensive. In the well itself, an entire 5-1/2" casing string of Hastelloy C276 has been used down hole. Inconel has been used in the high pressure pump and valve train as well as in the piping to the wellhead. A steel-based wellhead internally clad in Inconel is in use.

Given the current environmental conditions and the time since the original specifications, we recommend initiating a new study of the use of the CRA for PVU #2. This will require a reassessment of the current source, concentration, and volume of corrosion agents (H_2S, CO_2, chlorides, oxygen, sulfur, etc.) and various environmental conditions such as temperature and pressure throughout the system, from source to surface to injection disposal. Various tests will help determine the longevity and suitability of various corrosion mitigation techniques. These could range from the exotic C-276 to plastic coated tubulars or a chemical inhibition routine.

1.7 RECOMMENDATION #7 – SALT RHEOLOGY STUDY

Reclamation should conduct a study assessing the rate of salt movement near the candidate well sites. This is essential information for drilling and designing wells.

Because of containment issues, it is a Reclamation imperative that a layer of salt overlies the injection zone, and thus any PVU #2 well must penetrate one or more salt layers. Salts present a unique challenge in drilling and completion operations. These include dissolution and subsequent hole enlargement and the converse, deformation from plastic flow (a.k.a. creep) and subsequent hole shrinkage. Hole shrinkage can occur fast enough to close off a hole while drilling or over time, impose lithostatic loads on casing and cement that cover the salts. If these loads are not uniformly distributed, this will lead to casing collapse and loss of the wellbore (Perez et al. 2008). When drilling around salt bodies, there can be rubble zones, leading to wellbore instability, stuck pipe, and lost circulation. Localized abnormally high pore pressures may be encountered, and local tectonic stresses can arise due to salt intrusion.

Since the proposed lifetime for the proposed PVU #2 well is 50 years, successful drilling, completion, and well performance require understanding the expected behavior of the salt zone. Key properties to consider are the creep rate, anisotropic stress field, and corrosive properties of the salts.

When a salt layer overlies or is in direct contact with an injection reservoir compartment, the solubility of the salt can be important. Salt comes in many varieties, including chlorides, sulfates, and carbonates. Halite (NaCl) is the most common; however, there are over 35 types of salts, each with its own characteristics. The solubility of the salt depends upon its content. Among common salts, $CaCl_2$ is the least soluble salt, $MgCl_2$ and NaCl are of intermediate solubility, while KCl is the most soluble salt. Other evaporite minerals such as anhydrite, gypsum, limestone, and dolomite may bound or be intermixed with salt bodies. Water content is a strong driver of creep behavior, and temperature has a significant effect as well (Urai and Shi-Yuan 2016).

The data collected from exploratory wells and from the literature can provide input for the many salt models that have been proposed by investigators, thus informing the planning for the design and performance of the proposed PVU #2 injection well. Most salt models basically assume that salt is a homogenous material, but this is seldom a legitimate assumption—most salt bodies are highly inhomogeneous. This can lead to incorrect conclusions regarding the characteristics and subsequent behavior of the salt. For example, creep has been shown to be four orders of magnitude different than predicted (Urai and Kukla 2004). Extensive data are available for many salt areas around the world. Some of the United States Department Of Energy National Laboratories, such as Sandia National Laboratory, have made studies on salt movement for projects, such as nuclear waste storage. In addition, Respec Inc. (www.respec.com) may have data for purchase. There may be data available for the Paradox Valley; however, the CRB does not have any information regarding that.

Thus, as noted in the Cuttings and Core section of Recommendation #4, we recommend that as exploratory wells are drilled, that the salt layer above the injection zone should be cored and analyzed to determine its material and chemical properties. These data will significantly reduce uncertainties for the results of the proposed modeling.

1.8 RECOMMENDATION #8 – EMERGING TECHNOLOGIES FOR MONITORING POST-INJECTION GROUND RESPONSE

Various emerging technologies should be considered to evaluate and integrate existing data concerning the Paradox Valley operation.

The unconventional is fast becoming the conventional as we consider approaches to reservoir characterization and management. We recommend that a comprehensive plan for monitoring be included in the design of the exploratory wells, injection well PVU #2, and any monitoring wells. The highest priority should be to obtain data from multiple methods for proxy sensing of fluid pressure and movement of injected fluids. The propagation of the pressure field can be observed indirectly by monitoring ground deformation and changes in subsurface physical properties. Monitoring the pressure wave through the deformation and acoustic emissions fields provides a management tool for making decisions about changing rates of brine injection. The sensing methods we suggest include several recently developed technologies. Scoping computations should be made to assess their viability before deployment.

1.8.1 Distributed Acoustic Sensing

Installing fiber-optic cable behind casing in the exploratory well and the injection well makes it possible to perform repeat VSP surveys (Miller et al. 2016). Monitoring velocity structure in the near-field environment with fiber-optic cable is being used in the hydrocarbon industry and in demonstration projects for carbon sequestration (Daley et al. 2013).

Fiber-optic cable is also being deployed in horizontal trenches at kilometer scale in demonstration projects for carbon sequestration (Freifeld et al. 2016; Yavuz et al. 2016) and geothermal reservoir monitoring (Feigl and PoroTomo Team 2017). A kilometer-sized array that encircles the proposed PVU injection well could be used as a seismic monitoring network. The horizontal geometry of the near-surface cable combined with a vertical cable in the exploration hole could be used for highly accurate location of induced earthquakes within the array boundary. In addition, the array could monitor seismic velocity changes using active-source or ambient-noise tomography.

1.8.2 GPS, InSAR, and Borehole Tiltmeters

Ground uplift in response to injection at 4.8-km depth is highly muted. Nonetheless, calculations suggest that several centimeters of deformation have occurred over 25 years of injection at PVU #1 (Detournay and Dzik 2017), although this uplift was below the level of detection in the PVU InSAR study (Besana-Ostman 2016).

Anticipating the desire to calibrate future geomechanical models means collecting baseline ground deformation data prior to and following injection at the new well. Installation of borehole foundations for an array of permanent-station GPS stations would provide real-time deformation monitoring. Installing permanent corner reflectors for InSAR could be considered along with its tradeoffs in construction cost and spatial-temporal resolution.

Borehole and shallow tiltmeters have sensitivities of 5-10 nanoradians and are used elsewhere for hydrocarbon reservoir monitoring. This sensitivity is sufficient to record solid earth tides. The comprehensive plan should assess whether borehole tiltmeter technology is appropriate for monitoring the fluid-pressure front associated with PVU #2. This can be achieved through forward modeling using a mathematical formulation similar to that described by Detournay and Dzik (2017) in their report provided to Reclamation, or by using the methods of Dusseault and Rothenburg (2002). Given the depth of the pressurization process within the Leadville Formation, the tilt modeling should focus on predicting both the maximum tilts expected as well as the optimum locations for shallow-tiltmeter installation.

If a string of borehole tiltmeters is installed in a monitoring well, tiltmeters closer to the source of deformation will experience larger-magnitude tilt signals. However, the presence of the tiltmeter string does restrict access to the lower part of the monitor borehole.

We recommend installing tiltmeter arrays at near-surface sites if the modeling shows this approach is feasible. These are typically placed in 10-m-deep geotechnical boreholes. If the array is placed properly it will be useful for calibrating the coupled geomechanics model (see Recommendation #12), thereby increasing the value of this modeling, and increasing the usefulness of the pressure-monitoring data as well.

1.9 Recommendation #9 – Leadville Core Petrophysics

Laboratory analysis of existing Leadville cores could provide useful bounds on porosity, permeability, faulting, and seismic velocities.

We recommend performing a core analysis study to evaluate properties of the Leadville Formation in the vicinity of the injection well. This analysis would evaluate the heterogeneity within the Leadville and may also help constrain the velocity model used for earthquake location. Petrophysical measurements on a few cores will help to establish relationships between Vp/Vs, anisotropy, porosity, and permeability. Upscaling from core to well log to seismic scales provides essential information as geological/geophysical investigations move toward a dynamic reservoir characterization phase (see Recommendation #12).

1.10 Recommendation #10 – Modeling Study to Evaluate Minimum Distance from Fault

Geomechanical modeling could help assess the effects of distance from injection to sealing faults.

For the PVU #2 injection well, the proposed Dolores River Valley sites (near A in **Figure 1**) are relatively close to the PVU #1 well and to the supposedly impermeable sealing fault that bounds the new fault block and is situated between PVU #1 and the Dolores River Valley drilling target locations. Prior to finalizing the bottom-hole location, we recommend undertaking an investigation to assess whether the proximity to this fault affects the performance of PVU #2.

The distance between the injection target for PVU #2 and the supposedly impermeable fault influences the pore pressure and also the stress acting on the fault. Two questions to address are:

- What are the pore pressure change and the pore-pressure-induced stress change that will cause the sealing fault to slip? While the bounding fault is not expected to be critically stressed—based on what we currently know about regional stress and earthquakes in the region—it is nonetheless worthwhile to assess the factor of safety against a slip event, given plausible pore pressure and stress change caused by injection.

- What is a safe distance from the fault for injecting the brine?

While limited subsurface data make for considerable uncertainty concerning the presence, location, and orientation of faults/fractures within the new fault bounded block, geomechanical modeling in conjunction with probabilistic fault slip analysis can help assess risks associated with induced seismicity near potential well locations, especially at nearby bounding faults (e.g., Walsh and Zoback 2016).

Note that a pore pressure discontinuity is expected across the fault due to injection from PVU #1, even if the fault is not a perfect hydraulic barrier.

A preliminary recommendation is to carry out a back-of-the-envelope calculation to estimate the critical pore pressure change and the minimum safe distance between the injection point and the fault. This preliminary estimation of the critical pore pressure on the fault would ignore any poroelastic stress change. It simply relies on making assumptions about the orientation of S_{hMax}, the ratio S_{hMin}/S_{hMax}, and the orientation of the fault, and then calculating the pore pressure that will cause slip on the fault. The safe distance between the fault and the injection point can be deduced from a simple pore pressure field calculation using a singular source and its image on the other side of the fault. This safe distance will be a function of the injection rate history, the hydraulic properties of the reservoir, and the critical pore pressure change.

When these preliminary calculations are complete, a more elaborate geomechanical analysis that accounts for non-uniform poroelastic stress changes can be performed using fairly standard numerical simulation software. The preliminary scoping calculations will also serve to determine size of the region to be modeled in more detail.

1.11 Recommendation #11 – Model Permeability (or Mobility) and Diffusivity near PVU #1 using Early and Recent Injection Pressure History

A geomechanical model of the region within a few kilometers of the well can provide important information about reservoir properties.

Permeability (or mobility) and diffusivity are the two critical reservoir parameters that control the magnitude and evolution of the induced pore pressure. Indeed, the magnitude of the pore pressure at a given location and time is inversely proportional to the mobility, while the diffusivity affects the propagation of the diffusion front. For the reservoir affected by the PVU #1 well, estimates of large-scale values for the diffusivity have been inferred from the migration of the front of seismic activity and are broadly consistent with large-scale values of diffusivity estimates in other reservoirs.

There remains, however, significant uncertainty concerning the values of the permeability/mobility. The only direct measurements available to estimate the permeability are the surface injection pressures measured at PVU #1. Numerical simulations using a large-scale model (covering 22 years and 40 km X 56 km x 7.5 km) are able to match the observed pressure from about 2000 to the present by adjusting the permeability and assuming the impermeability of the faults with more than 500 ft offset (see **Figure 5**, Pressure vs Time at PVU #1).

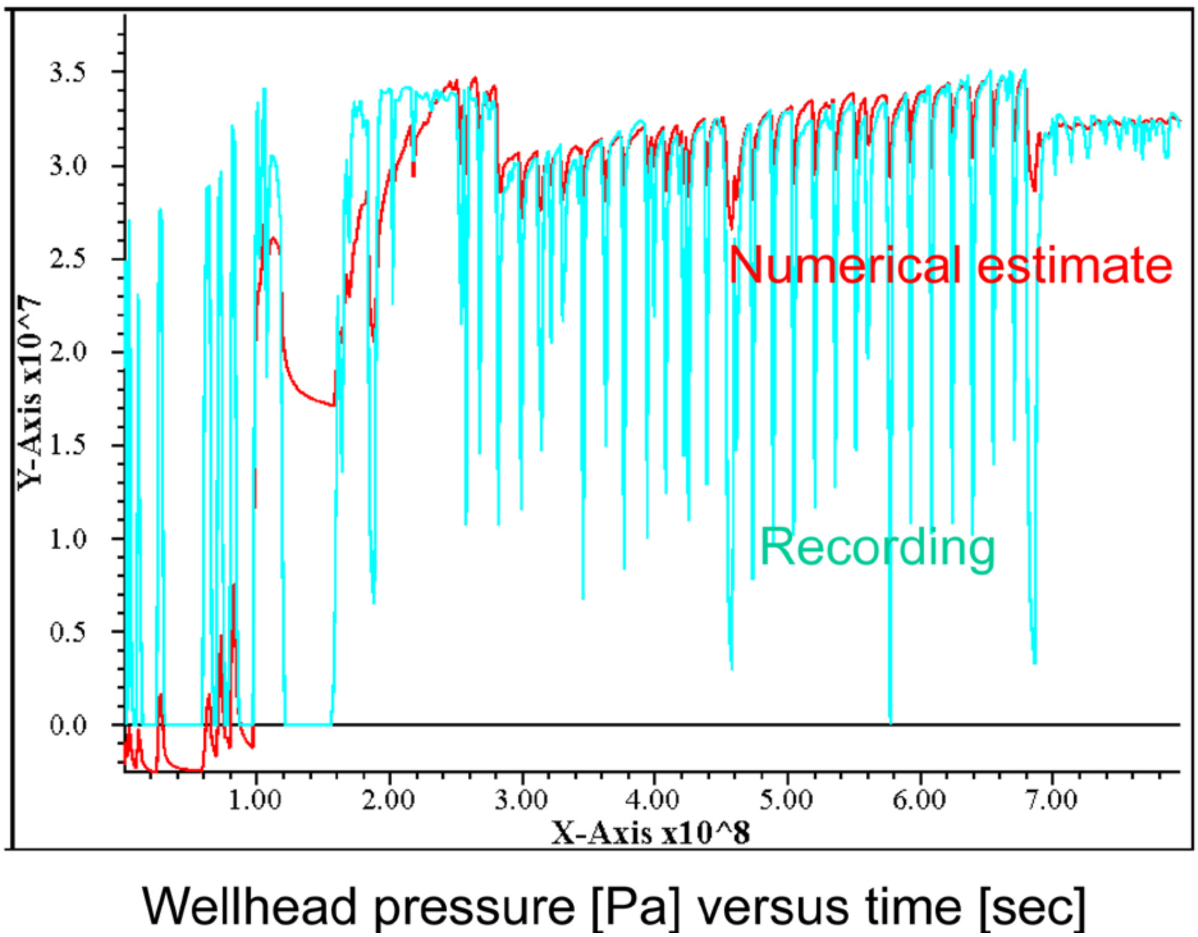


Figure 5. Pressure vs Time at PVU #1.
For the PVU #1 injection well, comparison of measured surface injection pressures (blue) and pressures calculated from a course-scale geomechanical reservoir model (red). The modeling covers the interval from late 1991 (0 sec) to December 2016 (almost $8x10^8$ sec). Note that measured and calculated pressures disagree over the early period, suggesting that the model poorly represents either the near-well environment, or that this environment has changed over the time. (Figure reproduced from Detournay and Dzik 2017)

However, the injection pressure measured during the period from the start of the injection to 1999 is not well matched by that model. This inconsistency provides an opportunity to obtain additional information about the global permeability and the topology of the reservoir in a region around PVU#1 at a "medium" scale ranging from hundreds of meters to kilometers. This analysis will also provide information on how skin or diffusivity changes with time. The analysis now available suggests that permeability near the well increases significantly over time due to pore pressure increase, cooling, and/or chemical reactions.

We therefore recommend conducting pore pressure modeling at this medium scale to evaluate permeability and topology of the reservoir, including the possibility that near-well permeability has changed over time. Initial scoping analysis could be performed with a 2D model at the expense of assuming that the head in the Leadville Formation does not depend on the depth. These preliminary calculations could be complemented by 3D diffusion computations.

1.12 Recommendation #12 – Modeling to Assess Slip along Faults

Construct a comprehensive, 20-km-scale, geomechanical model that includes stress, poroelasticity, and slip along faults.

Numerical simulations at a ~25 year, 10-20 km scale using modern geomechanical software can provide new insights constraining the in-situ stress within Paradox Valley region, the geomechanical properties of the Leadville Formation and of confining layers, as well as the strength of the faults intersecting the reservoir. King et al. (2017) reports estimates of the regional scale in-situ stress based on Anderson faulting theory. Moreover, Detournay and Dzik (2017) evaluate the risk of seismic events by assessing a safety factor based on the stress and the pore pressure fields (both a combination of initial fields and injection-induced fields) computed using 3D geomechanical software. However, in both calculations the induced stress (either poroelastic or elastic) is based solely on the linear response of the rock formations. Thus, the calculations do not account for possible slip on overstressed faults and the subsequent readjustment of the stress field.

A first recommendation is to carry out a simplified calculation, similar in some ways to that reported in King et al. (2017), but accounting for the poroelastic stress and assuming uniaxial strain in the reservoir—a reasonable hypothesis in view of the large lateral extent of the Leadville Formation (Marck et al. 2015). In that case, the local change in the horizontal stresses $\Delta\sigma_h$ and $\Delta\sigma_H$ is proportional to the pore pressure change Δp induced by fluid injection with

$\Delta\sigma_h = \Delta\sigma_H \simeq \Delta p/2$, approximately[1], while the vertical stress σ_v remains unchanged.

Along normal faults, $\sigma_1 = \sigma_v$ and $\sigma_3 = \sigma_h$. Because of poroelastic effects, not only the mean effective stress $s = (\sigma_1 + \sigma_3 - 2p)/2$ is changing but also the stress deviator $q = (\sigma_1 - \sigma_3)/2$. Thus, perturbations in stress and pore pressure due to the fluid injection are stable or unstable depending not only on the magnitude of the perturbations relative to the initial conditions, but also on the ratio $\Delta q/\Delta s$ itself, which is a function of Poisson's ratio ν and the Biot coefficient α. Namely, a necessary condition for the fault to slip is that $\Delta q/\Delta s < \sin\varphi\ (\Delta s, \Delta q < 0)$, where φ is the friction angle of the fault (Rudnicki 2011). Neglect of poroelastic effects is equivalent to assuming that $\Delta q = 0$, in which case the necessary condition is always satisfied. In other words, because of the stabilizing effect associated with a poroelastic stress change (resulting in $\Delta q < 0$), the initial conditions are actually closer to critical than would be deduced from interpreting a normal slip event without taking poroelasticity into account.

Along strike-slip faults, $\sigma_1 = \sigma_H$ and $\sigma_3 = \sigma_h$. Here $\Delta q = 0$ and the above necessary condition for slip is always met. Nevertheless, poroelastic effects have a stabilizing effect since then $\Delta s \simeq -\Delta p/2$ (see footnote 2), rather than $\Delta s = -\Delta p$ if injection-induced stresses are neglected.

We further recommend developing a geomechanical simulation model at the ~25 year, 10-20 km scale that accounts for both poroelastic stresses and for stress changes resulting from slip along overstressed faults. Because the pore pressure induced by injection is essentially governed by the classical diffusion equation, owing to the weak mechanical-to-hydraulic coupling in this class of problems, the induced pore pressure field $\Delta p(\boldsymbol{x}, t)$ need only be computed once. The induced stress and displacement fields and possible slip can then be calculated at suitable (probably variable) time intervals, chosen to accommodate periods of large pore pressure change. Such an approach would considerably reduce the computational burden inherent in performing such large-scale computations.

1.13 Recommendation #13 – Implementing a Modern Approach to Visualization and Integration

This includes the application of software for visualization and geomechanical modeling.

We commend Reclamation for their efforts sustained over more than two decades to characterize regional geology, hydrology, and tectonics, and to safely manage the injection operations at PVU #1. Their efforts over more than 25

[1] Under uniaxial strain conditions, $\Delta\sigma = 2\eta\Delta p$, where the poroelastic stress coefficient $\eta = \alpha(1-2\nu)/2(1-\nu)$, with ν is Poisson's ratio and α is the Biot coefficient. The range of η is $[0, 0.5]$, but typically $\eta \simeq 0.25$. Rudnicki (2002) discusses corrections to account for the geometry of the underground reservoir into which fluid is injected.

years to monitor and accurately locate earthquakes may well be superior to those at any other injection facility, worldwide. The collected seismicity data have been hugely useful for constraining these scientific characterizations.

However, we recommend that Reclamation consider implementing a more modern, integrated system for data analysis and reservoir management. Using modern visualization tools to allow for a perspective based on reservoir dynamics and geomechanics, the earthquake data should be integrated with stratigraphic information, hydrological data, 2D and 3D seismic data, a tectonic structural model, and a geomechanical model such as that described in Recommendation #12. This integrated model will change over time as data accumulate (3D and 4D seismics, earthquake hypocenters, and pressure information measured at monitoring wells).

The project must shift in this direction. It is not possible to eliminate risk but it can be well-managed, providing the modeling is executed properly and the right monitoring data are collected to inform the model. This project can be a showcase demonstrating how a proactive, integrated program of monitoring (Recommendation #8), modeling (Recommendations #10, #11, and #12), and management pays dividends with respect to managing the reservoir and mitigating the risk associated with deep-well injection.

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CHAPTER 2
RECLAMATION QUESTIONS TO THE CONSULTANT REVIEW BOARD

2.1 QUESTION 1. HAVE APPROPRIATE TECHNICAL CRITERIA FOR IDENTIFYING POTENTIAL INJECTION WELL SITES AND RESERVOIRS BEEN CONSIDERED?

As noted above, the CRB commends Reclamation personnel and their consultants for their combined research efforts investigating technical issues associated with the Second Injection Well Alternative in the Paradox Valley region–PVU #2. Generally the depth of technical analysis is excellent, the interpretations are logical, and the documentation is exhaustive (see Appendices B and C). These studies have served to eliminate several potential sites for PVU #2, and reduce the risks associated with siting of PVU #2 in comparison to what was known at the time of the 2015 external review panel report (Consultant Review Board 2015).

To further reduce development risks, Reclamation should obtain more detailed geological and geophysical information about the remaining sites to assess whether they provide the necessary access to the Leadville Formation in a location having favorable permeability and porosity conditions within it. In particular, for long-term disposal well performance, four major criteria must be satisfied:

1) Adequate porosity for the storage of anticipated volumes of brine;
2) Adequate permeability permitting access to the reservoir and its storage capacity;
3) Sufficient volumetric extent of the reservoir to allow injection for prolonged periods of time without excessive pressure build-up at a regional scale; and
4) Sufficient overlying salt thickness to serve as a top seal.

These four criteria are not all independent, but they are distinct. For example, even if permeability and porosity are adequate, the Piñon well sites are rejected because of too intense compartmentalization, leading to a risk of inadequate reservoir volume if the bounding faults are found to be sealing.

To reduce the degree of uncertainty, at local scales the geological model needs refinement, particularly to determine the fault block structure, to confirm the presence of salt, and to assess whether fault offsets are sufficient to be sealing. Also, reducing uncertainty concerning the geographic distribution of thickness, porosity, and permeability in the Leadville Formation (and deeper strata) is needed. Together, this additional information will further reduce the risks associated with choosing and developing a site for PVU #2.

To reduce uncertainty the CRB recommends undertaking two major efforts prior to drilling PVU #2:

- Of highest importance is the execution of a high-resolution 3D seismic survey over a limited area to constrain the vertical and lateral distribution of porosity in the injection interval below the Paradox salt, as well as to more precisely examine the lateral heterogeneity (Recommendation #3).
- Also important is the drilling of one or more exploratory wells (also called "biopsy wells" or "strat wells") to the base of the Cambrian sediments below the Leadville Formation (Recommendation #4). Logging with modern logging tools in these wells will help evaluate the nature of natural fractures in the target injection strata. Analysis of new and existing cores through the porous and permeable section of the Leadville Formation will provide more quantitative information concerning permeability and porosity (matrix vs. fracture; Recommendation # 9).

In addition to reducing uncertainty associated with the suitability of the Leadville Formation disposal interval for PVU #2, these efforts will provide the following additional benefits:

- Reducing risks associated with the design, drilling, and completion of PVU #2;
- Allowing the refinement of the velocity model for locating earthquake hypocenters and determining focal mechanisms;
- Providing more accurate measurements for determining principal stress orientations and minimum horizontal stress values; and
- Locate smaller, potentially seismogenic faults/fractures.

2.2 QUESTION 2. ARE EXISTING GEOLOGIC AND GEOPHYSICAL STUDIES ADEQUATE TO CHARACTERIZE THE SUBSURFACE STRUCTURE IN THE PARADOX VALLEY AREA AT A REGIONAL SCALE, FOR THE PURPOSE OF IDENTIFYING POTENTIAL WELL SITES?

The CRB recognizes that substantial progress has been made toward synthesizing regional geological and geophysical data to identify potential injection well sites for PVU #2. However, additional data are needed to aid in characterizing the target reservoir for injection:

- The application of emerging technologies for data collection and the application of modern integrated analysis/visualization techniques will make it possible to obtain the most comprehensive information possible using both existing data and any new data (Recommendations #8 and #13).
- There is a need to conduct detailed core studies of existing cores collected from the Leadville Formation (Recommendation #9). The core data will also facilitate the interpretation of the seismic data and sonic logs (see below).
- Before making final site selection among the alternatives in the southern new fault block (see **Figure 1** and Recommendation #1), we recommend performing a "regional" 3D seismic survey, but it must be designed to cover 60 square miles or more to encompass the two alternative target well sites (Recommendation #3). Such a 3D seismic survey is costly, but it can be designed with a sparse grid of shots and receivers. This design would constrain details of subsurface structure (stratigraphic thicknesses and presence of faults), but may not be effective for detailed reservoir characterization.
- We also recommend performing a higher-resolution 3D seismic survey at the site chosen for PVU #2 to provide needed information concerning reservoir characterization and completion of the well (Recommendation #3). Most valuable would be a nodal 3C seismic survey encompassing at least 15 square miles in the vicinity of the preferred site. A nodal seismic recording system is a cableless system, where data are recorded at each station without cabling to a central recording system. Individual stations are known as "nodes". This survey should be designed to incorporate a large number of multicomponent receivers while placing shot points or vibrating points wherever they can be placed. The survey may have to use both vibrators and heli-portable drills to provide adequate subsurface coverage. Analysis of both compressional and converted shear waves recorded by multicomponent receivers will provide enhanced reservoir characterization of the fault and fractures in the vicinity of the target well site. A logical path may be to do the large regional survey first, select the location for an exploratory well (see

below), then conduct a high-resolution 3D, 3C survey for detailed reservoir characterization.

The regional 3D survey will enable characterization of porosity and the fracture density in the Leadville Formation. Porosity is critical to provide storage capacity for the injected brine. The Leadville Formation is a karst reservoir; it is very heterogeneous and extensively fractured. The high-resolution survey will provide detail concerning the reservoir characteristics of the Leadville Formation in the vicinity of the preferred candidate site for PVU #2. Multicomponent seismic data allow for better porosity discrimination than do compressional seismic data alone. Azimuthal velocity studies of compressional and converted shear wave data can provide information concerning stresses in the subsurface and concerning the presence of fractures that provide the major control on permeability within the Leadville Formation and the Basement intervals.

- The seismic survey should be conducted in conjunction with drilling one or more "exploratory" wells (Recommendation #4). Following completion of drilling we recommend:
  - Logging with a cross-dipole sonic log or "sonic scanner;"
  - Acquiring 3D VSP data that will provide high-resolution seismic imaging in the vicinity of wells' bottom-hole locations, especially in the vicinity of the anticipated PVU #2 injection well; and
  - Instrumenting exploratory wells with fiber-optic cable for permanent, long-term monitoring purposes (see Recommendation #8). This monitoring system could also involve a surface array of multicomponent nodal receivers. That is, a subset of the receivers used in the seismic survey could provide a "sparse array," but the more dense nodal array and VSP data would constrain a velocity model precisely. Ultimately, as time passed this would provide the basis for a 4D survey that would dynamically characterize the reservoir during the initial "pressure up" period of the PVU #2 injection well.

2.3 QUESTION 3. HAVE POTENTIAL RESERVOIR FORMATIONS BEEN CHARACTERIZED ADEQUATELY, INCLUDING THEIR ESTIMATED DEPTH AND THICKNESS, SPATIAL EXTENT, PERMEABILITY, POROSITY, DEGREE OF HYDROLOGIC ISOLATION FROM THE CURRENT INJECTION WELL, AND THE PRESENCE OF A SUITABLE CONFINING LAYER?

If the PVU #2 well is drilled into the new fault block near either sites A or B in **Figure 1**, the reservoir formations that will be pressurized by brine injection are compartments of the Leadville Formation located south of a supposedly sealing boundary fault (designated as Fault A in **Figure 3**) situated just to the south of PVU #1. On the basis of existing data these formations have been characterized adequately. The available information includes 2D seismic reflection data (collected during various campaigns conducted prior to 1985, but recently reprocessed), logs from oil and gas wells drilled in the area, aeromagnetic and gravity data, and earthquake data (Block 2017; King et al. 2017).

However, these reservoir formations are highly heterogeneous, and there is a paucity of data regarding reservoir properties. Thus, the degree of confidence in the current characterization depends on various issues:

2.3.1 Degree of Isolation from the Current Injection Well

We are generally confident that the reservoir formations south of Fault A are hydraulically isolated from the PVU #1 injection well. Fault A appears to be an impermeable barrier as shown by three independent pieces of information: an offset of at least 500 ft deduced from the reprocessed 2D seismic surveys (Excel Geophysical Services 2016), the virtual absence of earthquakes south of fault A over the period of injection at PVU #1 well (Block 2017), and the generally successful match since 2000 between observed injection-pressures and numerical modeling simulations that assume fault A is impermeable (Detournay and Dzik 2016; see also **Figure 5**).

2.3.2 Estimated Depth and Thickness of the Reservoir

The estimation of reservoir depth and thickness is based mainly on the interpretation of seismic reflection data, well logs, and a gravity survey. However, there is significant uncertainty in these estimates for several reasons: the heterogeneity of the reservoir at the scale of the spacing between the 2D seismic lines, uncertainty concerning the seismic velocities used to interpret the seismic survey so as to constrain depth and formation thickness, and the quasi-absence of wells that have pierced the Leadville Formation within several miles from the potential well injection locations. Most of the existing wells are located along the southwest boundary of the area of interest. For example, the 2017 2D Seismic report on detailed site interpretation quotes depth errors for the Leadville Formation ranging from about 100 m to 450 m (Excel Geophysical Services and International Reservoir Technologies 2017).

2.3.3 Spatial Extent of the Reservoir

Based on the 2D seismic interpretation (**Figure 3**), there is reasonable confidence that the spatial extent of the reservoir in the new fault block is not locally compartmentalized. Although the 2D survey provides a reasonable preliminary basis for targeting this block for PVU #2 injection, further investigation is needed in the form of a 3D seismic survey at the preferred site, first at a coarse scale and then with subsequent refinement (Recommendation #3).

2.3.4 Permeability and Porosity

Little is known concerning the permeability and porosity for the relevant geographic regions within the Leadville Formation, i.e., those regions in the new fault block that will be pressurized by injection of brines at PVU #2. There are no direct measurements of the permeability while the porosity data, inferred from wells logs, mainly pertain to wells that are close to the southwest boundary of the area of interest.

2.3.5 Presence of a Suitable Confining Layer

The salt layer appears to cover the relevant region of the Leadville Formation, but its characteristics are incompletely constrained by the 2D seismic survey. Thus, uncertainty remains concerning both the extent and thickness of the salt layer.

2.4 Question 4. Have the Sites Been Characterized Adequately, Including Evaluation of Probable Flow Paths and Flow Barriers, Pressure-Flow Response, and the Potential for Induced Seismicity?

Sites have been well characterized given the available information, especially with respect to surface conditions, drilling complexities, major faults, and potentially sealing faults as inferred from the seismic reflection and microearthquake data. Information from PVU #1 and other wells suggests that flow paths are confined to portions of the Leadville and the upper basement where the porosity/permeability has been enhanced by fractures. Interpretation of available seismic reflection data suggests that reservoir compartments are bounded by flow barriers that are faults having 500 ft or more offset, where the Leadville are juxtaposed against salt.

The absence of seismicity to the south of the fault just south of PVU #1 supports this interpretation. The general spatial/temporal pattern of microearthquakes surrounding PVU #1 is consistent with a pressure-flow front in the Leadville Formation moving radially away from the injection point except in regions where it is restricted by a sealing fault. Wherever the front reaches a critically stressed fault it can induce microearthquake activity.

However, it would be valuable to obtain more detailed information concerning the hydrological properties of the Leadville Formation and basement rocks in the vicinity of sites A and B in **Figure 1**, the proposed injection zones (see Recommendation #1):

- Potential flow paths can be verified by well log/core analysis in an exploratory well (see Recommendation #4).
- A higher-resolution 3D seismic survey over the proposed injection zone will help assess whether faults are sealing, transparent, or leaky (Recommendation #3). Wellhead pressure curves for PVU #1 are well matched by both a simple radial diffusion model with negative skin and by a flow model containing compartmentalization

provided by two sealing faults. It is thus reasonable to assume that the proposed injection zones in the new fault block (sites A and B in **Figure 1**) will respond in a similar fashion, i.e., that the fluids injected at PVU #2 into the new fault block would not communicate across the supposed sealing fault and communicate with PVU #1's reservoir compartment.

- The 2D seismic reflection data available at present are unable to resolve the faults or fracture networks on which seismicity occurs; moreover, the larger faults that are identified from these data are aseismic. Since both the proposed injection zones to the south of PVU #1 (A and B in **Figure 1**) are currently aseismic, it is unknown whether or not critically stressed faults are present—a higher-resolution 3D survey might be able to detect potentially seismogenic faults. However, high-angle strike-slip faults are difficult to identify by interpreting seismic reflection data or data collected in exploratory wells (see below). Collecting and interpreting 4D and 3C seismic data may make it possible to monitor the pressure compartmentalization within the reservoir and to confirm that wells PVU #1 and PVU #2 are isolated from one another.
- Drilling one or more exploratory wells to allow associated log/core analysis will help confirm that the PVU #1 well and the target injection zone for PVU #2 have similar flow properties (see Recommendation #4). Drilling these wells will provide valuable information on the injectivity at the proposed site and the volume of the injection compartment.
- Additional modeling of the early injection history of PVU #1 can provide insight into the development/causes of enhanced permeability (thermal effects, hydrofracture, and reactivated fractures) near the wellbore as well as determine when the injection at the PVU #1 well first interacted with the supposedly sealing boundary faults (see Recommendation #11). It is also possible that seismicity above or below the Leadville Formation is induced both by pore pressure and also by poroelastic stress changes. Additional analysis/modeling could determine if poroelastic effects are important (see Recommendation #12).

2.5 QUESTION 5. HAS THE FEASIBILITY OF DRILLING, LOGGING, AND COMPLETING EXPLORATORY AND INJECTION WELLS AT THE PROPOSED SITES BEEN EVALUATED ADEQUATELY, INCLUDING REASONABLE CONSIDERATION OF GEOLOGIC FACTORS, AVAILABLE TECHNOLOGIES, RISKS, COSTS, AND BENEFITS?

Reclamation and their consulting team have performed a commendable preliminary technical evaluation of the feasibility for the drilling, logging, and completion for wells at the proposed sites. With the information available to them at the time of their report, the consulting team performed a reasonable review of the risks, costs, and benefits with the level of detail and uncertainty requested by Reclamation, and arrived at reasonable conclusions concerning their ranking of the six proposed wells for suitability as a site for PVU #2.

There are some gaps that should be considered for future analysis:

- Reclamation should consider drilling one or more low-cost expendable exploratory-only wells (see Recommendation #4). These wells would not ever be considered as potential sites for injection well PVU #2; however, if in a useful location, they could be converted to a long-term monitoring well. These wells should be designed to use the least amount of casing feasible with the minimal hole size needed for any core retrieval, wireline logging, logging while drilling (LWD) logging, mini-frac, and pressure tests. The drilling information that accrued from these wells would also be useful for reducing uncertainties in the engineering design for an injection well, should a site nearby be selected.
- We recommend undertaking a study targeting more specific surface and bottom hole locations for the two proposed sites (A and B in **Figure 1**; see Recommendation #5). These would consider surface issues as well as evaluate concerns about downhole trajectories. The completion technique used for the exploratory, monitoring, and final injection well will drive these well designs.
- For the two final areas of interest (A and B in **Figure 1**), Reclamation should develop a more comprehensive engineered approach for the construction of an injection well (see Recommendations #5, #6, and #7). Careful attention to these issues prior to drilling of any well is likely to significantly reduce costs, improve the performance of the well in operational mode, and reduce the possibility of well failures over both short-term (1 year) and long-term (decadal) time scales.

2.6 Question 6. If Existing Studies are Found to be Inadequate, What Additional Studies Should be Considered, and What Issues are They Likely to Resolve?

Prior to final site selection decisions concerning disposal alternatives for Paradox Valley brines, we urge Reclamation to seek additional expert technical review explicitly incorporating financial analysis of the various sites. The CRB was asked to assess technical issues related to the Second Injection Well Alternative—specifically issues related to choosing the site for and completing PVU #2. Although the CRB was not presented with a detailed financial analysis or asked to make decisions incorporating costs (and no member of the CRB is expert in this realm), our preconceived notions about these issues inevitably influenced our recommendations in this report. Recommendation #1 provides one example of this: the CRB favors the Dolores River Valley surface sites for

PVU #2 because of perceived infrastructure costs; however, in the absence of cost considerations the Monogram Mesa sites are clearly superior.

The 13 Recommendations of the CRB (see above) and our answers to Questions 1-5 are quite specific concerning the limitations (and strengths) of existing studies. These recommendations fall into two categories:

- Recommendations that Reclamation staff or their contractors clearly anticipated; i.e., recommendations that already have been suggested in the materials in Appendix B or during the oral presentations listed in Appendix C. In some cases the CRB has expanded or enhanced what had previously been suggested. These anticipated recommendations address:
  - Ranking of candidate wells (Recommendation #1);
  - Undertaking 3D seismic survey(s) (Recommendation #3);
  - Drilling exploratory and monitoring well(s) (Recommendation #4); and
  - Undertaking a more comprehensive engineering design study at proposed well site(s) (Recommendation #5).
- Recommendations from the CRB that were not implied or explicitly mentioned in Reclamation reports or presentations. These possibly unanticipated recommendations address:
  - If a surface site on the Monogram Mesa is chosen, installing and operating seismic stations for at least 2 years prior to commencing injection at PVU #2 (Recommendation #2);
  - Undertaking a design analysis of corrosion-resistant materials appropriate for all facility components in contact with brine at the proposed PVU #2 facility (Recommendation #6);
  - Undertaking a study focusing on anticipating salt movement in the Paradox Salt formation at candidate well sites (Recommendation #7);
  - Developing a program that employs various newly emerging technologies for monitoring well performance (Recommendation #8);
  - Analyzing existing cores collected from the Leadville Formation to provide better information concerning porosity, permeability, faulting, and seismic velocities, and the variability of these parameters (Recommendation # 9);
  - If a Dolores River Valley surface site is chosen, undertaking a modeling study to assess how proximity to the supposedly

sealing boundary fault may affect well feasibility, design, and bottom-hole location for the PVU #2 well. This study should be informed by published information collected at existing wells concerning salt composition/rheology and/or by reanalysis of existing salt samples collected at these wells (Recommendation #10);

- Undertaking a modeling study evaluating pressure-volume data collected over more than two decades at PVU #1, with the objective of better understanding porosity, permeability, and their variation over time within the Leadville Formation (Recommendation #11);
- Developing a comprehensive 20-km-scale 3D geomechanical model that aims to match data collected over the past 25 years to inform management decisions and predict the response to future injection (Recommendation #12); and
- Implementing a comprehensive program utilizing modern visualization software that integrates data collection, data management, interpretation, and geomechanical modeling (Recommendation #13).

2.7 QUESTION 7. ARE THERE OTHER ISSUES, OPPORTUNITIES, OR CONCERNS THE CRB BELIEVES ARE APPROPRIATE TO RAISE CONCERNING THE EVALUATION OF POTENTIAL SECOND INJECTION WELL SITES FOR THE EIS?

We urge Reclamation to take a very long-range view (50-100 years) as they evaluate strategies for disposing of Paradox Valley brines. The fault-bounded block to the south of PVU #1 is very large—substantially larger than the fault-bounded block into which PVU #1 currently injects—with potentially much greater capacity than the PVU #1 injection zone. Moreover, available information suggests the new block is hydrologically isolated from the current injection zone. This new fault-bounded block is sufficiently large that it is plausible that both the Dolores River Valley and Monogram Mesa locations could be utilized for injection in sequence over a 50-100 year period. This is important, because the need to dispose of Paradox Valley brines will certainly persist over this time interval and longer.

Two areas (Dolores River Valley and Monogram Mesa) have been identified as generally viable locations for a second injection well. Based on current information, the Dolores River Valley area is favored over the Monogram Mesa area. However, additional information is needed prior to drilling a second injection well. Especially important are the 3D seismic data needed to verify the structure of the reservoir and the presence of the top seal (salt), and to determine whether bounding faults are sealing. 3D seismic data can also improve estimates of porosity (and thus capacity for injection) of the Leadville Formation. Exploratory wells are needed to verify the porosity within the Leadville Formation and to measure both *in situ* stress and pore pressure.

Additional modeling and engineering analysis will also help to determine the best well location and completions method.

The CRB discourages Reclamation from selecting one location over another prematurely. Rather, we encourage the BoR to pursue a careful workflow with multiple decision points that utilizes new information as it is obtained, and does not lose sight of very long-range project objectives.

Finally, if Reclamation ultimately decides NOT to pursue the Second Injection Well Alternative, the CRB recommends that for a minimum of 4 years after injection ceases at PVU #1, operation of the Paradox Valley seismic network must continue, and monitoring pressure, etc., in the PVU #1 well and any available monitoring wells must also continue. There are three reasons for this:

- Past experience indicates that induced earthquakes may persist for several years following the cessation of injection, and sometimes these include the largest events associated with an injection project.
- If at some future time, even 20 or 30 years hence, a decision is made to install a second injection well in Paradox Valley, the data collected in the years following shutdown of PVU #1 could be essential for understanding the size and transport properties of reservoirs in Paradox Valley and surrounding regions, and thus informing the design for a future well.
- The earthquake data collected, and the technical analyses performed since the 1980s for the PVU project, are comprehensive and remarkable, especially because they span an interval prior to injection and continue throughout the injection process. Continuing data collection will allow future scientific researchers to utilize these data and draw conclusions that may reduce risks and costs associated with future efforts to dispose of liquid brines in the Paradox Valley, and worldwide as well.

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CHAPTER 3
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Appendix A
Consultant Review Board Members

APPENDIX A
CONSULTANT REVIEW BOARD MEMBERS

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Appendix B

List of Material Provided by Bureau of Reclamation

APPENDIX B
LIST OF MATERIAL PROVIDED BY BUREAU OF RECLAMATION

Reclamation provided the following documents to the CRB for consultation during their independent scientific review. This is not a list of literature cited in this report; that is included in **Chapter 3**, References.

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Appendix C

List of Presentations Made at the CRB Meeting in Denver, July 25-27, 2017

APPENDIX C
LIST OF PRESENTATIONS MADE AT THE CRB MEETING IN DENVER, JULY 25-27, 2017

1. Paradox Valley Unit EIS Alternatives Studies, Introduction. US Bureau of Reclamation.
2. Compilation of Well Data. US Bureau of Reclamation.
3. Geology. David List.
4. Paradox Valley Unit Seismic Data Interpretation. Project Overview by John F. Arestad, Ph.D.
5. Consultant Review Board (CRB) Meeting Paradox Bain Gravity and Aeromagnetics Interpretation. Michal Ruder, Wintermoon Geotechnologies, Inc.
6. Identification of Deformation in Paradox Valley using InSAR. US Bureau of Reclamation.
7. Integrated Geologic Model. US Bureau of Reclamation.
8. Paradox Valley Project, Geomechanical and Flow Modeling, Verification Tests, Results for Biotcoefficient < 1, and Detailed Results. Christine Detournay, Ed Dzik, Itasca Consulting Group, Inc.
9. Deep-Well Drilling Appraisal and Feasibility Study, Paradox Valley Unit. Lewis Wandke, P.E.; Hal Demus, M.S.; Ken Cooper, P.E.; Petrotek Engineering Corporation.
10. Integrated Geologic Model In Situ Stress. US Bureau of Reclamation.

11. Seismicity and Pressures Following the 2013 Change in Injection Operations at the Paradox Valley Unit. US Bureau of Reclamation.

12. Seismicity Constraints on Geologic Structure. US Bureau of Reclamation.

13. Paradox Valley Unit EIS Alternatives Studies, Site Selection. US Bureau of Reclamation.