Linking Desalinization Technologies to Geothermal Greenhouse Operations

Students and Faculty Explore Mason Radium Springs Geothermal Greenhouse (20 Acres)

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IWG Date: November 6-8, 2015

IWG Locations: Truth or Consequences, NM & Masson Radium Springs Greenhouse

1. SUMMARY

1.1 Objectives

Our innovative working group (IWG) explored the potential linkages and synergies between different desalination technologies and direct use of geothermal waters for and aquaculture operations in New Mexico. Applications to bio-algal industry were also discussed. In addition, we considered how geothermal heat could be used to increase the effectiveness and reduce the cost of desalination of oil field brines. We discussed opportunities to craft these ideas into upcoming water-energy proposals and papers.

1.2 Key Ideas & Questions

Linking geothermal and desalination technologies has not received much attention to date; however, such synergy can have significant environmental and economic benefits both locally and globally. We are only aware of one study that uses desalination (of seawater) to provide water to greenhouses. That study did not use geothermal energy (Mahmoudi et al. 2010). Several important questions were outlined at our IWG that need to be addressed by future studies/proposals: What would be the long-term hydrologic/thermal impacts of desalinating produced geothermal fluids and/or oil field brines? Do the long-term impacts affect large regional-scale topographically driven geothermal systems? What is the distribution of brackish water throughout the state of NM and in arid regions around the world? How does brackish water volume compare to freshwater resources? Are the produced water temperatures and volumes sufficient to provide the energy needed to enhance desalinization processes? How could the membranes used for geothermal distillation be modified to minimize the thermal leakage and at the same time, maximize the water flux? Are different geothermal fluid compositions and produced water salinities better suited for different agricultural, bio-algal, and industrial applications? Can geophysical techniques (e.g. TEM-MT systems) be used to quantify brackish water resources and identify optimal drilling targets? What regulatory hurdles would face using desalinated fluids in greenhouse and oil field operations?

Three transformative ideas linking desalination and geothermal technologies were discussed during our weekend meeting and are described below. Following our IWG meeting, we developed a document that fleshed out some of the ideas and questions initially discussed at our meeting. The material exceeded the page-limit requirements of this summary document. We have included this material in an appendix.

Idea 1: ***Reducing the Risk of Thermal Breakthrough in Direct Use Geothermal Operation using Desalination Technologies.*** Re-injection of large volumes of spent, cool geothermal fluids back into a geothermal reservoir after the heat is extracted can degrade a thermal resource through time (Stefansson, 1997; Shook, 2001). In New Mexico, thermal cooling of the fractured dike geothermal reservoir at Radium Springs was initially detected at the Masson Farms geothermal greenhouse. This required drilling a much deeper geothermal well to deal with this problem. Desalination of brackish geothermal fluids could be used for greenhouse irrigation, reduce the volume of re-injected water, and help to maintain reservoir temperatures. We developed some back of the envelope calculations to substantiate this idea (see Appendix, p. 13-14). Possible degradation of reservoir chemistry and permeability resulting from injection of concentrated fluids after desalinization were also discussed.

Idea 2: Using Membrane Technologies with Lower Energy Footprints for Desalination of Geothermal Fluids. Forward osmosis and membrane distillation (MD) are desalination technologies with potentially lower energy footprints than reverse osmosis (RO). Membrane distillation is particularly attractive because geothermal fluids could be used as an energy source. MD has many advantages compared with other separation methods. MD has theoretically complete rejection of inorganic compounds. This type of system can be operated at lower temperatures than other separation processes, and is therefore able to utilize waste heat, geothermal heat, and solar heat. MD is also relatively less sensitive to membrane fouling and feed salinity and is therefore able to treat high-salinity brackish waters (Adham, 2013; Hickenbottom and Cath, 2014). Reducing the thermal leakage not only can increase the water flux by maximizing the temperature gradient but also would enhance the energy efficiency of the process, allowing the possible utilization of low-grade heat from geothermal fluids.

Idea 3: Using Geothermal Heat to Drive Desalination Operations in Oil Producing Basins. Desalination oil field brines using humidification-dehumidification technologies requires a source of heat to enhance the amount of water that can be transferred to the vapor phase. A humidification-dehumidification system deployed in the Permian Basin by Dr. Balch used solar-thermal methods to heat the water (Balch and Muraleedharan, 2014). We propose that using the heat from the produced fluids can also be used to drive this operation (or make the systems more efficient when combined with solar thermal systems). This system produces freshwater at a rate of about 0.25 gpm. It can be scaled up to treat larger volumes of water.

1.3 Outreach Plans

We put together a one page ideas document, which we presented to Anne Jakle and William Michener at a recent town hall meeting at NM Tech on Nov. 20th. We will also work on an editorial style manuscript exploring the synergies between desalination of brackish water and the direct use geothermal industry.

2. Outcomes

2.1 Proposals

EPSCoR Track-1 Energy Center Proposal: We plan to advocate to the NM EPSCoR program the benefits of exploring the linkages between geothermal energy and desalination technologies in New Mexico. We will craft a white paper on this topic in preparation for the Track-1 Energy center proposal this spring. We have contacted Dave Hanson at UNM regarding possible synergies integrating these concepts with those of the bio-algal group for this white paper.

US Bureau of Reclamation Desalination Program Proposal, $150,000 for research and laboratory studies. Deadline is Feb. 8, 2016. Shari Kelley, Mark Person, Talon Newton, and Stacy Timmons will work on this proposal.
http://www.usbr.gov/newsroom/newsrelease/detail.cfm?RecordID=51727

NSF Food, Energy and Water Systems (INFEWS) NSF has recently announced a new program entitled "Innovations at the Nexus of Food, Energy and Water Systems to find sustainable ways to manage the food-water-energy system. We will explore the possibility of submitting a proposal on this topic when an appropriate RFP appears.
http://www.nsf.gov/pubs/2015/nsf15108/nsf15108.jsp

DOE Water Energy Nexus: When appropriate, we will submit grants to the DOE on the upcoming water energy nexus program.
http://energy.gov/downloads/water-energy-nexus-challenges-and-opportunities

2.2 Papers

Mark Person along with his students and collaborators has begun to explore the consequences of reduced volumes of oil-field brine reinjection (due to desalination) on induced seismicity as part of a manuscript to be submitted to a thematic issue entitled "Role of Pore Pressure in Naturally-Triggered and Human-Induced Seismicity" for the journal Geofluids. The guest editors for this thematic issue are Paul Hsieh, John Bredehoeft, and Katie Keranen. This manuscript is entitled, "*Exploring the Potential Linkages Between Oil-Field Brine Reinjection, Crystalline Basement Permeability, and Triggered Seismicity for the Dagger Draw Oil Field, Southeastern New Mexico, USA Using Hydrologic Modeling*". The manuscript is available on demand.

Jim Witcher, Mark Person, and Shari Kelley will work on an editorial format paper exploring the benefits of direct use geothermal for the journal EOS Transactions. This manuscript will promote the direct use industries that are in New Mexico and discuss the potential benefits, among other things, of desalination technologies.

3. Participants

Robert Balch, Senior Scientist and Section Head, Petroleum Research and Recovery Center, NMT. Humidification-Dehumidification Desalination Technologies. With support from RPSEA, Balch built and tested a pilot Humidification-Dehumidification Desalination facility within the Permian Basin, SE NM in collaboration with Harvard Petroleum.

Laura Crossey, Professor and department head, UNM, Department of Earth & Planetary Science. Crossey focuses on using noble gas geochemistry to infer the presences of magmatic geothermal systems across the Basin and Range. She and her partner, Karl Karlstrom have promoted the idea of "continental smokers".

Frank Huang, Professor of Civil and Environmental Engineering, NMT, Huang has developed a fabrication laboratory developing membranes for desalination processes. His research focus has been on osmotic power generation.

Jesus Gomez-Velez, Assistant Professor of Hydrology, NM tech. Jesus' research focuses on the analytical and numerical modeling of flow and transport in hydrogeologic systems. He is an early-career faculty in the Department of Earth & Environmental Sciences at NM Tech.

Karl Karlstrom, Geology, Department of Earth & Planetary Science. Karlstrom's research focuses on regional continental tectonics and using noble gas geochemistry to infer the presences of magmatic geothermal systems across the Basin and Range.

Shari Kelley, Research Scientist, NM Bureau of Geology & Mineral Resources. Heat flow geophysicist working on New Mexico geothermal resources. Kelley was a co-PI on several geothermal exploration grants in the last five years funded by the Department of Energy.

Mark Person, Professor and Head of Hydrology Program, NM Tech. Person uses mathematical modeling to understand the plumbing of geothermal systems across the western USA. Person was a PI and co-PI on several geothermal exploration grants in the last five years funded by the Department of Energy.

Randy Shaw, Facility Manager of the Brackish Groundwater National Desalination Research Facility, Alamogordo, NM; Manages the Brackish Groundwater National Desalination Research Facility of the Bureau of Reclamation in Alamogordo NM. Provided an overview of the Bureau of Reclamation research program and facilities.

Qiang Wei, NM Highlands University, Department of Chemistry, Research Scientist,. Wei's research focuses on membrane fabrication technologies.

James Witcher, James Witcher & Associates. Geothermal Industry Consultant. Witcher has authored numerous papers on NM geothermal system. He is widely seen as one of the leading advocates in the USA for direct use geothermal energy.

Jianjia Yu, Section Head, Produced Water and Petroleum Engineering. Petroleum Research and Recovery Center, NMT Fabrication of hollow fiber membrane technologies for water use reduction by petroleum industry.

Appendix

Innovative Working Group

On November 6-8, our team met as part of an NSF-EPSCoR sponsored innovative working group (IWG) in the spa town of Truth or Consequences, NM to consider the synergies between geothermal and desalination technologies. The meeting brought together experts in desalination technologies (Balch, Huang, Wei, Yu, Shaw) with geothermal scientists (Kelley, Witcher, Person, Crossey, Karlstrom). Each participant presented their work on geothermal and desalination science on Saturday (Table 1). On Sunday we visited Mason Radium Springs greenhouse. Jim Witcher was our tour guide (Fig. 1-2).

Table 1. *Presentations*

	Saturday, Nov 7, TorC, City Commission Chambers, 405 West 3rd St. Truth or Consequences NM	
Start Time	**Title**	**Speaker**
10.00	Welcome & Introduction to IWG Exploring the Synergies between Geothermal & Desalination	Mark Person (NMT)
10.30	New Mexico Geothermal Resources, Potential, and Uses.	Jim Witcher (Consultant)
11.30	Overview: Bureau of Reclamation Desalination Center	Randal Shaw
12.00	Lunch & Discussions	
1.00	Geothermal Resources of the Raton Basin	Shari & Richard Kelley (NMBRMR-LANL)
1.30	Geochemical Characteristics of Geothermal Fluids in NM	Laura Crossey Karl Karlstrom (UNM)
2.00	NSF-EPSCOR Osmotic Power Generation Program	Frank Huang (NMT), Qiang Wei (ENMU)
2.30	Desal using Humidification-Dehumidification Processes	Robert Balch (PRRC)
3.00	Deep Geothermal Systems within the Basin & Range: MT data and numerical modeling	Jesus Gomez-Velez (NMT)
3.30	Hollow Fiber Membrane based Technology for Produced Water Remediation	Jianjia Yu (PRRC)
4.00	Discussion & Writing Assignments	
5.00	Break	
6.30	Dinner Bella Luca	

Sunday, Nov 8, TorC, City Commission Chambers, 405 West 3rd St. Truth or Consequences NM

8.00	Discussion & Future Work
10.15	Depart for Mason Geothermal Greenhouse
3.00	Head for Home

Geothermal Resources in New Mexico

New Mexico is ranked 7th in the USA for its known geothermal resource potential (Williams et al. 2008). The State of New Mexico is endowed with relatively high background heat flow (Roy et al. 1972) and permeable, fractured bedrock (Mailloux et al. 1999, Pepin et al. 2015). This combination has given rise to numerous low-temperature geothermal systems throughout the state (Summers, 1976; Summers and Colpitts, 1980; Barroll and Reiter, 1990; Witcher, 2002a-h). These geothermal resources are part of convective systems (Smith and Chapman, 1983) with hot water discharge occurring in the lowland portion of watersheds through hydrologic windows. Mailloux et al. (1999) and Pepin et al. (2015) argue that these convective systems have relatively vigorous fluid circulation to depths of 4-8 km.

New Mexico geothermal fluids are brackish (500 to 5000 mg/l) with temperatures that range between 40-100 °C (Figure 3). Conductive geothermal resources also exist within the state of New Mexico, primarily within the oil and gas producing Raton, Permian and San Juan basins in NE, SE and NW New Mexico, respectively (dark blue patterns in the lower left and upper right and left corners of the state of Figure 4). Conductive geothermal reservoirs are essentially oil reservoirs that contain high heat due to their depth of burial rather than due to vigorous fluid circulation. Salinities of conductive resources are typically much higher (up to 200,000 mg/l; Figure 5) owing to their long residence time and fluid rock interactions with evaporite minerals. The temperature of these conductive geothermal fluids ranges between 30 to 75 °C (Figure 5).

Over the past several decades, geothermal greenhouses (e.g. Burgett Greenhouse, Lordsburg, NM; Masson Farms Greenhouse, Radium Springs, NM) and aquaculture facilities (Americulture, Lordsburg, NM) were established in southern New Mexico. Geothermal agribusiness accounts for over $12M in gross receipts (Witcher 2002a). In arid regions of the world, growing crops within greenhouses can have the added benefit of consuming less water relative to irrigated crops growing outdoors (Orgaz et al 2005). Across the USA, direct use of geothermal energy has grown by 72% between 2005-2010 to about 48,500 MWt (Lund, 2010). Geothermal greenhouses are attractive to the agricultural industry because they utilize low-temperatures (40 to 80 °C) fluids, which are often abundant at shallow depths (Lund, 2010; Karytsas et al. 2003). They also produce many jobs at a variety of educational levels when compared to electrical power plants that utilize geothermal energy.

Desalination Technologies in the Western USA

In arid regions of the world, desalination of brackish water is increasingly considered to be an unconventional water resource (Jaber and Mohsen, 2001). Desalination technologies include reverse osmosis (RO), forward osmosis (FO), membrane distillation (MD), thermal distillation (TH), and dehumidification-humidification (DH) techniques. Thermal distillation techniques are energy intensive and have not been widely deployed. Reverse osmosis methods create a pressure gradient across an osmotic membrane sufficient to overcome the natural osmotic pressure (Shannon et al. 2008). This method is considered the most economic when implemented at the large scale (thousands of m^3/day; Bourounia et al. 2001). State-of-the-art RO facilities can use as little as 2.2 kWh to generate a cubic meter of freshwater from seawater (Shannon et al. 2008). Membrane distillation (MD) is a separation process that relies on vapor pressure difference to drive the production of distilled water across the membrane (Susanto, 2011). There has been growing interested in DH technologies because of their economic benefits when deployed at the small scale (Bourounia et al. 2001). This may be ideally suited for processing oil field brines, as described below.

RO desalination facilities require significant amounts of energy and capital. However, interest in desalination technologies is growing within the State of New Mexico during the past decade due to growing water shortages during drought conditions and the perceived abundance of untapped deep brackish water reservoirs. The Bureau of Reclamation established a desalination research center near Alamogordo, NM to stimulate desalination research in NM and across the western USA. In El Paso, TX, a large scale desalination facility was constructed that is capable of producing 27MGD. The facility is being used during periods of drought or water shortages. Relatively shallow (> 500 m), brackish fluids (1000-5000 mg/l) are produced and treated using hollow fiber membrane technology.

Within the petroleum industry, there is great interest in desalination of oil field brines to treat produced waters within oil basins. Typically, co-produced waters are highly saline (100,000-200,000 mg/l), warm (40-80^{o}C) and contain organic compounds. These are typically reinjected into deep saline formations. Due to high transportation costs, reinjection is relatively expensive (typically ~ $2.5/barrel). Trucking oil field brines also adds additional societal costs due to its impact on infrastructure. Injection of high volumes of produced water have been linked to induced seismicity (up to M5.8) across the western USA (Zhang et al. 2013; Wiengarten et al. 2015). To date, the waste heat from these produced fluids are typically not used to drive the desalination process. The fluids are stored in separation tanks to await reinjection.

Assessing the Temperature and Salinity of New Mexico’s Geothermal Systems and Oil Field Brines

As part of this IWG, we have compiled data sets of the salinity and temperature of geothermal fluids in New Mexico (Figure 3) and oil field brines in the Permian Basin of southeastern NM (Figure 5). We note that almost nothing is known about the volume and depth of non-thermal brackish water resources around the state of New Mexico and arid regions of the world. The elevated temperatures of oil and gas field brines could be used to improve the efficiency of desalination systems (e.g. humidification-de humidification).

Thermal Consequences of Desalination

Re-injection of large volumes of spent, cool geothermal fluids back into a geothermal reservoir can degrade the thermal resource through time (Figure 6). A great deal of work has been done to determine optimal well distance and re-injection rates for fractured bedrock reservoirs to delay thermal breakthrough (Stefansson, 1997; Shook, 2001). In New Mexico, thermal cooling of the fractured dike geothermal reservoir at Radium Springs was initially detected at the Masson Farms geothermal greenhouse. This required drilling a much deeper geothermal well to deal with this problem.

The idea of desalination of brackish geothermal fluids for irrigation to reduce the volume of re-injected water and help to maintain reservoir temperatures was an important outcome of our IWG discussions. Consider the following example (see Table 2 for fluid and rock properties). A 100 m^3 fractured rock reservoir has an initial enthalpy (total heat) of $1.98x10^{14}$ Joules (J). This reservoir is filled with brackish, geothermal fluids, has porosity of 5%, an initial temperature of 90 ^{o}C , and a fluid density of 1010 kg/m^3 . The enthalpy (H) of the geothermal reservoir is given by:

$$H = \phi c_f \rho_f V_T + (1-\phi) c_r \rho_r V_T = 1.9x10^{13} J + 1.78x10^{14} J = 1.98x10^{14} J$$

where H is the total enthalpy of the reservoir, ρ_f is the fluid density, ρ_r is the rock density, c_f is the fluid specific heat capacity, c_r is the rock specific heat capacity, ϕ is porosity, V_T is the total volume of the reservoir. Let's assume that 10% of the fluids are produced. Assuming no cooling of the rock mass, if these fluids are reinjected at a lower temperature of 50 ^{o}C, then the total enthalpy of the fluid decreases from $1.9x10^{13}$ J to $1.69x10^{13}$ J resulting in a changing in total enthalpy of about 0.9%.

If, on the other hand, 4500 m^3 of fresh water is produced for irrigation and 500 m^3 of brine is reinjected at a lower temperature of 20 ^{o}C, then the fluid enthalpy of the reservoir after reinjection is higher ($1.88x10^{13}$) owing to the 90% decrease in the volume of the fluid reinjected (albeit at a lower temperature and enthalpy). The total change in system enthalpy is 0.1% for this scenario.

Table 2. Fluid and Rock Properties of a 100 m^3 Geothermal Reservoir Prior to and after Re-Injection

50000	Initial Reservoir Fluid Volume (m^3)
4185	Specific Enthalpy Fluid (J/kg/^{o}C)
90	Initial Temperature of Fluid (^{o}C)
1010	density of reinjected Fluid (kg/m^3)
1.90208E+13	Total Reservoir Fluid Enthalpy (J)
950000	Initial Reservoir Rock Volume (m^3)
790	Specific Enthalpy Rock (J/kg/^{o}C)
2650	Density Rock (kg/m^3)
90	Initial Temperature of Rock (^{o}C)
1.78994E+14	Rock Enthalpy (J)
5000	Reinjected Fluid Volume (m^3)
4185	Specific Enthalpy Reinjected Fluid (J/kg/^{o}C)
50	Temperature of Reinjected Fluid (^{o}C)
1010	Density of reinjected Fluid (kg/m^3)
1.05671E+12	Total Reservoir Fluid Enthalpy (J)
500	Reinjected brine Volume (m^3)
3500	Specific Enthalpy Reinjected Brine (J/kg/^{o}C)
20	Temperature of Reinjected Brine (^{o}C)
1200	Density of reinjected Brine (kg/m^3)
4.20E+10	Total Reservoir Fluid Enthalpy (J)

The desalinated fluids can be put to beneficial use within the greenhouse, increasing the sustainability of the geothermal operation in arid regions. Producing deep brines does not compete with shallow water users. However, the effects of possible pressure drops and other hydrologic impacts caused by the re-injection of less fluid volume need to be assessed. Very little is known about the long term consequences of producing (i.e., mining) brackish aquifers. Producing large volumes of water from shallow, unconsolidated formations can lead to land subsidence (Galloway et al. 1999). Regulatory questions about the consumptive use of the irrigation water derived from the geothermal fluid need to be addressed.

Using Membrane Technologies with Lower Energy Footprints for Desalination of Geothermal Fluids

Forward osmosis and membrane distillation are desalination technologies with potentially lower energy footprints than RO. Membrane distillation is particularly attractive because of lower energy consumption if geothermal fluids are used as a source of heat. MD has many advantages compared with other separation methods. MD has theoretically complete rejection of inorganic compounds. This type of systems can be operated at lower temperatures than other separation processes, and is therefore able to utilize waste heat, geothermal heat, and solar heat. MD is also relatively less sensitive to membrane fouling and feed salinity and is therefore able to treat high-salinity brackish waters (Adham, 2013; Hickenbottom and Cath, 2014).

MD membranes are typically made from hydrophobic polymers, such as polypropylene (PP), polyvinylidene fluoride (PVDF), and polytertafloro ethylene (PTFE). The hydrophobic membrane acts as a barrier to hold the liquid/vapor interfaces at the entrance of the pores, where only vapor is able to pass through the membrane. A lot of research has been focused on the impact of contact angle, porosity, pore size, pore-size distribution, and thickness on the water flux. For geothermal-based membrane distillation, we are particularly interested in the modifications of MD membranes to minimize thermal leakage from membrane conduction. For example, PVDF membranes typically have a thermal conductivity of 0.12 W/m-K and this translates to significant thermal leakage (loss) of 390 kW per m^2 of membrane for a temperature gradient of 50 °C and a membrane thickness of 100 μm. Reducing the thermal leakage not only can increase the water flux by maximizing the temperature gradient but also would enhance the energy efficiency of the process, allowing the possible utilization of low-grade heat from geothermal fluids.

Using Geothermal Heat to Drive Desalination Operations in Oil Producing Basins

Desalination oil field brines using humidification-dehumidification technologies requires a source of heat to enhance the amount of water that can be transferred to the vapor phase (Figure 7). The system deployed in the Permian Basin by Dr. Balch used solar-thermal methods to heat the water. We propose that using the heat from the produced fluids can also be used to drive this operation (or make the systems more efficient when combined with solar thermal systems). This system produces freshwater at a rate of about 0.25 gpm. It can be scaled up to treat larger volumes of water.

Geophysical Methods to Detect Brackish Water Resources

One promising approach to assess the volume of brackish water resources is the use of electromagnetic methods such as magenetotelluric, audio magnetotelluric, and transient electromagnetic techniques. Magnetotellurics (MT), audio-magnetotellurics, (AMT) and Transient Electromagnetics (TEM) are surface geophysical imaging methods that can be used to determine the distribution of fresh and brackish water resources between depths of 500-1000 m (TEM, AMT) to over 10 km (MT). The TEM method has been used for decades in coastal aquifer studies to locate the freshwater-seawater interface (e.g. Marksammer et al. 2009). MT imaging has been used for exploration of geothermal systems (Wannamaker et al. 2003) and for exploration of ore deposits (Zonge et al. 1991), but can also be used to delineate fresh to saline waters at great depths. MT utilizes naturally occurring electromagnetic waves generated by lightning and the interaction between solar winds and the Earth’s magnetosphere to measure electromagnetic induction within the Earth (Simpson and Bahr, 2005). The MT method is used to image the electrical conductivity (or resistivity) of rocks and fluids in the subsurface. Saline fluids are better conductors of electricity compared to fresh water. The TEM system induces an electromagnetic wave by passing a current through a 100m by 100 m copper wire loop as different frequencies. This method also measures the relative conductivity and resistivity of subsurface materials.

Because brackish water and brines are much more conductive than freshwater, they can potentially image subsurface water quality variations. TEM methods have typically been used in coastal aquifers aquifers to detect the mixing zone between fresh and salt water (Marksammer et al. 2009). NM Tech recently acquired both of these systems. MT methods have been used to identify geothermal systems at depths of up to 10 km (Wannamaker 2003).

MT and TEM methods have not typically been applied to study the distribution of freshwater and brackish waters in New Mexico. Some recent studies (Meqbel et al. 2013; Jiang et al. 2014) have begun to apply AMT and MT methods to assess salinity and groundwater flow patterns to depths hundreds of meters to several km (Figure 8). We think the time is ripe to apply these methods in New Mexico to explore for brackish water resources and geothermal systems. Dry alluvial material with air in its pore spaces is a relatively poor electrical conductor and has a high formation resistivity in the range of 120 to 400 Ohm/m (Figure 9). For freshwater saturated sands, electrical current moves primarily through the fluid phase. For relatively freshwater (20-50 mg/l TDS) formation resistivity ranges between 80-120 Ohm/m. Increased amounts of dissolved solids equates to increased ability to conduct electricity. Brackish water having a salinity of about 3000 mg/l, significantly decreases electrical resistivity to between 2-10 Ohm/m.

Regulatory Issues

The institutional, regulatory, and legal framework for geothermal desalination is tied to the variably arranged matrix of 1) owner of the surface land estate, 2) owner of the groundwater estate (generally, the State of New Mexico and permitted and licensed appropriated water rights), 3) owner of the geothermal mineral estate and lease holders, and 4) where geothermal is co-produced with oil and gas, the owner of the oil and gas estate and lease holders. The various land, water, and mineral estates may have only one owner as in the lands of the State of New Mexico. In others areas, the mineral estate may have been severed or even removed from the surface estate. In terms of dominance, the mineral estate has higher priority than the surface estate. In terms of priority, environmental and water quality concerns may give the ground water estate dominance over the mineral estate whether it is geothermal or oil and gas.

Geothermal energy is not water and is defined as a mineral by the Federal 1970 Steam Act where geothermal production is from the Federal mineral estate and requires a royalty. There are different royalty rate schedules depending upon whether the production is electrical power and how it is sold or whether it is direct use of geothermal heat. In New Mexico, geothermal produced from the State mineral estate is subject to royalty if the produced fluid is 121 ^{o}C and above and permitting is done through the New Mexico Oil Conservation Division (OCD). If the fluid produced is less than 121^{o} C, then the permitting is done through the New Mexico Office of the State Engineer (OSE) and no royalty is assessed and the water production is subject to New Mexico water law.

In general, New Mexico is owns the surface and subsurface water estates, except water that is reserved for Federal jurisdiction, such as in stream flow for wildlife, and reserved by interstate and international water agreements or compacts. However, New Mexico's surface and groundwater maybe privately permitted and licensed as an appropriated right for diversion and beneficial use. An appropriated right is a conditional property right that may be sold, leased, or traded. If the water is not applied for a period of time to beneficial use, the water right may be subject to forfeiture or abandonment, removing entitlement security. This issue could be important for geothermal desalination in case the geothermal operator shuts down for an extended period of time, goes out of business, or is no longer able to provide the heat or electrical energy for desalination. The means that the water right could be in jeopardy after four years of neglected use.

Use of geothermal resources for desalination has many layers of legal, regulatory, and permitting issues, and institutional domains and many are uncharted or tested in practice. Clearly, the economic application of desalinized water could be considered as a beneficial use and may be consistent with the Doctrine of Prior of Appropriation that is one of the foundations of New Mexico water law.

Several scenarios of geothermal desalination matrix are considered below with an outline of process jurisdiction to identify potential problems or hurdles that exist. The interface of geothermal and water is largely dependent upon dynamics of private, State, and Federal mineral (geothermal) estate with State water law. Potential "deep conductive" geothermal resources can clearly co-exist with the "deep" oil and gas production and co-produced brines of high temperature. Geothermal could provide an important solution to the managing co-produced brines with an economic benefit. An institutional, regulatory, and legal scenario will also be discussed for "oil patch" geothermal desalination.

The private geothermal mineral estate provides an example of the simplest scenario, water use from the geothermal desalination would be a fairly straightforward, provided the geothermal production was from the private mineral (geothermal) estate and the temperature was less than 121^{o} C and the end beneficial user of desalinated water has a consumptive water right with the OSE. This scenario requires well permits and authorization to pump or produce water from the wells for beneficial use from the ground water basin that applies. Injection would require authorization from the OCD consistent with the New Mexico Water Quality Control Commission (WQCC) and EPA rules applying to Class V injection wells.

State and Federal geothermal production requires a lease. In general, acreage is required to be nominated and a lease auction is held under both State and Federal rules. However, there is an exception under Federal leasing rules. If direct-use, the Federal lease is non-competitive, provided no competing applications are submitted with in a set time period starting with the initial application.

The State geothermal mineral estate requires a geothermal lease for production of fluids greater than 121^{o} C. Different royalty schedules apply for electrical power and direct-use.

The direct-use royalty rate is similar to the Federal formula and would apply to geothermal desalinization. The OCD permits the geothermal wells and production/injection and collects production data. For geothermal production at temperatures less than 121^{o}C, the OSE permits the geothermal wells and collects production data. Injection would be under the rules of the WQCC administered by the OCD.

The Federal geothermal mineral estate requires a geothermal lease for production of fluid and a royalty is due on production, whether for electrical power or direct-use. The U. S. Bureau of Land Management (USBLM) manages well permitting and production, with consultation with other Federal lands managers, if for example the geothermal lease is on National Forest Land. The U. S. Office of Natural Resource Revenue (ONRR) collects royalties and production data. In addition, the OCD also permits the wells and production and collects production data.

Co-production of geothermal (extraction of heat from produced “brines”) with oil and gas production raises a number of ownership and legal issues which probably go beyond current case law and may require legislative solution or administrative solution where all parties consult and agree.   For instance, an oil and gas lease does not allow extraction of heat or geothermal for desalination purposes. Therefore, the operator would require an oil and gas lease in addition to a geothermal lease. If the geothermal generates binary organic Rankine cycle (BORC) electrical power, then the geothermal lease would have to be acquired through a competitive lease sale where Federal minerals apply. With Federal minerals a non-competitive lease is allowed for direct-use.

Another potential problem rotates around the fact that the hydrocarbon fraction of the fluid production contains the highest value and would be the dominant estate for a lease operator; but, the hydrocarbon selling price can be highly volatile and an operator may wish to increase or decrease production in concert with the market while the geothermal desalination product, beneficial use of water, is tied to a particular annual acre-ft appropriation. Depending upon the beneficial use of the desalinated water, a drop below a certain threshold may not sustain a particular direct-use or fresh water end user business model. A sustainable and mutually compatible and beneficial scenario of hydrocarbon and geothermal would need to be engineered.

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Figure 1. *Inside view of Mason-Radium Springs 20-acre geothermal greenhouse. Looped pipes above plants circulated fluids heated by brackish geothermal waters. Heat exchangers transfer heat from the geothermal fluids to a freshwater loop used by the greenhouse.*

Figure 2*. Jim Witcher (left) standing next to a geothermal well at Radium Springs. Dr. Shari Kelley (NMBRMR) is in the foreground. To the right of Dr. Kelley is Jeff Pepin (grad student, NMT), Randy Shaw (BOR), Qiang Wei (NMHU), and Jesus Gomez-Velez (NMT).*

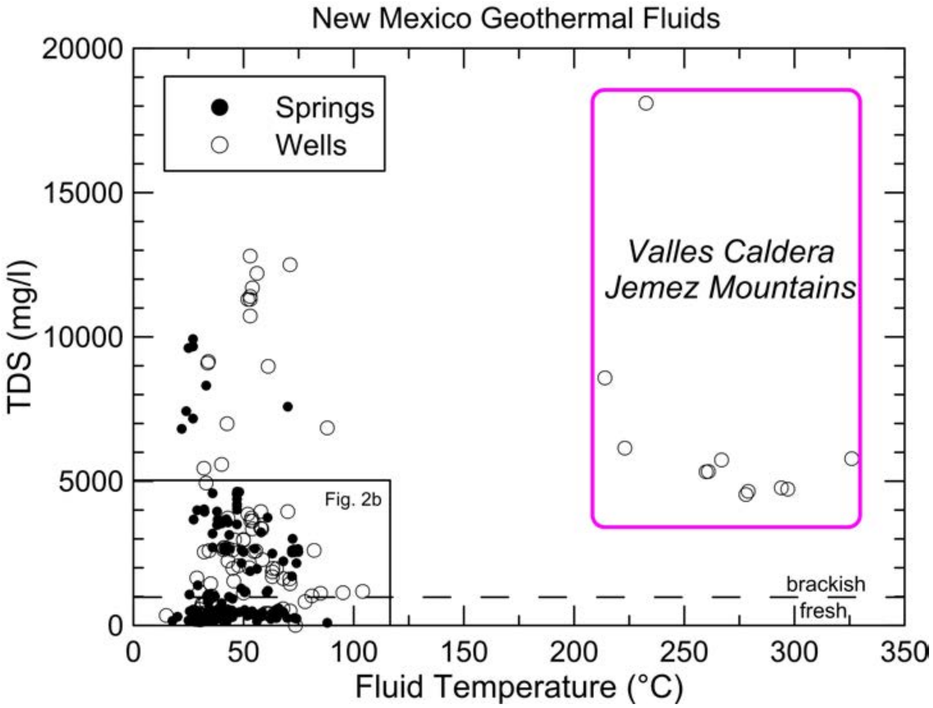

***Figure 3a**. Range of temperatures and salinities of all New Mexico geothermal fluids.*

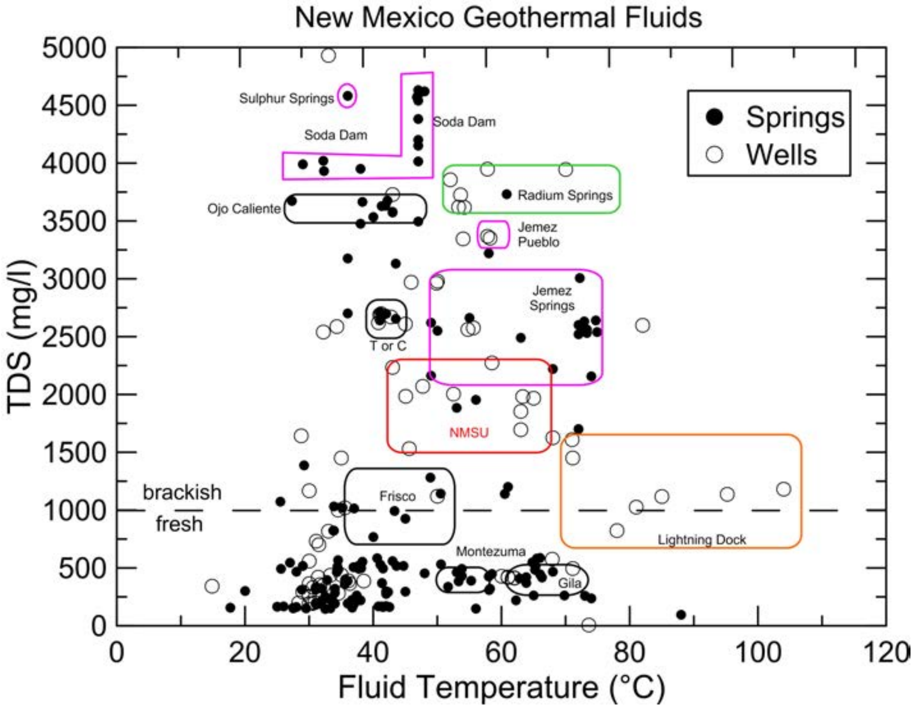

***Figure 3b.** Range of temperatures and salinities for geothermal fluids with TDS<5000 mg/l. The purple lines outline springs and wells associated with the Valles caldera outflow plume.*

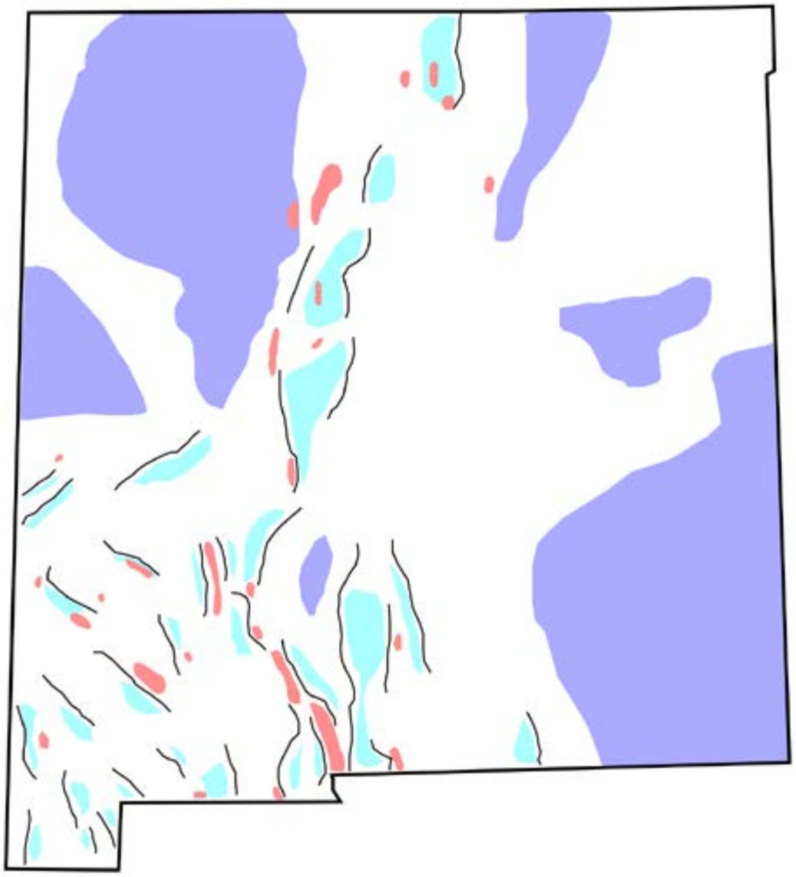

Figure 4. *Generalized geothermal resource map of New Mexico. Red: Convective systems, light blue: Deep Conductive Systems in relatively young (Tertiary) Basins; dark blue: Deep Conductive Geothermal Systems in relatively old Paleozoic and Mesozoic Basins.*

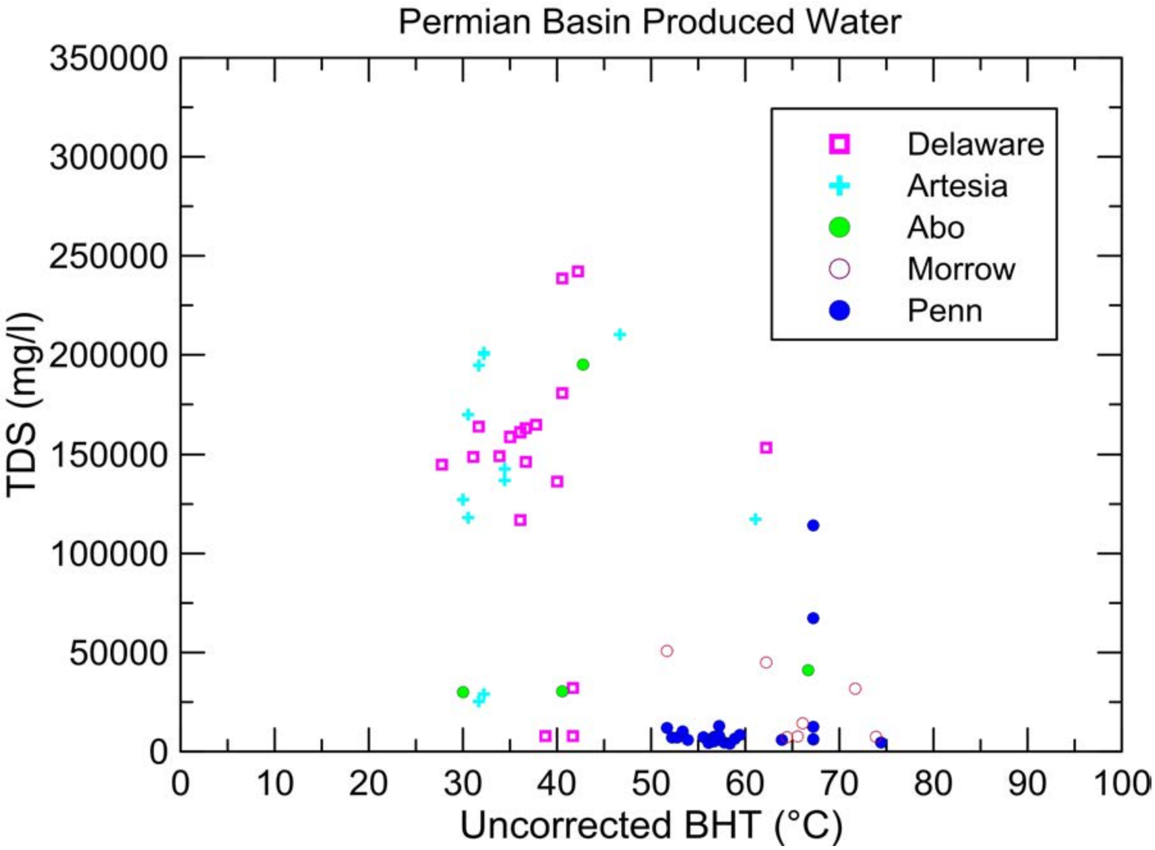

Figure 5. *Bottom hole temperatures (uncorrected) and salinity in five rock units within the Permian Basin of SE New Mexico (source: USGS Produced waters , OCD, and NMBGMR). Note that fluids in the older (deeper) Morrow and Pennsylvanian (Penn) strata are warmer and are generally less saline.*

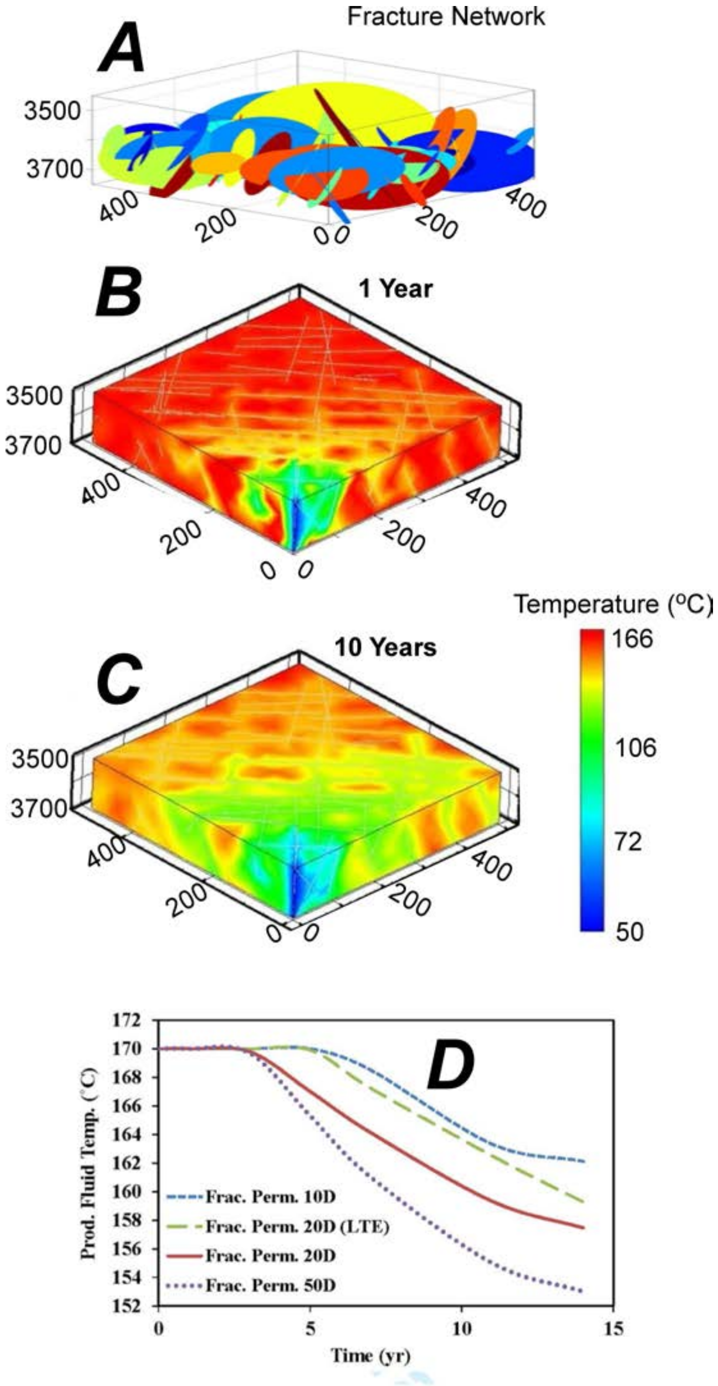

Figure 6. *Numerical model of thermal breakthrough of a fractured geothermal reservoir (Doonechally et al.,2015).*

Solar Thermal Units

Trailer holding HD Unit

Humidification-Dehumidification Unit

Schematic Diagram of Humidification-Dehumidification Unit

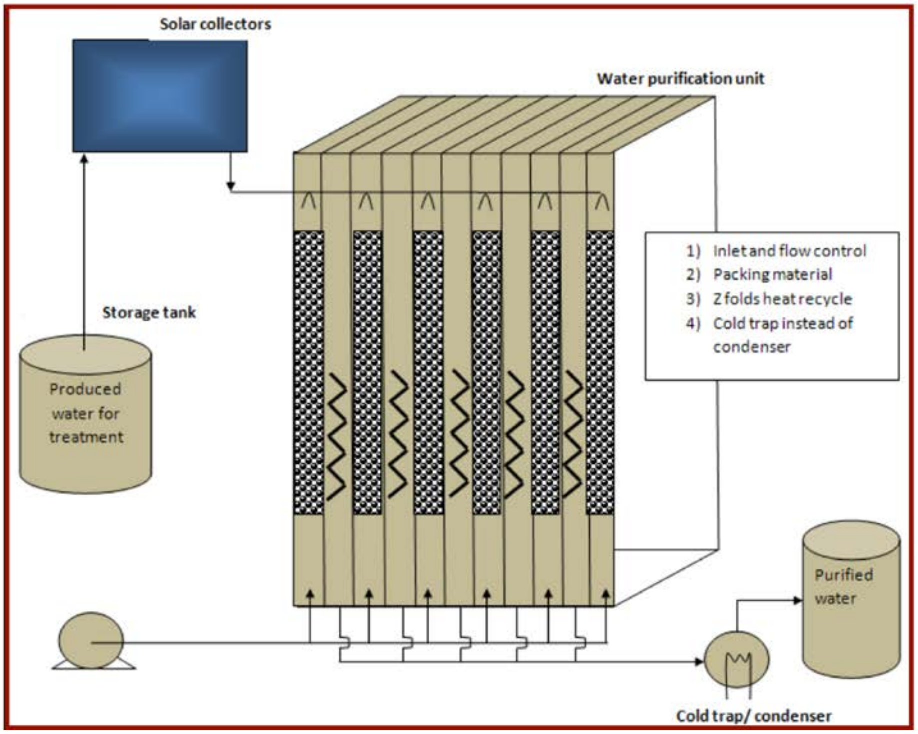

Figure 7. *Schematic diagram and photos of Permian Basin Humidification-Dehumidication Desalination system of Dr. Robert Balch, NM Tech Petroleum Resource and Recovery Center.*

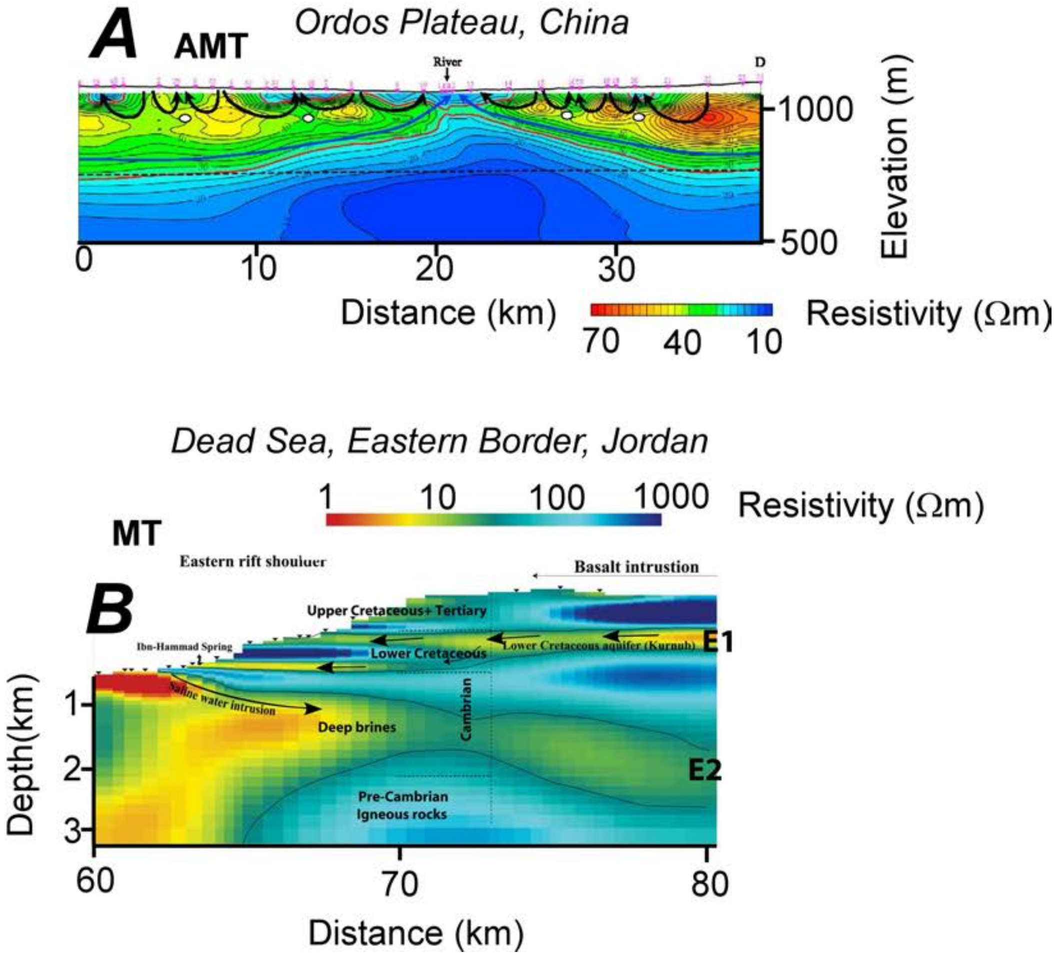

Figure 8. *(A) Inferred groundwater flow patterns (arrows) across Ordos Plateau, China using resistivity patterns from AMT survey. The circles denote stagnation zones where salinity is hypothesized to build up (after Jiang et al. 2014). Inferred groundwater flow directions using resistivity patterns from MT survey of the Dead Sea Rift, Jordan (after* Meqbel et al. 2013).

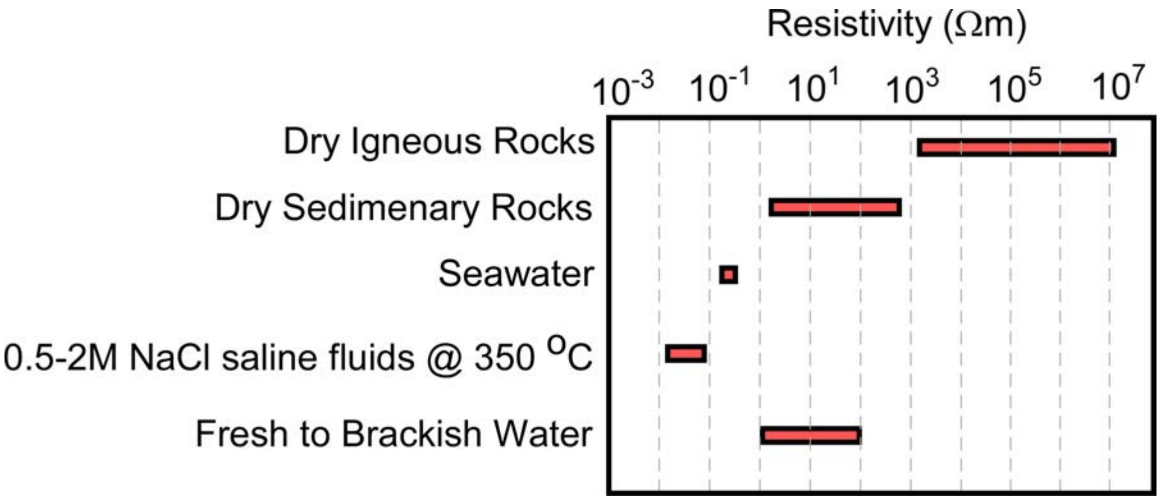

Figure 9. *Resistivity of different drained (fluid absent) geologic units, fresh, and saline water (after Simpson and Bahr, 2005).*