Loss of CO$_2$ Gas into Formation Water at the Natural CO$_2$ Deposit of Bravo Dome, New Mexico, USA*

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Abstract

Bravo Dome Field, in the NE corner of New Mexico, contains approximately 10 Trillion cubic feet of 98% pure CO$_2$ in the Permian age Tubb Sandstone formation on top of granite basement beneath a regional seal of the Cimmaron Anhydrite formation at the Eastern edge of the Quaternary Raton-Clayton Volcanic field. The trap for the deposit is a lateral facies change to the NW of the Tubb Sandstone draped over the SW plunging Sierra Grande uplift. The field is approximately 49 miles NW-SE and 50 miles NE-SW.

Evidence from distribution of noble gases in 14 wells spread across the field shows that within eight miles of the down-dip gas water contact in the east part of the field, CO$_2$ has left the reservoir by dissolution in the underlying formation water. Noble gases have partitioned into the CO$_2$ from the water. In the west the noble gases and their isotopes are in low concentrations and distinctive of the mantle. In wells to the east the noble gases increase in concentrations because they have entered the CO$_2$ from the water. The gradient allowed calculation of mantle concentration of the gases (Ballentine et al., 2005).

However, the $^3$He increases because it is left behind as the CO$_2$ dissolves in the water.

Maps of variation of each noble gas (except xenon, radon) will be presented, each showing an increase in concentration from west to east across the field. A surprise was that $^3$He doubles in concentration at the gas/water contact to the east, yet it is not carried in any quantity by the water below the field. The accumulation of $^3$He near the gas-water contact is therefore due to depletion of CO$_2$ in the gas due to dissolution in the underlying water.

From the doubling of $^3$He concentration at the gas-water contact one can surmise half of the volume of the CO$_2$ has been lost at the gas-water contact. More detailed calculations will be shown. The continued dissolution of the CO$_2$ into the brine may be favored by the sinking of the
dense CO₂ saturated water away from the gas-water contact. The mass transport of CO₂ away from the gas-water contact is due to natural convection and much larger than diffusive mass transfer and may explain the observed large ^3He build-up.

In summary, it is highly probable that CO₂ has been lost downdip in formation water, and this may well be a general situation in nature (Gilfillan et al., 2009) and in CO₂ sequestration projects.

**Selected References**


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Plan of Presentation

• Introduction and objective of investigation.

• Plate tectonic setting of CO$_2$ deposits in the Western USA and Geologic setting of Bravo Dome.

• Possible CO$_2$ sources and use of isotopes of carbon and noble gases to indicate the source of CO$_2$ at Bravo Dome.

• Examination of noble gas distribution in Bravo Dome showing it to be a dynamic CO$_2$ deposit changing with time.
Location Bravo Dome CO$_2$ natural gas field and associated basalt extrusive flows and intrusive centres of the Cenozoic Raton-Clayton volcanic field. (modified from Broadhead, 1993).
Tectonic Setting
Western US > 50% CO₂

Field | CO₂
-- | --
St Johns | 14.8 TCF
Bravo Dome | 10 TCF
Sheep Mtn. | 2 TCF
McElmo D. | 10 TCF
La Barge Platform | 100+ TCF

55 Significant deposits of gas, CO₂ over 50%
Typical carbon isotope values of major sources of CO$_2$ in the subsurface

After Thrasher & Fleet, 1995; Wycherley, 1999.
$^{3}\text{He} / ^{4}\text{He}$ R/Ra various geologic settings

From Cassidy, 2005; Newell et al., 2005; Graham, 2002; Ballentine et al., 2001; Sherwood Lollar et al., 1997.
Slow P wave velocity indicates mantle that is tectonically active and partly molten, High $^3$He/$^4$He/Ra in spring waters and gas deposits shows mantle access. Modified from Newell et al., 2005.
Helium 3 ($^3$He)  
Marker of the Mantle  

• Stable isotopes of Helium are $^3$He and $^4$He.  

• Helium 3 ($^3$He) is created in stars, including our sun, but it is not created on earth by any common process.  

• $^4$He is also created in stars but that in the earth is primarily from radioactive decay of uranium and thorium.
• $^3\text{He}$ now in the earth is from the original accretion. It is still leaking to the surface.

• From the atmosphere helium gradually escapes into space, unlike other noble gases that accumulate in the atmosphere. Helium content is $5.24 \times 10^{-6}$ cc/cc.

• The ratio in air of $^3\text{He}/^4\text{He}$ is $1.4 \times 10^{-6}$.

• That ratio in air (Ra) is the standard to which is compared the ratio of $^3\text{He}/^4\text{He}$ in subsurface gases.

• Helium from the upper mantle has an Ra of about 6 to 12 Ra, helium from the crust has .02 to .04 Ra.
Average Gas Composition

Bravo Dome
Tubb Sandstone Reservoir

<table>
<thead>
<tr>
<th>Compound</th>
<th>Average % (6 different wells)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>99.6266</td>
</tr>
<tr>
<td>N₂</td>
<td>0.1991</td>
</tr>
<tr>
<td>He</td>
<td>0.0168</td>
</tr>
<tr>
<td>H₂</td>
<td>0.0132</td>
</tr>
<tr>
<td>Ar</td>
<td>0.0033</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.0005</td>
</tr>
<tr>
<td>O</td>
<td>ND</td>
</tr>
<tr>
<td>H₂S</td>
<td>ND</td>
</tr>
<tr>
<td>CO</td>
<td>ND</td>
</tr>
</tbody>
</table>

Producing Reservoir Depth | 2500' - 3000'
Original Reservoir Pressure | 336 to 1082 psi
Reservoir Temperature | 92°F at 2400ft
Tubb Sandstone
Cimmaron Anhydrite
Abo
2500'
Figure 3.2-4A. Bravo Dome Field structure map at top of Tubb Sandstone. The gas-water contact is shown at top Tubb Sandstone and is poorly defined to the southwest.
# Noble Gases Concentration

## Air and Bravo Dome, cc/cc

<table>
<thead>
<tr>
<th>Noble Gas</th>
<th>In Air</th>
<th>BD West</th>
<th>BD East</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He</td>
<td>$7.36 \times 10^{-12}$</td>
<td>$1.87 \times 10^{-10}$</td>
<td>$4.00 \times 10^{-10}$</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$5.24 \times 10^{-6}$</td>
<td>$3.1 \times 10^{-5}$</td>
<td>$41.46 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{20}$Ne</td>
<td>$1.07 \times 10^{-5}$</td>
<td>$1.03 \times 10^{-9}$</td>
<td>$7.00 \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{36}$Ar</td>
<td>$3.08 \times 10^{-5}$</td>
<td>$1.10 \times 10^{-9}$</td>
<td>$14.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>$9.30 \times 10^{-3}$</td>
<td>$2.40 \times 10^{-5}$</td>
<td>$6.52 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{84}$Kr</td>
<td>$1.14 \times 10^{-6}$</td>
<td>$0.473 \times 10^{-10}$</td>
<td>$5.04 \times 10^{-10}$</td>
</tr>
</tbody>
</table>
Figure 3.2-11. Distribution of $^3$He/Ra in sampled wells at Bravo Dome Field.
Figure 3.2-8B. Distribution of $^3$He in sampled wells at Bravo Dome Field.
Figure 3.2-8A. Distribution of $^4$He in sampled wells at Bravo Dome Field.
1. Original magmatic gases fill Tubb Sandstone above dike sweeping water and noble gases down dip.
2. CO₂ dissolves in water laterally down dip.
3. Noble gases enter CO₂ laterally from water down dip.
History of Bravo Dome Gas Deposit.

1. CO₂ degassed from basalt magma of dike below field.

2. Rising through cracks in granite basement it entered and collected in the first reservoir with effective seal.

3. It swept down-dip connate water with noble gases.

4. CO₂ dissolves in the water leg, noble gases remain in reservoir and more noble gases enter from the water leg. Noble gases accumulate in the CO₂ with time.
Conclusions

1. Bravo Dome field is sourced from the mantle.

2. It is likely western US CO$_2$ deposits are sourced from the mantle.

3. CO$_2$ deposits are found in association with basic igneous rocks where they pierce sedimentary section with reservoirs and seals.

4. CO$_2$ gases carry noble gases distinctive of their source.

5. CO$_2$ deposits change with time as the gas dissolves in down dip water and noble gases enter the CO$_2$.

6. CO$_2$ escapes from the trap in moving formation water.
Acknowledgements

Thanks to the operators of Bravo Dome, Amoco, then BP, and now Occidental and also Hess for allowing sampling, providing data, consultations, and support of the project over the last several years.

Thanks are due to many individuals but especially to Herb Wacker, Steve McCants, Danny Holcomb, and David DeFelice, who are or were with of Oxy and Profs. Lawrence, Chafetz, Casey, and Burke of the University of Houston.

General funding for study of CO$_2$ in the subsurface has been provided by the University of Houston, by Amoco, and through a grant from Unocal. A new study by Prof. Marc Hesse and Ph. D. graduate student Kiran Sataye is funded by the NSF.

Dr. Chris Ballentine made all the analysis of the Noble gas content and isotopes in Bravo Dome gases.
Hypothesis

CO$_2$ rises in ultramafic basalt mantle magma.

It brings with it noble gases distinctive of the mantle.

It exsolves and enters the first porosity above basement. If seals are present it is trapped.

CO$_2$ dissolves in underlying and down dip water columns. The deposit is ephemeral in geologic time!
Productive Section
Bravo Dome field
1. Original magmatic gases fill Tubb Sandstone above dike sweeping water and noble gases down dip.
2. CO₂ dissolves in water laterally down dip.
3. Noble gases enter CO₂ laterally from water down dip.
Noble Gases in a Nutshell

- **He, Ne, Ar, Kr, Xe**
- **Three Sources**
  - Groundwater (air)
  - Crust (Radiogenic)
  - Mantle
- **Isotopically Distinct**
  - Resolvable
- **Quantify interaction/origin of fluids sourced from these different regions**
Comparison of Noble Gas Fingerprints

BD11 / BD2

BD7-BD2

BD5 / BD2

Noble Gas Fingerprints

BD11/BD2

Percentage of BD2

BD5/BD2

Noble Gas