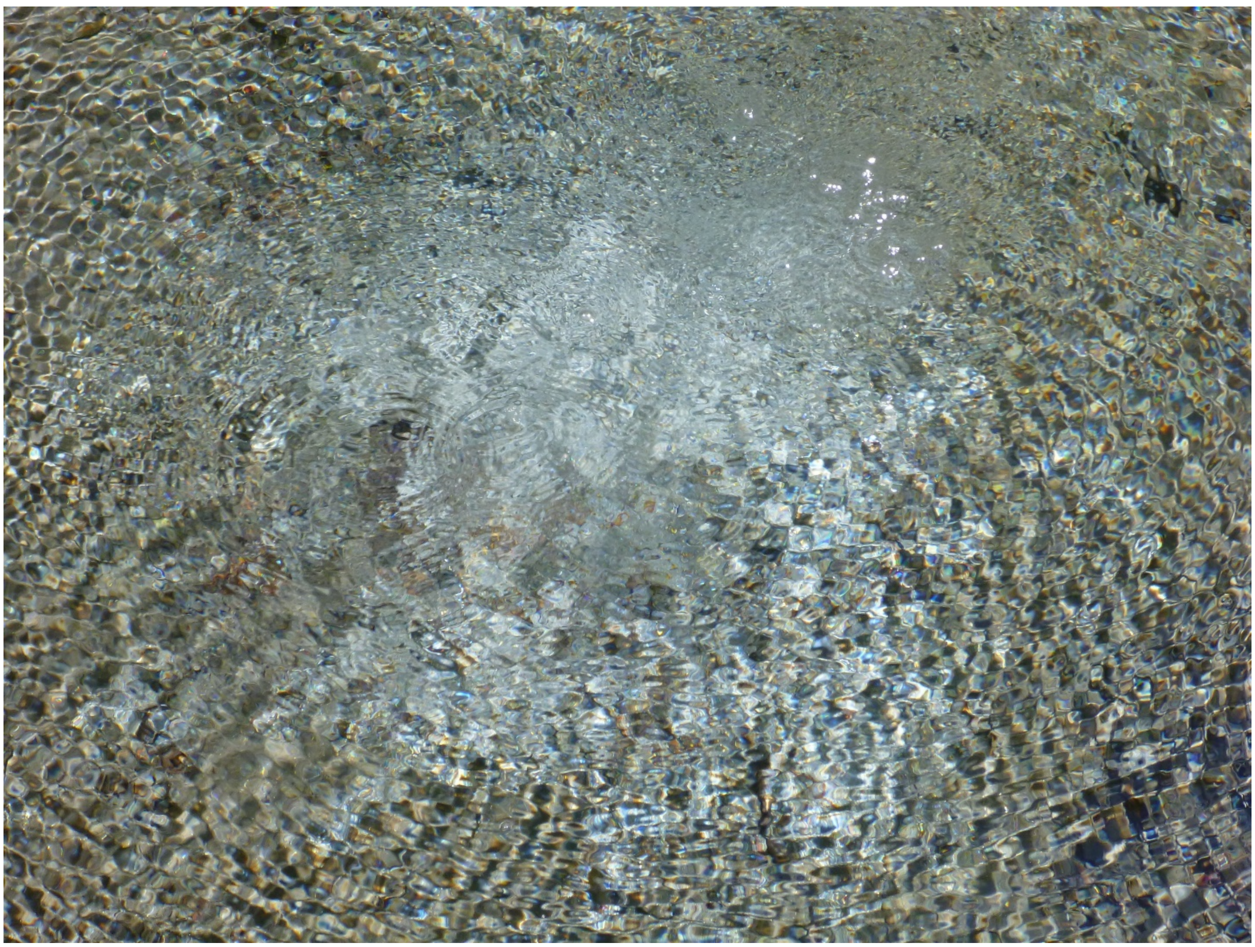
# Noble Gas Isotopes in Mineral Springs and Wells within the Cascadia Forearc, Washington, Oregon, and California

By Patricia A. McCrory, James E. Constantz, and Andrew G. Hunt



Open-File Report 2016–1203

U.S. Department of the Interior
U.S. Geological Survey

**Cover.** Close-up photo of gas bubbling up through a warm spring located alongside Elk Creek in Sulphur Springs Campground, California. Credit: Patricia McCrory, 2014.

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We would also like to thank the private landowners who permitted access to mineral springs and water wells on their land in Washington and Oregon, namely, Berry Family Nursery, Jackson WellSprings, Johan Vineyards, Jones Farm, Lithia Springs Resort, Mark Baird, Johna Cook, Ilsa Perse and Jake Rockwood, and Richard and Elaine Watkins, as well as the cities of Auburn and Lacey, Washington, and Kitsap PUD. Noble gas data on eight additional sites within the Cascadia forearc can be obtained at https://doi.org/10.3133/ofr20141064.

# Contents



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# Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| | Mass | |
| pound, avoirdupois (lb) | 0.4536 | kilogram (kg) |

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Volume | |
| liter (L) | 0.2642 | gallon (gal) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.
Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).
Molar volume is defined at 1 atmosphere pressure and 0 °C as: 1 mole = 22.414 liters.

# Abbreviations

| | |
|---|---|
| $A_e$ | initial amount of entrapped air per unit mass of water, given in cc STP/g |
| AEW | air equilibrated water |
| ASW | air saturated water |
| ASSW | air saturated sea water |
| Ar | argon |
| $^{36}Ar$ | argon-36 |
| $^{38}Ar$ | argon-38 |
| $^{40}Ar$ | argon-40 |
| BDL | below detection limit |
| cc | cubic centimeter |
| cc/g | cubic centimeter per gram of water |
| cc STP | cubic centimeter at standard temperature and pressure |
| cc STP/cc | cubic centimeter at standard temperature and pressure per cubic centimeter of water |
| cc STP/g | cubic centimeter at standard temperature and pressure per gram of water |
| CE | closed-system model |
| $CH_4$ | methane |
| $CO_2$ | carbon dioxide |
| E | scientific notation defining the exponent of ten (x $10^E$) |
| F | known fragmentation factors of specified gas for mass of gas species |
| He | helium |
| $^3He$ | helium-3 |
| $^4He$ | helium-4 |
| kg | kilogram |
| Kr | krypton |
| $^{84}Kr$ | krypton-84 |
| $^{86}Kr$ | krypton-86 |
| MAP | mass analyzer products |
| $N_2$ | nitrogen |
| Ne | neon |
| $^{20}Ne$ | neon-20 |
| $^{21}Ne$ | neon-21 |

| | |
|---|---|
| $^{22}Ne$ | neon-22 |
| NGRT | noble gas recharge temperature |
| $O_2$ | oxygen |
| P | probability that $X^2$ exceeds the observed value |
| QA | quality assurance |
| QC | quality control |
| $R/R_A$ | observed $^3He/^4He$ value normalized to atmospheric value |
| $R_C/R_A$ | $R/R_A$ corrected for potential air contamination |
| STP | standard temperature and pressure (0 °C, 1 atmosphere) |
| torr | unit of pressure used in measuring partial vacuums, equal to 1/760 of a standard atmosphere |
| trit | tritium |
| Xe | xenon |
| $^{130}Xe$ | xenon-130 |
| $^{132}Xe$ | xenon-132 |
| $X^2$ | sum of the weighted squared deviations between modeled and measured noble-gas concentrations, summed over all samples in data set (chi-squared test) |

## Symbols

| | |
|---|---|
| > | greater than |
| < | less than |
| ° | degree |
| °C | degrees Celsius |
| % | percent |
| ± | plus or minus |

## Datum

Vertical coordinate information is referenced to the World Geodetic System Earth Gravitational Model Geoid of 1996 (WGS84 EGM96 Geoid).

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS84).

Elevation, as used in this report, refers to distance above mean sea level.

# Noble Gas Isotopes in Mineral Springs and Wells within the Cascadia Forearc, Washington, Oregon, and California

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## Introduction

This U.S. Geological Survey report presents laboratory analyses along with field notes for an exploratory study to document the relative abundance of noble gases in mineral springs and water wells within the Cascadia forearc of Washington, Oregon, and California (fig. 1). This report describes 14 samples collected in 2014 and 2015 and complements a previous report that describes 9 samples collected in 2012 and 2013 (McCrory and others, 2014b). Estimates of the depth to the underlying Juan de Fuca oceanic plate beneath sample sites are derived from the McCrory and others (2012) slab model. Some of the springs have been previously sampled for chemical analyses (Mariner and others, 2006), but none of the springs or wells currently has publicly available noble gas data. The helium and neon isotope values and ratios presented below are used to determine the sources and mixing history of these mineral and well waters (for example, McCrory and others, 2016).

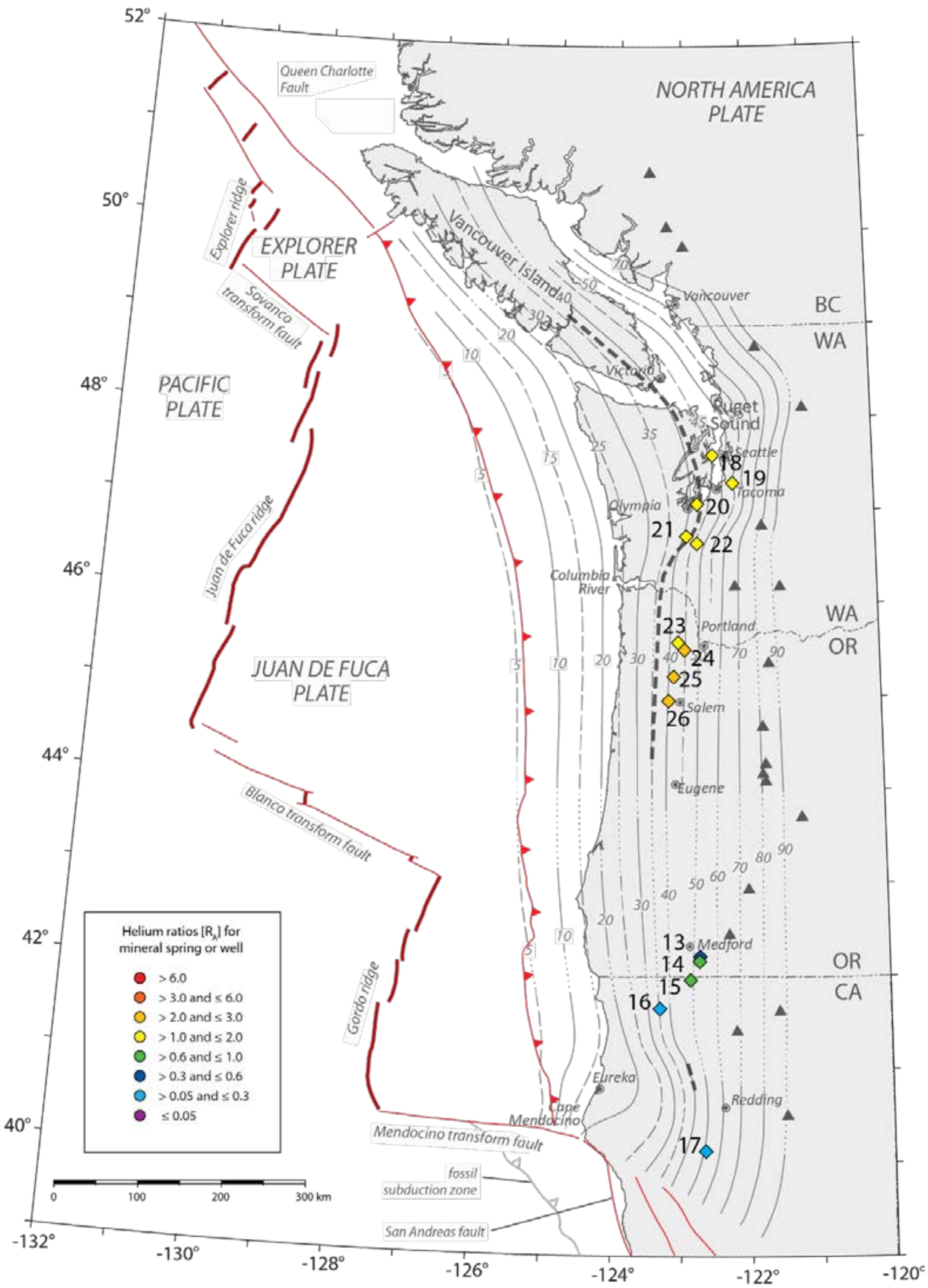


Figure 1. Map showing the location of mineral spring and well sites with respect to Juan de Fuca plate model of McCrory and others (2012) and the location of the forearc mantle corner (McCrory and others, 2014b). Isodepth contours of the Juan de Fuca slab are in kilometers below surface. Thick dashed line marks the inferred location of forearc mantle corner (Liu and others, 2012; McCrory and others, 2014b); labeled colored diamonds denote new sample sites; black diamonds denote earlier sample sites (McCrory and others, 2014a). Gray triangles indicate the location of Cascade arc volcanoes. Transverse Mercator projection, WGS84 datum, standard parallel long 128° W, centered at lat 46.8° N., long 128° W., with standard parallel rotated 3° clockwise of vertical (plate boundaries modified from Wilson, 2002).

# Methods

## Field

We collected water samples from the mineral springs and water wells in copper tubes that were pinched shut at each end with metal clamps, after first establishing siphon flow through Tygon tubing attached to both ends of each 18-inch length of copper tube. The copper tube was tilted so that water flowed vertically upward during collection. We then gently tapped the outside of the copper tube before tightening the downstream clamp to release any bubbles that might be stuck to the inside wall of the tube. The nuts on the downstream clamp were slowly tightened using a torque wrench set to 10 foot-pounds (ft-lbs). After the downstream clamp was closed, we closed the upstream clamp. Finally, we removed the Tygon tubes, filled both ends of the copper tube with spring water to add an additional barrier to leakage, and sealed the ends with rubber caps.

We determined sample site locations and elevations using a handheld GPS device that employs horizontal and vertical WGS84 datums. We measured water temperature and electrical conductivity using a handheld meter, previously calibrated with the appropriate solutions. For the 2015 samples, we also measured pH.

## Analytical

Gas analyses were performed in the U.S. Geological Survey Noble Gas Laboratory in Denver, Colorado. Gas samples were released into an ultra-low vacuum extraction line ($<5 \times 10^9$ torr) and passed through a set of ethanol/dry ice slush traps (approximately −72 °C) to remove water vapor. The volume of dry gas was measured with a calibrated capacitance manometer, and an aliquot was introduced to a quadrupole mass spectrometer for analysis of bulk gas (H, $CH_4$, $N_2$, and $CO_2$). The remaining gas was exposed to an STS-101 getter heated to 350 °C to remove reactive-gas components, leaving a mixed sample of the noble gases. An aliquot of the purified gas was admitted to an MAP-215-50 magnetic-sector mass spectrometer for analysis of argon, krypton, and xenon ($^{36}Ar$, $^{38}Ar$, $^{40}Ar$, $^{84}Kr$, $^{86}Kr$, $^{130}Xe$, and $^{132}Xe$), while the remaining gas was cryogenically separated and analyzed for both helium ($^{3}He$ and $^{4}He$) and neon ($^{20}Ne$, $^{21}Ne$, and $^{22}Ne$) isotopes. Gas from dissolved gas samples was separated using a gas extraction bulb connected to the ultra-low vacuum line. Each sample was introduced to the extraction bulb under vacuum and exposed to 15 minutes of agitation in an ultrasonic bath at 30 °C to promote complete extraction of dissolved gas. The extracted gas was then analyzed using the same method described above and presented as total elemental composition rather than isotopic composition. The resulting gas concentrations are based on the calibrated responses of the mass spectrometers and total volume of extracted gas. Noble gas solubilities were derived from Weiss (1970, 1971), Weiss and Kyser (1970), and Benson and Krause (1976).

# Mineral Spring and Well Sites Sampled for Noble Gas Isotopes

## Site 18—Kitsap Public Utility District (PUD) Well No. 2, Bainbridge Island, Kitsap County, Washington

**Sampled September 2015**
**Bremerton East 7.5-minute topographic quadrangle map**
**Lat 47.61621° N., long 122.53606° W.**
**Elevation: 105 feet (ft) (32.1 meters [m])**
**Juan de Fuca slab depth approximately 45.1 kilometers (km)**

The Bainbridge site contains several water wells that initially belonged to Port Blakely Tree Farm and currently belong to Kitsap PUD. We were assisted by a Kitsap PUD Operator. All the producing wells at this site are ~1,000 ft deep, with screens at ~900 ft. An observation well is also located at the site. The initially targeted Well No. 4 is situated in a tiny shed and has a complicated fitting for sampling purposes, so we sampled Well No. 2 instead (unique ID# AAC113; S03), which is situated in a large shed. Well No. 2 was drilled in 1999, and its water has a sulphur smell. We collected raw water from the spigot attached to the wellhead after letting the water flow for ~5 minutes.


Figure 2. Bainbridge Well. Note, wet cement area is due to water discharge from well pipe prior to sampling.

**Bainbridge Well**
**20150925-02 PMc (water)**
**Well depth: ~1,000 ft (~304.8 m)**
**Water temperature: 12.3 °C**
**Specific conductance: 210.0 µS/cm**
**pH: 8.3**

Table 1. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150925-02 PMc, collected at Site 18 on September 25, 2015, and run on December 1, 2015.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 5.245E−08 |
| He 1σ error ± (cc/g) | 5.200E−10 |
| Ne (cc/g) | 2.486E−07 |
| Ne 1σ error ± (cc/g) | 5.000E−09 |
| Ar (cc/g) | 4.558E−04 |
| Ar 1σ error ± (cc/g) | 9.100E−06 |
| Kr (cc/g) | 1.056E−07 |
| Kr 1σ error ± (cc/g) | 3.170E−09 |
| Xe (cc/g) | 1.551E−08 |
| Xe 1σ error ± (cc/g) | 4.700E−10 |
| $N_2$ (cc/g) | 1.888E−02 |
| $N_2$ 1σ error ± (cc/g) | 9.400E−04 |
| $CH_4$ (cc/g) | BDL |
| $CH_4$ 1σ error ± (cc/g) | -- |
| $^{3}He/^{4}He$ | 1.284E−06 |
| $^{3}He/^{4}He$ 1σ error | 9.600E−09 |
| $^{20}Ne/^{22}Ne$ | 9.783 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.6 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.5 |
| $^{86}Kr/^{84}Kr$ | 0.307 |
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.15 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.001 |
| He/Ne | 0.211 |
| Excess $^{4}He$ (ccSTP/g) | -4.803E−09 |

Run notes:
1. No $^{3}He_{trit}$; modern water, zero age.
2. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
3. All concentrations are in standard temperature and pressure (STP) corresponding to T = 0 °C and P = 101.325 kPa (for 22.414 liters gas/mole; McNaught and Wilkinson, 1997). BDL signifies below detection limit.

## Site 19—City of Auburn Municipal Well, Auburn, King County, Washington

**Sampled September 2015**
**Auburn 7.5-minute topographic quadrangle map**
**Lat 47.31311° N., long 122.21626° W.**
**Elevation: 64 ft (19.6 m)**
**Juan de Fuca slab depth approximately 54.5 km**

This well site, in Frank Fulmer Park, belongs to the City of Auburn. We were assisted by the Auburn Water Operations Supervisor. Wells at this location had been decommissioned, owing to significant iron and magnesium in water; they are currently being refurbished and brought back online. Unfortunately, the targeted well (1,295 ft deep) does not have a pump, so we sampled Well #6 (390 ft) instead; both are situated inside a large shed. We sampled raw water from the spigot attached to the wellhead after letting the water flow for ~5 minutes.

Auburn also has two springs; however, the Water Operations Supervisor told us that the larger spring source is underground and mixes directly with other water sources, so is not a viable sampling site.


Figure 3. Auburn Well. Note, wet cement area is due to water discharge from well pipe prior to sampling.

**Auburn Well**
**20150925-01 PMc (water)**
**Well depth: 390 ft (118.9 m)**
**Water temperature: 12.4 °C**
**Specific conductance: 210.0 µS/cm**
**pH: 6.9**

Table 2. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150925-01 PMc, collected at Site 19 on 25 September 25, 2015, and run on November 24, 2015.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 6.201E−08 |
| He 1σ error ± (cc/g) | 6.200E−10 |
| Ne (cc/g) | 2.431E−07 |
| Ne 1σ error ± (cc/g) | 4.900E−09 |
| Ar (cc/g) | 4.089E−04 |
| Ar 1σ error ± (cc/g) | 8.200E−06 |
| Kr (cc/g) | 9.361E−08 |
| Kr 1σ error ± (cc/g) | 2.810E−09 |
| Xe (cc/g) | 1.347E−08 |
| Xe 1σ error ± (cc/g) | 4.000E−10 |
| $N_2$ (cc/g) | 1.790E−02 |
| $N_2$ 1σ error ± (cc/g) | 8.900E−04 |
| $CH_4$ (cc/g) | BDL |
| $CH_4$ 1σ error ± (cc/g) | -- |
| $^{3}He/^{4}He$ | 1.674E−06 |
| $^{3}He/^{4}He$ 1σ error | 1.300E−08 |
| $^{20}Ne/^{22}Ne$ | 9.825 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.6 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.5 |
| $^{86}Kr/^{84}Kr$ | 0.305 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.15 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.15 |
| He/Ne | 0.255 |
| Excess $^{4}He$ (ccSTP/g) | 3.270E−09 |

Run notes:
1. Modern water; $^{3}He_{trit}$ noted.
2. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
3. All concentrations are in standard temperature and pressure (STP); BDL signifies below detection limit.

## Site 20—City of Lacey Municipal Well, Lacey, Thurston County, Washington

**Sampled September 2015**
**Lacey 7.5-minute topographic quadrangle map**
**Lat 47.08952° N., long 122.78005° W.**
**Elevation: 356 ft (109.5 m)**
**Juan de Fuca slab depth approximately 41.2 km**

This well site belongs to the City of Lacey. We were assisted by Lacey Public Works staff at the wellhead. We sampled a newer, deeper well (first screen at 585 ft) than the targeted one. The site is about 1 mile from Puget Sound shoreline thus exhibits some tidal influence on water level. The wellhead is situated inside a very modern facility adjacent to a huge tank that holds millions of gallons of water. We flushed the well for ~5 minutes with the overflow running into a drain on the floor, and we then sampled raw water coming directly from the well (not the storage tank) from the spigot attached to the wellhead. Similar to the Auburn well, this water contains significant iron and magnesium, which the City of Lacey filters out during treatment.

Figure 4. Lacey Well. Note, wet cement area is due to water discharge from well pipe prior to sampling.

**Lacey Well**
**20150924-01 PMc (water)**
**Well depth: 646 ft (197 m)**
**Water temperature: 12.2 °C**
**Specific conductance: 140.0 µS/cm**
**pH: 7.8**

Table 3. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150924-01 PMc, collected at Site 20 on September 24, 2015, and run on December 2, 2015.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 5.898E−08 |
| He 1σ error ± (cc/g) | 5.900E−10 |
| Ne (cc/g) | 2.491E−07 |
| Ne 1σ error ± (cc/g) | 5.000E−09 |
| Ar (cc/g) | 4.215E−04 |
| Ar 1σ error ± (cc/g) | 8.400E−06 |
| Kr (cc/g) | 9.654E+00 |
| Kr 1σ error ± (cc/g) | 2.900E−09 |
| Xe (cc/g) | 1.412E−08 |
| Xe 1σ error ± (cc/g) | 4.200E−10 |
| $N_2$ (cc/g) | 1.884E+00 |
| $N_2$ 1σ error ± (cc/g) | 9.400E−04 |
| $CH_4$ (cc/g) | BDL |
| $CH_4$ 1σ error ± (cc/g) | -- |
| $^{3}He/^{4}He$ | 1.359E−06 |
| $^{3}He/^{4}He$ 1σ error | 1.000E−08 |
| $^{20}Ne/^{22}Ne$ | 9.816 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.9 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.5 |
| $^{86}Kr/^{84}Kr$ | 0.308 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.148 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.001 |
| He/Ne | 0.237 |
| Excess $^{4}He$ (ccSTP/g) | -6.561E−10 |

Run notes:
1. No $^{3}He_{trit}$; modern water, zero age.
2. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
3. All concentrations are in standard temperature and pressure (STP); BDL signifies below detection limit.

## Site 21—Baird Well, Centralia, Lewis County, Washington

**Sampled September 2015**
**Centralia 7.5-minute topographic quadrangle map**
**Lat 46.73789° N, long 122.92881° W**
**Elevation: 439 ft (133.7 m)**
**Juan de Fuca slab depth approximately 42.9 km**

The Centralia site is on private land and is used by the landowner for irrigation. The wellhead is situated in a small shed. The owner assisted us by removing a sand filter from the wellhead. The flow rate is ~5 gallons per minute (gal/min), and the well was set to pump for 12 minutes each hour (min/hr). The owner reset the clock to pump for 30 min/hr, but even so, water came out in short bursts. It took a few tries to synchronize the flow rate to fill the sample tube correctly. The owner mentioned that the well stopped working after recent earthquake and needed to be replumbed.


Figure 5. Centralia Well. Note, wet cement area is due to water discharge from well pipe prior to sampling.

**Centralia Well**
**20150924-02 PMc (water)**
**Well depth: 494 ft (150.5 m)**
**Water temperature: 18.5 °C**
**Specific conductance: 220.0 µS/cm**
**pH: 6.8**

Table 4. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150924-02 PMc, collected at Site 21 on September 24, 2015, and run on November 30, 2015.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 4.760E−08 |
| He 1σ error ± (cc/g) | 4.800E−10 |
| Ne (cc/g) | 1.994E−07 |
| Ne 1σ error ± (cc/g) | 4.000E−09 |
| Ar (cc/g) | 3.808E−04 |
| Ar 1σ error ± (cc/g) | 7.600E−06 |
| Kr (cc/g) | 9.053E−08 |
| Kr 1σ error ± (cc/g) | 2.720E−09 |
| Xe (cc/g) | 1.323E−08 |
| Xe 1σ error ± (cc/g) | 4.000E−10 |
| $N_2$ (cc/g) | 1.384E−02 |
| $N_2$ 1σ error ± (cc/g) | 6.900E−04 |
| $CH_4$ (cc/g) | BDL |
| $CH_4$ 1σ error ± (cc/g) | -- |
| $^{3}He/^{4}He$ | 1.342E−06 |
| $^{3}He/^{4}He$ 1σ error | 1.000E−08 |
| $^{20}Ne/^{22}Ne$ | 9.83 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.5 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.500 |
| $^{86}Kr/^{84}Kr$ | 0.306 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.148 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.001 |
| He/Ne | 0.239 |
| Excess $^{4}He$ (ccSTP/g) | 1.840E−09 |

Run notes:
1. No $^{3}He_{trit}$; modern water, zero age.
2. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
3. All concentrations are in standard temperature and pressure (STP); BDL signifies below detection limit.

## Site 22—Reynolds Well, Chehalis, Lewis County, Washington

**Sampled September 2015**
**Logan Hill 7.5-minute topographic quadrangle map**
**Lat 46.66914° N., long 122.7740° W.**
**Elevation: 416 ft (126.8 m)**
**Juan de Fuca slab depth approximately 45.0 km**

The Chehalis site is on private land and is used by the landowner for both irrigation and household purposes. We sampled raw water from the well using a hydrant at the upstream side of the house (before it ran through house system). We flushed the water line for ~5 minutes before taking the sample, with outflow running into an adjacent field.

Figure 6. Chehalis Well.

**Chehalis Well**
**20150924-03 PMc (water)**
**Well depth: 303 ft (92.3 m)**
**Water temperature: 17.0 °C**
**Specific conductance: 240.0 µS/cm**
**pH: 8.4**

Table 5. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150924-03 PMc, collected at Site 22 on September 24, 2015, and run on November 24, 2015.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 8.013E−08 |
| He 1σ error ± (cc/g) | 8.000E−10 |
| Ne (cc/g) | 2.646E−07 |
| Ne 1σ error ± (cc/g) | 5.300E−09 |
| Ar (cc/g) | 4.535E−04 |
| Ar 1σ error ± (cc/g) | 9.100E−06 |
| Kr (cc/g) | 1.049E−07 |
| Kr 1σ error ± (cc/g) | 3.150E−09 |
| Xe (cc/g) | 1.545E−08 |
| Xe 1σ error ± (cc/g) | 4.600E−10 |
| $N_2$ (cc/g) | 1.902E−02 |
| $N_2$ 1σ error ± (cc/g) | 9.500E−04 |
| $CH_4$ (cc/g) | 3.100E−04 |
| $CH_4$ 1σ error ± (cc/g) | 1.500E−05 |
| $^{3}He/^{4}He$ | 1.396E−06 |
| $^{3}He/^{4}He$ 1σ error | 1.000E−08 |
| $^{20}Ne/^{22}Ne$ | 9.804 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.700 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.500 |
| $^{86}Kr/^{84}Kr$ | 0.307 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.152 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.002 |
| He/Ne | 0.303 |
| Excess $^{4}He$ (ccSTP/g) | 1.670E−08 |

Run notes:
1. Modern water; $^{3}He_{trit}$ noted.
2. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
3. All concentrations are in standard temperature and pressure (STP).

## Site 23—Berry’s Family Nursery Well, Cornelius, Washington County, Oregon

**Sampled September 2015**
**Forest Grove 7.5-minute topographic quadrangle map**
**Lat 45.57658° N., long 123.07437° W.**
**Elevation: 212 ft (59.7 m)**
**Juan de Fuca slab depth approximately 43.2 km**

The Berry site is located at a large commercial plant nursery. We were assisted by nursery workers who opened a valve at the wellhead. We let the water run for ~10 minutes to flush the system. Unfortunately, the flow rate was so high that collecting the water directly from the funnel attached to the Tygon tubing incorporated a significant quantity of bubbles. We collected the sample by transferring water from a beaker to the funnel, which likely resulted in the escape of the noble gases. Unless the flow rate at the wellhead can be reduced significantly, this is not a viable site.

Figure 7. Berry Well.

**Berry Well**
**20150923-01 PMc (water)**
**Well depth: 1,959 ft (597 m)**
**Water temperature: 20.6 °C**
**Specific conductance: 350.0 µS/cm**
**pH: 8.5**

Table 6. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150923-01 PMc, collected at Site 23 on September 23, 2015, and run on November 25, 2015.

[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 1.269E−07 |
| He 1σ error ± (cc/g) | 1.300E−09 |
| Ne (cc/g) | 1.716E−07 |
| Ne 1σ error ± (cc/g) | 3.400E−09 |
| Ar (cc/g) | 3.175E−04 |
| Ar 1σ error ± (cc/g) | 6.400E−06 |
| Kr (cc/g) | 7.218E−08 |
| Kr 1σ error ± (cc/g) | 2.170E−09 |
| Xe (cc/g) | 1.040E−08 |
| Xe 1σ error ± (cc/g) | 3.100E−10 |
| $N_2$ (cc/g) | 1.205E−02 |
| $N_2$ 1σ error ± (cc/g) | 6.000E−04 |
| $CH_4$ (cc/g) | 3.800E−04 |
| $CH_4$ 1σ error ± (cc/g) | 1.900E−05 |
| $^{3}He/^{4}He$ | 1.068E−06 |
| $^{3}He/^{4}He$ 1σ error | 8.000E−09 |
| $^{20}Ne/^{22}Ne$ | 9.832 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.1 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.5 |
| $^{86}Kr/^{84}Kr$ | 0.308 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.148 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.001 |
| He/Ne | 0.739 |
| Excess $^{4}He$ (ccSTP/g) | -- |

Run notes:
1. Gas stripped, does not fit solubility model.
2. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
3. All concentrations are in standard temperature and pressure (STP).

## Site 24—Jones Farm Well, Hillsboro, Washington County, Oregon

**Sampled September 2015**
**Hillsboro 7.5-minute topographic quadrangle map**
**Lat 45.54486° N., long 122.97127° W.**
**Elevation: 196 ft (59.5 m)**
**Juan de Fuca slab depth approximately 44.9 km**

The Jones site is in the Jones Farm housing development. The well water is used for irrigation. We were assisted by the Home Owners Association (HOA) Landscape Services Manager. The wellhead and a small pressure tank are situated in a small pump shed. Unfortunately, the faucet bib is too close to ground to use the funnel directly. Instead, we obtained a sample by pushing the Tygon tubing directly into the faucet orifice after letting the well flush for ~5 minutes.

Figure 8. Jones Well.

**Jones Well**
**20150922-01 PMc (water)**
**Well depth: 1,411 ft (430 m)**
**Water temperature: 20.2 °C**
**Specific conductance: 740.0 µS/cm**
**pH: 8.1**

Table 7. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150922-01 PMc, collected at Site 24 on September 22, 2015, and run on December 1, 2015.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 6.359E−06 |
| He 1σ error ± (cc/g) | 6.400E−08 |
| Ne (cc/g) | 2.434E−07 |
| Ne 1σ error ± (cc/g) | 4.900E−09 |
| Ar (cc/g) | 4.397E−04 |
| Ar 1σ error ± (cc/g) | 8.800E−06 |
| Kr (cc/g) | 9.711E−08 |
| Kr 1σ error ± (cc/g) | 2.910E−09 |
| Xe (cc/g) | 1.558E−08 |
| Xe 1σ error ± (cc/g) | 4.700E−10 |
| $N_2$ (cc/g) | 2.152E−02 |
| $N_2$ 1σ error ± (cc/g) | 1.100E−03 |
| $CH_4$ (cc/g) | 1.500E−03 |
| $CH_4$ 1σ error ± (cc/g) | 7.700E−05 |
| $^{3}He/^{4}He$ | 2.039E−06 |
| $^{3}He/^{4}He$ 1σ error | 1.500E−08 |
| $^{20}Ne/^{22}Ne$ | 9.790 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.9 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.5 |
| $^{86}Kr/^{84}Kr$ | 0.329 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.148 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.001 |
| He/Ne | 26.130 |
| Excess $^{4}He$ (ccSTP/g) | 6.310E−06 |

Run notes:
1. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
2. All concentrations are in standard temperature and pressure (STP).

### Site 25—Unnamed Mineral Spring on NE Mineral Springs Road near Lafayette, Yamhill County, Oregon

**Sampled September 2015**
**Carlton 7.5-minute topographic quadrangle map**
**Lat 45.25738° N., long 123.13451° W.**
**Elevation: 117.8 ft (35.9 m)**
**Juan de Fuca slab depth approximately 41.6 km**

This mineral spring is on private land at the site of a former hotel from the era when guests came up Willamette River on boats via a lock system. The hotel also sold bottled spring water. The spring water fills a concrete structure covered with a metal grid. Some sporadic bubble trains were noted. We collected a water sample using gravity flow after flushing the Tygon tubing for ~5 minutes. The landowner mentioned that this spring is also a study site for Oregon State University ornithology students because band-tail pigeons and other birds are attracted to the water (which is high in selenium). Groundwater is close to surface in the adjacent pasture, which does not host a typical plant assemblage for this area, presumably owing to the selenium.

Figure 9. Mineral Spring. Note, aperiodic bubbles are not detectable in this photograph.

**Mineral Spring**
**20150922-02 PMc (water)**
**Water temperature: 19.4 °C**
**Specific conductance: 10,560.0 µS/cm**
**pH: 8.1**

Table 8. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150922-02 PMc, collected at Site 25 on September 22, 2015, and run on December 2, 2015.

[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 1.344E−06 |
| He 1σ error ± (cc/g) | 1.300E−08 |
| Ne (cc/g) | 7.641E−08 |
| Ne 1σ error ± (cc/g) | 1.500E−09 |
| Ar (cc/g) | 1.348E−04 |
| Ar 1σ error ± (cc/g) | 2.700E−06 |
| Kr (cc/g) | 2.987E−08 |
| Kr 1σ error ± (cc/g) | 8.960E−10 |
| Xe (cc/g) | 4.623E−09 |
| Xe 1σ error ± (cc/g) | 1.400E−10 |
| $N_2$ (cc/g) | 1.093E−02 |
| $N_2$ 1σ error ± (cc/g) | 5.500E−04 |
| $CH_4$ (cc/g) | 1.400E−03 |
| $CH_4$ 1σ error ± (cc/g) | 7.000E−05 |
| $^{3}He/^{4}He$ | 2.520E−06 |
| $^{3}He/^{4}He$ 1σ error | 1.900E−08 |
| $^{20}Ne/^{22}Ne$ | 9.889 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 307.4 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.5 |
| $^{86}Kr/^{84}Kr$ | 0.306 |
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{130}Xe/^{132}Xe$ | 0.153 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.002 |
| He/Ne | 17.585 |
| Excess $^{4}He$ (ccSTP/g) | -- |

Run notes:
1. Dissolved gas stripped from fluid; significant excess helium (He).
2. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
3. All concentrations are in standard temperature and pressure (STP).

## Site 26—Johan Vineyard Well, near Dallas, Polk County, Oregon

**Sampled September 2015**
**Amity 7.5-minute topographic quadrangle map**
**Lat 45.00720° N., long 123.21896° W.**
**Elevation: 313.3 ft (95.5 m)**
**Juan de Fuca slab depth approximately 40.0 km**

The Johan site is on vineyard land. We were assisted by the winemaker (after he finished the day's grape harvest). The well water is used for irrigation. The winemaker needed to turn on the well pump because it had not been used for ~6 months. The winemaker first closed off the city water supply, then drained city water from uphill pipes for ~15 minutes (strong flow) before turning on the well pump. We let the well water flow an additional ~5 minutes (strong flow) before taking the sample.

Note, we are not sure how deep this well is because we could not verify that the well we sampled is the same as the one listed in the DOGAMI (Oregon Department of Geology and Mineral Industries) geothermal database (www.oregongeology.org/sub/gtilo/).

Figure 10. Johan Well.

**Johan Well**
**20150921-01 PMc (water)**
**Well depth: 5,525? ft (1,684? m)**
**Water temperature: 14.4 °C**
**Specific conductance: 1,230.0 µS/cm**
**pH: 7.4**

Table 9. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20150921-01 PMc, collected at Site 26 on September 21, 2015, and run on November 30, 2015.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 5.167E−07 |
| He 1σ error ± (cc/g) | 5.200E−09 |
| Ne (cc/g) | 2.481E−07 |
| Ne 1σ error ± (cc/g) | 5.000E−09 |
| Ar (cc/g) | 4.429E−04 |
| Ar 1σ error ± (cc/g) | 8.900E−06 |
| Kr (cc/g) | 1.027E−07 |
| Kr 1σ error ± (cc/g) | 3.080E−09 |
| Xe (cc/g) | 1.481E−08 |
| Xe 1σ error ± (cc/g) | 4.400E−10 |
| $N_2$ (cc/g) | 1.651E−02 |
| $N_2$ 1σ error ± (cc/g) | 8.300E−04 |
| $CH_4$ (cc/g) | 3.600E−04 |
| $CH_4$ 1σ error ± (cc/g) | 1.800E−05 |
| $^{3}He/^{4}He$ | 2.627E−06 |
| $^{3}He/^{4}He$ 1σ error | 2.000E−08 |
| $^{20}Ne/^{22}Ne$ | 9.790 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.3 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.5 |
| $^{86}Kr/^{84}Kr$ | 0.307 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.153 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.002 |
| He/Ne | 2.083 |
| Excess $^{4}He$ (ccSTP/g) | 4.580E−07 |

Run notes:
1. Mixed modern and submodern water.
2. 1σ error is defined as an instrumental error; error values based on replication of standards during the run.
3. All concentrations are in standard temperature and pressure (STP).

## Site 13—Jackson Spring, WellSpring Resort, Ashland, Jackson County, Oregon

**Sampled July 2014**
**Ashland 7.5-minute topographic quadrangle map**
**Lat 42.2219° N., long 122.7394° W.**
**Elevation: 1,622 ft (494 m)**
**Juan de Fuca slab depth approximately 53.0 km**

This hot spring is on private resort land and is currently used in soaking pools for presumed healing properties of water. The large, main pool is situated within concrete walls and enclosed by a locked cyclone fence. A pipe at bottom of pool transfers water to the resort soaking pools. We observed fairly continuous bubble streams in the spring, so we collected a gas sample for ~20 minutes using a large funnel attached to Tygon tubing and fastened to the end of a pole. This mineral spring had been previously noted by Waring (1965).

Figure 11. Jackson Spring. Note, aperiodic bubbles are barely detectable in upper photograph.

**Jackson Spring**
**20140722-01 PMc (gas)**
**Water temperature: ~31 °C**
**Specific conductance: 491.0 µS/cm**

Table 10. Abundances of noble gas isotopes, nitrogen, oxygen, carbon dioxide, and methane for gas sample 20140722-01 PMc, collected at Site 13 on July 22, 2014, and run on November 26, 2015.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{4}He$ (ccSTP/cc) | 151.6 E−06 |
| $^{4}He$ 1σ error (ccSTP/cc) | ± 1% |
| $^{20}Ne$ (ccSTP/cc) | 5442.4 E−09 |
| $^{20}Ne$ 1σ error (ccSTP/cc) | 2% |
| $^{36}Ar$ (ccSTP/cc) | 17.924 E−06 |
| $^{36}Ar$ 1σ error (ccSTP/cc) | ± 2% |
| $^{40}Ar$ (ccSTP/cc) | 5332 E−06 |
| $^{40}Ar$ 1σ error (ccSTP/cc) | ± 2% |
| $^{84}Kr$ (ccSTP/cc) | 525.5 E−09 |
| $^{84}Kr$ 1σ error ± (ccSTP/cc) | ± 5% |
| $^{132}Xe$ (ccSTP/cc) | 21.1 E−09 |
| $^{132}Xe$ 1σ error (ccSTP/cc) | ± 5% |
| $CH_4$ (ccSTP/cc) | BDL |
| $N_2$ (ccSTP/cc) | 0.9815 |
| $O_2$ (ccSTP/cc) | BDL |
| $CO_2$ (ccSTP/cc) | 0.0031 |
| $CO_2/^{3}He$ | -- |
| $R/R_A$ | 0.369 |
| $R_C/R_A$ | 0.362 |
| $^{20}Ne/^{22}Ne$ | 9.593 |
| $^{21}Ne/^{22}Ne$ | 0.0283 |
| $^{38}Ar/^{36}Ar$ | 0.190 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
| --- | --- |
| $^{40}Ar/^{36}Ar$ | 296.5 |
| $^{86}Kr/^{84}Kr$ | 0.274 |
| $^{130}Xe/^{132}Xe$ | 0.149 |
| $^{3}He/^{21}Ne$ | -- |
| $^{4}He/^{20}Ne$ (x air) | 90 |
| $^{4}He/^{40}Ar$ | -- |
| $^{20}Ne/^{36}Ar$ | 0.304 |

Run notes:
1. BDL signifies below detection limit.
2. Units for noble gas measurements obtained from gas samples differ from water samples.

## Site 14—Lithia Spring, Lithia Spring Resort, Ashland, Jackson County, Oregon

**Sampled July 2014**
**Ashland 7.5-minute topographic quadrangle map**
**Lat 42°13.198’ N., long 122°42.562’ W. ±15 ft**
**Elevation: 1,656 ft (505 m)**
**Juan de Fuca slab depth approximately 53.0 km**

This hot spring is on private resort land and is currently used in soaking pools for presumed healing properties of water. The wellhead is in a small, locked pump shed. We were assisted by a resort manager. The pump transfers artesian spring water to the resort soaking pools. We let water run for ~5 minutes through the Tygon tubing to flush well pipe, and we then tapped the tubing to clear visible bubbles. We collected a water sample using gravity feed from spigot attached to wellhead.

Figure 12. Lithia Spring. Note, wet cement area is due to water discharge from well pipe prior to sampling.

**Lithia Spring**
**20140722-02 PMc (water)**
**Water temperature: 29 °C**
**Specific conductance: 433.0 µS/cm**

Table 11. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20140722-02 PMc, collected at Site 14 on July 22, 2014, and run on December 1, 2014.

[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 4.952E−08 |
| He 1σ error ± (cc/g) | 4.952E−10 |
| Ne (cc/g) | 1.689E−07 |
| Ne 1σ error ± (cc/g) | 3.378E−09 |
| Ar (cc/g) | 2.595E−04 |
| Ar 1σ error ± (cc/g) | 5.191E−06 |
| Kr (cc/g) | 5.647E−08 |
| Kr 1σ error ± (cc/g) | 1.129E−09 |
| Xe (cc/g) | 7.427E−09 |
| Xe 1σ error ± (cc/g) | 2.228E−10 |
| $N_2$ (cc/g) | 1.000E−02 |
| $N_2$ 1σ error ± (cc/g) | 5.002E−04 |
| $CH_4$ (cc/g) | BDL |
| $CH_4$ 1σ error ± (cc/g) | -- |
| $R/R_A$ | 0.897 |
| $R/R_A$ 1σ error | 0.008 |
| $^{20}Ne/^{22}Ne$ | 9.802 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.020 |
| $^{40}Ar/^{36}Ar$ | 295.1 |
| $^{40}Ar/^{36}Ar$ 1σ error | 6.2 |
| $^{86}Kr/^{84}Kr$ | 0.304 |
| $^{86}Kr/^{84}Kr$ 1σ error | 0.0030 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{130}Xe/^{132}Xe$ | 0.151 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.007 |

Run notes:
1. BDL signifies below detection limit.

## Site 15—Cinnabar West Spring, Klamath National Forest, Siskiyou County, California

**Sampled July 2014**
**Condrey Mountain 7.5-minute topographic quadrangle map**
**Lat 41°57.977' N., long 122°52.794' W. ±22 ft**
**Elevation: 3,358 ft (1,024 m)**
**Juan de Fuca slab depth approximately 52.1 km**

The Cinnabar West Spring site is situated on U.S. Forest Service land adjacent to a former mining claim above the West Fork of Beaver Creek. The mineral spring is located near the junction of Forest Road 48N36 and an old mining road. The spring forms a seep that flows over what appears to be a light gray, fine-grained, carbonate precipitate on the uphill side of Forest Road 48N36. Abundant animal hoof prints in the mud surround the spring. We collected a water sample using gravity feed from a small existing, rectangular orifice formed from old wooden boards set into the spring. Sporadic gas bubble trains were noted in both the orifice and in the surrounding puddles of spring water, and some bubbles were noted in the Tygon tubing during sampling. Note, the electrical conductivity measurement for this water exceeded the measurement range of the device. We tested the conductance meter in the adjacent stream to verify that it was working correctly.

The nearby Cinnabar Spring (on Buckhorn Bally 7.5 minute topographic quadrangle map) was sampled by P.E. Hotz (July 1, 1962) as noted in the online USGS database (2006). We visited this spring but did not sample it.

Figure 13. Cinnabar West Spring. Note, aperiodic bubbles are not detectable in these photographs.

**Cinnabar West Spring**
**20140723-01 PMc (water)**
**Water temperature: 11 °C**
**Specific conductance: >3,999.0 µS/cm**

Table 12. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20140723-01 PMc, collected at Site 15 on July 23, 2014, and run on October 9, 2014.

[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 3.373E−09 |
| He 1σ error ± (cc/g) | 3.373E−11 |
| Ne (cc/g) | 3.548E−09 |
| Ne 1σ error ± (cc/g) | 7.096E−11 |
| Ar (cc/g) | 6.944E−06 |
| Ar 1σ error ± (cc/g) | 1.389E−07 |
| Kr (cc/g) | 3.752E−09 |
| Kr 1σ error ± (cc/g) | 7.504E−11 |
| Xe (cc/g) | 1.037E−09 |
| Xe 1σ error ± (cc/g) | 3.110E−11 |
| $N_2$ (cc/g) | BDL |
| $N_2$ 1σ error ± (cc/g) | -- |
| $CH_4$ (cc/g) | BDL |
| $CH_4$ 1σ error ± (cc/g) | -- |
| $R/R_A$ | 0.775 |
| $R/R_A$ 1σ error | 0.007 |
| $^{20}Ne/^{22}Ne$ | BDL |
| $^{20}Ne/^{22}Ne$ 1σ error | -- |
| $^{40}Ar/^{36}Ar$ | 299.1 |
| $^{40}Ar/^{36}Ar$ 1σ error | 6.2 |
| $^{86}Kr/^{84}Kr$ | 0.301 |
| $^{86}Kr/^{84}Kr$ 1σ error | 0.0030 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{130}Xe/^{132}Xe$ | 0.149 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.007 |

Run notes:
1. All $CO_2$ (not reported).
2. BDL signifies below detection limit.

## Site 16—Sulphur Spring, Sulphur Spring Campground, Klamath National Forest, Siskiyou County, California

**Sampled July 2014**
**Huckleberry Mountain 7.5-minute topographic quadrangle map**
**Lat 41°39.612' N., long 123°19.218' W. ±12 ft**
**Elevation 2,162 ft (659 m)**
**Juan de Fuca slab depth approximately 35.0 km**

The Sulphur site is situated within a U.S. Forest Service campground. Sulphur Spring is edged by stream cobbles to form a soaking pool adjacent to Elk Creek within the Sulphur Springs Campground. The hot spring has vigorous flow, and it overflows through the cobbles into Elk Creek. Two vigorous bubble trains were noted within the pool. We collected a gas sample for ~10 minutes using the large funnel attached to the Tygon tubing, after first flushing the tubing for ~10 minutes.

We examined another spring located upstream of Sulphur Spring, near the confluence of Lick Creek and Elk Creek. This spring also seeps toward Elk Creek. Abundant animal hoof prints in the mud surround the spring.

Sulphur Spring appears to be the same spring noted by Waring (1965), located 14 miles southeast of the town of Happy Camp.

Figure 14. Sulphur Spring. Note, blurriness in center of both photographs is due to steady, vigorous bubbling.

**Sulphur Spring**
**20140725-01 PMc (gas)**
**Water temperature 32 °C**
**Specific conductance: 450.0 µS/cm**

Table 13. Abundances of noble gas isotopes, nitrogen, oxygen, carbon dioxide, and methane for gas sample 20140725-01 PMc, collected at Site 16 on July 25, 2014, and run on November 26, 2014.

[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{4}$He (ccSTP/cc) | 208.0 E−06 |
| $^{4}$He 1σ error ± (ccSTP/cc) | 1% |
| $^{20}$Ne (ccSTP/cc) | 9109.8 E−09 |
| $^{20}$Ne 1σ error ± (ccSTP/cc) | 2% |
| $^{36}$Ar (ccSTP/cc) | 30.796 E−06 |
| $^{36}$Ar 1σ error ± (ccSTP/cc) | 2% < ? > |
| $^{40}$Ar (ccSTP/cc) | 9297 E−06 |
| $^{40}$Ar 1σ error ± (ccSTP/cc) | 2% |
| $^{84}$Kr (ccSTP/cc) | 865.1 E−09 |
| $^{84}$Kr 1σ error ± (ccSTP/cc) | 5% |
| $^{132}$Xe (ccSTP/cc) | 37.4 E−09 |
| $^{132}$Xe 1σ error ± (ccSTP/cc) | 5% |
| $CH_4$ (ccSTP/cc) | BDL |
| $N_2$ (ccSTP/cc) | 0.9773 |
| $O_2$ (ccSTP/cc) | BDL |
| $CO_2$ (ccSTP/cc) | 0.0033 |
| $CO_2/^{3}He$ | 4.06E+07 |
| $R/R_A$ | 0.212 |
| $R_C/R_A$ | 0.201 |
| $^{20}Ne/^{22}Ne$ | 9.874 |
| $^{21}Ne/^{22}Ne$ | 0.0287 |
| $^{38}Ar/^{36}Ar$ | 0.190 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{40}Ar/^{36}Ar$ | 300.9 |
| $^{86}Kr/^{84}Kr$ | 0.306 |
| $^{130}Xe/^{132}Xe$ | 0.159 |
| $^{4}He/^{20}Ne$ (x air) | 73 |
| $^{4}He/^{40}Ar$ | 1.3 |
| $^{20}Ne/^{36}Ar$ | 0.296 |

Run notes:
1. BDL signifies below detection limit.
2. Units for noble gas measurements obtained from gas samples differ from water samples.

## Site 17—Weemasoul Spring, near Rosewood, Tehema County, California

**Sampled July 2014**
**Cold Fork 7.5-minute topographic quadrangle map**
**Lat 40°12.259' N., long 122°41.533' W. ±7 ft**
**Elevation: 1,137 ft (345 m)**
**Juan de Fuca slab depth approximately 46.7 km**

Weemasoul Spring forms a shallow pool on southeast side of Weemasoul Road. Water seeps down a slope covered with green grass terraced by cattle as they graze in a very arid region of scattered oak trees and dry grass. Abundant animal hoof prints in the mud surround the mineral spring. Sporadic gas bubble trains were noted in spring water. We collected a water sample from a shallow pool using gravity feed. We had to watch for little beetles swimming in pool as they were getting sucked into Tygon tubing. Another smaller spring is situated just downslope. Note, the electrical conductivity measurement for this water was exceeded the measurement range of the device.

Figure 15. Weemasoul Spring. Note, aperiodic bubbles are not detectable in these photographs.

**Weemasoul Spring**
**20140724-01 PMc (water)**
**Water temperature: 24 °C (21.5 °C when probe stuck into mud at bottom of pool)**
**Specific conductance: >3,999.0 µS/cm**

Table 14. Abundances of noble gas isotopes, nitrogen, and methane for water sample 20140724-01 PMc, collected at Site 17 on July 24, 2014, and run on October 8, 2014.
[Spreadsheet file of this table is available for download at https://doi.org/10.3133/ofr20161203]

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| He (cc/g) | 1.661E−07 |
| He 1σ error ± (cc/g) | 1.661E−09 |
| Ne (cc/g) | 6.365E−08 |
| Ne 1σ error ± (cc/g) | 1.273E−09 |
| Ar (cc/g) | 1.025E−04 |
| Ar 1σ error ± (cc/g) | 2.050E−06 |
| Kr (cc/g) | 2.736E−08 |
| Kr 1σ error ± (cc/g) | 5.473E−10 |
| Xe (cc/g) | 3.965E−09 |
| Xe 1σ error ± (cc/g) | 1.190E−10 |
| $N_2$ (cc/g) | 2.929E−03 |
| $N_2$ 1σ error ± (cc/g) | 1.465E−04 |
| $CH_4$ (cc/g) | 2.389E−02 |
| $CH_4$ 1σ error ± (cc/g) | 1.195E−03 |
| $R/R_A$ | 0.246 |
| $R/R_A$ 1σ error | 0.002 |
| $^{20}Ne/^{22}Ne$ | 9.888 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.020 |
| $^{40}Ar/^{36}Ar$ | 296.1 |
| $^{40}Ar/^{36}Ar$ 1σ error | 6.2 |
| $^{86}Kr/^{84}Kr$ | 0.302 |
| $^{86}Kr/^{84}Kr$ 1σ error | 0.0030 |

| Gas abundance and measurement uncertainty | Laboratory measurement |
|---|---|
| $^{130}Xe/^{132}Xe$ | 0.154 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.007 |

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# Appendix 1

Table 1–1. 2015 QA/QC for air equilibrated water lab samples.

| Noble gas values | AEW#10 | AEW#23 |
|---|---|---|
| Date sampled | 10 Nov 2015 | 10 Nov 2015 |
| Date run | 17 Nov 2015 | 17 Nov 2015 |
| He (cc/g) | 3.963E−08 | 3.949E−08 |
| He 1σ error ± (cc/g) | 4.000E−10 | 4.000E−10 |
| Ne (cc/g) | 1.538E−07 | 1.525E−07 |
| Ne 1σ error ± (cc/g) | 3.100E−09 | 3.100E−09 |
| Ar (cc/g) | 2.609E−04 | 2.591E−04 |
| Ar 1σ error ± (cc/g) | 5.200E−06 | 5.200E−06 |
| Kr (cc/g) | 5.762E−08 | 5.830E−08 |
| Kr 1σ error ± (cc/g) | 5.762E−08 | 1.750E−09 |
| Xe (cc/g) | 7.880E−09 | 7.738E−09 |
| Xe 1σ error ± (cc/g) | 2.400E−10 | 2.300E−10 |
| $N_2$ (cc/g) | 9.956E−03 | 9.950E−03 |
| $N_2$ 1σ error ± (cc/g) | 5.000E−04 | 5.000E−04 |
| $CH_4$ (cc/g) | BDL | BDL |
| $CH_4$ 1σ error ± (cc/g) | -- | -- |
| $^{3}He/^{4}He$ | 1.353E−06 | 1.360E−06 |
| $^{3}He/^{4}He$ 1σ error | 1.000E−08 | 1.000E−08 |
| $^{20}Ne/^{22}Ne$ | 9.842E+00 | 9.839E+00 |
| $^{20}Ne/^{22}Ne$ 1σ error | 0.015 | 0.015 |
| $^{40}Ar/^{36}Ar$ | 296.700 | 295.100 |
| $^{40}Ar/^{36}Ar$ 1σ error | 1.5 | 1.5 |
| $^{86}Kr/^{84}Kr$ | 0.306 | 0.306 |

| Noble gas values | AEW#10 | AEW#23 |
|---|---|---|
| $^{86}Kr/^{84}Kr$ 1σ error | 0.003 | 0.003 |
| $^{130}Xe/^{132}Xe$ | 0.154 | 0.152 |
| $^{130}Xe/^{132}Xe$ 1σ error | 0.002 | 0.002 |
| He/Ne | 0.258 | 0.259 |
| Excess $^{4}He$ (ccSTP/g) | 1.89E−09 | 1.79E−09 |

Run notes:
1. AEW, air equilibrated water; QA, quality assurance; QC, quality control.
2. 1σ error defined as an instrumental error; values are based on replication of standards during run.
3. All concentrations are in standard temperature and pressure (STP).

Table 1–2. 2015 QA/QC for lab samples using a continuous equilibration (CE) model.

| Sample | Model used | Elevation (ft) | Ae (cc/kg) | F | $X^2$ | P | NGRT (°C) |
|---|---|---|---|---|---|---|---|
| AEW#10 | CE | 4467 | 0.0 | 0.0000 | 0.38 | 0.944 | 20.7 |
| AEW#23 | CE | 4467 | 0.0 | 0.0000 | 1.12 | 0.773 | 21.0 |
| 20150925-02 PMc Bainbridge | CE | 105 | 19.6 | 0.7420 | 0.92 | 1.000 | 6.2 |
| 20150925-01 PMc Auburn | CE | 64 | 2.4 | 0.0000 | 2.93 | 0.231 | 9.7 |
| 20150924-01 PMc Lacey | CE | 361 | 2.6 | 0.0000 | 0.12 | 1.000 | 8.3 |
| 20150924-02 PMc Centralia | CE | 436 | 4.1 | 1.0000 | 0.75 | 0.998 | 9.7 |
| 20150924-03 PMc Chehalis | CE | 413 | 3.2 | 0.0000 | 0.76 | 0.683 | 5.6 |
| 20150923-01 PMc Berry | CE | 194 | -- | -- | -- | -- | -- |
| 20150922-01 PMc Jones | CE | 197 | 14.3 | 0.8627 | 5.36 | 0.719 | 6.3 |
| 20150922-02 PMc Mineral | CE | 118 | -- | -- | -- | -- | -- |
| 20150921-01 PMc Johan | CE | 312 | 3.3 | 0.2696 | 1.55 | 0.956 | 6.5 |

Run notes:
1. AEW, air equilibrated water; QA, quality assurance; QC, quality control; NGRT, noble gas recharge temperature; CE, closed-system equilibration model of Aeschbach-Hertig and others (2000); F, known fragmentation factors of other gases for mass of gas species.
2. Noble gas recharge temperatures are derived from the air saturated water (ASW) component of noble gas concentrations (Ne, Ar, Kr, Xe) in groundwater.
3. All recharge temperatures are based on noble gas concentrations (Ne, Ar, Kr, Xe).

Table 1–3. 2014 QA/QC for ASW lab samples.

| Noble gas values | Analytical blank n=3 | Air | Lab error ± | %error | ASW | ASSW |
|---|---|---|---|---|---|---|
| $^{4}He$ (ccSTP/cc) × $10^{-6}$ | 0.003 | 5.240 | | 1.0 | | |
| $^{4}He$ 1σ error ± (ccSTP/cc) | | | | | | |
| $^{20}Ne$ (ccSTP/cc) × $10^{-9}$ | 0.1022 | 16453 | | 2.0 | | |
| $^{20}Ne$ 1σ error ± (ccSTP/cc) | | | | | | |
| $^{36}Ar$ (ccSTP/cc) × $10^{-6}$ | | 31.5 | | | | |
| $^{36}Ar$ 1σ error ± (ccSTP/cc) | | | | | | |
| $^{40}Ar$ (ccSTP/cc) × $10^{-6}$ | 0.14 | 9308 | | 2.0 | | |
| $^{40}Ar$ 1σ error ± (ccSTP/cc) | | | | | | |
| $^{84}Kr$ (ccSTP/cc) × $10^{-9}$ | 0.17 | 650 | | 5.0 | | |
| $^{84}Kr$ 1σ error ± (ccSTP/cc) | | | | | | |
| $^{132}Xe$ (ccSTP/cc) × $10^{-9}$ | 0.013 | 23 | | 5.0 | | |
| $^{132}Xe$ 1σ error ± (ccSTP/cc) | | | | | | |
| $CH_4$ (ccSTP/cc) | | | | 5.0 | | |
| $N_2$ (ccSTP/cc) | | 0.7808 | | 5.0 | | |
| $O_2$ (ccSTP/cc) | | 0.2000 | | 5.0 | | |
| $CO_2$ (ccSTP/cc) | | | | 5.0 | | |
| $CO_2/^{3}He$ | | | | | | |
| $R/R_A$ | | 1.000 | 0.005 | 0.50 | | |
| $R_C/R_A$ | | | | | | |

| Noble gas values | Analytical blank n=3 | Air | Lab error ± | %error | ASW | ASSW |
|---|---|---|---|---|---|---|
| $^{20}Ne/^{22}Ne$ | | 9.800 | 0.100 | 1.02 | | |
| $^{21}Ne/^{22}Ne$ | | 0.02900 | 0.000 | 1.03 | | |
| $^{38}Ar/^{36}Ar$ | | 0.188 | 0.005 | 2.66 | | |
| $^{40}Ar/^{36}Ar$ | | 295.5 | 5.000 | 1.69 | | |
| $^{86}Kr/^{84}Kr$ | | 0.305 | 0.015 | 4.91 | | |
| $^{130}Xe/^{132}Xe$ | | 0.151 | 0.010 | 6.61 | | |
| $^{4}He/^{21}Ne \times 10^{6}$ | | | 22.400 | | | |
| $^{4}He/^{20}Ne \times$ air | | 1.0 | 1.000 | 1.00 | 1.0 | 1.0 |
| $^{4}He/^{40}Ar$ | | | 8.000 | | | |
| $^{20}Ne/^{36}Ar$ | | 0.522 | | | | |
| F $^{4}$He ± 1σ error | | 1.000 ± 0.022 | | | 0.256 | 0.267 |
| F $^{84}$Kr ± 1σ error | | 1.000 ± 0.028 | | | 0.305 | 0.314 |
| F $^{86}$Kr ± 1σ error | | 1.000 ± 0.082 | | | 3.275 | 1.813 |
| F $^{132}$Xe ± 1σ error | | 1.000 ± 0.063 | | | 1.830 | 3.213 |

Run notes:

1. ASW, air saturated water; ASSW, air saturated sea water; QA, quality assurance; QC, quality control; F, known fragmentation factors of other gases for mass of gas species.
2. 1σ error is defined as an instrumental error; error values are based on replication of standards during run.
3. All concentrations are in standard temperature and pressure (STP).

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