HELIUM IN NORTHEASTERN BRITISH COLUMBIA

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ABSTRACT

Global demand for helium is increasing at a time when world reserves are in decline. The price of grade A helium has quadrupled in the past 12 years. Liquefied natural gas (LNG) processing can be used to capture helium as a value-added byproduct at concentrations as low as 0.04% by volume. The Slave Point, Jean Marie (Redknife) and Wabamun formations of northeastern British Columbia preferentially have helium associated with many of their natural gas pools. The mechanism for this accumulation appears to be flow in hydrothermal brines from helium-enriched basement granitic rocks along deeply seated faults. Separately, the Evie member of the Horn River Formation also has anomalous helium accumulation in its shale gas related to uranium decay in organic-rich shales.

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INTRODUCTION

Helium is a nonrenewable resource that has developed important strategic value. Helium (atomic number of 2) exists primarily as the stable isotope, ^{4}He, which is produced on the earth through alpha decay of radioactive elements such as uranium and thorium. It is a common constituent of natural gases and is believed to be present in trace amounts in all natural gases (Broadhead, 2005). Once formed, helium moves easily through the earth's crust, escapes into the atmosphere and leaves the earth's gravitational field. In larger deposits in the United States, helium is found in well-sealed natural traps within porous strata after having migrated from uranium-bearing granitic source rocks (Groat et al., 2010).

Helium is extremely light, stable and inert. Because of its low molecular mass, it has a thermal conductivity, a specific heat and a sound conduction velocity that are all greater than any other element except hydrogen. Liquid helium has the lowest boiling point of any substance. Because of this, it is used in cryogenics and to provide the low temperatures needed for superconducting magnets, such as those used in most MRI scanners in hospitals, which accounts for 28% of the global demand. It is also used to condense hydrogen and oxygen to make rocket fuel. Helium is commonly used as a shielding gas for welding, which accounts for 11% of global use. Because helium has very small atoms, it is more diffusive than air so it can be mixed with oxygen to make breathing mixtures for divers (2% of the United States consumption in 2011). Helium also has a refractive index very close to 1 so it is commonly used in optical fibre technology (8% of global use; Peterson and Madrid, 2012; Anonymous, 2012).

In recognition of its strategic value, the United States created the Federal Helium Reserve in the Bush Dome Reservoir, Texas, in 1925. The primary source for the Federal Helium Reserve is the world-class Hugoton Reservoir in Kansas, Oklahoma and Texas. Other helium resources in the United States are contained in the Panoma Field (Kansas), the Keyes Field (Oklahoma), Panhandle West and Cliffside fields (Texas) and the Riley Ridge area (Wyoming; Peterson and Madrid, 2012). In 1996, a decision was made to phase out the Federal Helium Reserve. In 2012, the Federal Helium Reserve contained 670 million cubic metres of helium (Madrid, 2012). This reserve is expected to be substantially depleted to a mandated 16.6 million cubic metres by 2015 (Groat et al., 2010).

For many years, the United States produced more than 90% of the commercially usable helium in the world. As of 2012, the United States accounted for 34% of the world's helium reserves and resources and 76% of global annual production (Table 1). Algeria, Qatar and Russia have reserve bases comparable to that of the United States, but large-scale production has been limited (Groat et al., 2010). Qatar developed its first dedicated helium plant in 2005 and Australia's first helium plant came online in 2010. Globally, seven international helium plants are in operation in Algeria, Qatar, Australia and Russia, and more are planned in the next 5 years (Fig. 1; Groat et al., 2010; Madrid, 2012). Production from these facilities is expected to be sufficient to meet worldwide helium demand for the next five years.

After that, access to additional reserves will be required (Madrid, 2012).

The helium supply and demand market is dynamic (Groat et al., 2010). As of 2012, the United States was the largest market for helium (36%), followed by Asia (28%) and Europe (22%; Garvey, 2012). In recent years, the price of grade A helium has quadrupled (Fig. 2; Madrid, 2012). The United States government's price for crude helium has risen from $49.50 per thousand cubic feet gas delivered in 1999 to $75.75 per thousand cubic feet in 2011 ($2.73 per cubic metre; Madrid, 2012). Meanwhile, the price of grade A refined helium, a higher value product, doubled. Between 2006 and 2011, the price of grade A refined helium rose from $80 per thousand cubic feet in 2006 to $160 per thousand cubic feet in 2011.

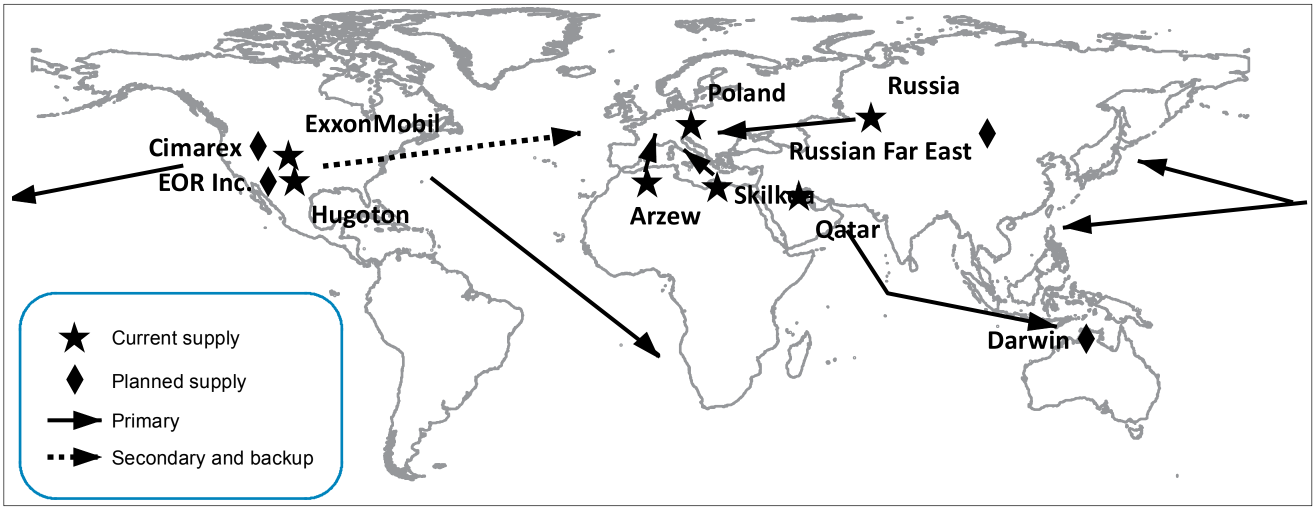

Figure 1. Origin and destination for large segments of the helium market in 2008 (the following values are the approximate amount of helium consumed in each region, in Bcf): United States, 2.8; Canada and South America, 0.3; Europe, 1.7; Asia, 1.5; Africa, Middle East, and India, 0.15. Source: CryoGas International (after Groat et al., 2010).

TABLE 1. WORLD PRODUCTION, RESERVES AND RESOURCES (MADRID, 2012).

	2011 production (million cubic metres)	Reserves (million cubic metres)	Resources (billion cubic metres)
United States (extracted from natural gas)	83	4 000	16.4
United States (from Cliffside Field Reserve)	57		4.3
Algeria	20	1 800	8.2
Canada	N/A	N/A	2
China	N/A	N/A	1.1
Poland	3	33	
Qatar	15	N/A	10.1
Russia	6	1700	6.8
other countries	N/A	N/A	
World Total	180	N/A	

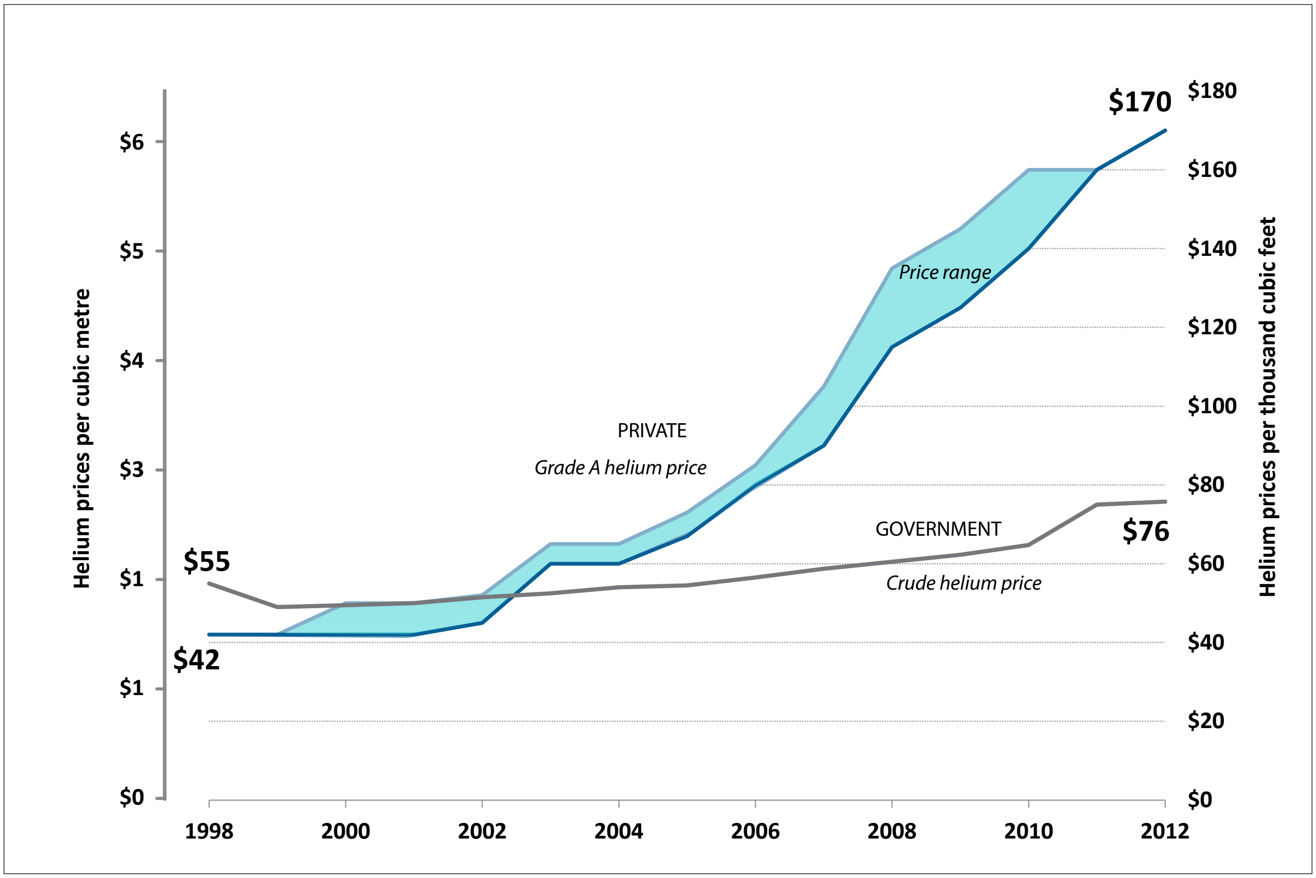

Figure 2. Price increases in grade A and crude helium between 1999 and 2011 (source: US Geological Survey; after Plumer, 2012)

Although a rising helium price has been partially driven by growth in the high-tech manufacturing sectors in China, Taiwan and South Korea (Fig. 2; Garvey, 2012), a perceived shortage in global helium supply associated with the sell-off of the United States Federal Helium Reserve has also been a factor. While there is currently sufficient helium to meet global demand, recent disruptions in helium supply (e.g., the Algerian plant explosion of 2004 and the Shute Creek Wyoming plant going offline in 2011) have been felt almost immediately by end users (Kynett, 2012). The average time between helium production by separation and delivery to the consumer is 45–60 days (Fig. 1; Kynett, 2012). Some market analysts anticipate that between 2016 and 2020, global demand will outstrip production, but in subsequent years a number of large-scale projects may be implemented (Anonymous, 2012).

Helium can be economically produced as a primary commodity or as a secondary byproduct. Primary helium reservoirs are not generally spatially associated with petroleum production. For primary helium production, concentrations in reservoirs vary over a broad range from a few parts per million to more than 7% by volume. Wells with helium concentrations of greater than 0.3% by volume can be commercialized solely for their helium content (Madrid, 2012). Most of the helium produced in the United States is obtained from reservoirs with less than 1.5% helium in their gases (Broadhead, 2005).

There are several geological models for helium accumulation. Generally, world-class helium deposits like the Hugoton Reservoir form over granitic basement rocks connected by a fault to a porous reservoir, and are capped by a tight anhydrite seal (Broadhead, 2005). Although commercial helium is not generally associated with petroleum production, there are exceptions. Helium may migrate upward with the assistance of a carrier fluid (e.g., saline water) and become trapped in the subsurface under conditions that also trap natural gases like methane (Brown, 2010). Helium in pore water fractionates easily into migrating gas. In the case of some petroleum basins (e.g., Anadarko Basin, San Juan Basin), it is thought that helium generated in basement rocks that underlie the gas basins diffuses vertically upward to become entrained with migrating gas and then migrates updip through overlying Paleozoic sedimentary rocks until it is trapped in a reservoir (Broadhead, 2005). Alternatively, in extensional terranes, helium may migrate through deep-seated fractures and concentrate within overlying reservoir rocks (Broadhead, 2005).

In natural gas production, helium tends to exist at low concentrations and is commonly vented to the atmosphere to improve the heating value of the gas; however, in cases where natural gas is to be liquefied for transport (i.e., LNG), helium can be effectively separated and concentrated. Natural gas reserves with helium concentrations as low as 0.04% by volume can have economic helium byproduct streams (e.g., the Las Raffan plant, from gas in Qatar's North Field; Groat et al., 2010). This process of helium recovery through LNG processing has led Qatar to become a world leader in helium production (Groat et al., 2010).

Industrial plants extract helium from natural gas by a process of fractional distillation (Fig. 3). Low temperature and high pressure are used to liquefy natural gases, but since helium has a lower boiling point than any other element, it remains a gas when other components in the gas stream have liquefied (Clarke and Van Schagen, 2010). At –193°C, most nitrogen and methane condense and can be drained. Helium can comprise up to 50–90% of the waste gas purged from a natural-gas plant after the natural gas has condensed (Andrieu et al., 2006). After initial separation, crude helium can then be further purified to generate grade A helium (99.997% by volume or better) by using either activated charcoal absorbers at very low temperature and high pressure or pressure swing adsorption processes (Beebe et al., 2000).

HELIUM ESTIMATES FOR NORTHEASTERN BRITISH COLUMBIA

British Columbia has the potential to produce helium in association with LNG. The British Columbia Oil and Gas Commission (OGC) recognizes 430 natural gas pools in northeastern British Columbia with 0.04% mole fraction or more of helium gas, the fraction required to produce helium for commercial venture. The top 22 pools account for 70% of the known helium and contain 50 × 10^6 m^3 of helium (Fig. 4). This is estimated by applying the helium fraction from the representative sample gas analysis for the pool to the listed remaining raw gas reserves for each pool (Table 2). The majority of these 22 pools have an average helium mole fraction between 0.04% and 0.1%.

Collectively, the largest helium accumulations in northeastern British Columbia are in pools in the Slave Point Formation associated with the Horn River Basin and the Cordova Embayment, and the overlying Jean Marie

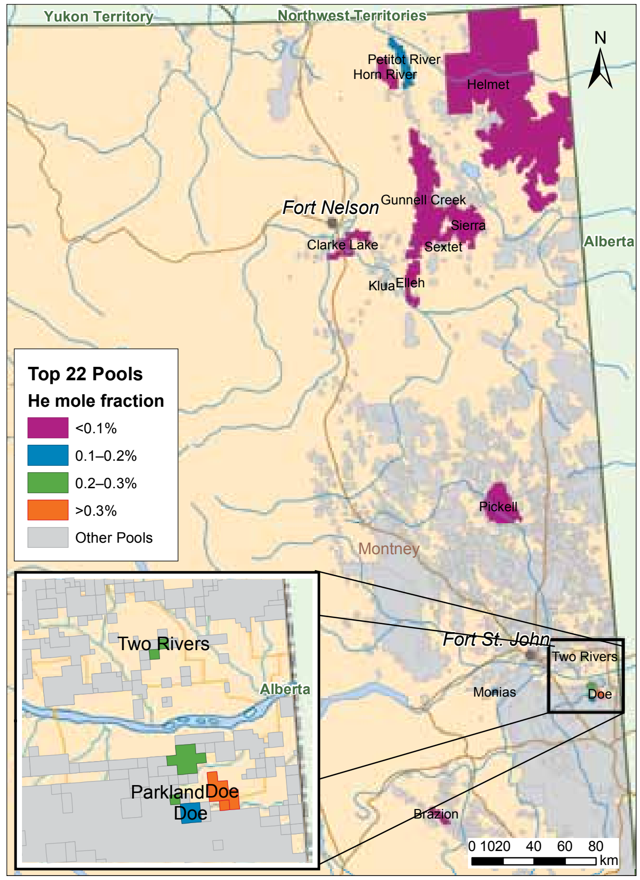

Figure 4. The 22 gas pools in northeastern British Columbia that hold the majority of helium in the province. Pools are colour coded by the helium mole fraction of the representative gas analysis for the pool.

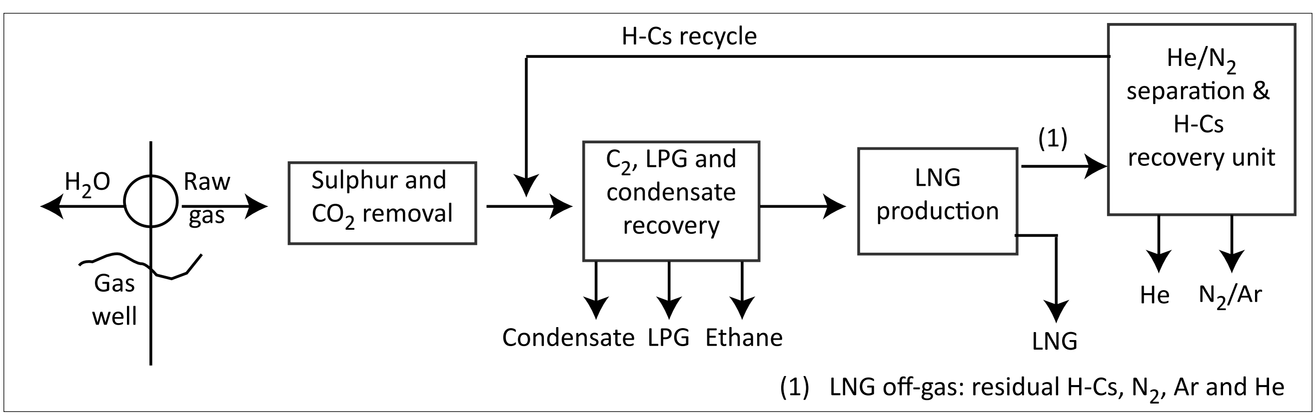

Figure 3. A liquefied natural gas (LNG) train with helium (and other byproduct) recovery (after Clarke and Van Schagen, 2010).

TABLE 2. BRITISH COLUMBIA POOLS WITH THE GREATEST HELIUM ACCUMULATIONS IN THE REMAINING RAW GAS.

Area	Formation/ member	Pool seq	Porosity	Reservoir initial pressure (kPa)	Formation temperature (°K)	Datum depth (m)	He mole fraction	OGIP He (e^3m^3)	Remaining gas raw He (e^3m^3)
Helmet	Jean Marie	A	6%	6 881	336	710	0.07%	44 954	17 312
Gunnell Creek	Jean Marie	A	8%	9 028	346	1 061	0.07%	17 464	6 401
Horn River	Evie	C	5%	28 700	408		0.04%	15 945	3 977
Clarke Lake	Slave Point	A	7%	20 064	383	1 524	0.09%	90 900	3 779
Sierra	Jean Marie	A	5%	9 105	339	834	0.05%	6 171	3 606
Parkland	Wabamun	A	2%	33 922	383	2 591	0.21%	13 926	1 652
Pickell	Notikewin	A	15%	4 612	315	3 687	0.05%	3 512	1 602
Monias	Halfway		15%	14 457	319	781	0.07%	15 398	1 390
Petitot River	Jean Marie	A	8%	6 731	361	1 010	0.10%	1 919	1 114
Klua	Pine Point	L	5%	17 949	393	1 696	0.11%	1 458	1 081
Doe	Wabamun	B	2%	33 503	375	2 701	0.36%	2 093	1 001
Two Rivers	Wabamun	C	3%	26 822	381	2 443	0.22%	1 031	817
Parkland	Wabamun	F	5%	50 136	388	2 868	0.21%	1 054	807
Doe	basal Kiskatinaw	A	10%	33 396	358	1 830	0.13%	1 522	803
Doe	Wabamun	A	6%	32 965	384	2 621	0.32%	6 041	791
Brazion	Belcourt-Taylor Flat	B	4%	50 650	398	3 435	0.04%	1 596	766
Brazion	Belcourt-Taylor Flat	A	3%	49 619	382	3 047	0.04%	2 266	747
Monias	Halfway	T	11%	14 662	320	821	0.10%	1 363	745
Two Rivers	Wabamun	B	8%	29 268	388	2 674	0.21%	817	735
Elleh North	Slave Point	A	8%	17 994	385	1 461	0.18%	1 131	712
Elleh	Jean Marie	B	8%	12 411	353	1 111	0.06%	1 680	691
Sextet	Slave Point	E	10%	18 189	380	1 491	0.14%	1 199	660

member of the Redknife Formation (Table 3, Fig. 5). Large helium reservoirs also occur in the Wabamun Formation near Fort St. John. The process that created these pools appears similar to that of large primary helium deposits in the United States. As with many Devonian and Mississippian reservoirs in the Western Canada Sedimentary Basin, these pools developed the porosity necessary for reservoir development through upward and lateral hydrothermal fluid flow (Petrel Robertson Consulting Ltd., 2003; Ma et al., 2006). Deep-seated faults, particularly strike-slip shear zones containing numerous small fault blocks prone to reactivation, promoted the movement of deep hydrothermal fluids, which accelerated reservoir-enhancing diagenetic processes (dolomitization) in carbonate reservoirs (Petrel Robertson Consulting Ltd., 2003).

Pools in the Slave Point Formation are associated with carbonates from reef banks that formed along the edge of the basins (Fig. 6). Faults along the Hay River fault zone linked deep hydrothermal fluids to Slave Point reservoirs and enhanced porosity through dolomitization (Madi et al., 2003; Janicki, 2006). Although the Slave Point Formation is conceptually very similar to the Keg River–Sulphur Point formations, capping shales provide better seals for Slave Point reservoirs (Petrel Robertson Consulting Ltd., 2003). Wells with anomalous measurements of helium occur in the pools and along the faults (Fig. 6).

The Jean Marie member of the Redknife Formation is, again, mainly limestone that is partially dolomitized by hydrothermal saline fluids. The parent fluids for the hydrothermal phase are interpreted to be residual evaporitic brines. During the latest Devonian to early Mississippian, heated brines flowed up through near-vertical fault-controlled conduits, bypassing approximately 850 m of overlying shale and basinal limestone, into the Jean Marie member, until the flow was impeded by the overlying impermeable shales of the unnamed upper member of the Redknife Formation. The brines then moved laterally into permeable limestone, creating a dolostone at the top of the Jean Marie member and the partial dolomitization of limestone distal to the faults (Wendte et al., 2009; Wierzbicki and Todorovic-Maranic, 2010).

TABLE 3. FORMATIONS WITH THE HIGHEST HELIUM ACCUMULATIONS. FOR THE PURPOSES OF THIS TABLE, ONLY POOLS WITH MORE THAN 100 E^3M^3 ABOVE THE THRESHOLD OF 0.04% MOLE FRACTION HE ARE INCLUDED. ONLY FORMATIONS WITH A CUMULATIVE VOLUME OF MORE THAN 1000 E^3M^3 HE ARE INCLUDED (OGIP: OFFICIAL GAS IN PLACE).

Formation	Pools	OGIP He (e^3m^3)	Remaining raw He (e^3m^3)	He (%)
Jean Marie	11	77 857	30 918	0.08
Slave Point	25	111 936	9 551	0.14
Wabamun	7	25 174	5 909	0.24
Evie	1	15 945	3 977	0.04
Pine Point	10	8 542	3 247	0.09
Halfway	4	17 309	2 523	0.12
Notike Win	3	5 086	2 214	0.05
Belcourt-Taylor Flat	2	3 862	1 513	0.04
Basal Kiskatinaw	2	1 884	1 080	0.09
Bluesky	3	1 928	1 011	0.21

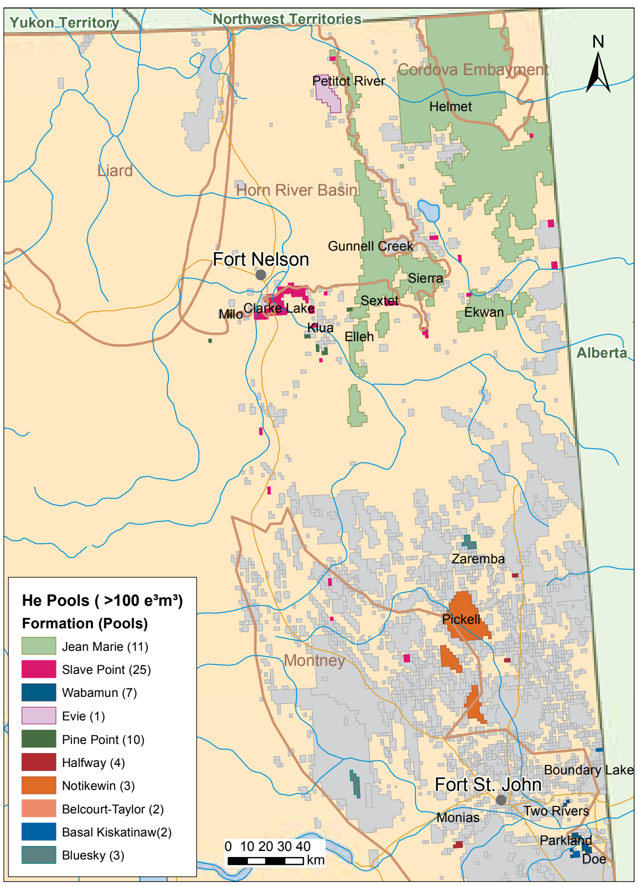

Figure 5. Pools of large helium accumulation, colour coded by formation. Only pools of with greater than 100 e^3m^3 were included and only formations where pools are cumulatively responsible for greater than 1000 e^3m^3 were included.

Reservoirs in the Wabamun Group of the Peace River Arch area have the highest concentration of helium with large accumulations in relatively small pools. These reservoirs are proximal, and related to, deeply seated faults that connect the Precambrian granitoid basement rocks with overlying Paleozoic sedimentary rocks. The Peace River Arch is a tectonic feature that began in the Precambrian and existed until its collapse in the late Devonian to early Mississippian (Halbertsma, 1994). Wabamun Group carbonates were deposited over the pre-existing topographic high of the Peace River Arch (Halbertsma, 1994). Postdepositional tensional faults associated with the formation of the Peace River rift basin allowed hot, magnesium-rich brines to penetrate the Wabamun limestone, thereby forming a secondary more porous dolomite (Halbertsma, 1994; Ma et al., 2006). Gas fields (e.g., Doe, Parkland) are believed to have formed later from reactivation of the fault system during the Laramide orogeny of the Late Cretaceous. Fractures were cemented shut with bladed anhydrites and coarse calcites at the time of hydrocarbon generation (Mount Joy and Halim-Dihardja, 1991).

The fourth largest accumulation of helium in British Columbia is associated with the Evie member shales in the Horn River. Many shale gas deposits contain little helium because helium molecules are small enough to diffuse through shale and because the helium-generating potential of the shale depends on the uranium and thorium content and the age of the shale. However, the shales in northeastern British Columbia basins (Horn River Basin, Cordova Embayment and Liard Basin) may be an exception. These shales tend to be dark grey to black, organic-rich, siliceous and (in the case of the Evie and Muskwa members of the Horn River Formation) highly radioactive (McPhail et al., 2008). The ‘hot’ zones (i.e., higher than normal uranium levels) usually correlate with the elevated organic content

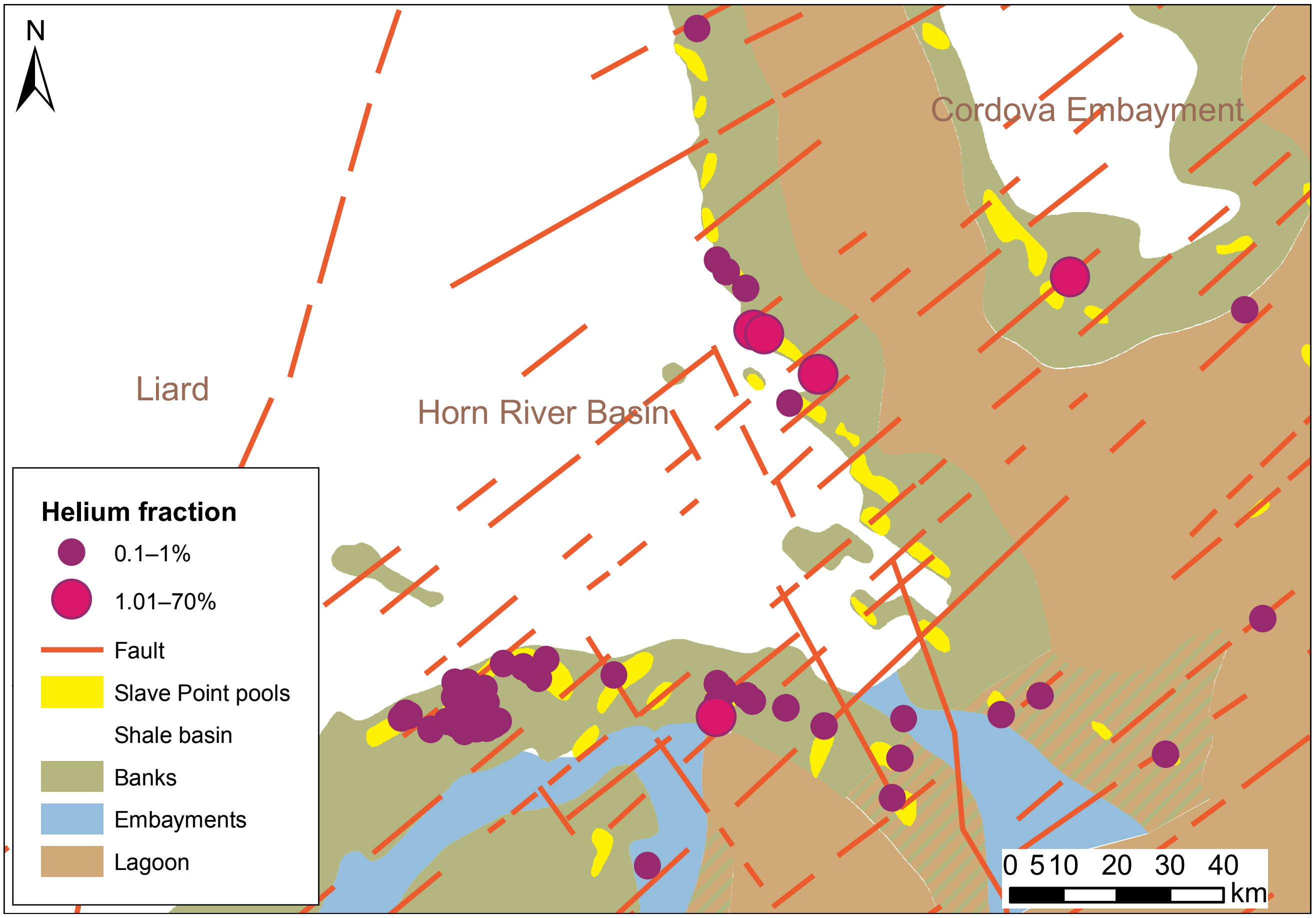

Figure 6. Slave Point paleo-environment with reef banks (green) proximal to shale basins (white). Gas pools (yellow) are thought to form from hydrothermal dolomitization associated with northwest-oriented, deep-seated faults. Faults (red) may be responsible for helium transport and accumulation. Dots represent mole fraction percent of helium in anomalous gas samples from wells.

in gas-rich horizons (Ferri et al., 2012). In the Horn River Formation, the Evie member has been measured in section as having up to 50 ppm uranium (Ferri et al., 2012). Hot shale has a helium-generating capacity eight times higher than normal shale and granite (Brown, 2010). The age of the shale (~390 m.y.) contributes to its ability to generate substantial helium over time. Additionally, Horn River Formation shales may be prospective because they are overpressured and the high basinal pressure may have countered the slow upward diffusion of helium.

SUMMARY

Many of the natural gas pools in northeastern British Columbia that are prospective targets for providing liquefied natural gas to the market may contain a value-added product that is currently not being realized. Liquefied natural gas has the potential to capture this potentially valuable byproduct. The normal processing procedure for refining of natural gas results in the release of the helium fraction of the gas to the atmosphere. The LNG process, however, facilitates the separation of helium from other natural gases. The prices of crude helium and grade A helium have risen dramatically in recent years, as United States reserves are reduced and global demand increases. Countries with high demand for grade A helium are located in Southeast Asia, where there is also a higher demand for LNG. In British Columbia, north of Fort Nelson, production from the Slave Point, Redknife (Jean Marie member) and Horn River (Evie member) formations may be enriched in helium. Near Fort St. John, gas production from the Wabamun Formation, in particular, may have added value from helium.

REFERENCES

Andrieu, F., Tsevery, J.-M., Schmitt, N., Peyron, J.-M., Blanc, S., Pareja, T. and Cognard, M. (2006): The Ras Laffan Helium Purification Unit; *Air Liquide Advanced technologies*, URL <http://www.airliquideadvancedtechnologies.com/en/library/publications-scientifiques-techniques/the-ras-laffan-helium-purification-unit.html> [February 2013].

Anonymous (2012): Innovative use of helium: Does Russia need to produce helium?; *Ernst & Young*, 17 pages.

Beebe, R.R., Reppy, J.D., Goldman, A.M., Lander, H.R., Macauley, M.K., Miller, M.A., Rose, A.Z., Siewert, T.A., Weisskoff, R.M., Shapero, D.C., Ehrenreich, R.M., Aylesworth, K.D. and Morgan, D.F. (2000): The Impact of Selling the Federal Helium Reserve; *The National Academies Press*, Washington, DC, 80 pages.

Broadhead, R.F. (2005): Helium in New Mexico—geologic distribution, resource demand, and exploration possibilities; *New Mexico Geology*, Volume 27, no 4, pages 93–100.

Brown, A. (2010): Formation of high helium gases: a guide for explorationists; *American Association of Petroleum Geologists*, AAPG Convention, April 11–14, 2010, New Orleans, LA.

Clarke, M. and Van Schagen, F. (2010): Liquified natural gas (LNG) carbon footprints and the development of methodologies for CDM estimation and verification; *Asian Journal on Energy and Environment*, Volume 11, no 2, pages 90–95.

Ferri, F., Hickin, A.S. and Reyes, J. (2012): Horn River basin–equivalent strata in Besa River Formation shale, northeastern British Columbia (NTS 094K/15); in Geoscience Reports 2012, British Columbia Ministry of Energy, Mines and Natural Gas, pages 1–15.

Garvey, M. (2012): Waiting for the light at the end of the tunnel: the worldwide helium market; *CryoGas International*, October 2012.

Groat, C.G., Richardson, R.C., Beebe, R.R., Campbell, J.R., Chan, M.H., Chermak, J.M., Dahl, C.A., Elam, T., Goldman, A.M., Hartness, N.E., Lee, W.J., Migliori, A., Mowery, D.C., Prats, M., Reinoehl, J.B., Sekachev, I., Siewert, T.A. and Thiemens, M.H. (2010): Selling the Nation's Helium Reserve; *The National Academies Press*, Washington, DC, 140 pages.

Halbertsma, H.L. (1994): Chapter 13—Devonian Wabamun Group of the Western Canada Sedimentary Basin; in Geological Atlas of the Western Canada Sedimentary Basin, Mossop, G.D. and Shetsen, I., Editors, *Canadian Society of Petroleum Geologists* and *Alberta Research Council*, Calgary, Alberta, pages 203–221.

Janicki, E.P. (2006): Distribution of Presqu'ile dolomite in the Great Slave Plain, Northwest Territories; in Potential for carbonate hosted lead-zinc Mississippi-Valley-type mineralization in northern Alberta and Southern Northwest Territories, Hannigan, P.K., Editor, *Geological Survey of Canada*, Bulletin 591, Calgary, AB, pages 179–194.

Kynett, K. (2012): What goes up must come down: Congress deadline looms: is helium doomed?; *AAPG Explorer*, December 2012, pages 10–12.

Ma, F., Al-Asam, I. and Yang, J. (2006): Numerical modeling of hydrothermal fluid flow coupled with mass transport: an example from the Devonian Wabamun Group, northeast British Columbia, Canada; *Journal of Geochemical Exploration*, Volume 90, no 3, page 216.

Madi, A.J., Damte, A. and Hayes, M. (2003): Fault-associated hydrothermally-dolomitized reservoirs (HTD) in Devonian strata of northeastern British Columbia—a large-scale geological exploration concept; 2003 CSPG/CSEG Joint Convention: Partners in a New Environment, *Canadian Society of Petroleum Geologists*, Calgary, Alberta.

Madrid, P.J. (2012): Mineral commodity summaries: Helium; *US Geological Survey*, Amarillo, Texas, URL <http://minerals.usgs.gov/minerals/pubs/commodity/helium/mcs-2012-heliu.pdf>.

McPhail, S., Walsh, W., Lee, C. and Monahan, P.A. (2008): Shale units of the Horn River Formation, Horn River Basin and Cordova Embayment, northeastern British Columbia; Petroleum Geology Open File 2008-1, *British Columbia Ministry of Energy, Mines and Natural Gas*, page 14.

Mount Joy, E.W. and Halim-Dihardja, M.K. (1991): Multiple phase fracture and fault-controlled burial dolomitization, Upper Devonian Wabamun Group, Alberta; *Journal of Sedimentary Petrology*, Volume 61, no 4, pages 590–612.

Peterson, J. and Madrid, P. (2012): 2010 Minerals Yearbook: Helium; *US Geological Survey*, Amarillo, Texas, URL <http://minerals.usgs.gov/minerals/pubs/commodity/helium/myb1-2010-heliu.pdf>.

Petrel Robertson Consulting Ltd. (2003): Exploration assessment of deep Devonian gas plays, northeastern British Columbia; *British Columbia Ministry of Energy, Mines and Natural Gas,* Petroleum Geology Open File 2003-4.

Plumer, B. (2012): Congress turns its attention to... America's helium crisis; *The Washington Post*, Washington, DC, May 13, 2012.

Wendte, J., Chi, G., Al-Asam, I. and Sargent, D. (2009): Fault/fracture controlled hydrothermal dolomitization and associated diagenesis of the Upper Devonian Jean Marie member (Redknife Formation) in the July Lake area of northeastern British Columbia; *Bulletin of Canadian Petroleum Geology*, Volume 57, no 3, pages 275–322.

Wierzbicki, R. and Todorovic-Maranic, D. (2010): Exploiting natural fracture and fault fairways in the Jean Marie Carbonate Platform, N.E. British Columbia; Canadian Unconventional Resources and International Petroleum Conference, 19–21 October 2010, *Society of Petroleum Engineers*, Calgary, Alberta.