International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2018)

Contribution ID: **192** Type: **ORAL**

Uranium-Lithium Deposits at Macusani, Peru: Geology, Processing & Economics along the path to production

Thursday, 28 June 2018 14:40 (20 minutes)

INTRODUCTION

The swarm of near-surface uranium orebodies of the Macusani district, southern Peru, controlled by Plateau Uranium Inc., contain mineral resources of 51.9 Mlbs at 248 ppm U3O8 (20.0 ktU at 210 ppm U - Measured & Indicated) and 72.1 Mlbs at 251 ppm U3O8 (27.8 ktU at 212 ppm U - Inferred) using 75 ppm U economic cut-off [1]. This Preliminary Economic Assessment study has shown the easily leachable, near surface mineralization constitutes a major, potential low-cost uranium source capable of producing uranium at cash costs of US$17.28/lbU3O8 (US$44.5/kgU). The deposits are genetically anomalous: although the predominant host-rocks are rhyolitic volcanics and hypabyssal intrusions with geochemical affinities with the U-rich Hercynian S-type granites, the hexavalent uranium mineralogy, comprising meta-autunite and weeksite, is akin to that of other surficial systems [2], and differs fundamentally from all recognized high- and low-temperature uranium deposit clans [3]. The uniqueness of the district is also highlighted by the exceptional, inherent, lithium endowment of the host volcanics. Both the Miocene bedrock geology and the Plio-Pleistocene geomorphology and climatic history of the district are critical to an understanding of the origin of these unique uranium deposits. This unique origin is key to the excellent potential economics of these near surface, low-grade uranium deposits.

GEOLOGICAL SETTING

The Macusani uranium district is located at Lat. 13° 57'S; Long. 70° 37'W in northern Puno Department, southern Peru, and is essentially cospatial with the Quenamari Meseta at an elevation ranging from ca. 4400 to 5000 m a.s.l. The Quenemari meseta separates the WNW-trending Carabaya-Apolobamba and Vilcanota segments of the Cordillera Oriental (Eastern Cordillera). The high plateau is underlain by an Upper Miocene (10.1-6.7 Ma) succession of subaerial glass-rich and unwelded rhyolitic flows assigned [4] to the Macusani Formation, which attains thicknesses in excess of 500 m and covers an area approaching 1500 km2. The Macusani Formation is the youngest unit of the Quenamari Group, locally the youngest major magmatic unit of the Central Andean Inner Arc Domain [5], and represents the sole important host for uranium mineralization. The rhyolites are dominated by lapilli-crystal-ash tuffs and pumice flows, extremely rich in broken phenocrysts, and lacking fabrics ascribable to ignimbritic, ash-flow processes. No early Plinian explosive stage occurred, and eruption of extremely viscous magma into an actively-subsiding tectonic basin is envisaged as occurring as frothy debris-flows]6] from vents around the southern margin of the field.

Subsidence and volcanism were nucleated by a series of NNW-striking, sinistral, transcurrent, crustal-scale faults which accommodated the initial rotation of the Bolivian Orocline in the latest-Oligocene, representing the beginning of the ongoing Quechua Orogeny [7].

The rhyolites are strongly-peraluminous (A/CNK, including Li = 1.19-1.35; normative corundum exceeding 2), exemplified by phenocrystic muscovite, andalusite, tourmaline, sillimanite and cordierite/osumulite, but are also enriched in alkalis (K, Na, Li, Rb, Cs), as well as lithophile metals (Sn, Nb, Be), HFSE (Ta, W, U), and "volatile"elements (B, F, P). Magmas were generated at moderate temperatures (max. 800℃) and high

pressures through vapour-undersaturated, low-fraction, partial melting of batches of mature, pelitic metasediments, probably induced by mantle melt incursion into thickening continental crust [7, 8, 9]. Magmatism occurred in a transpressional tectonic regime accompanying antithetic subduction and delamination of Brazilian Shield lithosphere. The uranium content of unaltered rhyolites, hosted by accessory monazite and apatite, but predominantly by pumiceous and matrix glasses, averages 10-30 ppm, and the rhyolites display geochemical affinities to the uraniferous, post-collisional SP, S-type, two-mica Hercynian granites [7,8].

The lithium potential of the district is entirely represented by the inherent magmatic endowment of the main succession of rhyolites. These average 400-600 ppm Li (8,9), hosted in part by phenocrystic biotite, muscovite and sodic plagioclase, but predominantly in volcanic glass, making 70% of the Li easily leached in dilute sulphuric acid at moderate temperatures of 85℃.

GEOMORPHOLOGICAL SETTING

The Macusani Formation flows dip at ca. 3° NE, but the surface of the meseta is defined by a more gently, NE-dipping, sub-planar, erosional pediment, generated through uplift under semi-arid climatic conditions at ca. 5 Ma.. To the west, the meseta surface exhibits an abrupt backscarp rising to the 5645 m a.s.l. Quelccaya temperate mountain ice-cap. Although Quelccaya is fast receding, it remains the world's largest tropical ice mass [10], with a firn-line at 5250 m and surrounded by steeply-plunging outlet glaciers. Quelccaya formed part of a continuous ice-cap extending from northern Bolivia to southern Peru in the Early Pleistocene, but had become isolated by the Late Pleistocene. It has expanded and contracted radically and abruptly over the past ca. 700 ka [11,12]. The meseta, now stripped of glacial/fluvioglacial sediments, is traversed by a series of ENE-trending fluvial canyons, converging on the valleys of the Macusani and San Gaban rivers which, in the austral summers channel warm, humid Atlantic air from the contiguous Amazonian lowlands. Annual precipitation, largely as rain, averages 3000 mm.

URANIUM MINERALIZATION

The major uranium mineral in the Macusani district is finely acicular-to- platy, yellow-orange meta-autunite (Ca[(UO2)(PO4)]2(H2O)6-8) [13,14] with subordinate weeksite (K2(UO2)2(Si5O13)(H2O)4) [3]. Despite previous descriptions [15], no uraninite or pitchblende has been observed. Meta-autunite and weeksite occur as disseminations in rhyolite, replacing apatite phenocrysts and infilling original volcanic cavities, and as stockworks of 1-3 cm-wide veins, controlled by subvertical cooling joints and steeply-dipping, NE-striking faults, as well by flat-lying structures sub-parallel to volcanic stratigraphy.

Deposition of the uranyl minerals is sometimes associated with powdery to crudely botryoidal, black oxide mineraloids, largely Mn-rich, but locally dominated by Fe and Si. White, clay-like moraesite (Be2(PO4)(OH)· 4H2O) occurs erratically with the uranium minerals, or forms separate veinlets. Over 95 percent of the strictly primary uranium mineralization is hosted in rhyolite flows and hypabyssal stocks, but high-grade mineralization occurs locally in coarse terrigenous clastic and epiclastic interbeds along the eastern margin of the volcanic field.

With the exception of radiation-induced smokiness in quartz phenocrysts, no hydrothermal alteration is associated with the deposits, and there is no evidence of uranium depletion surrounding mineralization, implying that the uranium was not largely locally derived. Although the rhyolites are enriched in lithophile metals, only beryllium appears to have been mobilised with uranium. Earlier hydrothermal activity, ranging from post-magmatic F-rich (topaz-muscovite-quartz) greisening, in the vicinity of intrusive bodies, to more widespread intermediate-argillization (F-rich illite and Ca-montmorillonite/ nontronite) was similarly ineffective in concentrating Sn, Nb, Ta, W and U. Barren, advanced-argillic (kaolinite-quartz) alteration is intense both in the vicinity of the faulted Rio Macusani trough and along contiguous interflow contacts, but predated uranium mineralization.

The uranium orebodies are focused in at least two 15-60 m-thick mantos, sub-parallel to the surface of the meseta, but discordant to volcanic stratigraphy. Mineralization is concentrated within ca. 200 m of surface, in the upper, 7 ±1 Ma flow sequence [4]. Here, the majority of the deposits occur adjacent to the upper slopes of the canyons dissecting the plateau, with a striking areal concentration in the vicinity of their confluence with the main Macusani River valley. However, high-grade mineralization with higher weeksite content occurs locally within and at the base of the 10 ±1 Ma flows, beneath the floor of the valley.

URANIUM DEPOSITION CONDITIONS

Fluid inclusions have not been observed in either meta-autunite or weeksite, but a low temperature and/or unusually brief duration of ore formation may be inferred from the preservation of the magmatic high-sanidine, disordered crystal structure of translucent K-feldspar phenocrysts in immediate contact with uranium mineralization. Investigation of the nature of the ore-forming aqueous fluids through light-stable isotopic chemistry is inhibited by the absence of mineral-water oxygen and hydrogen fractionation data for uranyl minerals, but the structural affinities of meta-autunite and smectite suggests that the latter may serve as a proxy. The δ18O and δ2H compositions of the meta-autunite, respectively are 5.2-14.7 and -141 to -83 per mil, and fall well

outside the "magmatic box", implying that meteoric waters were responsible for uranium mineralization. Application of the fractionation factors determined for smectite [16,17], and assuming that ore deposition took place at ca. 15℃, ambient near-surface temperatures on the meseta, yields oxygen and hydrogen isotopic water compositions of -21.7 to -12.2 per mil and -181 to -123 per mil, respectively [3], defining a field overlapping extensively with that of the Quelccaya ice-cap [18]. Similar water oxygen isotopic compositions are estimated [3] by applying the incremental fractionation calculation proposed for hydroxyl-bearing silicates by Zheng [19] to meta-autunite.

AGE OF MINERALIZATION

Application of U-Pb geochronology to the Macusani deposits [20] is precluded by the high content of common lead and minimal radiogenic lead in meta-autunite, evidence for youthful crystallization but defining only very imprecise ages in the approximate range 350 ka to 1.06 Ma. In contrast, U-series (U-Th-Pa) geochronology [21,22] applied using LA-ICP-MC (Multicollector)-MS analysis of natural and cut surfaces of meta-autunite and weeksite vein-fill from six prospects at the eastern/northeastern margin of the meseta, yields acceptable dates for crystallization or re-crystallization, all extremely young. The technique utilizes the gradual increase in 230Th and 231Pa through, respectively, 234U and 235U decay, until secular equilibrium is attained at, respectively, ca. 500 and 300 ka. Isotopic ratios for multiple sites in small volumes of mineral are plotted on Concordia diagrams with calculated 231Pa/235U activity ratios as the ordinate and 230Th/234U ratios as the abscissa. Four samples yielded concordant or near-concordant data, with ages of +500, 335, 130 and 75-65 ka, while five defined discordia extending from the origin to Concordia, with upper intercepts of +500, 397, 218-207 and 113-103 ka. Other samples gave discordant compositions with no meaningful intercepts with Concordia. The data are evidence for open-system behaviour, most probably involving variable, and in cases mutually differing, gains and losses of 230Th and 231Pa, a process extending over at least the past 500 ka, i.e., through much of the Late Pleistocene. Several samples, including one comprising both meta-autunite and weeksite, reveal multiple episodic mineralization events.

ORE-GENETIC MODELLING

The Macusani uranium mineralization has been widely assigned [e.g., 23] to the IAEA clan of "volcanic-related"deposits, exemplified by, Strel'tsovskoe, Sierra Pena Blanca and BaiYangHe. However, although uranium was certainly derived from strongly-peraluminous silicic magmas, the Macusani deposits lack U+4 minerals –the U+6 minerals, meta-autunite and weeksite are primary, not supergene. In addition, although post-magmatic and lower-temperature activity was widespread, this caused no mobilization or concentration of either uranium or lithophile metals. Instead, the uranyl minerals were directly precipitated at low temperatures from entirely meteoric waters at least 4 Ma after the local cessation of magmatic activity. Mineralization does locally occur in terrigenous sediments at the eastern margin of the basin, but, uranium precipitation is not associated with reductants as in traditional sandstone-hosted systems: in contrast, the close association with Mn-Fe oxide mineraloids is inferred to reflect their highly-absorbing nature, promoting meta-autunite precipitation even in undersaturated conditions [24]. Although the environment of mineralization is largely near-surface, it extends locally to depths of several hundreds of metres, precluding analogies with other "surficial"uranium deposit clans [e.g., 2, 23].

A critical constraint on ore-genetic modelling is the age of mineralization. The Macusani uranium deposits are undoubtedly extremely young, but the U-Th-Pa geochronology does not unambiguously discriminate between original deposition and subsequent modification of the dominant uranium mineral, meta-autunite. Nonetheless, the radiogenic isotope relationships show clearly that the ore assemblages were subject to multiple reconstitution since ca. 500 ka, demonstrating that surficial conditions in the Late Pleistocene were favourable for uranium transport and precipitation. A major consideration here is the enormous volume of meteoric water which was repeatedly required, both for leaching, largely from volcanic glass, and the rapid transport of several hundreds of millions of lbs. of uranium. The inherently porous rhyolites clearly acted as permeable aquifers, the through-going channels represented by flat-lying flow-contacts and faults, and steeply-dipping joints (hydrologically, "pipes") and faults (collectively, "macropores"), being interconnected by the cavity-rich ashy matrix of the tuffs. This hydrological environment, continuously opened up by ongoing orogenic surface uplift, would have permitted extensive mixing of overland and infiltrating shallow waters with "old"resident water stored in the volcanics, the latter providing an effective leaching agent for glass-bound uranium. Deep penetration of shallow waters would be optimized during flood run-off, channelled along pre-existing and actively deepening fluvial canyons, feeding the baseline drainage along the Macusani-San Gaban river valley. In this model, mineralization would be precipitated in riparian environments during episodes of sub-surface storm- flow.

The abrupt and radical shrinkage of the Quelccaya ice cap during the Tarantian (late-Late Pleistocene) and early Holocene revealed by terminal moraine dating [10,11], as well as the vastly more extensive glacial cover documented for the preceding Plio-Pleistocene [25], provides a rigorous geomorphological and climatic context for the inferred flooding events: the mineralization episodes documented by U-series dating correspond strikingly with climatic events of low The δ18O values and low ice volume (high sea-level) in the low-latitude oceanic, foramanifera-derived, time -scale [e.g., 26]. Concordant dates for mineralization coincide with events

at 315 ka, 120 ka and 69-79 ka, while the upper-intercept dates match events at 397 ka, 210-217 ka and 103-113 ka, which accounts for all of the major warming interglacial events of the Late Pleistocene.

The Macusani mineralization represents the final episode in the evolution of the major Carabaya polymetallic (Sn, Au, Pb, Zn, Ag, W) metallogenetic sub-province of northern Puno Department [5], with uranium deposits generated in an unparalleled periglacial environment resulting from catastrophic episodic flooding during Late Pleistocene global interglacial periods. The Macusani Uranium district truly hosts a unique class of uranium deposit, but with aspects of both surficial and sandstone systems.

ACKNOWLEDGEMENTS

This communication is based on Valeria Li's doctoral research at Queen's University, Kingston, Canada, funded by Cameco Corporation, Vena Resources Inc., Macusani Yellowcake Inc., Queen's University, The Society of Economic Geologists and The Natural Sciences and Engineering Research Council of Canada. Don Chipley was essential in designing and operating the U-series dating programme.

REFERENCES

[1] SHORT, M et al., NI 43-101 Report –Macusani Project Preliminary Economic Assessment prepared for Plateau Uranium Inc., (2016) 326. Filed on: www.sedar.com
[2] CUNEY, M. & KYSER, T.K., 2015, The Geology and Geochemistry of Uranium and Thorium Deposits, Min. Assoc. Canada Short Course Series 46, Montreal.
[3] LI, V., V., 2016, The Uranium Mineralization of the Macusani District, Southern Peru: Geochemistry, Geochronology and Ore-Genetic Model, Ph.D. thesis, Queen's University, Kingston, Ontario, 192p
[4] SANDEMAN, H.A. et al., Lithostratigraphy, petrology and 40Ar/39Ar geochronology of the Crucero Supergroup, Puno Department, SE Peru, 10 J. South Amer. Earth Sci. (1997), 223.
[5] CLARK, A.H. et al., Geologic and geochronologic constraints on the metallogenic evolution of the Andes of southeastern Peru, 85 Economic Geology, 1520.
[6] SANDEMAN, H.A. et al. Petrographic characteristics and eruption styles of peraluminous, rhyolitic pyroclastic rocks of the Quenamari Group, Puno, southeastern Peru (abstract), Geol. Assoc. Canada/Mineral. Assoc. Canada, 19, Program with Abstracts, A98.
[7] SANDEMAN, H.A. et al. An integrated tectono-magmatic model for the evolution of the southern Peruvian Andes (13°20'S) since 55 Ma, 37, International Geology Rev., 1039.
[8] PICHAVANT, M, et al. The Miocene-Pliocene Macusani Volcanics, SE Peru: I Mineralogy and magmatic evolution of a two-mica aluminosilicate-bearing ignimbrite suite, 100, Contrib. Mineral., Petrol. (1988), 300.
[9] PICHAVANT, M. et al. The Miocene-Pliocene Macusani Volcanics, SE Peru: (II) Geochemistry and origin of a felsic peraluminous magma, 100, Contrib. Mineral. Petrol (1988), 325.
[10] MERCER, J.H. et al. Peru's Quelccaya ice cap: glaciological and glacial geological studies, 10, Antarctic Journal of the U.S. (1975),19.
[11] MARK, B.G. et al. Rates of deglaciation during the Last Glaciation and Holocene in the Cordillera Vilcanota-Quelccaya Ice Cap region, southeastern Peru, 57, Quaternary Research, 287.
[12] GOODMAN, A.Y. et al. Subdivision of glacial deposits in southeastern Peru based on pedogenic development and radiometric ages, 56, Quaternary Research , 31.
[13] HERRERA, W. & ROSADO, F., Las manifestaciones uraniferas en rocas volcanicas de Macusani (Peru): Geologia y Metalogenesis de los Depositos Uraniferos de Sudamerica; INTERNATIONAL ATOMIC ENERGY AGENCY , Vienna, 219.
[14] RIVERA, R.C. et al. Metalogenia del Uranio en las Regiones de Cusco y Puno, Inst. Geol., Minero Metalurgico, Boletin, Ser. B., Geol. Econ., Lima, 121 p.
[15] ARRIBAS, A. & FIGUEROA, E. , Las mineralizaciones de uranio en las rocas volcanicas de Macusani (Peru), 41, Estudios Geologicos ,323.
[16] SAVIN, S.M. & LEE, M. , Isotopic studies of phyllosilicates, Baley, S.W., ed., Hydrous Phyllosilicates (Exclusive of Micas), 19, Reviews in Mineralogy, 189.
[17] CAPUANO, R.M. The temperature-dependence of hydrogen isotope fractionation between clay minerals and water: evidence from a geopressured system, 56, Geochimica et Cosmochimica Acta, 2547.
[18] THOMPSON, L.G. & DANSGAARDS, W. Oxygen isotope and microparticle studies of snow samples from Quelccaya Ice Cap, Peru, 10, Antarctic Journal of the U.S., (1975) 24.
[19] ZHENG, Y-F. Calculation of oxygen isotope fractionation in hydroxyl-bearing silicates, 120, Earth & Planetary Sci. Letts (1993), 247.
[20] LI, V.V. et al. The uranium deposits of the Macusani district, Puno, southeastern Peru: a new genetic model (abstract), Soc. Econ. Geologists, 2012 Conference, Lima, Peru.
[21] CHENG, H. et al. Uranium-thorium-protactinium dating systematics, 62-21/22, Geochimica et Cosmochimica Acta (1998), 3437.
[22] BOURDON, B. et al. Uranium-Series Geochemistry, Reviews in Mineralogy and Geochemistry, ed. Bour-

don, B., et al., 2003, 1-21.
[23] DAHLKAMP, F.J. Uranium Deposits of The World, Springer, Berlin, 520 p.
[24] SATO. T. et al. Iron nodules scavenging uranium from groundwater, 31, Environmental Science and Technology (1997), 2854.
[25] CLAPPERTON, C.M. The glaciation of the Andes, 2, Quaternary Sci. Revs. (1983), 83.
[26] BASSINOT, F.C. et al .The astronomical theory of climate and the age of the Brunhes-Matuyama magnetic reversal, 126, Earth & Planetary Sci. Letts.(1994), 91.

Country or International Organization

Canada

Primary author: Mr O'CONNOR, Terrence (Plateau Uranium Inc)

Co-authors: Dr CLARK, Alan (Queen's University); Prof. KYSER, Kurt (Queen's University, Canada); Dr STEFAN, Laurence (Plateau Uranium Inc.); Dr LI, Valeria (Queen's University)

Presenter: Mr O'CONNOR, Terrence (Plateau Uranium Inc)

Session Classification: Advances in Exploration

Track Classification: Track 4. Advances in exploration