The Geology and Geochemistry of Uranium and Thorium Deposits

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TABLE OF CONTENTS

DETAILED LIST OF CONTENTS

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7. LOW TO MEDIUM TEMPERATURE HYDROTHERMAL URANIUM DEPOSITS 169

PREFACE

The Mineralogical Association of Canada (MAC) has been an ardent supporter of short courses, particularly on uranium having sponsored a short course volume in 1978 entitled ***Uranium Deposits: Their Mineralogy and Origin*** and edited by M.M. Kimberley and another volume in 2008 entitled ***Recent and not-so-recent developments in uranium deposits and implications for exploration*** and written by M. Cuney and K. Kyser, and a volume in 2013 entitled ***Uranium – Cradle to Grave***, edited by Peter Burns and Ginger Sigmon. These proved to be among the most popular short course volumes ever for MAC, with the latter two volumes used in both undergraduate and graduate courses on mineral deposits geology and by the exploration industry. There have been various conferences supported by international uranium concerns such as the International Atomic Energy Agency (IAEA), but MAC is among the few professional organizations that see value in promoting a knowledge base for uranium deposits. Other organizations, such as the Prospectors and Developers Association of Canada, Saskatchewan Energy and Resources, Mineralogical Society of America, Canadian Institute of Mining, Metallurgy, and Petroleum and CREGU have supported short courses and conferences on uranium, with most of these occurring a few years ago in response to the renewed interest in uranium as an alternative energy source. An international group of scientists (Grenthe et al., 1992) supported by the NEA and OECD published the only available compilation of selected thermodynamic data on uranium in 1992.

A lack of interest in uranium by the mining industry and subsequently by the research community was largely the result of the low spot price since 1987, which has continued except for a short resurgence in 2008. Low uranium prices have a ripple effect in that not only are expenditures in exploration for uranium depressed, but support for research in uranium deposit studies also decreases. Despite the demise in uranium exploration and support for research, some government organizations and companies that specialized in uranium such as Uranerz, Cameco and Cogema (now AREVA) continued to support research, albeit at a reduced level. The authors of this volume are among those who continued with their research on uranium through this support and these companies are warmly thanked for their support.

During this time in the former Soviet Union, uranium geologists were considered critical, so that research continued. During the 1990's, other nations such as Japan, India and China continued their research efforts as nuclear energy was strategic in their energy mix. Research supported by state agencies and the IAEA continued during this time on aspects of the geochemistry of uranium in solution and in the environment (e.g. Grenthe et al., 1992). Studies of the Oklo natural reactors in Gabon (e.g. Gauthier Lafaye *et al.* 1996), the Cigar Lake deposit in the Athabasca Basin (e.g. Cramer and Smellie 1994), and Poços de Caldas in Brazil (e.g. Chapman *et al.* 1991) were undertaken as natural analogs for the long term disposal of nuclear waste in geologic formations and remediation of closed uranium mines (Merkel *et al.* 2006).

The purpose of this short course is to highlight data and research that have recently developed and place these results in a framework of the extensive knowledge base for uranium and thorium, as well as discuss new techniques and ideas that can be integrated into effective exploration strategies for uranium. New models developed for different deposits and the mechanisms that control their genesis are central themes in this short course volume as is the addition of thorium in this discussion. This volume is divided into the following chapters:

1. Nuclear Fuel Cycles and the Economics of Uranium discusses the discovery of uranium, which countries have the greatest reserves, who uses nuclear energy, and what is the nuclear fuel cycle. The interplay between the market price of uranium and exploration are discussed. As a commodity, interest in uranium is driven by its spot price, although the spot price serves only as a guide for the value of uranium because most of the uranium sold for use in reactors is brokered through long-term contracts.

2. New Classifications of Deposit Types discusses how deposits can be classified based on both their genesis and geological characteristics. What are the types of deposits and in which geological environments are they found. In reality, this section is focused on the natural uranium cycle and how various environments are conducive to accumulating significant concentrations of uranium and thorium.

3. Geochemistry and Mineralogy of Uranium and Thorium consists of a brief review of the geochemical properties of uranium and thorium that figure greatly in the development of deposits. Our goal here is not to discuss in detail the geochemistry of uranium and thorium, which are not very well known except by those in the processing or disposal industries, but to present an overview of the stability of uranium and thorium in natural fluids at a variety of temperatures.

4. Radioactivity, Heat Production and Flux, and Natural Reactors gets at the importance of uranium and thorium in producing radiation and heat and how this helps scientific research and exploration, how it affects the formation of deposits and the structure and color of minerals, how this has led to the existence of natural reactors in Gabon, and how U and Th bearing minerals can be dated through a wide variety of techniques. Radiation is also examined as this is both the benefit of uranium and thorium, but also for the reason they are feared.

5. Magmatic Fractionation describes uranium mineralization generated by high temperature magmatic processes related to magmas and granitoid bodies in migmatitic environments such as alaskite. Extreme fractional crystallization of peralkaline magmas can lead to the formation of very large low-grade U and Th resources because of the high solubility of U and Th in highly depolymerized magmas. The effects of crustal melting processes on the production of melts that host uranium mineralization are examined.

6. Metasomatic Deposits is concerned with high temperature hydrothermal processes associated with regional Na metasomatism and quartz dissolution, forming discontinuous occurrences of uraniferous Na-metasomatized granite, metasedimentary or metavolcanic units that extend over several tens of kilometres. The metasomatic deposits in Ukraine with their significant reserves are also examined. Less common uranium deposits associated with K-metasomatism at Elkon in Siberia and skarns are also reviewed.

7. Low to medium temperature hydrothermal uranium examines granite-related and volcanic-related deposits, a diverse category of deposits generally exhibiting vein-type morphology, but also as disseminated ore in episyenitic bodies. They are related to medium to low temperature hydrothermal remobilization of uranium within granitic, volcanic rocks, and metamorphic rocks and include the diverse hydrothermal deposits in the infamous Beaverlodge area in Canada.

8. Basins and Uranium Deposits examines uranium mineralization related to sedimentary basins. Unconformity-related deposits are associated with a reduction front near the unconformity between Proterozoic sandstone units and underlying metamorphosed basement lithologies. The deposits are structurally hosted either in the basement or in the overlying sandstone. Models involving the source of uranium from breakdown of uranium-bearing phases in altered basement rocks along fault zones or from an oxidized basinal brine carrying uranium leached from detrital phases are also discussed, as are the role of paleoaquifers in the prospectivity of a basin.

These types of deposits were largely replaced in the Phanerozoic by breccia pipes and sandstone-hosted low-temperature deposits such as roll-front, tabular and sedimentary copper associated deposits. These occur in medium to coarse-grained sandstone units deposited in a continental fluvial or marginal marine sedimentary environment such that impermeable shale/mudstone units immediately above and below the mineralized sandstone confine fluid flow so that uranium can precipitate under reducing conditions within the sandstone because of carbonaceous material, sulfides, hydrocarbons and interbedded basic volcanic rocks with abundant ferro-magnesian minerals.

9. Deposits Related to Low Temperature Processes examines quartz pebble conglomerate deposits at Elliot Lake in Canada and the Witwatersrand gold–uranium deposits in South Africa, the latter a resource of increasing importance. Also included as low-temperature deposits are surficial deposits in sediments and soils, with those in calcrete being the largest deposits.

10. Thorium Deposits discusses the wide spectrum of thorium deposit types, how they are classified, how they form and where they are—this is a relatively new energy commodity that is only now beginning to be understood. This chapter also shows that that the thorium resources can be of the same order of magnitude as the uranium resources, despite the much lower solubility of thorium in most geologic fluids.

11. Exploration Strategies and the Future of Uranium and Thorium as Energy Resources discusses what we have learned recently that may help us to explore for uranium deposits. The future use of uranium and thorium are discussed, with thorium emerging as a viable, but technologically challenging resource.

These chapters are by no means meant to be comprehensive as the knowledge base for uranium deposits is vast (see for example Dahlkamp 2009, 2010), and that for thorium is growing rapidly. Unfortunately, much of the knowledge on uranium is manifest in the literature from research prior to 1990, and much of this is outdated. We have learned a great deal in formulating this short course, and we hope that some of this knowledge will be useful to you. Those interested in uranium and thorium should find the list of books in the references, among many others, to be useful in expanding their knowledge base.

We are indebted to many for their support of this volume, including the Mineralogical Association of Canada and the Society for Geology Applied to Mineral Deposits for their sponsorship. In particular, Rob Raeside of the MAC is thanked for his patience and diligence in editing this volume. Several others at the Queen's Facility for Isotope Research provided constructive criticism and editorial skills that greatly improved this volume.

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