

## APPENDIX C

### Geoenvironmental Ore Deposit Model

This Appendix presents a direct comparison between the thorium and rare earth element vein deposit geoenvironmental ore deposit model (Armbrustmacher *et al.*, 1995) with the host rocks and granitic pegmatite-hosted U-Th-REE deposits of the Bancroft area. In addition, images showing the remediation efforts made by mining companies and the municipality are provided.

#### *Geoenvironmental Ore Deposit Model for Bancroft*

In the 1990s, the U.S. Geological Survey (U.S.G.S.) and others proposed the concept of geoenvironmental ore deposit modelling (Plumlee *et al.*, 1994; Plumlee and Nash, 1995). Plumlee and Nash (1995) defined a geoenvironmental model as a compilation of geological, geochemical, hydrological and geophysical parameters related to the environmental behaviour of a particular ore deposit from pre-mining to mining and post-closure phases of development (Fig. C1). They built a viable classification for 32 diverse mineral deposits based on ore deposit models of Cox and Singer (1986). The approach of the U.S.G.S. provides the steps to develop a quantitative geoenvironmental model for any ore deposit type to plan for closure at the discovery stage. In order to facilitate this, explorationists must look at a prospective deposit with an environmental lens, determining solutions in advance for potential environmental issues and concerns. Kwong (1993, 2003) was a strong proponent of more coordination at all stages of the mining cycle to address environmental issues.

In the descriptions of these models, Plumlee and Nash (1995) provide a comprehensive list of geological controls regarding the environmental characteristics of mineral deposits. Mineralogy is a key component of these controls, as it influences the behaviour of the deposit during environmental interactions. Information on lithology, wall-rock alteration, ore and gangue mineralogy, texture, trace element composition, susceptibility to weathering and oxidation, and formation of secondary minerals allow predictions on how mineral phases will behave during weathering (*i.e.*, climate conditions), mining, and mineral processing. The main objective of this part of the project was to define the mineralogical signature of the U-, Th- and REE-bearing veins associated with the granitic pegmatites in the Bancroft region.

The closest geoenvironmental ore deposit model for Bancroft is that of Armbrustmacher *et al.* (1995) who summarized the geological, environmental and geophysical parameters that inform a model for thorium and rare earth element vein deposits, based on Model 11d of Staatz (1992). Although the deposits and occurrences in Bancroft are uranium-rich, they do contain variable amounts of thorium and REE. A direct comparison between Bancroft and the Th-REE vein deposits is presented in Table C1.



Figure C1. Schematic diagram of a mineral exploration cycle, starting clockwise from the top. Modified after Mining 101 – Mine Development Cycle of the Mineral Resources Education Program of B.C. (<https://www.mineralsed.ca/learning-resources/student-resources/earth-science/>).

Based on this U.S.G.S. model, the thorium-vein deposits are considered low tonnage and high-grade whereas Bancroft deposits are low tonnage and variable grade in uranium. The host rocks are similar with respect to lithology, metamorphism and alteration; they both occur in intrusive complex terrains. The wall-rock alteration is due to metasomatism, and at Bancroft, according to Lentz (1991), is related to the formation of skarns. The ore tends to be structurally-controlled within veins and dykes and primary enrichment noted by Armbrustmacher *et al.* (1995) is U, Ba, Sr, Pb, Zn and Nb along with major amounts of Th, LREE, Fe-oxide, silica and S as sulphate. In contrast, Bancroft is enriched in U, Th, LREE, Mo and Mn within a large variety of ore minerals. Gangue mineralogy is comparable, with quartz, feldspars and other silicate and carbonate minerals. It is interesting to note that mineral characteristics are comparable, even to the mention of odiferous surfaces. Bancroft occurs in a bedrock area controlled by knobs and ridges whereas thorium-bearing veins tend to be in non-distinct topographic areas. With regard to hydrology, Armbrustmacher *et al.* (1995) indicated that there is no effect by these types of vein deposits. This would be the same observations for the Bancroft region. Finally, the processing methods have been limited to a few sites at Bancroft and consist of underground operations at three of four mines with on-site milling to produce a  $U_3O_8$  concentrate along with some trenching and surface pits with abundant diamond drillhole exploration over several decades. Overall, the geological parameters identified by Armbrustmacher *et al.* (1995) are directly applicable to the Bancroft region.

Table C1. Summary of the geological factors that inform environmental effects at thorium-rare-earth element vein deposits (after Armbrustmacher *et al.*, 1995). Notes for Bancroft are based on this study and those listed in the references below.

| <b>Geologic Factors</b>    | <b>Thorium-REE Veins</b>   | <b>Bancroft (Uranium, Thorium, REE)</b>   |
|----------------------------|--|---|
| Deposit Size               | ~0.2 Mt<br>Grades ThO <sub>2</sub> ~ 0.4 wt% [1]<br>Low tonnage, high grade  | 1.36 Mt (1981)<br>0.11% U <sub>3</sub> O <sub>8</sub> [2]<br>Moderate tonnage, low grade  |
| Host Rocks                 | Alkaline intrusive rocks<br>Granitic rocks<br>High-grade metamorphic rocks<br>Fenitized carbonatite complexes<br>Black shale   | Granite pegmatite/granite gneiss<br>Calc-silicate gneiss<br>Quartzo-feldspathic gneiss<br>Amphibolite gneiss<br>Mafic gneiss<br>Metapelite  |
| Geological Terrane         | Alkaline intrusive complexes<br>Carbonatite complexes<br>Stable, intracratonic areas   | Intrusive complexes in a region of high-grade metamorphic and metasomatic rocks [2]   |
| Wall-rock Alteration       | Surrounded by several m-wide aureoles of metasomatically altered rock<br>Alteration and fenitization caused by peralkaline fluids emanating from cooling alkaline silicate or carbonatite magmas | Hybridization/endoskarnification along pegmatite margins<br>Marble/clinopyroxene-hosted exoskarns<br>Fluorite/apatite/calcite veins [3]   |
| Nature of Ore              | Structurally-controlled  | Disseminated in structurally-controlled pegmatite granite dykes [2,4]   |
| Trace Element Geochemistry | Primary enrichments of uranium, barium, strontium, lead, zinc and niobium<br>Major amounts of thorium, rare earth elements (e.g., LREE), ferric iron oxide, silica and sulphur as sulphate       | Uranium, thorium, LREEs, molybdenum, manganese [5,6,7]  |
| Ore Mineralogy             | Thorite, thorianite, brockite, monazite, bastnäsite, parasite, synchysite ± sulphides (galena, sphalerite)   | Uraninite, uranothorite, thorite, allanite, cyrtolite, pyrochlore, betafite, fergusonite, fluorite, apatite, pyrite, pyrrhotite, molybdenite, secondary uranium minerals, corundum, marble (building stone), sodalite [8] |
| Gangue mineralogy          | Quartz, K-feldspar, barite, ferric iron oxide minerals + many carbonate minerals   | Quartz, plagioclase feldspar, K-feldspar, amphibole, clinopyroxene, epidote, biotite, hematite, scapolite,  |

| <b>Geologic Factors</b> | <b>Thorium-REE Veins</b>  | <b>Bancroft (Uranium, Thorium, REE)</b>  |
|-------------------------|---|--|
|                         | (carbonatite complexes) or other silicates and oxides   | calcite, titanite ± tourmaline, zircon, garnet [8]   |
| Mineral Characteristics | Quartz-barite veins + thorium-REE minerals, thorium-bearing veins, fine-grained, red and odoriferous fresh surfaces | In veins and pegmatites<br>Irregular grains and aggregates<br>Small to large well-developed crystals (suitable for mineral collecting)<br>In deep red to purplish zones due to intense hematization<br>Purple fluorite associated with uraninite produces a fetid odour when crushed [8] |
| Secondary Mineralogy    | Localized carbonate mineral dissolution   | Shattering of rock by radioactive minerals [4]; Fe- and Mn-(oxy)hydroxide precipitates on weathered surfaces, local sediments, and in areas where shallow groundwaters discharge at surface [10]   |
| Physiography            | No distinct topographic expressions   | Bedrock-controlled knobs and ridges; glaciated terrain rounded topography and deposited till on stoss and lee side of bedrock hills [9]  |
| Hydrology               | Unaffected by Th-REE vein deposits  | Unaffected by U-Th-REE vein deposits and pegmatites  |
| Processing Methods      | Small-scale exploitation<br>Shallow surface pits, trenches  | Underground operations for 3 (Bicroft, Canadian Dyno, Faraday) of 4 (Greyhawk-no mill) uranium mines with on-site milling to produce U <sub>3</sub> O <sub>8</sub> concentrates; some trenching and surface pits, diamond drill holes  |

[1] Bliss (1992), as cited in Armbrustmacher *et al.* (1995); [2] Griffith (1986); [3] Lentz (1991); [4] Bullis (1965); [5] Robinson and Sabina (1955); [6] Robinson and Abbey (1957); [7] Robinson (1960); [8] Sabina (1986); [9] Barnett (1983); [10] Parsons *et al.* (2014)

### ***Mine Safeguards***

A variety of mitigations have been emplaced in the Bancroft area to secure the sites and reduce potential human injury (Fig. C2). The mitigations are physical and include sealing of portals to adits, bulldozing waste rock into manageable piles, fencing off mine hazards such as pits and shafts as well as placing concrete platforms over shafts. Where needed, the platforms have been vented to reduce the build-up of gases. At some sites the original drill hole casings were not removed and some of these continue to flow. This provided direct access to deep groundwaters for this overall study. Core samples were found discarded in piles near the sites, but most represent the country rock. Samples for this study were collected from these piles.

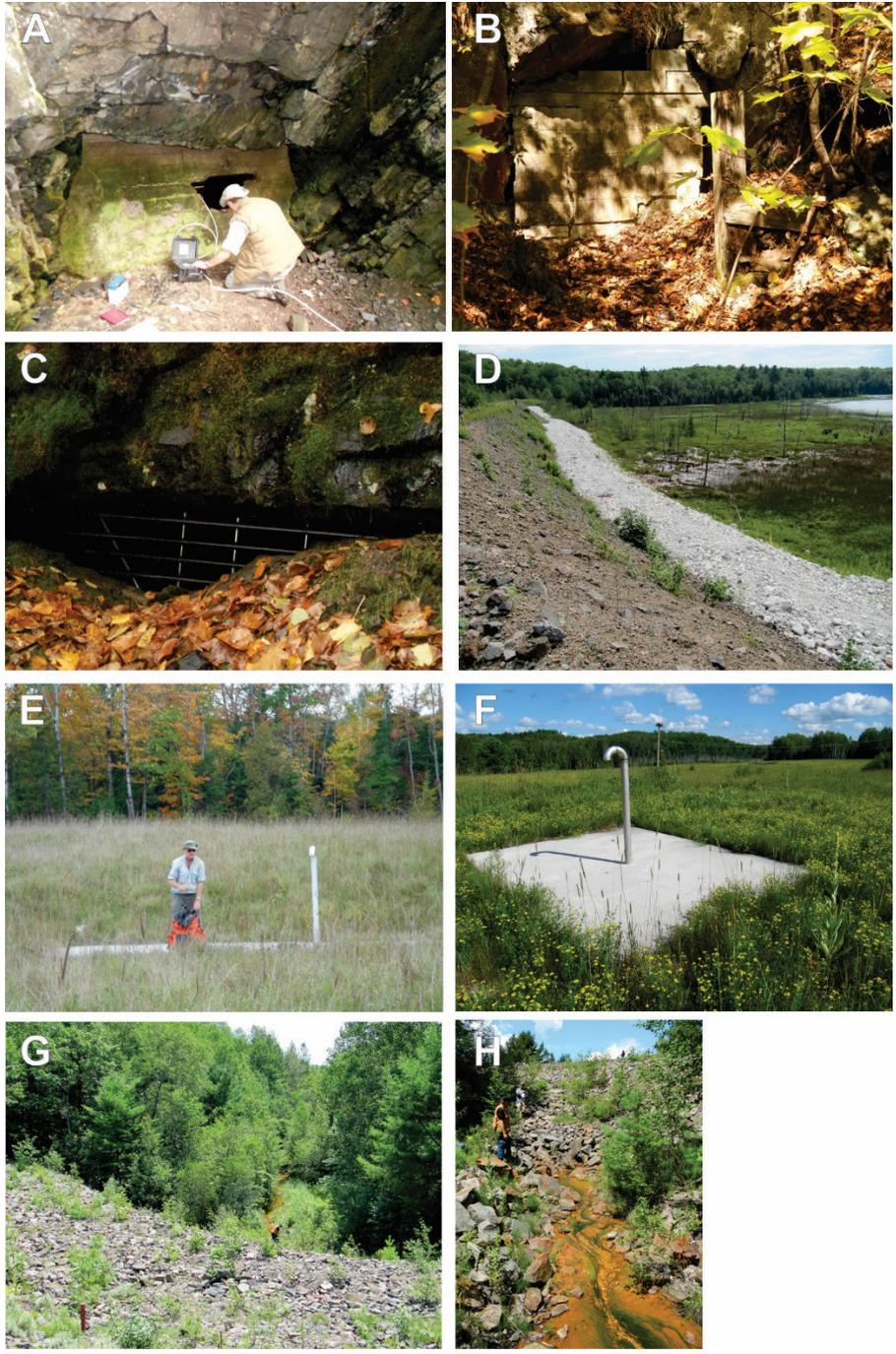


Figure C2. Safeguards emplaced for mine hazards in Bancroft area. A) partially sealed adit portal, Rare Earth Mine 2 (NRCan Photo 2025-016); B) secured adit portal, Halo Mine (NRCan Photo 2025-017); C) adit portal with metal barrier, Croft Mine (NRCan Photo 2025-018); D) rock toe berm to stabilize tailings dam, Dyno Mine (NRCan Photo 2025-019); E) AD in field standing on concrete pad over the Bicroft mine shaft (NRCan Photo 2025-020); F) concrete pad over Bicroft Mine shaft with ventilation pipe (F: Parsons *et al.*, 2014; NRCan Photo 2025-021); G) rock berm built along tailings dam, Bicroft Mine (NRCan Photo 2025-022); H) Fe-oxyhydroxide precipitates from water draining Auger Lake tailings (neutral water) (NRCan Photo 2025-023). Photos A, B, C, E and G by J.B. Percival and D, F and H by M.B. Parsons.