

VANADIUM POTENTIAL IN NEWFOUNDLAND AND LABRADOR: A REVIEW AND ASSESSMENT

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ABSTRACT

Vanadium is a minor commodity compared to base metals, but it plays a vital role as an alloy additive in steel and in the chemicals industry. Demand for vanadium is forecast to grow with increasing steel production, and there is also potentially significant future usage in energy storage. Much of the 'primary' vanadium supply is actually a steel industry by-product from slag reprocessing, and vanadium is generally a co-product in mining. For these reasons, meeting any increased demand is not simple. Prices are historically volatile, and presently depressed, but there is interest in undeveloped vanadium-rich deposits around the world.

The largest such deposits are orthomagmatic Fe–Ti oxide accumulations in layered mafic intrusions and large anorthositic complexes. Mesoproterozoic rocks of this clan are abundant in Labrador, and it is a large target area that has to date received limited evaluation. Oxide-rich ferrogabbroic cumulate sequences are known in the Kiglapait and Michikamau layered intrusions, and some of these are enriched in vanadium. Anorthositic complexes and related 'ferrodiorite' intermediate rocks in Labrador also contain vanadium-rich oxide zones, associated with titanium and locally with chromium and phosphorus. Many of these zones were encountered during exploration following the Voisey's Bay discovery of 1995, but were rarely investigated in detail. In orthomagmatic deposits, vanadium generally resides in magnetite, and its concentration in this mineral (V tenor) is an important economic parameter. The oxide mineralogy, grain sizes and intergrowth textures are also critical factors. The Island of Newfoundland also contains orthomagmatic vanadium mineralization, mostly associated with oxide-rich dykes and former iron mines within Precambrian inliers near Stephenville. A nearby Silurian mafic intrusion is now being explored for extensive oxide accumulations of probable cumulate origin, which show enrichment in vanadium and titanium.

Vanadium is also associated with some uranium deposits in Labrador. The Moran Lake C-Zone uranium deposit hosts a significant but low-grade vanadium resource, estimated to hold 61 million kg of vanadium pentoxide (V₂O₅). This is partly hosted in sandstones, but most is within older mafic volcanic rocks, which are pervasively altered and hydrothermally brecciated. The uranium and vanadium zones partially coincide, but the two elements are, in part, uncorrelated. Present information suggests that fracture-hosted uranium mineralization actually overprints a more extensive vanadiferous envelope, but both could ultimately be products of the same mineralizing system. Mineralization at Moran Lake does not readily fit into the established deposit spectra for either uranium or vanadium.

Vanadium is also enriched in black shale and other organic-rich sedimentary rocks, and low-grade mineralization of this type is currently being explored in Nevada. Similar environments might also exist in this Province. The Middle Ordovician shales of central Newfoundland, and the Paleoproterozoic Menihek Formation of western Labrador are suggested as possible targets for evaluation on the basis of known enrichments in metals, including vanadium.

INTRODUCTION

Vanadium (V) is a little-known but increasingly important economic commodity. It is a soft, dull, silver-grey, ductile transition metal, which plays a vital role in several industries, including steel-making, aerospace engineering,

bulk chemicals and medicine. Its most extensive uses are as an alloy component in steels, to which it imparts increased hardness and strength, and as a catalyst in the production of sulphuric acid. In these applications, there are presently no viable substitutes. Some 90% of vanadium presently finds its end use in the steel industry, but less than 10% of all steel

produced actually contains vanadium. This proportion is expected to increase in the coming years as a consequence of rapid infrastructure growth in emerging economies such as those of Asia. There are also several new and growing uses for vanadium, including Ti–Al–V alloys (used in jet aircraft and other aerospace applications), specialized ceramics and, perhaps most importantly, applications in the energy sector. Lithium–vanadium batteries are considered more efficient than the lithium–cobalt batteries currently used in hybrid and electric vehicles, and may in time gradually replace them. The Vanadium-REDOX storage battery, which uses vanadium pentoxide (V_2O_5) as an electrolyte, is viewed as a major innovation in clean and renewable energy generation. Vanadium-REDOX batteries provide an efficient mechanism for the storage of energy, and its release in a controlled fashion, according to demand. Although not yet in commercial use, these devices are anticipated to be used in the wider development of wind or solar power. Vanadium also has growing use (along with various rare-earth elements, or REE) in low density–high intensity magnets, which are also important in clean energy generation and hybrid vehicle manufacturing.

Vanadium demand has grown in recent years, with consumption in China increasing at 13% per year from 2003 to 2009, and further growth is anticipated with increasing steel production (Mining World, 2012; USGS statistics). The potential demand from the energy sector is harder to estimate, given uncertainties in the time frame for commercial development of this technology. However, the overall annual market for vanadium remains small compared to other metals, at about 60 000 tonnes of metal (107 000 tonnes of V_2O_5). Vanadium products do not trade on an open market or metal exchange, and prices are instead governed by sales agreements. The two end-use commodities are ferrovanadium (FeV; iron–vanadium alloy used in the steel industry) and vanadium pentoxide (V_2O_5), used for most other applications. Over the last 10 years or so, prices have been volatile, with notable price spikes in 2005 and prior to the economic downturn of 2008. Price highs in 2005 were over US\$120/kg for FeV and almost US\$60/kg for V_2O_5 . In 2008, prices peaked at over \$80/kg and about \$40/kg, respectively. Current prices (November 2012) are in the \$25–28/kg range for FeV; V_2O_5 prices are typically about half of that for FeV. Note that battery applications demand high-purity V_2O_5 (>99%) whereas most current production has lower purity standards (~97.5%). ‘Battery-grade’ V_2O_5 commands a price premium over standard material, and its prices in 2010 were approximately twice those of standard material. The best sources for general information on vanadium are on the internet; a commodity review by Liddell *et al.* (2011) for Ocean Equities Ltd. of the United Kingdom is very comprehensive, and contains much additional information on the vanadium industry.

On the basis of its importance and dependence upon imports, vanadium is considered a strategic metal by the United States Government. The commodity is attracting exploration attention and several undeveloped vanadium-bearing deposits around the world (Figure 1) are in advanced exploration or predevelopment stages, although company websites indicate that some are currently on hold. The present assessment of vanadium potential in Newfoundland and Labrador was initiated in 2009. The main focus was compilation of data from the Mineral Occurrence Data System (MODS), assessment files and other sources, but selective examination and re-analysis of samples and archived drillcore were also included. In the context of MODS, searching for vanadium occurrences will not always yield information, because in almost all cases it is a secondary commodity for occurrences of iron, titanium or nickel (*see* Table 1). There are currently only two vanadium occurrences in MODS. In some cases, it may not be listed at all, because oxide-rich zones might never have been assayed during exploration. In these cases, other sources such as survey projects or thesis studies have detected its presence. As work by the Geological Survey since 1996 was also directed toward magmatic sulphides, such material in some cases may have been overlooked. Analyses of samples and drillcore from Labrador Survey projects in the late 1990s are contained in a previous Open File (Kerr, 2002).

AN OVERVIEW OF VANADIUM DEPOSITS

WORLD SOURCES OF VANADIUM

The structure of the vanadium industry is complicated. About 80% of the vanadium used comes from ‘primary’ sources, and the remainder comes from secondary sources including residues and ashes from the petroleum industry, and recycled spent catalysts (*see* below). Of the ‘primary production’, only about 30% actually represents *direct* mining of vanadium-bearing ore, with the remainder coming largely from the reprocessing of slag from the steel industry. As discussed below, vanadium is variably enriched in crude oil, coal, oil shales and oil sands, and is also present at low levels in some iron ores, notably those containing magnetite. According to USGS sources, about 98% of primary vanadium production in 2010 was from three countries: China (41%), South Africa (32%) and Russia (25%). In terms of mining focused on vanadium, the largest contributions come from the Rhovan Mine in South Africa. Several large deposits in the Panzhihua region of China are mined primarily for Fe and Ti, with vanadium as a by-product. Deposits in the Ural Mountains and Siberia likewise produce vanadium largely as a by-product of iron-ore mining and steel production. Ilmenite destined for the titanium industry is an associated product of some, but not all, vanadium producers. The importance of by-product or secondary sources in the vanadium market means that increasing production in

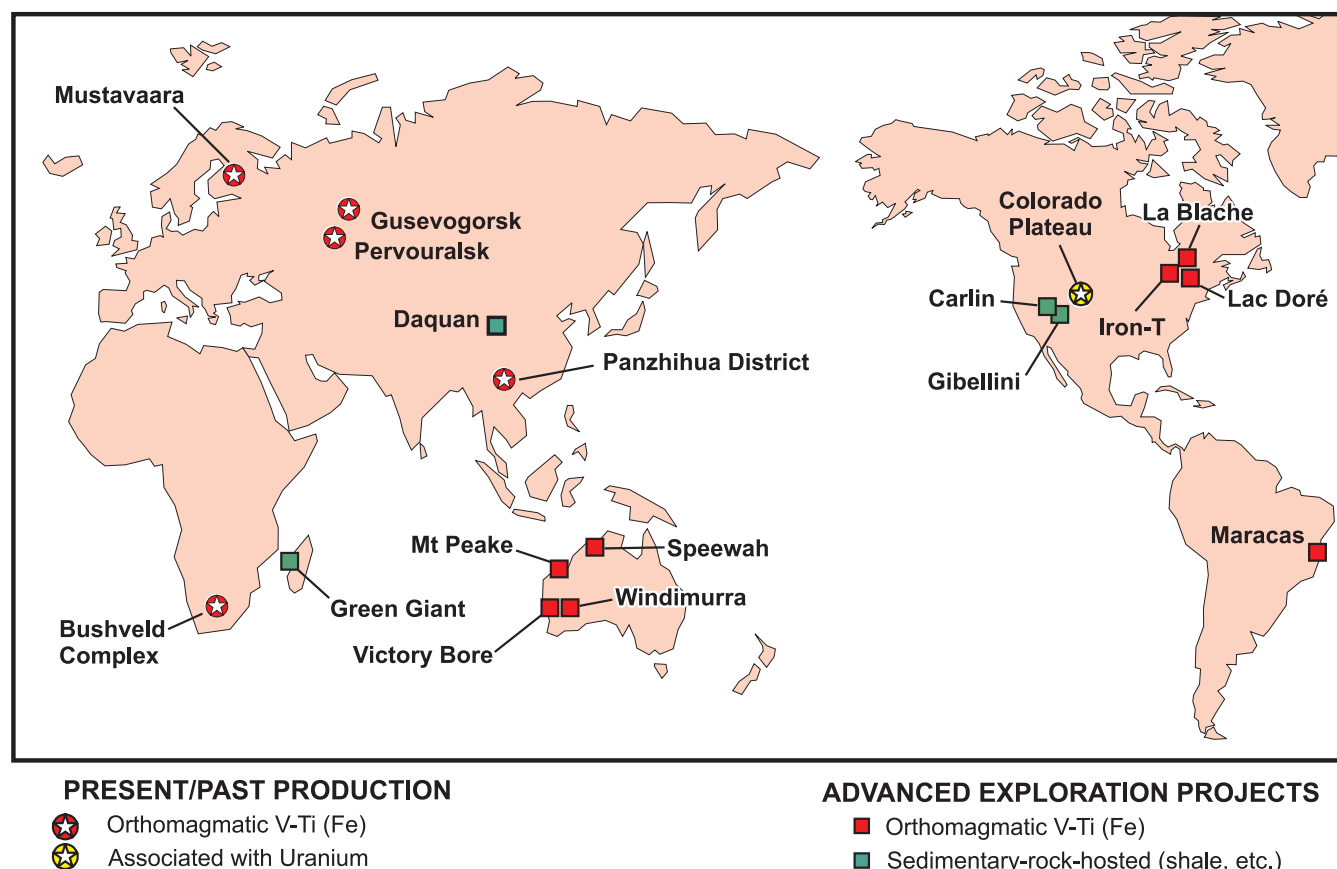


Figure 1. The map shows the locations of advanced exploration projects for vanadium and related commodities, and also the areas of producing deposits. Adapted from Liddell et al. (2011). Note that detailed information for deposits in Russia and China is not easily obtained, and the map may be incomplete for these areas.

response to growing demand is more complicated than for other more familiar metals.

VANADIUM DEPOSIT TYPES

The average concentration of vanadium in the Earth's crust is about 160 ppm, which is higher than for most base metals, e.g., Cu, Zn and Ni (Taylor and McLennan, 1985). However, vanadium rarely forms deposits in its own right, and is more commonly obtained as a by-product, or is rendered economic by the presence of other co-product metals. This situation could change if high commodity prices are sustained, and deposits in which vanadium would be the most important commodity are now under assessment (Figure 1).

Two types of primary vanadium deposit dominate current and historical production. The largest and most important are orthomagmatic deposits associated with mafic plutonic rocks, typically in the form of layered intrusions or large anorthosite complexes. These deposits are dominated by Fe- and Fe-Ti-oxides, with the vanadium typically hosted in magnetite. Such deposits form at high (magmatic) tem-

peratures in the deep subsurface, but opinions differ as to the exact processes involved (e.g., Gross, 1995; Cawthorn, 1996; Zhou et al., 2005). The subordinate source of vanadium was as a co-product from some types of uranium deposits, notably those hosted in Phanerozoic sandstones. These sandstone-hosted deposits formed in near-surface environments from meteoric waters, which transported and deposited uranium, vanadium and other metals (e.g., Shawe et al., 1991; Bell, 1995; Kyser and Cuney, 2008). The individual deposits were small, but the aggregate V production was significant. Vanadium mineralization is also associated with alkaline intrusive rocks in Arkansas, USA, where it was mined as primary commodity, but overall production from these was minor.

A third deposit type may be of future importance. Vanadium, along with other metals, is commonly enriched in fossil fuels and in black, organic-rich shales, and some of the latter may be exploitable. These are large deposits interpreted to be of sedimentary syngenetic origin, in which low grades may be offset by low mining and processing costs. Two examples in Nevada are currently under investigation (Figure 1).

Vanadium concentrations are reported in several ways, but the industry generally uses weight percent V_2O_5 , as this is the common end product. The V_2O_5 values differ substantially from weight percent V (elemental) values, such that $V_2O_5(\%) = 1.78 * V(\%)$. In igneous or mineral geochemistry, the element may be reported instead as V_2O_3 , because it generally occupies a trivalent site in magnetite or other minerals. For the sake of consistency, only V_2O_5 values (with conversion to or from elemental values as appropriate) are used in this report.

Orthomagmatic Oxide Deposits

This class of deposit is the most important primary source of vanadium. Prominent examples are associated with the Bushveld Complex in South Africa, and the Panzhihua Complex in China. Advanced exploration projects in Canada and northern Australia (Figure 1) are also mostly of this type, and contain large potential vanadium resources. All such deposits represent potential open-pit bulk-mining operations.

The Rhovan deposit in the Bushveld Complex of South Africa is the largest mined for vanadium, with about 26 Mt in reserves, and an additional 200 Mt in various resource categories (Xstrata alloys website). The average bulk grade at Rhovan is about 0.5% V_2O_5 [0.28% V]. Deposits in the Panzhihua region of China have been mined continuously since 1967, and reportedly contain resources of over 1300 Mt at about 0.3% V_2O_5 [0.17% V] and 12% TiO_2 in addition to large amounts of iron (Zhou *et al.*, 2005). In Canada, examples of orthomagmatic oxide deposits are in northeastern Québec, in the Lac Doré, Iron-T and La Blache deposits (Figure 1). Vanadium-bearing mineralization in such environments is associated with oxide-rich layered sequences, typically located in the upper sections of the host intrusions, within more fractionated Fe-rich gabbroic rocks and plagioclase cumulates. Individual oxide-rich layers range in thickness from a few centimetres to 10 m, and, commonly, have great lateral continuity. Potential orebodies in this setting are mixtures of oxide-rich and oxide-poor rock types, generally localized in the thickest and most continuous parts of the oxide-rich sequences. The accumulation of oxide-rich rocks is generally attributed to gravitational settling, and the ores are viewed as oxide cumulates (*e.g.*, Cawthorn, 1996). However, others have argued that remobilized cumulates, or immiscible oxide-rich liquids, provide a better explanation for massive ores, and associated discordant, dyke-like oxide bodies in some deposits (*e.g.*, Zhou *et al.*, 2005). Resource estimates for the Lac Doré deposit total about 100 Mt at a grade of 0.49% V_2O_5 [0.28% V] (Taner *et al.*, 2000; Pacific Ore Mining, website information), making it the largest undeveloped vanadium deposit in North America. The bulk

grades of deposits in this category range from around 0.3% to about 1.5% V_2O_5 [0.17% to 0.84% V]; the Maracas deposit in Brazil (Figure 1) is the highest in grade of advanced exploration projects.

Most deposits of this type also contain other commodities, notably iron, titanium and in some cases phosphorus, and mineralogy is thus critically important in all cases. The principal oxide minerals are generally magnetite (Fe_3O_4) and ilmenite ($FeTiO_3$). Vanadium is generally concentrated in magnetite, whereas titanium is in ilmenite. Apatite is the most common P-bearing host mineral, and apatite-rich rocks may themselves be important as phosphorus sources. However, these minerals may be intergrown finely, such that they can be very difficult to separate physically. In some cases, titanomagnetite (Fe_2TiO_4) may still be present, and can also host vanadium, but it more commonly exsolves into magnetite and ilmenite (Gross, 1995). The effective V_2O_5 grade is essentially a function of the amount of magnetite, and the V_2O_5 content of this mineral is a more constant and important parameter in economic assessment. This is known as *vanadium tenor*, as it provides an indication of the grade of magnetite concentrates from processing. Typical vanadium tenors range from about 0.5% to >4% V_2O_5 [0.28 to >2.3% V] (Liddell *et al.*, 2011).

Vanadium associated with Sandstone-type Uranium Deposits

These deposit types are discussed in recent reviews by Finch (1996), McLemore (2007) and Kyser and Cuney (2008), but these treatments are focused mostly on uranium. Only some of the various belts of sandstone-type uranium deposits in the Colorado Plateau contain significant associated vanadium, although anomalous values are widespread (Shawe *et al.*, 1991). The best-known districts are the Ura-van Mineral Belt in Colorado and Utah, and the Rifle Belt of central Colorado. In sandstone-hosted deposits, vanadium occurs mostly as vanadiferous clay minerals, chlorites and montroseite [$(V,Fe)O(OH)$] where ores are unoxidized. In oxidized zones, the distinctive uranium–vanadium mineral carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 3(H_2O)$) is present, along with a wide range of other uranyl vanadates and unusual minerals. In terms of geometry, uranium-rich and vanadium-rich zones are partly superimposed, but vanadium is generally more widely distributed than the high-grade uranium. Sandstone-type deposits record deposition of uranium, vanadium and other metals caused by localized reduction of oxidized meteoric waters circulating within sandstone aquifers. The sources for uranium and vanadium are not clearly established, but it is likely that the latter was derived from detrital Fe–Ti oxide grains in the host sequences. The vanadium-bearing minerals appear to have been deposited at the same

time as the uranium, and the grades for both are variable, including high-grade material with several percent of each element. The Uravan district produced some 250 000 tonnes of vanadium [445 000 tonnes of V_2O_5] in its history, equivalent to some 25 Mt of ore at an average grade of ~1% V [1.78% V_2O_5] (*see Shawe et al.*, 1991; McLemore, 2007; Kyser and Cuney, 2008). Although sandstone-type uranium deposits occur around the world, it does not appear that vanadium enrichment is a universal attribute.

Vanadium Deposits hosted in Sedimentary Rocks

Vanadium and other metals are commonly enriched in black, organic-rich shales. Two potential vanadium producers are hosted by such rocks in the Paleozoic sedimentary sequence of the western United States (Figure 1). The mineralization is believed to be syngenetic, caused by reduction effects from organic material in restricted anoxic basinal environments, possibly with a source input from hydrothermal venting. The vanadium is commonly hosted by Fe and Mn oxides in the shales, and has been further enriched by supergene processes. The Gibellini Project of American Vanadium is the largest such deposit, estimated to contain total resources of 37 Mt of 0.28% V_2O_5 , [0.16% V] and a nearby project in the Carlin area is estimated to contain some 28 Mt at 0.52% V_2O_5 [0.29% V] (EMC Metals, website information; Liddell *et al.*, 2011). The Green Giant deposit in Madagascar (Figure 1) is considered to be a metamorphosed black-shale-type deposit (Energizer Resources, website information). It is quoted to have resources of some 59 Mt at 0.68% V_2O_5 [0.38% V] (Liddell *et al.*, 2011).

Hydrothermal Vanadium Deposits associated with Alkaline Igneous Rocks

Arkansas, USA, was, at one time, a vanadium producer. Vein-style and metasomatic-replacement hydrothermal mineralization in this area is associated with Cretaceous alkaline intrusions of the Magnet Cove Complex, and was locally high-grade, with grades up to 4.8% V_2O_5 [2.68% V]. The mineral assemblages are complex, and are described in detail by Flohr (1994). Total production is estimated at some 11 Mt at 1.4% V_2O_5 (Richardson and Birkett, 1995; Owens, 2010). From 1972 to about 1980, Arkansas was actually the leading producer of vanadium in the United States, but mining ceased in 1989. The review of Richardson and Birkett (1995) does not list associated vanadium mineralization for any carbonatite complexes other than Magnet Cove.

VANADIUM MINERALIZATION ASSOCIATED WITH LABRADOR URANIUM DEPOSITS

The only currently defined vanadium resource in the

Province is in central Labrador, associated with uranium mineralization first defined in the late 1950s (Figure 2). The Central Mineral Belt of Labrador is well-known as a uranium province, and has seen renewed exploration since 2005; it contains mineralization of diverse character, discussed by Wilton (1996) and Sparkes and Kerr (2008). This section focuses mostly upon the area around Moran Lake, and is drawn largely from assessment reports and related documents filed by Crosshair Exploration and Mining, augmented by survey field work and data.

GEOLOGY AND MINERALIZATION

Regional Setting and Deposit Geology

The Central Mineral Belt of Labrador is defined by several Paleoproterozoic supracrustal sequences resting upon Archean basement rocks of the Nain Province. The regional geology is reviewed elsewhere (Ryan, 1984; Kerr *et al.*, 1996; Wilton, 1996) and uranium environments are reviewed by Sparkes and Kerr (2008). In the Moran Lake area, the undated (but pre-1800 Ma) sedimentary and volcanic rocks of the Moran Lake Group are overlain unconformably by terrestrial sedimentary rocks and volcanic sequence of the *ca.* 1650 Ma Bruce River Group. Uranium mineralization occurs in both groups, and is focused in areas around the structurally modified unconformity. The area has a long history of previous exploration (*see Wallis et al.*, 2011 for details) and also contains base-metal mineralization (Wilton, 1996). The uranium zones are described by Ryan (1984), Wilton (1996) and in numerous assessment reports; the review below is drawn from Sparkes and Kerr (2008), Wallis *et al.* (2011), and unpublished information from Survey projects.

Three main zones of uranium mineralization in the Moran Lake area are known as the A-, B- and C-zones (Figure 3); these are accompanied by several other areas of interest. The A- and B-zones are hosted in conglomerates and sandstones that form the basal units of the *ca.* 1650 Ma Bruce River Group. The C-Zone deposit, which is the largest, is partly hosted by these rocks, but is largely within brecciated and strongly altered mafic volcanic rocks (and possibly related subvolcanic intrusions) of the Moran Lake Group (Joe Pond Formation). The original unconformity between the Moran Lake and Bruce River groups is structurally disturbed, such that the older rocks sit above the Bruce River Group (Figure 4). The 'upper' C-Zone deposit is within the older mafic sequences, whereas the smaller 'lower' C-Zone sits within the Bruce River Group; however, the two zones are not physically connected (Figure 4). The only resource estimates presently available are for the C-Zone.

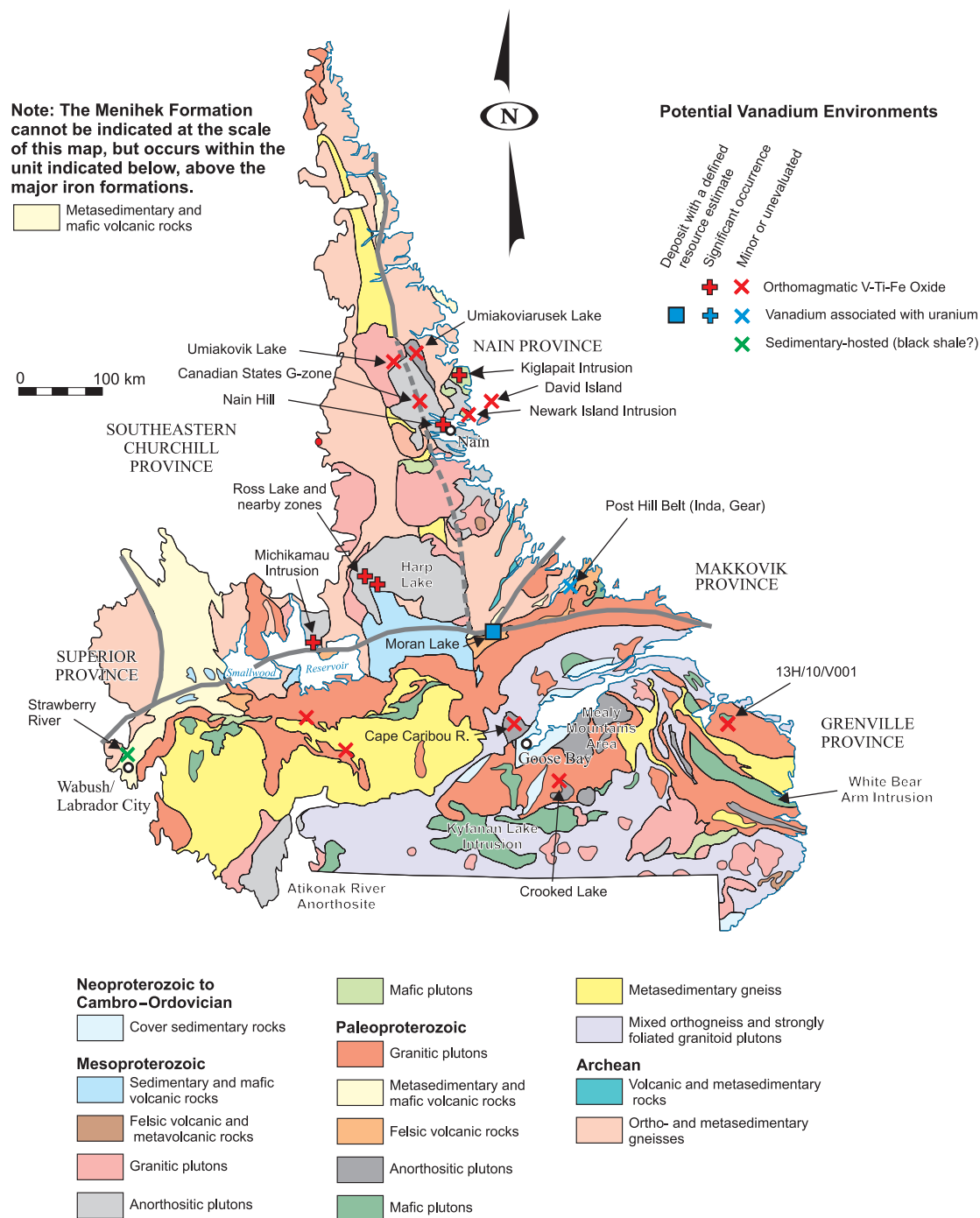


Figure 2. Simplified geological map of Labrador, showing the locations of areas holding possible interest for vanadium exploration, and locations of specific areas discussed in the text.

Resource Estimates for Uranium and Vanadium

For uranium, Wallis *et al.* (2011) estimate a NI 43-101 compliant indicated resource of 6.92 million tonnes at 0.034% U_3O_8 (equivalent to 2.4 million kg) with additional inferred resources of 6.16 million tonnes at broadly similar grades (equivalent to an additional 2 million kg). This is

now known to be accompanied by a vanadium resource that is, in part, coincident with the uranium, but of greater extent, particularly in the hanging wall of the uranium zones (Figure 3), and possibly along strike. Wallis *et al.* (2011) estimate indicated resources of 7.8 Mt at 0.18% V_2O_5 , and inferred resources of 21.6 Mt at 0.17% V_2O_5 (~50 million kg in total), for areas outside the uranium resource. There are

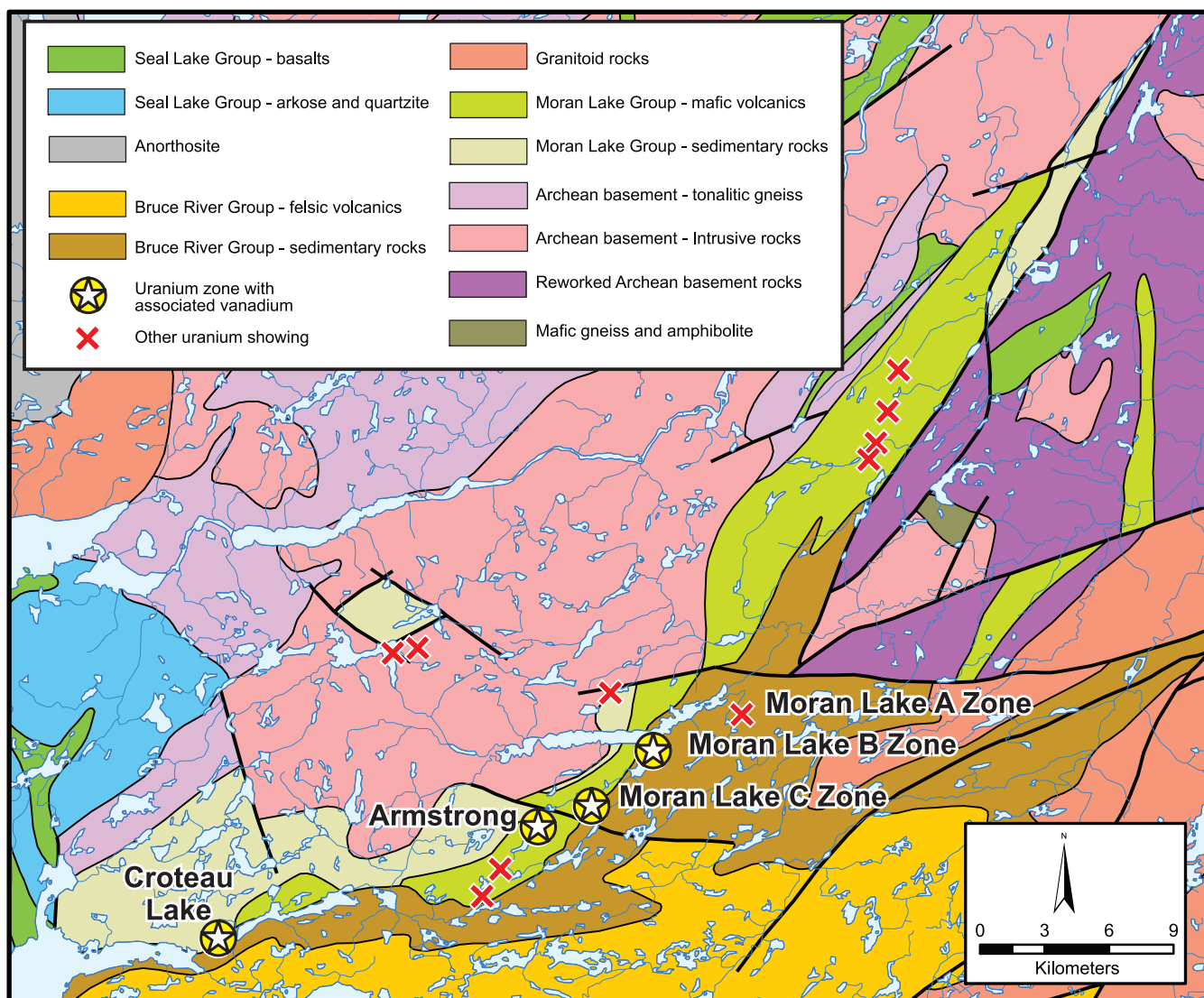


Figure 3. Simplified geological map of the Moran Lake area of central Labrador, showing the locations of uranium ($\pm$ vanadium) mineralization discussed in the text. For location of Moran Lake area, central Labrador, see Figure 2.

also smaller vanadium resources attributed to the uranium resource, but at lower average grades (0.06 to 0.08% V_2O_5). The total vanadium resource in all categories is estimated at around 61 million kg of V_2O_5 . The grade contrast between resources defined on the basis of uranium and vanadium implies that there is a partially inverse correlation between U and V tenor, with the highest grade vanadium mineralization situated outside the uraniferous zone. Geochemical data for individual drillholes show good correlation between vanadium and Cu, but lesser association between vanadium and uranium (Figure 5). Compared to the spectrum of advanced projects elsewhere (Figure 1) the overall V_2O_5 grades at Moran Lake are low, but only in 2011 did exploration work become specifically oriented toward vanadium (Wallis *et al.*, 2011).

Mineralization

The styles of uranium–vanadium mineralization in the upper and lower C-Zone deposits differ, as do their host rocks (Sparkes and Kerr, 2008; Wallis *et al.*, 2011). Mineralization in the lower C-Zone deposit is hosted by reduced zones within a more oxidized red and brown sandstone succession, forming discontinuous tabular concordant zones. The relationship between uranium and vanadium has not been investigated in detail, but there appears to be a general correlation, *e.g.*, a short intersection containing $>1\%$ U_3O_8 also contained 0.33% V_2O_5 (Sparkes and Kerr, 2008). The B-Zone prospect is also hosted by sandstones of the Bruce River Group; the best uranium mineralization appears to be spatially associated with younger mafic dykes, and is like-

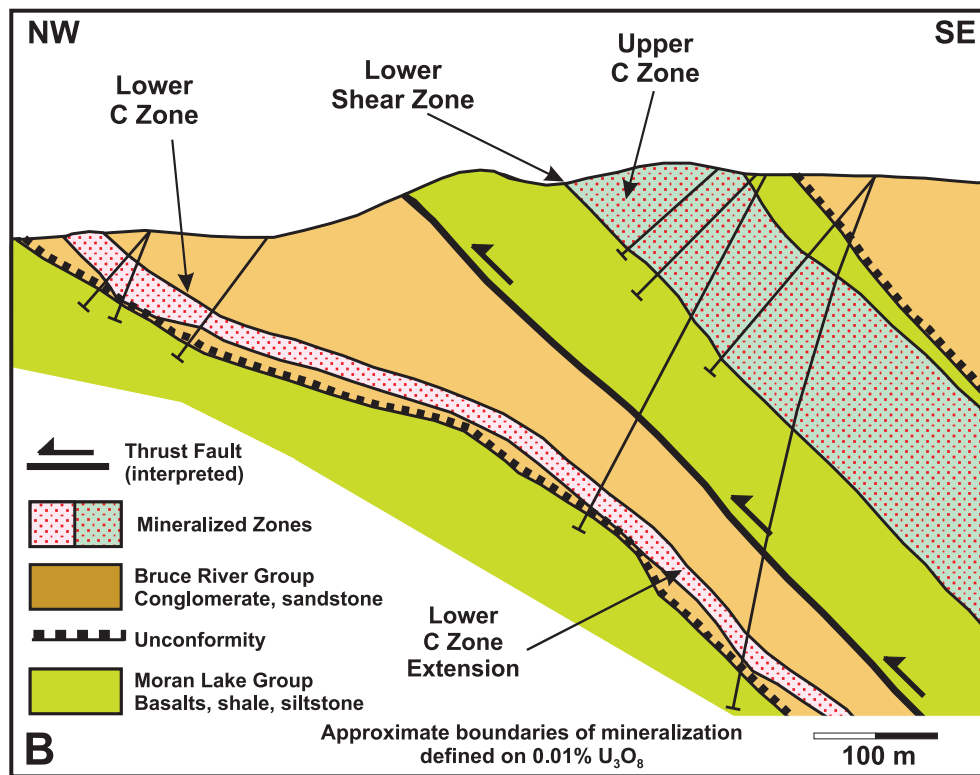
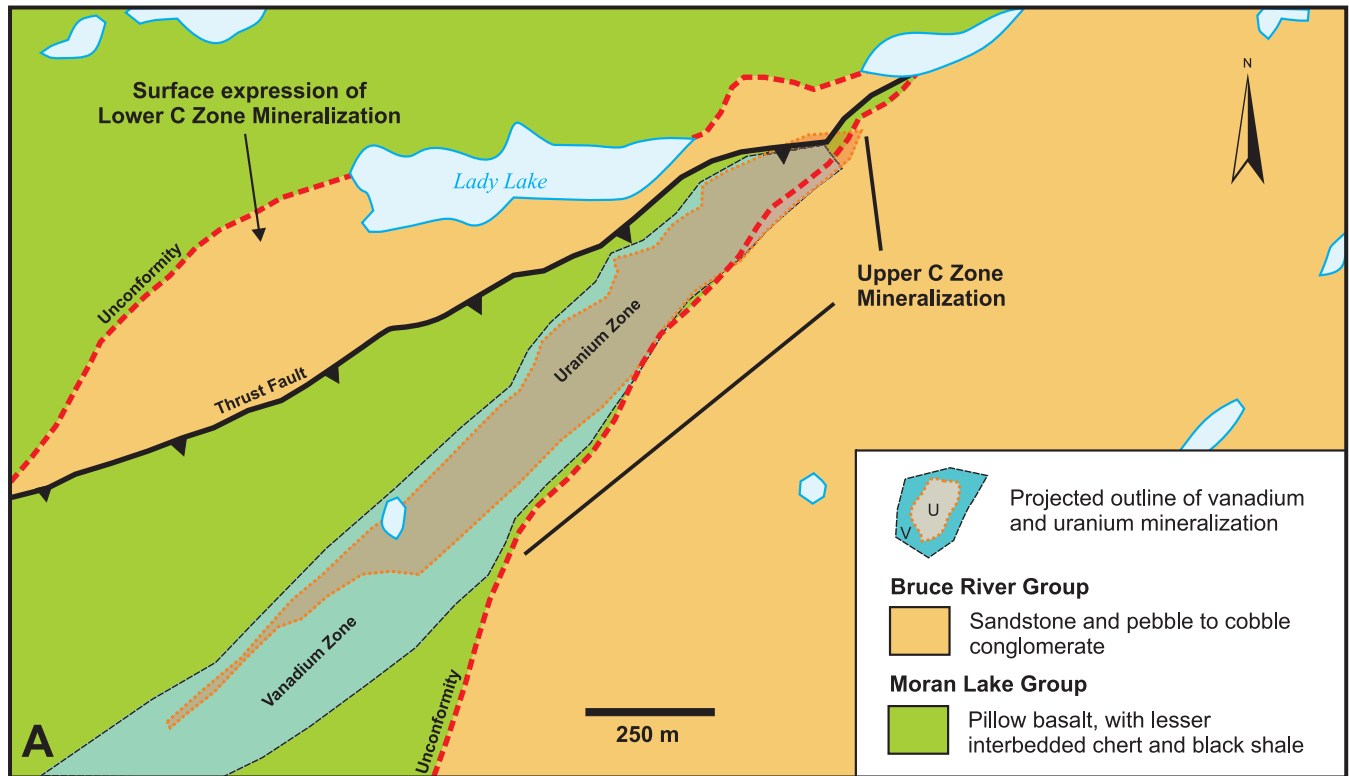


Figure 4. (A) Map of the area around the Moran Lake C-Zone, showing the outlines of uranium and vanadium mineralization in the upper C-Zone deposit. (B) Schematic northwest-southeast cross-section through the deposit, showing the relationship between the upper and lower C-Zone deposits and their host rocks.

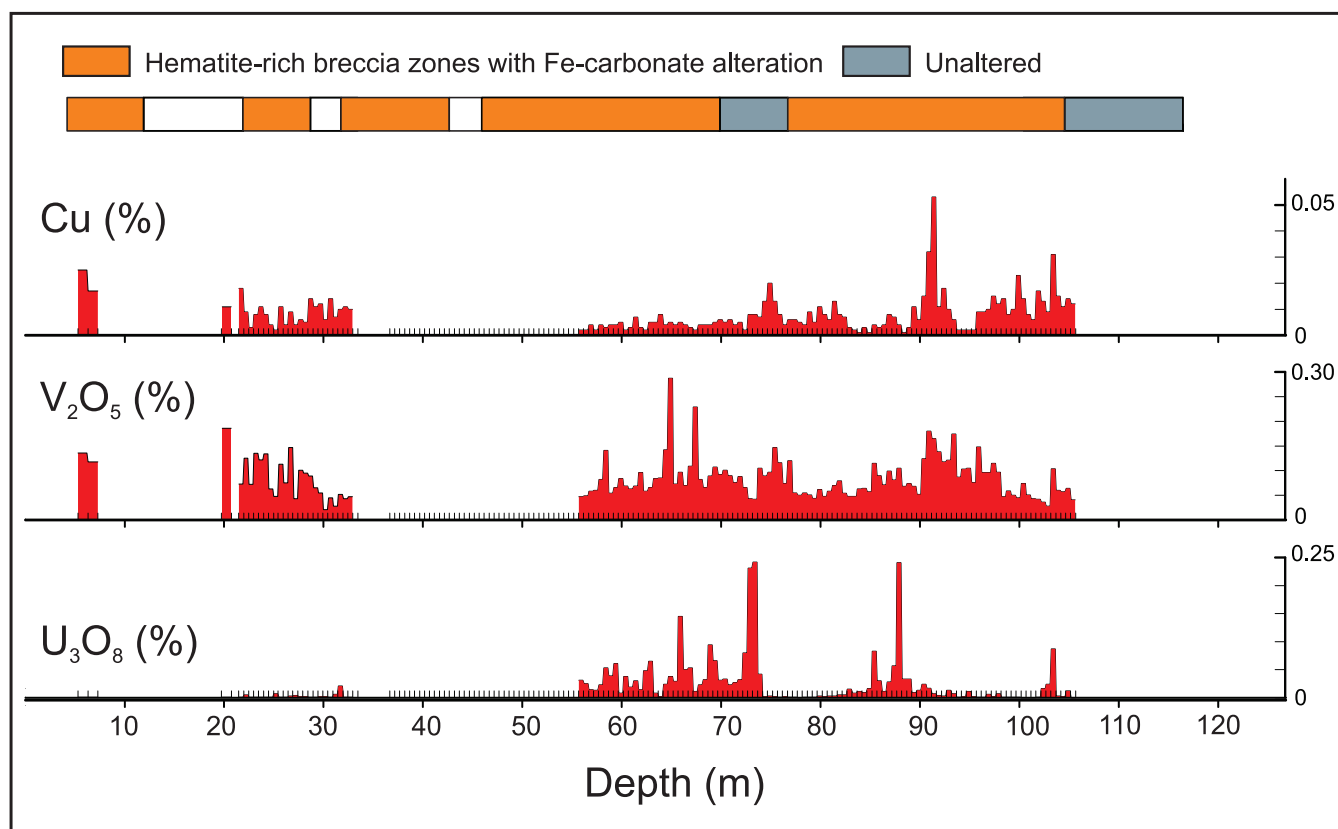


Figure 5. Chart showing the abundance of Cu, V_2O_5 and U_3O_8 with depth in drillhole M1-55 from the upper C-Zone deposit. Note that there is good correlation between Cu and V_2O_5 , but lesser correlation between these elements and U_3O_8 . Data from Morgan *et al.* (2007).

wise accompanied by vanadium (up to 0.53% V_2O_5). The A-Zone deposit is hosted by sheared conglomerates, and no vanadium is reported; however, there has been very little work at this site since the 1970s.

Mineralization in the upper C-Zone deposit is hosted by mafic volcanic ($\pm$ plutonic) host rocks that are pervasively transformed and brecciated, with widespread hematite and hematite-carbonate alteration. Intensely altered fragments (with iron carbonate) are surrounded by a dark, hematitic matrix, but the brecciation is *in-situ*, and of tectonic-hydrothermal origin. The presence of brecciated fragments implies that this process was multistage, and the altered rocks are cut by several generations of veinlets and fractures. Image analysis work (discussed in Eaton and Morgan, 2008) and high-resolution autoradiography (G. Sparkes, unpublished data) indicate that uranium is largely linked to late crosscutting fracture systems, and not related to the intensity of brecciation. The controls on vanadium mineralization appear different, and it is suggested that V_2O_5 grades are better correlated with the intensity of hematitic alteration and brecciation (Wallis *et al.*, 2011; Figure 5). Examination of archived drillcore in 2012 confirmed that the highest

grade vanadium intersections are associated with strong brecciation and alteration, and notably with an abundance of what appears to be fine-grained specular hematite.

The uranium minerals include uraninite, brannerite and coffinite, with the latter suggested to record later hydrothermal remobilization. Vanadium mineralization was investigated as part of a later study by SGS Mineral Services (discussed by Wallis *et al.*, 2011) and indicates that the dominant host mineral for vanadium is hematite, which typically contains around 3% V_2O_5 ; lesser amounts of vanadium were hosted in associated rutile, with <0.8% V_2O_5 . Magnetite was also reported in the SGS study, but no reference to its vanadium content was made.

Initial metallurgical investigations of the upper C-Zone mineralization are summarized by Wallis *et al.* (2011). Agitated sulphuric acid leach tests indicated good recoveries for uranium (~95%) but poor results for vanadium (~36%); subsequent work suggested >90% vanadium recovery with higher acid consumption. Caustic leach and salt roast leach methods (used elsewhere in the processing of vanadium-rich ores) provided generally poor recovery.

OTHER EXAMPLES OF VANADIUM IN LABRADOR URANIUM DEPOSITS

Localized vanadium enrichment also exists at the Armstrong and Croteau Lake prospects in the wider Moran Lake area (Figure 3), hosted by metasedimentary rocks of the Moran Lake Group. At the Armstrong prospect, uranium–vanadium mineralization is associated with hematite and Fe-carbonate alteration, and grades up to 0.43% V_2O_5 are reported, also with Ag and Cu enrichment (Gillies and Clarke, 2009). At the Croteau Lake prospect, uranium–vanadium mineralization occurs within black shale and cherty iron formation and is associated with brecciated magnetite-bearing iron formation (Morgan *et al.*, 2007).

Vanadium is also associated with uranium mineralization in the Post Hill Group of the Makkovik–Postville area, considered a possible equivalent of the Moran Lake Group (Figure 2). Values up to 0.5% V [0.89% V_2O_5] were first reported by Ruzicka (1971), and recent exploration by Aurora Energy has demonstrated that this mineralization is locally present over considerable widths at the Gear prospect, including 0.18% V_2O_5 over 20.5 m (Cunningham-Dunlop and Giroux, 2007). The Inda prospect contains the highest vanadium grades yet identified in the belt, including 0.65% V_2O_5 over 7 m (Cunningham-Dunlop and Giroux, 2007). Wilton (1996) also reports high V contents from these and other occurrences in the Post Hill Group. Exploration work to date in these areas has focused strongly upon uranium, and little is known about the lithology or mineralogy of vanadium-rich zones.

SUMMARY AND DISCUSSION

Vanadium–uranium mineralization in the Moran Lake area does not fit easily into the deposit model framework for either commodity. The mineralization in the lower C-Zone is hosted by reduced zones within terrestrial sedimentary rocks, and has some broad affinities with sandstone-hosted uranium deposits. However, there is no association with organic material and deposition must have had some other controlling factor (*see* also Sparkes and Kerr, 2008). Information about the geometry and mineralogy of the lower C-Zone, and the spatial relationships between U and V enrichment – or other metals – remains very limited, and it is not clear if the typical geometry and zonation of redox-fronts exist within the deposit. There is also no requirement that this mineralization have the same age or origin as the upper C-Zone, despite the physical proximity of the two.

The upper C-Zone mineralization has no counterparts elsewhere in the Central Mineral Belt, aside from perhaps the Two Time Zone, where similar hematitic breccia are developed in Archean basement rocks (Sparkes and Kerr,

2008). The defining feature is the pervasive hydrothermal alteration and brecciation, indicative of an epigenetic deposit, formed separately from its pre-1800 Ma host rocks. The partial coincidence of uranium- and vanadium-rich zones (Figures 4 and 5) implies a link, but the two metals were not necessarily deposited synchronously. There is evidence from autoradiography that uranium was deposited in late fracture systems superimposed upon the wider envelope of pervasive alteration (G. Sparkes, unpublished data, 2013). Also, there is at least a qualitative link between vanadium mineralization and the intensity of alteration, indicating a genetic link, but this needs to be confirmed using geochemical data. Mafic rocks of the Moran Lake Group provide a possible local source for vanadium, if original magnetite was destroyed by fluids, but it is unlikely that mafic rocks could be a source for uranium. However, the metalliferous shales of the underlying Warren Creek Formation could represent potential sources for both components, although there are presently little data upon which to assess this idea. Figure 5 suggests that U and V do not have a simple direct correlation, and U deposition likely postdates V enrichment (suggested also by Wallis *et al.*, 2011) but there are no constraints on the actual age difference. The lower C-Zone could indeed be an analogue for younger sandstone-hosted uranium–vanadium deposits, but it must have developed at or after 1650 Ma, perhaps drawing upon pre-existing upper C-Zone mineralization as a metal source. The alternative interpretation is that *all* uranium mineralization is post-1650 Ma, but this does not require that vanadium enrichment in the upper C-Zone formed at this time.

The Moran Lake area contains the most significant vanadium enrichment defined to date in Labrador, but the vanadium grades are low compared to the spectrum of vanadium deposits worldwide (Figure 1). The association with uranium may be advantageous, but resource estimates suggest some inverse grade correlation. There is evidence that the mineralized envelope for vanadium is considerably larger than that for uranium, and continued exploration focused toward vanadium may increase the extent and grade of such mineralization.

ORTHOMAGMATIC VANADIUM (+ IRON, TITANIUM) OXIDE MINERALIZATION IN LABRADOR

Labrador contains several layered intrusions, and also some of the world's best examples of Mesoproterozoic 'massif anorthosites' (Figure 2). In the north, these rocks are pristine and well preserved, but south of the Grenville Front they are variably deformed and metamorphosed. These rocks are exploration targets for large V-Ti ($\pm$ Fe) deposits akin to those producing vanadium or under active exploration (Figure 1). Early prospecting efforts unearthed indi-

cations of such potential, but systematic exploration of these rocks did not commence until after the Voisey's Bay Ni–Cu–Co discovery of 1994, and was oriented toward nickel sulphide deposits. In many areas, drilling based on electromagnetic anomalies intersected oxide-rich rocks instead of the desired sulphides, but such zones generally received little further attention. Table 1 contains locational and basic descriptive data for areas detailed in the text.

LAYERED INTRUSIONS IN NORTHERN LABRADOR

Northern and north-central Labrador north includes the well-known Kiglapait Intrusion, the Newark Island Intrusion and the Michikamau Intrusion, along with several smaller bodies described as compositionally layered (Figure 2). Most of these are of Mesoproterozoic age and associated with the protracted period of so-called 'anorogenic' magmatism from around 1500 to 1200 Ma.

The Kiglapait Intrusion

The Kiglapait Intrusion (Morse, 1969) is part of the 1340–1290 Ma Nain Plutonic Suite (Ryan, 1998), and was dated at *ca.* 1305 Ma (DePaolo, 1985). It has much in common with other layered igneous complexes, including the presence of Fe–Ti oxide accumulations.

The intrusion is roughly circular, and layering and lithological units are concentric, generally dipping inward. It is interpreted as a funnel-shaped lopolith, with the highest parts of its stratigraphy in the centre (Morse, 1969; Figure 6). The outer and inner border zones consist of foliated and recrystallized mafic rocks, passing inward into olivine gabbro and pyroxenite; collectively, these rocks are viewed as the base of the intrusion. The lower zone, dominated by gabbro and troctolite (mafic cumulate rocks), makes up much of the preserved thickness of the intrusion. This is overlain by the upper zone, containing olivine gabbro, ferrogabbro and anorthositic layers (plagioclase cumulates). The 'upper border zone', partially preserved in the centre of the body, may have formed close to the roof of the intrusion. The upper zone includes gabbroic cumulate rocks in which oxide-rich layers form positive-weathering ridges that can be traced for many kilometres. This zone has a horseshoe-like outcrop pattern, and likely defines a bowl-like structure (Figure 6). It includes one very distinctive oxide layer, up to 1 m thick, consisting of massive oxides with yellow olivine crystals and minor sulphides. This is called the 'main ore band' (Morse, 1969). Fifteen to twenty oxide-rich layers occur above and below the main ore band, defining a zone up to 1 km wide, traceable for about 17 km (Figure 6). Similar oxide-rich rocks are present in the south, but they are less numerous, thinner and less continuous in this region.

Sporadic exploration from 1970 to 1995 was aimed largely at magmatic Cu–Ni deposits and/or reef-type PGE deposits. The main targets for Cu and Ni were the border and lower zones, where sulphides are locally associated with pyroxenite and norite, and where country rocks containing sedimentary sulphides have been assimilated (Kerr and Ryan, 2000). Barr (1970) reported that the 'main ore band' contained 0.34% V₂O₅ (0.19% V) on the basis of chip sampling, but the exact location is unclear. No significant PGE enrichments were detected (Walls, 1988), but samples were not analyzed for V or Ti. More systematic exploration by the Voisey's Bay Nickel Company (VBN) commenced in 1995, and it included shallow drilling to test sulphide prospects, and deeper 'stratigraphic' drillholes targeted on geophysical anomalies. Surface samples collected during the late 1990s contain from 500 to 1500 ppm V [0.09 to 0.27% V₂O₅] from a range of geological units (Graves *et al.*, 1996, 1997).

Deep vertical drillholes completed by VBN (Figure 6) provide long sections through the cumulate rocks of the lower and upper zones. Hole KIG-98-02 was drilled to test a magnetic anomaly within the upper zone (total depth 690 m), and intersected mostly olivine gabbro, containing minor sulphides and 5–15% iron oxides locally, with iron-oxide-rich zones below 482 m depth (Butler *et al.*, 1999). Vanadium concentrations from assays were below 300 ppm, and Ti contents range from 2 to 5.6% TiO₂. Hole KIG-98-03 (Figure 6) was drilled in the lower zone near the western edge of the intrusion, and penetrated to a total depth of 581 m. The hole intersected numerous oxide-rich intervals with widths of up to 1 m, starting at a depth of 344 m and continuing to the end of the hole. Assay results from this hole range up to 2390 ppm V [0.43% V₂O₅] and up to 10% TiO₂ (Butler *et al.*, 1999). Hole KIG-99-04 was drilled in a nearby location, and also intersected oxide-rich zones, containing up to 0.27% V [0.48% V₂O₅] (Butler *et al.*, 2000). Hole KIG-99-03 was located closest to the surface expression of the magnetite-rich zones in the upper zone, and encountered multiple oxide-bearing horizons. 'Geochemical' samples from this hole generally contained <1000 ppm V, but there were no vanadium analyses from samples assayed for Ni, Cu and Co (Butler *et al.*, 2000). Without data to estimate magnetite contents, the V tenors cannot be calculated accurately, but the highest assays provide minimum values for this important parameter. Morse (1979) stated that the 'main ore band' consisted of at least 25% ilmenite and 75% 'titanomagnetite', but also noted that ilmenite to magnetite ratios varied systematically within the sequence, such that ilmenite becomes dominant toward the top. He also notes the presence of coarse composite magnetite–ilmenite grains, probably large titanomagnetites at the time of their crystallization. Analyses identified as 'main ore band' by VBN (Butler *et al.*, 1999) show anomalous but lower grade vanadium contents, but it is not clear if these actually represent the oxide-

Table 1. Locational information for areas in Labrador referenced in this report

Name	MODS number	NTS sheet	UTM zone	Eastings	Northing	Object located	V ₂ O ₅ value or range	Source Reference	Comments
Part 1: Vanadium associated with uranium deposits									
Moran Lake Upper C-Zone	13K/07/U 002	13K/07	20	632300	6038530	Original trench	0.17 to 0.18%	Wallis <i>et al.</i> , 2001	Total resource (including lower C) estimated at ~61 million Kg of V ₂ O ₅
Moran Lake Lower C-Zone	13K/07/U 002	13K/07	20	632300	6038530	Original trench	0.17 to 0.18%	Wallis <i>et al.</i> , 2001	In part located vertically below the Upper C Zone
Moran Lake B-Zone	13K/07/U 001	13K/07	20	635820	6040070	Original trench	up to 0.53%	Sparkes and Kerr, 2008	
Armstrong Showing	13K/07/U 009	13K/07	20	629700	6035850	Map symbol	up to 0.43%	Company press releases	
Croteau Lake	not listed	13K/06	20	616030	6031065	Outcrop	up to 0.8%	Morgan <i>et al.</i> , 2007	Occurrence hosted in shales of the Warren Creek formation
Gear Prospect	13J/13/U 010	13J/13	21	337056	6091227	Original trench	up to 0.2%	Cunningham-Dunlop and Giroux, 2007	Similar vanadium values listed by Wilton, 1996
Inda Prospect	13J/13/U 009	13J/13	21	334620	6089230	Original trench	up to 0.65%	Cunningham-Dunlop and Giroux, 2007	Similar but lesser enrichment noted by Wilton, 1996
Nash Prospect	13J/13/U 006	13J/13	21	332040	6087740	Outcrop	up to 0.6%	Wilton, 1996	Vanadium enrichment reported also by Aurora Energy
Knife Lake Showing	13J/13/U 008	13J/13	21	334310	6088890	drill hole	up to 0.53%	Wilton, 1996	Vanadium enrichment reported also by Aurora Energy
Part 2: Vanadium associated with orthomagmatic oxide mineralization									
Kiglapait Intrusion Area									
“Main Ore Band”	14F/03/Fe 001	14F/03	20	591850	6326850	Outcrops	about 0.34%	Barr, 1970; Walls, 1988; Butler <i>et al.</i> , 1999; others	This is just one location within an extensive unit, chosen to represent this zone within MODS
Drillhole KIG-98-003	not listed	14F/04	20	577766	6323283	drill hole	up to 0.43%	Butler <i>et al.</i> , 1999	Numerous oxide-rich intervals intersected
Drillhole KIG-99-004	not listed	14F/04	20	577597	6323291	drill hole	up to 0.48%	Butler <i>et al.</i> , 2000	Numerous oxide-rich intervals intersected
Drillhole KIG-99-003	not listed	14F/04	20	589622	6324677	drill hole	< 0.18%	Butler <i>et al.</i> , 2000	No vanadium assays for samples containing sulphides
Newark Island Intrusion (South Aulatsivik Island)									
Hogan #2	14C/11/Fe 001	14C/11	20	599500	6285930	Outcrop	up to 0.26%	Graves <i>et al.</i> , 1997	Several samples in this general area were anomalous in vanadium
Other Areas Near Nain and North of Nain									
David Island Sample AK96-308	not listed	14C/14	20	613556	6297134	Outcrop	0.28%	Kerr, 2002	Field sample from oxide-rich zone
Nain Hill - Unity East Zone	14C/12/Ni 002	14C/12	20	579815	6267450	Outcrop	0.18 to 0.36%	Hinchey, 1997; Barbour and Dearin, 1998	Oxide-rich zones encountered in many holes
Nain Hill - Valley Zone	14C/12/Ni 001		20	578675	6268525	Outcrop	0.18 to 0.36%	Hinchey, 1997; Barbour and Dearin, 1998	Oxide-rich zones encountered in many holes

Can Stanes G Zone Hole 1514-7; Sample AKC512	14E/01/Ni 001	14E/01	20	535450	6323620	Drill hole collar	0.65%	Kerr, 2002	Sampled at about 75 m depth. Hole located about 200 m south of MODS location for this zone, which is a showing
International Canalaska Hole VBE1-7; Sample AKC-960	not listed	14C/05	20	570350	6244000	Drill hole collar	0.86%	Kerr, 2002	Sampled at about 1300 m depth
Gallery Resources Hole OK-M1; Samples AKC923, 924	not listed	14E/07	20	508200	6351070	Drill hole collar	0.32% to 0.44%	Kerr, 2002	Sampled at about 480 m depth
Michikamau Intrusion									
Magnetite Lake	13L/04/Fe 001	13L/04	20	444680	6004340	Map Symbol	up to 2%	Emslie, 1968; Rose, 1973	Assay was a magnetite concentrate, not a rock sample, the exact location is difficult to determine, but assumed to be this site
Harp Lake Intrusive Suite									
Ross Lake	13L/14/Ti 001	13L/14	20	480760	6093630	Drill hole collar	0.45%	Theriault, 1997	Drillhole RL-2
Falconbridge Sample 6067	not listed	13L/14	20	497340	6088170	Outcrop	0.70%	Shore <i>et al.</i> , 1999	Associated magnetic anomalies noted
Falconbridge Sample 6068	not listed	13L/14	20	497056	6088237	Outcrop	0.70%	Shore <i>et al.</i> , 1999	Associated magnetic anomalies noted
Falconbridge Sample 6113	not listed	13L/14	20	496868	6089035	Outcrop	0.36%	Shore <i>et al.</i> , 1999	Associated magnetic anomalies noted
Kemco Gossan 172	13M/03/Ti 001	13M/03	20	486900	6110100	Outcrop	0.38%	McAuslan, 1973	Limited information
Kemco Gossan 39	13N/04/Fe 002	13M/03	20	592069	6103818	Outcrop	0.20%	McAuslan, 1973	Magnetite-rich lenses in leucogabbro
Kemco Showing 42	not listed	13N/04	20	593957	6105652	Outcrop	0.74% to 0.89%	Kerr, 2002	Oxides not described in Kemco assessment reports
Suzanna Lake	13N/04/Fe 001	13N/04	20	564432	6110077	Outcrop	0.50%	Belik, 1995	Described as massive magnetite
Southern Labrador									
NOTE: Precise locations are unavailable for occurrences described from the Mealy Mountains area and Cape Caribou River Allochthon									
Dykes River Tributary	13H/10/V 001	13H/10	21	510184	5933142	Outcrop	0.18%	Gower, 2010	Described as an altered ultramafic rock
Part 3: Vanadium associated with sedimentary or metasedimentary rocks									
Strawberry River South #1	23G/02/Zn 002	23G/02	19	639820	5889490	Outcrop	up to 0.44%	Simpson <i>et al.</i> , 1985	Hosted by Menihok Formation siltstone and shale - samples also contain elevated U and Zn

NOTE: Coordinates are UTM values with reference to the NAD1927 Datum

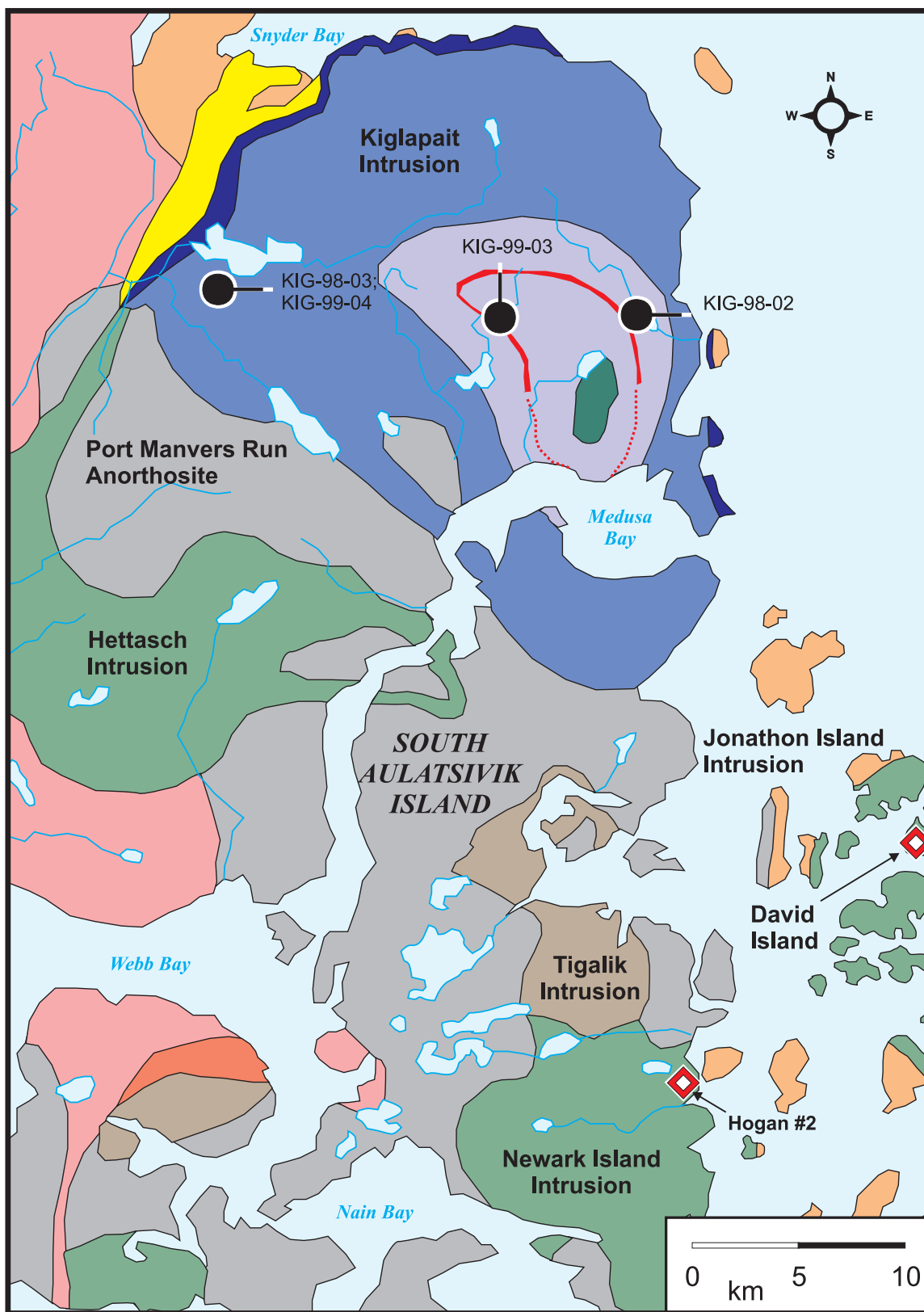
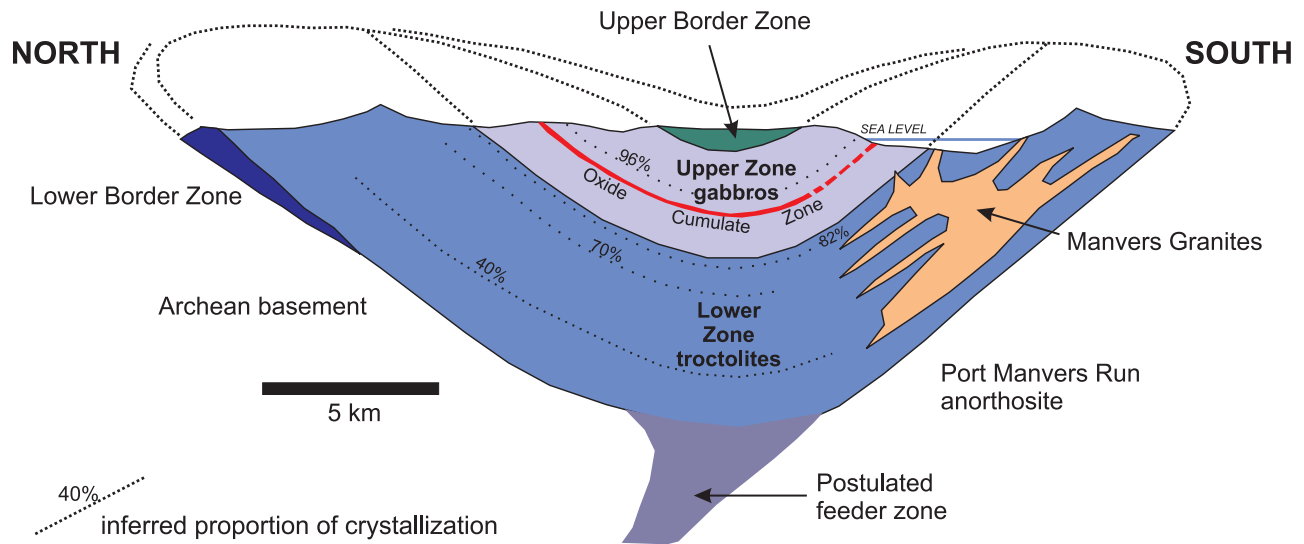


Figure 6. A geological map of the Kiglapait Intrusion and surrounding areas, and a schematic illustration of its inferred geometry. Adapted from various sources, including Morse (1969) and subsequent assessment reports. The locations of drill-holes discussed in text are also shown.



LEGEND

MESOPROTEROZOIC PLUTONIC ROCKS

Kiglapait Intrusion

-  Upper Border Zone gabbro
-  Oxide-rich cumulate sequence (includes "main ore band")
-  Upper Zone gabbro and ferrogabbro
-  Lower Zone gabbro and troctolite
-  Lower Border Zone gabbro, metagabbro, pyroxenite

Other Intrusive complexes

-  Ferrodiorite and monzonite
-  Granite and syenite
-  Layered and massive gabbro and troctolite
-  Anorthosite and leuconorite

PALEOPROTEROZOIC COVER SEQUENCES

-  Snyder Group clastic sedimentary rocks

BASEMENT ROCKS

-  Archean and Paleoproterozoic gneisses (Churchill Province)
-  Archean orthogneisses (Nain Province)

-  Diamond-drill hole and number KIG-98-02

-  Oxide-rich zone at surface

Figure 6. *Caption on opposite page.*

rich zones or associated silicate rocks containing sulphides, because the assays only report iron contents as '>10%'. Hole KIG-99-03 is archived in the Departmental Core Storage facility, and was re-logged and sampled in 2010. Some sections previously assayed by VBN were re-analyzed, and additional oxide-rich material was specifically selected for analysis. It is hoped that these data will allow calculation of vanadium tenors with greater confidence.

Newark Island Intrusion

The Newark Island Intrusion is located on South Aulatsivik Island, between Nain and the Kiglapait Intrusion (Figure 6). It is interpreted to be the lower mafic section of a large composite magma chamber, in which it is overlain by intermediate (dioritic) rocks and granites (Weibe and Snyder, 1993). The mafic rocks were explored in 1995 and 1996, but failed to yield evidence of magmatic Cu–Ni sulphides (Graves *et al.*, 1997). However, oxide-rich cumulate zones are exposed in coastal areas, and were locally sampled; these contained 1490 ppm V [0.27% V₂O₅]. These values generally resemble those from the Kiglapait Intrusion (*see above*).

Michikamau Intrusion

The Michikamau Intrusion is located in north central Labrador, near the Smallwood Reservoir (Figure 2) and is described by Emslie (1965, 1969). It has not been studied in the same detail as the Kiglapait Intrusion, but it has many of the same features and a similar inferred geometry. Above a lower border zone, a thick layered series is dominated by troctolite, olivine gabbro and olivine norite, and there is an upper section of iron-rich gabbro, diorite and syenitic rocks. The intrusion also includes a thick section of massive anorthosite and leuconorite rocks, which provided models for the development of such rocks by plagioclase flotation (Emslie, 1969). The intrusion has an emplacement age of 1469 Ma (Kerr and McNicoll, 2010); these authors also summarize the geology (after Emslie's work) and provide maps and interpretative cross-sections.

Exploration in the late 1980s discovered an extensive gossan zone near Fraser Lake, but drilling revealed poor Cu and Ni grades. The area was not available for staking following the Voisey's Bay discovery, but exploration since 2005 has found some similar sulphide zones elsewhere in the layered series. The mineralization is reviewed by Dyke *et al.* (2004) and by Kerr and McNicoll (2010), and in company assessment reports. Emslie (1968) described oxide-rich layers, and pods containing both magnetite and ilmenite were described in the southern part, especially near 'Magnetite Lake'. Rose (1973) provided analytical details for a 'composite magnetite sample' from here, but exact locations

are not provided. The analysis lists 9% Ti [12% TiO₂] and 1.2% V [2.1% V₂O₅]. Another sample was reported to contain 1.5% V₂O₃ [also about 2% V₂O₅] by Emslie (1968) who also noted the exploration potential. The site was described (Emslie, 1968) as containing 'layers and lenses up to 10 cm thick that are very rich in oxides, as well as zones up to a meter across that contain 30–50% magnetite plus ilmenite'. It is possible that both reports (Emslie, 1968, and Rose, 1973) refer to the same locality, but they certainly imply that relatively coarse-grained oxide-rich rocks exist in this area. The area was examined as part of an exploration program in 1995 (van Nostrand, 1995), who also noted oxide-rich rocks and reported values of up to 1300 ppm V [0.23% V₂O₅]. Emslie (1968) also noted oxide concentrations elsewhere in the intrusion, but the 'gabbroic series' most likely to contain oxide cumulates now lies in part beneath the Smallwood Reservoir.

Other Layered Mafic Intrusions

Several other units in northern Labrador are described as layered intrusions (Figure 2) although they generally lack the well-layered character of the three examples reviewed above. The Hettasch and Jonathon Island intrusions (Figure 6) are more mafic variants of the massive anorthosites that underlie much of this area (Ryan, 1998), and the Bridges Intrusion (Ashwal *et al.*, 1992) may be an older Paleoproterozoic body. A sample collected by the first author from David Island, part of the Jonathon Island intrusion, contained 1599 ppm V [0.28% V₂O₅] and 2151 ppm Cr [0.32% Cr₂O₃].

OTHER MAFIC AND INTERMEDIATE PLUTONIC SUITES IN NORTHERN LABRADOR

Massive mafic and intermediate plutonic rocks are common in northern Labrador, and most are Mesoproterozoic in age (1500–1200 Ma). The most widespread are leuconorites and anorthosites, but iron-rich, geochemically evolved intermediate plutonic rocks termed 'jotunites' or 'ferrodiorites' are also important, particularly within the Nain Plutonic Suite (Ryan, 1998; Figure 2). Ferrodiorites were popular targets for Ni–Cu exploration, due to positive magnetic anomalies with associated EM responses, most of which proved to be oxide-rich zones with minor Ni-poor sulphides. Post-1995 exploration of anorthosites revealed many localized low-tenor sulphide zones, commonly associated with gabbro-norite and pyroxenite, and some of these prospects contain associated Fe–Ti-oxide accumulations. Nickel tenors in sulphide were generally <1% Ni, so few of these zones experienced more than initial drill testing. Mineralization is in many cases discontinuous and hard to trace in these deposits (Kerr and Ryan, 2000).

Nain Hill–Unity Bay Area

The Voisey's Bay discovery finally prompted examination of prominent gossans located near Nain, and drilling in 1996 intersected sulphides that have modest metal contents (<2% combined Ni and Cu). The sulphides are associated with abundant iron oxides. The following summary is derived largely from Hinchey (1999), and Hinchey *et al.* (1999). Assessment reports by NDT Ventures also contain large amounts of valuable data (e.g., Barbour and Dearin, 1996).

The Unity and Valley prospects on Nain Hill are spatially associated with gently dipping gabbro-norite sheets intruding older anorthosite, or sitting as erosional remnants above it. The host rocks are norite, gabbro-norite and pyroxenite, commonly containing interstitial oxides and sulphides. Massive mineralization is generally dominated by iron oxides, with blebby interstitial sulphides, which locally grade into pyrrhotite-rich massive sulphide pods containing oxide inclusions. The sulphide–oxide material appears to have been liquid, or at least very mobile, because anorthosite xenoliths and thermally eroded plagioclase crystals are common within it, and discrete oxide–sulphide veins cut adjacent anorthosite. Hinchey *et al.* (1999) and Kerr and Ryan (2000) suggested that mafic magmas and immiscible sulphide–oxide liquids were emplaced into partially solidified anorthosite.

Both prospects include material containing from 5 to 12% TiO₂, and have vanadium enrichment. Mineralized samples routinely contain 1000 to 2000 ppm V [0.18 to 0.36% V₂O₅], even where oxides are accompanied by silicate material. Vanadium tenors in magnetite certainly exceed these values, because ilmenite is abundant, and this generally contains little vanadium. Petrographic studies (Hinchey, 1999) indicate that magnetite contains ilmenite exsolution features. Interestingly, mineralization also shows significant Cr enrichment, up to 0.8% Cr [1.17% Cr₂O₃]; however, no chromite was noted by Hinchey (1999).

Other Areas near Nain

The area north of Nain contains numerous sulphide-bearing zones that appear to be discordant, intrusive material associated with norite and gabbro-norite units that generally cut massive anorthosite (Kerr and Ryan, 2000). Oxide-rich zones are associated with some of these. At the Canadian States G-Zone (Table 1), drilling intersected bands containing 12.1% TiO₂, 3663 ppm V [0.65% V₂O₅] and 1763 ppm Cr [0.26 Cr₂O₃]. The extent of oxide-rich mineralization at sites like these is very hard to determine, because there was limited drilling, and the assessment reports commonly contain incomplete and contradictory data; locations

for some drillholes are not even reported. A deep drillhole completed by International Canals Resources in 1996, north of Nain, contained mostly anorthosite and leuconorite, but intersected a narrow oxide-rich zone containing 4860 ppm V [0.86% V₂O₅] and 15.8% TiO₂. These are amongst the best grades yet encountered in Labrador but, given the extreme depth of this zone (>1300 m) are unlikely ever to be followed up.

Harp Lake Intrusive Suite and nearby Areas

The ca. 1450–1425 Ma Harp Lake Intrusive Suite includes a large anorthosite massif surrounded by a partial ring of potassic granites (Figure 7; Emslie, 1980). It contains minor marginal gabbroic rocks, and also some younger gabbro, ferrogabbro and oxide-rich diorite. The overall compositional spectrum resembles that of the Nain Plutonic Suite (Ryan, 1998) albeit with different proportions, probably due to deeper erosion of these older rocks. Most of the mineralization was originally discovered by Kennco in the 1970s (McAuslan, 1973), and was explored by Falconbridge before and after the Voisey's Bay discovery. The Ni–Cu sulphide mineralization is summarized by Kerr and Smith (2000). Very little drilling has been completed at showings in the Harp Lake Intrusive Suite.

Falconbridge evaluated some semi-massive oxide concentrations in the southeast part of the intrusion (Figure 7), and described these as extending laterally for hundreds of metres, with thicknesses greater than 2 m (Shore *et al.*, 1999). Analyses show up to 16% TiO₂ and V concentrations up to 3800 ppm [about 0.7% V₂O₅], and ground geophysical surveys indicated associated magnetic anomalies. Several kilometres to the northeast, Tanqueray Resources drilled airborne EM-magnetic responses in 1996 and encountered oxide-rich mineralization. The thickest zone was 13 m in width, and contained coarse ilmenite and magnetite (Theriault, 1997), with up to 21.5% TiO₂, and up to 2700 ppm V [0.45% V₂O₅], with some associated Cr enrichment.

Elsewhere in the Harp Lake Intrusive Suite, there are scattered indications of significant vanadium enrichment (Figure 7 and Table 1). Strong vanadium enrichment is present at Kennco's showing 42, where two samples collected by the first author in 1998 contained 4160 and 5040 ppm V [0.74 to 0.89% V₂O₅], coupled with high TiO₂ (~10%) and enriched Cr (1.24 and 1.48% Cr₂O₃). Prospecting near Suzanna Lake (Figure 7) encountered oxide-rich material containing 3026 ppm V [0.5% V₂O₅], but few details are given (Belik, 1995). Exploration by Kennco in the 1970s indicated up to 2100 ppm V [0.38% V₂O₅] at their gossan 172, and lesser enrichment was also noted at Gossan 39, which is recorded as an iron occurrence (McAuslan, 1973; Table 1).

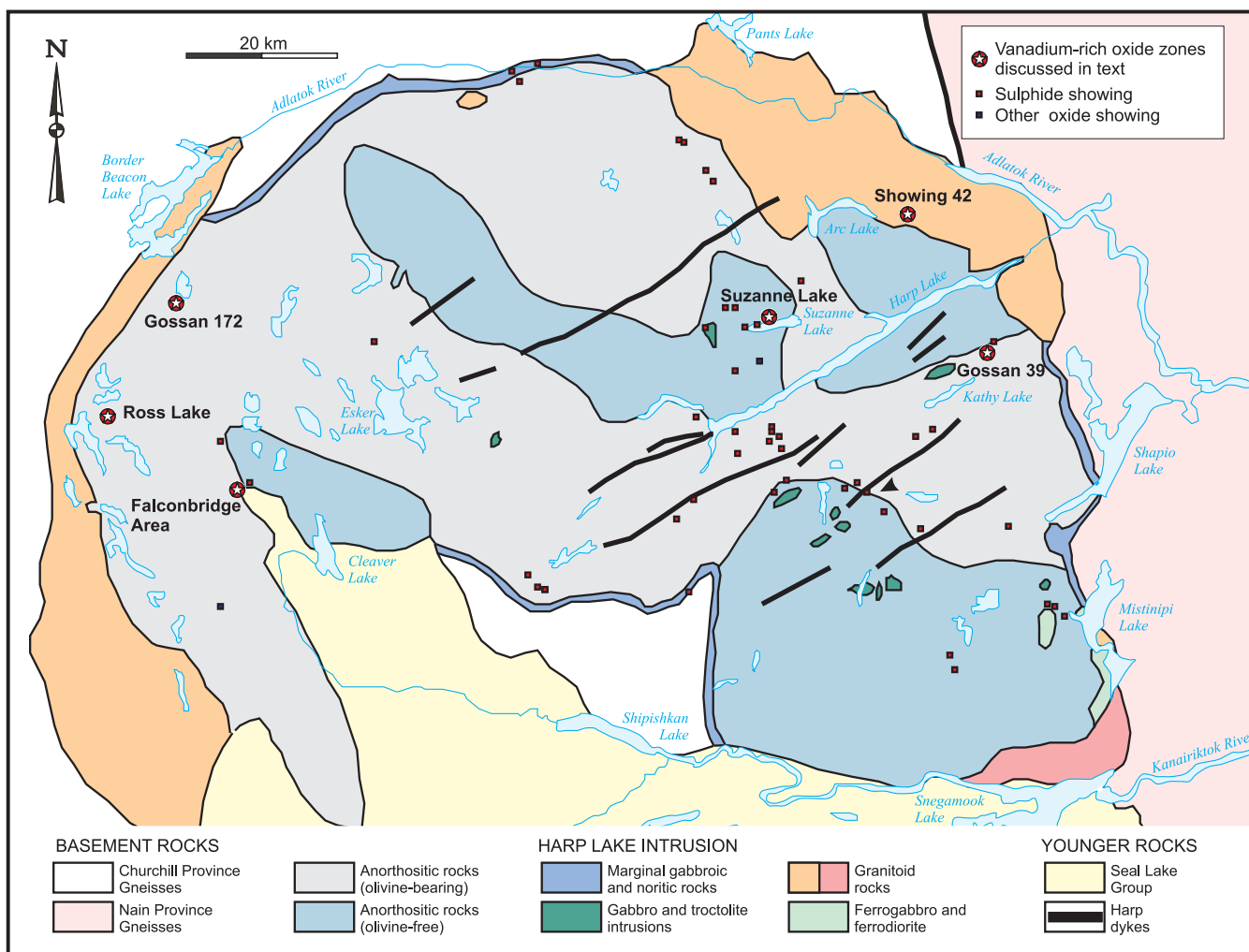


Figure 7. Geological map of the Harp Lake Intrusion (after Emslie, 1980) showing the locations discussed in the text, and also assorted Ni–Cu sulphide showings. Map adapted from Kerr and Smith (2000).

Okak Bay Area

This remote inland area located around Umiakovik Lake, west of Okak Bay, is underlain largely by coarse-grained rapakivi granite, although regional geological considerations and magnetic data imply that this is a thin, sheet-like body that sits above gneisses, anorthosite and ferrodiorite (Figure 2). Exploration attention was drawn to a prominent circular positive magnetic anomaly, but initial shallow drilling by Gallery Resources intersected only variably altered granite. A deeper hole was completed in 1997 to test a magnetotelluric anomaly. The upper section of this hole was rapakivi granite, but deeper sections contain grey to greenish intermediate rocks rich in iron oxides and apatite, which also contain interstitial sulphides. This weakly mineralized unit contains inclusions of anorthosite, and is locally cut by granite veins. Some shorter intervals are very oxide-rich, containing up to 75% magnetite and ilmenite. Analyti-

cal data from the exploration program were not included in the assessment reports (French *et al.*, 1998) and only selected data for Ni, Cu and Co were released. Two oxide-rich zones sampled by the first author from drillcore contained 5.9 and 9.2% TiO_2 , and 1785 to 2452 ppm V [0.32 to 0.44% V_2O_5]. There was also modest enrichment in Cr in these samples (2727 and 1365 ppm).

In the area south of Okak Bay, several companies evaluated Ni- and Cu-bearing sulphide zones hosted by anorthositic rocks. Prime Equities International completed prospecting and drilling work near Umiakoviarusek Lake (Figure 2) and intersected some thin sulphide zones. Surface prospecting identified two oxide-rich zones containing up to 0.29% V_2O_5 [0.16% V], but little information is given, and the exact locations are difficult to establish (Cullen and Churchill, 1996).

MAFIC AND INTERMEDIATE PLUTONIC ROCKS IN SOUTHERN LABRADOR

For the purposes of this report, the part of Labrador south of the Grenville Front (Figure 2) is treated separately. This broad region is generally not as well-exposed as more northerly latitudes, but it contains abundant mafic and intermediate plutonic rocks, and two large anorthositic complexes, in the Mealy Mountains area (Figure 2) and around Atikonak River. The Grenville Province in Labrador is largely a collage of juvenile tectonic terranes that developed during long-lived episodic orogenesis along the southern margin of Laurentia (Gower, 1996). Only a few rock units actually formed during the Grenvillian event at *ca.* 1000 Ma, notably the circular granitoid plutons of southernmost Labrador (Figure 2). A recent treatment of this area includes discussion of mineral showings and prospects on a terrane-specific basis (Gower, 2010).

Mealy Mountains Intrusive Suite Area

The Mealy Mountains Intrusive Suite (Emslie, 1976; Gower, 1996) forms a large area dominated by plutonic rocks of *ca.* 1646–1635 Ma age, which were only moderately affected by Grenvillian deformation and metamorphism. These plutonic rocks are mostly surrounded by metasedimentary gneisses and other metamorphic rocks. The plutonic rocks of the terrane vary widely in composition, but gabbro-norite and anorthosite rocks are common, and are likely the oldest assemblage (Gower, 1996). Intermediate and granitic rocks are also present. The proposed Mealy Mountains National Park is centred on a group of high peaks immediately south of Lake Melville (Figure 2). Some of the zones noted below lie within the park study area, and these areas are currently exempt mineral lands (EML), although they will eventually lie outside the park. Gower (2010) provides a review of known mineral occurrences, to which the following summary adds information relevant to vanadium.

The earliest exploration was by Newfoundland and Labrador Corporation (NALCO), who completed a reconnaissance aeromagnetic survey. Ground checking of anomalies in the southwest unearthed four samples that were reported to contain >80% magnetite and 0.55 to 0.65% V [0.9 to 1.2% V_2O_5]; no mention was made of ilmenite (Scharon, 1954). Unfortunately, no precise locations for these were provided, other than the general locations for the magnetic anomalies. Other anomalies located to the north were also sampled, but were apparently not assayed for vanadium; they indicated moderate enrichment in iron and TiO_2 , and oxide contents up to 30% (Scharon, 1954; MacDougall, 1954). These areas were reinvestigated following the Voisey's Bay discovery by Vulcan Minerals, who report-

ed TiO_2 enrichment, but generally low vanadium contents (Laracy, 1997; Laracy and Wilton, 1998). The Mealy Mountains Intrusive Suite also contains minor indications of Ti-bearing ilmenite and/or magnetite mineralization in massive anorthosites, noted during mapping (Emslie, 1976), but there is little record of exploration work, and these occurrences sit within the final park boundaries. These are discussed in more detail by Gower (2010).

Cape Caribou River Allochthon (Goose Bay–Grand Lake Area)

The area between Goose Bay and Grand Lake is largely occupied by the Cape Caribou River Allochthon (Figure 2), which consists largely of mafic, anorthositic and intermediate plutonic rocks and lesser granitoid rocks. This entire assemblage sits above a prominent mylonite zone, and is collectively interpreted as a segment of the Mealy Mountains Terrane, transported northwestward across the Lake Melville Terrane by a Grenvillian thrust (Wardle *et al.*, 1990). This area is accessible by Labrador standards, as forest access roads are plentiful, but it has not been widely explored, although there was some activity following the Voisey's Bay discovery.

In 1996, Labrador Nickel Ltd. identified massive to semi-massive oxide mineralization containing 1500 ppm to 1950 ppm V [0.27 to 0.35% V_2O_5], and elevated TiO_2 . Location information is poor, and it is not clear if samples came from outcrops, but based on the license extent, the host rocks are likely the anorthosite unit (Saunders, 1996). Two nearby licenses were investigated by prospectors, who reference sample locations with vanadium assays in the same general range. However, there are similar problems in establishing the exact locations for these samples (Gushue, 1997; Gushue and Shears, 1997).

Other Parts of Southern Labrador

In central Labrador, in and around the Trans-Labrador Highway, there are gabbro-noritic plutonic rocks within metasedimentary rocks of the Wilson Lake terrane; a similar situation exists in the Lac Joseph terrane, west of Labrador City (Figure 2). Minor iron showings are noted in the former area, notably around Winokapau Lake and Fig River (Thomas, 1993), and some of these returned weakly anomalous V contents up to about 650 ppm [0.1% V_2O_5]. These mostly lie below the threshold for discussion in this report (~1000 ppm V), but are still above typical values for such igneous rocks. Vanadium is also associated with an occurrence of altered and metamorphosed ultramafic rocks near Cartwright, described by Gower (2010). This is the only Labrador entry in MODS to actually list vanadium as a primary commodity, and contains 1040 ppm V [0.18% V_2O_5].

It is unusual in that it does not apparently contain abundant oxides or exhibit strong enrichment in iron, titanium or chromium.

SUMMARY AND DISCUSSION

There is an extensive inventory of potential magmatic environments for vanadium mineralization and associated commodities (Ti, Cr) in Labrador. The Kiglapait Intrusion is the subject of numerous papers, but this knowledge is centred on the evolution of basaltic magma systems, rather than oxide cumulate rocks. Exploration targeted on mafic plutonic rocks in Labrador since 1995 was directed at magmatic Ni–Cu sulphides, and associated oxide-rich mineralization was largely neglected, as it was not the desired commodity. There is a need for further assessment of this potential.

The presence and apparent continuity of oxide-rich cumulate rocks in the Kiglapait Intrusion implies that it holds mineral potential, but the systematic work needed to assess this has yet to come. Geochemical data imply that the vanadium tenor of magnetite is greater than 0.5% V_2O_5 , and perhaps more than 1% V_2O_5 , but mineralogical data are required to better constrain such estimates. Textural information is also important, because grain size, intergrowth and exsolution textures are critical factors in deposits of this type. The results from two of the deep holes drilled in the late 1990s suggest that the layered rocks of the lower zone also host oxide accumulations, possibly with higher vanadium tenor. Cumulate sequences are in many respects akin to sedimentary environments in that they exhibit lateral ‘facies variations’ including locally thicker and more consistent oxide accumulations. Geophysical (notably magnetic) data would obviously be useful in seeking these, but geological knowledge will be just as important. The Michikamau Intrusion of north-central Labrador is not as well-known as the Kiglapait Intrusion, but work from the 1960s returned some of the highest vanadium assays from anywhere in Labrador; these data require confirmation. Although it is possible that exact localities analyzed by Rose (1973) now sit beneath the waters of the Smallwood Reservoir, oxide-rich layered sequences typically have lateral continuity, and they may exist elsewhere in the body.

The Harp Lake Intrusive Suite contains several mineralized zones in which whole-rock vanadium contents exceed those of the Kiglapait oxide cumulates; the actual vanadium tenors must be higher still, because these zones appear to be ilmenite-rich. The information on this mineralization is presently very limited. The poorly known southwestern section of the suite, where Falconbridge identified oxide zones, and where Tanqueray Resources completed limited drilling, represents the most obvious target for further scrutiny.

Vanadium enrichment is also a feature of oxide–sulphide mineralization associated with mafic zones in anorthosites, and the Nain Hill deposits appear to be the most oxide-rich members of this group. In addition to Ti, these contain associated Cr, with values of the latter locally exceeding 1% Cr_2O_3 . There is little information on the mineralogical setting of Cr, but Cr and V are not always enriched in the same samples, so this is not a direct relationship. The Nain Hill deposits are just one end member of a widely distributed group of anorthosite-hosted oxide–sulphide occurrences within the Nain Plutonic Suite (Kerr and Ryan, 2000), and some of these other locations also show marked vanadium enrichment.

Intermediate rocks of the ferrodiorite or ‘jotunite’ clan might also represent potential vanadium targets, based on results from west of Okak Bay and elsewhere. The absolute oxide content of such rocks may be low (<20%), but they are compositionally evolved, and their bulk chemistry is strongly influenced by plagioclase fractionation (Emslie, 1980; Ryan, 1998). Vanadium is incompatible in plagioclase, so residual liquids are enriched, and there is good potential for crystallization of high-tenor oxide minerals. Geochemical data from such rocks need careful assessment, and as in other cases, direct mineralogical investigations are critical. Ferrodiorites are also typically medium- to coarse-grained, granular rocks, and contain fayalitic olivine, which transforms quickly to secondary oxides, causing friability and deep weathering. These qualities may be frustrating to geologists seeking fresh samples to study, but they could have positive implications for mineral economics.

Moving south across the Grenville Front (Figure 2), there is far less information upon which to assess potential, but there are tantalizing reports of V-rich oxide material from early stage exploration in the 1950s, for which exact locations are unknown. Although there was some exploration work in this general area following the Voisey’s Bay discovery, it was nowhere near the scale of activity in northern Labrador. In addition to the possible reassessment of these locations, attention should be drawn to other large mafic plutonic complexes within the Grenville Province, including locally layered mafic intrusions such as those of the Kyfanan Lake area and the White Bear Arm Complex (Gower, 2010; Figure 2).

VANADIUM POTENTIAL ON THE ISLAND OF NEWFOUNDLAND

Compared to Labrador, Newfoundland contains relatively few areas dominated by mafic plutonic rocks. Precambrian inliers in western Newfoundland are an extension of the Grenville Province. Smaller inliers in the south

include anorthosite and metagabbro, but the larger Long Range Inlier contains few mafic rocks (Figure 8). Plutonic rocks in the Paleozoic Appalachian Orogenic Belt are largely of granitoid composition, but composite intrusions in central Newfoundland include locally layered gabbroic rocks. These bimodal complexes are of Middle to Late Silurian age, as are gabbroic rocks of similar age in southwestern Newfoundland, which locally host magmatic Cu–Ni sulphide mineralization (Hinchey, *this volume*). Areas to the east of the Dunnage Zone are largely devoid of mafic plutonic rocks. All vanadium occurrences presently known in Newfoundland are of orthomagmatic type and most are located in, or close to, known Precambrian inliers in southwestern Newfoundland (Figure 8; Table 2).

MINERALIZATION IN PRECAMBRIAN INLIERS

Steel Mountain Anorthosite and Adjacent Areas

This large upland area is underlain by recrystallized anorthosite and leuconorite, locally affected by Paleozoic deformation but otherwise intact. The most significant oxide zone is the Bishop North deposit, which was mined in the 1980s for high-density aggregate to provide ballast for an offshore oil-production platform. The deposit is a dyke-like body of magnetite ($\pm$ ilmenite) traceable along trend for some 200 m, and up to 15 m wide. The total resource is estimated at around 0.75 million tonnes (Rose, 1973; MODS information), averaging 54% Fe, 7.5% Ti and 0.2% V [0.36% V_2O_5]. Sulphur and silica values are extremely low, and the vanadium tenor of magnetite must exceed 0.36% V_2O_5 if ilmenite is accounted for. Rose (1973) noted fine-scale ilmenite exsolution features in magnetite. There is little information on geology, but it is assumed to be Precambrian. A smaller occurrence (Bishop South) may represent its faulted extension or a separate body, and is estimated to contain about 0.5 Mt of material (Rose, 1973; MODS information). The Hayes Prospect, located about 2 km from Bishop, is described as closely similar and has given similar TiO_2 and V_2O_5 results. Although there has been some exploration for PGEs, the Steel Mountain area has not been examined systematically.

Indian Head Range Inlier (Stephenville Area)

This small area of Precambrian rocks near Stephenville contains varied plutonic rocks, including anorthosite, amphibolite to metagabbro and some retrogressed granitoid gneisses. The area was the site of the first iron mining in Newfoundland, which focused on magnetite-rich zones. The geology of the inlier and its iron occurrences are summarized by Heyl and Ronan (1954).

There are two abandoned iron mines in Drill Brook (Figure 8), which exploited concordant oxide-rich layers and bands within granitoid gneiss. The reserves at these were small (about 50 000 tonnes at 55% Fe). Rose (1967) reported vanadium concentrations that range from 0.07% to 0.38% V [0.13% to 0.70% V_2O_5]. The nearby Indian Head Mine (Figure 8) exploited similar oxide-rich layers in the same rock unit. The iron-ore grades were estimated at about 20% Fe, suggesting some dilution. Vanadium concentrations reported by Rose (1967) are around 1% V [1.78% V_2O_5], which are the highest recorded to date in Newfoundland. It is not clear if these results are whole-rock samples or magnetite separates, although the latter is suspected. The reported TiO_2 content is low, less than 0.5%.

PALEOZOIC MAFIC INTRUSIVE SUITES

Four Corners Project (Burgeo Highway Area)

This area is located around the Burgeo Highway near the junction of four NTS map sheets (12A/12, 12A/05, 12B/08, 12B/09). The first observations of mineralization were made in the 1930s when prospector John Keating found magnetite accumulations on a hilltop not far from the present highway (Triple Nine Resources website). During the Second World War, the prospect was examined by the Newfoundland Government as a potential iron-ore deposit (Thomson, 1941). The host rock was described as a medium-grained igneous rock rich in plagioclase, within which a more mafic variant contained more abundant magnetite. Seventy years later, Charles Keating, John's son, sent some samples to the Geological Survey. These were identified as oxide-rich mafic plutonic rocks (28% Fe), with some vanadium enrichment (1927 ppm V, or 0.35% V_2O_5); Ni and Cu values were weakly anomalous, at about 250 ppm for each, but Ti values were low at only 0.09% TiO_2 . The Keating Prospect has now grown into an early stage exploration project operated by Triple Nine Resources. Work to date consists of prospecting, geophysical surveys and limited diamond drilling, but few results have been released.

The area is located within the Dunnage Zone of central Newfoundland, close to its boundary with the adjacent Humber Zone (Figure 8). The most recent mapping in the area is from the Geological Survey of Canada (van Staal *et al.*, 2005), who defined a lenticular gabbro body in this area, on the flanks of a larger mafic intrusion. The host unit includes a wide variety of mafic rock types including norite, gabbro-norite, olivine gabbro, troctolite and anorthosite, and is considered to be a layered cumulate sequence. Outcrops in the area and drillcore display compositional layering and magnetite-rich bands. There is a strong associated positive

Note: The mid-Ordovician shales of central Newfoundland cannot be represented on the scale of this map, but largely occur near the contacts of the two units indicated below.

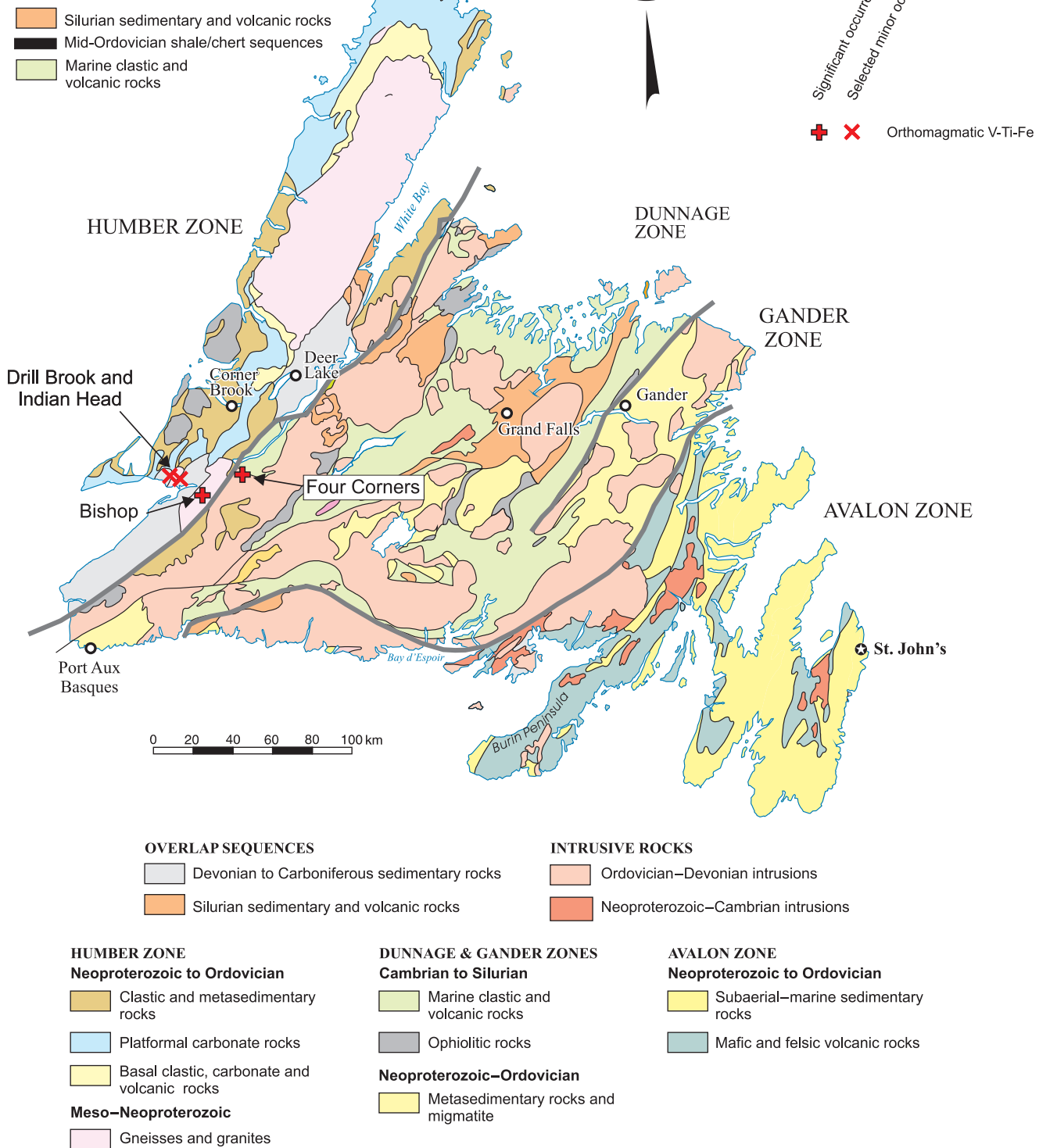


Figure 8. Simplified geological map of Newfoundland, showing the locations of areas holding possible interest for vanadium exploration, and locations of specific areas discussed in the text.

Table 2. Locational information for areas in Newfoundland referenced in this report

Name	MODS number	NTS sheet	UTM zone	Eastings	Northing	Object located	V ₂ O ₅ value or range	Source Reference	Comments
Vanadium associated with orthomagmatic oxide mineralization									
Bishop North	12B/08/Fe 001	12B/08	21	401450	5361750	Abandoned Pit	0.36% to 0.84%	Baird, 1954; Rose, 1973	Exploited for high-density ballast used in offshore oil production platforms - Hibernia Project
Bishop South	12B/08/Fe 002	12B/08	21	401050	5361400	Map Symbol	0.35% to 0.9%	Baird, 1954; Rose, 1967, 1973	Similar to Bishop North but smaller
Bishop #3	12B/08/Fe 003	12B/08	21	400800	5361100	Map Symbol	n/a	Baird, 1954	Reported to be similar to Bishop occurrences
Hayes Prospect	12B/08/Fe 004	12B/08	21	399800	5359450	Map Symbol	0.35%	Baird, 1954; Rose, 1973	Reported to be similar to Bishop occurrences
Upper Drill Brook Mine	12B/09/Fe 002	12B/09	21	390300	5376650	Abandoned Pit	0.41%	Heyl and Ronan, 1954; Rose, 1973	Magnetite concentrations in "gneiss"
Lower Drill Brook Mine	12B/09/Fe 003	12B/09	21	390150	5376650	Abandoned Pit	0.13% to 0.68%	Heyl and Ronan, 1954; Rose, 1973	Magnetite concentrations in "gneiss"
Indian Head Mine	12B/10/Fe 001	12B/10	21	388150	5375450	Abandoned Pit	up to 1.8%	Heyl and Ronan, 1954; Rose, 1973	Assay result is probably a magnetite concentrate
Keating Prospect (Four Corners Project)	12A/05/V 001	12A/05	21	426000	5368450	Drillhole FC-11-01	0.12% to 0.35%	Triple Nine Resources Website	Limited public domain information available, but reconnaissance drilling completed

magnetic anomaly, but also several other such anomalies in the wider area. Several drillholes were completed over a strike length of some 2 km, but results are only partially released; all intersected magnetite-rich rocks. Triple Nine Resources quotes a grade of 23.7% Fe₂O₃ (16.7% Fe), 6% TiO₂, and 0.12% V₂O₅, but there are higher grade intersections within these holes, containing up to 0.23% V₂O₅. The highest assays from surface grab sampling are around 0.35% V₂O₅, consistent with samples analyzed prior to exploration. A bulk-core sample from a higher grade interval, indicated values of 29.1% Fe (41.3% Fe₂O₃), 9.89% Ti (13.2% TiO₂) and 0.13% V (0.25% V₂O₅). Ilmenite and magnetite are complexly intergrown on a fine scale, and magnetic methods were shown to be effective for partial separation of Fe, Ti and V, but more investigation was recommended to optimize these results (MacFarlane, 2012). The work completed in the area certainly indicates potential for extensive zones of oxide-rich gabbro, and suggests consistent low-grade vanadium concentrations. The deposit has characteristics of orthomagmatic oxide mineralization, and implies that other Silurian mafic plutonic suites in southwestern Newfoundland could have similar potential.

VANADIUM POTENTIAL IN SEDIMENTARY ROCKS

As noted previously, there is interest in exploitation of bulk tonnage, low-grade vanadium deposits hosted by black shales, such as the Gibellini and Carlin deposits in Nevada (Figure 1). In these examples, grades are enhanced by supergene enrichment, which is unlikely in Newfoundland or Labrador. Despite such constraints, this deposit type merits brief consideration.

Rose (1967, 1973) analyzed the manganeseiferous black shales of the Conception Bay South area, and obtained results from 79 to 520 ppm V (<<0.1% V₂O₅), and the Carboniferous 'dark shale' of the Deer Lake area (now considered a potential oil shale), gave similarly low values. However, these analyses were limited in number, and given the vanadium enrichment in the Athabasca Basin oil sands (up to 500 ppm; Rose, 1967), some further assessment might be in order.

Two extensive shale sequences that may merit specific investigation are the Middle Ordovician black shales of central Newfoundland (Figure 8), and parts of the Paleoproterozoic Menihek Formation of western Labrador (Figure 2). Both sequences contain syngenetic sulphide-rich bands, and have been viewed as potential targets for sedimentary-hosted sulphide deposits (SEDEX deposits). There is also some direct evidence for vanadium enrichment. Meyer and Dean (1985) completed a lithogeochemical survey in the shale sequences of central Newfoundland. The vanadium contents vary geographically, but some of the stratigraphic sections examined show consistent vanadium enrichment, with average values of around 500 ppm V, ranging up to greater than 1000 ppm; the highest values from these equate to around 0.2% V_2O_5 . The Menihek Formation in Labrador is not studied in detail, but its basal section (immediately above the Sokoman (iron) Formation) is dominated by black shales; a reconnaissance study of these rocks in Québec indicates anomalous uranium and other metals (Clark *et al.*, 2008). Exploration by Labrador Mining and Exploration at Strawberry River, near Labrador City, returned surface samples from Menihek Formation siltstone and shale containing 1640 to 2450 ppm V [up to 0.44% V_2O_5]. This is listed as a zinc occurrence, because one sample contained 1300 ppm Zn, and also contains elevated uranium (Simpson *et al.*, 1985). These sequences both likely represent anoxic depositional environments in which hydrothermal input of iron and other metals occurred; some 'Algoma-type' iron formations, representing similar environments, also carry anomalous vanadium (Gross, 2009). Further work to evaluate the potential of these sedimentary environments may be justified in future years.

CONCLUDING REMARKS

Should interest in exploration for vanadium-rich deposits increase in future years, the Province contains several potential environments. The most obvious are mafic intrusive rocks in Labrador that provide analogues to host rocks of other well-known deposits around the world. The intense exploration following the Voisey's Bay discovery was focused on Ni–Cu mineralization, to the extent that oxide-rich zones received little attention, and some were not even analyzed. Nevertheless, this assessment work provides a valuable framework for exploration and research with a different emphasis. There is also potential for similar orthomagmatic deposits in Newfoundland, and one such exploration project already exists. The Central Mineral Belt of Labrador contains one uranium deposit that is associated with a significant vanadium resource, and there may be others; this association has not been evaluated in all cases. Amongst deposits under exploration elsewhere in the world are large, low-grade accumulations in black, organic-rich shales. Two such sequences in this Province are known to

have metal enrichment, including vanadium, and these may represent targets for future evaluation.

Exploration focused on one commodity, using techniques specific to that task, will not always illuminate instances of, or potential for, other deposit types. For example, Ni–Cu exploration in Labrador was to a large extent guided by electromagnetic techniques, but oxide-rich deposits would not exhibit the same response, and target areas may thus not have received attention. Nevertheless, the geophysical and other data acquired by such programs following the Voisey's Bay discovery remain vital tools in any search for other deposit types. It is hoped that this report will form a useful starting point for such efforts, and prompt re-evaluation of some of the work completed during that period. There is also scope for scientific work by the Geological Survey to better understand potential vanadium environments in Newfoundland and Labrador.

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