GS2019-6

Evaluation of graphite- and vanadium-bearing drillcore from the Huzyk Creek property, sub-Phanerozoic Kisseynew domain, central Manitoba (NTS 63J6)

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In Brief:

- An interbedded wacke-mudstone succession, tentatively correlated with the Burntwood group, hosts vanadium-enriched graphite mineralization at the Huzyk Creek property
- Vanadium was likely entrained by organic particles as they settled through the water column
- Graphite deposits elsewhere in the Kisseynew basin could be equally prospective for vanadium

Citation:

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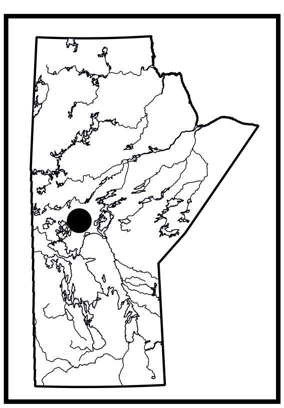

Summary

The Huzyk Creek property lies along the boundary between the sub-Phanerozoic Thompson nickel belt and the Kisseynew domain, and is host to graphite-mineralized and vanadium-enriched metasedimentary rocks. The metasedimentary rocks consist of an interbedded wacke-mudstone succession that is tentatively correlated with (although atypical of) the Burntwood group of the Kisseynew domain. A package of hornblende gneiss and calcsilicate is associated with the wacke-mudstone succession and could represent variably altered mafic volcanic rocks. The graphite mineralization occurs as an intersection of graphite-rich mudstone (14.3–16.7 m wide), which is likely analogous to black shale. The vanadium enrichment correlates closely with the graphite mineralization, and suggests that vanadium was likely entrained by organic particles as they settled to the bottom of the Kisseynew basin. Graphite deposits elsewhere in the Kisseynew domain could prove equally prospective for vanadium. Graphite and vanadium are considered critical elements/minerals by the U.S. Department of the Interior, and are in demand by the green technologies sector for use in electric motors, lithium batteries, and vanadium redox-flow batteries. The Green Giant and Balama prospects are similar metamorphosed black shale deposits investigated for vanadium and graphite mineralization in Madagascar and Mozambique, respectively.

Introduction

The Huzyk Creek property consists of two mineral exploration licenses and 10 mining claims, centred roughly 23 km south of Ponton. The property lies along the boundary between the sub-Phanerozoic Thompson nickel belt (TNB) and Kisseynew domain (Figure GS2019-6-1). A thick (~62 m) interval of sulphide-bearing, graphitic metasedimentary rocks was intersected in diamond-drill core by Hudson Bay Exploration and Development Co. Ltd. while exploring for Ni-Cu on the property in 1997 (Assessment File 73152, Manitoba Agriculture and Resource Development, Winnipeg). The graphitic interval was found to contain up to 40% graphite as fine to coarse flakes. Rocas del Norte, a private company, resampled a 68 m graphitic interval from drillhole NIM-19 in 2014, which yielded 0.14% V_2O_5, including 0.6% V_2O_5 over 0.6 m (Beaumont-Smith, 2018; Assessment File 73152). The property was optioned by Vanadian Energy Corp. (Vanadian; formerly Uracan) in August of 2018. Recent diamond-drilling by Vanadian attempted to twin NIM-19 as well as test a geophysical conductor, outlined by historical exploration work, believed to coincide with the graphitic horizon. Attempts to twin hole NIM-19 were not successful due to uncertainty of the original location of the drill collar; however, the first drillhole, HZ-19-01, intersected a 13.77 m sulphide-bearing graphitic zone grading 0.18% V_2O_5, including a 9.74 m zone grading 0.22% V_2O_5 (Vanadian Energy Corp., 2019). The second hole, HZ-19-02, was collared 200 m northeast along strike and intersected a 14.05 m graphitic zone grading 0.11% V_2O_5. Both graphitic horizons are hosted in metasedimentary rocks with broad zones of variable graphite content and anomalous vanadium (Vanadian Energy Corp., 2019).

Sulphide- and graphite-bearing argillaceous rocks occur in both the Burntwood group rocks of the Kisseynew domain and Ospwagan group rocks of the TNB (Zwanzig, 1999; Zwanzig et al., 2007). Because the Huzyk Creek property straddles the TNB–Kisseynew domain boundary, determining the affinity of the metasedimentary rocks has implications for locating additional vanadium-bearing graphitic rocks. Sulphide and graphite are also concen-

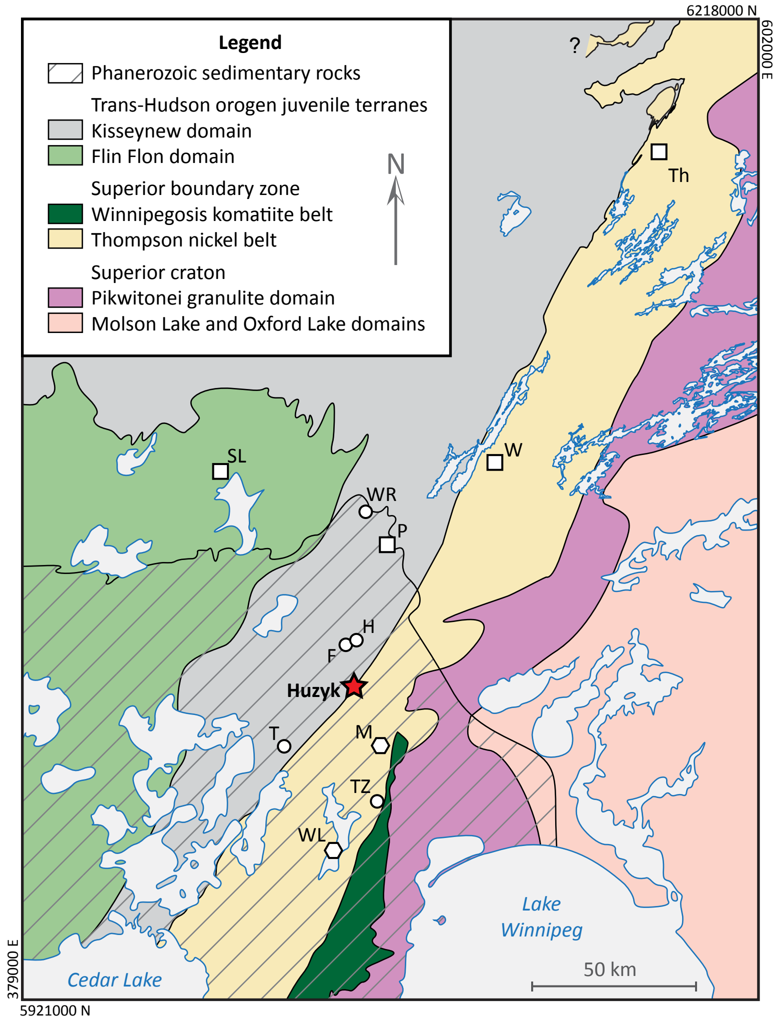

Figure GS2019-6-1: *Geological domains along the Superior boundary zone, central Manitoba (modified from Couëslan, 2018). Symbols: circles, Cu-Zn deposits in the sub-Phanerozoic Kisseynew domain and Superior boundary zone; hexagons, Ni-Cu deposits/occurrences in the sub-Phanerozoic Thompson nickel belt; squares, town/cities; star, location of the 2019 diamond-drilling campaign at the Huzyk Creek property. Abbreviations: F, Fenton deposit; H, Harmin deposit; M, Minago deposit; SL, Snow Lake; T, Talbot deposit; Th, Thompson; TZ, Tower zone deposit; W, Wabowden; WL, William Lake occurrence; WR, Watts River deposit. Co-ordinates are in UTM Zone 14, NAD83.*

trated in shear zones in the Kisseynew domain and TNB (e.g., Mumin and Trott, 2003; Zwanzig and Bailes, 2010), so the potential could exist for the vanadium-bearing graphitic rocks to be shear hosted and/or hydrothermal in nature. The objectives of this project are to evaluate the rocks hosting the graphite and vanadium mineralization at Vanadian's Huzyk Creek property and determine their affinity to either the TNB or Kisseynew domain, and to derive possible petrogenetic model(s) for the mineralization.

Regional setting

Kisseynew domain

The Huzyk Creek property lies along the sub-Phanerozoic boundary between the Kisseynew domain and the TNB. The Kisseynew domain is situated in the core of the juvenile Reindeer zone of the Paleoproterozoic Trans-Hudson orogen (THO; Figure GS2019-6-2). It is underlain by dominantly Burntwood group rocks, with subordinate calcalkaline plutons and sheets of anatectic granitoids. The Burntwood group forms a monotonous succession of graphite-bearing metagreywacke-mudstone, which was metamorphosed to garnet-biotite gneiss and migmatite throughout much of the Kisseynew domain during the terminal collision of the THO. The metagreywacke-mudstone is interpreted as turbidite deposits shed from the surrounding juvenile accretionary-arc complexes of the Flin Flon and Lynn Lake domains (Ansdell et al., 1995; Zwanzig and Bailes, 2010). Coeval fluvial-alluvial deposits on the margins of these volcano-plutonic domains consist of the Missi and Sickle groups, respectively (Stauffer, 1990;

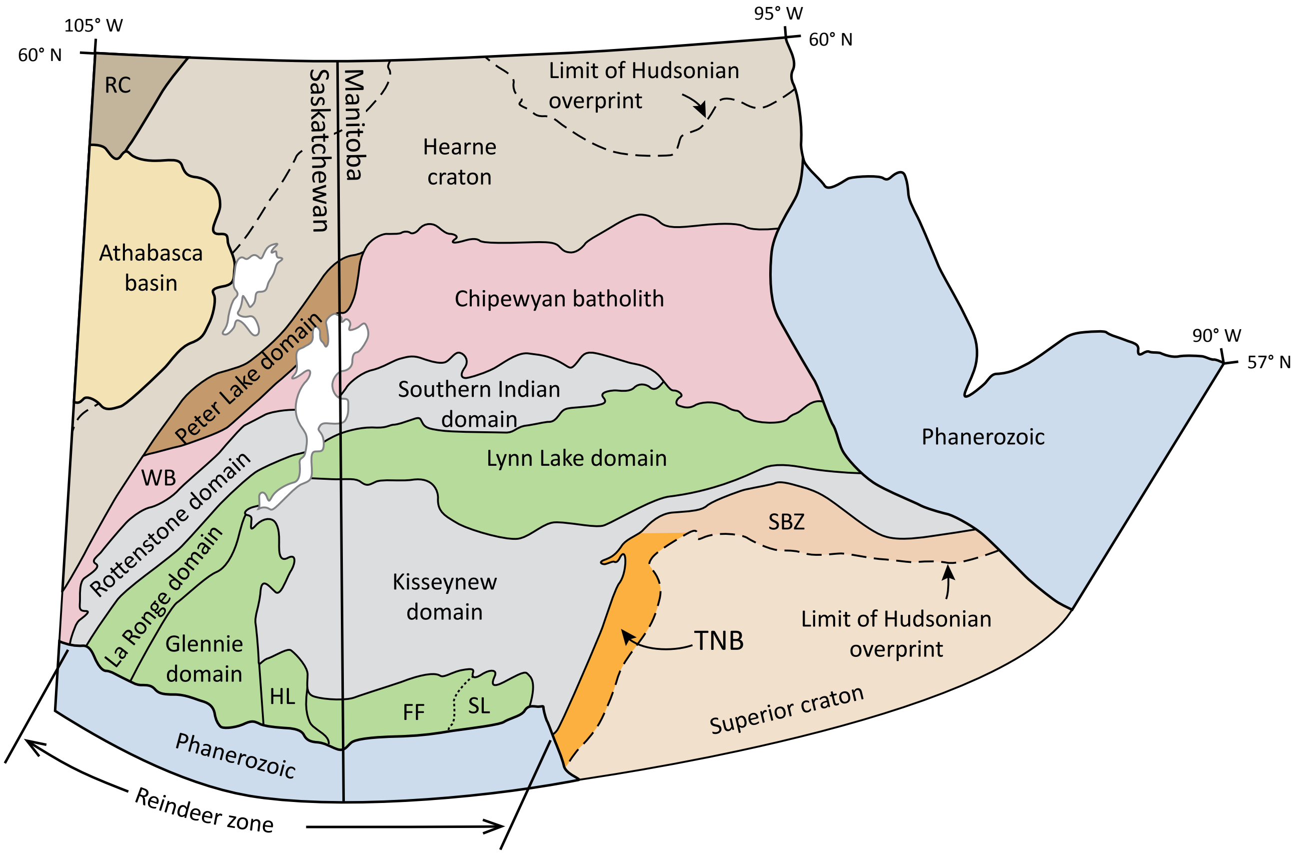

Figure GS2019-6-2: *Tectonic-elements map of the Manitoba–Saskatchewan segment of the Trans-Hudson orogen (modified from Lewry et al., 1990). Abbreviations: FF, Flin Flon domain; HL, Hanson Lake block; RC, Rae craton; SBZ, Superior boundary zone; SL, Snow Lake subdomain; TNB, Thompson nickel belt; WB, Wathaman batholith.*

Zwanzig and Bailes, 2010). The Kisseynew paleobasin is generally interpreted as a back-arc basin; however, an inter-arc or fore-arc basin environment could also be possible (Ansdell et al., 1995; Zwanzig, 1997; Corrigan et al., 2009; Zwanzig and Bailes, 2010).

Burntwood group

The Burntwood group consists of a succession of turbidite-derived greywacke-mudstone deposits. Over most of the Kisseynew domain these rocks occur as migmatitic garnet-biotite gneiss commonly with sillimanite and cordierite, and minor graphite. Locally preserved rhythmic layering alternates between more quartzofeldspathic gneiss and more biotite- and garnet-rich gneiss, and is interpreted as graded greywacke-mudstone beds. Local pods of calc-silicate are probably derived from calcareous concretions (Corrigan and Rayner, 2002; Zwanzig et al., 2007). The Burntwood group grades laterally and vertically into the fluvial-alluvial successions of the Missi, Sickle, and Grass River groups. Narrow packages containing sporadic hornblende, magnetite, or pyrrhotite are interpreted as part of the Burntwood group–Missi group transition (Zwanzig et al., 2007). Similar transitional deposits exist with the Sickle group.

Deposition of the Burntwood group likely began around ca. 1855 Ma as distal turbidites in prograding submarine fans along the margin of the Flin Flon domain (Ansdell et al., 1995; Machado et al., 1999; Zwanzig and Bailes, 2010). These deposits may have preceded that of the Missi group until ca. 1848 Ma, when deposition became synchronous. The youngest detrital zircons analyzed from the Burntwood group yielded ages of ca. 1845–1841 Ma (Machado et al., 1999), and a minimum age for deposition is provided by the ca. 1830–1820 Ma Touchbourne suite, which intrudes the Burntwood group rocks (Gordon et al., 1990; Machado et al., 1999; Zwanzig and Bailes, 2010).

Structure and metamorphism

The rocks of the Kisseynew domain were subject to multiple phases of deformation beginning with a ca. 1845–1825 Ma fold-and-thrust system (D_1/F_1), which likely resulted from the Sask craton under-riding the Flin Flon and Kisseynew domains (Zwanzig, 1999). Thrusting was likely coeval with deposition of the Missi and upper Burntwood groups and directed toward the Kisseynew basin, which would be consistent with the direction of sedimentary transport and the inferred direction of subduction polarity (Machado et al., 1999; Zwanzig, 1999; Zwanzig and Bailes, 2010). However, vergence has also been interpreted as toward the Flin Flon domain, based on the present-day orientation of these structures (Ansdell et al., 1995). D_1 was followed by two generations (F_2 and F_3) of recumbent folding accompanied by prograde metamorphism and the development of a penetrative S_2–S_3 foliation (Ansdell et al., 1995; Zwanzig, 1999). Westward overturning of D_1 structures during F_2 was a product of east-west compression during collision between the Superior craton and the Flin Flon and Kisseynew domains beginning ca. 1.83–1.82 Ga (Ansdell et al., 1995; Machado et al., 1999; Zwanzig, 1999; Zwanzig and Bailes, 2010). South- and southwest-verging F_3 folding amplified and overturned F_1–F_2 folds. Much of D_3 is interpreted to coincide with peak metamorphic conditions from ca. 1810 to 1800 Ma (Zwanzig, 1999). Late F_3 folding likely continued until ca. 1789 Ma, and likely resulted from rocks of the Lynn Lake belt attempting to over-ride the Kisseynew domain, as the Hearne craton attempted to over-ride the Reindeer zone (Zwanzig, 1999). A continuous progression may have occurred between the D_2 and D_3 phases of deformation. In the main portion of the Kisseynew domain, F_4 folds are generally upright and open, with north or east-northeast trends (Zwanzig, 1999). Folding may be accompanied by a retrograde S_4 foliation in hinge zones and lower amphibolite- to greenschist-facies assemblages. Adjacent to the TNB, F_4 folds become tighter, with northeast-trending fold axes, consistent with sinistral transpression along the north-northeast–trending Superior boundary zone (Zwanzig, 1998; Zwanzig, 1999).

The metamorphic grade increases from the margins of the Kisseynew domain toward the core (Bailes and McRitchie, 1978; Gordon, 1989; Couëslan and Pattison, 2012). Schists with mineral assemblages of greenschist to lower-amphibolite facies (chlorite-muscovite-garnet) along the north and south flanks of the domain, grade into granulite-facies migmatites (cordierite–garnet–melt/K-feldspar) in the core (Bailes and McRitchie, 1978). Peak metamorphic conditions in the high-grade core are believed to be relatively uniform and estimated at 750 ±50°C and 5.5 ±1 kbar (Gordon, 1989); however, Growdon (2010) suggested grades as high as 900°C and 12 kbar in the central Kisseynew domain. Prograde to peak metamorphism was likely ongoing during D_2–D_3 from ca. 1820 to 1800 Ma, with peak conditions likely attained at ca. 1810–1800 Ma (Ansdell et al., 1995; Machado et al., 1999; Zwanzig, 1999; Growdon, 2010).

Sub-Phanerozoic Kisseynew domain

The sub-Phanerozoic Kisseynew domain is the southern extension of the Kisseynew domain below the Phanerozoic cover (Figure GS2019-6-1). Situated between the Superior craton margin and the Flin Flon domain, it was interpreted to consist of migmatitic metasedimentary rocks of the Burntwood group interlayered with felsic metaplutonic veins and sheets (Leclair et al., 1997). However, the discovery of several volcanogenic massive sulphide (VMS) deposits (Watts River, Harmin, Fenton, and Talbot) in the domain has brought this interpretation into question (Simard et al., 2010). Recent studies (Simard et al., 2010; Bailes, 2015; Reid, 2018) suggest complex structural interleaving of Flin Flon domain arc rocks, Kisseynew domain Burntwood group rocks, and possibly TNB rocks within the sub-Phanerozoic Kisseynew domain. A similar situation occurs along the north, south, and east flanks of the exposed Kisseynew domain, where thrusts and recumbent folding have structurally interleaved rocks of the Kisseynew basin with rocks of adjacent juvenile volcano-plutonic terranes and evolved Archean crust (Zwanzig, 1999; Rayner and Percival, 2007; Zwanzig and Bailes, 2010).

Thompson nickel belt

The TNB forms a segment of the Superior boundary zone, flanked to the northwest by the Kisseynew domain of the Trans-Hudson orogen and to the southeast by the Pikwitonei granulite domain of the Superior craton (Figure GS2019-6-1). The TNB is underlain largely by reworked Archean gneiss of the Pikwitonei domain (Hubregtse, 1980; Mezger et al., 1990; Heaman et al., 2011), which was exhumed and unconformably overlain by the Paleoproterozoic supracrustal rocks of the Ospwagan group (Bleeker, 1990; Zwanzig et al., 2007). The Archean basement gneiss and Ospwagan group were subjected to multiple generations of deformation and metamorphic conditions, ranging from middle-amphibolite facies to lower-granulite facies, during the Trans-Hudson orogeny (Bleeker, 1990; Burnham et al., 2009; Couëslan and Pattison, 2012).

The dominant phase of penetrative deformation is D_2, which affected the Ospwagan group and Archean gneiss. This deformation phase resulted in the formation of F_2 nappe structures, which are interpreted as either east verging (Bleeker, 1990; White et al., 2002) or southwest verging (Zwanzig et al., 2007; Burnham et al., 2009). The recumbent folds are associated with regionally penetrative S_2 fabrics. The D_2 phase of deformation is interpreted to be the result of convergence between the Superior craton margin and the Reindeer zone of the Trans-Hudson orogen ca. 1830 to 1800 Ma. The D_3 phase of deformation resulted in isoclinal folds with vertical to steeply southeast-dipping axial planes (Bleeker, 1990; Burnham et al., 2009). Mylonite zones with subvertical stretching lineations parallel many of the regional F_3 folds. Tightening of D_3 structures continued during D_4, marked by localized retrograde greenschist metamorphism along northeast-striking, mylonitic and cataclastic shear zones that commonly record southeast-side-up sinistral movement (Bleeker, 1990; Burnham et al., 2009).

Ospwagan group

The following summary of the Ospwagan group is sourced largely from Bleeker (1990) and Zwanzig et al. (2007). The Paleoproterozoic Ospwagan group unconformably overlies Archean basement gneiss in the TNB. The lowermost unit of the Ospwagan group is the Manasan formation, a fining-upward transgressive sequence of sandstones and semipelitic rocks. This grades into the overlying Thompson formation, a sequence of calcsilicates and impure marbles that reflects a transition to a carbonate-dominated system. The Thompson formation is overlain by the Pipe formation, a succession of deep-water deposits including silicate- and sulphide-facies iron formations, cherts, mudstones, calcsilicates, and marble. Overlying this is the Setting formation, a coarsening-upward sequence of interbedded sandstones and mudstones that were likely deposited as turbidites. The Ospwagan group is capped by the Bah Lake assemblage, which consists of mafic to ultramafic volcanic rocks dominated by massive to pillowed basalt flows with local picrite and minor synvolcanic intrusions.

Geology of the Huzyk Creek area

Core from drillholes HZ-19-1 and HZ-19-2 were logged in August of 2019. The order of the rock units are described from the structural hangingwall of the graphite- and vanadium-enriched zone into the footwall (Figure GS2019-6-3). All the rocks described attained relatively high metamorphic grade during the Trans-Hudson orogeny. Protolith interpretation was used for naming rocks where a fair amount of certainty exists; however, where ambiguity remains metamorphic nomenclature was retained. The 'meta-' prefix has been omitted from rock names for brevity. All rocks have a well-developed penetrative foliation with the exception of some granite intrusions that are weakly foliated. Reported thicknesses are intersection lengths, not true thicknesses.

Hornblende gneiss and calcsilicate

Intervals of interlayered hornblende gneiss and calcsilicate occur at the top of the Precambrian in both drillholes. The hornblende gneiss is medium grained and quartzofeldspathic, with 30–40% hornblende. It commonly grades into amphibolite, which contains 60–70% hornblende. The gneiss and amphibolite locally contain garnet porphyroblasts <7 mm across that are characterized by plagioclase corona. More common are rounded aggregates of plagioclase <8 mm across that are likely pseudomorphous after garnet (Figure GS2019-6-4a). The calcsilicate is compositionally and texturally diverse. It can be texturally similar to the hornblende gneiss, with the hornblende replaced by pale green amphibole (and/or diopside) and the addition of sparse titanite; however, it can also appear as a coarse-grained rock (Figure GS2019-6-4b) with variable enrichment in diopside, sulphide, titanite and epidote. The calcsilicate and hornblende gneiss can be interlayered on scales ranging from <1 cm to 2.5 m, with diffuse contacts. In drillhole HZ-19-1 the hornblende gneiss and calcsilicate are interleaved with the underlying wacke at a scale of <35 m. This is assumed to be tectonic repetition; however, stratigraphic interlayering can not be ruled out.

Wacke-mudstone

The graphite- and vanadium-enriched horizon is hosted by a thick package of interbedded wackes and mudstones. The various wackes and mudstones are named for the dominant mafic mineral, exclusive of biotite, that is present in the rock. The wackes appear as medium- to coarse-grained quartzofeldspathic gneisses, typically with 10–20% biotite. The compositionally similar mudstones are medium to coarse grained, schistose, and arbitrarily defined as having >20% biotite (typically 20–30%). The wacke-mudstone units are described in order of decreasing abundance.

Orthopyroxene wacke-mudstone

Orthopyroxene wacke is the most abundant lithology in this package. It typically contains 10–20% orthopyroxene, which locally forms coarse-grained poikiloblasts <1 cm across (Figure GS2019-6-4c). Local horizons contain trace amounts of graphite and <3% pyrrhotite. The wacke is locally interbedded with orthopyroxene mudstone layers <2 m thick (Figure GS2019-6-4d). Local layers in the mudstone can contain trace amounts of graphite, and sparse garnet and pyrrhotite.

Garnet wacke-mudstone

The orthopyroxene wacke-mudstone hosts local layers of garnet wacke-mudstone <6 m thick (Figure GS2019-6-4e). In addition to biotite, the garnet wacke contains 3–5% orthopyroxene and 5–7% garnet. The garnet and orthopyroxene typically occur along diffuse, alternating

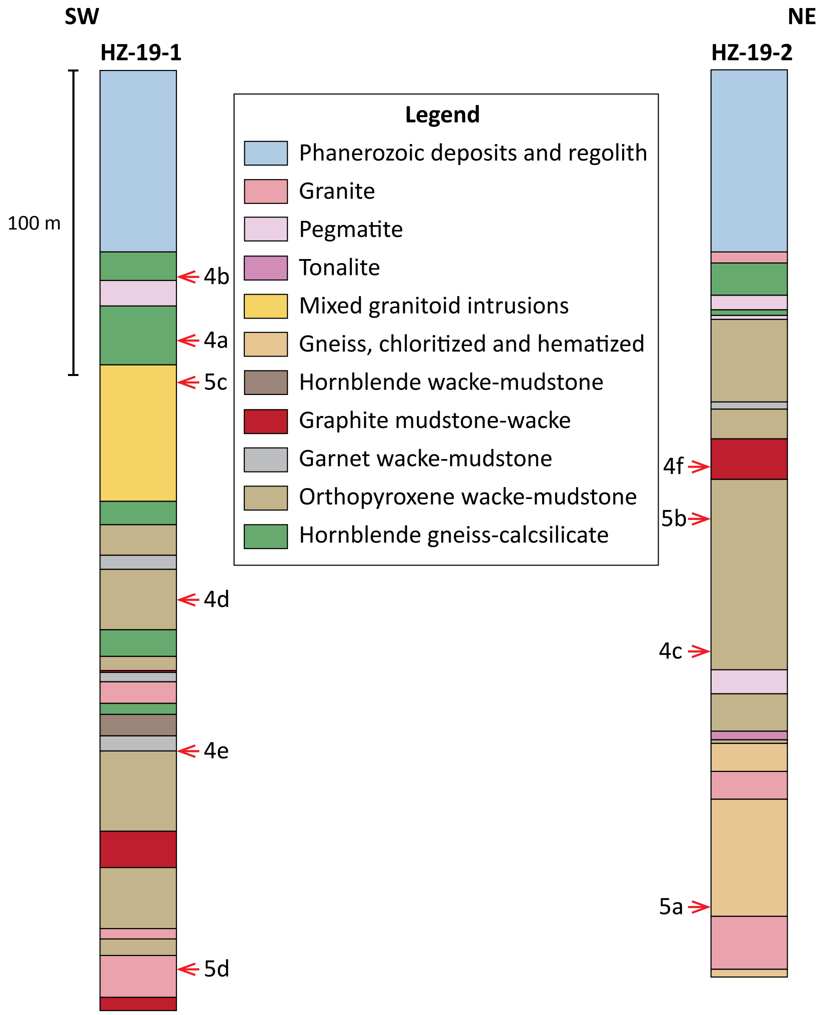

***Figure GS2019-6-3:** Schematic logs of drillcores HZ-19-1 and HZ-19-2 from the Huzyk Creek property; see Figure GS2019-6-1 for the approximate location. The vertical and horizontal scale are equivalent. The locations of images in Figure GS2019-6-4 and Figure GS2019-6-5 are indicated along the inside edge of each column.*

layers, likely controlled by primary compositional bedding of the sedimentary rock. Trace amounts of graphite and pyrrhotite are typically present, but up to 3% graphite and pyrrhotite can occur. The garnet wacke is locally interlayered with garnet mudstone beds <30 cm thick; in addition, the garnet mudstone can occur as layers <3 m thick within the orthopyroxene wacke-mudstone unit. The garnet mudstone typically contains trace to 2% graphite and 5–20% garnet. Orthopyroxene typically forms <5% of the rock, although the garnet mudstone and orthopyroxene mudstone can be interlayered on a scale of <1 cm.

Graphite mudstone-wacke

Graphite mudstone occurs as a discrete horizon, 14.3–16.7 m wide, within the overall wacke-mudstone sedimentary rock package. The graphite mudstone contains 7–10% pyrrhotite, 10–30% biotite, and 20–30% graphite. Trace amounts of chalcopyrite, molybdenite and sphalerite are typically present. The mudstone contains local beds of graphite-pyrrhotite wacke (Figure GS2019-6-4f) <1.8 m thick. The graphite-pyrrhotite wacke is typically fine to medium grained and contains 1–3% graphite, 2–5% pyrrhotite, 5–7% biotite, and sparse orthopyroxene. A second discrete horizon of graphitic wacke, at least 5.2 m thick, occurs at the bottom of drillhole HZ-19-1. This wacke is distinct from the one interbedded with the graphite mudstone in that it appears as graphite-bearing orthopyroxene wacke and garnet wacke interbedded on a scale <1.4 m. The graphite content in these interbedded wackes is typically 2–3% but is locally as high as 5%. Local sillimanite-rich beds <5 cm thick are also present.

Hornblende wacke-mudstone

A single hornblende wacke-mudstone layer (8.45 m thick) occurs within the core of drillhole HZ-19-1. The hornblende wacke contains 3–5% hornblende, whereas the

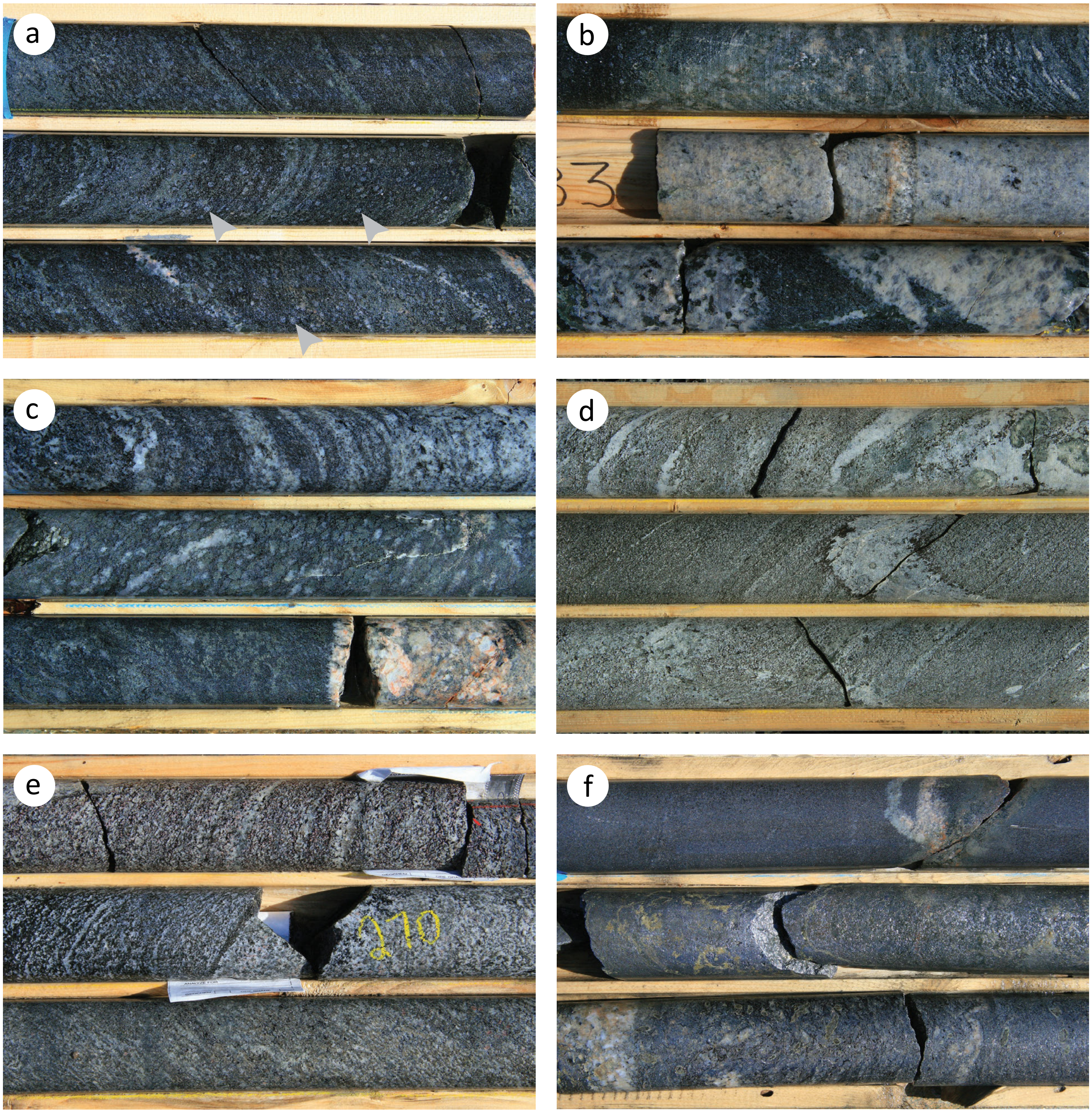

Figure GS2019-6-4: *Drillcore images from HZ-19-1 and HZ-19-2:* ***a)*** *hornblende gneiss with diffuse intercalations of calcsilicate, arrows indicate plagioclase pseudomorphs after garnet (HZ-19-1, 106.8 m);* ***b)*** *hornblende gneiss and coarse-grained calcsilicate (top row) intruded by pegmatitic granite (bottom two rows; HZ-19-1, 81.55 m);* ***c)*** *orthopyroxene wacke with coarse-grained orthopyroxene poikiloblasts (middle row; HZ-19-2, 239.7 m);* ***d)*** *orthopyroxene wacke (top and bottom rows) interbedded with orthopyroxene mudstone (middle row; HZ-19-1, 208.6 m);* ***e)*** *garnet wacke (top row) interbedded with orthopyroxene wacke (bottom row; HZ-19-1, 268.5 m);* ***f)*** *graphite-pyrrhotite wacke bed (top row) hosted in graphite mudstone (bottom two rows; HZ-19-2, 163.65 m). Drillcore is NQ with a diameter of 47.5 mm.*

mudstone contains 5–7% hornblende. The mudstone occurs as beds <30 cm thick within the wacke. The sequence is in direct contact with an interval of calcsilicate and hornblende gneiss. The hornblende wacke-mudstone could represent a more calcareous section, or an influx of volcaniclastic detritus. Alternatively, it could represent an interval of sheared and altered hornblende gneiss.

Chloritized and hematized gneiss

A 96 m interval of intensely chloritized and hematized gneiss occurs at the bottom of drillhole HZ-19-2. The gneiss is medium to coarse grained and is K-feldspar rich, with 7–10% hematite and 10–30% chlorite. Both specular and earthy hematite are present. Local zones within the gneiss have a mottled texture (Figure GS2019-6-5a). Sparse zones

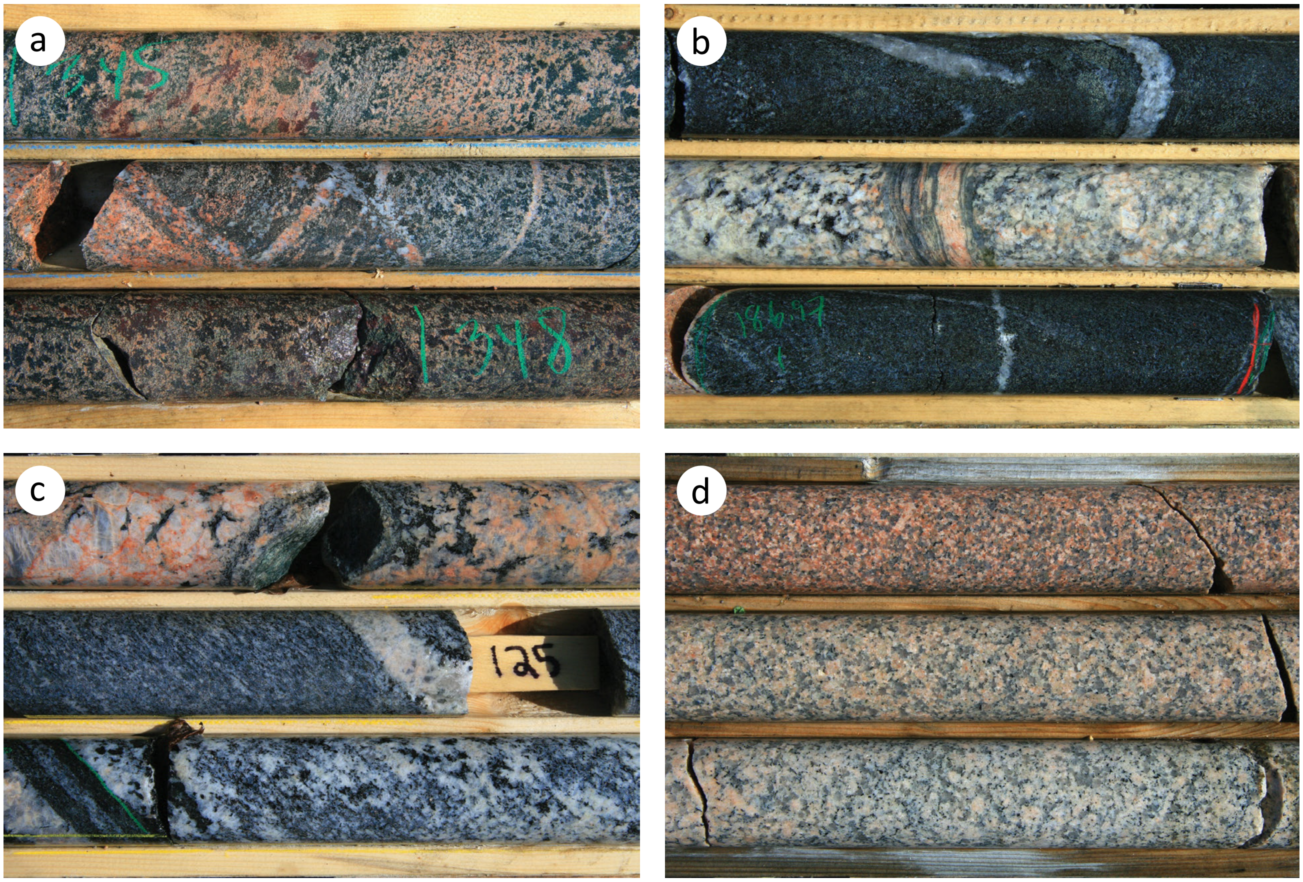

Figure GS2019-6-5: *Drillcore images from HZ-19-1 and HZ-19-2:* ***a)*** *chloritized and hematized gneiss with mottled texture (HZ-19-2, 345.0 m);* ***b)*** *pegmatitic granite with mylonitic band (middle row) intruded into orthopyroxene wacke (top and bottom rows; HZ-19-2, 184.25 m);* ***c)*** *granodiorite (middle row) intruded by pegmatitic granite (top row) and tonalite (bottom row; HZ-19-1, 123.3 m);* ***d)*** *weakly foliated biotite granite (HZ-19-1, 354.2 m). Drillcore is NQ with a diameter of 47.5 mm.*

of quartz-vein breccia <2 m wide can contain void-filling specular hematite. Intrusions of pegmatite and medium-grained granite within this interval are overprinted by the chlorite and hematite alteration. The protolith of the chloritized and hematized gneiss is uncertain; however, the mafic content is comparable to the wacke-mudstone rocks, and the local mottling could represent the pseudomorphous replacement of poikiloblastic orthopyroxene. A sample was collected for lithogeochemical analysis and comparison with other units in the sequence.

Intrusions

Several varieties of intrusive granitoid rocks are present in the drillcore. The intrusions appear to intersect all of the previously described units. Abundant pegmatitic granite occurs throughout the drill core as intersections ranging from centimetres up to 10 m in width. Several generations of pegmatite are likely present. They range from pink to light grey, and are typically biotite bearing; however, local intrusions may contain minor hornblende, pyrrhotite, titanite, and possibly orthopyroxene. Sparse bands of mylonite <5 cm wide can be present (Figure GS2019-6-5b). Local intersections of coarse-grained tonalite <3.5 m occur in both drillholes. The tonalite is light grey and typically contains 3–7% biotite and 3–7% hornblende, along with variable but minor amounts of orthopyroxene, pyrrhotite and titanite. The tonalite is intruded by pegmatite and medium-grained granite. Sparse intervals of granodiorite <6 m wide are present in drillhole HZ-19-1. It is pinkish grey and biotite bearing, with minor amounts of amphibole. The granodiorite is intruded by pegmatite and tonalite (Figure GS2019-6-5c). Pink, medium-grained biotite granite occurs as intrusions in both drillholes (Figure GS2019-6-5d). The granite intersections vary from centimetres up to 22 m wide. The rock is pink, weakly foliated to foliated, and relatively even textured, although local pegmatite segregations can be present.

Discussion

The Huzyk Creek area was previously reported as being underlain by upper amphibolite-facies rocks (Beaumont-Smith, 2018); however, the prevalence of orthopyroxene is suggestive of lower granulite-facies assemblages. This is supported by microscopy, which reveals the presence of orthopyroxene–K-feldspar assemblages in the wacke-mudstone rocks, orthopyroxene and inverted pigeonite in the hornblende gneiss and calcsilicate rocks, and widespread antiperthite.

The identification and correlation of sedimentary rocks in high-grade metamorphic terranes is challenging. The identification of Ospwagan group rocks in the TNB is typically made by recognizing key stratigraphic markers: arenaceous sandstones of the Manasan and Setting formations, calcsilicates and marbles of the Thompson and Pipe formations, and iron formations of the Pipe formation (Bleeker, 1990; Zwanzig et al., 2007). These rock types generally remain recognizable even in granulite-facies successions (Zwanzig et al., 2007; Couëslan and Pattison, 2012). Although some calcsilicate is associated with the hornblende gneiss, the wacke-mudstone succession does not correlate well with any portion of the Ospwagan group stratigraphy.

The hornblende gneiss and calcsilicate are petrographically similar to sequences described along the north and east flanks of the Kisseynew domain (Zwanzig, 2000, 2008; Couëslan, 2011, unpublished data, 2013). These rocks are interpreted as metabasalt with varying intensity of pre-metamorphic, epidote and carbonate alteration (Zwanzig, 2008). It is interpreted that the basalt was thrust into the Kisseynew basin along regional-scale faults.

The Burntwood group consists of a thick succession of interbedded wacke and mudstone. Upper amphibolite- to granulite-facies Burntwood group wacke typically consists of garnet-biotite gneiss, with more aluminous mudstone layers containing additional biotite±sillimanite and cordierite (e.g., Martins and Couëslan, 2019). Graphite is typically present in trace to minor amounts, although significant intersections of graphite have been reported from drillcore in the Kisseynew basin (e.g., Callinex Mines Inc., 2014; Assessment File 93001). Significant portions of the Huzyk Creek wacke-mudstone succession are devoid of garnet, which could be considered atypical for Burntwood group rocks. However, the interlayering of wacke and mudstone, and the presence of graphite, including significant accumulations, are comparable to rocks of the Burntwood group. Instances of garnet-free Burntwood group rocks are observed at Russell Lake, including rare occurrences of amphibole- or pyroxene-bearing rocks (Martins and Couëslan, 2019). Therefore, a tentative correlation is made between the Huzyk Creek wacke-mudstone rocks and the Burntwood group. Whole-rock lithogeochemical analyses are required to test this interpretation, as well as the possible correlation of the hornblende gneiss and calcsilicate with mafic volcanic rocks.

Semi-solid graphite occurs across relatively wide intersections (graphite mudstone, 14.3–16.7 m), and is disseminated throughout the wacke-mudstone sequence. This is more suggestive of a sedimentary-metamorphic origin (i.e., metamorphosed black shale), rather than a discrete, shear- or vein-hosted (hydrothermal) origin for the graphite (i.e., 'lump' graphite). If the wacke-mudstone sequence is correlative with the Burntwood group, this interpretation is further strengthened by the basin-wide presence of graphite in the Kisseynew domain.

The drilling results by Vanadian (2019) suggest a close correlation between graphite mineralization and vanadium enrichment. The basin-wide presence of graphite ±pyrrhotite in the Burntwood group suggests that the rocks were deposited in an anoxic environment, and remained so during diagenesis. Vanadium is considered relatively immobile in the reduced state (V^{3+}), so it is unlikely that the vanadium was mobilized during diagenesis (Breit and Wanty, 1991). Mobilization of soluble vanadium (V^{4+}, V^{5+}), and re-precipitation under reducing conditions as insoluble vanadium (V^{3+}), is generally considered a requirement to form sandstone-hosted vanadium deposits (Wanty et al., 1990; Shawe, 2011). It is more likely that the vanadium was deposited alongside carbonaceous material at the time of sedimentation and remained immobile. A general model proposed by Breit and Wanty (1991) involves dissolved V^{5+} in oxidized surface waters becoming adsorbed to organic particles in seawater. If the organic particles settle into anoxic conditions at depth, the adsorbed vanadium can be reduced to V^{4+} by dissolved organic compounds or hydrogen sulphide. Upon burial and diagenesis it can be further reduced to V^{3+} and partitioned into clay minerals. Assuming the graphite is largely derived from organic carbon, this model also provides a direct causal relationship between the graphite and vanadium enrichment in the Huzyk Creek rocks.

Economic considerations

Both graphite and vanadium are considered critical minerals/elements by the U.S. Department of the Interior (Schulz et al., 2017). Some of the many uses of graphite include refractory applications, brake linings, motor brushes, and steel making; however, higher valued coarse-grained graphite is used in high-temperature lubricants, and lithium battery and fuel cell applications (Robinson et al., 2017). Vanadium is used primarily in the production of high-strength steels, and specialty aluminum and titanium alloys. In the field of green technology there is growing interest around the use of vanadium redox-flow batteries for large-scale energy storage (Kelley et al., 2017). These batteries boast the potential for nearly unlimited storage capacity and unlimited lifespan.

There appears to be a direct relationship between graphite mineralization and vanadium enrichment in the Huzyk Creek sedimentary rocks, which are tentatively correlated with the Burntwood group of the Kisseynew domain. Thick accumulations of graphite are widespread in the Kisseynew domain (Callinex Mines Incorporated, 2014; Assessment File 93001). A proposed model calls for dissolved vanadium in the water column to be removed by settling organic material that accumulated on the basin floor. Burial, diagenesis, and metamorphism of these deposits produced the vanadium-enriched graphite mineralization present at Huzyk Creek. Assuming water circulation in the basin was unrestricted, it stands to reason that other graphite deposits in the Kisseynew domain should also be prospective for vanadium.

Black shales can be enriched in vanadium as well as a suite of other metals (molybdenum, copper, nickel, zinc, PGEs). Although these shales tend to be uneconomic, development is continuing at the Gibellini vanadium project in Nevada, where the black shale underwent secondary modification and enrichment by oxidizing fluids (Orbock, 2017). Metamorphosed examples of vanadium-enriched black shales include the Green Giant and Balama projects in Madagascar and Mozambique, respectively (AGP Mining Consultants Inc., 2011; Syrah Resources Ltd., 2014; Di Cecco et al., 2018). The Green Giant project hosts a NI 43-101–compliant resource estimated at 60 million tonnes grading 0.69% V_2O_5, while the Balama project has an inferred resource of 1.15 billion tonnes grading 0.23% V_2O_5.

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