Potential for critical mineral deposits in Maine, USA

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ABSTRACT

An analysis of the potential for deposits of critical minerals and elements in Maine presented here includes data and discussions for antimony, beryllium, cesium, chromium, cobalt, graphite, lithium, manganese, niobium, platinum group elements, rhenium, rare earth elements, tin, tantalum, tellurium, titanium, uranium, vanadium, tungsten, and zirconium. Deposits are divided into two groups based on geological settings and common ore-deposit terminology. One group consists of known deposits (sediment-hosted manganese, volcanogenic massive sulphide, porphyry copper-molybdenum, mafic- and ultramafic-hosted nickel-copper [-cobalt-platinum group elements], pegmatitic lithium-cesium-tantalum) that are in most cases relatively large, well-documented, and have been explored extensively in the past. The second, and much larger group of different minerals and elements, comprises small deposits, prospects, and occurrences that are minimally explored or unexplored. The qualitative assessment used in this study relies on three key criteria: (1) the presence of known deposits, prospects, or mineral occurrences; (2) favourable geologic settings for having certain deposit types based on current ore deposit models; and (3) geochemical anomalies in rocks or stream sediments, including panned concentrates. Among 20 different deposit types considered herein, a high resource potential is assigned only to three: (1) sediment-hosted manganese, (2) mafic- and ultramafic-hosted nickel-copper(-cobalt-platinum group elements), and (3) pegmatitic lithium-cesium-tantalum. Moderate potential is assigned to 11 other deposit types, including: (1) porphyry copper-molybdenum (-rhenium, selenium, tellurium, bismuth, platinum group elements); (2) chromium in ophiolites; (3) platinum group elements in ophiolitic ultramafic rocks; (4) granite-hosted uranium-thorium; (5) tin in granitic plutons and veins; (6) niobium, tantalum, and rare earth elements in alkaline intrusions; (7) tungsten and bismuth in polymetallic veins; (8) vanadium in black shales; (9) antimony in orogenic veins and replacements; (10) tellurium in epithermal deposits; and (11) uranium in peat.

RÉSUMÉ

L'analyse du potentiel de gîtes de minéraux et d'éléments critiques au Maine exposée aux présentes comporte des données et des examens concernant l'antimoine, le béryllium, le césium, le chrome, le cobalt, le graphite, le lithium, le manganèse, le niobium, les éléments du groupe du platine, le rhénium, les éléments des terres rares, l'étain, le tantale, le tellure, le titane, l'uranium, le vanadium, le tungstène et le zirconium. Les gîtes sont répartis en deux groupes selon les cadres géologiques et la terminologie des minéraux métallifères communs. Un groupe est constitué de gîtes connus [manganèse dans des roches sédimentaires, sulfures massifs volcanogènes, gîtes porphyriques de cuivre-molybdène nickel-cuivre (-cobalt-éléments du groupe du platine) dans des roches mafiques et ultramafiques ainsi que gisements pegmatitiques de lithium-césium-tantale] qui sont dans la majorité des cas relativement vastes, qui sont bien documentés et qui ont fait l'objet d'une exploration poussée par le passé. Le second groupe, beaucoup plus nombreux, de minéraux et d'éléments différents, est composé de petits gîtes, de zones prometteuses et de venues ayant été peu explorées ou inexplorées. L'évaluation qualitative utilisée dans le cadre de l'étude repose sur trois critères clés : 1) la présence de gîtes, de zones prometteuses ou de venues minérales connus; 2) les cadres géologiques favorables en raison de la présence de certains types de gîtes basés sur les modèles de dépôts de minerai courants; et 3) les anomalies géochimiques dans les roches ou les

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sédiments fluviatiles, notamment les concentrés lavés à la batée. Parmi les 20 différents types de gîtes considérés aux présentes, seuls trois se voient conférer un potentiel de ressources élevé : 1) les gîtes de manganèse dans des roches sédimentaires, 2) le nickel-cuivre (-cobalt-éléments du groupe du platine) dans des roches mafiques et ultramafiques, et 3) les gîtes pegmatitiques de lithium-césium-tantale. Un potentiel moyen est attribué à 11 autres types de gîtes, notamment : les gîtes porphyriques de cuivre-molybdène (-rhénium, sélénium, tellure, bismuth, éléments du groupe du platine); 2) le chrome dans des ophiolites; 3) les éléments du groupe du platine dans des roches ultramafiques ophiolitiques; 4) l'uranium-thorium dans du granite; 5) l'étain dans des plutons et filons granitiques; 6) le niobium, le tantale et les éléments des terres rares dans des intrusions alcalines; 7) le tungstène et le bismuth dans des filons polymétalliques; 8) le vanadium dans des schistes noirs; 9) des filons orogéniques et des substitutions; 10) le tellure dans des gîtes épithermaux et 11) l'uranium dans la tourbe.

[*Traduit par la redaction*]

INTRODUCTION

Certain minerals have long been recognized as being critical for industrial, military, medical, and recently low-carbon technologies (e.g., Price 2013; Fortier *et al.* 2017; Sovacool *et al.* 2020; Simandl *et al.* 2021). Most countries prioritize critical minerals differently owing to individual national parameters such as local resources and economies. In the United States, a critical mineral is defined by federal statute as (1) a nonfuel material that is essential to the economic and national security of the USA, (2) part of a supply chain that is vulnerable to disruption, or (3) serving an essential function in the manufacturing of a product, the absence of which would have significant consequences for the U.S. economy or national security (Presidential Executive Order No. 13817 2017). The USA currently relies on imports for 50 to 100% of 50 different critical minerals (U.S. Geological Survey 2021b). As of 2018, the U.S. Geological Survey (USGS) listed 35 critical minerals (and elements), specifically Al, Sb, As, barite, Be, Bi, Cs, Cr, Co, fluorspar, Ga, Ge, graphite, Hf, He, In, Li, Mg, Mn, Nb, platinum-group elements (PGEs), potash, rare earth elements (REE), Re, Rb, Sc, Sr, Ta, Te, Sn, Ti, W, U, V, and Zr (Fortier *et al.* 2018).

In this study, we report on the potential in Maine for resources of 20 critical minerals and elements including Be, Co, Cr, Cs, graphite, Li, Mn, Nb, PGEs, Re, REE, Sb, Sn, Ta, Te, Ti, U, V, W, and Zr. This group was selected because it focuses on metals that are known to occur in previously mined deposits, in documented (but unmined) deposits, and that may exist within minimally explored or undiscovered deposits. The last types include not only known mineral occurrences and small mines (typically without recorded production), but also areas lacking deposits that nonetheless have a speculative potential based on favourable geological, geochemical, and/or geophysical signatures. Not discussed in this report are critical minerals and elements such as arsenic, barite, and fluorspar that occur in a few deposit types in Maine but without sufficiently large tonnages or high grades to be economically viable now and in the near future, or alternatively reside in the crystal lattice of other minerals for which economic recovery is not commercially feasible.

Lacking detailed data on tonnages and grades for most of the deposits and prospects considered herein, we cannot provide a quantitative mineral resource assessment for critical minerals and elements in Maine (e.g., Singer and Menzie 2010). Such quantitative assessments also require estimates by an expert panel of economic and exploration geologists on the number of undiscovered deposits, which are currently not possible for Maine, and on the density distributions of different deposit types occurring elsewhere, which are unavailable for nearly all major metal deposits known in the state. As a result, our study is necessarily a qualitative assessment using high, moderate, and low designations, as has been done elsewhere in New England by the USGS for the Glens Falls and Sherbrooke-Lewiston 1° × 2° quadrangles (Slack 1990; Moench *et al.* 1999). In this present study, we distinguish between ore reserves (proven, indicated, and inferred) for deposits that could be mined economically under current market and technological conditions, and mineral resources that are concentrations of materials for which economic extraction of a commodity is potentially feasible, either currently or at some future time. Note that except as indicated in the cited references, data for reserves and resources are not compliant with modern exploration practices and related guidelines (e.g., NI 43-101 and JORC). Also, the resource evaluations presented herein do not consider state restrictions that may exist on exploration or mining, regardless of land status or commodity.

Throughout this paper all measurements originally reported in the Imperial system have been changed to the metric system. These changes include surface and underground dimensions as well as depths in mines and drill cores.

KNOWN DEPOSIT TYPES

Sediment-hosted manganese

Manganese is one of the most critical elements used in modern society. Its principal use is in the manufacture of steel as a purifying agent and an alloy that converts iron into steel (Cannon *et al.* 2017). Based on recent research, manganese may also serve an important role as a replacement for cobalt in rechargeable Li-ion batteries (Liu *et al.* 2021). The United States and Canada are totally dependent on foreign sources of manganese, which is imported chiefly from Gabon, Australia, South Africa, and Brazil. There are no defined U.S. domestic reserves, but some significant low-grade resources exist of which the largest known is in Maine (Cannon *et al.* 2017).

Sediment-hosted manganese deposits typically occur within marine black shales. Such deposits are abundant in weakly metamorphosed (prehnite-pumpellyite facies) Silurian shale and locally in limestone of eastern Aroostook County (Fig. 1). These deposits were first described in the early 19th Century by Jackson (1838), but little interest was shown until the late 1930s (Pavlides 1962). Due to the critical importance of manganese in steel making, and the fact that at that time the United States imported all of its manganese, in 1941 the USGS and the State of Maine began an intensive study of the deposits (White 1943). From 1942 through 1944, the Manganese Ore Company sampled by trenching many of the deposits in both the northern (Presque Isle) and southern (Houlton) areas, as well as in the central (Maple Mountain and Hovey Mountain) area, including diamond drilling of two of the deposits in the northern area. The northern, central, and southern areas are considered separate districts for descriptive purposes. There are 19 known deposits in the northern district, one in the central district, and 15 in the southern district. Dimensions of the various deposits are poorly constrained in general, owing to limited drilling and scarcity of outcrops, among other factors. Moreover, as a result of current field work in the manganese districts, lithologic settings and correlation of map units are problematic and stratigraphic revisions are thus likely. The following descriptions of the three districts are taken mainly from the older literature, with formational assignments provisionally revised on the basis of recent studies by Prof. Chunzeng Wang of the University of Maine at Presque Isle (C. Wang, written communication 2022).

The iron-manganese deposits in the northern district occur as three sedimentary lenses within and just above a limestone (White 1943) assigned herein to the Silurian New Sweden Formation. Below the surficial oxidized zone, principal manganese minerals are the Mn-carbonate rhodochrosite ($MnCO_3$) and the Mn-silicates braunite [$(Mn^{2+}Mn^{3+})_6(SiO_4)O_8$] and bementite [$Mn_7Si_6O_{15}(OH)_8$]. In places, up to 20 wt% Fe is present in hematite, magnetite, and limonite (Pavlides 1962).

The central manganese district is represented solely by the large Maple Mountain-Hovey Mountain deposits. These lenticular Mn-Fe deposits (Pavlides 1962) are contained within grey and grey-green slate of the Silurian Maple Mountain Formation. Metavolcanic rocks are closely associated with the Mn- and Fe-bearing units, but are probably older (Pavlides 1962). The deposits of the Maple and Hovey Mountains area consist mainly of Mn-silicates such as braunite, with minor Fe-rich rhodochrosite, hosted within hematitic ironstone.

The southern manganese district differs from the central and northern districts in complexity of geology, absence of igneous rocks, likelihood of numerous faults, higher degree of metamorphism, and paucity of outcrops (White 1943; Miller 1947; Pavlides 1962). Manganiferous rocks there occur in slate and locally in siliceous limestone of the Silurian Smyrna Mills Formation. The principal manganese mineral is rhodochrosite, accompanied by minor Mn-siderite, chlorite, and magnetite (Earl and Eilertsen 1962). Early studies concluded that the magnetite in these southern deposits formed during metamorphism, but a primary sedimentary or early diagenetic origin cannot be ruled out for some occurrences.

In 1949, the U.S. Bureau of Mines (USBM) became involved in studies of the Aroostook County deposits. These studies included trenching, drilling, and airborne magnetic surveys. In 1951 and 1952, the USBM conducted numerous metallurgical tests on ores from the Maple Mountain and Hovey Mountains deposits (MacMillan and Turner 1954). The ores proved to be highly refractive and not amenable to conventional ore dressing techniques such as flotation, or magnetic or gravity separation. However, the ores were amenable to leaching using a variety of acids.

An early USBM estimate of the crude ore reserves in the region amounted to 232 Mt grading 8.9 wt% Mn and 20.7 wt% Fe (Eilertsen 1952). A later USBM evaluation by Kilgore and Thomas (1982), which is the most recent, determined a resource of 260.0 Mt @ 8.87 wt% Mn for the central district (Maple Mountain and Hovey Mountain deposits), and a resource of 63.1 Mt @ 9.54 wt% Mn for the north Aroostook district (e.g., Dudley and Gelot Hill deposits). However, this total excludes much smaller deposits in the southern district (e.g., Littleton Ridge, Henderson Hill), for which estimated reserves amount to 3.7 Mt at an average grade of 7.5 wt% Mn (Miller 1947). Based on these values, a combined resource (including reserves designated in early studies) for the Aroostook County deposits is calculated here to be ~327 Mt @ 9.0 wt% Mn.

Future exploration in the Aroostook County districts would benefit by considering the two main genetic models proposed for sedimentary manganese deposits. One model, developed by Cannon and Force (1983) and Force and Cannon (1988), involves syngenetic manganese concentration along the margins of anoxic marine basins, at the redoxcline between deep anoxic to sulphidic waters and variably oxidized surface waters. A modern example may be formation of the Mn-rich sediments in Gotland Deep of the Baltic Sea (Huckriede and Meischner 1996). In this model, dissolved manganese at high concentrations in oxygen-deficient deep seawater is transported by upwelling currents to the redoxcline, where Mn-carbonates precipitate on the seafloor. Mn-silicates are also deposited below this redox interface, similarly on the seafloor, whereas Mn-oxides form above, within oxidized surface waters. The second model is based on a wholly diagenetic process, from the studies of Okita (1992) and Okita and Shanks (1992) of the giant Molango manganese deposit in southern Mexico. This deposit is the largest known in North America, containing 1.52 Gt of ore at an average grade of about 10% Mn. The ore occurs within Upper Jurassic limestone and in part of the district directly overlies black pyritic shale. The high-grade ore zone contains 30% Mn but only 3% Fe, unlike the Fe-rich manganese deposits in Aroostook County. Carbon and sulphur

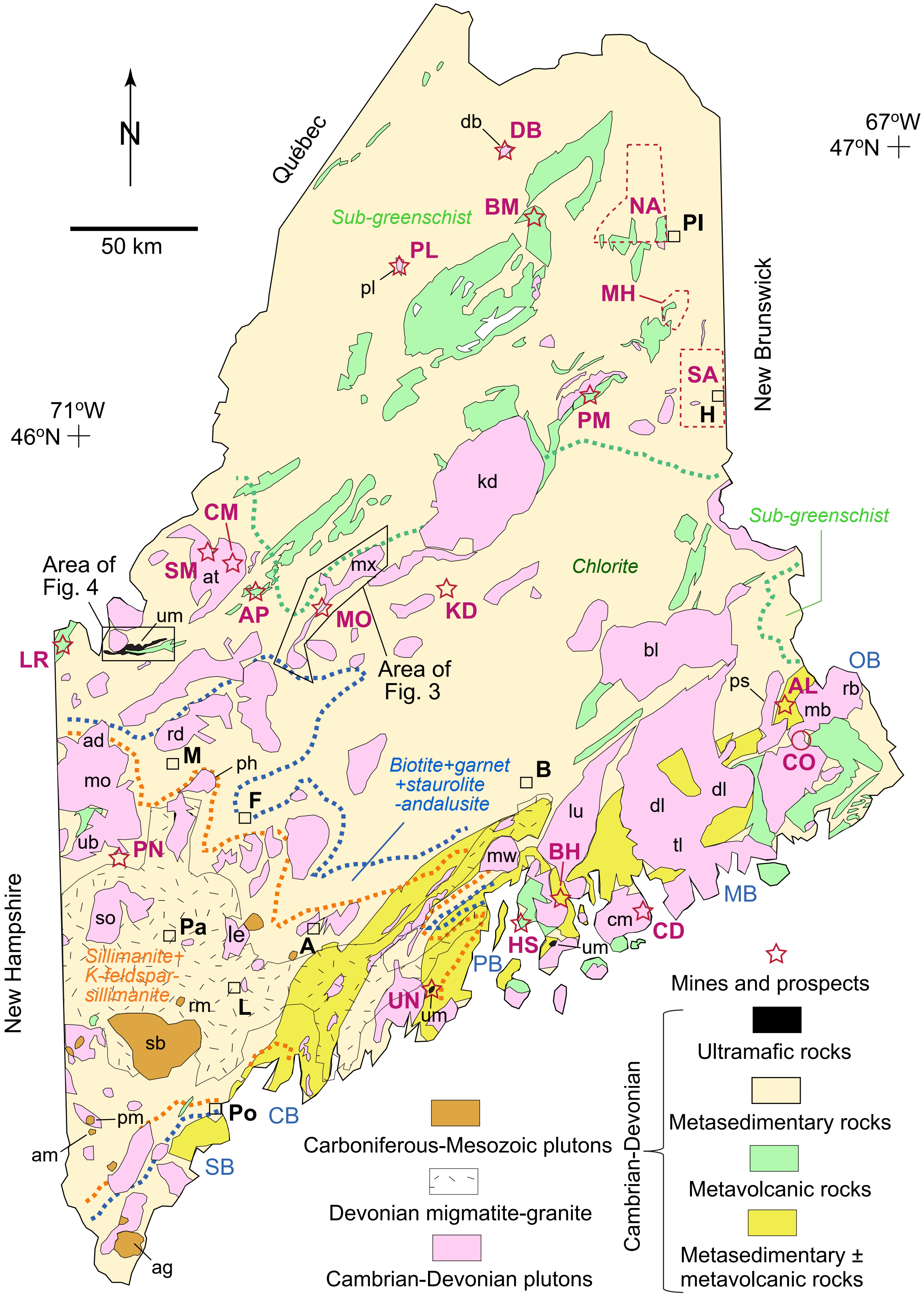
Figure 1. (next page) Simplified geologic map of Maine showing regional metamorphic zones and locations of mines and other significant mineral deposits having known concentrations of critical minerals or elements. Cambrian–Devonian plutons consist mainly of granite with subordinate gabbro; Carboniferous–Mesozoic plutons are mostly granitic or alkalic. Sedimentary (and metasedimentary) rocks are chiefly Cambrian to Devonian; not shown are small areas of Mesoproterozoic metasedimentary rocks in the western Penobscot Bay area. Volcanic (and metavolcanic) rocks are both mafic and felsic, and are dominantly Ordovician but include some Cambrian, Silurian, and Early Devonian strata together with minor sedimentary (and metasedimentary) rocks. Geology and metamorphic zones (coloured dashed lines) modified from Osberg *et al.* (1985). Faults are not shown. Abbreviations for cities and towns: A, Augusta; B, Bangor; BH, Blue Hill; F, Farmington; H, Houlton; L, Lewiston; M, Madrid; Pa, Paris; PI, Presque Isle; Po, Portland. Abbreviations for igneous plutons (some are grouped) and other igneous bodies: ad, Adamstown; ag, Agamenticus; am, Abbott Mountain; at, Attean; bl, Bottle Lake Complex; cm, Cadillac Mountain; db, Deboullie; dl, Deblois; kd, Katahdin; le, Leeds; lu, Lucerne; mb, Meddybemps; mo, Mooselookmeguntic; mw, Mount Waldo; mx, Moxie; ph, Phillips; pl, Priestly Lake; ps, Pocomoonshine; rb, Red Beach; rd, Redington; rm, Rattlesnake Mountain; sb, Sebago; tl, Tunk Lake (Catherine); ub, Umbagog; um, ultramafic rocks. Abbreviations for coastal bays: CB, Casco Bay; MB, Machias Bay; OB, Oak Bay; PB, Penobscot Bay; SB, Saco Bay. Distribution of migmatite-granite terrane, and of Sebago pluton, from Solar and Tomascak (2016). Abbreviations for mines, prospects, and important (key) occurrences, grouped by deposit type, are (1) Volcanogenic massive sulphide: BM, Bald Mountain; PM, Pickett Mountain; AP, Alder Pond; LR, Ledge Ridge; BH, Black Hawk; HS, Harborside; (2) Sediment-hosted Mn districts: MH, Maple Mountain-Hovey Mountain; NA, North Aroostook; SA, South Aroostook; (3) Porphyry Cu-Mo: CM, Catheart Mountain; SM, Sally Mountain; DB, Deboullie; PL, Priestly Lake; CO, Cooper; CD, Cadillac Mountain; (4) Mafic- and ultramafic-hosted Ni-Cu(-Co-PGE): AL, Alexander (includes Frost); KD, Katahdin; MO, Moxie; UN, Union (Warren); and (5) Pegmatitic Li-Cs-Ta: PN, Plumbago North.

isotope data for the Molango deposit, and for other large stratiform sediment-hosted manganese deposits in China and Hungary, also point to deposition in an anoxic marine basin, analogous to the model of Cannon and Force (1983), but with manganese mineralization occurring during early diagenesis in the shallow subsurface (Okita *et al.* 1988; Polgári *et al.* 1991; Okita and Shanks 1992). The carbon isotope values, in particular, indicate that rhodochrosite deposition was linked to the oxidation of organic matter.

The pyritic black shale directly below the high-grade Mn-carbonate ore zone at Molango may have played an important role in this diagenetic process, by providing dissolved organic matter (OM) for the oxidation process, when pore waters contained high concentrations of OM prior to lithification. More recent studies of the Úrkút deposit in Hungary also suggest that manganese mineralization there involved microbes (Polgári *et al.* 2012). Application of the organic matter oxidation model to the Aroostook County manganese districts is problematic, however, because of the apparent scarcity of black shale within the host sedimentary sequence (e.g., Pavlides 1962), but outcrops and drill core are very limited in the northern and southern districts, where a siliceous limestone unit directly underlies the manganese deposits. However, if the microbial model is correct, then black shale within the manganese ore sequence is not required, hence only a limestone host is needed. Regardless of the applicable ore-forming model, these two districts have a high potential for the discovery of additional manganese deposits, including low-Fe deposits similar to Molango occurring within one or more limestones of the district. Also possible, although less likely from our perspective, are Mn-carbonate or Mn-oxide deposits occurring in the Smyrna Mills Formation. Potential also exists for more manganese deposits in hematitic ironstone of the central district (Maple and Hovey Mountains area) but the economic viability of such Fe-rich deposits is uncertain. Sediment-hosted manganese deposits in Silurian strata of the Woodstock area of New Brunswick ca. 19 km east of Houlton were mined for iron in the 19th Century (Miller 1947). This area is currently being explored by a Canadian company, Manganese X Energy Corporation, which has announced measured and indicated reserves for the Battery Hill deposit of 34.9 Mt grading 6.42 wt% Mn and 10.7 wt% Fe, and an additional inferred reserve of 25.9 Mt grading 6.66 wt% Mn (Ténière *et al.* 2021). Incorporating these reserves with the resources compiled by Way (2014) for the Woodstock area (six deposits) yields a total of 212 Mt @ ~8 wt% Mn. Metallurgical testing of manganese in the Battery Hill deposit, using a novel leaching process to produce ultrapure $MnSO_4$, is reportedly encouraging with manganese recoveries of greater than 85% being achieved (Manganese X Energy Corporation 2021). It is unclear whether this metallurgical technology could be applied successfully to the manganese deposits of Aroostook County.

Volcanogenic massive sulphide

Maine has a lengthy history of mining volcanogenic massive sulphide (VMS) deposits (e.g., Lepage *et al.* 1991; Beck 2012; Marvinney 2015; Marvinney and Berry 2015; Slack 2019; Fig. 1). These deposits are well known in terms of geological setting and modes of formation, based on extensive studies of ancient and modern examples (Shanks and Thurston 2012, and references therein). In addition to common base (Cu, Zn, Pb) and precious (Ag, Au) metals, VMS deposits may contain appreciable amounts (tens to thousands of ppm) of numerous critical elements including As, Bi, Cd, Co, Ga, Ge, In, Mo, Sb, Se, Sn, Te, and PGEs (e.g., Monecke



et al. 2016). Early mining of VMS deposits in Maine took place chiefly from 1878 to 1882 at very small deposits hosted within Cambrian volcanic and volcaniclastic rocks on or near the coast (Emmons 1910; Hussey *et al.* 1958; Lepage *et al.* 1991). During the period 1968 to 1972, much larger deposits were mined in the same Cambrian volcanic belt at the Black Hawk (Second Pond) Zn-Cu-Pb-Ag deposit that prior to production contained 0.9 Mt @ 7.4% Zn, 0.9% Cu, and 0.4% Pb, and at the Harborside (Callahan) Zn-Pb-Ag-Au deposit that had 0.7 Mt @ 5.5% Zn, 1.3% Cu, 0.5%

Pb, and 14 g/t Ag (Beck 2012; Marvinney and Berry 2015). From the mid-1970s to the mid-1980s, four other significant VMS deposits were discovered in Ordovician volcanic rocks of western and northern Maine (Beck 2012), including Bald Mountain (30.0 Mt @ 1.0 wt% Cu, 1.0 wt% Zn, 14 g/t Ag, 0.5 g/t Au; Slack *et al.* 2003), Ledge Ridge (4.0 Mt @ 2.0 wt% Zn, 1.0 wt% Cu, 1.0 wt% Pb, 17 g/t Ag, 0.6 g/t Au), Alder Pond (3.4 Mt @ 9.0 wt% Zn, 2.2 wt% Cu, 0.5 wt% Pb, 84 g/t Ag), and Pickett Mountain (measured + inferred resources of 6.3 Mt @ 9.1 wt% Zn, 3.8 wt% Pb, 1.1 wt% Cu, 102 g/t Ag, 0.7 g/t Au; Wolfden Resources Corporation 2021). The last deposit, previously named Mount Chase, has been studied recently by McCormick (2021) and is the subject of ongoing exploration and economic evaluation by Wolfden Resources Corporation. Early exploration in the 1960s in western Maine for VMS-type mineralization identified additional areas of interest, such as the Squirtgun prospect where one drill hole intersected felsic tuffs with 3.3 wt% Cu and 31.8 g/t Ag, together with appreciable Zn, over an interval of 4.9 m (Young 1968).

Economically recoverable critical metals in VMS deposits are limited. Importantly, on a global scale few of these metals are recovered from VMS deposits by current mining and processing methods, except as byproducts. With respect to cobalt, VMS deposits constitute less than 1% of global production, and each typically contains at most 0.3 wt% Co (Slack *et al.* 2017). A very large North American example is the Triassic Windy Craggy VMS deposit in British Columbia (297 Mt @ 1.38 wt% Cu) that has an average of 820 ppm Co (Peter and Scott 1999). Importantly, at Windy Craggy discrete Co-bearing minerals like cobaltite are rare, suggesting that the majority of the cobalt there resides in abundant pyrite and lesser pyrrhotite (Peter and Scott 1999), neither of which would likely be recovered and processed for cobalt during potential mining of copper, although recent technology may make this feasible in some cases (Luganov *et al.* 2020). The same interpretation can be applied to the Bald Mountain deposit in Maine, which lacks cobaltite or other Co-rich minerals but has up to 1400 ppm Co in bulk massive sulphide (pyrite ± pyrrhotite ± chalcopyrite ± sphalerite ± arsenopyrite ± galena) and as much as 0.25 wt% Co in pyrite, as determined by electron microprobe analysis (Slack *et al.* 2003). Also present at Bald Mountain are elevated bulk values for other critical metals including arsenic and antimony (up to 1.52 wt% and 1670 ppm, respectively); maximum values of others in massive sulphide facies of the deposit are relatively low (Bi, 26.3 ppm; In, 6.8 ppm; Sn, 58 ppm; Te, 64 ppm)(Slack *et al.* 2003). The mineralogical residence of arsenic and antimony is complex, and includes not only separate grains of arsenopyrite and tetrahedrite but also probable crystallographic substitutions of arsenic and antimony in pyrite and sphalerite, and locally in pyrrhotite (Slack *et al.* 2003). Bulk analysis of a representative composite sample of high-grade sulphide-rich rock from the Pickett Mountain deposit (A-Z Mining Professionals Limited 2020) shows relatively high average contents of As (953 ppm), Cd (246 ppm), Bi (81 ppm), and W (518 ppm); the cadmium and tungsten, and possibly bismuth, probably do not reside in pyrite, hence these critical elements could be recovered as byproducts during mining. Excluding Bald Mountain and Pickett Mountain, no published data are available on the contents of critical metals in the other VMS deposits of Maine.

Porphyry copper-molybdenum

Porphyry-type Cu-Mo deposits are major global sources of Co, Mo, Re, Se, and Te and locally contain trace to minor amounts of other critical metals and minerals including As, Bi, fluorite, PGEs, and W (John *et al.* 2010; John and Taylor 2016). Rhenium concentrations in such deposits and in granite-related Mo-rich veins are important because this metal is fundamental in the manufacture of high-temperature superalloys for jet aircraft engines and of Pt-Re catalysts for the petroleum industry (John *et al.* 2017). Numerous porphyry-type deposits and prospects are documented in Maine (Hollister *et al.* 1974; Ayuso 1989; Fig. 1). The best known and most explored is at Catheart Mountain, a Cu-Mo deposit hosted in a Devonian quartz-porphyry pluton that intrudes a larger Ordovician body of the Attean Quartz Monzonite (Ayuso 1989). This deposit has not been delineated fully in terms of tonnage and grade, but an early estimate suggested an endowment of 20 to 25 Mt @ 0.25 wt% Cu and 0.04 wt% Mo (F.C. Canney *in* Nowlan 1989). Sulphide mineralization at Catheart Mountain comprises disseminations and fracture-fillings of pyrite, chalcopyrite, molybdenite, and rare bornite and stannite in a gangue of quartz, sericite, K-feldspar, and local albite and carbonate (Atkinson 1977; Ayuso 1989). Typical whole-rock metal concentrations for entire drill cores, averaged over hundreds of metres, are 1000 to 2500 ppm Cu and 100 to 500 ppm Mo; the highest values for individual (separate) drill cores are 3600 ppm Cu over 240.5 m and 1100 ppm Mo over 135.6 m (Atkinson 1977). Wall-rock alteration of the host porphyry is characterized by an inner potassic zone and outer phyllic, argillic, and propylitic zones (Schmidt 1974; Atkinson 1977). Reconnaissance data for rhenium in molybdenite separates from Catheart Mountain ($n = 9$) show concentrations of 80 to 280 ppm with an average of 146 ppm (Atkinson 1977); this range and average are low relative to those of many porphyry Cu-Mo deposits worldwide (John and Taylor 2016) based on existing data that indicate, on a global scale, that molybdenite in porphyry molybdenum deposits and molybdenite-rich quartz veins have low contents of rhenium (typically <200 ppm) compared to the those in porphyry copper deposits that typically contain 1000 to 3000 ppm Re (John *et al.* 2017). In addition to rhenium, analysis of eight pyrite separates from the Catheart Mountain deposit indicates the presence of elevated bismuth and tungsten, up to 394 and 182 ppm, respectively (Atkinson 1977).

The other porphyry-type deposits in the state have not been described in detail. The Sally Mountain Cu-Mo deposit, ca. 10 km west of the Catheart deposit, has a similar style of mineralization dominated by disseminated and veinlet-hosted chalcopyrite and lesser molybdenite within a Devonian quartz-porphyry pluton (Ayuso 1989). A regional geochemical survey of stream sediment by Nowlan (1989) shows areas of anomalously high copper and molybdenum that extend beyond the known bedrock sites of porphyry-type Cu-Mo mineralization, suggesting that the potential for this deposit type is spatially larger than was recognized previously.

In northern Maine, the Devonian syenite pluton at Deboullie contains weakly developed Cu-Mo mineralization within pyrite-bearing quartz-porphyry dikes (Ayuso and Loferski 1992; Loferski and Ayuso 1995). To the south, the Priestly Lake granodiorite pluton, of Devonian age, locally has quartz-molybdenite veins up to 15 cm wide and fracture-controlled molybdenite in granodiorite (Ayuso and Shank 1983). A different type of molybdenum occurrence is found in northeastern Maine, consisting of molybdenite with pyrite and minor chalcopyrite and arsenopyrite in a calc-silicate rock near a small granitic pluton (Canney *et al.* 1961; Burbank and Miller 1965). On and near the coast, minor disseminated and vein-hosted molybdenite occurrences are known within the Cooper, Cadillac Mountain, and Catherine (Tunk Lake) plutons (Burbank 1965; Young 1968; Hollister *et al.* 1974), in parts of the Bottle Lake Complex (Post *et al.* 1967; Nowlan and Hessin 1972), and elsewhere in the state (Hess 1908). Other areas in Maine that may have porphyry Cu-Mo potential are described by Schmidt (1978).

Mafic- and ultramafic-hosted nickel-copper (-cobalt-platinum group elements)

Mafic and ultramafic igneous intrusions that contain significant deposits of nickel and copper may have elevated concentrations of cobalt and/or PGEs that can be recovered as byproducts during mining and processing (Slack *et al.* 2017; Zientek *et al.* 2017). In the United States, cobalt and PGEs are defined as critical elements because of use in rechargeable lithium batteries and catalytic converters, respectively, and minimal domestic production. Three mafic- and ultramafic-hosted Ni-Cu(-Co-PGEs) deposits in Maine, known for many decades, have been moderately explored by several mining companies. Except for iron production in the 19th Century from the large Katahdin deposit east of Greenville (Fig. 1), no other deposits of this type in Maine have been mined for other metals such as nickel, copper, cobalt, or PGEs.

The Katahdin (also known as Ore Mountain) deposit was reportedly used by the native population since 4000 B.C. as a source of red pigment used for decorative purposes. The gossan of this deposit was mined intermittently from 1848 to 1890 and smelted on site at the nearby community of Katahdin Iron Works; the underlying hypogene pyrrhotite body, estimated to total more than 200 Mt @ ~45 wt% Fe (Slack 2019), was not mined. In 1976, the Superior Mining Company did deep drilling and conducted metallurgical testing to develop a method to separate the cobalt from the nickel and copper. As a result of this work, a resource of 60 Mt with a grade of 0.10 wt% Co, 0.13 wt% Ni, and 0.07 wt% Cu was defined, with reported metallurgical recoveries of 65% for Co and Ni, and 80% for Cu (Beck, review of landowner files, 1980–2000). The Katahdin deposit, ca. 600 m long and 120 m wide on average, consists of massive (>75 vol%) to disseminated or interstitial pyrrhotite with minor (<2 vol%) chalcopyrite in a syntectonic, Acadian norite intrusion, the 405.6 ± 3.3 Ma Ore Mountain pluton (Miller 1945; Houston 1956; Bradley and Tucker 2002).

The Union-Warren deposits near the coast (Fig. 1) form two main mineralized bodies within a ~13-km-long, northeast-striking zone of Devonian basic rocks that includes peridotite in the northeast and gabbro and diorite in the southwest. Host strata are chiefly sulphidic black shale of the Ordovician Penobscot Formation. Sulphide minerals are dominantly Ni-rich pentlandite, chalcopyrite, and pyrrhotite, together with minor niccolite and cobaltite; magnetite is a common accessory (Young 1968; Rainville and Park 1976). In 1965, the No. 5 deposit was discovered in Warren using a variety of geophysical techniques. In 1980, the Boliden Company conducted geochemical and additional geophysical surveys (F.M. Beck files, 1980-2000). In 1989, Black Hawk Mining Company did additional drilling and mine planning. A stringent mining ordinance that was adopted by the Town of Warren in 1992 apparently led Black Hawk to give up its leases in the mid-1990s. No work has been done on the properties since then. At the time of Boliden's work, proven and probable open-pit reserves were reported to be 13.6 Mt grading 0.925 wt% Ni, 0.423 wt% Cu, and 0.08 wt% Co (Boliden reports in F.M. Beck files).

The Black Narrows deposit in west-central Maine (Fig. 2) is within the southern part of the elongate Moxie mafic-ultramafic pluton of Early Devonian age (406.3 ± 3.8 Ma; Bradley *et al.* 2000). Early exploration in the area, carried out by several companies from 1948 to 1961, included airborne and ground geophysical surveys, and diamond drilling of six holes by Beers and three by Freeport Sulfur Company, none of which intersected significant nickel, cobalt, or copper mineralization (Beers *et al.* 1962; Beck, purchased Knox files, 1980–2000). Reconnaissance data for a limited number of rock samples from the Moxie pluton show relatively low total PGE concentrations of ca. 250 ppb (Paktunc 1990). The dominant igneous rocks are troctolite and olivine gabbro, with local peridotite, dunite, norite, and gabbro (Visher 1960; Espenshade 1972; Thompson 1984). Sulphide mineralization consists of pyrrhotite with minor pentlandite and chalcopyrite hosted within an altered peridotite. Other Ni-Cu sulphide prospects at Big Indian Pond and Burnt Nubble, in the northern part of the pluton, occur in troctolite and olivine gabbro (Fig. 2).

The Alexander and nearby Frost Ni-Cu-Co prospects in eastern Maine (Fig. 1) comprise massive and disseminated pyrrhotite with minor chalcopyrite in a small gabbroic body east of the large Pocomoonshine Gabbro that intrudes sulphidic metasedimentary rocks of the early Paleozoic Cookson Formation (Young 1963; Thompson 1984; U.S. Geological Survey 2021a). The gabbro-hosted St. Stephen Ni-Cu

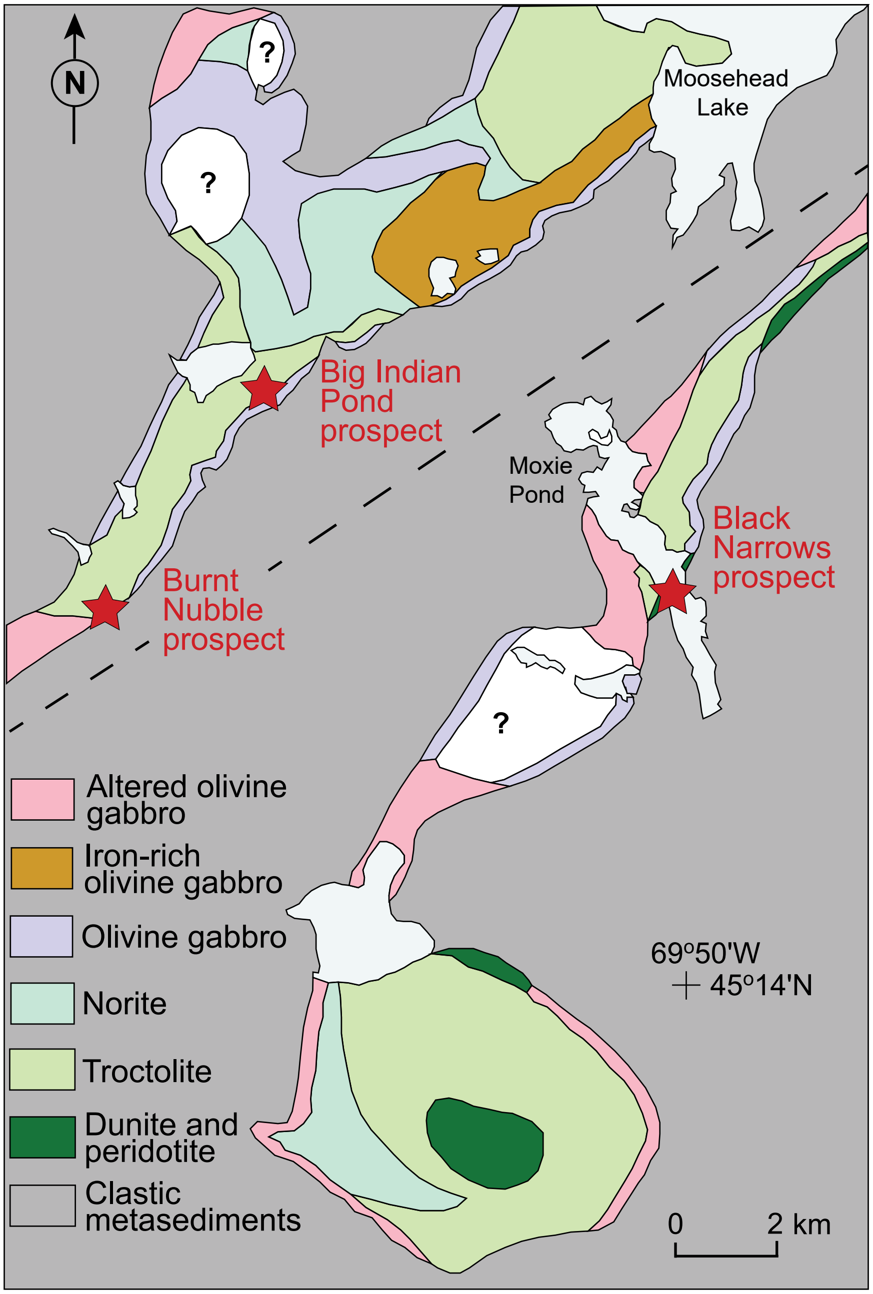


Figure 2. Geologic map of Moxie pluton and surrounding area showing locations of Cu ± Ni deposits and prospects. Regional geology modified from Osberg *et al.* (1985); detailed pluton geology from Thompson (1984).

deposit in southwestern New Brunswick, ca. 50 km to the northeast, contains reserves of 1.0 Mt @ 1.05 wt% Ni and 0.53 wt% Cu (Paktunc 1986, 1987), and in places as much as 0.24 wt% Co with up to 863 ppb Pd and 270 ppb Pt (Continental Nickel Ltd. 2012).

A high potential is proposed here for Ni-Cu(-Co-PGE) deposits in mafic/ultramafic dike-sill complexes. The model of Schulz et al. (2014) suggests that this deposit type, which is widespread worldwide and includes giant orebodies such as those in Noril'sk in Russia, Voisey's Bay in Labrador, and Jinchuan in North China, forms preferentially in mafic dikes or sills that served as conduits to overlying large intrusions. The very elongate nature of the Moxie pluton is similar to that of the pluton hosting the Jinchuan deposit, which contains 515 Mt of ore at an average grade of 1.06% Ni and 0.67% Cu, with byproduct Co and PGEs (Chai and Naldrett 1992; Song *et al.* 2009), and thus strongly suggests formation as a dike complex and a favourable setting for Ni-Cu-(Co-PGE) mineralization. Moreover, low nickel contents in olivine (<0.1 wt % NiO) for all but the most forsterite-rich compositions ($\leq Fo_{80}$) in the Moxie deposits (Thompson 1984) are consistent with early removal of nickel in sulphides, by which interaction of the igneous melt with sulphide-rich country rocks (e.g., black shale) results in sulphur saturation of the magma followed by segregation of sulphides into basal zones or conduits (Naldrett 1989, 1992). Because of high metal grades, conduit-type deposits are now recognized as having greater economic potential than basal deposits like those in the Duluth Complex of Minnesota (e.g., Schulz *et al.* 2014). In a reconnaissance study of peridotite in northern Michigan, electron-microprobe analysis documented low-Ni olivine in this peridotite that suggested early sulphur saturation of the magma and hence a potential for Ni-Cu mineralization at depth (Klasner *et al.* 1979). This report led, in part, to the 2002 discovery within this peridotite of the high-grade Eagle Ni-Cu-Co orebody in the Upper Peninsula of Michigan (Ding *et al.* 2010, 2012). At the end of 2016, Eagle operations had produced 1.67 Mt of ore @ 3.97 wt% Ni and 3.19 wt% Cu, with then-unmined reserves (including for the East Eagle deposit) of 4.82 Mt @ 2.8 wt% Ni, 2.4 wt% Cu, 0.1 wt% Co, 0.3 g/t Au, 3.4 g/t Ag, 0.7 g/t Pt, and 0.5 g/t Pd (Clow *et al.* 2017). The Eagle mine is the largest producer of nickel in the United States.

Pegmatitic lithium-cesium-tantalum

The critical elements lithium, cesium, and tantalum have diverse uses including for rechargeable batteries, ceramics, and glass; for high-pressure and high-temperature well drilling in oil and gas production and photoelectric cells; and for gas turbines, mobile phones, and personal computers (Bradley *et al.* 2017a; Jaskula 2021; Tuck 2021; Callaghan 2021). Lithium-cesium-tantalum (LCT) pegmatites, one of three compositionally defined categories of granitic pegmatite, account for about one-fourth of the world's lithium production and nearly all of the cesium and tantalum production (Bradley *et al.* 2017b). In addition to enrichments in lithium, cesium, and tantalum (whence the acronym), LCT pegmatites are also typically enriched in rubidium, beryllium, and tin. Lithium enrichment is generally indicated by the presence of spodumene [$LiAlSi_2O_6$], petalite [$LiAlSi_4O_{10}$], lepidolite [$(K,Rb)(Li,Al)_2(Al,Si)_4O_{10}(OH,F)_2$], montebrasite [$LiAl(PO_4)(OH,F)$], and/or elbaite [$Na(Li_{1.5}Al_{1.5})Al_6Si_6O_{18}(BO_3)_3(OH)_4$]; cesium by pollucite [$(Cs,Na)_2(Al_2Si_4O_{12})\cdot 2H_2O$]; and tantalum, most commonly, by minerals of the columbite-tantalite group [$(Fe,Mn)(Nb,Ta)_2O_6$].

Maine's many LCT pegmatites have been mined for gemstones, mineral specimens, feldspar, muscovite, quartz, and beryl, with minor spodumene and pollucite produced as co-products in a few cases (Cameron *et al.* 1954; King and Foord 1994; King 2000). As of October 2021, the database of Mindat.org listed 48 pegmatites in Maine with spodumene, 17 with tantalite, and 23 with pollucite. Maine's LCT pegmatites occur in six clusters, which Wise and Francis (1992) termed "series" (Fig. 3). Available geochronology (Bradley *et al.* 2016; D.C. Bradley, unpublished data) shows that the six series formed during at least four, and probably as many as six, middle- to late Paleozoic episodes: the Waldoboro series before 356 Ma, the Phillips series before 324 Ma, the Rumford series before 295 Ma, the Topsham series at 273 Ma, the Oxford series at 264 Ma, and the undated Georgetown series. Pegmatites of the Waldoboro series were described by Sundelius (1963). The Oxford, Rumford, and Topsham series have been the most thoroughly investigated (e.g., Tomascak *et al.* 1998; Brown and Wise 2001; Roda-Robles *et al.* 2015; Simmons *et al.* 2016, 2020). Pegmatites of all these series are late orogenic bodies that were emplaced during the staged assembly of Pangea (Bradley *et al.* 2016).

Until a few years ago, the potential for significant lithium resources in Maine appeared to be low. Spodumene occurs in various pegmatites of the Rumford series in the Newry area, one being the Spodumene Brook locality on Plumbago Mountain. Now known as Plumbago North, this pegmatite contains spodumene crystals up to 11.5 m in length (Simmons *et al.* 2020). Also present are montebrasite, beryl, cassiterite, pollucite, almandine-spessartine garnet, fluorapatite, and columbite-group mineral species. Exploratory drilling has outlined a preliminary lithium resource of 10 Mt with an average Li_2O content of 4.68 wt% (Simmons *et al.* 2020). This is undoubtedly the most important critical mineral resource yet discovered in Maine, and if confirmed by more detailed exploration (including compliance with NI 43-101 guidelines), it may be the 10th-largest resource of pegmatite-hosted lithium in the world. Importantly, the Newry area shows promise for additional lithium discoveries; it is well mapped and hosts a number of LCT pegmatites. Giant spodumene crystals, reminiscent of those at Plumbago North, have also been reported from the Martin (6.3 m long), Kinglet (3 m), and Main (3 m) pegmatites, all in the Newry area (Shainin and Dellwig 1955; Barton and Goldsmith 1968; King and Foord 2000). None of Maine's other five LCT pegmatite series has yet shown comparable evidence of world-class lithium resources.

Known cesium resources in Maine are insignificant. In the 1800s and 1900s, pollucite was mined at times from three pegmatites of the Oxford series (e.g., Bennett), and from the Dunton pegmatite of the Rumford series. Total production of cesium, however, was only about 15 t (King and Foord 2000). For comparison, the original cesium reserve at the giant Tanco LCT pegmatite in Manitoba was over 350 000 t at an average grade of 23.3 wt% Cs_2O (Černý and Simpson 1978). Despite the presence of Ta-bearing minerals in a number of Maine pegmatites (e.g., tantalite-Mn [$MnTa_2O_6$] and tantalowodginite [$Mn(Ta,Sn)Ta_2O_8$]; King and Foord 2000), these minerals commonly occur as relatively small (<6 cm), isolated crystals (authors' observations). There appears to be no significant past production or resource potential for tantalum in the state.

Additional research will be needed to better evaluate Maine's pegmatites, with special attention to undiscovered lithium endowment. Important issues include evaluating known pegmatites, finding new pegmatites in areas where others are known, and elucidating the origins of each of the pegmatite fields. The last issue can be framed this way: why did the LCT pegmatites form in six geographically distinct clusters during an approximately 100 m.y. interval? Although the Rumford pegmatite series has the greatest potential for lithium, most past research on the mineralogy

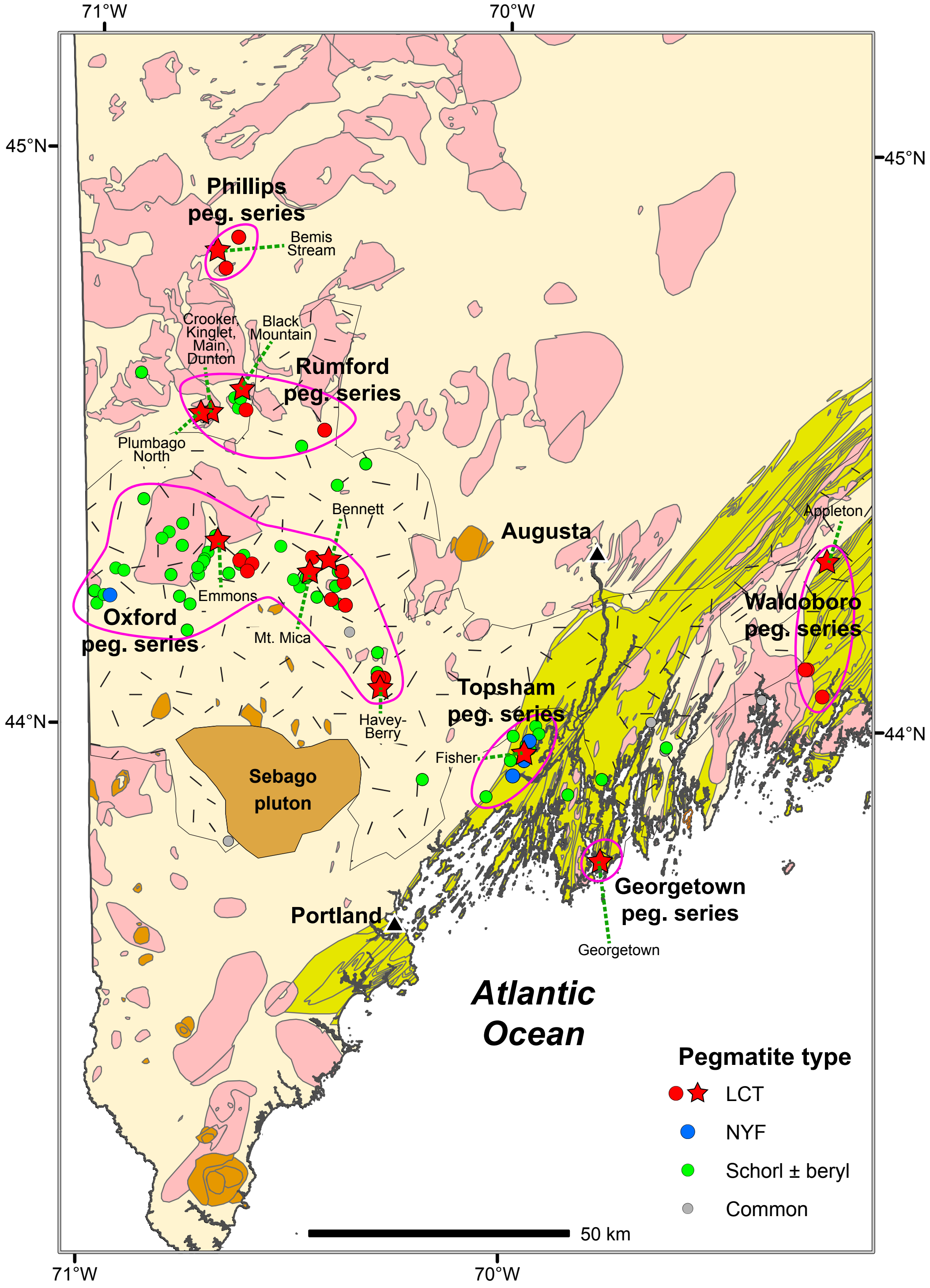


Figure 3. Geologic map of western Maine showing distribution of LCT and other granitic pegmatites. Abbreviations: peg., pegmatites; LCT, lithium-cesium-tantalum; NYF, niobium-yttrium-fluorine. Various pegmatite series typically include more than one type of pegmatite. Geology from Figure 1; note hachured area that represents Devonian granite-migmatite terrane. Pegmatite locations modified from MRDS mineral deposit database of the U.S. Geological Survey.

and origins of Maine pegmatites has focused on the substantially younger Oxford series. Three hypotheses have been proposed that bear on the genesis of the Oxford pegmatites. In the "parental granite" model, LCT pegmatites are highly fractionated offshoots from a granite pluton (Trueman and Černý 1982). The problem with this model, as applied to western Maine, is that there are no identified plutons with ages close to the 264 Ma zircon age of the Mt. Mica pegmatite (Bradley *et al.* 2016). The same problem also applies to the other five LCT pegmatite series in Maine: a lack of age matches between the numerous, tightly dated plutons and the few tightly dated pegmatites. An alternative, the "direct anatexis" model, interprets LCT pegmatites as the products of low-degree partial melting during anatexis (Webber *et al.* 2019). In this scenario, the Oxford pegmatites formed as a result of decompression melting of previously formed migmatites, the melting being triggered by post-collisional unroofing, with additional heat supplied from below during initial rifting at the onset of Pangea's breakup (Webber *et al.* 2019). However, these special circumstances cannot account for any of Maine's five older LCT pegmatite series. A third hypothesis follows a very different thread. As proposed by Bradley (2019) and amplified by Hillenbrand *et al.* (2021), this model postulates that LCT pegmatites form below salars in active orogenic belts, where downward-circulating brines enriched in lithium, boron, and other fluxing elements interact with orogenic magmas. This process is consistent with the reconstructed paleolatitude of Maine at 264 Ma, which puts Mt. Mica in arid latitudes where salars exist today. Therefore, much depends on reconstructing the paleolatitudes of what is now western Maine during the interval of LCT pegmatite formation. Continued research on these genetic models is needed, integrating constraints from all six of Maine's LCT pegmatite series.

MINIMALLY EXPLORED AND UNEXPLORED DEPOSIT TYPES

Chromium and platinum-group elements in ophiolites

Maine is unique among New England states in having a nearly complete ophiolite sequence. The Boil Mountain ophiolite in western Maine (Fig. 4), the largest such body known in the eastern U.S., is ca. 1500 m thick and has a spatial extent of up to 30 km. Boudette (1982, 1991) distinguished three main intrusive facies of the ophiolite: (1) a lower serpentinite composed of variably altered harzburgite, dunite, and websterite; (2) a middle and upper sequence of gabbro, epidiorite, and pyroxenite; and (3) semi-concordant bodies of tonalite. The ophiolite apparently lacks a sheeted dike complex. Overlying the ophiolite are abundant felsic metavolcanic rocks, in addition to mafic metavolcanic rocks, which together constitute the Jim Pond Formation. The lower contact with the Chain Lakes Massif is tectonic, whereas the upper contact with the Jim Pond Formation is conformable (Boudette 1982, 1991). U–Pb zircon geochronology indicates that the ophiolite was emplaced in the Early Ordovician at 477 ± 6 Ma (Gerbi *et al.* 2006). The ophiolite is cut both by thrust faults and high-angle faults (Osberg *et al.* 1985; Moench *et al.* 1995). Geochemical data suggest formation in a supra-subduction zone (SSZ) setting related to a backarc environment, and not in a mid-ocean ridge setting (Coish and Rogers 1987; Gerbi *et al.* 2006). Widespread serpentinized ultramafic rocks have lherzolite, websterite, and harzburgite protoliths; dunite protoliths are inferred locally.

Chromium

Numerous industries rely on chromium for diverse uses that chiefly involve stainless steel and superalloys. As of 2020, the United States was totally dependent on foreign sources of this critical metal (U.S. Geological Survey 2021b). In the Boil Mountain ophiolite, layered chromite-rich rock (chromitite) occurs within ultramafic rocks at the base of the ophiolite in the Blanchard Pond area (Moench *et al.* 1999), but with an unknown thickness and extent. Concentrations of chromite are also present, together with magnetite, in amphibolite in the Arnold Pond area to the northeast (Harwood 1973). This latter occurrence was interpreted by Moench *et al.* (1999) as a tectonic block of the ophiolite encased in mélange of the Hurricane Mountain Formation; other chromitite occurrences in this general area may be large xenoliths within younger granite. Nowlan *et al.* (1987, 1990a) reported high chromium contents of up to 7000 ppm in stream sediments in the Boil Mountain region, but these high values reflect in part glacial dispersion from ophiolite up to 160 km to the northwest in the Thetford mines area of southeastern Québec.

Importantly, the SSZ setting of the Boil Mountain ophiolite is considered more favourable than mid-ocean ridge ophiolites for containing economic deposits of chromium and PGEs, as discussed by Yumul and Balce (1994) and Prichard and Brough (2009). Deposits of chromium and PGEs in ophiolites are generally very small and thus not commercially viable (Foose 1991; Mosier *et al.* 2012; Zientek *et al.* 2017). However, some ultramafic bodies in this setting may have significant amounts of ore, such as within the Zambales ophiolite in the Philippines (Zhou *et al.* 2000; Yumul 2001; Zhang *et al.* 2020) that in total contain 27.0 Mt of high-grade chromite (Mosier *et al.* 2012). Another example is a chromitite orebody at the base of the Oman ophiolite that is several hundred metres in diameter and ca. 50 m thick (Rospabé *et al.* 2019).

Processes that post-date the crystallization of ophiolitic ultramafic rocks are also important to consider in evaluating potential for chromium resources. Tectonic overprints such as faults and shear zones, which are reported in the Boil Mountain Complex (Moench *et al.* 1995), can localize and concentrate chromite into large bodies. One example is from the Vourinos ophiolite in Greece where the richest chromite ores, exploited at the Xeerolivado mine, occur in schlieren zones that represent the highest degree of deformation within the ophiolite complex (Rassios *et al.* 2020).

Platinum-group elements

Platinum-group elements have diverse uses including in the manufacture of catalytic converters, fertilizers, chemicals, fiberglass, jewelry, and computers, and in the refining of crude oil (Zientek *et al.* 2017). As of 2020, the U.S. had a 79% net reliance on foreign sources of PGEs; sole domestic production is from the layered mafic-ultramafic Stillwater Complex in Montana. Platinum and palladium contents of

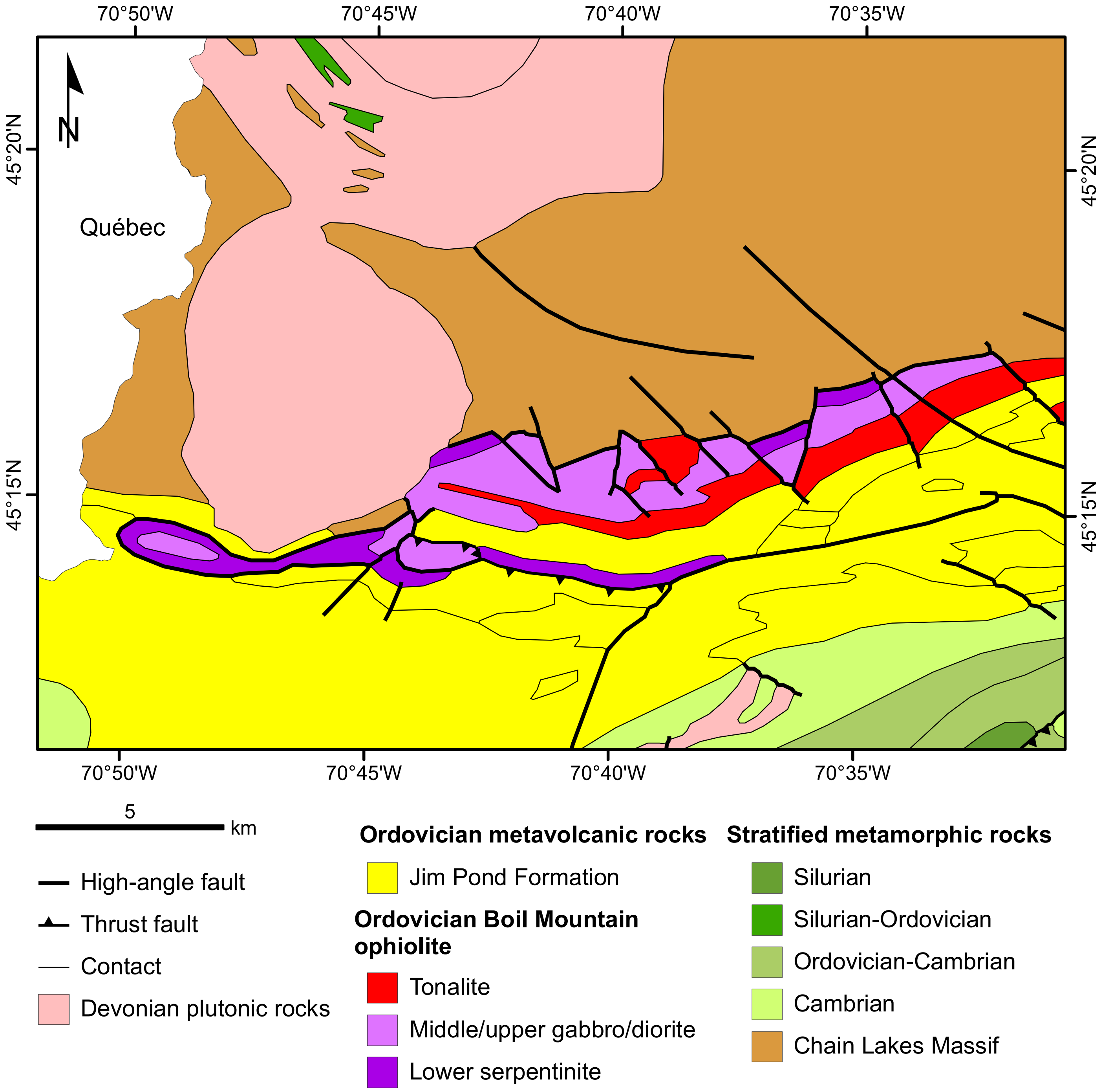


Figure 4. Simplified geologic map of Boil Mountain ophiolite and surrounding region, modified from Boudette (1982) and Osberg *et al.* (1985). Internal contacts shown within plutonic bodies and groups of stratified rocks separate different units as identified in Osberg *et al.* (1985).

ophiolite-hosted chromitites are typically very low (<40 ppb Pt and <18 ppb Pd, respectively), whereas Ir and Ru can be relatively high (up to ca. 350 ppb each) (Mosier *et al.* 2012). Importantly, sulphide-rich chromitites—which are uncommon globally—may have very high platinum and palladium concentrations, in some cases totaling more than 20 ppm (Economou-Eliopoulos 1996; Tsoupas and Economou-Eliopoulos 2008; Prichard and Brough 2009). In the Zambales ophiolite, Philippines, ore-grade values of PGEs in chromite bodies hosted within cumulate peridotites and dunite pods contain up to 550 ppb Ir, 1100 ppb Ru, 760 ppb Rh, 5960 ppb Pt, and 8350 ppb Pd (Bacuta *et al.* 1990). In the central Advocate ophiolite, Newfoundland, total PGE values in chromitite and dunite are up to 1028 and 216 ppb, respectively (Escayola *et al.* 2011).

A detailed study of the Leka ophiolite in Norway by Pedersen *et al.* (1993) identified high PGEs both in chromitites and enclosing ultramafic rocks. Chromitites within orthopyroxenite veins average 4.77 ppm PGEs + Au (Pt>Pd), with maximum values of 4.6 ppm Pt and 2.7 ppm Pd; separate sulphide-bearing layers within olivine cumulate zones have up to 4 ppm total PGEs (Pd>Pt). Based on these data and local geological relationships, Pedersen *et al.* (1993) suggested that exploration for PGE deposits in ophiolites (1) should not focus solely on chromitites but also on ultramafic rocks just above the chromitites; (2) that if chromitites are absent, then sampling should be done close to the base of macrorhythmic cumulate units; and (3) that Pt may be preferentially enriched within or near the central parts of the magma chambers. Serpentinized ophiolitic dunites, such as those in the Zambales ophiolite, contain up to 3.7 ppm Pt + Pd that likely reflect remobilization and concentration during the serpentinization process (Yumul 2001). Importantly, these PGE-rich serpentinized dunites typically are volumetrically much larger than tectonically emplaced podiform chromitites, and hence have greater economic potential for exploitable PGEs.

Reconnaissance sampling of serpentinized ultramafic rocks from the base of the Boil Mountain ophiolite in the Blanchard Pond area ($n = 45$) revealed up to 150 ppb Pt and 350 ppb Pd from a zone ~1 km long and 50 m thick (Foose 1998). Importantly, however, samples of chromitite that occur in the Blanchard Pond and Arnold Pond areas (Harwood 1973; Moench *et al.* 1999) were not collected for analysis. Nonetheless, these locally elevated values for Pt and Pd suggest a high potential for PGE concentrations within the Boil Mountain ophiolite.

Potential for PGEs may also exist in the ultramafic body on the north end of Deer Isle ca. 18 km south of Blue Hill (Stewart 1998). This oblate body, 1.5 km in diameter, consists of variably serpentinized harzburgite and minor dunite (Reusch 2002). Although no PGE data are available for this body, it may have potential for ultramafic-hosted concentrations of these metals and hence warrants consideration for geochemical sampling.

In addition to remobilization and concentration of PGEs that can occur during serpentinization (Bussolesi *et al.* 2020), gold may be concentrated in carbonate-altered ultramafic rocks, termed listwanite or listvenite, which typically are localized along faults (e.g., Buisson and Leblanc 1986; Belogub *et al.* 2017). Based on analogy with these occurrences, ultramafic rocks of the Boil Mountain Complex could have potential for gold deposits within serpentinized zones. To our knowledge, none of these zones has been sampled geochemically for gold or other metals.

Granite-hosted uranium-thorium

Uranium and thorium are critical to the United States economy. Uranium is used for fuel in nuclear reactors and in the production of isotopes for industrial, medical, and defense purposes. On a global scale, most production comes from unconformity-type deposits within sedimentary rocks and from concentrations in evolved granites. Thorium, used chiefly for metal alloys and radiation shields, occurs economically in placers, veins, and carbonatites (U.S. Geological Survey 2021b). More than 95% of the uranium and all of the thorium consumed in the U.S. is imported. Although neither uranium nor thorium has been mined in Maine, many occurrences are known in the state, mostly within granitic pegmatites. Grauch and Zarinski (1976) list 43 such occurrences in non-sedimentary rocks of Maine.

Some evolved granites are well known for having uranium and/or thorium resources (e.g., Cuney 2014). Examples are the granite-hosted uranium deposits in the Liueryilin district of southeast China where major orebodies formed in two-mica granites with low U (<14 ppm) by multistage hydrothermal processes that increased uranium contents up to 3000 ppm, concentrating uraninite ± coffinite in faults and shear zones (Min *et al.* 2005). Two-mica granites are evolved felsic igneous bodies that contain both muscovite and biotite as primary magmatic phases. In New England, the Conway Granite in northern New Hampshire has been known for many years as one of the world's largest, low-grade resources of uranium and thorium, estimated to contain on average 11 ppm U and 53 ppm Th (Adams *et al.* 1962; Page 1980). Other coeval intrusions of the White Mountain Magma Series in New Hampshire have up to 25.5 ppm U and 77.0 ppm Th (Butler 1975). In Maine, among more than a dozen two-mica granites, one of the largest is the Permian Sebago pluton (Tomascak *et al.* 1996; Fig. 1), which in places has uranium contents up to 17.5 ppm (Dorais and Paige 2000). Prospects within this intrusion were drilled in the 1970s by Kerr-McGee and Exxon Corporation (W.A. Anderson, oral communication 2018), but no results are available. Other granitic bodies in eastern Maine locally have elevated uranium and/or thorium contents, including the Meddybemps Granite that in one sample has 25.6 ppm U and 46.8 ppm Th (Ludman and Hill 1990). These and other granites in the southern part of the state, such as the Lucerne, Mount Waldo, and Red Beach intrusions contain high radon values in associated groundwaters (Norton *et al.* 1989). Based on analogy with the large granite-hosted uranium deposits of southeast China, faults and shear zones that cut these uraniferous granites may be favourable sites for hosting potentially economic deposits.

The National Uranium Resource Evaluation (NURE) program was initiated by the U.S. Atomic Energy Commission (AEC) in 1973 with the goal of identifying uranium resources in the United States. Many surveys were conducted throughout the nation including in Maine. Of particular interest were the results of two projects, including reconnaissance hydrogeochemical and stream sediment surveys (Smith 1997) and aeromagnetic and aeroradiometric surveys (Hill *et al.* 2009). Aerial gamma-ray data obtained for the southern part of the state (Figs. 5 and 6) show regional anomalous highs on and surrounding the Permian Sebago pluton, the Devonian Lucerne and Tunk Lake plutons, and the western part of the Devonian Deblois pluton; high gamma-ray values occur mostly within the Devonian granite-

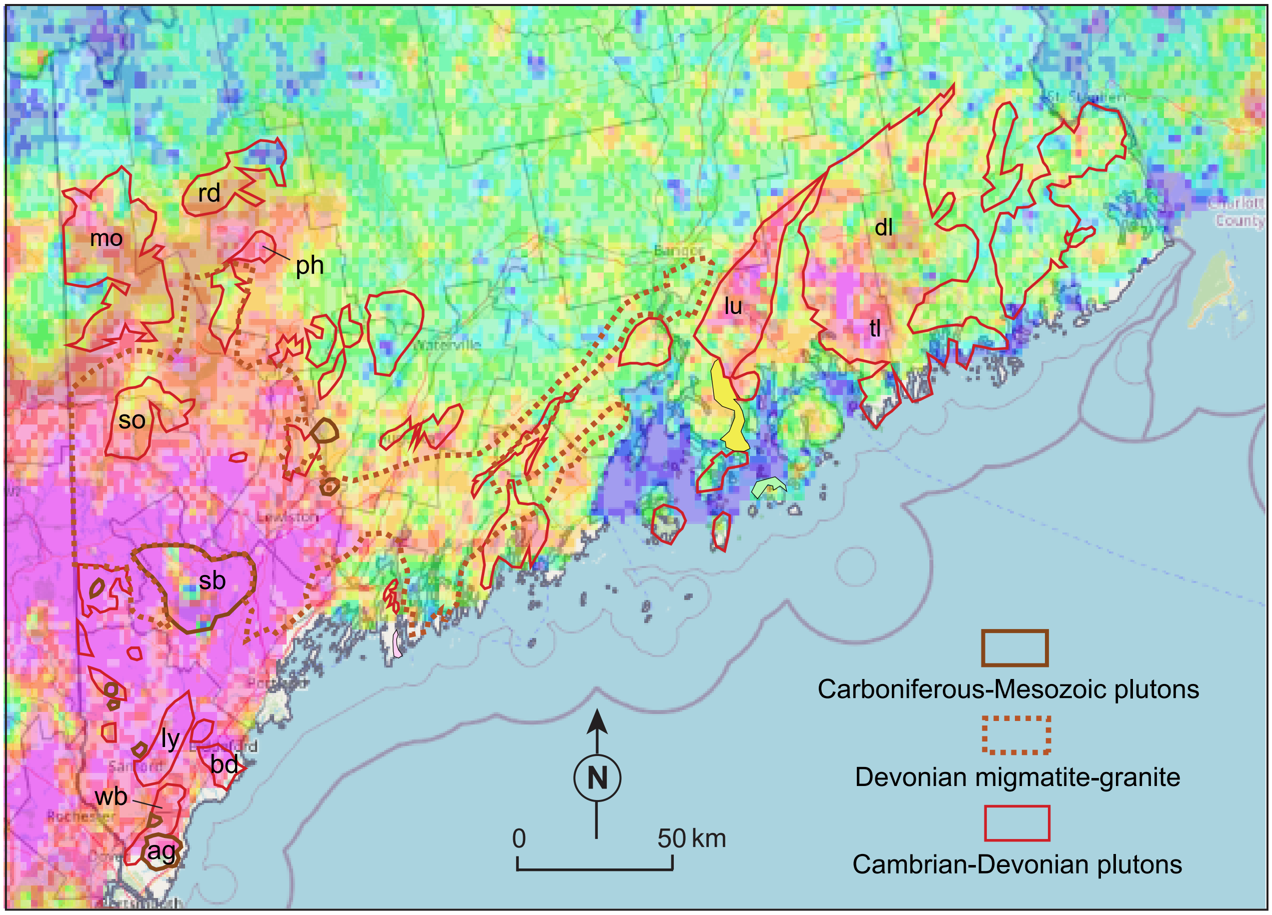


Figure 5. Map of southern Maine showing uranium anomalies determined by aerial gamma-ray spectrometer surveys conducted by NURE (Hill *et al.* 2009). Note general correspondence between highest values (hot colours) and selected igneous plutons. Abbreviations for labelled plutons: ag, Agamenticus; bd, Biddeford; dl, Deblois; lu, Lucerne; ly, Lyman; mo, Mooselookmeguntic; ph, Phillips; rd, Reddington; sb, Sebago; so, Songo; tl, Tunk Lake (Catherine); wb, Webhannet.

migmatite terrane of Solar and Tomascak (2016), except for the two elongate eastern lobes. Other anomalous areas in western Maine coincide with various Devonian granitic intrusions such as the Phillips, Adamstown, and Mooselookmeguntic plutons.

Many contractors were involved in the collection of both the geochemical and airborne data. Unfortunately, these data were reported in a variety of formats. There was a concerted effort by the USGS to reformat all the data, but according to Smith (1997) many problems remain. To our knowledge, there has been no follow-up by the USGS or others to do additional exploration work on the geochemical or airborne anomalies identified during the NURE program, nor has there been any systematic sampling of the two-mica granites for uranium or thorium potential. In 1989, the Maine government enacted legislation prohibiting the mining of uranium and thorium in the state (MRS Title 38, Section 489-B).

Tin in granitic plutons and veins

Tin has not been mined in the United States since 1993 (Kamilli *et al.* 2017). Seventy-five percent of the U.S. tin supply was imported in 2020, mostly from Peru, Indonesia, Malaysia, and Bolivia (Merrill 2021b). The balance came from recycling. Tin is used principally as solder, but also as tinplate and in alloys. The United States has no tin reserves, and hence this metal is considered critical and strategic for national security (McGroarty and Wirtz 2012). Approximately 70% of the world's tin output is from cassiterite in placer deposits, the remainder being derived from granitic plutons, greisens (mica-rich altered granites), and granite-related veins. Tin-bearing veins and greisens characteristically occur within the upper portions of shallowly emplaced, felsic and highly fractionated granites and in overlying country rocks. Such granites are typically silica rich, and peraluminous, metaluminous, or less commonly alkaline (Černý *et al.* 2005). For example, many granite plutons in southern and west-central New Brunswick are enriched in tin (Wilson and Kamo 2016; Mohammadi *et al.* 2020) including economic concentrations of this and other metals at the large Mount Pleasant Sn-Zn-In-W-Mo-Bi deposit (Kooiman *et al.* 1986; Yang *et al.* 2003). Maine has many tin occurrences, but with few exceptions these are small concentrations in

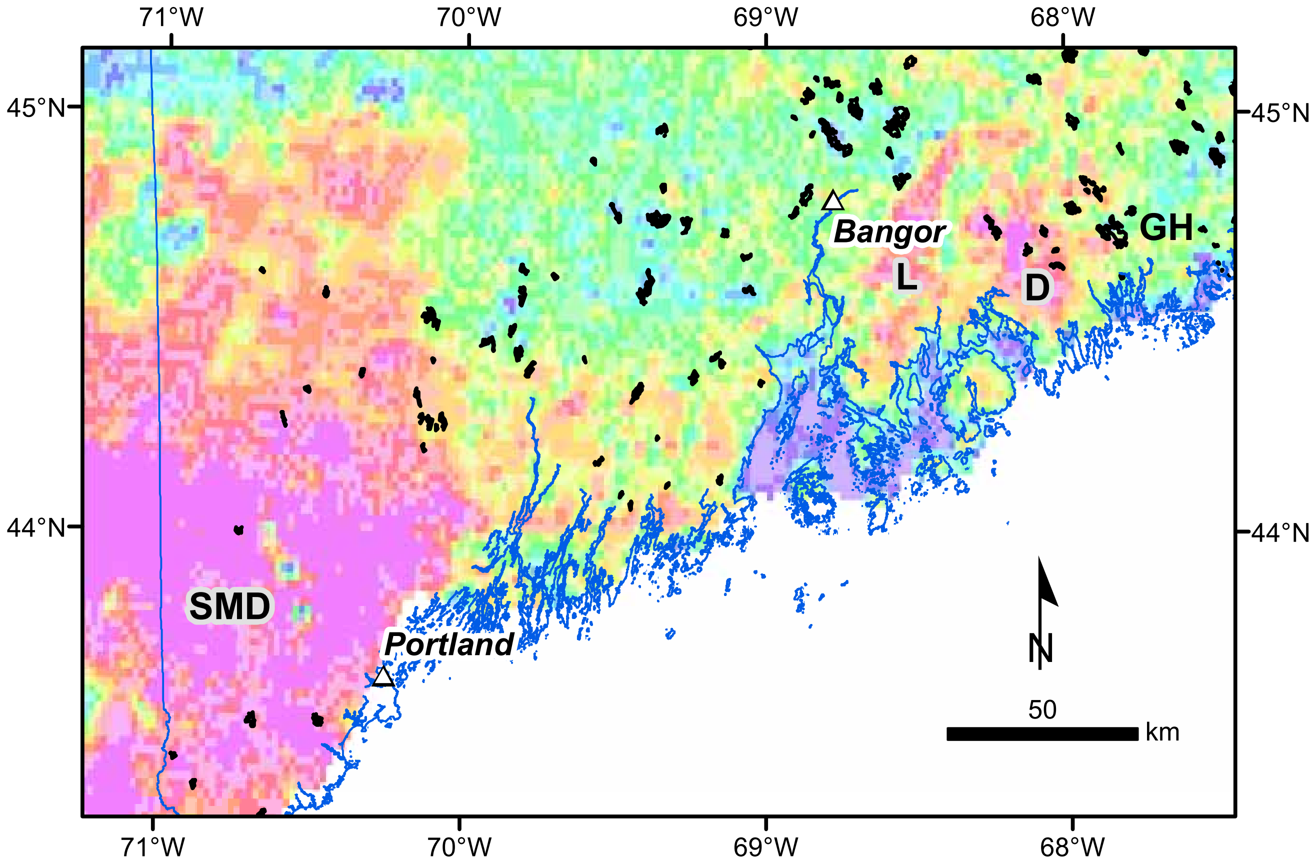


Figure 6. Map of southern Maine showing peat deposits (black) and uranium anomalies determined by aerial gamma-ray spectrometry (Hill *et al.* 2009). Distribution of peat deposits from Cameron *et al.* (1984a, b, c, d, e). Note location of Great Heath (GH) peat deposit (Cameron and Anderson 1980a).

granite pegmatites that lack resource potential.

Only one non-pegmatitic deposit in Maine has been mined and produced tin. The Winslow tin mine, located just south of Waterville, was operated in 1880 and 1881. A shaft reportedly 29 m deep with one or more crosscuts was described in the Maine Mining Journal in 1881 (King 2000). An unknown number of ingots of tin were smelted from the ore. The ore forms a series of veins up to ca. 50 cm in diameter that define a zone ca. 4.5 m wide and at least 67 m long; cassiterite is the sole tin mineral accompanied by minor galena, with a gangue composed of quartz, fluorite, calcite, and muscovite, all hosted in calcareous slate of the Silurian Waterville Formation (King 2000). The nearest exposed pluton is a granite body ca. 10 km to the west. Billiton Exploration, USA, Inc., undertook a regional and detailed survey in the vicinity of the Winslow tin mine in the early 1980s (Lippitt 1984). This survey included geologic mapping, regional and local gravity surveys, soil geochemical surveys, and diamond core drilling. The targets were suspected buried granitic cupolas within highly evolved granites that might have economic concentrations of tin in greisen veins associated with the cupolas. Owing to extreme deflection of the drill pipes, the targeted cupolas were not reached at depth. Drilling of the down-dip extension of the near-surface vein lacked promising results according to Lippitt (1984).

Tin exploration programs elsewhere in Maine included reconnaissance surveys in the coastal belt between Ellsworth and the New Brunswick border. Of particular interest in the coastal belt was the discovery in the 1970s of a large boulder containing abundant cassiterite (F.M. Beck files, 1980–2000). Stream-sediment heavy mineral, rock-chip, and stream-water surveys were conducted on drainages surrounding many of the granite bodies. Anomalous tin and tungsten contents were evident in the vicinity of the biotite granites, but no obvious source for the “tin boulder” was discovered during this survey.

One other small non-pegmatitic tin occurrence warrants mention. The Piper Hill (Bergensdahl) prospect, in York County, is a vein that contains molybdenite, pyrite, pyrrhotite, chalcopyrite, orpiment, galena, sphalerite, and argentite (Morrill 1958). Cassiterite is likely present, although stannite or a different Sn-sulphosalt may occur; no tin mineral has been identified. The host lithology is a calc-silicate rock near the Mesozoic Pickett Mountain syenite pluton (U.S. Geological Survey 2021a).

Niobium, tantalum, and rare earth elements in alkaline intrusions

Niobium, tantalum, and REE are critical minerals in the United States because of supply risk and minimal or no domestic production. Chief uses of these metals are in high-strength steel alloys; cell phones, computer drives, and implanted medical devices such as pacemakers; and in glass, magnets, and catalysts in petroleum refining, catalytic converters, and for making phosphors in cathode ray tubes and flat panel display screens, respectively (Schulz *et al.* 2017; Van Gosen *et al.* 2017). Many alkaline igneous rocks globally contain significant concentrations of these metals (e.g., Dostal 2016). Based on current knowledge, this is the only type of REE occurrence reported in Maine, although the economic potential is tenuous. Two Paleozoic ultrapotassic syenite intrusions in the eastern part of the state (Turner Mountain syenite; Wang *et al.* 2014) and in central-coastal Maine (Lincoln syenite; West *et al.* 2007) have somewhat elevated concentrations of light rare earth elements (LREE). Maximum LREE values are higher for the Lincoln syenite, including 96.3 ppm La, 210 ppm Ce, and 100 ppm Nd (West *et al.* 2007).

One of the most promising intrusions from a resource standpoint is the Carboniferous Litchfield pluton in south-central Maine (West *et al.* 2016). This alkaline syenite complex, ca. 16 km southwest of Augusta (Fig. 7), is the type locality for litchfieldite that is a coarse-grained nepheline syenite containing albite, microcline, nepheline, sodalite, cancrinite, and calcite, with local magnetite, Fe-rich biotite, and in places zircon crystals up to 4 cm in length. Barker (1965) also reported the presence of the Nb-rich mineral pyrochlore [$(Na,Ca)_2Nb_2O_6(OH,F)$]. Susceptibility to weathering has limited the exposure of this intrusion. The composite pluton is a geographic depression with its extent and compositional heterogeneity inferred by surface boulders (West and Ellenberger 2010). Lithologically, the pluton can be divided into several units based on mineralogy, although scarce exposures make this division somewhat conjectural. Whole-rock geochemical data for six samples (West *et al.* 2016) lack enrichment in Y (<15 ppm) and REE (e.g., La <28 ppm), but show locally high Zr and Nb (up to 1809 and 68.0 ppm, respectively). Other reported occurrences of nepheline ± cancrinite such as at the South Cochnewagon Pond locality ca. 25 km southwest of Augusta, apparently are in glacial boulders (King and Foord 1994) and are unlikely to have been transported ca. 15 km west from the Litchfield pluton, thus suggesting the presence of additional bedrock sources of these mineralogically distinctive boulders from other (one or more) unmapped alkaline igneous intrusions in the area.

Nearly a dozen alkaline igneous complexes and stocks, some including peralkaline units, are reported from southwestern Maine. These intrusions occur in a south-southeast-trending belt and are inferred to be part of the Mesozoic White Mountain Magma Series based on spatial, compositional, and geochronological similarities. The Osceola Granite, one phase of this magma series in northern New Hampshire, contains up to 158 ppm Nb, 12.1 Ta, 289 ppm La, 566 ppm Ce, and 270 ppm Nd (Eby *et al.* 1992). In Maine, whole-rock analyses by Gilman (1989, 1991) of samples from small Mesozoic intrusions included results for two samples from the Triassic Abbott Mountain pluton (Fig. 1) that separately contain 140 ppm Nb and 1010 ppm Zr; no REE data were reported for this pluton or others analyzed in these studies. The Jurassic Rattlesnake Mountain pluton locally has higher contents of Nb (up to 203.9 ppm) and Zr (up to 1136.0 ppm), within nepheline syenite and trachyte, but has relatively low REE, e.g., maximum of 105 ppm La (Creasey 1989). The anomalous values for niobium and zirconium warrant additional analyses of these plutons, and of other alkaline intrusions in the region, for proper evaluation of potential economic resources of these metals, and possibly also for REE.

A small area in northern Maine may also have resource potential for this deposit type. Results of a 2021 airborne radiometric survey by the U.S. Geological Survey identified a high-Th zone ca. 800 m long and 300 m wide within altered trachyte tuff (Duff *et al.* 2022). The trachyte host rock in this area, within the Ordovician Winterville Formation, locally contains very high concentrations of REE, Zr, Nb, Ta, Th, and Ba (C. Wang, written communication 2022). More work will be required to evaluate this occurrence and determine whether it is an economically viable Nb-Ta-REE deposit.

Tungsten in skarn and replacement deposits

Tungsten is a critical metal used mainly in the manufacture of steel and other alloys, for cemented carbide parts in hardening tools, and in light bulbs, X-ray tubes, radiation shields, and industrial catalysts (U.S. Geological Survey 2021b). Tungsten occurs in several types of mineral deposits, but on a global basis the most important economically are granite-related skarn deposits. Scheelite is the main host mineral; wolframite is subordinate. Historically, these skarn deposits, together with local granite-hosted greisens and veins, have provided the vast majority of tungsten production and resources (Green *et al.* 2020). Important examples in North America include the Pine Creek deposit in eastern California (Newberry 1982) and the high-grade Cantung and Mactung deposits in Northwest Territories and Yukon Territory, respectively (Elongo *et al.* 2020). The last mine production of tungsten concentrates in the United States was in 2015; currently, the U.S. is wholly dependent on imports of this metal.

A different type of tungsten deposit consists of stratabound concentrations of scheelite in regionally metamorphosed rocks lacking a clear relationship to granites or other felsic intrusions (e.g., Cheilletz 1988). These deposits, typically within calc-silicate rocks, consist of scheelite together with quartz, sericite, garnet, pyroxene, plagioclase, clinozoisite, and local vesuvianite, fluorite, apatite, scapolite, and molybdenite (Gibert *et al.* 1992; Höll and Eichhorn 2000; Guo *et al.* 2016); tourmaline is abundant locally (Raith 1988). The garnet in stratabound scheelite deposits typically has a major component of grossular [$Ca_3Al_2(SiO_4)_3$] (Gibert *et al.* 1992; Guo *et al.* 2016), whereas in granite-related scheelite skarns the garnets can be compositionally diverse, with major proportions of grossular, almandine [$Fe^{2+}{}_2Al_2(SiO_4)_3$], andradite [$Ca_3Fe^{3+}{}_2(SiO_4)_3$], or spessartine [$Mn_3Al_2(SiO_4)_3$] (Meinert 2000). Limited published data for stratabound scheelite deposits suggest that associated pyroxenes contain a large component of hedenbergite [$(Fe,Ca)Si_2O_6$], in contrast to scheelite skarn pyroxenes that have compositions dominated by diopside [$(Mg,Ca)Si_2O_6$] and/or hedenbergite (Meinert 2000). Long-standing controversy surrounds the origin of the stratabound deposit type, specifically as to whether the tungsten mineralization formed during emplacement of a hidden granite or instead by metamorphic fluids that were focused along chemically reactive carbonate layers (Raith and Prochaska 1995). An older model involving syngenetic-exhalative processes on the seafloor (e.g., Boyer and Routhier 1974) is not considered viable by most workers. The economically most important stratabound deposit is Mittersill (Felbertal) in Austria, which is the largest scheelite mine in Europe, having a production of 7.0 Mt @ 0.5% W and unmined resources of 6.1 Mt @ 0.5% W (Bureau de Recherches Géologiques et Minières 2002); the total amount of contained tungsten at Mittersill (>65 500 t) ranks high in comparison to all large tungsten skarns of the world (cf. Green *et al.* 2020). The genesis of the Mittersill deposit is still debated, but the weight of evidence suggests formation by metamorphic fluids and not magmatic-hydrothermal fluids derived from a hidden granite (Raith and Stein 2006). Geologically and mineralogically similar stratabound scheelite deposits in other metamorphic terranes, such as those in France (Gibert *et al.* 1992), Norway (Larsen 1991), Australia (Barnes 1983), Pakistan (Leake *et al.* 1989), and Myanmar (Guo *et al.* 2016), are probably metamorphogenic in origin.

In Maine, several small prospects of granite-related scheelite or wolframite are known along the coast (U.S. Geological Survey 2021a) but likely have limited resource potential, although new exploration efforts could change this outlook. A more promising region in our estimation is the western part of the state, where widespread tungsten anomalies occur in stream sediments and panned concentrates (Nowlan *et al.* 1987, 1990b). Most of the high concentrations, in the range of 60 to 3000 ppm W, are within or near Devonian granite plutons (Fig. 7) that intrude early Paleozoic metasedimentary rocks including local carbonate strata that would be favourable for development of skarns via replacement by magmatic-hydrothermal fluids. Importantly, however, other high values in sediment and concentrate samples—above 120 ppm W—were collected 3 to as much as 15 km from known granite contacts, e.g., south of Madrid, west of Farmington, and within the Farmington area. Some of these anomalies likely reflect glacial transport from granite plutons to the north or northwest, but others instead may be derived from local bedrock. The latter possibility is supported by the presence in this region of numerous outcrops containing scheelite in quartz ± calcite veins and quartz-garnet lenses within metasedimentary rocks, such as several occurrences in the Farmington area (Trefethen *et al.* 1955; Moench *et al.* 1999). It is unclear, without more detailed field investigations, whether these bedrock scheelite occurrences as well as the many tungsten anomalies in panned concentrates are linked to stratabound deposits or granitic skarns. No examples of the former type are known in New England and vicinity, but a small scheelite skarn is present at Lac Lyster, just north of the Vermont-Québec border within the contact aureole of a Devonian granite pluton (Gauthier *et al.* 1994). Most of the bedrock scheelite occurrences and panned concentrate anomalies in western Maine are likely very small and lack economic significance, but some may have resource potential (cf. Case *et al.* 2022). One candidate is on the south border of the Umbagog pluton where locally abundant scheelite (0.7 wt% W) occurs in the lower part of the Ordovician Quimby Formation, within a calc-silicate unit 9 m thick that extends along strike for at least 11 km (Moench *et al.* 1999). Other scheelite occurrences and prospects are known within calc-silicate layers of several other metasedimentary rock units in this region, including Silurian strata of the Rangeley, Greenvale Cove, and Smalls Falls formations (Moench *et al.* 1999). In the southern part of the state, excluding pegmatites, scheelite has been found in metasedimentary rocks in skarn-type assemblages with quartz, calcite, garnet, diopside, molybdenite, vesuvianite, epidote, scapolite, wollastonite, apatite, pyrite, and/or axinite near the towns of Sanford and Cornish (Morrill 1958) and Phippsburg (Mindat.org 2021).

Tungsten and bismuth in polymetallic veins

Some polymetallic Mo-rich veins in Maine contain critical elements such as tungsten and bismuth. Bismuth is included in this category owing to total dependence of the United States on foreign sources and the importance of this metal in cosmetic, industrial, laboratory, and pharmaceutical industries, and in the foundry industry as an additive to improve metallurgical quality (Merrill 2021a). Polymetallic Mo-rich veins are typically associated closely with granitic plutons, including at the giant Sisson Brook W-Mo-Cu deposit in central New Brunswick (Fyffe and Thorne 2010; Zhang 2015) that has proven and probable ore reserves of 334.4 Mt @ 0.066% W and 0.021% Mo (Northcliff Resources Ltd. 2022). In eastern Maine, two Mo-rich prospects with minor tungsten and bismuth are known at the Catherine Hill and Cooper prospects. Mineralization at the Catherine Hill prospect, in the western lobe of the Devonian Deblois Granite, consists of disseminations and fracture-fillings of molybdenite and pyrite with lesser scheelite and wolframite in a gangue of quartz and minor fluorite (Emmons 1910; Morrill and Hinckley 1959; Young 1963). The Cooper prospect, containing molybdenite, scheelite, chalcopyrite, quartz, and fluorite, is similarly hosted in a Devonian granite but with associated pegmatite (Emmons 1910; Young 1963; Burbank 1965). The minimal amount of data available on these two

Figure 7. (next page) Simplified geologic map of Maine showing regional metamorphic zones and locations of mines, prospects, and important (key) occurrences (including areas with geochemical anomalies) of critical minerals or elements. Geology and abbreviations for cities and towns, coastal bays, and igneous plutons and other igneous bodies after Fig. 1. Abbreviations for mines, prospects, and key occurrences (including for areas of geochemical anomalies): (1) Ophiolite-hosted Cr: AP, Arnold Pond; BP, Blanchard Pond; (2) Sn in granitic plutons and veins: PH, Piper Hill (Bergensdahl); WL, Winslow; (3) Nb, Ta, and REE in alkaline intrusions: LF, Litchfield; SC, South Cochnewagon Pond; TH, thorium anomaly; (4) W in skarn and replacement deposits: CN, Cornish; PB, Phippsburg; SF, Sanford; UP, Umbagog pluton contact; green dotted lines outline western Maine geochemical anomalies (120-3000 ppm W) in nonmagnetic heavy-mineral panned concentrates; (5) W and Bi in polymetallic veins: CH, Catherine Hill; CO, Cooper; CP, Crocker Pond area; GC, Golden Circle; (6) V in black shales: BM, Bowers Mountain Formation; PF, Penobscot Formation; (7) Sb in granite-related settings: DH, Drew Hill; GB, Gouldsboro; HT, Hector; WS, West and Soule; (8) Sb in orogenic veins and replacements: CM, Carmel; LR, Lawrence; LV, Levant; SR, Shorey; (9) Te in epithermal deposits: BB, Big Hill and Barrett; (10) Be in evolved and altered felsic tuffs: CI, Cranberry Islands; (11) Graphite in high-grade metamorphic rocks: MV, Milletville; PL, Phillips; (12) Ti, Zr, and REE in heavy-mineral sands: HB, Hunnewell barrier; (13) U in peat: GH, Great Heath.

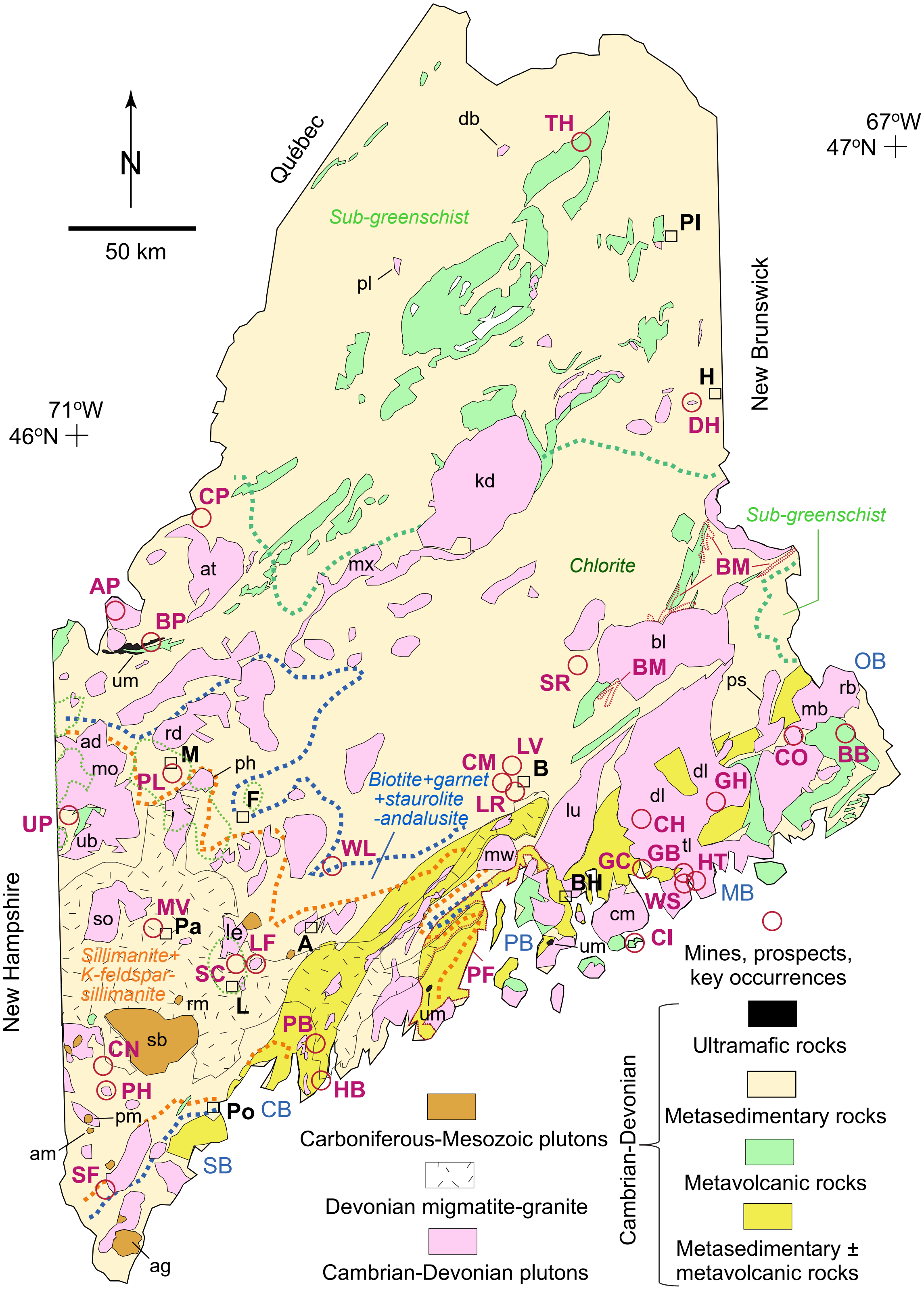
prospects limits an understanding of the deposit type (e.g., alternatively porphyry Cu-Mo) and an assessment of potential resources of tungsten and bismuth. The Golden Circle prospect near the mid-coast consists of one or more Au-Ag-Bi-Te veins containing sylvanite [$(Ag,Au)Te_2$] and native bismuth (U.S. Geological Survey 2021a) along the projected trend of a nearby Devonian granite. This assemblage suggests an epithermal metallogenic association, but more work will be required to evaluate this model. Importantly, however, the presence of large ore reserves of tungsten in the granite-related Sisson Brook deposit in New Brunswick suggests a moderate potential for this deposit type within or near Devonian granites of eastern and coastal Maine.

Relevant to western Maine is the St-Robert W-Pb-Zn-Ag-Bi-Au vein deposit in southeastern Québec 10 km northwest of the border (Cattalani 1987; Gauthier *et al.* 1994; Athurion 2013). Production from the central zone of this deposit in 1958 was 1000 t @ 6.28 wt% Pb, 0.91 wt% Zn, 0.64 wt% Bi, 0.06 wt% Cu, and 381 g/t Ag. Reserves in this zone are reported to be 129 000 t @ 0.6 wt% WO_3 and 6000 t @ 1.36 wt% Pb, 0.5 wt% Bi, and 105 g/t Ag; an additional 250 000 t @ 11.3 g/t Au has also been identified (Gauthier *et al.* 1994). The St-Robert vein system forms a northeast-trending mineralized zone dominated by quartz veins containing pyrite, sphalerite, Ag-rich galena, scheelite, cosalite [$Pb_2Bi_2S_5$], chalcopyrite, bismuthinite [Bi_2S_3], and pyrrhotite. The host rock is a metasedimentary hornfels of the Devonian Frontenac Formation; presence of this hornfels and proximity of the veins to quartz-feldspar porphyry dikes suggest a genetic link to an unexposed felsic intrusion at shallow depth (Moench *et al.* 1999). Importantly, however, the St-Robert vein system parallels a major pre-ore regional fault and hence may be controlled by it. Based on the presence in westernmost Maine of similar northeast-trending regional faults, such as the Woburn and Thrasher Peak faults in the Crawford Pond area (Moench *et al.* 1999), a resource potential may exist there for polymetallic vein deposits containing tungsten and bismuth, in addition to other metals such as lead and zinc.

Vanadium in black shales

Vanadium is used in a variety of industrial applications including steel alloys, ceramics, glasses, pigments, chemical catalysts, and redox-flow batteries (Kelley *et al.* 2017). The majority of the world's vanadium is mined from vanadiferous titanomagnetite concentrations in mafic plutons, with minor production coming from sandstone-hosted deposits and some other sources. Although not mined in the past, black shales have recently been identified as potentially containing important vanadium resources. For example, in eastern Nevada, detailed exploration of Devonian black shales has identified two deposits with economic potential, at the Carlin and Gibellini prospects that have measured + indicated reserves of 24.6 Mt at an average grade of 3440 ppm V and 23.0 Mt @ 1625 ppm V, respectively (Phenom Resources Corp. 2021; Nevada Vanadium Mining Corp. 2022). Much larger resources occur in Cretaceous oil shale at Julia Creek in Queensland, Australia (220 Mt @ 1680 ppm V; QEM Limited 2021) and in Neoproterozoic black shale at Häggån in Sweden (90.0 Mt @ 2350 ppm V; Mining Technology 2018). Black-shale hosted vanadium deposits are also known in South China, Madagascar, and other countries (Kelley *et al.* 2017). To date, none of these shale-hosted vanadium deposits has been mined on a large scale but several, including those in Nevada, are currently being evaluated for development and mining; at the Gibellini deposit, mine construction is scheduled to begin in 2022. The primary concentration of vanadium in black shales is generally attributed to a specific redox facies that reflects deposition within bottom waters or pore fluids that were suboxic with very low dis-solved oxygen contents, at the redox couple where V^{4+} is re-duced to V^{2+} (e.g., Algeo and Li 2020).

Black shales and metamorphic equivalents (graphitic schists) occur in many parts of Maine. These strata, in early Paleozoic formations, are exposed chiefly in central and eastern Maine, with some known along or near the coast. Despite extensive geological mapping, however, few of these formations have been studied by whole-rock geochemistry. One of the best known is the Smalls Falls Formation, of Silurian age, but reconnaissance data indicate that this



widespread stratigraphic unit lacks elevated vanadium contents (<220 ppm; Slack *et al.* 2020). Black shale and schist of the Ordovician Penobscot Formation, on the west side of Penobscot Bay (Fig. 7), has up to 1600 ppm V (Foley *et al.* 2001), but importantly only a few samples from this unit have been analyzed. The Penobscot Formation thus could have potential for vanadium resources. Potential also may exist in Early Ordovician black shales of the Miramichi belt in eastern Maine, including within the Bowers Mountain Formation (Fig. 7; see Ludman *et al.* 2018), based on mostly high vanadium contents of 723 to 3016 ppm (avg 1917 ± 778 ppm; *n* = 7) reported for approximately coeval black shale of the Bright Eye Brook Formation in southwestern New Brunswick (Hennessy and Mossman 1996). A previous study by Fyffe and Pickerill (1993) reported comparable values for this formation, with average concentrations for three samples at two sites of 2429 and 1617 ppm V. The Greenfield Formation in eastern Maine, correlated by Ludman *et al.* (2018) with the Bowers Mountain Formation to the northeast, is lithologically similar in containing black shale but also has Mn-rich mudstone and iron formation, suggesting a more oxidizing depositional environment above the V^{4+}/V^{2+} redox couple that consequently would have prevented high vanadium concentrations during sedimentation (see Algeo and Li 2020), hence the Greenfield Formation probably lacks a potential resource of this metal.

Antimony in granite-related settings

Antimony has diverse uses including in batteries, chemicals, ceramics, glass, flame-retardant materials, heat stabilizers, and plastics (Seal *et al.* 2017). Concentrations of stibnite, the predominant economic antimony mineral, are mined mainly from orogenic deposits without a link to granitic intrusions. Granite-related stibnite veins and breccias are also economically important in some countries. In western New Brunswick, the Lake George antimony deposit (~2 Mt @ 3.0–4.2 wt % Sb), which at one time was the largest antimony producer in North America, forms quartz + stibnite ± arsenopyrite veins in Silurian greywacke and slate within the contact aureole of an Early Devonian granodiorite pluton (Scratch *et al.* 1984; Seal *et al.* 1988). The antimony ores there formed paragenetically late, following earlier stages of W-Mo quartz and Au-bearing quartz-carbonate vein mineralization (Lentz *et al.* 2020).

Several granite-related antimony deposits are known in Maine. One is at the Drew Hill (Eben Lake) prospect west of Houlton. This deposit, in early Paleozoic metasedimentary rocks within the contact aureole of a Devonian granite accompanied by felsic and local mafic dikes, consists of stibnite-rich quartz veins in metasedimentary hornfels. Other mineralized zones occur in this area, including (1) pyrite and pyrrhotite in massive replacements of marble; (2) pyrite, chalcopyrite, and arsenopyrite in phyllite-hosted veins; and (3) pyrite, galena, and chalcopyrite in quartz veins within hornfels and phyllite (Houston 1956; Pavlides and Canney 1964).

Several polymetallic Sb-bearing vein deposits related to igneous plutons occur in coastal Maine. The largest of these was exploited at the Gouldsboro Pb-Cu-Zn-Ag-Au-Sb mine, which produced a minor amount of lead and copper ore from 1878 to 1928. This deposit consists of thin fissure veins of sulphides and sulphosalts (tetrahedrite, stephanite) in a gangue of quartz and orthoclase, hosted within a quartz diorite cut by granitic and pegmatitic dikes (Emmons 1910; Li 1942; Young 1962). Other small Sb-bearing deposits in the area were exploited at the Hector and West and Soule Sb-Cu-Au-Pb-Ag mines (Morrill and Hinckley 1959; Young 1962; U.S. Geological Survey 2021a).

Antimony in orogenic veins and replacements

A major source of global antimony production is from the giant Xikuangshan deposit in China. This deposit, the largest in the world, contains ca. 50 Mt of ore at an average grade of 4.0 wt% Sb (Yang *et al.* 2006). Xikuangshan and other geologically similar deposits in South China are characterized by Sb, Sb-Au, Sb-Hg, and Au veins and siliceous replacements in deformed Devonian and Cretaceous carbonate and minor clastic sedimentary rocks, with the orebodies being controlled by fault intersections and anticlinal structures (Hu and Peng 2018; Zhang *et al.* 2019; Yan *et al.* 2022).

Small antimony prospects and occurrences are known within deformed early Paleozoic metasedimentary rocks in the Bangor area of Maine (Fig. 7) in a geological setting broadly similar to that in parts of South China. Examples are the Carmel and Levant Sb prospects, the Shorey Sb-Au-Ag prospect, and the Lawrence Sb-Cu-Au-Pb-Ag prospect (Morrill and Hinckley 1959; U.S. Geological Survey 2021a). No granitic or igneous bodies are known in this area, and hence are classified here as having formed by orogenic Sb-rich hydrothermal systems. Although the host rocks to these prospects are predominantly clastic, limestone has been mapped locally as in the Stetson quadrangle northwest of Bangor (Griffin 1971) and hence is likely a favourable lithology for hydrothermal replacement mineralization, as documented at the Xikuangshan deposit (Hu and Peng 2018). To our knowledge, none of the antimony prospects or occurrences in the Bangor area has been studied or explored using modern concepts and methods, or application of current ore deposit models (Slack 2022).

Tellurium in epithermal deposits

Tellurium is a critical element because of its use in photovoltaic solar cells (Goldfarb *et al.* 2017). Some epithermal mineral deposits have elevated contents of tellurium including up to hundreds of ppm in local ore zones. Such deposits typically contain appreciable amounts of silver and gold together with variable amounts of zinc, lead, and copper (John *et al.* 2018). Host rocks are chiefly subaerial volcanic rocks, both felsic and mafic; less common are submarine volcanics that formed in relatively shallow seawater, a setting termed hybrid epithermal-VMS by many workers. In addition to precious and base metals, and tellurium, some epithermal deposits contain trace quantities of a variety of critical metals including As, Bi, Sb, Se, Sn, and W, some of which can be recovered economically (Goldfarb *et al.* 2016, 2017; John *et al.* 2018).

Maine has two important epithermal-type deposits located in the Eastport-Machias area near the New Brunswick border. These are the Big Hill and Barrett deposits, both of which are hosted by shallow-marine felsic and mafic volcanic rocks of the Silurian Leighton Formation (Gates and Moench 1981; Piñán Llamas and Hepburn 2013). The only mining in this area was for lead in the early 1900s at Big Hill; no production figures are recorded. Exploration and drilling in the area took place intermittently in the 1960s until the early 1980s (Young 1968; Lepage *et al.* 1991).

The Big Hill deposit has proven (drilled) reserves of 4.44 Mt @ 1.58 wt% Zn + Pb, 0.15 wt% Cu, 63.5g/t Ag, and 0.28 g/t Au, and indicated reserves of 20.0 Mt @ 1.75 wt% Zn + Pb and 17.0 g/t Ag (Schaaf 1985). Mineralization there comprises irregular veins and disseminations of quartz, galena, and sphalerite with minor pyrite, chalcopyrite, pyrrhotite, and silver sulphides hosted mainly in basalt of the Leighton Formation (Li 1942; Young 1968). Wolfden Resources Corporation (2022) is currently involved in exploration of the Bill Hill (Big Silver) deposit.

The smaller Barrett deposit contains 0.35 Mt @ 1.75 wt% Cu, 20.6 g/t Ag, and 7.9 g/t Au. Major mineralized zones consist of chalcopyrite and sphalerite, with local gold, all occurring as amygdules, replacements, and breccia fillings within basalt of the Leighton Formation (Emmons 1910; Li 1942; Gates and Moench 1981).

Deposits of the Eastport-Machias area are best classified as hybrid epithermal-volcanogenic (e.g., Hronsky *et al.* 2012). This classification is based on the high concentrations of precious metals and on evidence of predominantly shallow-water deposition of the host Leighton Formation (Gates and Moench 1981; Piñán Llamas and Hepburn 2013). We emphasize that elsewhere, hybrid epithermal-volcanogenic sulphide deposits may have high concentrations of tellurium and other critical elements that can be recovered as byproducts during mining. For example, the Eskay Creek deposit in western British Columbia, mined from 1995 to 2008, produced 2.1 Mt of ore averaging 2221 g/t Ag and 48.4 g/t Au with appreciable Cu and Zn, plus locally elevated Ba, Cd, As, Sb, Pb, Te, and Hg; these critical elements occur locally in the Eskay Creek deposit and also in geologically and mineralogically similar deposits elsewhere in the district (Lindsay *et al.* 2021). Note, however, that no analytical data are available for critical elements that may be present in the polymetallic deposits of the Eastport-Machias area.

Beryllium in evolved and altered felsic tuffs

The light element beryllium is widely used in many industries including medical, defense, computer, aerospace, and telecommunications, among others (Foley *et al.* 2017). The United States is self-sufficient in beryllium based on production from the giant volcanogenic Spor Mountain deposit in western Utah that is the largest in the world, containing 9.6 Mt of ore at an average grade of 0.25 wt% Be (Foley *et al.* 2012; Ayuso *et al.* 2020). However, beryllium nevertheless is listed as a critical element because the U.S. Department of Defense requires a long-term domestic supply given that U.S. production has diminished in the past decade. Other countries rely on beryllium contained in pegmatite-hosted beryl. The beryllium in the Spor Mountain deposit is concentrated in the mineral bertrandite, a hydrous Be-rich silicate mineral [$Be_4Si_2O_7(OH)_2$] that occurs in limestone clasts within alkaline lithic-rich rhyolite tuffs of Tertiary age. Abundant fluorite and high uranium contents (up to 2000 ppm U) are also characteristic of the ores (Lindsey *et al.* 1973). An integrated model for the formation of this deposit involves low-temperature (<200°C) hydrothermal alteration of calcite in the clasts by a Be-F aqueous complex, which together with water and dissolved silica yield products of bertrandite plus fluorite and CO_2 (Foley *et al.* 2012). Three important components of the model are (1) occurrence of lithic-rich alkaline rhyolite tuff; (2) presence of carbonate rocks stratigraphically below the tuffs to provide a source for the calcite-rich clasts, and (3) post-depositional hydrothermal alteration by F- and Be-rich fluids that are concentrated via dissolution of these elements in the host alkaline tuff.

A major limitation to applying the Spor Mountain model to Maine is the apparent lack of alkaline rhyolite tuffs in Maine. Some large-volume rhyolite tuffs are known in the state (Seaman *et al.* 2019) including the thick ignimbrites of the Devonian Traveler Rhyolite that contains groundmass fluorite, but limited whole-rock geochemical data for major, trace, and rare earth elements suggest that both members of this tuff are calc-alkaline and not alkaline (Hon 1976). Widespread rhyolites also occur in the coastal volcanic belt of the Penobscot Bay area (Pinette and Osberg 1989; Schulz *et al.* 2008) and the Machias-Eastport area (Gates and Moench 1981; Piñán Llamas and Hepburn 2013), all of which are compositionally calc-alkaline or tholeiitic and not alkaline.

One possible candidate for undiscovered beryllium mineralization in Maine is in lithic-rich rhyolite tuffs of the Late Silurian Cranberry Island series (Fig. 7). Described by Seaman *et al.* (1999), these volcanic rocks are mainly tholeiitic although one sample of dacite has a high Na_2O + K_2O content that plots compositionally in the alkaline field; several samples of rhyolite ignimbrite contain elevated La (up to 47.6 ppm), Y (up to 280 ppm), and Zr (up to 384 ppm), but uranium concentrations are uniformly low (<3.2 ppm). No whole-rock data are available for beryllium or fluorine. Importantly, the lithic clasts are rhyolite, granite, basalt, or siltstone, without reported carbonate. Basement to the Cranberry Islands volcanic rocks is not exposed in the area, but likely is dominated by siliciclastic metasedimentary rocks (e.g., Cambrian Ellsworth Schist), although limestones of this approximate age are known elsewhere in the coastal region, such as on the west side of Penobscot Bay (i.e., Coombs Limestone), and potentially could underlie the Cranberry Islands at depth. On balance, the possibility for Spor Mountain-type beryllium mineralization in the Cranberry Islands volcanic rocks is considered to be low, but we nonetheless suggest a speculative potential based on several favourable criteria. More focused mineralogical studies and whole-rock geochemical analyses (i.e., for Be and F) are recommended, in order to better evaluate this volcanic series for cryptic beryllium mineralization.

Graphite in high-grade metamorphic rocks

Graphite is a critical component used in many industries including for electronics, lubricants, metallurgy, steelmaking, and recently for batteries in electric vehicles (Simandl *et al.* 2015; Robinson *et al.* 2017). Since the 1990 closure of the last graphite mine in the U.S., in Montana, the nation has been totally dependent on foreign sources of this mineral. The economically most important deposit type contains flake graphite, which commonly occurs in high-grade metamorphic terranes dominated by metasedimentary rocks. Major deposits that contain large reserves and/or resources of abundant flake graphite include Zavalyevskiy in Ukraine (100.0 Mt @ 5.5% graphitic C; Robinson *et al.* 2017) and Graphite Creek in northwestern Alaska (102.8 Mt @ 8.0% graphitic C; King *et al.* 2019).

The setting and origin of the Graphite Creek deposit can be used as a template for evaluating the potential of other regions with similar geology. At the Graphite Creek deposit, flake graphite is concentrated in veins and massive lenses up to 0.5 m thick within upper amphibolite- to granulite-facies, quartz-plagioclase-biotite paragneiss of late Paleozoic age, and near Late Cretaceous granitic intrusions (Case *et al.* 2020). In Maine, many granitic pegmatites contain small amounts of flake graphite (Smith 1906), but these are not commercially viable. Importantly, however, three small graphite mines and prospects in the western part of the state are within highly metamorphosed sedimentary rocks like those that host the Graphite Creek deposit. The graphite mine on Plumbago Mountain southwest of Farmington, the Milletville prospect west of Paris, and the Phillips mine in Madrid, are all in amphibolite- to granulite-facies metasedimentary rocks, and most have spatially associated granitic intrusions (Fig. 7). More work will be required to evaluate the potential of these small mines and prospects for containing significant undiscovered resources of flake graphite.

Titanium, zirconium, and rare earth elements in heavy-mineral sands

Heavy-mineral sands are important sources of critical minerals worldwide (Van Gosen *et al.* 2014). Such sands may contain economic concentrations of resistant minerals like rutile, ilmenite, zircon, and monazite that can be mined for titanium, zirconium, and REE. These metals are of critical importance to the U.S. economy because of minimal domestic production and importance in the manufacturing of paint, paper, and metal alloys; in the chemical and nuclear-reactor industries; and in glass, magnets, and catalysts in petroleum refining, catalytic converters; and for making phosphors in cathode ray tubes and flat panel display screens (Woodruff *et al.* 2017; Jones *et al.* 2017; Van Gosen *et al.* 2017). Heavy-mineral sands have been mined on the U.S. Atlantic Coastal Plain since 1949 (Van Gosen *et al.* 2014); current mining of ilmenite and rutile in these types of sands is ongoing in Florida, Georgia, and South Carolina (Gambogi 2021). Several publications have suggested a potential exists for important accumulations of heavy-mineral sands both onshore and nearshore coastal Maine (Kelley *et al.* 1997; Buynevich and FitzGerald 2001), but to date there has not been a comprehensive analysis for such deposits in the state.

Most sand deposits onshore in Maine are products of erosion of the landscape by Pleistocene glaciation and subsequent fluvial processes that redistributed meltwater sediments. The majority of these deposits are in southern and coastal Maine (Thompson and Borns 1985), occurring as outwash plains, deltas, esker ridges, beaches, and ice-contact deposits. Many of these readily accessible deposits have been exploited for aggregate resources. Most of the glacial sand deposits were reworked by marine processes as sea-level fell to a low of -60 m below current sea level, and then rose again in response to long-term isostatic adjustment coupled with eustatic sea-level rise during the late Pleistocene and early Holocene (Barnhardt *et al.* 1995).

The work summarized in Kelley *et al.* (1998), based on maps created during a decade-long research program, is the most comprehensive presentation of the geologic environments of the inner continental shelf of Maine. Results of this mapping generally extend offshore to Maine's territorial limit of three nautical miles, and mostly extends to depths beyond the -60 m post-glacial lowstand. About 8% of the ocean bottom materials in the entire region surveyed is sand. Kelley *et al.* (1998) provided statistical summaries of the ocean bottom types, divided into key physiographic zones. The nearshore ramp zone, a region that slopes gently seaward with widely spaced, shore-parallel bathymetric contours, contains the majority of sand resources and represents nearly 350 km^2 of ocean bottom and 66% of this zone. Other physiographic zones have considerably less sand, but the shelf valley zone may have locally abundant sand bodies.

The most detailed analysis of heavy minerals in onshore deposits was done by Buynevich and FitzGerald (2001) in their study of progradation in coastal barrier beach systems. Among the studied field localities were three paraglacial barrier beach systems near the mouth of the Kennebec River in mid-coastal Maine. Their analysis of progradation included the collection of ground penetrating radar data and coring. One core taken at the Hunnewell barrier (Fig. 7) through reflectors recognized in ground-penetrating radar (GPR) data revealed medium- to fine-grained sands with a significant content of heavy minerals (>30 vol% magnetite + ilmenite + garnet) at a depth of between 2 and 3 m. These heavy-mineral sands are interpreted as lag deposits produced by erosion during significant storms. Unfortunately, Buynevich and FitzGerald (2001) did not analyze for monazite, zircon, or other critical minerals (I.V. Buynevich, oral communication 2021) that are likely present in trace amounts, at least. Similar erosional lag deposits probably exist in other onshore deposits of Maine, but additional work has not been done to assess their resource potential.

Several researchers have analyzed offshore deposits for heavy mineral content. Luepke and Grosz (1986) collected and analyzed 12 vibracore samples from Saco Bay in southern Maine, one of the nearshore ramps that contains abundant sand as noted by Kelley *et al.* (1998). Heavy minerals of economic interest—ilmenite, leucoxene, rutile, zircon, and aluminosilicates (sillimanite and andalusite)—constitute an average of about 14 wt% of the heavy minerals in the analyzed sediments, and an average of about 0.1 wt% of the bulk samples. Monazite was not detected in any of their samples. Grosz (1987) summarized what was then known of heavy mineral deposits along the Atlantic continental shelf. This study noted several areas in the Gulf of Maine where heavy minerals in surficial materials of the ocean bottom contain at least 4 wt% heavy minerals, including one offshore Saco.

As part of the inner continental shelf mapping effort, Kelley *et al.* (1997) collected 1303 grab samples of all bottom types. For 31 sand-rich samples collected in bays spanning the coast (Saco Bay, Casco Bay, Penobscot Bay, Machias Bay, Oak Bay in New Brunswick; Fig. 1), heavy minerals were separated using standard techniques. The highest concentration in a single sample, 6% of the dry sample weight, was found in Casco Bay, where the bay-wide average was higher than elsewhere, 2.6%. Although each of the areas studied was variable, Oak Bay contained the lowest concentrations with a mean of 0.21%. Mineral species were identified via microscopy, X-ray diffraction, or both techniques. The highest average concentration of ilmenite was in Oak Bay (6.19%), followed by Casco Bay (3.89%), and Saco Bay (3.66%). The highest concentrations of zircon were in Saco Bay (1.70%) and Machias Bay (1.15%); all other areas averaging less than 1% zircon. Rutile averaged less than 0.50% in all samples. Kelley *et al.* (1997) did not report REE mineral species, presumably because they were not present or occurred only in trace amounts.

Although some work has been done on heavy-mineral sands both onshore and nearshore Maine, these efforts were not comprehensive. Importantly, the tantalizing data of Buynevich and FitzGerald (2001) do indicate a potential for onshore concentrations of heavy minerals. However, many readily accessible sand deposits onshore have already been mined for aggregate. The results of Kelley *et al.* (1997) suggest the potential for undiscovered heavy-mineral concentrations in the sand-dominated nearshore ramp environment offshore (e.g., Kelley *et al.* 2003), with areas in southern and central Maine having the highest potential, particularly for titanium and zircon resources. High-resolution aeroradiometric surveys like those described by Shah *et al.* (2021) could reveal Th-rich sands that may have economic potential for REE present in monazite and other minerals.

Uranium in peat

Uranium in peat was mined during the 1980s in Washington State at the Flodelle Creek deposit (Johnson *et al.* 1987). A geological reserve of uranium in this deposit has been estimated at 200 t (J.K. Otton *in* Zielinski and Burruss 1991). The local bedrock source of the uranium is a Cretaceous two-mica granite that contains 9 to 16 ppm U (Zielinski and Burruss 1991).

The studies of Cameron *et al.* (1986, 1990) on trace elements in thirty-eight Holocene peat deposits of New Hampshire and Vermont highlight their potential as uranium resources. Uranium concentrations in these samples range from 1.0 to 467.0 ppm, with a mean of 48.3 ppm. The highest values, in western Vermont, occur in peat underlain by a Cambrian dolostone, which is ca. 4 km from Proterozoic granitic gneiss in the Green Mountains massif. In the New Hampshire occurrences, the ultimate source of uranium is the two-mica Sunapee granite of Late Devonian to Early Mississippian age. Results of these studies suggest that uranium-rich rocks beneath or near peat deposits leach uranium into shallow groundwater (Cameron *et al.* 1986, 1990). As groundwater flows, uranium is fixed in peat-hosted organic matter largely by processes of adsorption and ion exchange.

Two-mica granite is recognized for its metallogenic specialization in concentrating tin, tungsten, beryllium, lithium, fluorine, and uranium (Boudette 1977; Cuney 2014). Two-mica granites in New England are the products of tectonic interactions of ancestral North America with island arcs, microplates, and continents that thickened the crust through Ordovician-Devonian time. Metasedimentary rocks near the base of the thickened crust melted partially to form felsic magma that migrated upward through the crust to crystallize as two-mica granite.

Most two-mica granites in Maine occur in the western and coastal regions of the state. Geochemical data collected through the North American soil geochemical landscapes project (Smith *et al.* 2014) and airborne radiometric data collected through the National Uranium Resource Evaluation (NURE) program (Hill *et al.* 2009; Kucks 2005) show anomalously high concentrations of uranium in the Sebago migmatite domain area of western Maine (Figs. 5 and 6). The Sebago granite proper occupies only the southernmost part of this area, the remainder being underlain by a complex association of high-grade metamorphic rocks, migmatite, granitic dikes, and pegmatite (Solar and Tomascak 2016). The uranium anomaly in the NURE data for the Sebago area is similar to that in central New Hampshire studied by Cameron *et al.* (1986, 1990). Additionally, water from private wells in this area of southern Maine have some of the highest uranium concentrations found anywhere in the state. According to data compiled by the Maine Department of Health and Human Services (MEDHHS 2021), up to 58% of tested wells in some area towns exceed the state guideline for uranium of 30 μg/l.

In addition to the two-mica granites, the alkali-calcic Lucerne and Deblois plutons (Ayuso and Arth 1991) in eastern coastal Maine may also provide uranium to peat deposits in the manner described by Cameron *et al.* (1986). The NURE airborne radiometric data (Kucks 2005; Hill *et al.* 2009) show anomalously high uranium concentrations in close geographic association with these two plutons (Fig. 5). Similarly, private well waters in this region of eastern Maine underlain by the Lucerne and Deblois plutons have high uranium concentrations (MEDHHS 2021).

Cameron and Mullen (1982) summarized the peat resources of southern and coastal Maine as part of a comprehensive effort led by Cameron to investigate peat resources statewide (Cameron 1975; Cameron and Massey 1978; Cameron and Anderson 1979, 1980a, 1980b). The deposits characterized by these studies contain air-dried peat amounts ranging from 34,300 t to nearly 9.1 Mt, with a total in the studied deposits of ca. 36 Mt. Although many peat deposits occur in the area underlain by the Sebago Migmatite Domain, these tend to be small in area and of low total tonnage. The largest peat deposit characterized by Cameron and Mullen (1982) of just over 1.8 Mt falls within the area underlain by the Deblois granite pluton. In a focused study of the Great Heath, Cameron and Anderson (1980a) identified nearly 9.1 Mt of air-dried peat that is also underlain by the Deblois pluton. Norton (1990) investigated the geochemistry of the Great Heath and three other large peat deposits in Maine, but this study did not analyze for uranium. Although no studies have been done to assess the uranium content of peat in eastern Maine, given the high uranium concentrations there as suggested by the NURE data, and by elevated concentrations of uranium in groundwater, we conclude that a considerable potential exists for uranium resources in peat underlain by the Lucerne and Deblois plutons.

DISCUSSION

Our qualitative assessment of potential for the occurrence of critical mineral deposits in Maine is based on several factors. Following the approach used elsewhere in New England by the USGS for the Glens Falls and Sherbrooke-Lewiston 1° × 2° quadrangles (Slack 1990; Moench *et al.* 1999), this assessment ranks the potential into high, medium, and low categories. A quantitative mineral resource assessment (Singer and Menzie 2010), like those described for some major deposit types worldwide (e.g., Zientek *et al.* 2010), cannot be done for Maine owing to a lack of adequate data on tonnages and grades for most of the mines and deposits in the state. Key consideration in the qualitative assessment is given to (1) the presence of known deposits, prospects, or occurrences; (2) geological settings that are favourable for the formation of certain deposit types; and (3) geochemical data including those obtained on stream sediments and panned concentrates in regional surveys, and on rocks whether visibly mineralized or not. Descriptive and genetic geologic models for the origin of the mineralization are also used (e.g., Pirajno 1999; Hagemann *et al.* 2016), where applicable to Maine (Slack 2019, 2021, 2022). Importantly, data on small mines or prospects unworked for a century or more can nevertheless be valuable if the nature of the mineralization and geological setting are comparable to those of major orebodies elsewhere in the world. Geophysical data may be helpful for some cases, but in Maine few areas have modern coverage by high-resolution aerial magnetic and radiometric surveys.

Table 1 summarizes the potential in Maine for occurrence of 20 different deposit types and possible contained resources of critical minerals (and elements). A high resource potential is assigned only to three deposit types: (1) sediment-hosted manganese, (2) mafic- and ultramafic-hosted Ni-Cu(-Co-PGE), and (3) pegmatitic lithium-cesium-tantalum. In all designated areas, large deposits are either known or considered likely to exist based on various criteria including the presence of documented prospects that contain critical minerals and that can be evaluated using modern ore deposit models. Also important is the fact that the specified critical minerals within these three deposit types are potentially recoverable during mining and processing, assuming economic viability of the deposit.

Moderate potential is suggested for 11 other deposit types. These include: (1) porphyry Cu-Mo (Re, Se, Te, Bi, PGE); (2) chromium in ophiolites; (3) PGE in ophiolitic ultramafic rocks; (4) granite-hosted uranium-thorium; (5) tin in granitic plutons and veins; (6) niobium, tantalum, and REE in alkaline intrusions; (7) tungsten and bismuth in polymetallic veins; (8) vanadium in black shales; (9) antimony in orogenic veins and replacements; (10) tellurium in epithermal deposits; and (11) uranium in peat. Deposit types such as VMS that are known in some cases to have elevated concentrations of critical elements are nonetheless designated as having low resource potential because the contained critical elements are typically present in solid solution within other minerals (e.g., pyrite) that would likely not be recovered economically during mine beneficiation. Other small deposits such as Pb-Zn, Cu, and Mo veins (U.S. Geological Survey, 2021a) that apparently lack elevated concentrations of critical elements are not discussed.

Only the sediment-hosted manganese deposits in northeastern Maine and the pegmatitic lithium (spodumene) deposit at Plumbago Mountain in the western part of the state have reported mineral resources. However, in both areas, more exploration work such as extensive drilling and sampling will be required in order to accurately define mineral reserves that are compliant with internationally recognized codes such as NI 43-101 and JORC. The other deposit types for which we assign a moderate or low potential for critical minerals (Table 1) need significant field-based efforts to better characterize local geological settings and the nature and extent of mineralization, plus detailed laboratory studies to accurately define the mineralogical siting of the critical elements and whether these can be extracted during milling and beneficiation of the ores.

After this manuscript was completed the USGS released a new list of critical minerals for the United States (U.S. Geological Survey 2022). With respect to minerals and elements considered in this report, deletions include rhenium and uranium, with additions of nickel and zinc. Nickel is already discussed, but zinc is not. Potential for new zinc resources in Maine will likely be restricted to VMS deposits within pre-Devonian volcanic belts that occur throughout the state (Fig. 1).

Table 1. Qualitative ranking of potential for resources of critical minerals in different deposit types in Maine, USA.

Deposit type	Critical minerals	Occurrence potential	Resource potential
Sediment-hosted Mn	Mn	High	High
Volcanogenic massive sulphide Cu-Zn(-Pb-Ag-Au)	Co, As, Sb, Te	High	Low
Porphyry Cu-Mo	Re, Se, Te, Bi, PGE	High	Moderate
Mafic- and ultramafic-hosted Ni-Cu(-Co-PGE)	Co, PGE	High	High
Pegmatitic Li-Cs-Ta	Li, Cs, Ta	High	High
Cr in ophiolites	Cr, PGE	High	Moderate
PGE in ophiolitic ultramafic rocks	PGE	Moderate	Moderate
Granite-hosted U-Th	U, Th	Moderate	Moderate
Sn in granitic plutons and veins	Sn	Moderate	Moderate
Nb, Ta, and REE in alkaline intrusions	Nb, Ta, REE	Moderate	Moderate
W in skarn and replacement deposits	W	Moderate	Low
W and Bi in polymetallic veins	W, Bi	Moderate	Moderate
V in black shales	V	Moderate	Moderate
Sb in granite-related settings	Sb	Moderate	Moderate
Sb in orogenic veins and replacements	Sb	Moderate	Low
Te in epithermal deposits	Te	Moderate	Moderate
Be in evolved and altered felsic tuffs	Be	Low	Low
Graphite in high-grade metamorphic rocks	Graphite	Low	Low
Ti, Zr, and REE in heavy-mineral sands	Ti, Zr, REE	Moderate	Low
U in peat	U	High	Moderate

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