CHAPTER F: OBSERVATIONS ON THE ECONOMIC GEOLOGY OF NORTHEAST TANACROSS

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INTRODUCTION

The known and potential mineral resources of the Northeast Tanacross map area include minor placer gold and a variety of prospects that are likely related to one or more porphyry copper-gold-molybdenum (Cu-Au-Mo) systems. The best-defined lode mineralization is located in the Taurus-Bluff area (fig. 1), where exploration since 1970 has identified an inferred mineral resource of 68 million metric tons grading 0.275 percent Cu, 324 ppm Mo, and 0.166 ppm Au at East Taurus (Harrington, 2010). Prospects and mineral occurrences also cluster in the Pika-Fishhook area (fig. 1). Mineralization in both areas appears to be magmatic-hydrothermal in origin and latest Cretaceous in age. An evaluation of the similarities and differences between the two prospect clusters is of particular interest in assessing the potential for as-yet undiscovered porphyry Cu–Mo–Au systems in the Pika-Fishhook area.

While the Taurus-Bluff area contains multiple intrusive phases, the mineralization appears to be associated with, and genetically related to, quartz-feldspar porphyry intrusions of granitic composition. Our fieldwork did not locate any intrusions of this composition at the surface in the Pika-Fishhook area, although they may occur at depth or under vegetative cover.

The Taurus-Bluff and Pika-Fishhook areas are somewhat similar in terms of the Cu-poor styles of observed mineralization; mineralization enriched in either gold (Au) or silver-lead-bismuth-arsenic (Ag–Pb–Bi–As) occurs at both. Such mineralization could be the distal expression of porphyry Cu–Mo–Au systems. Further, both have broad alteration footprints consisting of locally developed sericite alteration, and potassic alteration occurs locally within the broader footprint. Tourmaline occurrences form notable clusters around each area; however, this pattern cannot be interpreted solely as alteration because our field observations include both pre- and post-metamorphic (latest Cretaceous?) tourmaline.

Placer gold, which has been mined at a small scale from Liberty Creek (fig. 1), could be interpreted as the southernmost locality of the Fortymile placer district, which concentrates Jurassic orogenic-type gold known to occur regionally in the Fortymile River Assemblage. However, given the lack of placer mining in nearby creeks (e.g., Dewey Creek) and the Liberty Creek placer's location downstream of the Fishhook prospect, placer gold is most likely sourced from intrusion-related mineralization in the Pika-Fishhook area. Alternatively, the gold could be re-sedimented from Late Cretaceous conglomerates mapped in the headwaters of Liberty Creek.

INTRUSIVE ROCKS

At the scale of our mapping, the Cretaceous intrusions in the Taurus-Bluff area are generalized into three groups: pre-mineralization peraluminous granite, syn-mineralization quartz-feldspar porphyry, and post-mineralization intrusions of granodiorite to quartz monzonite composition. In the Pika-Fishhook area, we mapped hypabyssal intrusions of diorite to granodiorite composition and volcanic flows of mostly andesitic composition.

Granite (Unit Kg)

The oldest of the post-metamorphic intrusions in the map area are broadly scattered dikes,

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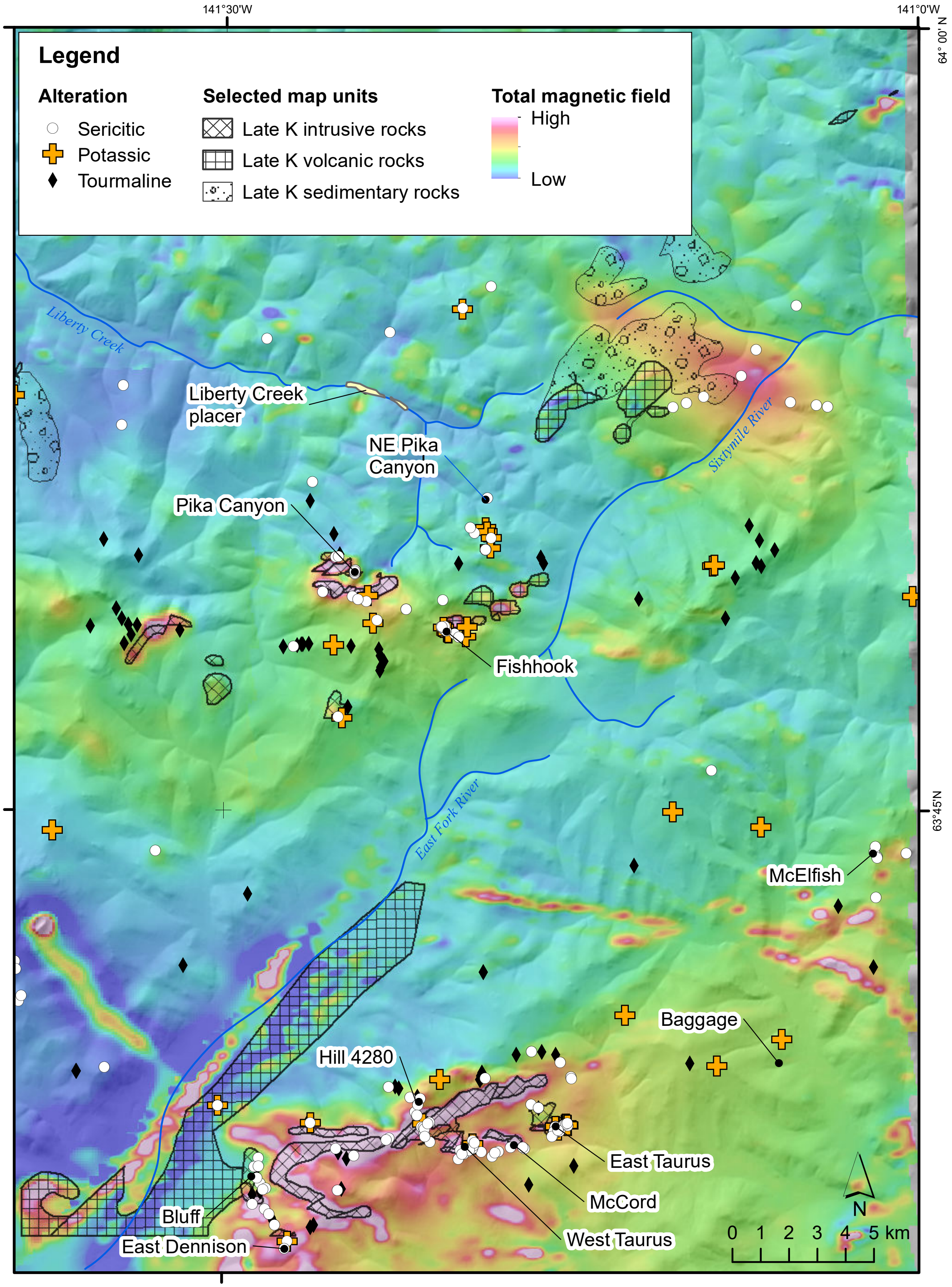

Figure 1. Map of the study area showing mineral prospects and occurrences (labeled), selected Late Cretaceous geologic units, and selected alteration assemblages based on DGGS field observations and geochemical data. Note that tourmaline occurrences include multiple events (pre-metamorphic and latest Cretaceous?) that we have not differentiated. The base map is a topographic hill shade image overlain by color-shaded simulated total magnetic field from airborne magnetic surveys of Burns and others (2011) and Emond and others (2015).

sills, and stocks of locally garnet- or muscovite-bearing granite, aplite, and pegmatite. Intrusions of this type are most abundant in the area northeast of Taurus and southwest of Fishhook; the spatial distribution of this unit does not appear to have any relation to the distribution of the Late Cretaceous intrusions or the alteration footprints around Taurus-Bluff or Pika-Fishhook. This unit occurs as both sills intruding along foliation and dikes cutting foliation, and in some field exposures it appears to be strained; therefore, we infer that it was intruded during the final stages of regional metamorphism and deformation. $^{40}Ar/^{39}Ar$ dating of this intrusive suite in the map area yields Early Cretaceous ages around 105 to 110 Ma (Naibert and others, 2018).

Quartz-Feldspar Porphyry (Unit Kqp)

One or more phases of intrusions that are most closely associated with Cu–Mo–Au mineralization at Taurus and Bluff are moderately to intensely altered but retain porphyry textures and relict quartz and feldspar phenocrysts. This unit also includes the strongly quartz-sericite-pyrite-altered intrusion breccias at the East Taurus camp and airstrip area. Whole-rock geochemical data indicate that the less-altered samples from this unit have 18–29 percent normative quartz out of total quartz and feldspar. They are therefore best described as granites. A molybdenite-bearing sample taken from this unit at West Taurus yielded U-Pb zircon age of 70.6 ± 0.9 Ma (Todd and others, 2019), while Allan and others (2013) obtained a U-Pb zircon age of 71.4 ± 0.3 Ma from altered and mineralized quartz feldspar porphyry at the Bluff prospect.

Taurus Granodiorite (unit Ktgd)

The youngest suite of intrusions in the Taurus-Bluff area is significantly more mafic and has compositions from granodiorite to quartz monzonite (unit Ktgd; map sheet 1). Smaller dikes have porphyry textures (hornblende-feldspar porphyry), while a 200- to 500-meter-thick dike (true thickness) north of Taurus is medium grained and equigranular in texture. Mafic minerals include hornblende, biotite, and clinopyroxene. Magnetite is relatively abundant; the characteristically high magnetic susceptibility of this unit makes it easily mapped or modeled from aeromagnetic surveys, as shown in the magnetic modeling section of this report. This unit was intercepted by drilling in the heart of the East Taurus prospect (Kenorland Minerals, 2017) and displays only propylitic alteration; it is convincingly post-mineralization in timing. Wypych and others (2020) obtained a U-Pb zircon age of 71.0 ± 1.1 Ma from a sample of this unit from East Taurus; this age is within error of zircon ages from the syn-mineralization quartz-feldspar porphyry and indicates a compressed time frame for emplacement of the intrusive phases in the area.

Pika Diorite (Unit Kpd)

Our mapping in the Pika-Fishhook area found a single group of relatively shallowly emplaced intrusions having a compositional range of diorite to granodiorite (unit Kpd; map sheet 1). Textures depend on the size of the intrusive body and range from porphyry to medium-grained seriate or equigranular. Porphyry intrusions are characterized by plagioclase, hornblende, and biotite in an aphanitic groundmass, while holocrystalline samples are dominated by plagioclase, quartz, pyroxene, biotite, and hornblende. Up to 5 percent primary magnetite is present in most samples. U-Pb dating of this unit yielded ages of 70.3 ± 0.5 and 68.09 ± 0.94 Ma for diorite and porphyry intrusions, respectively (Todd and others, 2019). Biotite from the Pika diorite yielded an $^{40}Ar/^{39}Ar$ plateau age of 66.3 ± 0.7 Ma (Naibert and others, 2018).

As discussed in chapter E (Wypych and others, 2020), the Pika diorite and the Taurus granodiorite are similar in geochemistry, mineralogy, and age, although the Pika diorite is somewhat more mafic in terms of major element geochemistry. The Pika diorite may also be more shallowly exposed given its smaller area of exposure and the presence of coeval andesitic volcanic flows in the immediate vicinity of Fishhook.

PORPHYRY STYLE MINERALIZATION AND ALTERATION

The mineralization of greatest economic potential in the study area is the porphyry-type Cu–Mo–Au defined by drilling in the East Taurus area. Much of the surface exposure is characterized by weathered quartz-sericite-pyrite-altered material that comprises a leached cap of variable thickness extending in places to depths of 40 to 58 meters (Leriche, 1995). Recent drilling by Senator Minerals (drill hole T08-40) intercepted relatively un-leached mineralization (compared to the adjacent drill holes), hosted in potassic-altered intrusive rock, from a depth of 7.9 meters to the end of the hole at 440 meters (Harrington, 2010).

Our petrographic observations of East Taurus mineralization show that it occurs with the assemblage pyrite, chalcopyrite, molybdenite, magnetite, and local hematite. Pyrite locally contains inclusions of pyrrhotite and chalcopyrite. Mineralization occurs as hairline A-type veinlets, local B-veinlets, and as disseminated sulfides. Potassic alteration is mostly present as secondary biotite replacement of primary biotite and rare hornblende; it occurs only locally as potassium (K)-feldspar flooding. Weak to moderate sericitic and propylitic alteration comprising sericite, chlorite, calcite, epidote, and rutile variably overprint the potassic zone. Moderate sericitic alteration includes replacement of plagioclase phenocrysts by sericite, but residual primary or secondary biotite may remain. In pervasively sericitized samples, mafics may be altered to chlorite, epidote, and rutile; D-type pyrite-quartz veinlets, and 5 percent disseminated pyrite and trace chalcopyrite are typical of this assemblage. Tourmaline does not occur in any significant abundance within the immediate East Taurus resource area.

No core was available from the West Taurus prospect; however, our examination of variably weathered surface samples indicates that the geology may be similar to that of East Taurus. Observed mineralization included disseminated and veinlet-hosted pyrite, chalcopyrite, magnetite, and molybdenite; pyrite locally contains inclusions of pyrrhotite and chalcopyrite. Samples collected for thin section show weak potassic alteration characterized by replacement of mafics by secondary biotite; rocks do not have high K_2O bulk compositions or K-feldspar flooding. Potassic alteration is partially overprinted by sericitic alteration or a propylitic assemblage of chlorite, epidote, calcite, titanite, and sericite. The greater exposure of potassic alteration at surface plus the larger footprint of the soil geochemical anomalies (Leriche, 1995) may suggest a deeper level of exposure at West Taurus than at East Taurus.

Our examination of the Bluff prospect found several types of altered dikes or stocks, intrusive breccia, and well-developed quartz-sericite-pyrite alteration. Tourmaline occurs with sericitic alteration in both intrusive and metamorphic rocks. Surface samples are strongly weathered and may be leached of copper.

OTHER STYLES OF MINERALIZATION AND ALTERATION

We sampled mineralization at the East Dennison prospect, which lies about 2.5 km south of Bluff. Based on the observed texture and relict mineralogy of the altered intrusive rock we interpret that this prospect is hosted by feldspar-hornblende porphyry (granodiorite; unit Ktgd) overprinted by quartz-tourmaline veins and sericite-pyrite alteration. This mineralization has a Ag–Pb–Bi–As–Sb geochemical signature. Our mapping found similar Ag-enriched, tourmaline-associated mineralization elsewhere in the Taurus-Bluff area. It is unclear whether the distribution of this style of mineralization is controlled by intrusions, especially unit Ktgd, structures such as the Tourmaline fault of Leriche (1995), or a combination of both features.

We observed pervasive quartz-sericite-pyrite alteration of orthogneiss along 650 m of ridgeline at Hill 4280, about 2.5 km northwest of West Taurus.

Samples from this zone carry weakly anomalous Ag, Bi, Pb, and Zn; however, one sample from this zone assayed 2.67 ppm Au, plus weakly anomalous Ag, Bi, and Te (sample 18MBW082 of Wypych and others, 2018). This gold-mineralized sample is not anomalous in its content of sulfide and did not contain vug-bearing quartz veinlets that occur locally in the area.

Mineralization in the Pika and Fishhook area appears to be largely structurally controlled and hosted in veins, breccias, or in altered rocks close to mappable structures. Some mineralization is also hosted in altered intrusive rocks without evidence of a clear structural control. Gold is the most economically significant element at the Fishhook prospect. Our highest-grade sample carried 2.15 ppm Au, plus 9.14 ppm Bi, 6 ppm Te, and 310 ppm Cu (sample 17MBW119 of Wypych and others, 2017). The sample is of faulted metamorphic rock carrying up to 5 percent iron oxide (after sulfide) occurring as both foliation-parallel bands and disseminations. The sample is one of about 20 in the area (fig. 1) where major element geochemistry yields higher than normal molar K/Al ratios (0.5–0.7) suggesting potassic alteration. These samples are massive to mylonitic in texture, light in color, and dominated by fine-grained quartz and potassium feldspar (identified in hand sample with support of whole rock geochemistry). White mica and minor biotite are present in some samples. Gill (1977) also describes local potassic alteration; in this case within an intrusive stock at the Northeast Pika Canyon prospect. We sampled another style of mineralization about 200 m to the west of 17MBW119; this sample assayed 0.7 ppm Au associated with stockwork veinlets and pervasive sericitic alteration (17MBW130 of Wypych and others, 2017). We dated alteration sericite from a felsic dike at the Fishhook prospect, yielding an ^{40}Ar/^{39}Ar plateau age of 63.7 ± 0.5 Ma (Naibert and others, 2018).

We observed Ag-bearing veins and vein breccias at a few scattered locations within the broader Pika-Fishhook area. All of these were deeply oxidized, but from their gossanous appearance they apparently contained a sulfide-rich infill. One such sample, displaying relict banded sulfide textures, assayed 56.5 ppm Ag, 3.5 percent Pb, 592 ppm Sb, 422 ppm Cu, and 323 ppm Zn. At another location near the Pika prospect, approximately 1 cm thick, unoxidized, medium-grained galena veins are locally associated with druzy quartz and assay 4420 ppm Ag, 30 percent Pb, and 3430 ppm Sb (sample 17MLW002 of Wypych and others, 2017). Silver mineralization also occurs in quartz-sericite-pyrite altered intrusive rocks (unit Kpd); one sample from the Pika prospect assayed 14.4 ppm Ag and 2070 ppm Pb (17ET008 of Wypych and others, 2017). Another sample of iron-stained, weakly altered intrusive rock from the Pika area assayed 0.175 ppm Au.

ALTERATION FOOTPRINT OF MINERALIZATION

Potassic alteration consisting mainly of secondary biotite and lesser K-feldspar replacement of intrusive rock is narrowly distributed and closely correlated with Cu–Mo–Au porphyry type mineralization at East and West Taurus (fig. 1). Potassic alteration in the Fishhook area differs in that it comprises K-feldspar-quartz alteration of metamorphic rocks. It is not accompanied by the Cu–Mo–Au mineralization, intrusive rocks, or quartz veinlets that are typical of potassic alteration in porphyry systems.

Sericitic alteration is more broadly distributed (fig. 1) and affects a wider variety of rocks. At East Taurus, quartz-sericite-pyrite alteration forms a pervasive zone peripheral to the potassic alteration. In places within the greater Taurus-Bluff area and the Pika-Fishhook area, sericitic alteration affects both intrusive and metamorphic rocks, is discontinuous from outcrop to outcrop, and varies in intensity. The distribution of intermittent sericitic alteration noted by DGGS field geologists forms two generalized clusters, one around Taurus-Bluff and a second in the Pika-Fishhook area (fig. 1).

Tourmaline observed by DGGS field geologists occurs in both igneous and metamorphic rocks as disseminations, veinlets, and breccia infills. Tourmaline observations form two broadly generalized clusters: one in the Taurus-Bluff area, and one in the Pika-Fishhook area (fig. 1). For this report we have not made any attempt to discriminate among tourmaline observations based on chemistry, textural style, or other variables, and it is likely that the tourmaline distribution presented in fig. 1 is the combined pattern of multiple original events such as a combination of Late Cretaceous and Paleozoic magmatic episodes.

All varieties of tourmaline contain about 10 percent B_2O_3 (Deer and others, 1992). It is, for the purposes of this report, a field-mappable boron anomaly. Boron is an incompatible and volatile element typically enriched in the most evolved magmas, including pegmatites. The distribution of tourmaline found during mapping does not appear to be spatially related to the mapped distribution of mid-Cretaceous granite and pegmatite (unit Kg) or Late Devonian to Mississippian Divide Mountain augen gneiss (unit MDag; map sheet 1), although tourmaline may be found in both units. Instead, DGGS tourmaline observations are clustered around the latest Cretaceous Taurus-Bluff and Pika-Fishhook intrusive centers, both of which appear to root in larger intrusive complexes concealed at depth (see magnetic modeling results, chapter G).

Tourmaline in the Taurus-Bluff area appears to be temporally associated with latest Cretaceous intrusions, even though it only rarely occurs in the proximal (Cu–Mo–Au mineralized) portions of the East and West Taurus prospects. A tourmaline-bearing quartz-sericite-pyrite assemblage at the East Dennison prospect yielded an $^{40}Ar/^{39}Ar$ sericite age of 65.8 Ma (Doug Kreiner, U.S. Geological Survey, personal commun., 2018). Intense tourmaline alteration on the ridge north of Taurus is crosscut by latest Cretaceous granodiorite (unit Ktgd; late syn-mineralization at East Taurus) indicating the tourmaline is related temporally to the hydrothermal system (Doug Kreiner, U.S. Geological Survey, personal commun., 2018).

Tourmaline in the Pika-Fishhook area occurs locally within Late Cretaceous igneous rocks, but it is mostly observed in the metamorphic country rock. Gill (1977) identified tourmaline as an alteration mineral locally in granodiorite and andesite (units Kpd and Kv, respectively, of this report). Within a sample of chalcopyrite-bearing granodiorite at the Northeast Pika Canyon prospect, tourmaline rosettes accompany alteration comprising orthoclase replacement of plagioclase, plus lesser sericite, epidote, and carbonate (Gill, 1977). DGGS was not able re-locate this occurrence during this project. In thin sections of metamorphic rocks from this area examined for our project, 1–5 percent tourmaline occurs as a fine (sub-100 to 500 micron) disseminated phase in otherwise unaltered rocks, or as macroscopic, randomly oriented 0.5–1.5 mm grains within foliation-parallel bands. Two thin sections consistently show tourmaline in trigonal cross section suggesting the mineral could be aligned to a cryptic mineral lineation perpendicular to the plane of the thin section. We did not observe tourmaline partially replacing or forming pseudomorphs of metamorphic minerals such as biotite or hornblende.

DISCUSSION OF LODE MINERAL SYSTEMS

The Taurus-Bluff and the Pika-Fishhook areas have some important geologic similarities: clusters of shallowly emplaced latest Cretaceous intrusions, scattered to pervasive sericitic alteration of latest Cretaceous age, and scattered “distal” (?) type Ag–Pb–Bi–As and Au mineralization. For example, the metamorphic host rock, alteration, and trace-element profile of gold mineralization at Fishhook are similar to the mineralization at Hill 4280 near West Taurus.

The most notable differences between Taurus-Bluff and Pika-Fishhook are geologic elements that are lacking in the Pika-Fishhook area including significant (mappable) volumes of granitic composition intrusive rocks that are closely associated with mineralization at Taurus. Further, DGGS sampling encountered no Cu–Mo–Au mineralization at Pika-Fishhook; although Gill (1977) reported chalcopyrite-mineralized rock, DGGS was unable to re-locate this presumably small occurrence.

Some of the differences between the two areas could be explained by the apparently shallower depth of exhumation in the Pika-Fishhook area. Smaller volumes of intrusive rock are exposed at Pike-Fishhook, and coeval volcanic rocks (i.e., the paleo-surface) are preserved locally. The sulfide-rich veins carrying Ag-Pb-Bi-As mineralization and the Au mineralization associated with sericite alteration could conceivably be the distal expression of a porphyry system. However, these veins and localized sericite are not the advanced-argillic alteration ‘lithocap’ described for the near-surface levels *above* porphyry systems elsewhere in the world (e.g., Sillitoe, 2010).

While both Pika-Fishhook and Taurus-Bluff areas feature similar clusters of tourmaline observations, the two areas differ in the timing of tourmaline formation. Much of the tourmaline observed in the Pika-Fishhook area may have a pre-metamorphic origin. In the Taurus-Bluff area, tourmaline appears to be spatially and temporally associated with latest Cretaceous intrusions, and we infer that this ‘boron footprint’ is an expression of the latest Cretaceous magmatic-hydrothermal systems mapped and geophysically modeled at depth in the area.

Finally, the size of the underlying magmatic systems may also help explain the differences between the Taurus-Bluff and Pika-Fishhook areas. Three-dimensional geophysical models accompanying this report (chapter G; figs. 1 and 2) suggest that the mapped intrusions in the Taurus-Bluff area represent only the shallowest expressions of a much larger intrusive complex that is almost entirely concealed. Geophysical models do not show a similar intrusion at depth in the Pika-Fishhook area.

PLACER POTENTIAL

A small amount of placer gold was produced from Liberty Creek during periods of mining in the 1930s, 1970s, and 1990s. According to the Alaska Resource Data File (ARDF), it is the only creek in the study area with known gold production (U.S. Geological Survey, 2018). The area of mining, as determined from aerial photographs, lies approximately 1 km downstream of the confluence of a north-flowing tributary that drains the immediate Pika area (fig. 1). Active mining claims extend eastward along the main stem of Liberty Creek approximately 2 km above this confluence.

There are three possible lode sources for the placer gold in Liberty Creek. The most logical source for the gold is the intrusion-related mineralization in the Pika-Fishhook area (fig. 1), which is described above. A second possible source is the newly mapped Late Cretaceous conglomerate and sandstone (unit Kc) at the headwaters of Liberty Creek. Sedimentary rocks of this age are spatially associated with placer gold in the Chicken area (Werdon and others, 2001), and a source from this unit might explain the extension of mining claims above the tributary that drains the Pika Canyon lode prospect. Finally, gold may be sourced from broadly distributed, as-yet-undiscovered auriferous veins hosted by the Fortymile River assemblage, possibly re-concentrated from Neogene to Pleistocene alluvial gravels; this is the geologic model for the Fortymile placer deposits outlined by Yeend (1996).

If intrusion-related mineralization in the Pika-Fishhook area is the source for placer gold, portions of upper East Fork and Sixtymile rivers may be prospective for undiscovered placer resources. Our work seems to indicate that the Fishhook prospect, which is drained by these rivers, has actively eroding gold mineralization at surface. If gold is sourced from Late Cretaceous sedimentary rocks, then placer gold should also occur in tributaries to the Sixtymile River as well as the headwaters of Liberty Creek.

CRITICAL MINERAL POTENTIAL OF THE STUDY AREA: RHENIUM

The map area contains significant potential for one critical mineral: rhenium (Re). With an average abundance of less than 1 parts per billion (ppb), Re is one of the rarest elements in Earth's continental crust. It has an extremely high melting point, and thus its primary industrial application is as a component in high-temperature alloys used in jet aircraft engines. Rhenium is produced as a byproduct of Cu and Mo production, with Chile being the world's leading producer (John and others, 2017). In 2018, the U.S. relied on imports for about 80 percent of its Re consumption (U.S. Geological Survey, 2019).

DGGS geochemical sampling of the study area is the first, to our knowledge, to include low-detection-limit Re analyses (Wypych and others, 2018). These analyses indicate that the East Taurus Cu–Mo–Au prospect contains significant concentrations of Re and could potentially host a resource of this critical mineral. The average Re concentration from 38 samples of East Taurus Cu–Mo–Au mineralized drill core was 525 ppb, and the maximum Re concentration was 3,500 ppb. Excluding one high-Re outlier, Re is closely correlated to Mo (R^2 0.91) and to a lesser extent Cu (R^2 0.51). The Re/Mo indicated by these well-correlated samples is 0.0021.

East Taurus contains an inferred mineral resource of 68 million metric tons grading 0.275 percent Cu, 324 ppm Mo, and 0.166 ppm Au (Harrington, 2010). Assuming a Re/Mo of 0.0021, the average Re grade of this resource is 672 ppb,

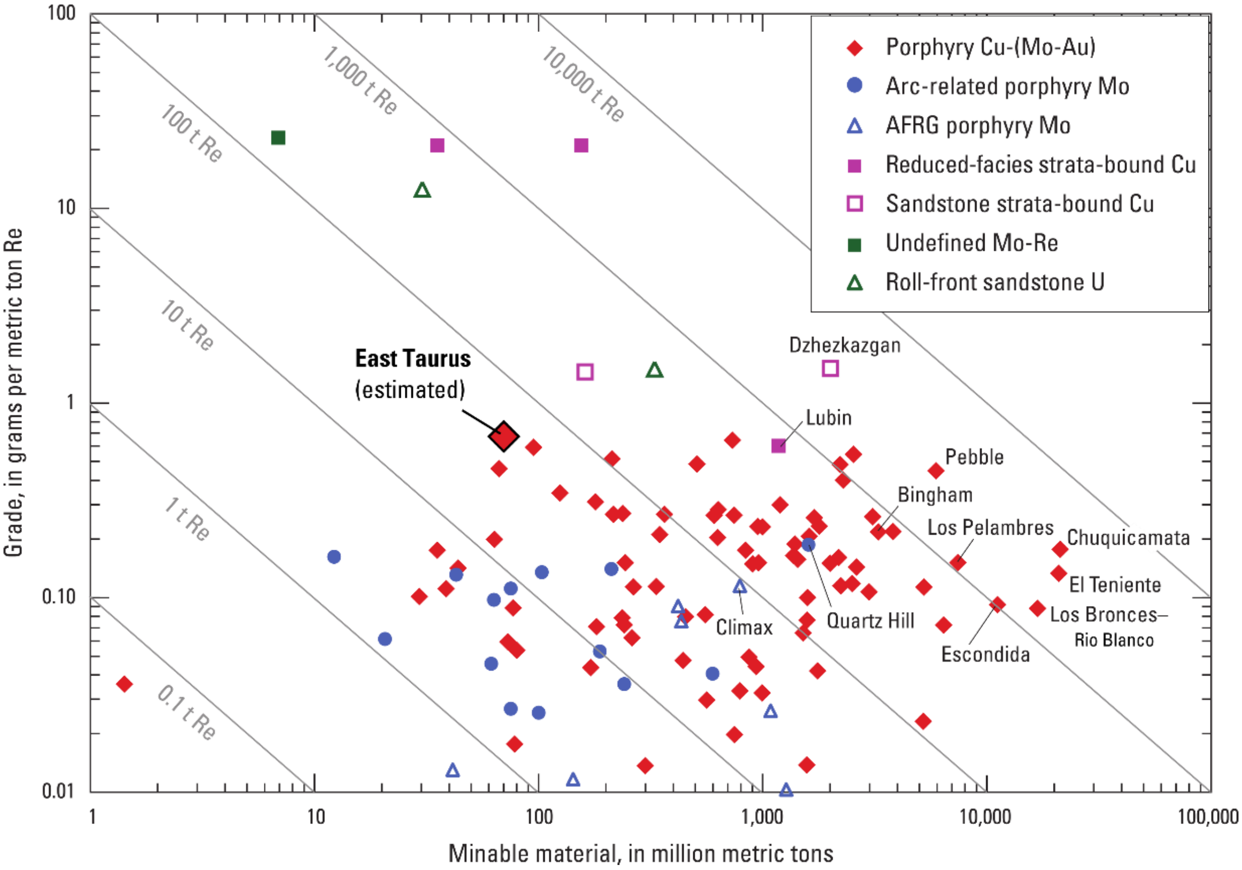

Figure 2. Rhenium grades and resources worldwide by deposit type. Gray diagonal lines are isolines of contained Re in metric tons (t). AFRG: alkali-feldspar rhyolite-granite. Modified from John and others (2017).

and contained Re totals 46 metric tons. By this extrapolation, Re grades at East Taurus are at the high end of the range for global porphyry copper systems (fig. 2). Future exploration may expand the total Re endowment.

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