BEDROCK GEOLOGIC MAP OF THE EASTERN MORAN AREA, TANANA B-6 AND C-6 QUADRANGLES, ALASKA

L.K. Freeman, R.J. Newberry, G.A. Griesel, B.A. Elliott, D.J. Szumigala, T.A. Lough, and Evan Twelker

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The view from Moran Dome across part of the map area. Photo: L.K. Freeman.

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INTRODUCTION

The eastern Moran geologic map area is 150 miles west of Fairbanks, Alaska, north of the Yukon River between the communities of Ruby and Tanana (fig. 1). Historical and active placer mines in the Melozitna mining district, which encompasses the Moran Dome area, have produced more than 12,000 ounces of gold and an undetermined amount of tin, yet little is understood about sources for the placer metals, or the area's gold and polymetallic lode occurrences.

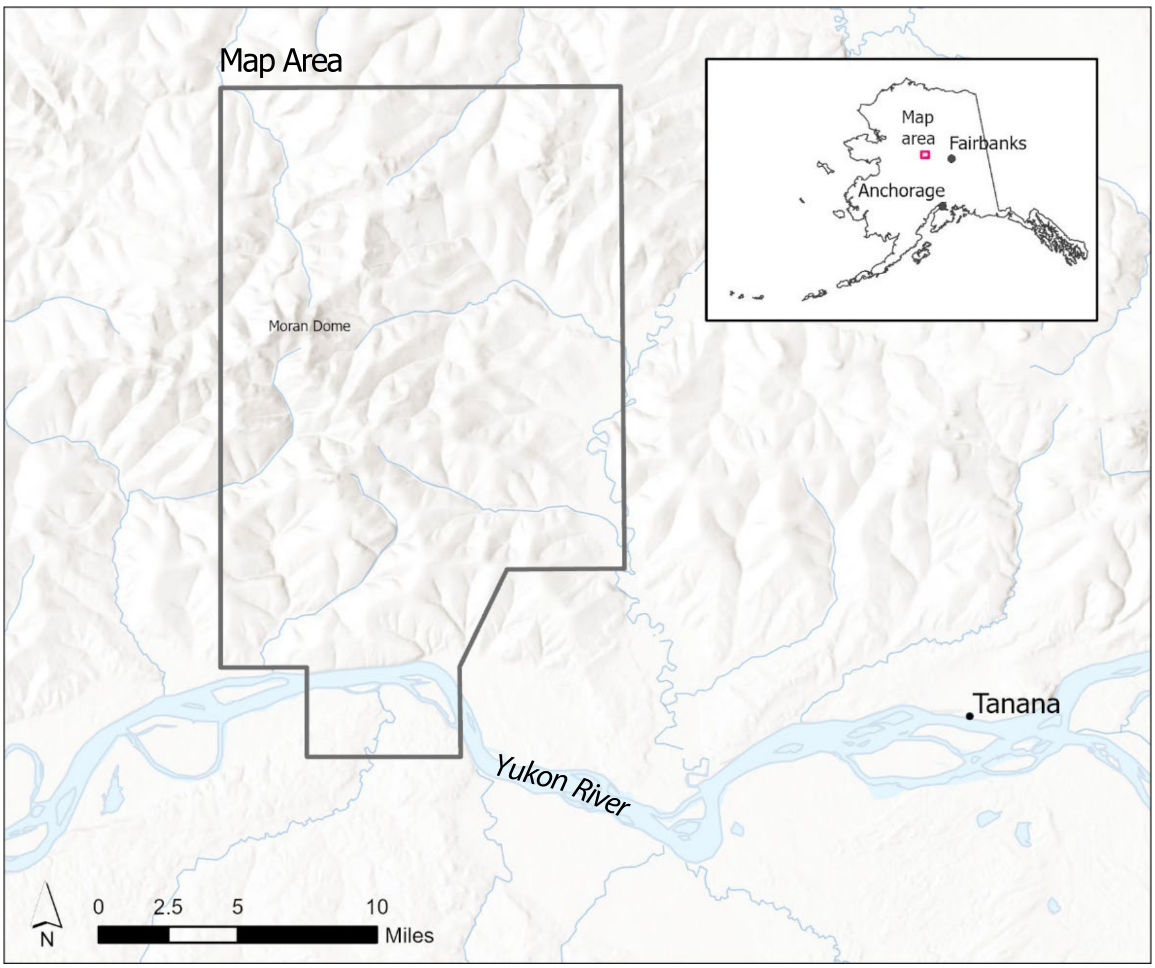

Figure 1. Location of Moran-area geologic map.

During the summer of 2011, geologists from the Alaska Division of Geological & Geophysical Surveys' Minerals Resources Section carried out a geologic field survey, including mapping and sampling of the 301-square-mile eastern Moran area in the Tanana A-6 and B-6 quadrangles, Alaska. The mapping is part of an integrated program of airborne geophysical surveys followed by geologic mapping; it gives geological context to the Moran airborne geophysical survey (Burns and others, 2019) and provides basic information critical to understanding Alaska's geology and mineral-resource potential.

CORRELATION OF MAP UNITS

Figure 2 illustrates the relative age ranges, terrane affiliations, and structural or stratigraphic relationships between map units.

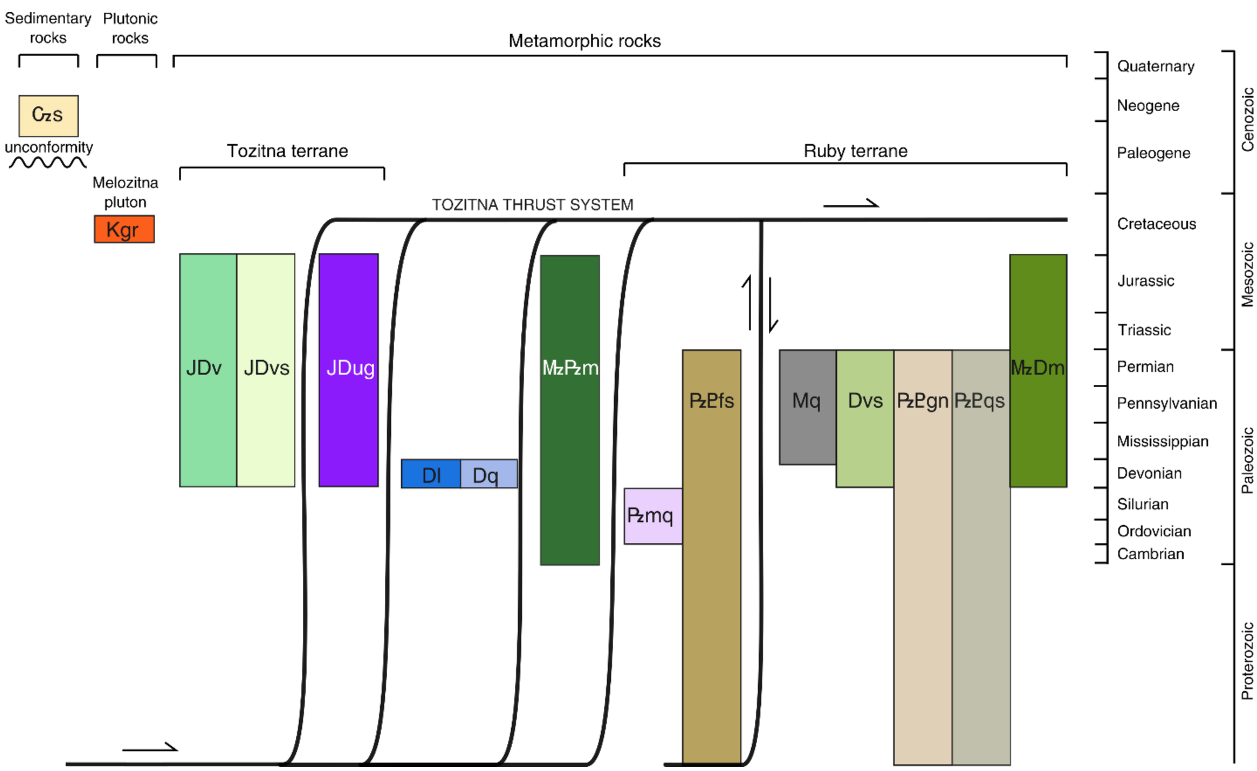

Figure 2. Schematic diagram illustrating the ages, correlations, and relationships between map units.

DESCRIPTION OF MAP UNITS

Sedimentary Rocks

Czs CLASTIC SEDIMENTARY ROCKS (CENOZOIC)—Poorly consolidated pebbly sandstone, sandy siltstone, brown shale, and minor lignite coal of non-marine, fluvial origin. Restricted to the southernmost map area and exposed in a single bluff north of the Yukon River. Age is based on palynomorphs recovered from carbonaceous material which is consistent with the Homerian Stage of the Cook Inlet region (P.A. Zippi, written commun., 2019). Age is consistent with Oligocene-Miocene pollen found outside of map area (Chapman and others, 1982). Corresponds to unit Ts of Chapman and others (1982), Tcb of Wilson and others (1998), and Ts of Patton and others (2009).

Igneous Rocks

Kgr MELOZITNA GRANITE (CRETACEOUS)—The easternmost portion of the Cretaceous Melozitna granite body occupies most of the northwest map area. Granitic dikes (presumably related) are present within one kilometer of the main body. Melozitna granite intrudes several Ruby terrane units (Dvs, PzPgn, PzPqs), and unit Dq. Within the map area the body is approximately 80 percent monzogranite and 20 percent syenogranite, with rare alkali-feldspar granite. Texturally most of Kgr is coarse-grained, porphyritic alkali-feldspar megacrystic granite, with lesser sub-equigranular granite, and granite aplite and granite porphyry dikes. Magnetic susceptibility is highly variable (0.01–6.7, average 0.56 $x10^{-3}$ Système International units [SI]) despite little variation in composition. Most (about 80 percent) values are low (average 0.08 $x10^{-3}$ SI), and about 20 percent are greater than 1 $x10^{-3}$ SI. Higher magnetic susceptibility values occur in clusters that are most common near the southern border of Kgr and are never present near the northern border. Kgr in the map area yields U-Pb zircon ages of 112 ± 1 to 115 ± 1 Ma (Freeman and others, *in prep.*) and $^{40}Ar/^{39}Ar$ biotite ages of 106 ± 1 to 116 ± 1 Ma (Benowitz and others, 2019). Based on trace-element compositions, especially elevated rubidium (Rb), niobium (Nb), yttrium (Y), tantalum (Ta), and ytterbium (Yb) (Lough and others, 2012), the rocks plot as within-plate granite (Freeman and others, 2014; Tuzzolino, 2016). Based on the peraluminous character and relatively high K_2O/Na_2O ratios (Tuzzolino, 2016), the rocks plot as 'S-type' granite (discriminant of Chappell and White, 2001). A single sample from the westernmost part of the body yielded an initial $^{87}Sr/^{86}Sr$ ratio of 0.719 (DeCarlo, 2004), which is consistent with suggestions that this body represents melted lower crust caused by extension-related decompression (Miller and Hudson, 1991). Corresponds to unit Kg of Chapman and others (1982), Kgr of Dover (1994), Kg of Wilson and others (1998), and Kgr of Patton and others (2009).

Monzogranite consists of quartz (20–45 percent, invariably smoky), alkali feldspar (20–45 percent), plagioclase (15–50 percent), biotite (2–12 percent), muscovite (0–5 percent), tourmaline (0–7 percent), and chlorite (trace to 5 percent, replacing biotite). Syenogranite is similar, but with higher alkali feldspar (40–65 percent), and lower plagioclase (10–20 percent) and biotite (1–6 percent) contents. In both subunits, alkali feldspar is commonly 3 mm to 5 cm long; other minerals are typically 1–4 mm. Granite aplite contains sub-equigranular, 0.5- to 2-mm-diameter crystals. In thin section, trace to 0.5 percent fluorite and trace to 0.1 percent allanite are locally present; zircon, apatite, and monazite are invariably present in small amounts. Both texturally primary and secondary white mica occur; the latter is more common. Kgr in the map area typically displays little alteration, which is generally restricted to chlorite replacement of biotite, and some secondary muscovite, fluorite, and (or) tourmaline. Locally, however, biotite is completely replaced by muscovite and chlorite and feldspars are largely replaced by fine-grained muscovite.

Metamorphic Rocks of the Tozitna Terrane

The Tozitna terrane, as defined by Silberling and Jones (1984), includes metamorphosed mafic, ultramafic, and sedimentary rocks that occur as a continuous belt across the Tanana, Livengood, and Circle quadrangles and is generally considered to represent oceanic crust thrust onto continental rocks (Dover, 1994). Originally called the Rampart Group (Mertie, 1937), it is also known as 'Rampart assemblage' (Dover, 1994), 'Tozitna assemblage' (Wilson and others, 1998), and 'Angayucham-Tozitna Terrane' (Patton and others, 2009). Chapman and others (1982) refer to it as unit JMms (mafic and sedimentary rocks) in the Tanana Quadrangle, including this studies' map area.

Tozitna terrane rocks in the map area are predominantly augite-porphyroclastic greenschist with mineral assemblages suggesting incomplete metamorphic reactions at poorly defined conditions. Major-element compositions indicate they are almost exclusively mafic (basalt and rare basaltic andesite; Lough and others, 2012) but due to pervasive schistosity, it is commonly unclear whether they were intrusive, extrusive, or volcaniclastic. Immobile element trace-element compositions are consistent with mid-ocean ridge basalt (discriminants of Pearce and Cann, 1973; Pearce, 1982; and Meschede, 1986) in almost all cases. Rocks with coarser and more abundant augite (± hornblende) are commonly less foliated and appear to have been gabbro. Such rocks are better described as greenstone. In both rock types, the original plagioclase compositions are rarely preserved, and albite (identified by electron microprobe analyzer [EMPA] and X-ray diffraction [XRD]) is ubiquitous. Albite is typically intergrown with fine-grained chlorite and pumpellyite (confirmed by EMPA and XRD). Blue amphiboles (0.1–5 percent) are common. Limited EMPA analyses indicate these are crossite rather than glaucophane, with uncertain metamorphic-grade implications. However, most of the amphibole present is actinolite (EMPA confirmed), with primary late-magmatic(?) hornblende in a few samples. Stilpnomelane and titanite are variably present.

Age is based on Devonian to Jurassic radiolarians in chert and Devonian to Permian megafossils in carbonate rocks (Patton and others, 2009) found within the unit (outside of map area). In the map area, hornblende from a hornblende metagabbro (unit JDv) yields an $^{40}Ar/^{39}Ar$ plateau age of 232 ± 2 Ma (Triassic; Benowitz and others, 2019).

Based largely on hand-specimen characteristics, three sub-units are defined in the map area: (1) meta-volcaniclastic and metamafic rocks, (2) metamafic rocks, and (3) metagabbro and meta-ultramafic rocks. These are described below.

JDvs META-VOLCANICLASTIC AND METAMAFIC ROCKS (JURASSIC TO DEVONIAN)—This is the least abundant Tozitna terrane sub-unit in the map area and is poorly characterized. It comprises 15–30 percent metamafic rocks with clastic textures, 50–60 percent metamafic rocks lacking clastic textures, about 10 percent siliceous phyllite, and 5–10 percent meta-ultramafic rocks. Excluding rare serpentinite, the magnetic susceptibility is low to moderate (0.08–0.81, average 0.38 $x10^{-3}$ SI) Rocks with metaclastic textures have lower magnetic susceptibility (average 0.33 $x10^{-3}$ SI) than those lacking such (average 0.42 $x10^{-3}$ SI).

Meta-volcaniclastic rocks are medium to pale green, contain sand- to pebble-sized clasts, and have strong mylonitic fabric. In thin section the clastic texture is less obvious, obscured by the strong mylonitic fabric, and in one sample a mafic blastomylonite. Augite porphyroblasts are ubiquitous. Samples contain 15–30 percent albite, 5–25 percent chlorite, 20–25 percent little-altered augite, 0–10 percent epidote, 0–10 percent prehnite, 0–15 percent plagioclase, 5–10 percent pumpellyite, and 2–15 percent blue amphibole (crossite).

Metamafic rocks in JDvs include both greenschist and greenstone (as described in hand specimen) and metabasalt and metagabbro, the former finer-grained than the latter. Siliceous phyllite is green, maroon, or purple, very fine-grained, and may represent a weakly metamorphosed cherty clastic rock. Meta-ultramafic rocks include both black, massive serpentinite and partly serpentinized feldspathic peridotite.

JDv METAMAFIC ROCKS (JURASSIC TO DEVONIAN)—This is the characteristic unit of the Tozitna terrane in the map area. This unit has a wide range in magnetic susceptibility (0.01–33 x10^{-3} SI), reflecting a wide variety of contained rock types, but moderate (0.3–0.7 x 10^{-3} SI) values are most common. Excluding serpentinite, the average magnetic susceptibility is 0.51 x 10^{-3} SI. Metamafic rocks (both greenschist and greenstone) comprise about 90 percent of the unit; it also contains about 5 percent meta-chert and siliceous metasedimentary rocks, about 5 percent metaclastic(?) rocks, and 1 percent serpentinite.

Greenschist has a strong schistose fabric with 20–30 percent augite porphyroclasts 'floating' in a matrix of 0–15 percent actinolite, 5–35 percent albite, 10–35 percent chlorite, 0–20 percent clinozoisite-epidote, 0 (most commonly) –15 percent plagioclase, 5–25 percent pumpellyite, 0–5 percent blue amphibole (crossite), 0–7 percent stilpnomelane, and 1–5 percent titanite. In some cases, the protolith appears to be volcanic, in other cases gabbroic (holocrystalline), but most commonly schistose texture obscures rock origin.

Greenstone, in almost all cases a mafic rock with little schistosity, appears to possess a gabbroic texture in thin section. Either the original gabbroic texture resisted developing foliation, or more-foliated rocks simply represent gabbroic rocks subjected to higher strain. In thin section, gabbroic greenstone contains 5–40 percent albite, 5–30 percent chlorite, 20–50 percent augite, 5–15 percent epidote, 0–10 percent actinolite, 0–20 percent (late magmatic?) hornblende, 0.5–1 percent opaque, 0–15 percent pumpellyite, 0–2 percent blue amphibole (crossite), 0–10 percent stilpnomelane, 0.2–3 percent titanite, and 0–3 percent quartz. A single sample of dioritic greenstone (XRF analysis) lacks clinopyroxene and contains 5 percent opaque mineral(s) and 30 percent residual plagioclase in a matrix of chlorite, albite, stilpnomelane, and minor quartz.

Metaclastic rocks include both metamafic rocks containing sand- to pebble-sized clasts ('volcanoclastic') and metawacke. Major oxide analysis of one sample (Lough and others, 2012) suggests it contains 10 percent chlorite, 15 percent quartz, and 75 percent albite.

Metasedimentary rocks are of two types: meta-chert and albite-quartz schist. In thin section meta-chert is a fine-grained, quartz-rich (85–90 percent quartz) rock with 0-10 percent muscovite, 0-10 percent blue amphibole (crossite), and minor opaque mineral(s), albite, and (or) stilpnomelane. Based on hand specimens and major oxide analyses (Lough and others, 2012), albite-quartz schist is relatively SiO_2-rich (69–87 percent), with abundant albite (3.7–8.8 percent Na_2O), and lesser chlorite (approximately 5–15 percent). The protolith is unclear; it might represent a highly altered mafic rock, or one mechanically mixed with chert.

Meta-ultramafic rocks are the least abundant component. These rocks are dark-colored and have high magnetic susceptibility (1–45 x10^{-3} SI). Based on hand specimen appearance and major oxide analyses (Lough and others, 2012), they are partly to largely serpentinized feldspathic peridotite and possibly pyroxenite.

JDug METAMAFIC AND META-ULTRAMAFIC ROCKS (JURASSIC TO DEVONIAN)—Unit constitutes about one quarter of Tozitna terrane in map area and is characterized by moderate to very high magnetic susceptibility (0.3–107, average 16 x10^{-3} SI). Based on hand specimen identification and major oxide analyses, approximately 60 percent of this unit is metamafic and 40 percent is meta-ultramafic. Metamafic rocks include both greenstone and greenschist; in thin section, the former possesses remnant gabbroic textures, and the latter are too foliated to determine protolith texture but could have been gabbroic. Based on major oxide analyses, 10–20 percent of the metagabbroic rocks were likely troctolite (olivine- and plagioclase-rich rocks) with olivine largely serpentinized (Lough and others, 2012). More than a third of the metagabbroic rocks analyzed contain anomalously high Na_2O (5.4–9.9 percent) and elevated SiO_2, suggesting silica-albite alteration. In thin section the metamafic rocks contain 0–15 percent actinolite, 10–45 percent albite, 0–35 percent chlorite, 0–15 percent clinozoisite, 10–25 percent residual augite, 0–5 percent (late magmatic?) hornblende, 2–7 percent opaques, 0–10 percent residual plagioclase, 0–20 percent pumpellyite, 0.3–15 percent blue amphibole (crossite), and 0.3–3 percent titanite. Compared to metamafic rocks from JDvs and JDv, those from JDug contain higher amounts of blue amphibole and albite and lack stilpnomelane.

Meta-ultramafic rocks in unit JDug appear to mostly represent variably serpentinized peridotite. Thin section examination indicates they contain 10–20 percent augite, 5–20 percent orthopyroxene, 5–10 percent opaque, 5–40 percent olivine, and 20–55 percent serpentine. Olivine is the most strongly serpentinized and augite is the least-altered silicate present.

Metasedimentary Rocks of Probable Devonian Age

Low grade metamorphosed rocks of primarily sedimentary origins are located between the Tozitna terrane and the Ruby terrane. They correspond to the 'Devonian metaclastic sequence' of Dover (1994) and to quartzite (meta-chert), carbonate rocks, and phyllite of the Angayucham-Tozitna terrane of Patton and others (2009). Two sub-units (described below) are broken out: quartzite, quartz schist, and meta-conglomerate (Dq), and dolomitic limestone (Dl), corresponding to 'blastomylonitic quartz wacke' (Dmw) and 'limestone and dolomite' (Dl) of Dover (1994), respectively. Wilson and others (1998) include the quartz-rich rocks as part of the Ruby terrane, but identify the carbonate-rich rocks as 'Devonian marble' (Dm). Age is based on U-Pb minimum depositional age from detrital zircon (392 ± 7 Ma; Freeman, *in prep.*) for unit Dq, and on upper Devonian conodonts found in Dl from outside the map area (Dover, 1994; Harris, written commun., 1983, *in* Patton and others, 2009).

Dq QUARTZITE (DEVONIAN)—Primarily quartz-rich low grade metamorphic rocks, but also includes some metamafic and meta-intermediate rocks. The unit is about 65 percent quartzite, 25 percent quartz schist, 3 percent quartz-poor schist, 2 percent metaconglomerate, and 5 percent meta-mafic and intermediate greenschist, with magnetic susceptibilities of 0.01–0.15 x10^{-3} SI, 0.02-0.3 x10^{-3} SI, 0.1–0.3 x10^{-3} SI, 0.01–0.14 x10^{-3} SI, and 0.2–0.7 x10^{-3} SI, respectively. The average magnetic susceptibility for the unit is 0.07 x10^{-3} SI, reflecting the predominance of quartz-rich rocks. Quartzite in Dq contains 85–98 percent quartz, is variably graphitic (but usually not), and locally displays a bimodal grain size distribution (1- to 5-mm-diameter quartz grains in a 0.1–0.3 mm matrix). Other minerals present include 1–10 percent muscovite, 0–5 percent chlorite, and 0–1 percent opaque mineral(s). In thin section, a common texture consists of fine-grained mosaic quartz cut by anastomosing to planar discrete mylonitic bands. Quartz schist is similar, but with higher muscovite (up to 15 percent) and chlorite (up to 10 percent) and lower quartz (typically 60–70 percent). Rare quartz-poor schist contains more mica (up to 60 percent) and less quartz (typically 20–40 percent). Metaconglomerate contains quartz-rich stretched pebbles up to 2 cm in length in a quartz-rich sand-sized matrix. Meta-mafic rocks are poorly exposed and consist of two types: those with mid-ocean ridge (MORB) trace element characteristics (similar to JDv) and those with oceanic arc trace element characteristics (similar to unit MzPzm). (Mafic rock assignments based on Lough and others (2012); discriminant diagrams in Pearce and Cann, 1973; Pearce, 1982; Pearce, 1983; and Meschede, 1986.) Based on hand-specimen descriptions, the former contains possible augite porphyroblasts in a fine-grained green matrix; the latter is an ambiguous greenschist. A thin section of the latter contains 10 percent actinolite, 35 percent albite, 15 percent chlorite, 15 percent clinozoisite, 2 percent blue amphibole, 15 percent stilpnomelane, and 7 percent opaque. Meta-intermediate rocks contain 56–62 percent SiO_2 (Lough and others, 2012) and a mineralogy dominated by albite, chlorite, and epidote-clinozoisite, and quartz. The meta-mafic rocks might represent tiny thrust slivers of JDv and MzPzm within unit Dq.

Unit Dq differs from Ruby terrane quartzite units by virtue of its lower metamorphic grade, seen as remnant sedimentary features (for example, conglomerate) and the absence of biotite, chloritoid, and paragonite. Ruby terrane quartzite units also contain a lower proportion of quartzite (*sensu stricto*) than unit Dq and much higher proportion of quartz schist.

Dl DOLOMITIC LIMESTONE (DEVONIAN)—Unit occurs as a single outcrop within Dq. Its size, as shown on other maps (for example, Wilson and others, 1998), is grossly exaggerated. Black to gray sparry limestone with dark, irregular to wavy bands of micrite, which contains abundant microscopic dolomite rhombs. Local concentric structures resembling oolites occur within sparry bands. Observed textures can be interpreted as a sparry, oolitic algal mat boundstone. No macrofossils were observed and an attempt to recover conodonts was unsuccessful.

Metamorphic Rocks of Uncertain Affinity

MzPzm GREENSCHIST-METAMORPHOSED MAFIC ROCKS (MESOZOIC TO PALEOZOIC)—Unit occurs as thrust(?) slivers within Dq, and between Dq and Ruby terrane metamorphic rocks. Based on major-oxide analyses (Lough and others, 2012), unit is entirely mafic schist, but it is distinctly different from metamafic rocks in the Tozitna and Ruby terranes. Unlike Tozitna terrane metamafic rocks, MzPzm rarely contains residual augite, lacks pumpellyite, and lacks a MORB trace-element signature (Lough and others, 2012). Unlike Ruby terrane metamafic rocks, it displays no evidence for earlier amphibolite-facies metamorphism and uniformly displays an oceanic arc trace-element signature (Lough and others 2012; discriminant of Pearce, 1983). MzPzm is the only metamafic unit in the map area that consists almost exclusively of metamafic rocks. Consequently, the magnetic susceptibility is uniformly moderate (0.18–2.3, average 0.57 $x10^{-3}$ SI). Age is only constrained by being older than early Cretaceous metamorphic ages (128–140 Ma; Benowitz and others, 2019) documented for other units in the area.

Unit is typically a medium to dark green schistose rock (greenschist); although some rocks are more massive in hand specimen, they uniformly display schistosity in thin section. One-third of analyzed samples contain anomalously high (6.7–7.9 percent) Na_2O, suggesting spilitic alteration (Lough and others, 2012). One-tenth of field samples contain calcite; most are calcite-free. One field sample contains visible augite. In thin section, rocks contain 10–20 percent actinolite, 20–35 percent albite, 0–10 percent calcite, 15–25 percent chlorite, 25–30 percent clinozoisite-epidote, 0–10 percent augite (residual porphyroclasts), 0–2 percent stilpnomelane, and 0.3–5 percent titanite.

Metamorphic Rocks of the Ruby Terrane

The Ruby terrane, as defined by Silberling and Jones (1984), is a structurally complex assemblage of greenschist- and amphibolite-facies metamorphic rocks that stretches for several hundred kilometers along the Ruby geanticline. Lithologies and metamorphic conditions vary considerably within the terrane. Rocks of this terrane have experienced multiple deformational and regional metamorphic events (Dover, 1994; Moore and Box, 2016). The Ruby terrane is generally considered to be Proterozoic to Paleozoic, based on sparse geochronologic data. Strongly recrystallized marble yielded poorly preserved Paleozoic corals (Chapman and others, 1982; Patton and others, 2009). Three siliceous metamorphic rocks yielded detrital zircons with Mesoproterozoic peaks and youngest age of latest Mesoproterozoic, suggesting an early Neoproterozoic depositional age (Bradley and others, 2007). One detrital zircon sample yielded a late Neoproterozoic youngest age (Bradley and others, 2007). In the map area youngest detrital zircon U-Pb ages of 338 ± 32 Ma, 379 ± 4 Ma, 946 ± Ma, and 982 ± 28 Ma (Freeman and others, *in prep.*) suggest a bimodal age distribution, with both early Neoproterozoic and mid-Paleozoic components. Within the map area, cooling from the last regional metamorphism took place between 128 ± 2 and 140 ± 2 Ma (early Cretaceous), based on $^{40}Ar/^{39}Ar$ mica ages (Benowitz and others, 2019). Remnant almandine garnet, hornblende, plagioclase, and kyanite (confirmed by EPMA; this study) are variably present, indicating the Ruby terrane in the map area experienced early amphibolite-facies metamorphism and a later, extensive, greenschist-facies overprint. Dover (1994) reports similar findings for an area 50 km northeast of the map area. In contrast, Roeske and others (1995) report eclogite-facies metamorphic conditions in Ruby terrane metamorphic rocks of the Kokrines Hills, 75 km southwest of the map area. Contact metamorphism to hornfels and skarn, and granitic dikes, are locally present within a kilometer of the Cretaceous Melozitna pluton (Kgr) in the northwest map area. Ruby terrane units in the map area correspond to 'schist, quartzite, phyllite, and slate (PzpЄm)' of Chapman and others (1982), 'metamorphic suite of the Ray Mountains (Pzs)' of Dover (1994), 'Ruby terrane' of Patton and others (1994), 'Ruby metamorphic complex (PzZrqs, pelitic and quartzitic schist)' of Wilson and others (1998), and 'Ruby terrane (PzPsr, pelitic schist, calc schist and quartzite)' of Patton and others (2009).

Ruby terrane rocks are divided into seven sub-units, described below. These divisions are similar to those of Dover (1994) for Ruby terrane rocks near the map area.

MzDm METAMAFIC ROCKS (MESOZOIC TO DEVONIAN)—This could be the youngest Ruby terrane unit in the map area; it occurs as lenticular bodies in Dvs and Mq and between Mq and other units.

These bodies could (in part) represent mafic intrusions, and if so, are younger than Mq. Alternatively, they could represent locally preserved mafic extrusions and thus are of Devonian-Mississippian age, or some combination of the two. Smaller metamafic bodies are also sporadically present in units Dvs and Mq, but are too small to depict on the map. This unit is equivalent to MzPzm (metabasite) of Dover (1994).

Magnetic susceptibility of MzDm is low to moderate (0.01–0.93, average 0.43 x10^{-3} SI), reflecting the presence of multiple rock types. Based on field characteristics and major oxide analyses (Lough and others, 2012), approximately 75 percent of unit is metamafic, 5–10 percent is meta-intermediate, and 15-20 percent is quartz-rich schist. Intermediate-composition rocks usually contain high (5.7–7.3 percent) Na_2O, suggesting they represent spilitized mafic rocks. Trace-element compositions suggest that nearly 90 percent of the mafic rocks have a continental arc origin, less than 10 percent have an oceanic arc origin, and one rock has a within-plate origin (discriminant diagrams in Pearce and Cann, 1973; Pearce, 1982; Pearce, 1983; and Meschede, 1986).

Metamafic rocks are typically green to black, fine to medium grained, and strongly to weakly foliated. In thin section, most contain hornblende (0–35 percent) and minor (residual) plagioclase (0–6 percent), and locally minor garnet (3–5 percent). However, the predominant minerals present are actinolite (2–57 percent), albite (8–35 percent), chlorite (2–35 percent), and clinozoisite-epidote (15–25 percent), which are consistent with or require lower-temperature metamorphic conditions. In particular, cores of green-brown pleochroic hornblende surrounded by paler green actinolite, and garnet altered to chlorite, require early amphibolite-facies and later extensive greenschist-facies overprinting metamorphism. Ubiquitous titanite (3–6 percent) and sporadic stilpnomelane (0–5 percent) are also present; calcite occurs in about 5 percent of the rocks. Meta-intermediate rocks are usually described as quartz-chlorite-epidote-albite semischist. Quartz-rich schist typically contains 50-75 percent quartz, with the remainder mostly muscovite and chlorite, with lesser plagioclase, albite, and titanite and variable clinozoisite-epidote or calcite. One tourmaline-quartz hornfels sample was found near the Melozitna granite, a contact-metamorphosed version of quartz schist.

Because quartz schist invariably occurs interlayered with metamafic rocks in unit MzDm, it is likely that the metamafic rocks—at least in part—represent sills, highly deformed dikes, or flows.

Mq QUARTZITE AND QUARTZ SCHIST (MISSISSIPPIAN)—Unit occurs in a band across the south-central map area, apparently within Dvs, and in thrust contact with PzPfs to the south. Mq contains mostly sub-equal (40–45 percent) amounts of micaceous quartzite and quartz-rich schist and smaller amounts (5–10 percent) of quartz-poor schist and metamafic rocks. Discreet metamafic rock bodies (MzDm) also occur within and adjacent to Mq. Unit Mq is characterized by variable, but generally low (0.005-0.86, average 0.09 x10^{-3} SI) magnetic susceptibility, due to the abundance of quartz-rich rocks and the variable presence of metamafic rocks. Mq is distinguished from Dq by the higher abundance of quartzite and lower metamorphic grade of Dq. Mq is distinguished from PzPqs by the restriction of that unit to PzPgn and the absence of quartz-poor schist and metamafic rocks in PzPqs. Metamorphic conditions experience by Mq are mostly greenschist-stable, suggested by the widespread occurrence of chlorite. One sample contains residual kyanite in thin section, suggesting an earlier amphibolite-facies metamorphic event. Such is also suggested by residual hornblende, plagioclase, and (or) garnet in MzDm bodies that occur in or adjacent to Mq. Unit age is based on youngest detrital zircon age of 337 ± 20 Ma (Freeman and others, *in prep.*). A pyrite clast of a gastropod, recovered in a placer mine concentrate from a bedrock cut from unit Mq west of the map area, is interpreted to be an internal cast of an euomphalid gastropod of Ordovician to Permian age (R.B. Blodgett, written commun., 2015).

Quartzite is white to black, variably graphitic, and contains 85–98 percent quartz; the remainder is mostly muscovite ± chlorite. Approximately 5 percent apatite (based on major element analysis, Lough and others, 2012) occurs in one sample (interpreted to be a meta-chert). Quartz-rich schist is also variably graphitic, but more variable mineralogically. In thin section it contains 40–80 percent quartz, 0–5 percent albite, 0–10 percent biotite, 0–5 percent calcite, trace to 15 percent chlorite, 0–3 percent chloritoid, 0-5 percent kyanite, 0–5 percent graphite, and 10–35 percent muscovite. Quartz-poor schist contains 5–35 percent quartz and is variably muscovite-, calcite-, chlorite-, albite- and (or) chloritoid-rich. One sample contains significant paragonite (identified by EMPA). In hand specimen the metamafic rocks are medium green and contain abundant chlorite, epidote, actinolite, minor calcite, and likely albite. Their trace element compositions suggest a mix of oceanic arc, continental arc, and within-plate origins (discriminant diagrams in Pearce and Cann, 1973; Pearce, 1982; Pearce, 1983; and Meschede, 1986).

Protoliths for most rocks in this unit appear to have been quartz-rich sandstone and mixtures of quartz- and clay-rich sediments. The metamafic rocks could represent mafic dikes, thin sills, or possibly thin flows.

Dvs SCHIST OF PROBABLE VOLCANIC ARC ORIGIN (DEVONIAN)—Unit accounts for much of the Ruby terrane in the map area. It structurally overlies PzꞐgn and contains several coherent bodies of MzDm. Based on structural relationships, it both overlies and underlies Mq. It corresponds (in part) to PzpꞒsq of Chapman and others (1982), Pzs of Dover (1994), PzZrqs of Wilson and others (1998), and PzꞐsr of Patton and others (2009). Age is based on a youngest detrital zircon age of 379 ± 4 Ma (Freeman and others, *in prep.*). Dvs is approximately 55 percent quartz-rich schist, about 20 percent each of quartz-poor schist and (mafic-intermediate) greenschist, and about 5 percent quartzite. Serpentinite is a rare (less than 1 percent) constituent with a very high magnetic susceptibility (3.5–66, average 32 $x10^{-3}$ SI). Excluding serpentinite, the magnetic susceptibility of unit Dvs is low to moderate (0.01–0.91, average 0.23 $x10^{-3}$ SI), reflecting the presence of a wide variety of schistose rocks. In thin section, residual hornblende and plagioclase are locally present in metamafic rocks and residual kyanite, garnet, and (or) plagioclase are present in metapelitic rocks. Chlorite and albite, however, are nearly ubiquitous in all rocks. These minerals are consistent with early amphibolite-facies metamorphism pervasively overprinted by a younger greenschist-facies event. Where adjacent to the Cretaceous Melozitna granite, rocks locally display hornfels textures or quartz-tourmaline veining.

Quartz-rich schist is black, grey, and greenish grey, reflecting variable graphite and chlorite contents. In thin section it contains significant quartz (45–75 percent) and muscovite (10–30 percent), and lesser chlorite (1–15 percent) and albite (2–5 percent). Half of the samples contain graphite (1–4 percent) and nearly half contain chloritoid (5–15 percent). Iron oxide spots, possibly after calcite, were commonly noted in the field but only about 10 percent of samples contained sufficient calcite to react with dilute hydrochloric acid (HCl). A fifth of quartz-rich schist thin sections from Dvs contained calcite, suggesting that 10–20 percent of the quartz-rich schist of Dvs is calcareous. Other less-frequently present minerals include biotite (0–18 percent), paragonite (0–10 percent), plagioclase (0–15 percent), kyanite (0–1 percent), garnet (0–5 percent) and opaques (0–2 percent).

Quartz-poor schist (excluding greenschist) contains 10–40 percent quartz, is black, grey, or greenish grey, and contains a higher phyllosilicate abundance (15–40 percent muscovite, 1–25 percent chlorite, 1–20 percent paragonite) than the quartz-rich schist. Notably, most quartz-poor schists investigated by XRD or major element analysis (Lough and others, 2012) contain significant paragonite (Na-mica). About 20 percent of the quartz-poor schist contains calcite in hand specimen tests; the actual abundance might be higher. As much as a third of quartz-poor schist samples contain graphite. Other minerals present in a few thin sections include biotite (0–15 percent), albite (0–5 percent), chloritoid (0–5 percent), plagioclase (0–10 percent), and opaques (0–5 percent).

Greenschist rocks have whole rock compositions or mineralogy suggesting intermediate and mafic igneous protoliths, in proportions of one third and two thirds, respectively. In thin section, all samples contain albite (10–40 percent), commonly as 1-2 mm porphyroblasts; chlorite (10–40 percent), usually responsible for the schistosity; epidote-clinozoisite (15–40 percent), locally porphyroblastic; fine-grained titanite (1–4 percent), and quartz (1–8 percent). Mafic greenschist also contains actinolite (5–35 percent), which is nearly absent from intermediate greenschist. Residual hornblende and plagioclase are present in about half of mafic greenschist samples; residual plagioclase is present in all intermediate greenschist samples. About one-fifth of greenschist hand samples of both compositional types contain calcite. Mafic greenschist trace-element characteristics point to mostly arc-related origins (discriminant diagrams in Pearce and Cann, 1973; Pearce, 1982; Pearce, 1983; and Meschede, 1986). Nearly half of samples analyzed have continental arc signatures, a third have oceanic arc, a fifth have low TiO2, P_2O_5, K_2O, Zr, Y, and Nb concentrations (Lough and others, 2012), making them difficult to classify, but are probably of oceanic arc type. Two (of 72) samples have within-plate compositional characteristics. The low titanium (Ti)-phosphorous (P)-Zr type is unique to Dvs. It is also characterized by low strontium (Sr), vanadium (V), zinc (Zn), and Na_2O and high MgO relative to the other metamafic types (Lough and others, 2012). It might represent an alteration type seen only in Dvs or perhaps mechanical mixtures of basaltic rocks and chlorite-rich sediments.

Quartzite is usually pale grey, lacks visible graphite, and contains quartz (85-98 percent) and muscovite. Minor calcite and clinozoisite are present in thin section.

Serpentinite was observed at five (of 706) sites; its high magnetic susceptibility and dark color are distinctive. A single thin section contains mostly serpentine, with minor chlorite and opaque mineral(s). Primary silicate minerals are absent.

Although all Ruby terrane schistose units in the map area are superficially similar, Dvs has several distinguishing features. It contains a higher proportion of metamafic rocks (greenschist and green semischist) than other schists. Albite-porphyroblastic schist is notable, although not common. Both quartz-rich and quartz-poor schist contain more chlorite and calcite than seen in the other units. Quartzite is rare relative to the others and serpentinite, although rare, is restricted to Dvs. The common chloritic character of schist in Dvs suggests a protolith derived from mafic or intermediate composition igneous rocks. Given the arc trace-element signatures of metamafic rocks, the unit appears to have a significant volcanic arc derivation.

Pzmq MARBLE AND QUARTZITE (PALEOZOIC)—Occurs as two small bodies surrounded by unit PzPfs in the southeast map area. The dominant rock type is a nearly pure, pale-gray marble, but graphitic quartzite and graphitic quartz schist are also present. Corresponds to unit Pzm of Dover (1994), Pzrm of Wilson (1998), and Pzcr of Patton and others (2009). Age is based on poorly preserved Ordovician to Mississippian corals (Patton and others, 2009) outside the map area.

Marble is nearly pure, 1-mm-diameter, recrystallized calcite. Quartzite contains mostly quartz (97 percent), with minor graphite and muscovite. Quartz schist contains less quartz (80 percent), 2–3 percent graphite, 5–10 percent chlorite, and 5–10 percent muscovite. Pzmq is distinguished from Dl based on the complete recrystallization of Pzmq and its lack of dolomite.

PzPfs SCHIST AND QUARTZITE (PALEOZOIC TO NEOPROTEROZOIC)—Southernmost Ruby terrane unit in the map area. It appears to be thrust onto unit Mq and to contain isolated lenses of unit Pzmq. It corresponds (in part) to Pzp€sq of Chapman and others (1982), Pzs of Dover (1994), PzZrqs of Wilson and others (1998), and PzPsr of Patton and others (2009). Age is based on a youngest detrital zircon age of 982 ± 55 Ma (Freeman and others, *in prep.*) and the inclusion of likely Paleozoic marble (Pzmq) bodies. PzPfs is about 50 percent quartz-rich schist, 32 percent quartzite (commonly metagrit), 15 percent quartz-poor schist, and 3 percent metamafic rocks. The first three rock types commonly occur interlayered at centimeter to decimeter scale, suggestive of original flysch deposits. Magnetic susceptibility is low (0.005–0.67, average 0.12 $x10^{-3}$ SI), consistent with preponderance of quartz-rich rocks. Mineral assemblages present are mostly consistent with greenschist-facies metamorphism. Only the rare occurrence of non-albite plagioclase in quartz schist suggests an earlier amphibolite-facies event. PzPfs differs from other Ruby terrane schist-rich units in the map area by the relatively high proportion of quartzite and the low proportion of metamafic rocks. Rocks with bimodal quartz grain sizes are also restricted to this unit.

Quartz schist is usually black or grey and contains 45–75 percent quartz. Nearly two-thirds of samples in thin section display bimodal grain sizes, usually 1–3 mm and 0.1–0.3 mm in diameter. Approximately one-quarter to one-third of samples contain graphite and about 5 percent contain calcite. Quartz schist always contains muscovite (10–30 percent); biotite (0–10 percent), chlorite (0–15 percent), and albite (0–7 percent) are less common. A few samples contain 5–10 percent non-albite plagioclase. Based on major oxide analyses, approximately one-third contain paragonite (5–20 percent).

Quartzite is black, grey or white, contains abundant quartz (85–95 percent), and about one quarter of samples display bimodal grain sizes. Graphite is present in half of samples and calcite is rare. The non-quartz mineralogy is dominantly muscovite; biotite or chlorite are locally present.

Quartz-poor schist is typically grey or greenish-grey, and usually lacks graphite. About 20 percent of hand specimens contain detectable calcite. In thin section the rocks contain 10–30 percent quartz, 25–70 percent muscovite, 5–30 percent chlorite, and 2–5 percent albite. Based on major oxide analyses (Lough and others, 2012) and XRD, most samples also contain at least some paragonite.

Metamafic rocks (greenschist-semi-schist) occur as rare, isolated layers in PzPfs. About one-third contain calcite (2–20 percent). In thin section metamafic rocks contain 35-50 percent porphyroblastic albite, 20–50 percent chlorite, 5–10 percent clinozoisite-epidote, and 2–10 percent titanite. One sample contains 15 percent stilpnomelane and another sample contains 5 percent biotite. Actinolite (and hornblende) are notably absent. Trace-element signatures are almost exclusively indicative of within-plate origins (based on discriminant diagrams in Pearce and Cann, 1973; Pearce, 1982; Pearce, 1983; and Meschede, 1986). Given their limited size and low abundance, they most likely represent dikes or sills intruded during one or more extensional event following sedimentation and lithification.

PzPqs QUARTZ SCHIST AND QUARTZITE (NEOPROTEROZOIC)—This unit occurs exclusively in or adjacent to PzPgn and contains about 60 percent quartz schist and 40 percent quartzite. The magnetic susceptibility is low (0.005–0.33, average 0.11 $x10^{-3}$ SI), consistent with its quartz-rich character. Age is based on association with PzPgn and the fact that other quartz-rich Ruby rocks exclusively possess Neoproterozoic depositional ages (Bradley and others, 2007). Distinguished from Dq and Mq in that it contains only quartz schist and quartzite—it lacks metamafic and metapelitic rocks. Compared to Mq, the rocks are much less graphitic. Based on the presence of non-albite plagioclase in one sample (partly replaced by fine-grained muscovite), the rocks experienced early amphibolite-facies metamorphism, overprinted by greenschist-facies metamorphism.

Quartzite is usually pale grey to pink, with 85–98 percent quartz; the remainder is muscovite ± biotite. Quartz schist is rarely graphitic and usually grey to green-grey, with 65–75 percent quartz. In thin section other minerals include 10–15 percent biotite, 0-3 percent calcite, 0–5 percent chlorite, 5–15 percent muscovite, and, in one sample, 10 percent non-albite plagioclase. Based on its mineral composition, the protolith for PzPqs was likely quartz sandstone grading to shaley sandstone.

PzPgn PARAGNEISS AND SCHIST (NEOPROTEROZOIC)—Generally quartz- and biotite-rich unit located near the Cretaceous Melozitna granite; commonly exhibits contact metamorphic and metasomatic effects. Consists of approximately 20 percent biotite paragneiss, 25 percent quartz schist, 15 percent quartzite, 10 percent quartz mica schist, 15 percent hornfels and skarn, 5 percent marble, and 10 percent granitic dikes. Magnetic susceptibility varies widely (0.005–31 $x10^{-3}$ SI) due to the variable rock types, including rare magnetite-rich skarn and biotite schist. Excluding these rare magnetic rocks, the magnetic susceptibility is low to moderate (0.005–0.79, average 0.28 $x10^{-3}$ SI). PzPgn corresponds (in part) to PzpЄsq of Chapman and others (1982), to CZg of Dover (1994), to PzZrpg of Wilson and others (1998), and (in part) to PzPsr of Patton and others (2009). Age is based on a youngest detrital U-Pb zircon age of 946 Ma (Freeman and others, *in prep.*). The sporadic occurrence of partly retrograded garnet, sillimanite, and (or) plagioclase, and the relatively widespread occurrence of chlorite, suggests an early amphibolite-facies metamorphic event overprinted by younger greenschist-facies metamorphism. Local recrystallization to hornfels is a later Cretaceous contact-metamorphic overprint. Distinguished from other Ruby terrane units in the map area by common occurrence of paragneiss and absence of metamafic rocks. Biotite, garnet, and aluminosilicate minerals are also more common than in other Ruby terrane units; chlorite and calcite (outside of marble) are relatively rare.

Paragneiss is typically black and white, fine- to medium-grained, and dominated by quartz (40–70 percent), plagioclase (15–25 percent), and biotite (10–20 percent). In thin section, other minerals include 0–15 percent alkali feldspar, 0–10 percent muscovite, 0–5 percent chlorite, 0–2 percent clinozoisite, and 0–1 percent titanite.

Quartz schist contains 40–60 percent quartz, 5–15 percent biotite, 15–20 percent muscovite, 0–5 percent chlorite, 0–10 percent plagioclase, 0–10 percent albite, and 0-5 percent almandine garnet. One thin section contains 2 percent sillimanite and another (from close to the Melozitna granite) contains 5 percent andalusite.

Quartz mica schist contains 20–35 percent quartz, 10–35 percent muscovite, 15–35 percent biotite, 0–5 percent chlorite, 0–5 percent garnet, 0–15 percent plagioclase, and 0–2 percent tourmaline. Alkali feldspar is present in a few thin sections. Approximately 1–3 percent magnetite is locally present, based on high magnetic susceptibility. Quartz mica schist from samples located near the Melozitna granite commonly contain porphyroblastic andalusite (5–35 percent) and partly recrystallized biotite, with semi-random orientations.

Quartzite is usually white or pale gray; graphitic quartzite is rare. Quartzite is mostly quartz (85–95 percent); the remainder is mostly muscovite and (or) biotite.

Marble is a rare constituent of PzPgn, but more common than in most other Ruby terrane units. It is typically medium-grained, completely crystalline, and greater than 90 percent calcite. Impure marble contains 75–90 percent calcite; the remainder is mostly quartz (15–20 percent) and some combination of muscovite, biotite, and (or) chlorite (5–10 percent).

Contact metamorphic/metasomatic rocks are of several different varieties. The most common type is fine-grained, dark, siliceous with 5–15 percent randomly oriented biotite, presumably derived from quartzite or quartz schist. Hornfelsed quartz-mica schist commonly contains visible andalusite in addition to some randomly oriented biotite. Rare skarn contains sub-equal amounts of hedenbergitic clinopyroxene and grandite garnet (determined by EMPA). Endoskarn, with abundant scapolite and clinopyroxene, in addition to plagioclase, alkali feldspar, and quartz, probably represents altered paragneiss.

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