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PRELIMINARY INTERPRETIVE REPORT 2004-3

GEOLOGIC MAPS OF THE LIVENGOOD SW C-3 AND SE C-4 QUADRANGLES, TOLOVANA MINING DISTRICT, ALASKA

by
J.E. Athey and P.A. Craw

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This accompanying booklet contains unit descriptions for the Livengood comprehensive geologic map (PIR 2004-3a), bedrock geologic map (PIR 2004-3b), surficial geologic map (PIR 2004-3c), and engineering-geologic map (PIR 2004-3d). Not all of the units in this document will appear on any one of these maps.

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[booklet accompanies the following maps]

GEOLOGIC MAPS OF THE LIVENGOOD SW C-3 AND SE C-4 QUADRANGLES, TOLOVANA MINING DISTRICT, ALASKA

INTRODUCTION

This booklet, Preliminary Interpretive Report 2004-3, accompanies four geologic maps that cover the SE ¼ of the Livengood C-4 Quadrangle and SW ¼ of the Livengood C-3 Quadrangle. The booklet contains unit descriptions for the following maps: comprehensive geologic map (PIR 2004-3a), bedrock geologic map (PIR 2004-3b), surficial geologic map (PIR 2004-3c), and engineering-geologic map (PIR 2004-3d). Please note that not all of the units in this document will appear on any one of these maps.

During the summer of 2003, personnel from the Alaska Division of Geological & Geophysical Surveys (DGGS) and the University of Alaska Fairbanks spent approximately 90 person days conducting field work in the Livengood area. The objective of this project is to produce 1:50,000-scale geologic maps of the area to foster a better understanding of the bedrock and surficial geology, and the mineral and engineering-material resource potential of the Livengood area. Field traverses cover the entire map area; however, more field time was spent mapping the Money Knob area because of its proximity to lode gold prospects, more abundant exposures, and easier access.

The map area covers the northern 123 square miles of the Livengood airborne geophysical survey. That survey includes total field magnetic and electromagnetic data (DGGS and others, 1999). Our bedrock mapping is enhanced by airborne geophysical data, especially in areas covered by vegetation and unconsolidated Quaternary and Tertiary deposits. Our interpretation of the geophysical data reveals locations of magnetic units (for example, the Amy Creek metabasalt [unit lPzZmb] and Cambrian mafic and ultramafic rocks [units Ꞓgs, Ꞓc, Ꞓmg, Ꞓlg, and Ꞓs]) and structures that would otherwise remain undetected by conventional surface mapping methods.

Surficial geologic units are delineated from interpretation of air photos and site-specific field investigations. Air photos used in this study include 1:6,000-scale, true color photography of Livengood Bench and 1:63,360-scale, false color infrared photography taken in 1986 and 1978. Only the 1978 air photos cover the entire field area.

Bedrock geologic units are primarily defined by field observations and rock samples collected at more than 1,100 stations in 2003. Field traverses conducted in 2001 by DGGS personnel are also included in this study (36 stations). Fifty samples were analyzed for major- and minor-oxide and trace elements (Athey and others, 2004b). Unit descriptions are also based on the petrographic examination and modal analysis of 154 thin sections and modal analysis of 57 rock slabs stained with sodium cobaltinitrite to discriminate potassium feldspar.

Weight percent CIPW normative compositions were assigned to igneous rocks using the methodology of Irvine and Baragar (1971). Trace-element-composition profiles were used to differentiate Amy Creek metabasalt (unit lPzZmb) from Cambrian mafic rocks (units Ꞓgs and Ꞓmg). Eight $^{40}Ar/^{39}Ar$ ages (this study; Athey and others, 2004a) were used to constrain timing of igneous events and the sericite + arsenopyrite + gold mineralization in the Money Knob area. One Sm-Nd age is pending on the Amy Creek metabasalt (unit lPzZmb).

Major oxide analyses and dilute hydrochloric acid effervescence tests define the composition of the Amy Creek dolomite (unit lPzZd). The presence and ages of megafossils and microfossils were used to constrain timing of sedimentary unit deposition and to correlate sedimentary units in this study with other units in the Livengood Quadrangle (tables 1 and 2).

The comprehensive geologic and engineering–geologic maps are derivative products of the bedrock and surficial geologic maps. For the comprehensive map, the bedrock and surficial geologic units are digitally merged to create a single map that reflects the geologic units one would actually observe on the ground. This comprehensive geologic map depicts the bedrock geology, covered by Quaternary and Tertiary units, with bedrock units exposed in areas mapped as bedrock (unit b) or thinly covered bedrock (unit b') on the surficial geologic map.

The engineering-geologic map portrays near-surface geologic materials and may be useful for identifying construction materials and potential geologic hazards directly related to surficial geologic units. Because each geologic unit has a definite range of composition, geologic materials can generally be interpreted from the spatial distribution of primary units (Wagner, 1957). Principal hazards and engineering considerations may be associated with mapped geologic units based on their general physical properties, conditions that are characteristic of their depositional environment, and topography. For example, natural hazards in lowlands are related to a lack of bearing strength (such as saturated, organic-rich swamp deposits and thawing of ice-rich permafrost). This map is intended only as a general guide to some common hazards that may be present and does not preclude the presence of other unevaluated or site-specific hazards.

To evaluate the mineral resource potential of the Livengood area, 54 samples of visibly mineralized rock, or rock exhibiting features associated with mineralization, were analyzed for geochemical trace elements (Athey and others, 2004b). A study of placer and lode gold compositions determined by electron microprobe analysis was employed to address the questions of Livengood Creek stream reversal and the location of the lode source of the placer gold (Newberry and Athey, in prep.). Historical and mineral industry data were incorporated into the dataset wherever possible.

We especially thank Alaska Placer Development, Inc., Avalon Development Corporation, and Placer Dome Exploration, Inc. for providing us with geologic information, which greatly enhanced the quality of our maps and interpretations (Freeman and others, 1997; Minehane and Rogers, 1997; Hanneman, 1998; Freeman, 2003). Other maps and project reports that were used in this study but not cited in the text directly include: DGGS, 1973; Hite, 1977; Albanese, 1983; Bundtzen, 1983; Robinson, 1983; Smith, 1983; Morrison, 1990; and University of Alaska Fairbanks geologic field camp, 2001.

ECONOMIC GEOLOGY

Placer Gold

The Livengood subdistrict, located 75 miles northwest of Fairbanks, is the most productive part of the Tolovana mining district. Approximately 530,000 ounces of placer gold have been mined from the region since 1914 (Szumigala and others, 2003). Deposition of the known Livengood placer deposits spans 10 million years with the bulk of the placers, although not the bulk of the gold, probably being deposited within the past 250,000 years. Livengood Bench, located to the north and slightly topographically above the present Livengood Creek, is the richest gold placer in the district (Bundtzen and others, 1982) and the oldest dated placer at ≈10 Ma (Karl and others, 1988). The Amy Creek placer may also be of Tertiary age (about 10 Ma). A large debris fan ≈1,160 m across at its widest dimension may either truncate or bury the Amy Creek placer, indicating that the placer gravel was deposited first. We believe both the fan and Amy Creek gold placer are relatively old deposits.

The Gertrude Creek placer was probably deposited during the Pleistocene or earlier, as the host gravels are overlain by a thick bed of loess. Woolly mammoth, Saiga antelope (Péwé, 1975), and other Pleistocene fauna were found in Lillian Creek, indicating that this deposit is probably of Late Pleistocene or earlier age. The ages of placer gravels in Lucky, Ruth, and Olive creeks are unknown. The proximity of lode gold prospects (for example, Old Smoky, Sunshine No. 2, and Griffin prospects; Freeman and Schaefer, 1999) allows for the possibility of recent placer deposition in Ruth, Lillian, and Olive creeks. Placer gold in current Livengood Creek is reworked from other gold-bearing gravels present in the existing Livengood watershed.

Mertie (1917) proposed that a portion of Livengood Creek once drained northeast into Hess Creek (Yukon River drainage) and was subsequently captured by the Tanana River drainage, reversing its flow into the drainage pattern present today. Livengood Creek currently flows to the southwest into the Tolovana River (Tanana River drainage). Placer gold nugget compositions and morphologies from Livengood Bench compared with grains from other Livengood placers substantiate a drainage reversal hypothesis and restrict the reversal timing to within the past 10 million years.

The historic headwaters of Livengood Creek probably drained from the Money Knob area, an obvious potential lode source of gold for the formation of Livengood Bench. In the Money Knob area, gold grains sampled from a quartz vein (average fineness 891; Newberry and Athey, in prep.) and an intrusive body (average fineness 902; Newberry and Athey, in prep.) have finenesses remarkably similar to Livengood Bench placer gold grain cores (average fineness 895; Newberry and Athey, in prep.).

Rounding and fineness of nuggets increase down first-order streams draining the Money Knob–Amy Dome ridge (average rim + core finenesses of 854–915; Smith, 1941; Glover, 1950; Cathrall and others, 1987; Minehane and Rogers, 1997). In Livengood Creek, nugget rounding and fineness increase toward the creek's present headwaters (average rim + core finenesses of 902–925; Smith, 1941; Glover, 1950; Cathrall and others, 1987; Minehane and Rogers, 1997), which is away from the Money Knob area. This trend is more pronounced in the morphology and composition of gold nugget rims (electron microprobe analyses from Newberry and Athey [in prep.]). Silver-depleted rims on gold nuggets collected toward the present headwaters of Livengood Creek are progressively thicker (no rim to a 100-micron-thick rim) and higher in fineness (from essentially a pristine core fineness of 872 to an average rim fineness of 996).

Although Livengood gold nugget composition and morphology data suggest the stream capture hypothesis is valid, the current southwesterly slope of Livengood Bench is inconsistent with a reversal of drainage direction. Because the existing surface of Livengood Bench parallels the surface of present Livengood Creek, one would expect the older stream to have had a southwesterly flow as well. To restore Livengood Bench to its presumed past northeasterly flow along the paleo-surface, the bench must be raised up ≈260 m on its southwestern end. A paleo-surface restored to horizontal requires ≈120 m of uplift, and a paleo-surface with a gradient similar to that of the current Livengood Creek requires an additional ≈140 m of uplift. This suggests an equivalent, and not unreasonable, amount of subsidence has occurred since about 10 Ma to create the current Livengood Creek drainage conditions. A subsidence rate of only 0.026 mm/year for the past 10 million years is required to change the stream gradient from northeast-flowing to southwest-flowing.

The Myrtle Creek Fault shows evidence of tectonism within the past 10 million years. This fault, which bounds the western edge of Livengood valley and truncates the southwestern end of Livengood Bench, appears to have only vertical movement and no associated strike-slip movement. Our interpretation of geophysical data (DGGS and others, 1999) indicates no apparent offset in the strike–slip faults that are bisected by the Myrtle Creek Fault immediately north of Livengood. On the west side of the Myrtle Creek Fault, and not present to the east, a gravel layer that is barren of gold and greater than 45–60 m thick indicates subsidence (drill results from west of the town of Livengood; B.I. Thomas, written commun., 1972; Karl Hanneman, oral commun., 2003). According to Ronald Tucker (oral commun., 2003), the surface of the bedrock steps down to the west 17 m in two places (for a total of 34 m) on lower Lillian Creek. Tucker indicated about 15 m of horizontal distance between the two faults, which are located on the trace of the Myrtle Creek Fault. Changes in base level as a result of tectonic lowering of the Nenana basin (Barnes, 1961; Péwé and others, 1966; Reger, 1987) may also have influenced erosion rates in the Livengood area.

In addition to tectonism, southwesterly headward erosion may have been a contributing mechanism of ancient Livengood Creek's capture by the Tanana River drainage system. Headward erosion of the formerly northeast-flowing Livengood Creek may have allowed the creek to break through a former drainage divide and flow southwestward to the topographically lower Minto flats, the northern branch of the Nenana basin.

Lode Gold

Although no lode gold has been produced from the Livengood area, the Money Knob area appears to be the main lode source for placer gold in the Livengood valley. Bedrock mineralization in the map area is expressed as: (1) gold-bearing quartz + carbonate-altered serpentinite (this study; Saunders, 1955), (2) quartz + arsenopyrite ± gold veins (one anomalous sample contains 34.7 ppm Au; Athey and others, 2004b), (3) arsenopyrite + gold replacement of intrusions (^{40}Ar/^{39}Ar sericite plateau age of 88.9 ± 0.3 Ma; map location A3; Athey and others, 2004a), (4) brecciated quartz + stibnite ± arsenopyrite ± gold ± galena veins, and (5) cinnabar disseminations in an intrusion (Joesting, 1941). Major-oxide data (Athey and others, 2004b) and modal analyses of feldspar-stained rock slabs indicate that plutons and dikes of both calc-alkaline and alkaline compositions are present; the intrusions are an obvious potential fluid and metal source. The two intrusion compositional suites appear to be coeval and both are highly variable in texture. They are generally hypabyssal, reduced, sericite + quartz + carbonate-altered, and brecciated, indicating rapid end-stage water loss. These features are commonly found in other world-wide shallow plutonic-related gold systems. A quartz monzonite dike from unit Kmk yields an ^{40}Ar/^{39}Ar biotite plateau age of 91.7 ± 0.4 Ma (map location A2; Athey and others, 2004a). Biotite from a quartz syenite dike yields a similar ^{40}Ar/^{39}Ar plateau age of 93.2 ± 0.4 Ma (map location A4; Athey and others, 2004a).

Plutons in the Livengood area occur within a regional, east–west-trending belt of back-arc(?)-related, ≈90 Ma alkaline dikes and plutons, most of which are spatially associated with granite (Nokleberg and others, 1987; Weber and others, 1992; Newberry and Clautice, 1997; Reifenstuhl and others, 1997; Rinehart and others, 1997; Reifenstuhl and others, 1998). Other regional intrusive centers with associated lode or placer gold include Elephant Mountain, Wolverine, Sawtooth Mountains, and the Eureka area dikes. Within the same belt, the Roughtop, Roy Creek, and Cascaden Ridge igneous bodies are apparently barren of gold. Controls on economic mineralization may include the presently exposed level of the hydrothermal mineralizing system, presence of both calc-alkaline and alkaline intrusions, abundant structural pathways for fluid mobilization, and reactive host rocks.

DESCRIPTION OF MAP UNITS

SURFICIAL GEOLOGIC UNITS

UNCONSOLIDATED DEPOSITS

ALLUVIUM

Qaa ALLUVIUM OF MODERN STREAM CHANNELS (Holocene)—Elongate deposits of moderately sorted to well stratified fluvial pebble gravel, sand, and silt with scattered boulders deposited in active stream channels. Streams are characterized by low gradients and meander within a broad, hydrologically active zone. Shrubs and willows are common, indicating that the deposits are relatively permafrost free.

Qa UNDIFFERENTIATED ALLUVIUM (Holocene to Late Pleistocene)—Elongate to broad deposits formed primarily by small streams and overbank deposition during floods. Predominantly stratified silt and sand with local point bar gravels containing moderately to well sorted pebbles and cobbles. Some areas are mantled by colluvial silt near lateral margins (Waythomas and others, 1984). In the Lost Creek area these elongate alluvial deposits are present within fine-grained lowland colluvium (Qcfl) and range from about 40 to 300 m wide with streams that are no more than 10 m wide in most places. Near Ready Bullion Creek, in the southern part of the map area, deposits are broad and are characterized by abandoned channels. Permafrost-free zones may be identified based on the presence of shrubs and willows. Thick moss and tussock cover indicates permafrost presence within the unit.

Qaf ALLUVIAL-FAN DEPOSITS (Holocene to Late Pleistocene)—Fan shaped, heterogeneous mixture of moderately to poorly sorted, subangular to subrounded pebbles, cobbles, and boulders in a sand and silt matrix. Deposits are channelized across fan surfaces. Scattered silt lenses and poorly sorted debris flow deposits may occur in the deposit. Potentially auriferous in apices and basal strata of fans around Amy Dome and Money Knob (Waythomas and others, 1984).

COLLUVIUM

Qc UNDIFFERENTIATED COLLUVIUM (Holocene to Late Pleistocene)—Irregular, homogeneous blankets, aprons, and fans of angular to subangular rock fragments in a silty matrix, moving downslope by complex mass movement processes driven by gravity, alluviation, and cryoturbation. Deposit thickness is variable, thickest at slope bases. Contains Pleistocene mammalian fossils including mammoth, horse, caribou, bison, sheep, and fox (Ronald Tucker, oral commun., 2003). Qc grades into Qcfu downslope.

Qca COLLUVIAL–ALLUVIAL–FAN DEPOSITS (Holocene to Late Pleistocene)—Fan-shaped deposit in the northwestern part of the map area consisting predominantly of poorly sorted, angular rock fragments in a silt–clay matrix. Deposit probably formed by mass movement processes driven by gravity, alluviation, and cryoturbation. Scattered interbedded lenses of rounded clasts and laminated sand and silt with alluvial characteristics. Subject to local flooding.

Qcfl FINE-GRAINED LOWLAND COLLUVIUM (Holocene to Pleistocene)—Basin fill of unknown depth composed of reworked eolian or fluvial silt, scattered areas where sand and angular clasts are mixed. Deposit is usually cryoturbated, frozen, organic rich, and devoid of sedimentary structures or strata that can be traced over a significant distance (Waythomas and others, 1984). Surface is smooth and undulating with round and irregularly shaped thaw lakes ranging from less than 20 m across to about 230 m across in the northeastern part of the map area. Near Goldstream and Alabam Creeks there are abundant small (< 20 m) thaw lakes and only 1 elongate lake greater than 150 m in diameter. May contain Pleistocene mammalian fossils including mammoth, horse, caribou, bison, sheep, and fox.

Qcfu FINE-GRAINED UPLAND COLLUVIUM (Holocene to Pleistocene)—Reworked eolian or fluvial silt with scattered areas where sand and angular clasts are mixed. Typically thickens toward slope bases. Deposits are usually cryoturbated, frozen, organic rich, and devoid of sedimentary structural features or strata that can be traced over a significant distance (Waythomas and others, 1984). Thermokarst features including patterned ground and thaw lakes less than 20 m diameter are developed on the surface of these deposits. Probably contains Pleistocene mammalian fossils including mammoth, horse, caribou, bison, sheep, and fox. Covers the Livengood placer deposits in Livengood Creek. Qcfu grades into Qcfl downslope.

COMPLEX DEPOSITS

Qdf DEBRIS FAN (Pleistocene to Late Tertiary)—Well-compacted debris fan deposit at the mouth of Amy Creek. Heterogeneous diamicton composed of locally derived pebble- to boulder-sized clasts in a silty/clayey matrix. Bedding apparent at base of deposit. The deposit either truncates or covers the Amy Creek placer deposit.

Qe-c REWORKED AND DISSECTED LOESS (Holocene to Pleistocene)—Ridges form by in-situ dissection of upland loess and are separated by gullies composed of reworked alluvial and/or colluvial silt. This deposit often occurs as triangular "flatironlike" ridges pointing upslope (Kreig and Reger, 1982). These features are generally shallowly frozen except where birch and aspen are well established on their upper reaches (Kreig and Reger, 1982). Distribution of permafrost is variable throughout the map area. West of Willow Creek, gullies have convex walls and narrow floors, suggesting that dissected loess may be frozen. In contrast, where gullies with broad floors occur between ridges, loess may be thawed, such as on the west side of the divide between Myrtle and Lost Creek watersheds. Kreig and Reger (1982) describe these contrasts, which are observable on 1:63,360-scale topographic maps. The infiltration capacity of thawed, unsaturated loess is often greater than the amount of water produced from melting snow or normal rain events. As a result, gullies occurring in thawed, unsaturated silt are generally dry. During spring or fall, pore spaces in dissected loess deposits may be saturated and frozen. Under frozen, saturated conditions the equilibrium infiltration rate decreases by about two orders of magnitude in interior Alaska silts (Kane and Stein, 1983). Under such conditions, gullies may be inundated and/or subject to significant runoff during heavy rains and/or snowmelt. Thermokarst features are present in this deposit. Small (< 20 m diameter) thaw lakes occur in this deposit on the north side of an unnamed ridge south of Lost Creek and west of Livengood Dome. Qe-c grades into Qcfu downslope.

EOLIAN DEPOSITS

Qe UPLAND LOESS (Pleistocene)—Massive or finely laminated, very well sorted, gray to buff, windblown silt. Deposit is weakly coherent, very porous, friable, and is usually restricted to generally flat upland areas. Often contains plant stems in growth position and laterally continuous soil or organic strata (Waythomas and others, 1984). At the time of deposition, during Pleistocene glacial intervals, loess blanketed much of the field area. Deposits thicken from the Livengood area toward the Yukon River to the north, indicating that the Yukon Flats are the probable source area for loess in the map area (F.R. Weber, 2004, written commun.). Deposits are often frozen to within 1 m or less of the surface, and display thermokarst features in some areas (Waythomas and others, 1984) including thaw lakes usually less than 20 m in diameter. Loess often maintains its original low density and, as a result, is especially sensitive to disturbance and wetting (Goodman, 1993). During construction of the Dalton Highway near Livengood, road cuts made in ice-rich loess were near vertical, engineered to slump and self stabilize (Brown and Kreig, 1983). In ice-rich loess, such design is more effective than cuts made with a standard 1:1 slope (Kreig and Reger, 1982). Loess retransported by alluvial and colluvial processes may be incorporated into all surficial deposits in the area.

PALUDAL DEPOSITS

Qs

SWAMP DEPOSITS (Modern [Late Holocene])—Elongate deposit of silt and organic material at the headwaters of Hess Creek where water was impounded behind the Hess Creek Dam. Since draining of the reservoir, hydrophyllic vegetation colonized the site and standing water is about 1 m deep in places. Hess Creek dam was constructed to supply water to mining operations in Livengood Creek and was one of the largest earth-filled dams built on permafrost in Alaska (Brown and Kreig, 1983). The dam was completed in 1949 and used intermittently until the 1984 (Parker, 2003). While in use, the dam was drained in winter to allow embankments and related structures to refreeze (Brown and Kreig, 1983).

MAN-MADE DEPOSITS

Qt

PLACER-MINE TAILINGS AND ARTIFICIAL FILLS (Modern [Late Holocene])—Includes mine tailings, excavated overburden, siltation-pond fillings, ditches, active surface-mining pits, and borrow pits for road construction. Most deposits are coarse gravel or angular-bedrock rubble; heterogeneous mixtures that range from silt to boulders are included. Mapped extents mostly determined from 1978 and 1986 aerial photography. Tailings in western Livengood Creek determined from 2001 aerial photography.

BEDROCK
(Shown on surficial geologic map PIR 2004-3c)

b

EXPOSED BEDROCK—Outcrop and rubble crop that show little or no evidence of transport.

b’

THINLY COVERED BEDROCK—Thin cover of frost-shattered and weathered bedrock with some mineral soil, silt, occasional outcrop, and sparse, typically mat-forming vegetation.

Notes:

Surficial geologic units were photointerpreted from 1:63,360-scale aerial photography taken in August 1978 and August 1986 and verified with 5 days of fieldwork during the 2003 field season. Tailings location in western Livengood Creek determined from 1:6,000-scale, aerial photography from 2001 and transferred to a 1:63,360-scale base map. Some units were digitized directly from a 1:63,360-scale orthophoto of the map area (Staft and Craw, in prep.).

Map locations of b/b' units are mapped primarily based on photointerpretation, some field observations by the author, and structural measurement points taken by J.E. Athey, R.J. Newberry, D.J. Szumigala, M.B. Werdon, and L.K. Freeman. The size of some b/b' unit polygons were enlarged to provide adequate space on the map for structural symbols and representative unit colors at 1:50,000-scale.

BEDROCK GEOLOGIC UNITS

IGNEOUS ROCKS

Tl

LAMPROPHYRE DIKE (Tertiary)—Fine-grained, black, biotite- and clinopyroxene-porphyritic lamprophyre dike located 1.1 km north of the town of Livengood. Modal composition of 7 percent clinopyroxene, 5 percent feldspar (primarily orthoclase), 4 percent biotite, <1 percent interstitial quartz, rare accessory apatite, iron oxide, and very fine-grained groundmass. Contains clinopyroxene phenocrysts up to 3 mm long with an average diameter of 1.5 mm. Most euhedral feldspar crystals are thinly zoned. Alignment of phenocrysts’ long dimension is evidence of poorly formed flow banding. Sample contains one matted, recrystallized(?) xenolith 2 mm by 2.5 mm wide of biotite and opaque minerals. Magnetic susceptibility of dike is low (0.05–0.15, averaging 0.10 x 10^{-3} SI [Système International]). $^{40}Ar/^{39}Ar$ biotite plateau age of 56.6 ± 2.9 Ma (map location A1; this study). The analysis methodology and nomenclature described in Athey and others (2004a) was used for this sample.

Kmk

MONEY KNOB PLUTON (Cretaceous)—Dike swarm of granite, quartz monzonite, monzonite, and quartz syenite located 0.8 km northeast of Money Knob. Occurs with both abrupt and transitional textural and compositional contacts between dikes. Porphyritic texture with biotite and feldspar up to 1.5 cm in diameter is more common than fine- to medium-grained, equigranular texture; texture may vary significantly within a single dike. Mineralogy for the pluton as a whole includes K-feldspar, biotite, clinopyroxene, plagioclase, quartz, and ilmenite. Magnetic susceptibility is uniformly low (0.03–0.19, averaging 0.10 x 10^{-3} SI). A light- to medium-gray, porphyritic quartz monzonite dike yields an $^{40}Ar/^{39}Ar$ biotite plateau age of 91.7 ± 0.4 Ma (map location A2; Athey and others, 2004a). Dikes are weakly to completely altered to sericite and quartz. Disseminated arsenopyrite locally replaces the groundmass and phenocrysts, and scorodite-stained, arsenopyrite-bearing quartz veins contain anomalous gold. A strongly sericite- and arsenopyrite-altered dike within the Money Knob pluton contains 2.16 ppm Au and yields an $^{40}Ar/^{39}Ar$ sericite plateau age of 88.9 ± 0.3 Ma (map location A3; Athey and others, 2004a; Athey and others, 2004b). Quartz, sericite, and limonite veins 1–3 mm thick are common. Intrusions locally contain xenoliths of the host rocks (unit Dc).

Krc

RUTH CREEK PLUTON (Cretaceous)—Hypabyssal dike swarm of fine-grained, commonly porphyritic granite to granodiorite and less common quartz syenite to quartz alkali-feldspar syenite. Light- to dark-gray, greenish gray, and white dikes with an aphanitic, sucratic, locally flow-banded matrix containing variable amounts of carbon and 0–8 percent feldspar phenocrysts up to 8 mm in length. In some intrusions the groundmass is composed of feldspar spherulites indicating rapid quenching. Magnetic susceptibility is uniformly low (0.00–0.20, averaging 0.06 x 10^{-3} SI). Intrusions locally contain xenoliths of the host rocks (unit Dc). Alteration includes weak to strong, light-orange-yellow, supergene iron-oxide staining, local pervasive hydrothermal sericitization, and silicification with 0–8 percent pyrite and limonite-filled cubic voids. Contains 1–3-mm-thick veins of vuggy, crystalline quartz and limonite.

Ko

OLIVE CREEK PLUTON (Cretaceous)—Fine-grained, grayish green, K-feldspar-porphyritic felsic intrusion located at the intersection of Olive Creek and the old Elliott Highway. Contains K-feldspar phenocrysts (3–4 mm long) in an aphanitic to very fine-grained, occasionally flow-banded matrix. Magnetic susceptibility from one location is low (0.00–0.17, averaging 0.10 x 10^{-3} SI). Locally brecciated, argillically altered, and contains phenocrysts (K-feldspar?) that are being replaced by quartz and sericite. Locally limonite and malachite stained.

Ka

MONZONITE TO SYENITE DIKES (Cretaceous)—Cream to light-gray, porphyritic to rarely equigranular alkaline dikes up to 50 feet across and small bodies (see 'Map Symbols,' sheets PIR 2004-3a and b, for additional explanation of compositional variations). Average modal composition includes 60–82 percent fine-grained feldspar (proportion of orthoclase and plagioclase is dependent on rock chemistry), 0–40 percent porphyritic K-feldspar up to 3 cm in diameter, 2–20 percent interstitial quartz, 0–15 percent biotite, 0–2 percent clinopyroxene, and trace accessory ilmenite and magnetite(?). Biotite and feldspar crystals are occasionally zoned. Clinopyroxene, and biotite to a lesser degree, are preferentially altered to matted, fine-grained mixtures of carbonate, sericite, iron oxide, epidote(?), and sphene(?). Magnetic susceptibility is generally low (0.00–0.37, averaging 0.11 x 10^{-3} SI). One anomalous "plutonic-textured", equigranular, fine-grained syenite dike composed of 55 percent orthoclase and 45 percent hornblende has a moderate magnetic susceptibility (0.35–0.43, averaging 0.38 x 10^{-3} SI). Biotite from an equigranular quartz syenite dike yields an $^{40}Ar/^{39}Ar$ plateau age of 93.2 ± 0.4 Ma (map location A4; Athey and others, 2004a). Dikes contain weak to locally strong pervasive sericite, silica, and lesser carbonate alteration. One alkaline(?) intrusion located ≈250 m north of the Olive Creek pluton contains pyrite, gold-bearing arsenopyrite disseminations and veins, and disseminated cinnabar (Joesting, 1941).

Kc

GRANITE AND GRANODIORITE DIKES (Cretaceous)—Cream to dark-gray, hypabyssal, aphanitic to very fine-grained calc-alkaline dikes (see 'Map Symbols,' sheets PIR 2004-3a and b, for additional explanation of compositional variations). Average modal composition includes 0–10 percent K-feldspar phenocrysts up to 8 mm long, 0–4 percent embayed quartz phenocrysts up to 0.5 mm in diameter, rare plagioclase, rare biotite, and up to 30 percent carbon in the groundmass. Groundmass is commonly composed of spherulitic feldspar; spherulites range from dense, dendritic, and felted masses to “open” sprays with quartz in the interstices between elongate crystals. Occasionally groundmass is a very fine-grained mixture of feldspar, quartz, and sericite; some of the quartz may be from alteration. Dikes and phenocrysts are commonly brecciated, possibly as a result of rapid intrusion into cool host rocks and water loss. Occasionally dikes are flow banded and contain quartz-filled amygdules and recrystallized xenoliths of host rock (unit Dc). Magnetic susceptibility is generally low (0.00–0.30, averaging 0.08 x 10^{-3} SI) with two anomalous high values of 0.91 and 1.00. Altered dikes commonly contain sericite, quartz, and pyrite and are cut by numerous quartz veins.

METAMORPHOSED SEDIMENTARY AND IGNEOUS ROCKS

NORTH OF VICTORIA CREEK FAULT

Incipiently metamorphosed Jurassic(?) to Triassic gabbro and chert (unit TRg), Triassic to Devonian sedimentary rocks (unit TRDs), and Permian(?) to Devonian sedimentary rocks (unit PDs) crop out in the northwest corner of the map area, northwest of the Victoria Creek Fault. The Victoria Creek Fault, a major right-lateral strike-slip fault, is considered to be a strand of the Tintina Fault (Wheeler and Weber, 1988).

The Jurassic(?) to Triassic gabbro and chert (unit TRg) is equivalent to unit TRMrv of the Rampart Group (Weber and others, 1992) and is described within unit JTRtmu of the Tozitna assemblage (table 2; Wilson and others, 1998). The Rampart Group forms a semi-continuous belt of volcanic, igneous, and sedimentary rocks that extends for at least 225 km along an east–west axis through the Circle, Livengood, and Tanana quadrangles (Weber and others, 1992; Wilson and others, 1998). The Rampart Group is composed of oceanic igneous rocks and associated sedimentary rocks (Wilson and others, 1998). The age of this unit is constrained by Triassic radiolaria found in interlayered chert from the Livengood C-5 Quadrangle (Weber and others, 1994). Hornblende from gabbro that intrudes Rampart Group volcanic rocks yields a minimum K-Ar age of 210 ± 6 Ma (Brosgé and others, 1969; age recalculated by Wilson and others [1998]). These igneous rocks in the Rampart and Livengood areas have a trace-element-indicated within-plate signature that may indicate back-arc rifting in a marine environment (this study; Newberry and Haug, 1997; Athey and others, 2004b).

Sedimentary unit PDs correlates with unit PDms of Weber and others (1992). Within the map area, the Permian(?) to Devonian sedimentary rocks (unit PDs) occur as rare low mounds and float of shale and mudstone. Elsewhere, unit PDms of Weber and others (1992) contains limestone debris flows and turbiditic sedimentary structures. The age of the unit is based on Devonian conodonts from the Livengood C-3 Quadrangle 15.2 km northeast of the map area and late Paleozoic (Early Permian?) echinoderm debris from the Livengood C-3 Quadrangle 7.6 km north of the map area (Weber and others, 1994).

Regionally we interpret the contact between the Permian(?) to Devonian sedimentary rocks and the Rampart Group as a high-angle fault that is sub-parallel to the Victoria Creek Fault. In the map area, however, the relationship between sedimentary unit TRDs and adjacent units TRg and PDs is unclear (table 2). The mixed sedimentary unit (TRDs) may be equivalent to either the Triassic sedimentary rocks of the Rampart Group to the north (unit TRMrs; Weber and others, 1992) or the Permian to Devonian sedimentary rocks to the south (PDms; Weber and others, 1992). Because of the stratigraphic uncertainty associated with sedimentary unit TRDs, the high-angle fault may be located at either the TRDs–TRg contact or the TRDs–PDs contact. Until this ambiguity can be resolved, this unit is assigned a Triassic to Devonian age.

TRg

RAMPART GABBRO, QUARTZ GABBRO, AND MINOR CHERT (Triassic)—Coarse- to lesser medium-grained, equigranular, pale- to dark-green and white gabbro to quartz gabbro. Average modal composition approximately 35–60 percent clinopyroxene, 35–50 percent labradorite ≈An_{55}), 0–30 percent hornblende (some with pyroxene cores), 0–20 percent biotite, 0–10 percent quartz, 3 percent skeletal magnetite, and accessory zircon. Secondary minerals include actinolite, sericite, stilpnomelane, albite, lawsonite(?), chlorite, zoisite, and iron oxide, which indicate a maximum metamorphic grade of lower greenschist facies. Unit includes white, light- to medium-gray, and tan chert with iron-oxide-coated fractures. Magnetic susceptibility for the unit as a whole is moderate (0.16–0.74, averaging 0.38 x 10^{-3} SI).

TRDs

SANDSTONE, SHALE, AND CHERT (Triassic to Devonian)—Mixed sedimentary unit containing sandstone/quartzite > shale/siltstone > chert. Clast-supported, possibly reworked, bimodal(?) sandstone is composed of fine-grained, rounded to subangular grains of quartz averaging 0.02 mm in diameter and highly altered, very fine-grained white mica + quartz pseudomorphs of original sedimentary clasts (<1 mm in diameter). Cemented by iron oxide and mud (recrystallized to white mica). Sandstone is pale-greenish gray, orange, tan, and brown. Lesser gray shale, gray siltstone, and white, light-gray, and tan chert. Iron oxide and pyrite locally coat fractures. Magnetic susceptibility is low (0.04–0.08, averaging 0.07 x 10^{-3} SI).

PDs

SHALE (Permian? to Devonian)—Green, tan, and red shale and mudstone. Fissile with a few quartz veins and trace iron oxide. Petrographic analysis indicates poorly formed S-C fabric (Lister and Snoke, 1984) and a composition of sericite, rounded quartz, iron oxide, and trace chlorite. Magnetic susceptibility from one sample is 0.09 x 10^{-3} SI.

SOUTH OF VICTORIA CREEK FAULT

The map area south of the Victoria Creek Fault contains three loosely grouped belts of rocks with different structural styles. From northwest to southeast they include:

1. The Early Cambrian(?) to Late Proterozoic Wickersham shale (ЄZwa) and limestone (Єwl),
2. The Ordovician and Silurian sedimentary rocks (Old, Ss, and Sl), and
3. The lower Paleozoic to latest Proterozoic Amy Creek units (lPzZd, lPzZmb, and lPzZmc), an Early Cambrian ophiolite assemblage (Єgs, Єc, Єmg, Єlg, and Єs), and Devonian sedimentary rocks (Dc).

The first two belts are bounded by northeast-trending, right-lateral, strike-slip faults. The Early Cambrian(?) to Late Proterozoic Wickersham shale (ЄZwa) and limestone (Єwl) belt is poorly exposed. The presumed stratigraphic contact between the two Wickersham units is sub-parallel to the trend of regional strike-slip faulting. Belt 2, Ordovician Livengood Dome Chert (Old) unconformably overlain by Silurian Lost Creek sedimentary rocks (Ss and Sl), contains at least two generations of tight folds; one set of fold axes is sub-parallel to the trend of regional strike-slip faulting.

The structural history of the third belt of rocks in the southeastern portion of the map area includes two possible thrusting events and a late high-angle faulting event. The Amy Creek assemblage (units lPzZd, lPzZmb, and lPzZmc) generally occurs as the structurally lowest set of rocks. The Amy Creek units are broadly folded, with fold axes sub-parallel to the trend of regional strike-slip faulting. Folds in the Amy Creek units are tighter and limbs are occasionally overturned closer to thrust fronts, possibly in response to compression from one or both of the thrusting events; our interpretation of geophysical data in DGGS and others (1999) and structural data suggest axial planes dip to the south. The Early Cambrian ophiolite assemblage (Єgs, Єc, Єmg, Єlg, and Єs) represents a slab of ocean floor obducted onto the Amy Creek assemblage. Stacked thrust slivers of greenstone (Єgs), metagabbro (Єmg), and Amy Creek sedimentary rocks (lPzZmc) are separated by thin sheets of serpentinite (Єs). $^{40}Ar/^{39}Ar$ ages from two Amy Creek metabasalt (lPzZmb) samples (map locations A5 and A6; Athey and others, 2004a) and a metagabbro (Єmg) sample (sample DT87-16 located 3.3 km south of the map area; Athey and others, 2004a) suggest a reheating event during the Permian (200–250 Ma) that may reflect the timing of ophiolite emplacement.

The second episode of low-angle faulting thrust Devonian sedimentary rocks (Dc) on top of the Early Cambrian ophiolite assemblage in the Money Knob area. Regionally, the Devonian sedimentary rocks (Dc) and the Early Cambrian ophiolite assemblage have been interpreted to be in an unconformable relationship (Foster, 1966; Weber and others, 1992). Devonian sedimentary rocks (Dc), which presently overlie the ophiolite assemblage, contain chert and chlorite-rich mafic volcanic clasts potentially derived from the Amy Creek, Livengood Dome, and ophiolite units. No serpentine was identified through petrographic or X-ray diffraction analysis (this study) in the Devonian conglomerates. Similarly, Loney and Himmelberg (1988) did not find serpentine in the Devonian unit, but a chromite grain was identified. There is no evidence to suggest that debris was shed directly from the ophiolite assemblage into the sediments creating an unconformable contact. We believe the contact between the ophiolite assemblage and the Devonian sedimentary rocks to be a low-angle thrust fault in the Money Knob area, but an unconformable contact is not precluded elsewhere.

In the Money Knob area, the Devonian sedimentary unit (Dc) anomalously crops out ≈5 km north of the generally uniform, 30-km-long, NE–SW-oriented contact dividing the Early Cambrian ophiolite assemblage to the north from Devonian sedimentary rocks (Dc) to the south (Weber and others, 1992). The northern sections of unit Dc are interpreted to be emplaced by a second episode of thrust faulting. Other post-Devonian thrust faults, inferred from mapping and our interpretation of structural relationships in drill core (Minehane and Rogers, 1997), place slivers of metagabbro (Ꞓmg) and serpentinite (Ꞓs) of the Early Cambrian ophiolite assemblage and Amy Creek sedimentary rocks (lPzZmc) over part of the northern section of unit Dc.

Post-Devonian thrusting likely occurred during the late Early Cretaceous (pre-90 Ma), accommodating stresses related to compression of the Manley basin (located approximately 6 km south of Livengood). The Manley sedimentary basin is dominated by folded, locally overturned, deep marine turbidite deposits of Jurassic and Early Cretaceous age (Weber and others, 1985; Weber and others, 1992). Its current size and shape—a NE-trending belt approximately 400 km by 10–20 km wide—indicate severe NW–SE compression occurred after sediment deposition and prior to intrusion of 90 Ma plutons.

Units in the map area south of the Victoria Creek Fault correlate with Paleozoic units mapped by Weber and others (1992) throughout the Livengood Quadrangle (table 2). The Devonian Cascaden Ridge unit (Dc) of this map may be facies-equivalent to mid-Devonian limestone and clastic units present 25 km to the west (limestone of Quail unit; Weber and others, 1992) and 25 km to the southeast (Beaver Bend sedimentary unit and upper part of Tolovana limestone; Weber and others, 1992). Lost Creek units (Sl and Ss) of this map may be correlative with the Silurian Tolovana limestone in the White Mountains (Weber and others, 1992), located 25 km southeast of the map area. Livengood Dome chert (Old) of the current map may correlate with an upper(?) sedimentary portion of the Ordovician Fossil Creek unit of the White Mountains (Weber and others, 1992), located 40 km to the east.

Equivalents of the lower Paleozoic to Late Proterozoic Amy Creek assemblage (lPzZd, lPzZmb, and lPzZmc) recognized in the current map area are uncertain. The marked absence of megafossils and conodonts in lPzZd could be due to extensive dolomitization and silicification; presence of algal chips and lack of shelly fauna is compatible with a Late Proterozoic age (Weber and others, 1992; Weber and others, 1994; Reifenstuhl and others, 1998; Clough and Goldhammer, 2001). One example of a dolomite unit of known Late Proterozoic age is the Katakturuk Dolomite of Clough and Goldhammer (2001), located approximately 1,000 km to the north. The Amy Creek dolomite (lPzZd) is distinguished from the Katakturuk Dolomite by the absence of stromatolites and sedimentary structures and the presence of a >884-m-thick section of siliceous mudstone and chert, although these discrepancies could be due to a change in facies. The greenstone unit that underlies the Katakturuk Dolomite has a trace-element-indicated within-plate tectonic signature (Moore, 1987), as does the Amy Creek metabasalt (unit lPzZmb). Alternatively, the Amy Creek assemblage may be facies-equivalent with the lower(?) sedimentary portion of the Ordovician Fossil Creek unit of the White Mountains (Weber and others, 1992). The alkaline volcanic rocks within the Fossil Creek unit (Weber and others, 1992) present 37 km to the east are also similar in chemical composition to lPzZmb, and both units have a within-plate trace-element-indicated tectonic signature (R.J. Newberry, unpub. data, 2004).

Cascaden Ridge Unit

This sandstone, shale, and conglomerate unit (Dc) is equivalent to the Cascaden Ridge unit (Dc) of Weber and others (1992). The Cascaden Ridge unit is derived from a collisional orogen source and composed of debris from local units (Gergen and others, 1988). Blodgett (1992) suggests that the clastic rocks were deposited in a shallow-water basin in the vicinity of local uplift. A fossil locality 1.2 km south of the map area indicates a Middle Devonian age for this unit (figure 1, inset map location F1; table 1; Blodgett, 1992). Fossils are found in debris flows, thought to have been transported contemporaneously with sediments in a wave-based environment (Weber and others, 1985). Sedimentary structures present include thin, planar, internally laminated beds, ripple beds, and sole marks (Weber and others, 1992). Weber (oral commun., 2004) suggests a total thickness for this unit of 1,036 m, based on a section located on Cascaden Ridge, 4.5 km south of the map area.

Dc

SANDSTONE, SHALE, AND CONGLOMERATE (Middle Devonian)—Mixed sedimentary unit composed of interbedded sandstone and shale >> siltstone/mudstone/argillite > conglomerate > graywacke. Sandstone is medium- to dark-brownish gray and light-grayish yellow. Fine- to medium-grained and lesser coarse-grained to small pebble sandstone contains rounded to angular clasts of chert, quartz, carbon, opaque minerals, and lesser plagioclase (An_{11-18}), chlorite, and lithic fragments. Sandstone is clast supported to slightly matrix supported. Cements include variable amounts of carbonate, limonite, and mud (recrystallized to fine-grained white mica). Carbonate cement is partially leached out of most surface samples. Sandstone with high carbonate content verges on sandy limestone, and several samples contain crinoids (map locations F2, F3, and F4; table 1). Sandstone increases in grain size to clast-supported, small pebble conglomerate. Sandstone beds frequently fine upward into medium-gray to black, fissile, laminated shale with planar to rarely crenulated cleavage.

Shale contains up to 50 percent diagenetic pyrite. Several fining-upward sequences were identified, indicating the presence of both normally oriented and overturned beds. Multiple generations of folds were observed in outcrop.

Other sedimentary rocks in this unit include very fine- to minor medium-grained, hard, blocky, foliated, non-fissile, gray-black siltstone, mudstone, and argillite, which are composed of carbon, quartz, sericite, carbonate, chert, limonite, diagenetic pyrite, and magnetite. Conglomerate in the Cascaden Ridge unit contains subrounded to angular clasts up to 1.5 cm in diameter of chert, mudstone, sandstone, and felsic- to intermediate-composition igneous rocks (feldspar with ≈$An_{7–37}$). Clasts are cemented by iron oxide, carbonate, quartz, and trace mud (recrystallized to white mica). Magnetic susceptibility for the unit as a whole is generally low (0.00–1.60, averaging 0.10 x 10^{-3} SI), with higher values associated with argillite layers.

Rare, pale- to dark-green, massive, coarse- to fine-grained graywacke contains subrounded to angular clasts of chert, quartz, albite ($An_{4–10}$), chlorite, opaque minerals, K-feldspar, and lithic fragments (carbonate, chert + carbonate, clastic sedimentary rocks). Clasts are cemented by iron oxide, carbonate, and mud (recrystallized to white mica). Magnetic susceptibility is low (0.18–0.33, averaging 0.26 x 10^{-3} SI).

Unit locally crosscut by 1–10-mm-thick veins of clear crystalline and milky quartz + limonite ± carbonate ± pyrite ± arsenopyrite ± rare visible gold having iron-oxide staining, and a few iron-oxide-rich vuggy, gossanous areas. Hornfelsing and locally strong silicification proximal to alkaline and calc-alkaline dikes is common and described in detail by Allegro (1984). Based on a mineral assemblage of white mica + chlorite ± albite, this unit exhibits a maximum metamorphic grade of lower greenschist facies.

Lost Creek Units

Lost Creek unit (SDl) of Weber and others (1992) is partitioned here into two units, Silurian limestone (Sl) and Silurian sedimentary rocks (Ss). The limestone contains fauna suggestive of a carbonate platform, and is interpreted to have shed debris downslope into a deeper water clastic environment (represented by unit Ss; Blodgett and others, 1988). A total combined thickness of >75 m is suggested for these two units (Chapman and others, 1980). Lower clastic unit (Ss) lies unconformably on the Ordovician Livengood Dome chert unit (Old; this study; Weber and others, 1992).

Sl

LOST CREEK LIMESTONE (Late Silurian)—Fine-grained to very fine-grained, light-gray to dark-bluish gray limestone with local, thin, shaly partings 0.1–0.5 mm thick in 10 percent of the rock. Forms platy to massive outcrop. Occasional conglomerate with 2–3 cm rounded limestone clasts (syn-sedimentary?). Limestone is mostly recrystallized with occasional to common calcite veins. Magnetic susceptibility is extremely low (0.00–0.01, averaging 0.00 x 10^{-3} SI). Slightly recrystallized, light-gray lime wackestone contains abundant crinoid ossicles (columnals, and in several cases, articulated) as well as other indeterminate small biotic debris (map location F5; table 1). Two other samples of limestone had no visible megafossils or conodonts (map locations F6 and F7; table 1). Other fossils identified from a location 4.7 km west of the map area in the Livengood C-4 Quadrangle are Late Silurian (Blodgett and others, 1988). Unit is equivalent to the upper limey portion of the Lost Creek limestone (SDl; Weber and others, 1992). Limestone is 12–15 m thick (Chapman and others, 1980; Blodgett and others, 1988).

Ss

LOST CREEK SANDSTONE, SILTSTONE, SHALE, AND CONGLOMERATE (Silurian)—Mixed sedimentary unit primarily containing chert pebble sandstone with less abundant finer and coarser sedimentary rocks and graywacke. Medium- to dark-gray, grayish green, and tan sandstone with angular to rounded clasts of chert, quartz, shale, argillite, plagioclase, and rare opaque grains. Sandstone is cemented with carbonate, iron oxide, mud (recrystallized to white mica), carbon, and black to dark-gray silica. While mostly very fine-grained sand to coarse granule (1–3 mm sand-sized), the clast-supported to slightly matrix-supported sandstone contains clasts up to 2 cm in diameter. Bedding is not locally visible in the sandstone. Although the sandstone is finer grained and more sorted, the sandstone and conglomerate have very similar clast compositions, and both weather to an orange color.

Gray and tan, matrix-supported, basal conglomerate contains subrounded clasts <5 cm in diameter of multicolored chert, argillite, shale, limestone (crinoid cast; map location F8; table 1), and tuff (plagioclase, quartz, opaque minerals, and chlorite). Conglomerate is cemented by iron oxide and silica. There is a very fine- to very coarse-grained, poorly sorted sandstone component in the conglomerate.

Pale-grayish green, dark-gray, and black limey shale, argillite, and siltstone weather to black and orange and are commonly interbedded with sandstone. Sedimentary rocks are foliated and blocky fracturing to fissile. Fine-grained sedimentary rocks contain clasts of chert, fossils (crinoids; map location F9; table 1), sericite, feldspar, chlorite, hornblende, and trace zircon. Cemented by iron oxide, carbonate, and quartz.

Green graywacke has a similar clast composition to the shale, argillite, and siltstone but contains a greater amount of volcanic lithic fragments. Fine- to medium-grained, clast-supported graywacke contains chert, quartz, biotite, opaque minerals, sedimentary and volcanic lithics, chlorite, hornblende, plagioclase, and fossils. Graywacke is cemented with a matrix of up to 70 percent carbonate, carbon, iron oxide, and mud (partially recrystallized to white mica).

Magnetic susceptibility for the whole unit is generally low (0.00–0.36, average 0.07 x 10^{-3} SI). Sedimentary rocks are crosscut by carbonate veins and, less frequently, crystalline quartz veins. Unit is equivalent to the lower clastic portion of the Lost Creek limestone (unit SDl; Weber and others, 1992). A 60 m thickness of clastic sedimentary rocks was proposed by Chapman and others (1980). Interpretation of a schematic cross section developed from our work suggests a thickness of > 92 m.

Livengood Dome Unit

The mixed chert and clastic sedimentary rock unit (Old) is equivalent to unit Old of Weber and others (1992). This unit is biostratigraphically dated as Late Ordovician by graptolites from the Livengood C-4 Quadrangle, located 4.2 km west of the map area (Weber and others, 1994). The Livengood Dome chert represents a relatively deep, probably outer continental shelf to upper slope depths, environment of deposition (R.B. Blodgett, written commun., 2004). The presence of only graptolites, radiolaria, and sponge spicules are consistent with this interpretation, as well as the notable lack of shelly fauna (Weber and others, 1994; R.B. Blodgett, written commun., 2004). Chapman and others (1980) suggest a thickness for this unit of 300–600 m.

Old

LIVENGOOD DOME CHERT (Ordovician)—Massive, variegated chert with minor argillite/siltstone >> sandstone/graywacke > breccia/conglomerate > rare limestone. Chert colors include light- to dark-gray, bluish gray, white, orange, red, tan, greenish blue, and black. Occasionally mottled. Commonly rhythmically bedded or color banded on a scale of <0.1 mm to 3 cm and sometimes up to 20 cm. Fine lamellae of clay locally define bedding.

Siltstone, claystone, mudstone, shale, and argillite are commonly interbedded with and transition into chert; 2–5-cm-thick beds of very fine- to fine-grained argillite are more commonly interlayered with chert than with other sedimentary rocks. Textures range from hard, cherty, and blocky breaking to platy breaking to soft and fissile depending on the quartz and clay content of the rock. Fine-grained clastic rocks are commonly color banded; colors include maroon, gray, orange, red, medium- to pale-green, white, black, tan, and olive green. A sample of mudstone contains no visible megafossils or graptolites (map location F10; table 1). Another sample of friable siltstone potentially contains sponge spicules (map location F11; table 1).

Dark-brown, tan, medium- to dark-gray, and grayish green sandstone and graywacke contain angular to subrounded clasts of chert, quartz, argillite, chalcedony, plagioclase, sericite, chlorite, rare crystal tuff, opaque minerals, and zircon. Graywacke is cemented by carbon, carbonate, quartz, mud, and limonite. Locally, bedding is apparent. Very fine- to fine-grained and minor coarse-grained to granule sandstone and graywacke are almost matrix supported. Sandstone commonly transitions into conglomerate and breccia.

Gray, black, or tan conglomerate and breccia contain angular to rounded, 1–10 mm diameter clasts of chert and lesser argillite, shale, sandstone, and rare crystal tuff (plagioclase, chlorite, and opaque minerals). Breccia/conglomerate is clast supported with a variably vuggy matrix of drusy silica, chert, sericite, carbon, chalcedony, and iron oxide. Locally recrystallized or possibly hydrothermally replaced. Trace amount of a sulfide mineral occurs at one location. One breccia sample is cemented with a light-green copper(?) mineral. Unit also contains rare, gray, medium-grained, crystalline limestone.

Magnetic susceptibility for the unit as a whole is very low (0.00–0.09, averaging 0.03 x 10^{-3} SI), but rare siltstone and graywacke layers have magnetic susceptibilities up to 0.42 x 10^{-3} SI. Unit contains rare to locally abundant, randomly oriented, milky white quartz veins <0.1–3 mm thick, and rare local areas with black, possibly iron- or manganese-oxide-filled veins. Weak limonite on fractures and occasional manganese-oxide staining.

Amy Creek Assemblage

A sequence of siliceous mudstone and chert (unit lPzZmc) and dolomite and limestone (unit lPzZd) with interlayered metabasalt (unit lPzZmb) correlates with unit SZa of Weber and others (1992). The age of the assemblage is poorly constrained by fossil, radiometric, and interpretive stratigraphic ages. A Sm-Nd date on microgabbro (unit lPzZmb) is in process (map location S1; this study). Whole rock samples of metabasalt yield minimum $^{40}Ar/^{39}Ar$ integrated ages of 192.2 ± 1.0 Ma and 199.1 ± 0.9 Ma (map location A5; Athey and others, 2004a) and 235.5 ± 1.0 Ma (map location A6; Athey and others, 2004a). Age spectra contain pseudoplateaus, which indicate that the metabasalt samples have experienced partial resetting events at approximately 200–250 Ma and 100 Ma. Radiolaria collected from chert (unit lPzZmc) suggest a Paleozoic to latest Proterozoic age for this unit (map locations F12 and F13; respectively, samples 85Awr64A and 90Awr13 from Weber and others [1994]). A siltstone (unit lPzZmc) contains sponge spicules in a 3-mm-thick spicule-rich layer, suggesting a maximum age of latest Proterozoic for the unit (map location F14; table 1). Overlying Devonian sedimentary unit (Dc) contains clasts of dark-gray-black mudstone and chert that are interpreted to be eroded from the Amy Creek mudstone and chert unit (lPzZmc); hence a lower Paleozoic (pre-Devonian) to latest Late Proterozoic age is assigned to this unit.

A homogeneous layer of dolomite (lPzZd) lies above a thick section of lPzZmc and is capped by a mixed layer of predominantly dolomite and lesser siliceous mudstone, chert (lPzZmc), and metabasalt (lPzZmb). The dolomitic portion (lPzZd) represents a relatively shallow-water depositional environment (probably inner shelf, i.e., shallow subtidal to supratidal) built on the lower siliceous mudstone and chert unit that represents a moderately deep-water (outer shelf or deeper) environment of deposition (lPzZmc; R.B. Blodgett, written commun, 2004). Metabasalt (unit lPzZmb) displays within-plate elemental signatures (this study; Athey and others, 2004b), suggesting extrusion of flows and (or) sills in a rift environment. Based on stratigraphy inferred from interpretations of geophysical data (DGGS and others, 1999) and mapping, we agree with Weber and others' (1992) suggested total thickness of at least 1,158 m for the Amy Creek assemblage.

lPzZd

AMY CREEK DOLOMITE AND LIMESTONE (lower Paleozoic to latest Late Proterozoic)—White to light-gray, buff, pale-yellow, and orange-brown dolomite and rare limestone variably replaced by quartz. Quartz occurs as veins and web-like structures as well as massive replacement within carbonate. SiO_2 ranges from less than 1 percent to >50 percent (Athey and others, 2004b). Unit varies from almost pure dolomite (17.75–21.12 percent MgO; pure dolomite contains 21.7 percent MgO) to rare, almost pure limestone (54.1 percent CaO; pure limestone contains 56 percent CaO; Athey and others, 2004b). The limestone pattern on the map depicts the few areas in this unit that are not dolomitized. Rarely interbedded with siliceous mudstone and chert (lPzZmc) layers that are approximately >90 m thick. Occasionally contains bands, fractures, and interlaminations of black carbon and silica, possibly an indication of proximity to a contact with lPzZmc. Weathered surfaces occasionally exhibit popcorn-like, vuggy, and rough textures depending on the amount of carbonate leaching. Commonly crops out as mounded rubble. Magnetic susceptibility is very low (0.00–0.19, averaging 0.02 x 10^{-3} SI). Commonly brecciated with a quartz matrix and crosscut by <1-mm- to 3-cm-thick, gray, translucent to sucratic quartz veins and up to 5-cm-thick calcite veins. Occasional limonite stains on fracture surfaces. Samples of lime mudstone (map locations F15, F16, and F17; table 1), dolomitic wackestone (map location F18; table 1), and dolomudstone (map location F19; table 1) contain no conodonts or visible megafossils. Three samples contain algal biolithites with no biostratigraphic significance (F15, F16, and F19; table 1). Equivalent to dolomite portion of unit SZa (Weber and others, 1992). A total thickness of 274 m for this unit was estimated from a schematic cross section through the map area. A homogeneous ≈122-m-thick layer of lPzZd lies above lPzZmc and is capped by a >152-m-thick, mixed layer of the Amy Creek units.

lPzZmb

AMY CREEK METABASALT (lower Paleozoic to latest Late Proterozoic)—Aphanitic metabasalt, greenstone, fine-grained microgabbro, and trace diabase flows and (or) sills. Occurs as laterally continuous horizons interlayered with Amy Creek dolomite and limestone (lPzZd) and Amy Creek siliceous mudstone and chert (lPzZmc). Metabasalt is dark-green or greenish brown to black and when weathered is brown, black, orange, or red. Average modal composition is approximately 35–70 percent plagioclase (≈An_{35}), 0–70 percent clinopyroxene, 5–35 percent magnetite, 0–10 percent orthopyroxene, and 0-65 percent altered glass(?). Massive and blocky in outcrop and rarely slightly foliated or slightly brecciated. Magnetic susceptibility is generally very high, but significantly variable within the outcrop (0.19–115.0 x 10^{-3} SI, averaging 9.7 x 10^{-3} SI). Protolith had a CIPW normative basaltic composition with a within-plate trace-element-indicated tectonic signature (this study; Athey and others, 2004b). Relict amygdules are common and are frequently filled with carbonate ± chlorite. Degree of alteration varies. Alteration minerals include chlorite, carbonate, prehnite, clinozoisite, epidote, sericite, pumpellyite, and iron oxide. Unit is metamorphosed to prehnite–pumpellyite facies. Fractures are coated with chlorite and commonly stained with iron- and manganese-oxide, and rocks are crosscut by rare 1–3 mm carbonate veins. Equivalent to greenstone portion of unit SZa (Weber and others, 1992). Regionally, metabasalt layers are at least 100 m thick (Weber and others, 1992). Our estimated thickness from a schematic cross section through the map area is approximately 30–45 m.

lPzZmc AMY CREEK SILICEOUS MUDSTONE AND CHERT (lower Paleozoic to latest Late Proterozoic)—Mixed sedimentary unit primarily containing siliceous mudstone > chert > conglomerate/breccia > argillite, sandstone, siltstone, and shale. Mudstone, which breaks along hackly fractures instead of conchoidal surfaces, is the largest component of this unit and is intermediate in composition between chert and the other fine- to coarse-grained sedimentary rocks. Black and rare dark- to pale-gray siliceous mudstone weathers orange, brown, and red. Manganese- and iron-oxide staining variably present and locally intense. Mudstone is locally brecciated and cut by 1–5-mm-thick, vuggy, milky quartz ± limonite ± carbonate veins.

Chert is variegated, mottled, and rarely color banded. Colors include black, dark- to light-gray, grayish green, yellowish brown, and maroon. Float is massive and blocky. Chert is homogeneous, occasionally laminated with few white clay partings, and in one location contains nodules of clay 1.3 cm in diameter. Occasional occurrences of intense, milky white quartz veins averaging 0.5–1 mm thick with rare veins up to 1 cm thick. Chert weathers brown, orange, red, yellow, and white, and exhibits iron- ± manganese-oxide on fractures, rare brecciated and jasperoidal quartz, and limonite after rare 1–2 percent disseminated pyrite. Chert is rarely interbedded with mudstone, sandstone, siltstone, and tuff(?) on a millimeter- to 10-cm-scale.

Black, gray, tan, and white, clast-supported conglomerate and breccia contain subrounded to angular, flattened clasts of chert, mudstone, and quartz 2 mm to 2 cm in diameter. Gray, green-gray, and tan, interbedded sandstone, graywacke, siltstone, and shale contain variable amounts of sericite, quartz, carbon, lithic fragments (chert and glassy tuff), plagioclase, chlorite, and opaque minerals. The vuggy, porous, and friable matrix is composed of silica + limonite ± carbonate ± opaque minerals ± carbon ± chalcedony ± trace mud (recrystallized to very fine-grained white mica). Very fine- to fine-grained, fissile, black argillite is locally interlayered with the other sedimentary rocks. The weathered orange, brown, and red sedimentary rocks are occasionally iron-oxide-stained, quartz veined, and contain rare disseminated pyrite.

Magnetic susceptibility for this unit is generally very low (0.00–0.23, averaging 0.03 x 10^{-3} SI), but rare argillite layers have magnetic susceptibilities up to 0.63 x 10^{-3} SI. Unit equivalent to chert and other clastic rocks from unit SZa of Weber and others (1992). Unit comprises a >884-m-thick section at the base of the Amy Creek assemblage. Lithologies of this unit are also interlayered with the dolomite and metabasalt above the main dolomite and limestone (lPzZd) section.

Ophiolite Assemblage

The Early Cambrian ophiolite assemblage, a mixture of greenstone (Єgs), metagabbro (Єmg and Єlg), serpentinite (Єs), and mafic intrusions (Єc) correlates with unit ЄZum of Weber and others (1992) and is described in detail by Foster (1966). The ophiolite assemblage displays a mid-ocean ridge basalt (MORB) trace-element signature (this study; Athey and others, 2004b) and probably represents an obducted slab of oceanic crust. The ophiolite assemblage is metamorphosed to prehnite–pumpellyite facies (this study; Foster, 1966). Hornblende from a metagabbro (unit Єmg) 0.75 km southwest of the town of Livengood (map location A7; sample DT87-15) yields an $^{40}Ar/^{39}Ar$ plateau age of 535.3 ± 2.7 Ma (Athey and others, 2004a). The sample yields a K-Ar hornblende age of 548 ± 16

(Rinehart and others, 1997); the older age is explained by excess argon released from the lowest step-heated fractions during the ^{40}Ar/^{39}Ar dating process (Athey and others, 2004a). Sample DT87-16 (located 8.5 km southwest of Money Knob in the Livengood B-4 Quadrangle) also released excess argon during the ^{40}Ar/^{39}Ar dating process (Athey and others, 2004a); this metagabbro yields an anomalously young ^{40}Ar/^{39}Ar age (390.0 ± 1.8 Ma from hornblende) due to alteration (Athey and others, 2004a). Several samples of hornblende from metagabbro within the greenstone unit (Ꞓgs) yield K-Ar ages ranging from 539 ± 16 to 566 ± 17 Ma (map locations K1-K4; Rinehart and others, 1997), however the samples probably also contain excess argon. An Early Cambrian age is assigned to the ophiolite assemblage present in the map area.

Ꞓgs

GREENSTONE (Early Cambrian)—Mixed unit composed primarily of greenstone, volcaniclastic rocks, minor lenses of metagabbro, and locally abundant metabasalt. Aphanitic to fine-grained, massive greenstone is composed of plagioclase (≈An_{27-32}), hornblende, clinopyroxene (altering to hornblende), possible iddingsite and serpentine after olivine, and devitrified glass. Greenstone is pale- to dark-green, grayish green, black, and brown. Weathered black and orange greenstone is commonly altered to sucratic mixture of quartz + clinozoisite + carbonate + chlorite + opaque ± epidote ± actinolite ± sericite ± albite. Forms large, blocky boulders and outcrop.

Clast-supported agglomerate with angular to subrounded clasts <1 mm to 10 cm in diameter reveal their agglomeratic texture on weathered surfaces. Clasts include basaltic tuff, gabbro, and altered serpentinite. Grain size and texture of clasts varies greatly. Unit frequently is penetratively deformed. Foliated/sheared bands break into sheets 0.5 cm to 1 m thick. Crosscut by 2-mm-thick veins of chlorite + quartz + carbonate ± albite ± very fine-grained sericite. Iron- and manganese-oxide staining is common. Alteration includes trace sulfide, limonite-filled vugs, and trace malachite.

Also contains equigranular, very fine- to coarse-grained metagabbro lenses with an average modal composition of 40–70 percent plagioclase, 30–60 percent clinopyroxene (some exsolving orthopyroxene), 0–10 percent hornblende, and opaque minerals. Secondary minerals include epidote, sericite, scapolite, chlorite, and trace pyrite. Metagabbro occurring within the greenstone unit appears more propylitically altered than that from within the metagabbro unit itself. Glassy-, porphyritic-, and diabasic-textured basalt also occurs within the greenstone. Fairly unaltered basalt contains elongate needles of plagioclase and clinopyroxene in a groundmass of devitrified glass, which has been altered to carbonate, chlorite, and iron oxide. Magnetic susceptibility is generally moderate (0.10–0.81, averaging 0.34 x 10^{-3} SI), but rare metagabbro bodies exhibit values up to 27.5 x 10^{-3} SI.

Ꞓc

OLIVINE CLINOPYROXENITE DIKE (Early Cambrian)—Fine- to coarse-grained, equigranular, dark-green olivine-bearing clinopyroxenite dike intruding metagabbro (Ꞓmg) at the top of Amy Dome. Modal composition is 88 percent clinopyroxene, 10 percent olivine (altering to serpentine), and 2 percent orthopyroxene. Locally contains clinopyroxene crystals up to 2 cm in diameter. Secondary minerals include serpentine, magnetite and prehnite(?). Magnetic susceptibility is very high (4.74 to 16.7, averaging 10.7 x 10^{-3} SI). Age assignment of this dike is based on correlation with the metagabbro (unit Ꞓmg).

Ꞓmg

METAGABBRO (Early Cambrian)—Primarily massive, blocky, homogeneous metagabbro with rare, massive, equigranular, very fine- to fine-grained greenstone. Metagabbro is green, white, dark-gray, and black. Equigranular, fine-grained and minor medium-grained metagabbro has an average modal composition of about 35–80 percent mafic minerals (hornblende > clinopyroxene) and 20–65 percent andesine (An_{35}). Occasional coarse-grained metagabbro with plagioclase phenocrysts up to 1 cm long. Multiple intrusions of gabbro presumably account for observed textural and compositional variability. Magnetic susceptibility is low to moderate (0.14 to 0.72, averaging 0.41 x 10^{-3} SI). Alteration mineralogy consists of chlorite, epidote, carbonate, sphene, opaque minerals, and clinozoisite. Metagabbro is crosscut by carbonate, chlorite, and quartz veins and contains local disseminated chalcopyrite(?) and pyrite. Hornblende from this unit (map location A7; sample DT87-15) yields an ^{40}Ar/^{39}Ar plateau age of 535.3 ± 2.7 Ma (Athey and others, 2004a).

Ꞓlg

LAYERED METAGABBRO (Early Cambrian)—Fine- to very coarse-grained layered metagabbro. It is uncertain whether metagabbro bodies are klippen above, or intruded into the greenstone (unit Ꞓgs). White and green layering defined by alternating, equigranular bands of plagioclase and clinopyroxene having flattened, elongate crystals up to 0.5 cm in diameter; layers average 2–3 mm thick. Average modal composition is about 50–70 percent plagioclase and 30–50 percent clinopyroxene. Magnetic susceptibility is moderate (0.10 to 0.42, averaging 0.35 x 10^{-3} SI). Numerous magnesite(?) + albite(?) + epidote veins up to 4 mm thick crosscut unit layers. Age assignment based on correlation with associated metagabbro (unit Ꞓmg).

Ꞓs

SERPENTINITE, METAGABBRO, AND GREENSTONE (Early Cambrian)—Recognized as a composite unit primarily containing serpentinite and minor lenses of altered metagabbro and rare greenstone. Hard, massive, waxy, aphanitic, green and black serpentinite with anastamosing serpentine veins. Mineral composition of antigorite, minor chrysotile, and magnetite. Occasionally fissile, sheared, and folded and usually altered to quartz-carbonate listwaenite (or listwanite). Serpentinite is commonly found in local thrust fault zones, apparently acting as a slide-plane between faulted plates. Altered serpentinite is colored orange, white, brown, pale-grayish brown, blue, and pale-green. Alteration mineralogy includes quartz, talc, magnesite, chlorite, fuchsite/mariposite, brucite, iron oxide, and manganese oxide. Silica occurs in many forms: Milky, massive, drusy, vuggy, opalescent, botryoidal, chalcedony, breccia matrix, veins, and replacement. Occasionally pyrite, rare pyrrhotite(?), and rare malachite are found with the alteration. Locally, total replacement by quartz ± carbonate renders the rock's original composition almost unrecognizable. Alteration is also reported to be locally gold-bearing (Saunders, 1955). A trench 1.1 km west of the town of Livengood intersects an intensely silicified felsic dike intruding quartz–carbonate-altered serpentinite. Altered rocks are crosscut by pyrite + stibnite + arsenopyrite + quartz veins yielding 2.91 ppm Au and 2.11 percent As (Athey and others, 2004b).

Serpentinite unit also contains fine- to lesser medium-grained, equigranular, green and white metagabbro composed of plagioclase (occasionally poikilitic), hornblende, clinopyroxene (altering to hornblende), and opaque minerals. Average modal composition is about 50 percent plagioclase and 50 percent mafic minerals. Rare metabasalt contains clinopyroxene phenocrysts. Metabasalt forms blocky, massive outcrops. Associated minor, mottled, medium- and dark-green and white greenstone is blocky, aphanitic, and granular. Metagabbro and greenstone are frequently brecciated and altered to epidote, chlorite, carbonate, clinozoisite, iron oxide, and sphene, and contain minor milky to clear quartz–carbonate veins and rare malachite and chrysocolla in fractures.

Magnetic susceptibility is extremely variable (0.12–84.8, averaging 7.5 x 10^{-3} SI), in line with the primary compositional variability of the rocks and the presence of silica–carbonate alteration. Very high magnetic susceptibility values are due to secondary magnetite produced during serpentinization. Prehnite–pumpellyite facies metamorphic grade is indicated by a secondary mineral assemblage that includes chlorite, epidote, pumpellyite, relict augite, actinolite(?), and rare albite. X-ray diffraction studies indicate prehnite is also present (Foster, 1966).

Wickersham Units

Our Wickersham limestone (Ꞓwl) and shale (ꞒZwa) units correspond respectively with Weber and others (1992) Wickersham subunits of Ꞓwl and ꞒZwa. The ages of these units are unknown, however a maximum age of Late Proterozoic is assigned because of their stratigraphic position above the Wickersham ꞒZwg unit (Weber and others, 1988; Weber and others, 1992), which in the Livengood D-2 Quadrangle contains trace fossil *Oldhamia* (Cambrian to Precambrian age; Weber and others, 1994). ꞒZwg (Weber and others, 1988) does not crop out within the map area; ꞒZwg is mapped in the northeast corner of the Livengood Quadrangle (Weber and others, 1988) and in the Tanana Quadrangle (Reifenstuhl and others, 1998). Quartzite from the Wickersham unit is compatible with a craton interior provenance, based on its uniform composition of subrounded to well-rounded, monocrystalline quartz (Gergen and others, 1988).

Ꞓwl

WICKERSHAM LIMESTONE (earliest Cambrian?)—Very fine- to medium-grained, medium- to dark-gray, sparry, recrystallized limestone with abundant white calcite veins up to 1 cm thick. Forms massive and blocky outcrops, sometimes with visible bedding. Variably sandy with rounded to subrounded grains and occasional dolomite rhombs and pelloids. Carbonate grains average about 0.02–0.5 mm in diameter. Composition includes very minor mud, carbon, quartz, and iron oxide. Locally foliated with white shale partings and contains a few iron-oxide-filled fractures. Three samples of recrystallized lime mudstone contain no conodonts or visible megafossils (map locations

F20, F21, and F22; table 1). Age of unit is unknown, however it presumably lies stratigraphically above the earliest Cambrian(?) to Late Proterozoic Wickersham shale (unit ꞒZwa) and is tentatively assigned an age of earliest Cambrian. Distinguished from other limestone units in the map area by its coarser grain size and high degree of recrystallization. Magnetic susceptibility is extremely low (0.00 x 10^{-3} SI).

ꞒZwa WICKERSHAM SHALE (earliest Cambrian? to Late Proterozoic)—Maroon shale. Exposed in Willow Creek 0.8 km north of the map area. Unit occurs in low-lying, loess-covered hills and swamps. Magnetic susceptibility is low (0.10–0.20, averaging 0.15 x 10^{-3} SI). Likely correlates with Wickersham unit ꞒZwa of Weber and others (1992), which contains maroon and green argillite, grit (sandstone with bimodal grain size), quartzite, siltstone, graywacke, and phyllite. Age of unit is unknown, but is tentatively assigned an earliest Cambrian(?) to Late Proterozoic age because of its stratigraphic position above the Wickersham unit ꞒZwg (Weber and others, 1992; Weber and others, 1994).

ENGINEERING-GEOLOGIC UNITS

UNCONSOLIDATED MATERIALS

GS Fluvial gravel, sand, and silt. Chiefly (estimated >80 percent) clean sand and gravel. Grain size, sorting, and degree of stratification are variable. Permafrost may be present, especially in older deposits. Older deposits may contain highly weathered clasts and thus may not be suitable as construction materials. Rare oversized materials may include boulders. Includes primarily GP and GW of the Unified Soil Classification (Wagner, 1957).

GM Poorly- to moderately well-sorted clay, silt, sand, gravel, and diamicton of colluvial and fluvial origins. Engineering applications vary widely due to large range of grain size and sorting properties. Commonly frozen. Estimated 20–80 percent coarse, granular deposits with considerable oversized material. Includes primarily GC and GM of the Unified Soil Classification (Wagner, 1957).

SM Silt deposited primarily by wind and reworked by fluvial and colluvial processes. May be organic rich. Commonly frozen and ice-rich, especially on north-facing slopes. Chiefly fine materials. Estimated > 80 percent silt, sand, and clay. Includes primarily ML, MH, and SM of the Unified Soil Classification (Wagner, 1957).

OR Organic-rich silt in swamp deposit resulting from drainage of Hess Creek reservoir. Commonly frozen and ice-rich due to the excellent insulating properties of peat. Generally water-saturated. Chiefly organic materials. Estimated > 50 percent peat, organic sand, or organic silt. Includes Pt of the Unified Soil Classification (Wagner, 1957).

BEDROCK MATERIALS

BC Medium-jointed, fine- to coarse-grained sedimentary carbonate rocks. Includes limestone and dolostone.

BG Coarse-jointed, medium- to coarse-grained intrusive igneous lithologies and their metamorphic equivalents. Chiefly granitic rocks. Includes coarse-grained gneiss.

BO Lithologies that are generally poorly suited for use as construction materials. Includes shale, siltstone, graywacke, and argillite.

BU Rocks of mixed lithology or very fine-grained sedimentary or igneous lithologies or both, which are generally poorly suited for use as construction materials.

BV Medium-jointed, fine-grained igneous rocks. Chiefly volcanic flow rock, dikes, and greenstone.

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Table 1. *Megafossil and microfossil identifications in the Livengood area, Alaska.*

Map No.	Sample	Easting[a] (m)	Northing[a] (m)	Rock Type	Unit	Megafossils	Megafossil Identified By	Megafossil Age	Microfossils	Microfossil Identified By	Microfossil Age	Reference
F1	USNM 38755	432054	7263542	Fine- to coarse-grained sandstone	Dc	Gastropods	R.B. Blodgett	early Middle Devonian	---	---	---	Blodgett, 1992
F2	2003MBW251B	428969	7267187	Medium gray- to orange-weathered limestone	Dc	Crinoids		Permian to Ordovician	---	---	---	This study
F3	2003MBW252A	429099	7266957	Fine-grained, orange-weathered sandstone interbedded with shale	Dc	Crinoids	DGGS	Permian to Ordovician	---	---	---	This study
F3	2003MBW252B	429099	7266957	Gray shale	Dc	Crinoids	DGGS	Permian to Ordovician	---	---	---	This study
F4	2003MBW253A	429128	7266908	Gray- to orange-weathered sandstone with carbonate cement	Dc	Crinoids	DGGS	Permian to Ordovician	---	---	---	This study
F5	2003RN202A	442526	7278410	Slightly recrystallized, light-gray limewackestone	Sl	Abundant crinoid ossicles; columnals, and, in several cases, articulated. Other indeterminate small biotic debris.	R.B. Blodgett	Permian to Ordovician; possibly Late Silurian based on lithologic similarity to Lost Creek unit (Blodgett and others, 1988)	---	---	---	This study
F6	2003RN154A	432500	7277158	Light-gray dolomudstone	Sl	No visible megafossils	---	---	No conodonts	N.M. Savage	---	This study
F7	2003RN203A	442473	7277963	Medium-gray lime mudstone	Sl	No visible megafossils	R.B. Blodgett	---	No conodonts	N.M. Savage	---	This study
F8	2003RN187B	419952	7270008	Limestone clast in chert pebble sandstone–conglomerate	Ss	Crinoids	DGGS	Permian to Ordovician	---	---	---	This study
F9	2003Z164B	420580	7270177	Gray-olive green limey siltstone	Ss	Crinoids	R.B. Blodgett	Permian to Ordovician	---	---	---	This study
F10	2003Z32A	433023	7275793	Brown-green blocky argillite	Old	No visible megafossils	R.B. Blodgett	---	---	---	---	This study
F11	2003RN162A	432734	7277833	Fragile, interbedded siltstone and sandstone	Old	Unidentified biotic debris	DGGS	Unknown	Possible sponge spicules	DGGS	< 650 Ma, Precambrian and younger	This study
F12	85AWr64A	433209	7269029	Chert(?)	lPzZmc	---	---	---	Radiolaria observed in thin section	C.D. Blome	Paleozoic	Weber and others, 1994
F13	90AWr13	425473	7265779	Chert(?)	lPzZmc	---	---	---	Radiolaria observed in hand sample	F.R. Weber	Paleozoic	Weber and others, 1994
F14	2003Z136A	430286	7272120	Brown and olive-green siltstone	lPzZmc	---	---	---	Sponge spicules	R.B. Blodgett	< 650 Ma, Precambrian and younger	This study
F15	2003MBW23A	431921	7273249	Medium-gray lime mudstone	lPzZd	No visible megafossils. Common thin, laminar "algal" chips.	R.B. Blodgett	No biostratigraphic significance	No conodonts	N.M. Savage	---	This study
F16	2003Z98A	428685	7270868	Light-gray lime mudstone	lPzZd	No visible megafossils. Texture suggestive of algal biolithites.	R.B. Blodgett	No biostratigraphic significance	No conodonts	N.M. Savage	---	This study
F17	2003Z127A	431260	7273416	Light-gray lime mudstone	lPzZd	No visible megafossils	R.B. Blodgett	---	No conodonts	N.M. Savage	---	This study
F18	2003RN96A	434572	7270448	Light-gray dolomitic "wackestone"	lPzZd	No visible megafossils. Small, probable algal biolithites.	R.B. Blodgett	No biostratigraphic significance	---	---	---	This study
F19	2003Z206A	430636	7272038	Light-gray dolomudstone	lPzZd	No visible megafossils	R.B. Blodgett	---	No conodonts	N.M. Savage	---	This study
F20	2003LF12A	419133	7275274	Medium-gray lime mudstone	Ꞓwl	No visible megafossils	R.B. Blodgett	---	No conodonts	N.M. Savage	---	This study
F21	2003LF13A	419362	7275270	Medium-gray lime mudstone	Ꞓwl	No visible megafossils	R.B. Blodgett	---	No conodonts	N.M. Savage	---	This study
F22	2003LF14A	419433	7275222	Fine-grained limestone	Ꞓwl	---	---	---	No conodonts	N.M. Savage	---	This study
F22	2003LF14B	419433	7275222	Medium-gray lime mudstone	Ꞓwl	No visible megafossils	R.B. Blodgett	---	---	---	---	This study

[a]Coordinates given in Universal Transverse Mercator (UTM) projects, zone 6; based on Clark 1866 spheroid, North American Datum (NAD) 27.

Table 2. *Preliminary stratigraphic correlations in the Livengood Quadrangle, Alaska.*

Map Unit (this report)	Livengood Quadrangle *Livengood area equivalent* (Weber and others, 1992)	Livengood Quadrangle *Schwatka–Rampart area equivalent* (Weber and others, 1992)	Livengood Quadrangle *Fairbanks–White Mountains area equivalent* (Weber and others, 1992)	Other Equivalents
Rampart gabbro, quartz gabbro, and minor chert (T̄Rg)	---	Rampart group intrusive and extrusive mafic rocks, and sedimentary rocks (T̄RMrv)	---	Described within Tozitna assemblage mafic and ultramafic rocks (JT̄Rtmu; Wilson and others, 1998)
Sandstone, shale, and chert (T̄RDs)	---	Rampart group sedimentary rocks (T̄RMrs) **<u>or</u>** Metamorphic amd sedimentary rocks (PDms)	---	---
Shale (PDs)	---	Metamorphic and sedimentary rocks (PDms)	---	---
Cascaden Ridge sandstone, shale, and conglomerate (Dc)	Cascaden Ridge sedimentary unit (Dc) **<u>and</u>** Quail sedimentary unit (Dq)	---	Beaver Bend sedimentary unit (Dcg) **<u>and</u>** upper Devonian section of Tolovana limestone (DSt)	---
Lost Creek limestone (Sl)	Lost Creek unit limestone (SDl)	---	lower Silurian section of Tolovana limestone (DSt)	---
Lost Creek sandstone, siltstone, shale, and conglomerate (Ss)	Lost Creek unit sedimentary rocks (SDl)	---	lower Silurian section of Tolovana limestone (DSt)	---
Livengood Dome chert (Old)	Livengood Dome chert (Old)	---	upper(?) sedimentary portion of Fossil Creek unit (Ofs)	---
Amy Creek dolomite (lPzZd), metabasalt (lPzZmb), and mudstone and chert (lPzZmc) assemblage	Amy Creek dolomite, chert, argillite, mudstone, and greenstone (SZa)	---	**(?)** lower(?) sedimentary portion of Fossil Creek unit (Ofs) and Fossil Creek volcanics (Ofv)	**(?)** Precambrian Katakturuk Dolomite of Clough and Goldhammer (2001)
Ophiolite assemblage – greenstone (Єgs), metagabbro (Єmg and Єlg), serpentinite (Єs), and mafic intrusions (Єc)	Ultramafic and mafic rocks (ЄZum)	---	---	---
Wickersham limestone (Єwl)	Wickersham dark gray limestone (Єwl)	---	---	---
Wickersham shale (ЄZwa)	Wickersham maroon and green argillite, phyllite, quartzite, graywacke, siltite, and grit (ЄZwa)	---	---	---

Table 3. *Generalized engineering properties of unconsolidated units.*

Map unit	Drainage	Permafrost	Frost susceptibility	Slope stability	Bearing strength	Potential primary products	Potential engineering considerations	Component geologic units[a]
GS	Good in recently deposited alluvium above stream level; fair to poor in older alluvium where permafrost has developed and where covered by silty colluvium and retransported loess and peat; good in young, unfrozen terrace deposits; generally restricted on older inactive surfaces mantled by appreciable silt and organic material.	Generally absent in young alluvium and mine tailings; sporadic to continuous; ice rich in organic silt and peat; ice typically limited to fine-grained overburden.	Minimal in well-drained young alluvium; moderate to intense in active layer in silt and organic material; gravels not susceptible to heaving.	Generally stable, except ice-rich permafrost subject to thaw instability; areas adjacent to cut banks and free faces subject to sudden collapse due to undercutting or surface loading.	Variable; generally fair to good, especially beneath silt and peat overburden.	Crushed aggregates and miscellaneous clean fills.	Older deposits with permafrost and significant covers of eolian, organic, or colluvial sediments are generally undesirable as material sources, steep cutbanks along active streams may fail suddenly and thus not be suitable for structure sites; high potential for seasonal floods, including rapid buildup of surface icings along margins of major streams and in narrow tributary valleys.	Qa, Qaa, Qt
GM	Variable, depending on content of fines and extent of permafrost; poor to fair where deposits are fine grained and permafrost is shallow and continuous.	Discontinuous in valley bottoms; continuous beneath northern slopes and lower valley walls; not present beneath upper south-facing slopes; ice rich in silty colluvium.	High in silty deposits, especially organic silt with fair to poor drainage.	Thaw unstable where perennially frozen and ice rich; silty materials susceptible to creep, especially where drainage is restricted; slow flow of rubble sheets affects steep slopes where bedrock is shallow; surfaces of rubble sheets subject to local settling due to piping of interstitial fines; bedrock locally susceptible to creep.	Variable, but generally fair to poor during thawing of seasonal frost and permafrost, especially where ice rich; moderate where thawed and well drained.	Unclassified fills, except for small pods of gravel and gravelly fluvial sand.	Thaw settlement occurs in ice-rich permafrost; sudden floods may occur in small tributary valleys on the north and west flanks of Livengood Dome during intense summer rainstorms and snowmelt; seasonal icings flood slopes and floors of tributary valleys.	Qaf, Qc, Qca, Qdf
OR	Very poor, often with standing water.	Generally frozen except near stream cuts.	Very high. Thaw unstable following surface disturbance.	Thaw unstable; subject to failure due to saturation.	Generally poor, especially where thawed.	May be suitable for horticultural or energy applications.	Surface subject to inundation; extreme frost heaving, and thaw subsidence in saturated soils; generally unsuitable as structure sites unless structures are pile supported.	Qs
SM	Generally poor due to extensive shallow permafrost and low permeability.	Widespread and ice rich; includes interstitial, segregation, and massive ice, especially where organic rich.	High, especially where drainage is poor.	Generally poor; thaw unstable where permafrost is ice rich.	Generally poor when thawed.	Perhaps unclassified fill material, but generally unsuitable as material source.	May be subject to slumping, sloughing, subsidence, liquefaction, mudflow, and thaw settlement; flooding by seasonal icings may be a local problem	Qcfl, Qcfu, Qe, Qe-c

[a]Source of geologic units: Sheet PIR 2004-3c, this report.

Table 4. *Engineering properties of bedrock units.*

Map unit	Principal rock characteristics	Potential primary products[a]	Component geologic units[a]
BC	Medium-jointed, fine- to coarse-grained sedimentary carbonate rocks and their metamorphic equivalents	· Dimension stone · Ornamental stone · Crushed rock · Cement	S1, 1PzZd, Ꞓwl
BG	Coarse-jointed, coarse-grained intrusive igneous rocks and their metamorphic equivalents	· Dimension and ornamental stone · Riprap, armor, gabion, and drain rock · Crushed rock and grüs	Kmk, Krc, Ŧg, Ꞓmg, Ꞓlg
BV	Medium-jointed, fine-grained igneous rocks and their metamorphic equivalents	· Riprap and drain rock · Crushed rock · Unclassified fills	Ko, Ꞓgs, 1PzZmb
BO	Other lithologies	· Unclassified fills	PDs, Old
BU	Rocks of mixed lithology and character	· Unclassified fills	ŦDs, Dc, Ss, 1PzZmc, Ꞓs

[a]Source of geologic units: Sheet PIR 2004-3a, this report.

Note: Some bedrock units are not assigned engineering-geologic map units because they are of limited extent and may not be of economic importance. These units include: T1, Ka, Kc, Ꞓc.