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GEOLOGIC MAP OF THE TANANA A-1 AND A-2 QUADRANGLES, CENTRAL ALASKA

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GEOLOGIC BACKGROUND

The Tanana A-1 and A-2 quadrangles map area is part of the Yukon–Tanana Upland physiographic province. The Alaska Division of Geological & Geophysical Surveys (DGGS) geologically mapped these two quadrangles in 1997, after a DGGS airborne geophysical survey (resistivity and magnetics, Burns, 1996, 1997) of the Manley–Rampart area. These airborne geophysics are fundamental to accurate geological mapping in this poorly exposed region. Additional DGGS reports on the geology of the A-1 and A-2 quadrangles relate to geochemistry (Liss and others, 1998) and Quaternary geology (Pinney, 1998a, 1998b). The Tanana B-1 Quadrangle, which is adjacent to and northeast of the Tanana A-1 and A-2 quadrangles, was mapped by DGGS in 1996 (Reifenstuhl and others, 1997); related reports include rock geochemistry (Liss and others, 1997), ^{40}Ar/^{39}Ar geochronology (Reifenstuhl and others, 1997b), chert geochemistry (Haug and others, 1997), Quaternary geology, construction materials, and hazards (Pinney, 1997a, 1997b, 1997c), and gold geochemistry (Newberry and Clautice, 1997).

Historic work includes reconnaissance mapping of the Manley–Rampart area (Mertie, 1937), and more recently the Tanana Quadrangle, at 1:250,000 scale (Chapman and others, 1982). Rock units in the Tanana A-1 and A-2 quadrangles trend northeast into the Tanana B-1 Quadrangle mapping (Reifenstuhl and others, 1997a), and into the Livengood Quadrangle mapping (Weber and others, 1992). Unpublished mapping of the Tanana A-1 and A-2 quadrangles by D.M. Hopkins and Bond Taber (written commun., 1996) has been useful in our work. Numerous topical studies have been completed on the geology of the area (Blodgett and others, 1987; Jones and others, 1984; Loney and Himmelberg, 1985, 1988). Regional geologic compilations, which include the Tanana A-1 and A-2 quadrangles, have been published by Dover (1994), Dover and Miyaoka (1983a), Dusel-Bacon (1994), Nokleberg and others (1994), and Silberling and others (1994). Plafker and others (1994) addressed faulting, and Barnes and others (1994) reported on gravity.

STRUCTURE AND STRATIGRAPHY

Regionally northeast-trending, thrust fault bounded, layered rock packages (cut late-stage, high-angle faults) crop out northwest and southeast of the Albian-age, Wilber Creek unit of the central and southcentral map area. The map units northwest of these Albian basinal rocks are, from southeast to northwest: (1) the Early Cretaceous to Jurassic Wolverine quartzite unit; (2) the Triassic to Permian clastic unit (argillite, sandstone, lesser conglomerate, and cross-cutting carbonatite); (3) the late Late Devonian (Famennian) lime mudstone (fault slivers at Granite Creek), with quartz grains, crinoid ossicles, conodonts, and conglomerate; (4) Late Proterozoic to Silurian Amy Creek dolomite (dolostone, chert, siliceous argillite, and greenstone); and (5) Late Ordovician age Livengood Dome Chert (siliceous argillite, quartzite, and cherty argillite; structurally complex), with pre-Late Ordovician Orum limestone (ooid grainstone-bearing, lime mudstone). In the southeastern part of the map area only (Dugan Hills) and on the southeastern flank of the Albian basinal rocks are, from northwest to southeast: the Mississippian Globe Quartzite unit; the Ordovician Fossil Creek Volcanics unit; and the Late Proterozoic to Cambrian Wickersham Grit unit (calcareous sandstone, grit, and siliceous rocks). These three map units do not crop out in the Tanana A-1 or Tanana A-2 quadrangles but are inferred based on outcrops in the immediately adjacent Livengood and Kantishna River quadrangles where structure and stratigraphy indicate northwest-directed imbrication. Timing of thrust fault deformation is pre-90 Ma because Roughtop pluton (92 Ma; 88.5 Ma) is not notably deformed and apparently cross-cuts ('stitches') a major thrust fault (based on magnetic signature), and post-Albian (97 Ma) because the Wilber Creek unit is involved in thrusting. Timing of high-angle faulting is post 58 Ma (Hot Springs pluton) and post 56 Ma in the Tanana B-1 Quadrangle where Tertiary age-dated, bimodal rhyolite and basalt are juxtaposed by high-angle faults (Reifenstuhl and others, 1997a, 1997b). Historic high angle faulting is important, as documented by numerous historic earthquake epicenters along the Minook

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Creek fault (Tanana B-1 and A-1 quadrangles), and several on the Stevens Creek fault (Gedney and others, 1972).

The Stevens Creek fault is a prominent structural feature, trends west-northwest, and has about 10 km of right lateral displacement and an unknown amount of vertical movement. In the northwesternmost Tanana A-2 Quadrangle, the Kaltag fault zone is topographically subdued but cuts the Amy Creek dolomite unit and the Livengood Chert unit. Farther northeast, in the Tanana B-1 Quadrangle, the Kaltag fault lies south of Rampart Group rocks (Reifenstuhl and others, 1997a). Previously, this major right-lateral strike-slip fault zone has been variously called: the Kaltag, Tozitna, and Victoria Creek fault. Details of structural relationships between major rock units were largely ignored by some previous authors (Chapman and others, 1982; Silberling and others, 1994). Other authors show rock units bounded by north-vergent thrust faults (Weber and others, 1992) or south-vergent thrust faults (Dover, 1994; Dover and Miyaoka, 1983b; Dusel-Bacon, 1994; Nokleberg and others, 1994).

Another thrust fault-bounded rock package is a klippe composed of mafic and ultramafic rock which forms Serpentine Ridge, and which continues west into the Tanana A-3 Quadrangle. This klippe correlates well with the prominent airborne magnetic signature. Modeling of airborne total field magnetic data using field-measured rock magnetic susceptibilities also supports the klippe structure (S.A. Liss, written commun., 1998). In contrast, the highly magnetic carbonatite north of Tofty is not fault juxtaposed. This 30-m-thick, northwest-dipping igneous sill (?) has thermally altered the enclosing Triassic to Permian age clastic succession.

The layered rocks have been subjected to regional lower greenschist metamorphism (Dusel-Bacon and others, 1989, 1994). Rocks of the northwestern part of the map area are highly deformed by southeast-vergent folding and thrust faulting (based on microscopic, mesoscopic, and inferred megascopic structures). In the southeasternmost Tanana A-1 Quadrangle, fold vergence is apparently to the northwest based on small-scale fold axes and regional stratigraphic relationships. Northwest of the Dugan Hills, there is virtually no exposure. Here we interpret Albian-age basinal rocks (Wilber Creek unit) beneath the Quaternary cover, based on airborne geophysics and regional considerations. Details of structural relationships within the covered area are poorly constrained. In the covered areas, airborne geophysics, and their contrasting geophysical signatures are the basis for our structural interpretation; the magnetic signature observed for the Albian-age rocks is best explained by the presence of high-angle faults. Late-stage, high-angle faults, predominantly oriented north-northeast and north-northwest, offset all rock packages. In many cases thrust faults and high-angle faults are recognized by both mapping and by airborne geophysics (for example, the northwest side of Hot Springs pluton; see below).

AIRBORNE GEOPHYSICS

Detailed airborne total field magnetics and coplanar resistivity (900 Hz and 7200 Hz) of the Rampart–Manley area were compiled by DGGS (Burns, 1996, 1997). These data are fundamental to understanding the poorly exposed bedrock geology in the Tanana A-1 and A-2 (and B-1) quadrangles and surrounding areas. In the Tofty area, where a magnetite-rich carbonatite is essentially at the surface, airborne magnetics indicate a strong northwest-dipping anomaly. Magnetic anomalies northeast and southwest of the Tofty area suggest that the carbonatite sill(?) extends into the subsurface away from the Tofty area. Slight offsets in the trends of these anomalies suggest that the carbonatite sill(?) is offset by high-angle faults. Geophysics documents the nature and extent of offset along the Stevens Creek fault, and the location of the Kaltag fault zone. The Roughtop pluton is characterized by a strong magnetic high truncated on the eastern side by the Stevens Creek fault, and has a notable magnetic low in its central region. Geologic mapping indicates that the central low is due to a non-magnetic granite body. Granite is also present as sporadic dikes in the surrounding magnetic, alkalic body. Large lobate geophysical anomalies between Eureka and Tofty with low magnetic and very low resistivity signatures (see map sheet) are associated with deeply buried bedrock. We interpret these as possible buried plutons, since their signature is similar to the Tertiary age, non-magnetic Hot Springs granite. However, carbonate-rich stratigraphy within the area (Amy Creek dolomite; Livengood Dome chert) also produce a low magnetic, and very low resistivity signature, and thus are also possibilities. A single, lobate, high-magnetic, low-resistivity geophysical anomaly is located north of the Stevens Creek fault, and on trend with southwest-trending igneous bodies related to the Elephant Mountain pluton (Tanana B-1 Quadrangle; Reifenstuhl and others, 1997a). We interpret this lobate geophysical anomaly, which is in a covered area, as a buried pluton of the 90 Ma plutonic suite of Newberry and others (1995). Regionally, for rocks with low magnetic variability, such as most of the sedimentary section, the resistivity data (900 Hz and 7200 Hz) are extremely useful.

ECONOMIC GEOLOGY

The Tanana A-1 and A-2 quadrangles are part of the Hot Springs mining district (Saunders, 1962; Cobb, 1972). Total production of area placer mining is more than 765,000 ounces of gold and 720,000 pounds of by-product tin. Small-scale placer mines are currently in operation. A carbonatite at Idaho Gulch, near Tofty, contains an estimated 340,000 pounds of niobium resources (Southworth, 1984; Warner and others, 1986), and dips steeply northwest, based on diamond drilling and detailed ground magnetics. Maximum grades of 0.1 percent Nb, 0.2 percent Ce, 6 percent BaO, and 20 percent P_2O_5 are reported by Warner and others (1986). Airborne geophysical data suggest that the carbonatite exposed by trenching and drilling at upper Idaho Gulch is only a small part of a sill-like body with a strike length of at least 10 km. Ground geology and magnetic survey indicate that the more than 10-km-long aeromagnetic anomaly does indeed match with carbonatite in several locations and that this unit is highly anomalous in Nb, Ce, and P several kilometers from Idaho gulch. Consequently, the Nb resource stated by Warner and others (1986) for the Idaho gulch area understates the Nb resources of the Tofty area by several orders of magnitude. However, none of the carbonatite samples examined are significantly anomalous in Au or Sn, and the carbonatite is not a likely source for either placer or lode Sn or Au.

Two major plutonic suites are recognized in Interior Alaska: a 90–105 Ma suite with a range of mafic to felsic plutons and a 50 to 75 Ma composite suite of mostly felsic plutons (Newberry and others, 1995; McCoy and others, 1997; Newberry and Haug, 1997; Newberry and others, in press; Burns and others, 1991). In the Manley–Eureka area the older igneous rocks show distinctive alkalic compositions relative to other Interior Alaska mid-Cretaceous plutons (Newberry and Solie, 1995). The Elephant Mountain pluton (89 Ma, Weber and others, 1992; Doyon Inc., unpublished report), north of Eureka, in the adjacent Tanana B-1 Quadrangle, contains several lode gold occurrences (Reifenstuhl and others, 1997a). All known lode mineralization in the area which is hosted by, or adjacent to, 90 Ma plutonic rocks has a distinctive As–Sb–Bi–W–Sn–Te signature. Anomalies of these elements in Tofty, Eureka, and Rampart district placer gold suggest that all were derived directly (Eureka; Tofty) or indirectly (Rampart) from 90 Ma plutonic sources. However, the highly magnetic character of the Roughtop complex (Leveille and others, 1988 for example) and the lack of significant hydrothermal alteration or mineralization in its granite core suggest that Roughtop—unlike Elephant Mountain—does not contain significant gold resources at the present erosion level.

Based on its age (58 Ma) and composition (syenogranite), the Hot Springs pluton north of Manley Hot Springs is part of the early Tertiary extension-related suite of Interior Alaska (Newberry and others, 1995). Granites of this age and composition in Interior Alaska commonly contain placer or lode Sn (for example: Lime Peak, Smith and others, 1987; Circle Hot Springs, Wiltse and others, 1994). A high-angle fault on the Hot Springs pluton's northwestern side, with the igneous body upthrown, exposes a deep, unmineralized level of the pluton; although anomalous in tin, fluorine, lithium, and boron, the granite shows no indications of significant mineralization at the present level of erosion. Contact-metamorphosed rock near the western contact with this granite has long been known to contain Ag-rich, Zn–Pb veins. Maloney (1971) reports up to 274 ppm Ag and 5.8 ppm Au from the veins. Our work shows that similar mineralization, with maximum values of 33.8 ppm silver and 2.7 ppm gold, is also present near the eastern contact, and that mineralization in both areas is anomalous in Sn. Cassiterite grains and cobbles in Tofty-area placers are thus probably derived from erosion of the upper, cassiterite-mineralized part of the Hot Springs pluton. A modest proportion of the Tofty gold may be similarly derived from this system.

Glaciation in the upper Minook Creek apparently removed placer gold accumulations proximal to Elephant Mountain. Reworking of locally preserved, early Tertiary gravels is the apparent genesis of present placers in the Rampart, and probably the Tofty areas (Yeend, 1990). Given their location on the northern side of the Kaltag fault, the Tertiary gravels responsible for the Rampart placers may in turn represent tectonic offsets of Tertiary gravels present at the far western end of the Tofty district (Tanana A-3 Quadrangle). Placer gold in the Eureka region is both derived from recent weathering of gold–quartz veins, probably related to the Elephant Mountain intrusions, and to reworking of early Tertiary gravels.

Electron microprobe analyses of 54 placer gold nuggets from 13 placer deposits (Newberry and Clautice, 1997) indicate the highest fineness (purity) near the town of Rampart (>.9), and the lowest near Eureka (<.8), and constrains gold genesis. Placer grains commonly contain silver (Ag), mercury (Hg), anomalous tellurium (Te), and locally bismuth (Bi). Placer gold grain rims are up to 100 microns thick and show variable Hg and Ag depletion due to weathering. Gold grains proximal to bedrock sources (Eureka Creek and Gunnison Creek in the Livengood B-6 Quadrangle) show the least rim depletion, whereas grains derived from late Tertiary gravels commonly show well developed rim depletion or complete grain depletion (Rampart and Tofty). This suggests that degree of depletion is correlated with the amount of time the placer gold has been in the weathering cycle. Grains with anomalous Te and Bi indicate a plutonic-related genesis. Placer grains containing native nickel (New York, Hunter, Tofty, Little Minook Jr., Deep, and Gunnison creeks) indicate a genesis involving ultramafic rocks. This is further supported by the presence of anomalous Pt in the Hunter Creek placer (Cathrall and others, 1987).

Geochronologic studies show that: (1) the 55 Ma basalt–rhyolite suite of the Rampart area (Reifenstuhl and others, 1997b) is time-correlative with the Hot Springs granite (indicating major differences in uplift and erosional levels between them), (2) mafic–ultramafic rocks at the western end of the study area are most likely correlative with similar-appearing rocks in the Livengood area, (3) the older suite of intrusions in the Manley–Eureka area show a significantly greater age range (88–95 Ma) than indicated by previous K-Ar dating, and (4) the carbonatite is most likely of early Jurassic age and is unrelated to either of the main igneous episodes in the area.

Surficial geology of the Tanana A-1 and A-2 quadrangles, including radiocarbon age dates, measured sections, and faunal listing are addressed by Pinney (1998a), and engineering geologic data including construction materials and potential geologic hazards are addressed by Pinney (1998b).

DESCRIPTION OF MAP UNITS

UNCONSOLIDATED DEPOSITS

Alluvial Deposits

Qaf	**Alluvial fan deposits**—Fan-shaped, heterogeneous mixtures of gravel with some sand and silt and few to numerous, subangular to rounded boulders, especially in proximal areas; clasts locally derived; may include debris-flow deposits; thick to thin bedded; surface smooth, except for numerous shallow, interconnected channels; locally covered by reworked silt.
Qa	**Alluvium in modern stream channels**—Elongated deposits of stratified gravel and sand with few to numerous boulders underlying active streams, floodplains, and associated low terraces; well sorted and medium to thick bedded, locally crossbedded; shows fining-upward cycles.
Qap	**Alluvial plain deposits**—Irregular blankets and low-angle fans of stratified gravel and sand with silt interbeds and few to numerous boulders underlying much of Baker Creek flats; well sorted and medium to thick bedded, locally crossbedded; surface flat to gently sloping with numerous shallow, interconnected channels; wood collected from an exposure in a gravel pit (map locality A) yielded a minimum limiting date of 2,565 ± 75 yr B.P., or 2,996 (2,734; 2,721) 2,211 calibrated yr B.P. at the 2s level (GX-23476).
Qas	**Silty alluvium in modern stream channels**—Irregular, elongated deposits of stratified silt beneath modern channels and floodplains of streams draining loess-mantled slopes; may include fine-grained debris flow deposits, especially in the upper reaches; moderately to well sorted and medium to thin bedded, locally crossbedded.
Qfp	**Floodplain alluvium bordering modern streams**—Elongated deposits of stratified pebble-cobble gravel and medium sand with few to numerous boulders forming modern floodplains and associated low (<3 m) terraces; typically mantled by thin layer of silty overbank deposits; lower surfaces may be flooded during periods of maximum stream discharge; surface smooth to hummocky with local low scarps and bogs; commonly frozen.
Qsf	**Silt fan deposits**—Fan-shaped deposits of dark brown to gray silt with some sand and angular to subrounded pebbles in proximal areas; may include fine-grained debris flow deposits, especially in the upper reaches; thick to thin bedded; surface smooth, except for numerous shallow, interconnected channels; organic material recovered from underlying colluvium (map locality C) yielded a minimum limiting date of 3,140 ± 130 yr B.P., or 3,976 (3,375; 3,372; 3,357) 2,744 calibrated yr B.P. at the 2s level (GX-23480).
Qag	**Old, high-level alluvial gravels**—Irregular residual deposits of gold-bearing, pebble-cobble gravel with well rounded quartzite boulders up to 3 m diameter preserved on high interfluves in the Eureka Creek area; up to 4 m thick, but generally much thinner; locally extensively reworked by mining activity; organic material recovered from successive benches exposed in a placer cut in Doric Creek (map locality B) yielded minimum limiting dates of >36,130 yr B.P. (GX-23477), 36,650 +3,490/-2,430 yr B.P. (GX-23478), and >42,770 yr B.P. (GX-23479).

Colluvial Deposits

Qac	**Undifferentiated alluvial and colluvial valley-fill deposits**—Fan-shaped and elongated heterogeneous mixtures of subangular rock fragments and gravel with some silt and sand deposited in upper stream courses primarily by brief, intense summer stream flow, debris flows, and gelifluction; surface smooth, except for local low scarps and shallow, steep-sided channels.

Qc **Undifferentiated colluvium**—Irregular, heterogeneous blankets, aprons, and fans of angular to subrounded rock fragments, gravel, sand, and silt that are left on slopes, slope bases, or high-level surfaces by residual weathering and complex mass-movement processes, including rolling, sliding, flowing, gelifluction, and frost creep; probably perennially frozen; locally washed by meltwater and slope runoff; surface generally reflects configuration of underlying bedrock surface.

Qca **Colluvial apron and fan deposits**—Apron- and fan-shaped, heterogeneous mixtures of angular rock fragments with trace to some gravel, sand, and silt deposited at the bases of steep walls of modern stream valleys; may include or be capped by a considerable amount of redeposited eolian silt; locally washed by meltwater and slope runoff; surface steep to gently sloping.

Eolian Deposits

Qel **Loess**—Homogeneous blankets of well-sorted, mottled, light grayish-brown silt deposited by eolian processes; generally structureless, but with broadly horizontal bedding and some laminations, wavy bedding, and small-scale crossbedding; contains scattered small charcoal fragments and root casts; local cryoturbation structures; weathered deposits are light yellowish brown to orange; thicknesses in exposures range from 1 m to greater than 5 m, and may exceed tens of meters in valley bottoms; forms vertical scarps many meters high; generally perennially frozen; surface smooth to deeply gullied.

Qelp **Pitted loess**—Homogeneous blankets of mottled, light grayish-brown silt and organic silt deposited by eolian processes and subsequently modified by melting of ice-rich permafrost; generally massive to locally bedded; contains scattered small charcoal fragments and root casts; measured thicknesses exceed 8 m in natural exposures and tens of meters in drift shafts; forms vertical scarps many meters high; surface pitted and hummocky with abundant small lakes and boggy areas.

Qer **Reworked upland silt**—Heterogeneous blankets of silt and organic silt originally laid down by eolian processes and subsequently minorly to extensively reworked by fluvial and colluvial processes; includes silt-rich debris-flow deposits; may contain angular clasts of local origin; massive to thinly bedded, with some wavy bedding and crossbedding; commonly perennially frozen and ice rich; locally contains abundant Pleistocene faunal remains; surface steep to gently sloping with numerous shallow, interconnected channels and local low scarps; organic material recovered from a placer cut in Dalton Gulch (map locality D) yielded conventional radiocarbon minimum limiting dates of 35,070 +2,800/-2,080 yr B.P. (GX-23481) and 37,760 +4,470/-2,860 yr B.P. (GX-23482), and an AMS minimum limiting date of 33,260 ± 670 yr B.P. (GX-23475).

Lacustrine Deposits

Qld **Delta deposits**—Fan-shaped, heterogeneous mixture of well sorted silt, sand, and gravel; thick to thin bedded; shows crossbedding and fining-upward cycles; surface smooth, except for numerous shallow, interconnected channels.

Paludal Deposits

Qs **Swamp deposits**—Semicircular to irregular deposits of silt and peat in poorly-drained areas; saturated and locally frozen below a depth of about 1 m, locally ice rich; surface flat and smooth, may have standing water.

Manmade Deposits

Qmt **Mine tailings**—Water-washed pebble-cobble gravel with trace to some sand reworked by placer mining operations; typically well sorted; surface irregular or forming symmetrical ridges and cones.

BEDROCK UNITS

Cretaceous and Jurassic rocks

Clastic rocks of the southeastern and central map areas are part of a Cretaceous and Jurassic age flysch basin, variously called the Beaver Creek terrane (Dover, 1994) or Manley terrane (Silberling and others, 1994; Nokleberg and others, 1994; Dusel-Bacon, 1994) that is intruded by a 90 Ma plutonic belt (discussed below). The gold-bearing Elephant Mountain pluton intrudes this belt, and crops out just to the northeast in the Tanana B-1 Quadrangle (Reifenstuhl and others, 1997a). Clastic rocks include the Early Cretaceous (Albian) age Wilber Creek unit (Weber and others, 1992), and the Early Cretaceous to Jurassic age Wolverine quartzite unit (Weber and others, 1992). The Wilber Creek unit is composed of argillaceous lithic sandstone, shale, and locally important conglomerate. The upper part of the Wilber Creek unit includes argillaceous lithic sandstone with up to 10 percent felsic volcanic clasts (map unit 'Kwv'), and differs significantly from the lower part of the Wilber Creek unit (map units 'Kws; Kwq'). Age and stratigraphic relationship of the volcanic clast-rich rocks is poorly constrained in the Tanana A-1 and A-2 quadrangles. However, we infer it to be Albian age, and further infer it to be the upper part of the Wilber Creek unit of Weber and others (1992) on the basis of strong lithologic similarity, regional distribution, and structural and stratigraphic relationships. Regional stratigraphic considerations suggest this volcanic clast-rich unit may be correlative with the volcanic clast-rich, Early Cretaceous (Albian) age, upper Kathul Graywacke (Brabb, 1969) of the Kandik basin, east-central Alaska. All collections to date in the Tanana Quadrangle are taxonomically indeterminate, hence, age-indeterminate. However, in the western Livengood Quadrangle, the ammonite *Paragastropilites flexicostatis* of mid-Albian age was recovered; the same ammonite is found in mid-Albian rocks of the Alaska North Slope (Weber and others, 1992).

The Cretaceous and Jurassic age Wolverine quartzite unit yielded no age-diagnostic fossils in the Tanana A-1 and A-2 quadrangles. However, the unit yields better preserved material in the Livengood B-6 Quadrangle, where collections are dominated by the bivalve *Buchia. Buchia* is thought to indicate mostly an Early Cretaceous age; however one collection suggests a possible Late Jurassic age (Weber and others, 1994). The Wolverine quartzite unit (map units KJwq; KJw) is probably partly correlative with the Keenan Quartzite of the Kandik basin. The lower part of the Wolverine unit is likely equivalent to part of the Jurassic age Vrain unit (Weber and others, 1992) of the Livengood Quadrangle.

Kwcv **Wilber Creek unit siliciclastic and volcaniclastic rocks** (late Albian(?): Weber and others, 1992)—Very dark gray to dark greenish dark gray, volcanic clast-bearing, poorly sorted, sub-angular, medium- to coarse-grained, marine, argillaceous lithic sandstone, shale and siltstone. Estimates of the framework grain composition are: 55 percent chert, 25 percent quartz, 15 percent plagioclase (which includes about 5 percent obvious volcanic clasts), and 5 percent sedimentary and metamorphic rock fragments, and minor white mica. Matrix consists of clay and opaque minerals, is about 10 percent of rock, and displays a tectonically-induced, anastamosing fabric. This unit is very poorly exposed, and only on the northwestern side of the Dugan Hills in small stream cut-banks. Outcrops and rubble in this area consist of volcaniclastic sandstone and finer-grained lithologies, but bedding details are poorly known. Locally, quartz veining is up to 10 cm wide. Age of this unit is inferred from regional stratigraphic relations and correlation with the volcanic-rich, Albian age upper Kathul Graywacke of the Kandik basin (Brabb, 1969).

Kwcs **Wilber Creek unit sandstone, shale, siltstone, undivided** (Albian: Weber and others, 1992)—Very dark gray to dark greenish gray, poorly sorted, marine, argillaceous lithic sandstone, shale and siltstone containing white mica-bearing argillaceous sandstone as laminae and thin interbeds; rare conglomerate. Beds are typically thin, parallel, laterally continuous, sharp-based, and graded; from fine to medium grained at the base, grading up to silt at the top of beds. Framework grains are chert, quartz, white mica, and feldspar. Opaque material is abundant and disseminated, and tourmaline is the most common accessory detrital mineral. Locally, the rocks of this unit are cut by white quartz veins up to several cm thick, have a strong metamorphic fabric defined by alignment of abundant detrital white mica, and are tightly folded. Hornfels near intrusions are very dark gray to black, very fine to fine grained, hard, dense rocks with common disoriented crystals or rosettes of muscovite, biotite, and locally andalusite. Palynology analyses (seven) of shale yielded no palynomorphs (H. Haga, written commun., 1998).

Kwcq **Wilber Creek unit quartzite** (Albian: Weber and others, 1992)—Medium gray to light gray, highly quartzitic, hard, dense, argillaceous lithic quartzite. Quartzite interbeds occur locally as abundant laminae up to 20 cm thick in the Wilber Creek unit (map unit 'Kwcs') on the northern side of Manley Dome (where it is a mappable unit).

KJwq **Wolverine quartzite unit** (Early Cretaceous and Late Jurassic: Weber and others, 1992)—Very light gray to tan, white- to medium gray-weathering, moderately well-sorted, subrounded, fine- to medium-grained quartzite, and sublitharenite with interbedded shaley rocks. Estimates of sandstone clast composition indicate greater than 90 percent quartz (rare light-blue color), two to five percent chert, and locally trace amounts of feldspar and white mica. Matrix is siliceous, includes no trace of carbonate, and commonly contains two to five percent limonite spots. Thick quartzite successions commonly form resistant outcrops and black lichen-covered, large blocky talus. Bedding is rarely discernible; quartzite commonly appears massive (bioturbated?), is up to 30 m thick, and locally contains argillaceous partings. Sedimentary structures include load casts and feeding traces (*Nereites*?). Locally abundant bivalve shell fragments are the only fossils found and occur in a shelly quartzite facies which crops out prominently in the Eureka Dome vicinity (northeastern Tanana A-1 Quadrangle). All collections to date from the Tanana Quadrangle are taxonomically indeterminate, hence, age indeterminate. However, the unit yields better preserved material in the Livengood B-6 Quadrangle, where collections are dominated by the bivalve *Buchia,* thought to indicate an Early Cretaceous age. However, one collection suggests a possible Late Jurassic age (Weber and others, 1994). The quartzite unit forms the upper part of the Wolverine unit. Wolverine quartzite unit occurs as hornfels near plutons and dikes. Thickness is estimated as 200 m.

KJws **Wolverine quartzite unit sandstone and shale-undivided** (Early Cretaceous and Late Jurassic: Weber and others, 1992)—Medium gray to light gray, locally black, lichen-covered, quartz-rich sandstone and interbedded shale. Sandstone is silica-cemented, well-indurated quartzarenite but lacks the prominent outcrop pattern, continuity, and thickness of the quartzite unit (map unit ‘KJwq’). Sandstone is petrographically similar to the quartzite unit, and consists of moderately well sorted, subrounded detrital grains, and contains minor chert clasts. Rocks of this Wolverine quartzite-undivided map unit form the lower part of the Wolverine section based on mapping relationships. Occurs as hornfels adjacent to plutons and dikes. This mixed unit is estimated to be greater than 400 m thick.

Triassic to Permian succession

This succession in the Tanana A-1 and A-2 quadrangles consists of siliciclastic rocks with characteristic subphyllitic to phyllitic textures. Chapman and others (1982) previously mapped these rocks in the Tanana Quadrangle, and Weber and others (1992) mapped their extension into the Livengood Quadrangle. In the Tanana B-1 Quadrangle, along Minook Creek, this succession includes rare tuff, and coarse-grained limestone debris flows and sandy turbiditic flows containing crinoid ossicles and bryozoans, and was assigned a Triassic to Permian age range based on the fossil assemblage (Reifenstuhl and others, 1997a). Conodonts recovered from 1996 DGGS collections from two localities in the Tanana B-1 Quadrangle indicate an Early Pennsylvanian to Early Permian age range for one locality, and Early Permian to Triassic for the other locality (N.M. Savage, written commun., 1997). Both localities are similar lithologically, and not far separated stratigraphically. Because both localities have a sparse associated megafauna, dominated by bryozoans of late Paleozoic aspect, they were consequently considered to be of Permian age (R.B. Blodgett, written commun., 1998). However, regionally contiguous strata in the east-central Tanana B-1 Quadrangle contain Triassic-age radiolarian chert (D.L. Jones, unpublished report), and a Triassic age (potassium-argon) gabbro from the same area (Weber and others, 1994). In the Livengood B-6 Quadrangle, northeast of Minook Creek, previous fossil age-calls interpreted this succession to be Devonian age (Kindle, in Prindle, 1908, p. 22), but were later reassigned a Mississippian age, as were additional new collections from this unit (Mertie, 1937, p. 115, 120). These collections were re-examined by J.T. Dutro, Jr. in 1970 and assigned an Early Permian (?) age in Weber and others (1994). One new collection made by R.M. Chapman in 1973 (73ACh59) yielded Permian foraminifera and conodonts (identified by A.K. Armstrong and A.G. Harris, respectively, and reported in Weber and others, 1992). Consequently, the Triassic to Permian age range is used here, even though no fossils were recovered in the Tanana A-1 and A-2 quadrangles. We consider the phyllitic siliciclastic succession to the northeast to be time-correlative, at least in part, with the contiguous, clastic succession in the Tanana A-1 and A-2 quadrangles. This clastic succession is separated from sequences above and below by low- to moderate-angle thrust fault contacts. Thickness is estimated to be greater than 2,000 m.

The unfossiliferous bedrock of poorly constrained age that floors the large ‘Dalton’ pit near Tofty is very dark gray, phyllitic to semischistose, fine- to medium-grained argillaceous sandstone and argillite, that locally contains 2 to 3 percent euhedral pyrite cubes to 6 mm. These pyrite-bearing rocks appear similar to the Vrain unit in the Livengood Quadrangle (Weber and others, 1992). Regional correlation of the Triassic to Permian age succession is unclear north and east of the Tintina fault system. Possibilities include the lower part of the Triassic to Lower Cretaceous age Glenn Shale (Brabb, 1969) of the Nation River and Kandik basin area of east-central Alaska. The Permian part of the section in the Tanana A-1 and A-2 quadrangles is also time-correlative with and lithologically similar to the chert-pebble conglomerate of the Step Conglomerate (Brabb, 1969) in the Kandik basin area. Further, the Triassic age is time-equivalent with the Shublik Formation of the Alaska North Slope.

TrPs **Argillite, sandstone and shale** (Triassic and Permian: Reifenstuhl and others, 1997a)—Dark gray to very dark gray, typically fine to very fine grained, argillaceous siliciclastic rocks, with common orange-brown-weathering surfaces. Rocks have a better developed low-grade metamorphic fabric (phyllitic) compared to the Cretaceous to Jurassic age sandstone and shale lithologies above (map units ‘KJwq’, ‘KJws’). Locally thinly laminated and fissile, massive or with cherty layers. Rare zones with pyrite cubes to 2 mm. Includes dark brownish gray to dark gray, and gun-metal gray, fine- to medium-grained, locally carbonate-cemented lithic sandstone and shale. Sandstone is thinly laminated to thin bedded, with uniform grain size, rare graded bedding, convolute lamination, cross bedding, load casts, burrows, and bioturbation(?). Argillaceous sandstone is interbedded with argillite. Locally, black fresh surface, and rare dusty-white, slightly calcareous coating. Rocks are commonly phyllitic, with pencil cleavage, and have calcite veins 1-2 mm thick.

TrPp **Conglomerate** (Triassic and Permian: Reifenstuhl and others, 1997a)—Very dark gray, orange-brown-weathering, matrix-supported, chert-pebble to cobble conglomerate. Matrix is dark gray argillite to very fine sand, and clasts are sub-rounded pebble to cobble size. Estimates of framework clasts are: 10 to 15 percent light gray to white quartz, 30 percent very dark gray argillite, shale, and low grade metamorphic fragments, and 50 percent black, red, green, and dark-gray chert, with minor quartzite and feldspathic clasts. A strong, tectonic fabric is characteristic of the conglomerates, and is partly a function of the clay-rich matrix. Conglomerate forms prominent outcrops but this lithology is probably only several percent of the total Triassic to Permian succession. Conglomerate occurs in poorly defined, 3 cm to several-meter-thick beds, interbedded with the far more abundant fine-grained lithologies (map unit ‘TrPs’).

Mississippian to Upper Proterozoic rocks

Detailed geologic mapping in the Tanana A-1 and A-2 quadrangles indicates six pre-Permian age rock units including: two early Paleozoic to Late Proterozoic age units (Wickersham grit and Amy Creek dolomite, Weber and others, 1992); three early Paleozoic age units (Livengood Dome Chert and Fossil Creek volcanics, Weber and others, 1992; and a Mafic to Ultramafic unit, Patton and others, 1977); and one Mississippian age unit (Globe quartzite, Weber and others, 1992). Previous workers assigned the bulk of these rocks to the Baldry terrane (Dover, 1994; Silberling and others, 1994; Dusel-Bacon, 1994) or Livengood terrane (Nokleberg and others, 1994) with an assumed early Paleozoic age. Our investigations support a Late Proterozoic to early Paleozoic age range for the unfossiliferous Wickersham Grit based on our mapping and correlation with the rocks in the Livengood Quadrangle of Weber and others (1992). The Livengood Dome Chert (Early, to earliest Middle Ordovician, Weber and others, 1992) crops out in the northern map area and is closely correlated with the exposures in the Tanana B-1 Quadrangle (Reifenstuhl and others, 1997a) and Livengood Quadrangle (Weber and others, 1992). The correlation is supported by conodont analyses, chert geochemistry (Haug and others, 1997), local detailed stratigraphy, lithologic associations, and regional stratigraphy.

Paleozoic and Upper Proterozoic rocks do not crop out in the Tanana A-1 Quadrangle-segment of the Dugan Hills, but occur as rubble and float only. The discussion below, outlining pre-Permian bedrock exposures in the immediately adjacent quadrangles, is from our work and from Weber and others (1992), and is important to the regional geologic framework. In summary, southeast of the Lower Cretaceous (Albian age Wilber Creek unit) basinal rocks, the Dugan Hills consist of southeast-dipping, older-over-younger, fault-bounded packages of Mississippian Globe quartzite, Ordovician Fossil Creek volcanics, and early Paleozoic to Upper Proterozoic Wickersham Grit (see cross section). All three of these distinctive units crop out 1 to 3 km east, in the Livengood Quadrangle, and some units extend discontinuously northeast, across the Tintina fault to the Yukon Territory, Canada (Weber and others, 1992). We infer that these units extend southwest, and underlie the southeastern Dugan Hills (see cross section B-B’). The Wickersham Grit unit also crops out immediately adjacent to the Tanana A-1 Quadrangle, in the Kantishna River D-1 Quadrangle—part of the Dugan Hills. Geophysical data do not cover the Dugan Hills, precluding a more definitive bedrock assessment.

Although the Tolovana Limestone does not crop out in the Tanana A-1 and A-2 quadrangles, it does crop out in the immediately adjacent Fairbanks, Livengood, and Kantishna River quadrangles. Consequently, the discussion below relates to the refinement of regional stratigraphic correlations and paleo-reconstructions. The northeastern part of the Kantishna River D-1 Quadrangle includes exposures of the Devonian age “Tolovana Limestone,” which Weber and others (1992; 1994) suggested forms a separate (and upper) lithostratigraphic unit from the Silurian age Tolovana Limestone of the White Mountains (Livengood Quadrangle). Exposures of this Devonian carbonate unit extend southwest from the vicinity of “Grapefruit Rocks” on the north side of the Elliott Highway (Livengood B-3 Quadrangle) to VABM Minto, 8 km east of COD Lake (Livengood A-4 Quadrangle), and even further southwest, to include the exposures described below in the Dugan Hills area (Fairbanks D-6, Kantishna River D-1, and Tanana A-1 quadrangles). Here, this unit includes well-bedded, light gray-weathering, light gray to gray-brown lime mudstone, locally with abundant cryptalgal lamination, as well as dark gray, and dark gray-weathering, fossiliferous lime mudstone. Fossils, in the dark-gray limestone, include rugose corals, probable dendroid tabulate corals, and Amphipora (a stick-like stromatoporoid). The fossiliferous beds are identical in lithology and fossil content to exposures at "Grapefruit Rocks" (Livengood B-3 Quadrangle). Two Middle Devonian age, coral-bearing collections (USGS localities 6457-SD and 6458-SD) were reported from the Kantishna River D-1 Quadrangle by Oliver and others (1975, p. 33). These two localities yielded the rugose coral Dendrostella sp. cf. D. rhenana (Frech) and the stick-like stromatoporoid Amphipora. This Middle Devonian age unit differs from the Silurian age Tolovana Limestone of the White Mountains, in being darker, having better defined bedding, and lacking peloid- and ooid-rich lime packstone and grainstone which dominate the upper and greater part of the Devonian Tolovana Limestone.

In summary, limestone mapped as Tolovana Limestone in the Dugan Hills area is Middle Devonian age and is lithologically identical and shares similar fauna with the Devonian age "Tolovana Limestone" of the Grapefruit Rocks and COD Lake areas (Livengood B-3 and A-4 quadrangles, respectively). Consequently, this Devonian-age unit forms a separate (and upper) lithostratigraphic unit from the Silurian-age Tolovana Limestone, whose type area is even further to the northeast in the White Mountains of the Livengood Quadrangle (Weber and others, 1992; 1994).

Mg **Globe quartzite unit** (Mississippian: Weber and others, 1992; Mortensen and Thompson, 1990)—Light gray, light- to medium-gray weathering and iron-stained, fine to medium-grained, bimodal to moderately sorted, distinctive vitreous quartzite, with interbedded medium to dark gray slate, phyllite, and shaley rocks. Framework grains are well rounded to subrounded monocrystalline quartz, and minor chert clasts. Accessory grains are zircon, augite, and hornblende. The Globe Quartzite unit is cross-cut by mafic rocks. The age of the Globe Quartzite unit is based on: (1) the age of an intrusive body (232.1 Ma, U/Pb) (J.K. Mortensen, written commun., 1991, in Weber and others, 1992) of regionally extensive gabbro and diabase in the Livengood Quadrangle, and (2) distinctive lithologic similarities to the Mississippian conodont-bearing Keno Hill Quartzite in Yukon Territory, Canada, which is also cut by 232 Ma mafic rocks (J.K. Mortensen, written commun., 1991 in Weber and others, 1992). The Globe quartzite and the Keno Hill Quartzite units are apparently offset along the Tintina fault system. Thickness of the Globe unit is unknown.

Late Late Devonian (Famennian) age rocks—Famennian-age rocks are uncommon in Interior Alaska, although they are common in the Brooks Range (Kanayut Conglomerate, Brosgé and Tailleur, 1969, for example). Documented Famennian-age rocks of Interior Alaska include: (A) The lower part of the Ford Lake Shale (Brabb, 1969) in the Nation Arch area (Charley River and Eagle quadrangles), (B) An isolated exposure along Bear Creek, central Livengood Quadrangle (Weber and others, 1994), and (C) Limestone in an area some 40 km northwest and west-northwest of the Tofty area (Tanana B-3 Quadrangle), between the Yukon and Tozitna Rivers (Dover, 1994). The late Late Devonian age of these later carbonates ('C' above) is based on detailed conodont biostratigraphy (A.G. Harris, U.S. Geological Survey fossil collections: 11154-SD, 11118-SD, 11389-SD, 11172-SD; J. Dover, unpublished fossil report, 1998). In the Tanana A-1 Quadrangle, on the south side of Granite Creek, the limestone- and carbonate-rich matrix, siliciclastic clast-supported conglomerate represent a considerably different and shallower-water unit than either 'A' or 'B' of the above-cited occurrences, both of which represent deep-water environments. The Ford Lake Shale is dominantly radiolarian-bearing chert and shale, and the exposure along Bear Creek is a predominantly carbonate turbidite, deposited in a relatively deep-water, siliciclastic-dominated environment. The conglomerate described below (Dc) is lithologically similar and, in part, time-equivalent with the conglomeratic Nation River Formation (Late Devonian, Brabb and Churkin, 1967) of the Kandik basin area, and the Imperial Formation (Norris and others, 1984) of the Yukon Territory, Canada.

Dl **Devonian limestone fault slivers at Granite Creek** [Famennian (late Late Devonian): this report]—Dark gray, light gray-weathering, lime mudstone. Uppermost strata of the largest fault sliver include abundant floating quartz grains up to 3 mm in diameter, which are increasingly abundant down-section. Megafossils (small crinoid ossicles) were recovered only from the basal strata of the limestone of these fault slivers. Conodonts from two different localities in separate fault blocks in the upper Granite Creek area (96RB124, locality 1; 96RB129, locality 2) indicate that locality 1 belongs to the rhomboidea-marginifera zones of late Late Devonian (lower Famennian) age, whereas locality 2 suggests only a generalized Late Devonian age (N.M. Savage, written commun., 1997). The lithologic similarity of each fault block suggests both are probably Famennian (late Late

Devonian). Limestone grades down-section into chert- and quartz-pebble conglomerate with carbonate matrix material, and ultimately into a conglomerate with a siliciclastic matrix (map unit Dc). Unit forms prominent fault blocks situated along the thrust contact between the Amy Creek unit and the Triassic to Permian succession in the upper reaches of Granite Creek, in the Tanana A-1 Quadrangle.

Dc **Conglomerate** (Late Devonian?: this report)—Dark gray to very dark gray, brown-weathering, clast-supported, chert-pebble to cobble conglomerate; matrix consists of siliciclastic and carbonate material, and clasts are sub-rounded pebble to cobble size. Estimates of clast composition are 60 percent chert (black, red, green, and dark-gray), 10 to 15 percent light gray to white monocrystalline quartz, 30 percent sedimentary and low-grade metamorphic rock fragments and quartzite, and trace amounts of volcanic rock fragments and potassium feldspar clasts. Framework clast types plot on ternary diagrams in the ‘recycled orogenic’ field of Dickinson and others (1983). Matrix is dark gray, very fine to coarse-grained sandstone, with less than 5 percent silt and clay material. Porosity is negligible. Rock fabric is partly a function of the clast-supported texture of the rock, and deformation appears more brittle compared to the well-developed ductile fabric of the matrix-rich Triassic to Permian-age conglomerate above (map unit TrPp). At one locality on Granite Creek, the matrix of the conglomerate becomes progressively enriched in carbonate material, and the clast size and abundance decreases up-section; this gradational transition is complete within 50 m of section, and the resulting lithology is a relatively pure limestone with Famennian-age fossils (map unit Dl). Bedding is not visible in the conglomerate. This unit forms small but prominent outcrops. Unit may be correlative with the Quail conglomerate (Weber and others, 1992) of the Livengood Quadrangle.

Livengood Dome Chert (Ordovician: Chapman and others, 1979; Weber and others, 1988)—This succession is correlated with the Livengood Dome Chert unit of Weber and others (1988), and shows pervasive cataclasis, low-grade recrystallization, and is in low- to moderate-angle thrust contact with successions above and below. Chert geochemistry is similar to the geochemistry of the Livengood Dome Chert at its type locality (Haug and others, 1997). All carbonate lithologies submitted for conodont analysis from the Tanana B-1 Quadrangle were barren (N.M. Savage, written commun., 1997). Megafossils were not recovered from any of the field or laboratory samples (R.B. Blodgett, written commun., 1997; 1998). The Livengood Dome Chert was named for exposures in the adjacent Livengood Quadrangle (Chapman and others, 1979) for multicolored chert, siliceous slate, rare greenstone, tuff, limestone, and shale with Late Ordovician graptolites.

Pzlca **Chert and cherty argillite** (Ordovician)—Heterogeneous unit composed dominantly of light gray to gray, thinly laminated, recrystallized sericitic chert and siliceous argillite, commonly with phyllitic argillite partings; ‘cherty argillite’ typically has cherty or mylonitic aspect on weathered surfaces, but fine-grained clastic or recrystallized texture on fresh surfaces. In places this unit is a distinctive creme color to mottled light gray, fine-grained, typically micro-fractured recrystallized chert that is poorly exposed, forms coarse talus, and produces ‘sandy powder’ on freshly broken surfaces. This variety is associated with a black and white laminated variety of argillite containing several laminations per cm that are usually intricately crenulated or contorted. The chert unit contains subordinate interbeds of carbonaceous argillite, tuffaceous and volcaniclastic rocks, argillaceous, gritty quartz-plagioclase arkose, limestone, and minor basaltic rocks or greenstone. Locally texturally and mineralogically immature sandstone is important, and consists of dark gray, fine to coarse grained, poorly-sorted to bimodal, sub-angular, quartz-plagioclase-chert-bearing rock. The quartz-plagioclase-chert ratio varies considerably, but quartz plus plagioclase is much greater than chert. The unit contains rare grit-sized blue quartz ‘eyes’, and numerous single-crystal medium to coarse grained quartz clasts in thin section. Contains minor detrital tourmaline, zircon, and sphene, and shows moderately strong cataclastic foliation and synkinematically recrystallized micas. Chert samples yield a “Livengood Dome Chert-type” geochemical signature (Haug and others, 1997).

Pzlv **Volcanic unit** (Ordovician)—Greenish-gray, chloritic and feldspathic rocks and greenstone. Protolith of volcanic rocks is volcaniclastic, tuffaceous, and flow rocks of basaltic to intermediate composition. Some rocks are diabasic and may be meta-intrusive rocks; the number of metavolcanic layers uncertain. Rocks contain chlorite, epidote, zoisite, altered plagioclase, and calcite recrystallization products. Outcrops are very poor, and most commonly rubble is all that is visible at the surface. Thickness is unknown.

Pzlo **Orum limestone** (Middle Ordovician to Neoproterozoic: informal name, Hopkins and Taber, unpublished manuscript)—Light to medium gray, tan to reddish brown-weathering, extensively recrystallized, typically thin- to medium-bedded lime mudstone. Unit is locally thick-bedded, and locally includes ooid grainstones and cryptalgal(?) lamination. The platy character recognized in thinner-bedded intervals may be due to well-developed axial planar fracture cleavage. This unit is a distinctive regional marker unit, which can be traced from the Tanana B-1 Quadrangle (Reifenstuhl and others, 1997a), southwest into the Tanana A-1 and A-2 quadrangles; it is also traceable west of the Stevens Creek fault, where it is exposed in both the Tanana A-2 and A-3 quadrangles. The Orum limestone type area was “the area of limestone exposures in the south wall of Orum Creek valley lying between 4½ and 5½ miles upstream from the confluence of Orum Creek and Stevens Creek” (Hopkins and Taber, unpublished manuscript). The exposures along Orum Creek are poor and inaccessible. Better, and more typical, exposures are in the Tanana B-1 Quadrangle (southern side of Baldry peak) and in the Tanana A-3 Quadrangle (NE¼ of Section 6, T.4N., R.17W.). The age of the unit is not known with certainty; it is here included with the Livengood Dome Chert assemblage, which is situated at least in part above the Orum limestone. Consequently its age is probably pre-Late Ordovician. No megafossils have been identified from the unit and no conodonts were recovered. Based on regional correlations with similar appearing units in Alaska, this informal unit may be as old as Neoproterozoic, or as young as Middle Ordovician.

Ofc **Fossil Creek volcanics** (Late to Early Ordovician: Weber and others, 1992)—Heterogeneous assemblage of basalt, agglomerate, volcaniclastic conglomerate, lime wackestone, calcareous feldspathic sandstone, shale, siltstone, chert, slate, and phyllite. The age of this unit is based on fossil data from the Livengood Quadrangle (Blodgett and others, 1987; Weber and others, 1992), that consist of Late Ordovician brachiopods, gastropods, trilobites, and conodonts in the uppermost part of the sedimentary section; Early Ordovician trilobites and conodonts have been recovered from the lower section. The total thickness is more than 610 m. This unit is inferred from previous work to underlie part of the Dugan Hills based on exposures 1 to 3 km east in the adjacent Livengood A-6 Quadrangle and one in the Tanana A-1 Quadrangle (Weber and others, 1992).

Amy Creek unit (Silurian to Late Proterozoic: Weber and others, 1992)—This succession is lithologically similar to, and we correlate it with, the Silurian(?) to Late Proterozoic(?) Amy Creek unit (informal name, Weber and others, 1988) of the Livengood Quadrangle. In the Tanana A-1 and A-2 quadrangles, lithologies assigned to the unit include oolitic dolostone, siliceous argillite, basaltic greenstone, nonfossiliferous limestone, and dark-gray, massive chert. Rocks show non-pervasive cataclasis and low grade recrystallization, and are in low- to moderate-angle thrust contact with successions above and below. The Silurian(?) to Late Proterozoic(?) age range is based on the absence of megafossils (including within all shallow-water deposits); the precise age of the Amy Creek unit remains unresolved. Unidentifiable radiolarians have been reported from chert of the unit suggesting a Paleozoic age. However, a Neoproterozoic to possible Cambrian age is suggested (Blodgett, written commun., 1998) by lithologic similarity to ooid-rich intervals in Alaskan Proterozoic carbonate units, for example the Katakturuk Dolomite of northeastern Alaska (Dutro, 1970; Robinson and others, 1989), and the Kuchaynik Dolostone of west-central Alaska (Babcock and others, 1994). Conodont samples analyzed were barren (N.M. Savage, written commun., 1997). Our Amy Creek unit was previously mapped as the Livengood Dome Chert on the 1:250,000-scale Tanana Quadrangle map of Chapman and others (1982), whereas Silberling and others (1994) included it in their polymetamorphic Baldry terrane of probable early to middle Paleozoic age.

PzPad **Dolostone and limestone**—White to light gray, massive-bedded, locally laminated, siliceous dolostone and medium gray to dark gray lime mudstone, in approximately equal amounts. Dolostone is typically extensively silicified and characterized by box-work silica network. Typically weathers white, but also weathers to light and medium gray, or light yellow to orange brown, and commonly weathers to form ‘chippy’ soils, which are more common than good outcrops. Where extensively silicified, this unit forms rubble crop. Large, irregular-shaped coated grains are locally present in dolostone intervals, and are similar to those in the Amy Creek unit in the Livengood Quadrangle. Limestone consists of medium gray-weathering, medium to dark gray fresh, lime mudstone. The precise age of the Amy Creek unit remains unresolved (Weber and others, 1994). The character of dolostones rich in large coated grains suggests regional correlation to units of Neoproterozoic age in west-central Alaska (Big River Dolostone of Babcock and others, 1994) and the Katakturuk Dolomite of the northeastern Brooks Range (Clough and others, 1988). This unit is equivalent to the Wolverine Limestone of Hopkins and Taber (unpublished manuscript), who designated the type area of their unit as the “limestone exposures in the steep southeast wall of the Wolverine Creek valley between 2 and 3½ miles above the confluence of Wolverine Creek and the North Fork of Baker Creek” (Tanana A-2 Quadrangle). Recent examination of the type section of the Wolverine limestone indicates that dolomudstone is the dominant lithology. The unit is widely exposed throughout the northern half of both the Tanana A-1 and A-2 quadrangles, but an isolated east-west trending outcrop belt is also exposed on both the northern and southern sides of Overland Bluff and to the west, on the northern side of Bean Ridge in the southwestern part of the Tanana A-1 Quadrangle. The outcrops on the southern side of Overland Bluff include minor roadside exposures along northern side of the Elliott Highway, where it is composed of gray-brown weathering, dark gray fresh, lime mudstone. The lime mudstone is recrystallized in places and cut by numerous veinlets of calcite. At this location the unit also contains minor interbeds of light-green weathering metavolcanics. Outcrops on the north side of Overland Bluff are composed primarily of dolomudstone, commonly with the box-work silica network. This unit is correlated with the dolomite in the Amy Creek unit of Weber and others (1988); this unit is inferred to be of Proterozoic age, and possibly as young as Silurian.

PzPag **Greenstone**—Dark greenish gray, massive to well-foliated, locally magnetic greenstone, amygdaloidal greenstone, and agglomeratic greenstone; basaltic to intermediate composition. Contains calcite amygdule fillings, locally abundant pyrite cubes, and slightly stretched volcanic and carbonate clasts up to cobble size. Greenstone is associated with or interlayered within the chert and argillite unit, and contains limestone pods or lenses less than 1 m thick locally. Two attempts at whole-rock $^{40}Ar/^{39}Ar$ dating of the greenstone in the Livengood area yielded only minimum ages of 230 and 260 Ma (this report).

PzPac **Cherty-argillite and chert**—Heterogeneous unit of dominantly black to dark gray chert and siliceous to carbonaceous argillite with well-developed phyllitic to subphyllitic slate-like cleavage, and containing one or more dark gray limestone layers or lenses. The geochemical signature of this unit is typical of the chert in the Amy Creek unit (Haug and others, 1997) of Weber and others (1988). Limestone locally crops out, and is dark gray to very dark gray, up to 3 m thick, and is here included in the cherty-argillite and chert unit.

Wickersham unit (Lower Paleozoic and Upper Proterozoic, Weber and others, 1988)—This succession has strong lithologic similarities to, and is correlated with, the lower Paleozoic to Upper Proterozoic Wickersham unit of Weber and others (1988). This unit is exposed only as rubble in the Dugan Hills of the Tanana A-1 Quadrangle. These rocks are well exposed in the Tanana B-1 Quadrangle (Reifenstuhl and others, 1997a) and in the Dugan Hills of the immediately adjacent Kantishna D-1 Quadrangle. The lithologic description below is in part based on outcrops in the Kantishna D-1 Quadrangle, and these rocks are similar to rocks assigned to the upper part of the Wickersham unit in the Schwatka belt of the Livengood Quadrangle (Weber and others, 1994). In the Tanana B-1 Quadrangle (Reifenstuhl and others, 1997a), the Wickersham unit includes quartzite, and grit with local characteristic milky or blue quartz ‘eyes’ and granules.

PzPwg **Siliciclastic rock**—Medium gray, tan-weathering, thin-bedded, fine-grained argillaceous sandstone, siltstone, rare greenstone (?), and phyllitic argillite. Locally, these rocks include up to 30 percent calcite that likely represents recrystallized matrix. Black, non-calcareous, carbonaceous, phyllitic argillite interbeds and partings are common. Sandstone occurs as layers and laminae and is poorly sorted to bimodal, subangular quartzite with framework grains of monocrystalline quartz, plagioclase, and minor chert, in a clay-rich matrix. Correlative siliciclastic rocks in the Tanana B-1 Quadrangle are petrographically similar to the greenstone unit, suggesting a genetic association (Reifenstuhl and others, 1997a). Accessory minerals include tourmaline and zircon. Rocks weather recessively, forming rubble crops.

Igneous Rocks

Two major plutonic suites are recognized in Interior Alaska: a 90 to 105 Ma suite with a compositional range (Pearce and others, 1984) from mafic to felsic plutons and a 50 to 75 Ma composite suite of mostly felsic plutons (Newberry and others, 1995). In the Manley-Eureka area the older rocks show distinctive alkalic compositions relative to other Interior Alaska, mid-Cretaceous plutons, and here include the following plutons: Roughtop (92±5 Ma and 90±10 Ma, Chapman and others, 1982), Elephant Mountain (89.3±1.0 Ma; Tanana B-1 Quadrangle, Reifenstuhl and others, 1997b), and Sawtooth (88.4±1.7 Ma; Livengood B-5 Quadrangle, Weber and others, 1992). Alkalic dikes just north of Eureka are part of the northeast-trending Elephant Mountain plutonic body and suggest significant vertical displacements on west-northwest or east-west trending high-angle faults (Reifenstuhl and others, 1997a). Roughtop pluton includes a megacrystic potassium feldspar phase, a central granite body (similar to Elephant Mountain), and is commonly block faulted. Lack of anomalous gold values, and low gold potential may be due to the high oxidation state (abundant primary magnetite). The Hot Springs pluton (58 Ma, Reifenstuhl and others, 1997b) is part of the younger plutonic suite, and is north of the town of Manley. A high angle fault on the pluton's northwest side, with the igneous body upthrown, exposes a deep, unmineralized level of the pluton.

Tg **Hot Springs granite pluton** (58 Ma)—Medium- to coarse-grained biotite granite and rare tourmaline-biotite granite. Outcrops as subdued, blocky rubble or a brown gruss. The dominant textural variety contains coarse-grained potassium feldspar (30 percent) in a matrix of medium-grained smoky quartz (30 percent), albitic plagioclase (30 percent), and slightly chloritized biotite (10 percent). Less common textural varieties include fine- and medium-grained, equigranular granite and granite pegmatite. Tourmaline contents range from 0 to 5 percent, as both a disseminated and vein mineral. No primary oxide minerals have been identified, and the granite displays an extremely low magnetic susceptibility ($< 10 \times 10^{-5}$ SI). Contacts with the surrounding rocks are rarely observed on the southern and southeastern sides of the body and the true dimensions are not known.

Kdm **Mafic dikes** (95 Ma)—Very dark gray and greenish very dark gray, very fine grained hypabyssal dikes. Composition ranges from monzodiorite to monzonite, with little or no quartz, abundant clinopyroxene, and plagioclase subequal in abundance to alkali feldspar. Thickness is typically less than 3 m. Not all dikes encountered are shown on the map.

Roughtop Mountain pluton

Kgs **Granite and quartz syenite**—Buff to light gray, fine to coarse grained, sub-equigranular, holocrystalline rock. The rock exhibits slight hydrothermal alteration, with feldspar partly converted to fine-grained white mica. Quartz/(quartz + total feldspar) ratios vary from 15 to 35 percent, and the bulk of the feldspar appears to be K-feldspar. Biotite (5 to 10 percent) is the sole mafic mineral. Granite/quartz syenite is locally yellowish with a light orange weathering rind. Contacts with the surrounding rock are only exposed in rubble, but the occurrence towards the center of the Roughtop intrusion and rare dikes in the syenite and monzonite units suggests that this unit represents the most fractionated portion of the body.

Ksy **Syenite and quartz syenite** - Black and white-'peppered,' coarse to medium grained, subequigranular to trachytoid, syenite and quartz syenite. With the exception of euhedral, megacrystic, alkali feldspar, the minerals are typically subhedral and anhedral. This unit contains 60 to 80 percent total feldspar, with alkali to plagioclase feldspar ratios of >2:1 and quartz content typically between 0 and 5 percent, rarely to 10 percent. This unit generally lacks the well-developed alkali feldspar foliation of the monzonite and the elevated quartz contents of the granite. Biotite and pyroxene are the only mafic minerals, with biotite more common. Average abundance of the major minerals are: quartz (5 percent), biotite (10 percent), plagioclase (20 percent), pyroxene (5 percent), and alkali feldspar (60 percent).

Kmo **Monzonite** - Black and white 'peppered,' coarse to medium grained, locally foliated, subequigranular to trachytoid, porphyritic monzonite and quartz monzonite. Mineralogy is typically subhedral and anhedral, with the exception of euhedral megacrystic alkali feldspar. Monzonite includes quartz (0 to 5 percent), hornblende (10 percent), biotite (10 percent), plagioclase (20 percent), light brown, subhedral to euhedral pyroxene (25 percent), and alkali feldspar (40 percent). Petrographically the plagioclase (andesine) is fine to medium grained, anhedral, and twinned and zoned; alteration is typically minor. Potassium feldspar typically occurs as phenocrysts in the coarse trachytoid rocks, as interstitial crystals, and anhedral poikilitic crystals that enclose other minerals. Foliation defined by parallel alignment of alkali feldspar crystals is typically steeply dipping and sub-parallel to the contact of the body. Where present, quartz occurs as minor late interstitial fillings. Some samples are nepheline-normative, although feldspathoid minerals have not been identified in hand specimen or thin section. Mafic minerals comprise 30 to 40 percent of the rock and in decreasing abundance are clinopyroxene, hornblende, and biotite. Clinopyroxene occurs as equant, pale grayish tan to pale green, equant anhedral poikilitic crystals with ragged edges. Hornblende occurs as rims encasing augite pyroxene. Biotite occurs as subhedral to anhedral, fine to medium grained elongated shreds that are deep reddish brown and locally black. Magnetite is a common accessory mineral (up to 1 percent). ^{40}Ar/^{39}Ar dates (table 1) are 92 Ma from a dike on Boulder Creek, and 88.5 from Roughtop mountain pluton.

Kmzd **Monzodiorite**– Black and white 'peppered,' medium grained, subequigranular, alkalic plutonic rock lacking quartz and with more plagioclase than alkali feldspar. Mafic minerals (clinopyroxene > biotite > hornblende) commonly make up more than 50 percent of the rock. Hornblende in this rock is entirely deuteric, replacing early-formed clinopyroxene. Plagioclase exhibits a dusting of sericite; the other minerals are usually unaltered. This unit is especially noticeable along the southern contact of the Roughtop body with hornfels, but sporadically occurs on the northern contact and as isolated bodies east of the Stevens Creek fault. The apparent absence of this unit along the western and eastern margins of the Roughtop body suggests that Roughtop is essentially a series of east-northeast-trending dikes, rather than a circumferentially zoned body. The presence of small bodies of this same rock type south of the Stevens Creek fault in covered areas suggests that bodies similar to Roughtop are present at depth in the area (see Airborne Geophysics section above). ^{40}Ar/^{39}Ar dates (table 1) are 88 Ma (biotite) and 98.2 Ma (hornblende) from two small igneous bodies that trend northeast into the Elephant Mountain pluton of the Tanana B-1 Quadrangle (Reifenstuhl and others, 1997a). The age range (98.2 to 88 Ma) suggests a protracted igneous event in this region; the wide range of igneous rock chemistry is consistent with this (Liss and others, 1998; 1997).

Jrc **Carbonatite —** (approximately 200 Ma) Medium to coarse grained, dolomite–calcite–magnetite–apatite-rich rock, which weathers to a deep red gossan and is characterized by an intense magnetic high. Occurs as two steeply-dipping sills (?) up to 30 m thick, which may be a single sill or dike that is repeated by isoclinal folding. Gradational contacts with hornfels with the carbonatite indicate that this was an igneous intrusion and not a flow; ^{40}Ar/^{39}Ar dating of the hornfels indicates an age of about 200 Ma. Average composition is 87 percent carbonate (dolomite>calcite), 3 percent apatite, and 10 percent coarse magnetite. Minor phases include medium-grained barite, and fine-grained phlogopite, zircon, monazite, and columbite; all present at <1 percent abundance. Phyllite surrounding the carbonatite is altered to a carbonate–white mica-rich rock within 10 m of the carbonatite. Massive to foliated, fine-grained, clinozoisite–chlorite–dolomite, talc–clinozoisite–magnetite–dolomite, and actinolite–chlorite–dolomite–albite rocks, with variably elevated Ni and Cr contents, are present adjacent to the carbonatite body. The unusual mineralogy and composition of these rocks suggests that they are carbonate-altered mafic–ultramafic rocks genetically associated with the carbonatite. Since talc-chlorite-carbonate rocks with very high Ni, Cr, and MgO contents also contain substantial Al_2O_3, the protoliths must have included feldspathic peridotites (that is alkalic mafic rocks).

Pzum **Ultramafic rocks** – (approximately 540 Ma) Serpentinite, gabbro, and minor roddingite, which weather to a buff-colored massive rubble. Predominantly serpentinite, consisting of fine-grained, moderately foliated to unfoliated serpentine-talc with 2 to 5 percent fine- to medium-grained magnetite, 0 to 20 percent magnesite, 0 to 25 percent altered, medium-grained orthopyroxene, 0.1 to 0.5 percent fine- to medium-grained chromite, and 0 to 1 percent fine-grained chlorite. No residual olivine has been observed in the rock and orthopyroxene is only locally present. Based on the bulk composition and residual minerals present, the protolith is primarily dunite and harzburgite. Due to secondary magnetite, the rock is highly magnetic. Gabbro constitutes <5 percent of the mapped body, as 1 to 2 m by 5 m pods that might have originally been dikes or sills in the ultramafic rocks. Gabbro is fine- to medium-grained and unfoliated, containing colorless clinopyroxene and calcic plagioclase in subequal amounts. Clinopyroxene is variably surrounded and replaced by medium-grained, deuteric hornblende; plagioclase is partly to largely altered to fine-grained clinozoisite±actinolite. Gabbro with abundant hornblende and clinozoisite also contains 1 to 2 percent medium-grained, subhedral sphene, probably after Fe-Ti oxide. Roddingite is a rare rock type present with gabbro, consisting of massive, non-foliated, fine-grained idocrase and clinozoisite, and represents a calcium-enriched, sodium-depleted, altered gabbro. ^{40}Ar/^{39}Ar dating of hornblende gabbro from this unit indicates a minimum age of 465 Ma; hornblende gabbro samples virtually identical in mineralogy, texture, and composition from the Livengood area yield a minimum age of 485 Ma and a plateau age of 536±3 Ma. Trace element data indicate (Pearce and Cann, 1973) the gabbroic rocks are derived from a mid-ocean-ridge basalt (MORB) or arc setting; most likely the assemblage of altered ultramafic and ultramafic rocks represents the roots of a mid-Cambrian ophiolite, thrust over the Jurassic-Cretaceous flysch at about 110 to 100 Ma (see Airborne Geophysics section above).

Table 1. *^{40}Ar/^{39}Ar data for samples from the Tanana A-1 and A-2 quadrangles and some related areas*

Sample	Rock type	Location/ Quadrangle	Phase dated	^{40}Ar/^{39}Ar age[a]	Estimated reset ages
97RN215	Gabbro	Serpentinite Ridge Tanana A-3	Amphibole	Minimum age 465 Ma (htf)	About 100 Ma
97RR13D	Monzonite dike	Boulder Creek, Tanana A-2	Biotite	92±0.5 Ma (pl)	—
97KC71	Pegmatite dike	North of Roughtop, Tanana A-2	Biotite	90.6±1.3 Ma (pl)	—
97KC7	Monzonite	Roughtop complex, Tanana A-2	Biotite	88.5±0.3 Ma (pl)	—
97RN247	Massive basalt- Amy Creek unit	Dalton Highway (5 mile), Livengood Quadrangle	Whole rock	Minimum age 230 Ma (htf)	About 200 Ma & about 100 Ma
DT-87-15	Gabbro	Old Livengood Highway— Livengood area	Hornblende	536±2.6 Ma (pl)	
DT-87-16	Gabbro	Old Livengood Highway— Livengood area	Hornblende	Minimum age 485 Ma (htf)	About 240 Ma
DDH4-153 ft	Altered phyllite adjacent to carbonatite	Idaho gulch, Tofty, Tanana A-2	Whole rock	Estimated 193±15 Ma (htf)	About 55 Ma
97RN49	Monzodiorite dike	Tanana A-1	Hornblende	98.2±0.6 Ma (pl)	—
97RN98	Monzodiorite pluton	Tanana A-1	Biotite	88±0.4 Ma (pl)	—
97RN54A	Mafic dike	Tanana A-1	Biotite	89.3±0.5 Ma (pl)	—
96RN16	Granite	Manley Hot Springs Dome	Biotite	59±0.8 Ma (pl)	—

[a] htf =high temperature fractions; pl= plateau.

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