

GEOLOGY AND GOLD MINERALIZATION AT THE DONLIN CREEK PROSPECTS, SOUTHWESTERN ALASKA

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SUMMARY

The Donlin Creek property in southwestern Alaska is a large gold system with mineralization extending more than 6 mi (9.6 km) in a northeast/southwest direction. The Queen–Lewis–ACMA area in the southern part of the property has the largest gold resource identified to date, with an estimated measured and indicated resource of 5.4 million oz (167.8 tonnes) of gold at a grade of 0.088 oz/ton gold (3.0 g/tonne). Total estimated gold resource at Donlin Creek, including the inferred category, is 11.5 million oz (357.7 tonnes). Mineralization is open to depth and along strike.

Gold mineralization parallels a 5-mi-long (8.2-km-long) Late Cretaceous to early Tertiary bimodal rhyodacitic and mafic dike swarm intruding mid-Cretaceous Kuskokwim Group interbedded graywacke and shale. Intrusive contacts are highly irregular along strike and there are both sill- and dike-like components. Dike morphologies dominate in the northeastern Lewis and Rochelieu areas, whereas igneous sills are dominant in the 400 Area, and the southern Lewis and ACMA areas. Gold mineralization is associated with disseminated sulfides, sulfide veinlets and quartz–carbonate–sulfide veining in sericite-altered igneous rocks and sedimentary rocks. There is a consistent positive correlation between zones of high fault and fracture density, areas of intense sericite alteration, and high gold grades. Alteration (sericite formation) and felsic dike crystallization (biotite formation) ages by ⁴⁰Ar/³⁹Ar dating overlap and are interpreted to indicate that crystallization of the dikes was closely followed by sericite and carbonate alteration accompanied by pyrite–arsenopyrite–gold mineralization. Stable isotope and fluid inclusion results suggest that fluids responsible for sericite alteration (and at least part of the mineralization) at Donlin Creek formed by mixing of magmatic water and meteoric water. Interpretation of sulfur isotopes suggests that at least some sulfur is derived from clastic sedimentary rocks.

Gold mineralization is structurally controlled and refractory (arsenopyrite-hosted). Higher-grade mineralization occurs at the juxtaposition of favorable lithology (most favorable is rhyodacite, least favorable is shale) and mineralized shear zones/faults (355°–040° trends

with moderate to steep, easterly dips). North-trending structures appear to be normal faults having minor displacement (east–west extensional event). Earlier, northwesterly trending thrust faults, occurring along shale beds also have minimal displacements but only minor gold mineralization. Deformation has been minimal since mineralization.

INTRODUCTION

Plutonic-hosted gold deposits have become an important exploration target in Alaska since the discovery and subsequent operation of the five-million-ounce Fort Knox gold deposit. The Fort Knox deposit near Fairbanks remains the best-documented intrusive-hosted gold deposit in Alaska. Other plutonic-hosted gold deposits in Alaska vary dramatically from the Fort Knox model in fundamental aspects such as ore mineralogy and alteration styles (McCoy and others, 1997). Nevertheless, most recent exploration for plutonic-hosted gold deposits in Alaska has focused on the Yukon–Tanana uplands of the eastern Interior. The discovery of the Donlin Creek gold deposit in southwestern Alaska emphasizes that potential for world-class gold deposits in Alaska is not restricted to the Yukon–Tanana uplands.

The Donlin Creek property, in the Kuskokwim Mountains of southwestern Alaska, is approximately 300 mi (480 km) west of Anchorage and 15 mi (20 km) north of the village of Crooked Creek on the Kuskokwim River (fig. 1, inset), the closest navigable waterway. The property is on approximately 42 mi² (109 km²) of privately owned Native land. Calista Corp., a regional Native corporation, has patent to subsurface rights, and The Kuskokwim Corp., a Native village corporation, has patent to surface rights. The project is controlled 100 percent by Placer Dome Inc. under a lease agreement signed with Calista Corp. in March 1995. Calista has the right to earn up to a 15 percent interest in the project upon completion of a positive feasibility study. Locus of exploration activity is in the SE¼ T. 23 N., R. 49 W., Seward Meridian (62°03'N latitude, 158°10'W longitude). The property has a 5,400-ft-long (1,650-m-long) gravel airstrip for access and an 80-person camp on

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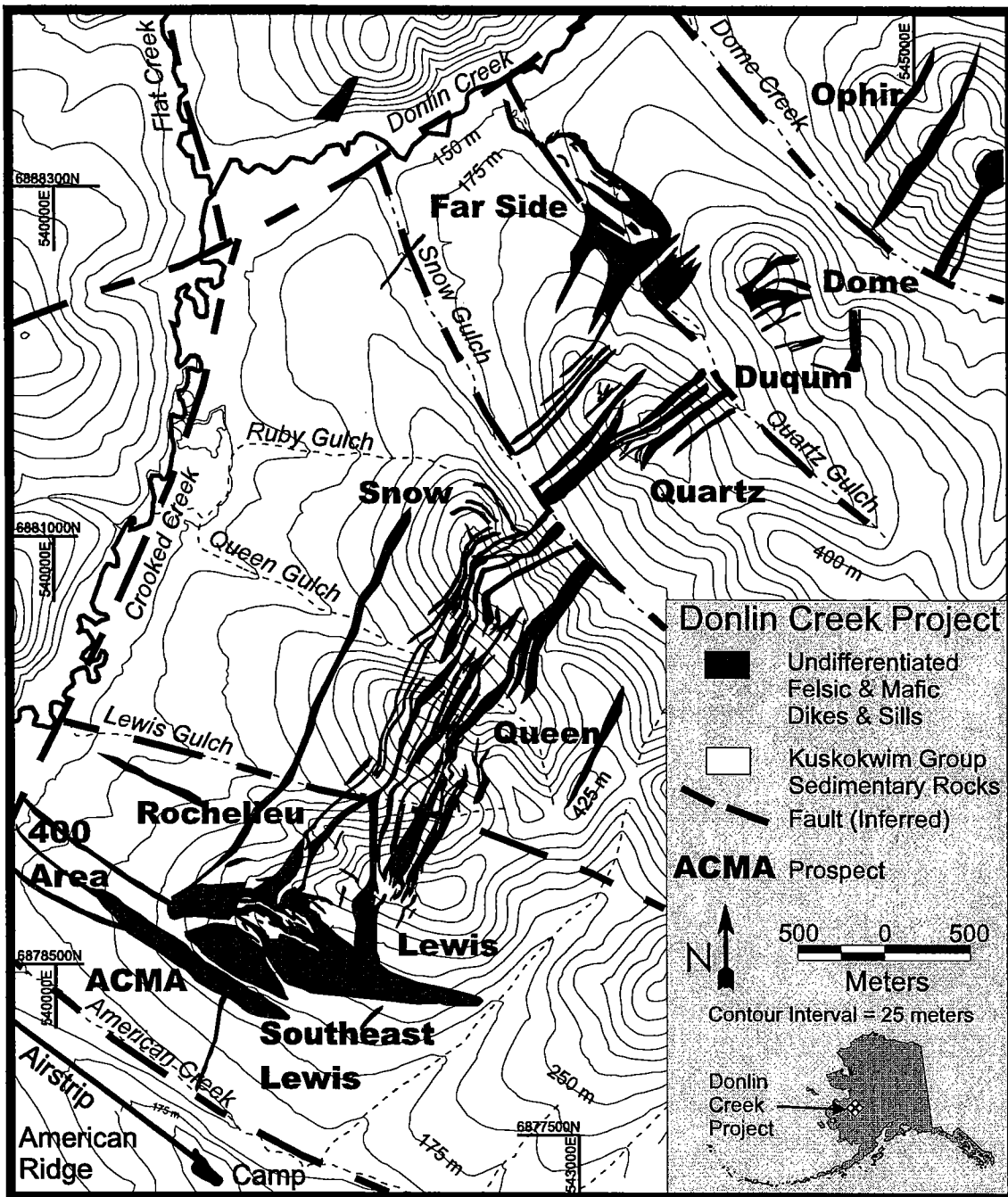


Figure 1. Simplified geology of the Donlin Creek property and location of gold prospects. Topographic base from aerial survey flown by Aeromap U.S. for Placer Dome Exploration, Inc. Grid marks are Universal Transverse Mercator (UTM) projection 1927 North American datum, zone 4. Geology modified from maps by Western Gold Exploration and Mining Co. and Placer Dome Exploration, Inc. Inset map shows location of the Donlin Creek project in southwestern Alaska.

American Ridge, immediately south of the exploration area (fig. 1).

The Donlin Creek project is in an area of low topographic relief on the western flank of the Kuskokwim Mountains. Elevations range from 500 to 1,500 ft (150–460 m) above sea level. Ridges are well rounded and ridgetops are typically covered with rubble crop and alpine tundra. Soil solifluction lobes blanket virtually all hillsides; these hillsides are forested with black spruce, tamarack, alder, birch, and larch. Soft muskeg, stunted black spruce forest, and discontinuous permafrost are common at lower elevations in poorly drained areas.

Placer gold was discovered near the Donlin Creek property in 1909 and significant lode exploration at Donlin Creek began in the 1980s. WestGold Exploration and Mining Co. identified eight gold prospects over a 3-mi (5-km) strike length through extensive soil sampling (over 10,000 samples), trenching, and drill programs in 1988 and 1989. These prospects, from north to south, were named Far Side (formerly called Carolyn), Dome, Quartz, Snow, Queen, Rochelieu, Upper Lewis, and Lower Lewis (fig. 1).

Placer Dome began working at Donlin Creek in 1995 and spent approximately \$26 million on the Donlin Creek project from 1995 to 1998. Based on WestGold's work, the Lewis–Rochelieu area was deemed the most favorable target for a large bulk tonnage gold deposit and exploration by Placer Dome Exploration Inc. has focused there. Placer Dome's exploration efforts have been largely drill focused, with approximately 39,000 ft (11,900 m) of reverse-circulation drilling and 249,280 ft (76,000 m) of NQ- and HQ-diameter core drilling from 1995 to 1998. Placer Dome also completed 13,850 ft (4,200 m) of excavator and bulldozer trenching, airborne and ground geophysical surveys, and a soil-sampling program. Placer Dome has discovered several additional prospects on the Donlin Creek property, including Duqum, 400 Area, and ACMA (fig. 1). Placer Dome Exploration Inc. is continuing exploration efforts at present.

Extensive core drilling by Placer Dome Exploration Inc. from 1995 through 1998 defined a large gold resource extending from the Queen prospect through the Lewis (formerly Upper Lewis), Rochelieu, Southwest Lewis (formerly Lower Lewis), and Southeast Lewis (formerly Lower Lewis) prospects to the ACMA area. The Queen–Lewis area has the largest gold resource identified at the Donlin Creek property, defined by over 175 core holes with drill spacing varying from 165 to 650 ft (50 to 200 m) centers. Placer Dome announced an estimated measured and indicated resource of 5.4 million oz (167.8 tonnes) of gold contained in 51.7 million tons (57 million tonnes) of gold-bearing material grading 0.088 oz/ton (3 g/tonne) gold, using a 0.06 oz/ton (2 g/tonne) gold cutoff. The total estimated gold resource at

Donlin Creek, including the inferred category, increased to 11.5 million oz (357.7 tonnes) with an average grade of 0.085 oz/ton (2.91 g/tonne) gold at a cutoff grade of 0.04 oz/ton (1.5 g/tonne) gold (Placer Dome press release, 2/18/99).

REGIONAL GEOLOGY

The regional geology of southwestern Alaska is summarized in Decker and others (1994), Patton and others (1994), and Szumigala (1993, 1996). Metamorphosed Early Proterozoic sedimentary and plutonic rocks occur as isolated exposures in southwestern Alaska and serve as depositional basement for Paleozoic units of the Ruby, Innoko, and Farewell terranes. The Farewell terrane, a nearly continuous sequence of Paleozoic continental margin rocks over 18,000 ft (5,500 m) thick, underlies much of the southwestern Alaska Range and northern Kuskokwim Mountains and unconformably overlies Early Proterozoic units. The predominantly Upper Cretaceous Kuskokwim Group, a post-accretionary basin-fill flysch sequence, is the most extensively exposed unit in the region and is interpreted to have formed one continuous marine embayment that stitched together most of the terranes of southern and western Alaska by Albian time. The Kuskokwim Group consists largely of interbedded lithofeldspathic sandstone and shale, and in large part rests unconformably on all older rock units. The Kuskokwim Group is at least 7.5 mi (12 km) thick in the region surrounding Donlin Creek and the underlying basement rocks are unknown. Late Cretaceous to early Tertiary plutonic and volcanic rocks intrude and/or overlie all of the younger units.

Two major northeast-trending faults traverse southwestern Alaska, the Denali–Farewell fault system to the south, and the Iditarod–Nixon Fork fault to the north. Latest Cretaceous and Tertiary right-lateral offsets of 56 mi (90 km) to less than 94 mi (150 km) occurred on both faults (Bundtzen and Gilbert, 1983; Miller and Bundtzen, 1988). Numerous high-angle faults are parallel and conjugate to these large faults. Pre-Tertiary rocks have undergone at least two folding phases: open to isoclinal folds with 1–2 mile (2–3 km) amplitudes and northeast-trending axes, and later broad folds with 15 mi (25 km) wavelengths and north-northeast-trending fold axes. Regional structural elements have been modeled by right lateral wrench fault tectonics with accompanying compressional and tensional stresses (Miller and Bundtzen, 1988).

The Kuskokwim Mountains represent one of several latest Cretaceous to earliest Tertiary magmatic belts found in southern and western Alaska. The Kuskokwim Mountains belt consists of calc-alkaline to alkaline basaltic to rhyolitic volcanic fields, isolated calc-alkaline stocks, felsic to mafic dike swarms, and sub-alkaline to

alkaline volcano-plutonic complexes (Moll-Stalcup, 1994). Plutonic rocks of the Kuskokwim Mountains magmatic belt extend over a northeast-trending area of approximately 540 mi by 120 mi (900 km by 200 km). Potassium-Argon (K-Ar) dates from igneous rocks in the Kuskokwim Mountains belt range from 58 to 77 Ma, whereas K-Ar dates for plutonic rocks range from 61 to 73 Ma, with an average age of 69 Ma (Szumigala, 1996, 1993). Geochemical characteristics of the igneous rocks suggest a common arc related petrogenesis for the Kuskokwim igneous centers (Szumigala, 1993). Most plutons of the Kuskokwim Mountains magmatic belt have quartz-monzonitic to monzonitic compositions and are calc-alkaline. Petrographic, magnetic susceptibility, and compositional data for plutonic rocks fit criteria for ilmenite series granitoids and geochemical signatures are compatible with I-type granitoids. Field relationships and limited laboratory measurements indicate the intrusions were emplaced at maximum depths of 0.6 to 2.5 mi (1 to 4 km). On the basis of previous K-Ar dating, mineralization is contemporaneous with plutonism at several localities in the Kuskokwim region (Szumigala, 1993).

PROPERTY GEOLOGY

Graywacke and shale of the Kuskokwim Group occur in subequal proportions at Donlin Creek (fig. 2). Kuskokwim Group rocks generally strike east to northwest (280° to 320°) and dip moderately (40° to 60°) to the south. Graywacke varies from a light gray to dark gray color, from fine-grained sandstone to fine-grained conglomerate, is massively bedded to 40 ft (12 m) thickness and breaks into blocks. Shale and siltstone units have prominent bedding and are good bedding indicators when present in core. Shale and siltstone units are black, carbonaceous, and occasionally contain fine-grained (diagenetic?) pyrite.

A northeast-trending, anastomosing, felsic (rhyodacite) and mafic (alkali basalt/andesite) dike swarm intrudes the Kuskokwim Group sedimentary rocks at Donlin Creek and crops out over approximately 5 mi (8.2 km) of strike length from American Creek to Ophir Creek (figs. 1, 2). In general, igneous units in the Northeast Lewis and Rochelieu areas are dikes with northeast strikes and moderate southeast dips that are clearly discordant to bedding. Igneous units in the Southeast and Southwest Lewis and ACMA areas are mostly sills with northwest strikes and moderate to steep southwest dips. This morphological change is reflected in the bedrock geologic map by the thick mass of rhyodacite present in the southern Lewis area (figs. 1, 2).

In detail, individual rhyodacite body orientations vary greatly. Igneous rocks occur as dikes, sills, and fault-bounded bodies. Igneous units are highly irregular along

strike and can have both sill and dike components. Some sills may be thin apophyses to larger dikes. Sills commonly occur below thick shale horizons within the sedimentary rock package. Regional contact relationships between sedimentary and igneous rocks are typically sharp and generally without metamorphic or metasomatic effects. Chilled margins on igneous bodies occasionally occur along all contact types. Individual dikes may be up to 200 ft (60 m) wide, but the average width is 35 to 70 ft (10–20 m). There is no drill evidence that these dikes coalesce into a larger plutonic body within 1,300 ft (400 m) of the surface.











IGNEOUS LITHOLOGIES

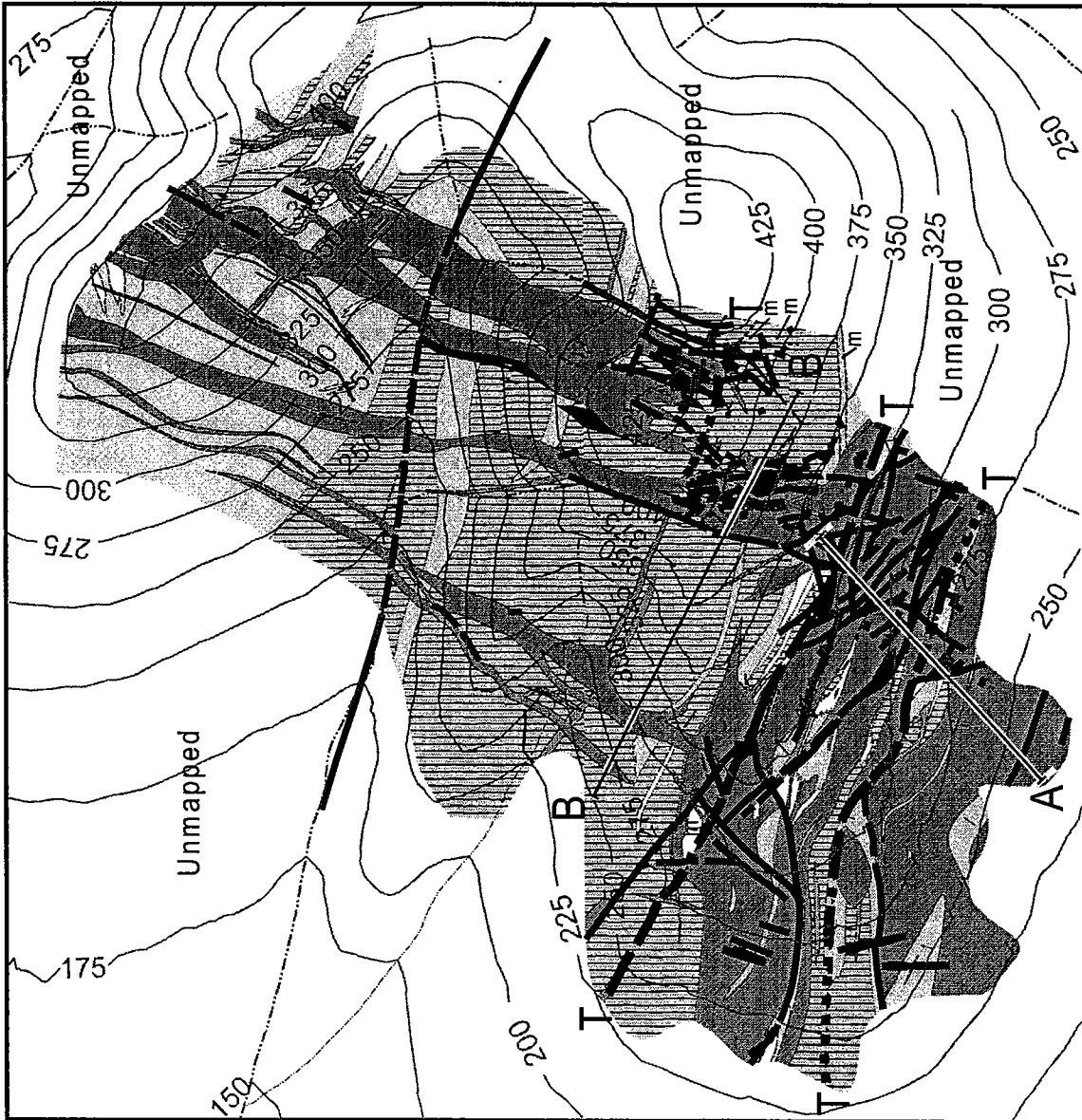
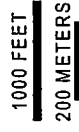
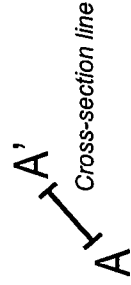
Donlin Creek intrusive units comprise a dike swarm; hence, conflicting age relationships are likely. Individual dikes and sills pinch and swell throughout the prospect areas. Igneous units in the Donlin Creek area have been divided into five field categories: aphanitic rhyodacite porphyry (RDA), crystalline rhyodacite (RDX), fine-grained rhyodacite porphyry (RDF), rhyolite (RHY), and mafic dikes (MD).

Rhyodacite porphyry with aphanitic groundmass and porphyritic phenocrysts (RDA) and rhyodacite with medium- to coarse-grained crystalline texture (RDX) are the most common igneous units, representing approximately 80 percent of the dike volume. RDA and RDX can have gradational contacts, probably as textural differences within one dike, but contacts with distinct chilled margins also occur. Overall, the rhyodacite units have similar mineralogy and characteristics. Textures are typical for hypabyssal igneous rocks and vary from porphyritic with very fine-grained matrix ("volcanic") to almost coarse-grained equigranular ("plutonic"). Color varies from light gray to dark blue-gray and phenocrysts compose approximately 50 percent of rock volume. Quartz phenocrysts are subrounded to equant, vary from 0.04 to 0.31 in (1 to 8 mm) diameter and represent 10 to 20 volume percent. Quartz phenocrysts are typically partially to completely resorbed, embayed, and surrounded by sericite. Feldspar phenocrysts range from 0.02 to 0.39 in (0.5 to 10 mm) diameter (average 0.15 to 0.20 in [4–5 mm]) and 5 to 40 rock volume percent. There is a 1:1 to 1:2 ratio between plagioclase and orthoclase. Biotite phenocrysts are similar in size to quartz and feldspar phenocrysts and comprise 2 to 5 volume percent. Trace amounts of rutile, sphene, apatite, titanium oxide, allanite (?) and zircon are present. Red garnet phenocrysts are present in some core samples, but they are extremely rare overall (less than 10 garnets reported in 250,000 feet [76.2 km] of drilling). Graphite spherules up

Figure 2 (right). *Geologic map of the Queen, Rochelieu and Lewis prospects, Donlin Creek property.*

Queen-Lewis
Area Geology
Donlin Creek
Project
Southwest
Alaska

-  rhyodacite
 -  fine rhyodacite
 -  porphyry
 -  mafic intrusions
 -  graywacke
 -  shale
 -  interbedded
 -  graywacke & shale
 -  shears & faults
 -  thrust fault
- Kuskokwim Group*



to 1.1 in (3 cm) in diameter occur locally and indicate a low magmatic oxidation state.

Whole rock analyses of the least altered rhyodacite samples available from drill core are shown in table 1 and plot within the rhyolite and rhyodacite fields (fig. 3). Samples with elevated gold values, high loss-on-ignition values and high normative corundum were eliminated from this data set. The loss of sodium, potassium, and calcium during alteration of feldspar to mica and clay minerals produced major oxide analyses that are strongly peraluminous. Even the least altered samples of igneous rocks from Donlin Creek appear weakly peraluminous due to alteration. It is unclear from the present data whether the original magma was also peraluminous. Most likely, the Donlin Creek igneous rocks have primary metaluminous compositions like Late Cretaceous plutonic rocks throughout the Kuskokwim Mountains (compare Szumigala, 1993). Limited trace-element data in table 1 are similar to data from Kuskokwim plutonic rocks with clear volcanic arc signatures.

Fine-grained rhyodacite porphyry (RDF) occurs as narrow dikes with a fine crystalline matrix and smaller phenocrysts than other rhyodacite units. Extensive drilling indicates that RDF occurs throughout the Lewis and Queen prospects. Maximum apparent thickness in core is 70 ft (22 m). RDF contains 5 percent 0.04–0.08 in (1–2 mm) feldspar phenocrysts and 5 percent 0.04–0.08 in (1–2 mm) quartz phenocrysts, commonly in a flow-banded-like matrix with wispy hairline graphite veinlets. RDF dikes are always strongly altered and no primary minerals for dating have been found. However, RDF dikes fit best in geologic modeling and cross-section building if assumed to be younger than mafic dikes and older than other rhyodacite units.

Rhyolite dikes occur at the northern end of the Donlin Creek property at the Dome and Duqum prospects. The rhyolite appears more siliceous than the rhyodacite units and generally is a light gray to cream color. Quartz phenocrysts have square to slightly rounded shapes that occupy 20 to 25 percent of the rock volume.

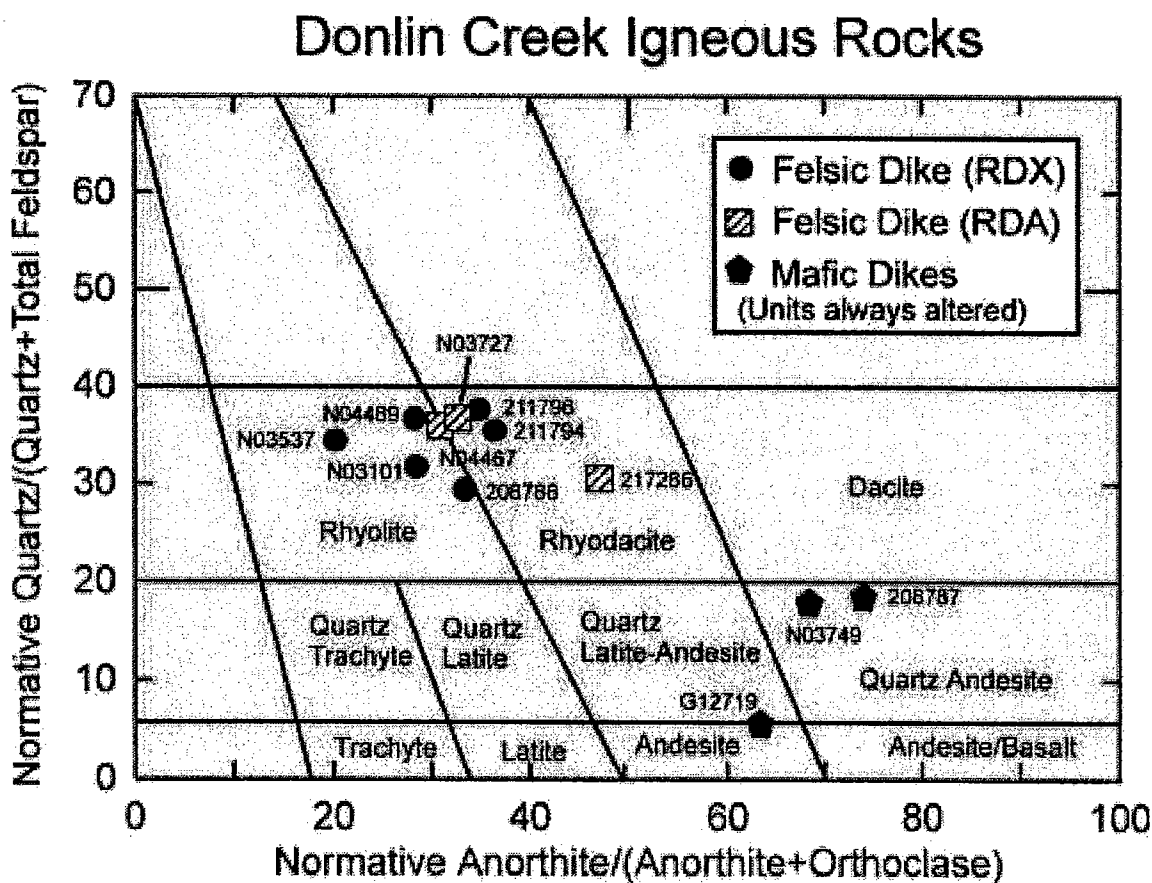


Figure 3. Compositional plot for Donlin Creek dikes (modified from Streckeisen and LeMaitre, 1979). Dike compositional data shown in table 1.

Mafic dikes exposed at the surface in the southern part of the Donlin Creek property weather a distinct reddish-brown color with a fine granular texture. Mafic dikes are generally only 5–10 ft (1.5–3.0 m) thick. Sparsely distributed mafic dikes crop out along the runway on American Ridge, beyond the known southern limit of mineralization. Field relationships and $^{40}\text{Ar}/^{39}\text{Ar}$ dating indicate that mafic dikes are the earliest igneous phase in the Donlin Creek area. Several drill intercepts of fresh mafic dike are biotite-rich (up to 75 percent) and hence lamprophyres. Mafic dikes are generally almost completely altered to carbonate and sericite, with a bleached cream to greenish tan color. A characteristic alteration/oxidation mineral is bright green fuchsite occurring as isolated grains. Petrographic examination shows that mafic dikes contain 2–5 percent opaques (including trace amounts of fine-grained gersdorffite [NiAsS]), 10 percent secondary silica (chalcedony) filling voids, up to 80 percent very fine-grained plagioclase laths (An_{50}), 5 percent possible augite phenocrysts, and highly variable amounts of biotite phenocrysts (10–75 percent) (John McCormack, written commun.). Three relatively unaltered samples of mafic dikes plot in the andesite and quartz andesite fields in figure 3.

RADIOMETRIC DATING

Results from radiometric dating studies on Donlin Creek igneous rocks and alteration are summarized in table 2. Age spectra for the $^{40}\text{Ar}/^{39}\text{Ar}$ data are shown in figure 4 and separated by rock type.

K-Ar dates for biotite from rhyodacite dikes in the Donlin Creek area range from 65.1 ± 2.0 to 69.5 ± 2.1 Ma (Miller and Bundtzen, 1994). These ages are within the age range for igneous rocks (61 to 73 Ma) of the Kuskokwim Mountains plutonic belt (Szumigala, 1993). Hydrothermal sericite at Donlin Creek has previously been dated at 70.0 ± 0.3 Ma by $^{40}\text{Ar}/^{39}\text{Ar}$ (Gray and others, 1997, 1992), and 70.9 ± 2.1 Ma by K-Ar (Miller and Bundtzen, 1994), indicating that mineralization is broadly contemporaneous with emplacement of the dike swarm.

Mafic dikes are the oldest igneous rocks in the Donlin Creek area. A mafic dike at the Queen prospect yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ -biotite age of 72.6 ± 0.9 Ma and a whole-rock age of 74.4 ± 0.8 Ma. Biotite from a rhyodacite dike at the Queen prospect yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ -plateau age of 70.3 ± 0.2 Ma. Sericite $^{40}\text{Ar}/^{39}\text{Ar}$ ages from altered feldspar phenocrysts in rhyodacite dikes from the Queen–Lewis area range from 73.6 ± 0.6 Ma to 67.8 ± 0.3 Ma. Overall, good plateau ages of igneous biotite and sericitized feldspar from rhyodacite dikes yield similar results within analytical error, indicating that alteration (and mineralization?) ages of igneous rocks are indistinguishable from igneous cooling ages.

Sericite from rhyolite dikes at the Dome prospect have the youngest $^{40}\text{Ar}/^{39}\text{Ar}$ ages (65.1 ± 0.9 Ma and 68.0 ± 1.0 Ma) from the Donlin Creek area. These young ages suggest that mineralization at Dome may be related to a different, younger hydrothermal system than that responsible for gold mineralization at Queen and south Lewis. Alternatively, the Dome rhyolite ages may simply reflect a longer time to cool below the argon blocking temperature for the apparently deeper Dome system.

STRUCTURE

Structural patterns at Donlin Creek are complex and still being deciphered, but several features appear to be important in understanding and predicting mineralization. Structural controls appear to be very important in the deposit's genesis, from ground preparation prior to emplacement of the dike swarm through possible post-mineralization displacements. Core logging with core orientation by the clay impression method and deep trenching programs begun in 1997 were critical in deciphering the structural history.

Major faults in the project area are not exposed, but topographic lineaments and airborne-geophysical data interpretation suggest that modern stream channels follow fault traces. Miller and Bundtzen (1994) mapped northeast-trending Donlin and Crooked creeks as Cretaceous-age splays of the Iditarod–Nixon Fork fault and interpreted a right-lateral motion for these faults. Other drainages (American Creek, Dome Creek, and Snow Gulch) are interpreted to be fault traces based on airphoto lineaments and aeromagnetic patterns (Szumigala, 1997).

Drill core shows numerous shears ranging from micros shears to extensive shear zones. The abundance of shears present in drill core is much greater than indicated by previous mapping and figure 2. North-northeast- and northwest-trending faults reflect the dominant structural trends. Many of the igneous/sedimentary contacts observed in core are structural (shears or faults) rather than intrusive.

Multiphase rhyodacitic intrusions are both concordant and discordant to sedimentary rock bedding. Intrusion of these dikes probably occurred during an extensional tectonic phase and may have been controlled by anticlinal structures within the Kuskokwim Group country rocks. Late intrusive phases may have remobilized or dislocated mineralized zones and very minor post-mineralization faulting may have offset both intrusions and mineralization.

Most faults and shear zones appear to be sub-parallel to rhyodacite bodies and have moderate to steep dips. A family of moderately to steeply, east- and west-dipping, normal or oblique-slip faults that strike between 000° and 030° dissects dikes, sills, and sedimentary rocks

Trace Element Geochemistry

Sample Number	C %	Ba ppm	Ce ppm	Cs ppm	Co ppm	Cu ppm	Dy ppm	Er ppm	Eu ppm	Gd ppm	Ga ppm	Hf ppm	Ho ppm	La ppm	Pb ppm	Lu ppm	Nd ppm
211794	1.06	1480	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
211796	0.92	1395	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
217286	1.04	1920	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
208786		1505	62.5	3.4	4.5	40	4.6	2.5	1.3	5.7	19	4	0.9	31	30	0.3	26
208787		875	35	5.9	25.5	40	3.2	1.9	1.2	3.9	16	2	0.7	17	<5	0.3	16
Sample Number	Ni ppm	Nb ppm	Pr ppm	Rb ppm	Sm ppm	Sr ppm	Ta ppm	Tb ppm	Th ppm	Tm ppm	U ppm	V ppm	Yb ppm	Y ppm	Zn ppm	Zr ppm	
211794	--	10	--	128	--	220	--	--	--	--	--	--	--	18	--	165	
211796	--	10	--	134	--	214	--	--	--	--	--	--	--	18	--	153	
217286	--	10	--	88	--	282	--	--	--	--	--	--	--	22	--	123	
208786	10	16	7.6	104	5.7	332	2.0	0.9	6	0.4	4	25	2.2	23	60	179	
208787	75	9	4.5	36	3.9	359	1.0	0.6	3	0.3	2	125	0.5?	15	80	128	

Table 2. $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar dates from the Donlin Creek area, Alaska ^a

Prospect Area Sample ID	Rock Type	Mineral Dated	Plateau Age (Ma) ^b	Comments
Queen DC96-231C@93.5m	Mafic Dike (MD)	Biotite/ whole rock	none	Mixed phases with relic ages. Coarse fraction.
Queen DC96-231C@93.5m	Mafic Dike (MD)	Biotite	72.6 ± 0.9	Fair plateau. Biotite separate from fine-grained rock matrix.
Queen DC96-231F@93.5m	Mafic Dike (MD)	Whole rock	74.4 ± 0.8	Good plateau. Biotite/whole rock separate from fine-grained matrix.
Queen DC96-240@71m	Rhyodacite (RDX)	Sericite	73.6 ± 0.6	Good plateau, but possible ^{39}Ar recoil loss results in an older age than the "true" age.
Queen DC96-240@288.9m	Rhyodacite (RDA)	Biotite	70.3 ± 0.2	Good plateau.
Southwest Lewis DC96-217@132m	Rhyodacite (RDA)	Sericite	70.5 ± 0.2	Good plateau.
Southwest Lewis DC96-217@35m	Rhyodacite (RDA)	Sericite	70.5 ± 0.3	Good plateau.
Southeast Lewis DC96-261@250.9m	Rhyodacite (RDA)	Sericite	70.9 ± 0.3	Good plateau
Rochelieu DC96-210B@156.5m	Rhyodacite (RDX)	Sericite	67.8 ± 0.3	Bimodal plateau.
Dome DC96-250@131m	Rhyolite (RHY)	Sericite	65.1 ± 0.9	Good plateau.
Dome DC96-253@166m	Rhyolite (RHY)	Sericite ^c	68.0 ± 1.0 ^c	Mini plateau = 68.6 ± 0.8; agrees with isochron age using only low Ca/K fractions.
Far Side DC96-255@11.3m	Rhyodacite (RDA)	Sericite	68.0 ± 3.1 ^c	Isochron ages used due to downstepping plateau.
Lewis Gulch DC96-266@125.3m	Rhyodacite (RDX)	Sericite	72.3 ± 1.4 ^c	Downshifting plateau, isochron age agrees well with low Ca/K fractions plateau age.
Snow Gulch USGS1	Rhyodacite	Sericite	70.0 ± 0.3	$^{40}\text{Ar}/^{39}\text{Ar}$ method. Gray and others (1992).
Snow Gulch USGS2	Rhyodacite	Sericite	69.5 ± 1.1	Isochron-disturbed sample. Gray and others (1997).
West side of Crooked Creek USGS3	Rhyodacite	Biotite	65.1 ± 2.0	K-Ar age, K ₂ O very low. Miller & Bundtzen (1994).
East side of Dome Creek USGS4	Rhyodacite	Sericite	70.9 ± 2.1	K-Ar age. Miller & Bundtzen (1994).
East side of Dome Creek USGS5	Rhyodacite	Biotite	69.5 ± 2.1	K-Ar age, K ₂ O very low. Miller & Bundtzen (1994).

^aDates via $^{40}\text{Ar}/^{39}\text{Ar}$ method and analyzed by UAF Geochronology Lab unless noted otherwise, 1 sigma analytical error on ages.

^bPlateau Age is Best Interpreted Age.

^cIsochron Age (Ma) = Interpreted Age for more complex or disturbed samples.

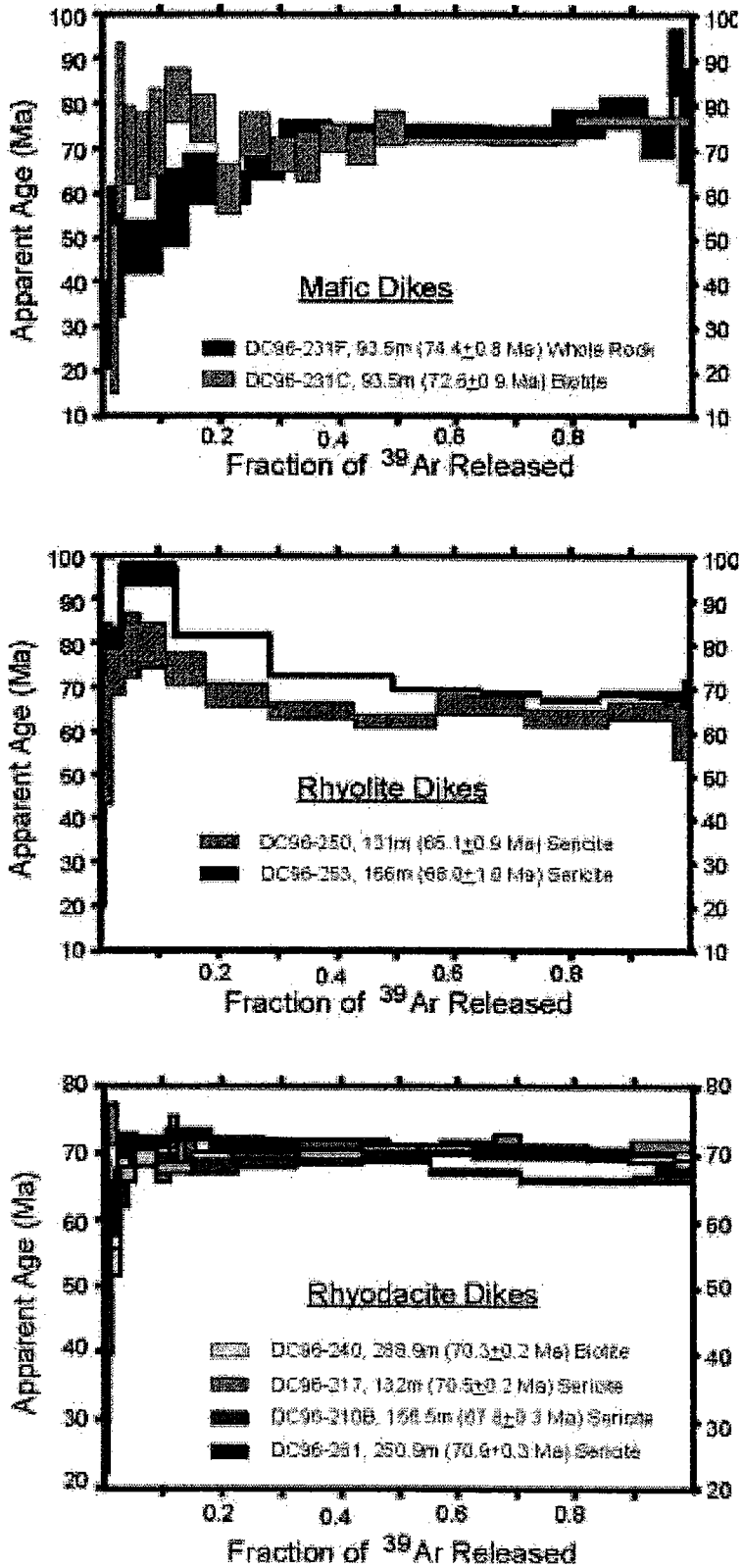


Figure 4. $^{40}\text{Ar}/^{39}\text{Ar}$ spectra for sericite and biotite from Donlin Creek igneous rocks. Mafic dike data are slightly erratic, but yield fair plateaus. Rhyolite samples from Dome show a downstepping plateau, with a mini plateau. Biotite and sericite from rhyodacite samples yield good plateaus.

across the Donlin Creek property (O'Dea, 1997). A well-exposed sequence of Kuskokwim Group sedimentary rocks is present on American Ridge along the airstrip. The sedimentary rocks are cut by a number of north-northeast- to northeast-striking faults, with fault surfaces dipping moderately east or west and characterized by well-developed down-dip slickenside lineations. Several of the faults have broad, open, drag folds developed in their hanging walls (O'Dea, 1997). The absence of cleavage development parallel to the axial planes of these folds and the open geometry of the folds suggest that the folding and faults are a consequence of extensional faulting (O'Dea, 1997).

Fault surfaces in the Lewis trenches are filled with abundant graphite and/or limonite (oxidation of sulfides). Broad zones, up to 7 ft (2 m) wide, of intense microfracturing filled with arsenopyrite occur within highly sericitized dikes. Discontinuous, vuggy quartz-carbonate veins occur near fault zones. Quartz-carbonate veins developed in fault wallrocks dip more steeply than the faults and have approximately horizontal fibers. These features are compatible with east-west extension and normal displacement. This north-northeast-trending shear set correlates well with zones of high-grade gold mineralization.

The amount of displacement on any individual fault is less than several feet based on drillhole and trench mapping. Cumulatively, the normal displacement across the fault system in the Lewis area is estimated to be less than 100 ft (30 m) (O'Dea, 1997).

There is widespread evidence from across the Donlin Creek property for a deformational event (D1) that preceded the development of the north-south oriented normal fault system (D2) (O'Dea, 1997). Some important evidence for an early deformational event include:

- Kuskokwim Group strata are tilted and consistently dip shallowly to moderately to the south-southwest. The tilted bedding is cut by north-northeast-striking normal (extensional) faults.
- Kuskokwim Group strata are often imbricated across shallowly south-dipping faults.
- Shale and siltstone strata commonly display zones of bedding-parallel shear and gouge.
- Many igneous units mapped in the trenches display a pervasive shear fracturing that is sub-parallel to layer-parallel shearing in the sedimentary rocks. In many instances, the same tectonic fabric can be traced through bedding and into rhyodacite.
- Consistent overprinting relations indicate that bedding-parallel fabric and faults pre-date steeper oriented northeast-trending fabric and shears. These relations have been observed in exposures from American Ridge to the Queen prospect.

The deformation documented above may have been caused by (1) northward stratigraphic imbrication along south-dipping thrust faults, or (2) rotational tilt block development during north-south extension. A preliminary interpretation of this evidence strongly suggests that the D1 event was a north-directed thrusting event. The development of layer-parallel fabrics within the sedimentary and igneous rocks and the imbrication of strata across south-dipping faults are consistent with thrust fault development (O'Dea, 1997). The intrusive bodies must have been subjected to at least part of the D1 deformation because pervasive shear fracturing in igneous rocks can be traced into layer-parallel shearing in the sedimentary rocks. It is concluded that sills were intruded during the waning of the D1 event because sedimentary rock-igneous rock contacts are not displaced across bedding-parallel D1 faults (O'Dea, 1997).

In summary, structural studies by Placer Dome Exploration Inc. hypothesize two deformation events at Donlin Creek (O'Dea, 1997). The D1 event was compressional with north-directed movement, resulting in imbrication of stratigraphy and layer-parallel fabrics. Low-angle faults dominate this event and shaley units localized most of the movement. Local imbrication of rhyodacite suggests that the D1 event was syn- to post-dike emplacement. The D2 event was an east-west extensional event that fractured all rock units and led to later localization of gold in open fractures. Post-mineralization movement on any given fault or shear plane appears to range from a few inches (centimeters) to less than 10 ft (a few meters).

ALTERATION

Alteration styles are fairly simple at Donlin Creek. All intrusive units are altered and fresh rocks are uncommon. Sericite is the main alteration product replacing both phenocrysts and matrix. Sericite-dominant alteration (sericite \pm illite \pm kaolinite \pm carbonates \pm pyrite) is pervasive, but varies in intensity. Most sericite is a whitish color, but some plagioclase phenocrysts are replaced by light green sericite (montmorillonite?), especially in less altered intrusive rocks. It is unclear whether there was a supergene alteration event at Donlin Creek. Carbonate replaces phenocrysts and rhyodacite matrix.

Pervasive carbonate alteration (mostly dolomitic and ankeritic) is common in all igneous rock units. Quartz-carbonate-sulfide veinlets crosscut clay- and sericite-altered rock, but relative timing between sericite and carbonate alteration has not been determined. However, relative carbonate alteration intensity appears independent of sericite alteration intensity.

Silicic alteration is weak to absent at Donlin Creek, and confined to weak replacement of porphyry and

