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

David Szumigala,[1] Stan P. Dodd,[2] and Antonio Arribas, Jr.[3]

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 $^{40}Ar/^{39}Ar$ 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 mineraliza-tion. 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 mi^2 (109 km^2) 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

[1]Alaska Division of Geological & Geophysical Surveys, 794 University Ave., Suite 200, Fairbanks, Alaska 99709-3645.
Email for David J. Szumigala: zoom@dnr.state.ak.us
[2]Consulting Geologist, 3732 Magrath Road, Bellingham, WA 98225.
[3]Placer Dome Exploration, Inc., 240 South Rock Blvd., Suite 117, Reno, NV 89502-2345.

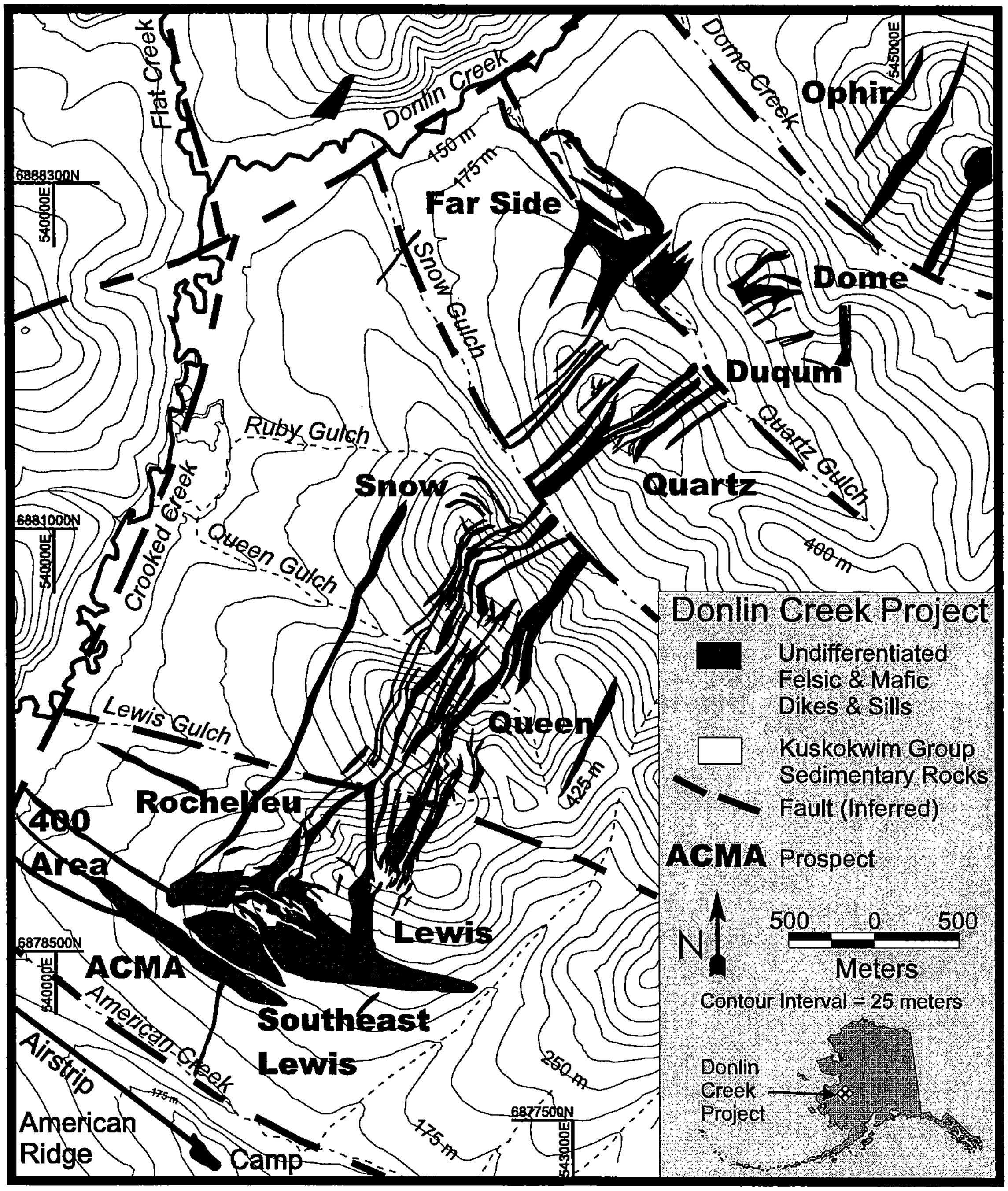


Figure 1. *Simplified geology of the Donlin Creek property and location of gold prospects. Topographic base from aerial survey flown by Aeromap U.S. for Placer Dome Exploration, Inc. Grid marks are Universal Transverse Mercator (UTM) projection 1927 North American datum, zone 4. Geology modified from 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).

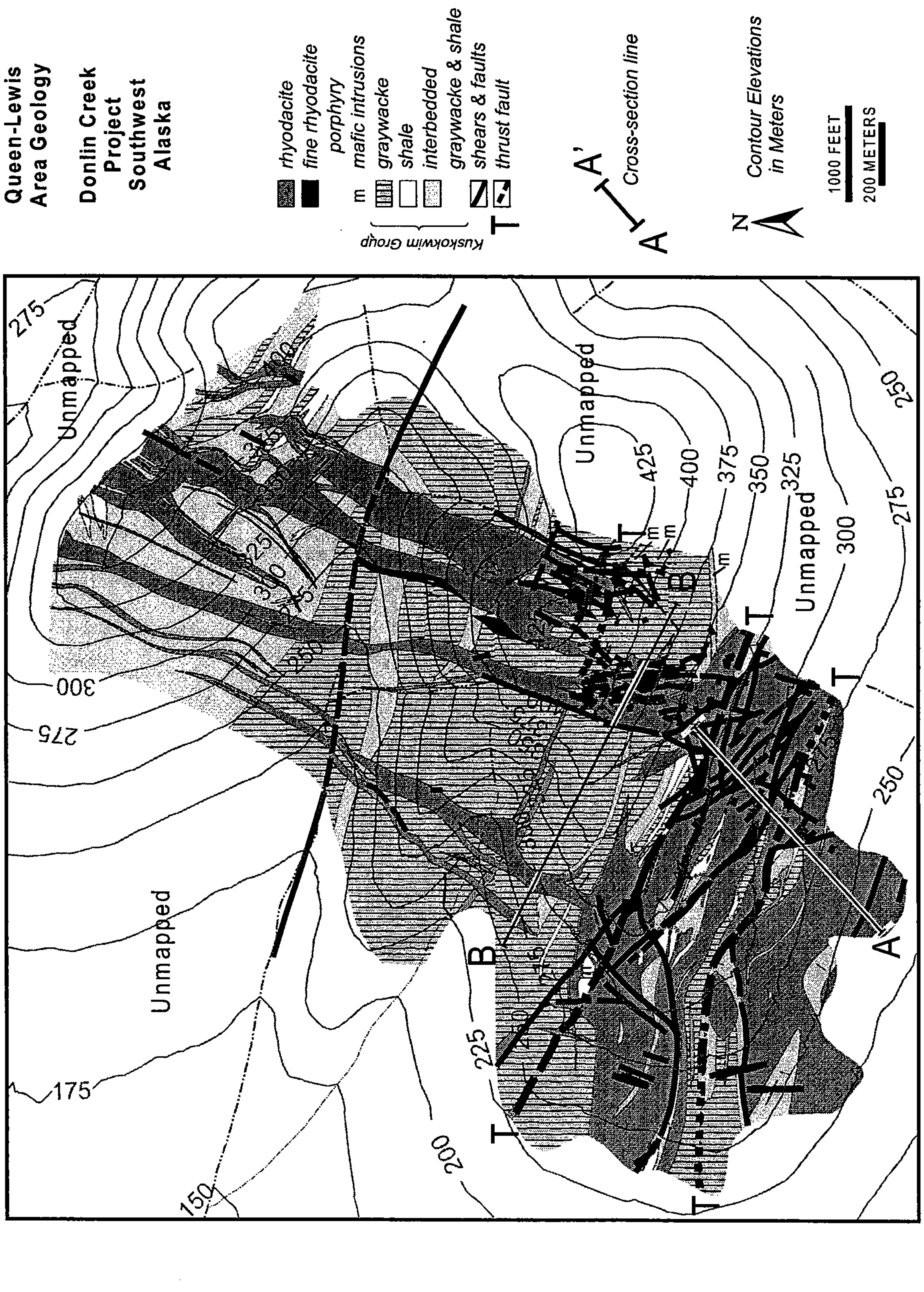
In detail, individual rhyodacite body orientations vary greatly. Igneous rocks occur as dikes, sills, and fault-bounded bodies. Igneous units are highly irregular along strike and can have both sill and dike components. Some sills may be thin apophyses to larger dikes. Sills commonly occur below thick 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
Cross-section line
Contour Elevations in Meters
1000 FEET
200 METERS
Unmapped
Unmapped
Unmapped
Unmapped

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.

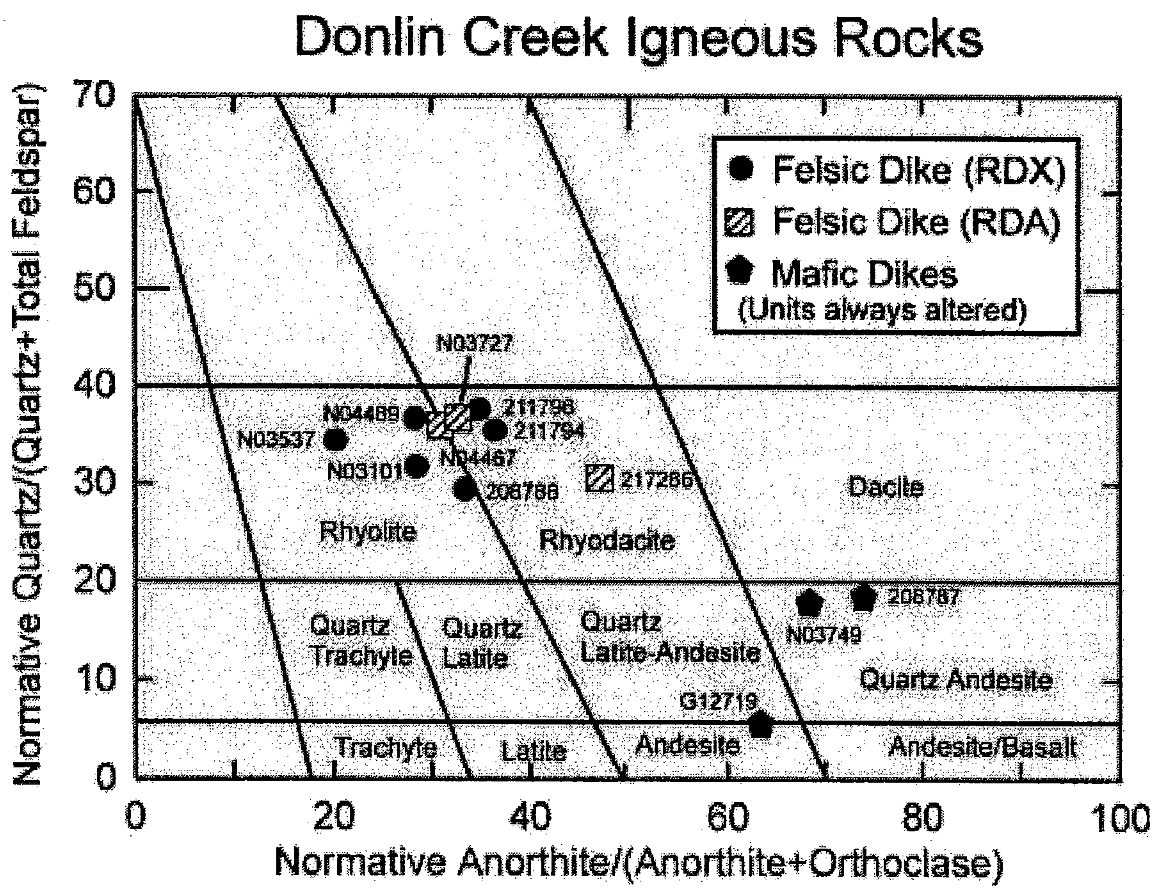


Figure 3. *Compositional plot for Donlin Creek dikes (modified from Streckeisen and LeMaitre, 1979). Dike compositional data shown in table 1.*

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 $^{40}Ar/^{39}Ar$ 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 $^{40}Ar/^{39}Ar$ 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 $\pm$2.0 to 69.5 $\pm$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 $\pm$0.3 Ma by $^{40}Ar/^{39}Ar$ (Gray and others, 1997, 1992), and 70.9 $\pm$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 $^{40}Ar/^{39}Ar$-biotite age of 72.6 $\pm$0.9 Ma and a whole-rock age of 74.4 $\pm$0.8 Ma. Biotite from a rhyodacite dike at the Queen prospect yielded a $^{40}Ar/^{39}Ar$-plateau age of 70.3 $\pm$ 0.2 Ma. Sericite $^{40}Ar/^{39}Ar$ ages from altered feldspar phenocrysts in rhyodacite dikes from the Queen–Lewis area range from 73.6 $\pm$0.6 Ma to 67.8 $\pm$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 $^{40}Ar/^{39}Ar$ ages (65.1 $\pm$0.9 Ma and 68.0 $\pm$ 1.0 Ma) from the Donlin Creek area. These young ages suggests 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 microshears 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

Table 1. *Whole-rock analyses of representative, least altered igneous rock types at Donlin Creek*

Rock Type		RDX	RDX	RDX	RDX	RDX	RDX	RDA	RDA	RDA	MD	MD	MD
Sample		**N03101**	**N03537**	**N04489**	**211794**	**211796**	**208786**	**217286**	**N03727**	**N04467**	**208787**	**N03749**	**G12719**
Al_2O_3	%	14.36	13.59	14.25	14.93	14.95	15.55	15.25	14.47	14.20	13.48	9.93	8.91
CaO	%	2.06	1.48	2.16	2.61	2.52	2.49	3.50	2.41	2.18	5.82	5.67	5.64
Cr_2O_3	%	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.15	0.13
Fe_2O_3	%	0.27	0.21	0.55	0.71	1.14	0.10	0.48	0.27	0.25	0.57	0.36	0.53
FeO	%	2.15	1.57	2.08	2.50	1.88	2.43	3.34	2.66	2.49	5.16	6.46	6.24
K_2O	%	4.19	4.65	4.42	3.63	3.75	3.92	3.13	3.92	3.83	1.44	1.83	1.51
MgO	%	0.62	0.38	0.88	0.93	0.85	0.89	1.10	0.92	0.89	6.64	10.73	13.23
MnO	%	0.04	0.02	0.09	0.08	0.07	0.03	0.08	0.07	0.06	0.10	0.15	0.14
Na_2O	%	3.05	2.94	2.06	2.38	2.26	3.37	2.65	2.17	2.42	2.11	0.43	1.09
P_2O_5	%	0.10	0.09	0.10	0.14	0.15	0.16	0.20	0.15	0.13	0.22	0.26	0.32
SiO_2	%	68.25	70.37	67.14	65.41	66.67	68.73	63.41	65.94	66.03	53.19	47.75	47.27
TiO_2	%	0.28	0.18	0.29	0.36	0.36	0.38	0.54	0.37	0.36	0.90	0.59	0.54
LOI	%	3.43	3.14	4.82	5.44	5.03	1.22	5.98	5.64	5.87	9.01	13.78	12.96
TOTAL		**98.81**	**98.63**	**98.85**	**99.12**	**99.63**	**99.27**	**99.66**	**99.00**	**98.73**	**98.67**	**99.11**	**98.51**

CIPW NORMS

Sample		N03101	N03537	N04489	211794	211796	208786	217286	N03727	N04467	208787	N03749	G12719
Quartz	%	29.250	32.333	33.175	31.456	33.822	26.699	26.864	32.456	32.200	12.378	8.814	2.199
Corundum	%	1.365	1.304	2.541	2.856	3.119	1.652	1.728	2.823	2.608	0.000	0.000	0.000
Orthoclase	%	25.964	28.781	27.783	22.900	23.427	23.627	19.745	24.817	24.380	9.495	12.802	10.447
Albite	%	27.061	26.055	18.540	21.498	20.215	29.083	23.937	19.670	22.057	19.920	4.307	10.798
Anorthite	%	10.031	7.074	10.703	12.846	12.180	11.533	17.141	11.758	10.735	25.727	23.392	17.514
Diopside	%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.947	6.355	10.241
Hypersthene	%	5.118	3.557	5.579	6.271	4.401	6.144	8.255	6.933	6.570	25.137	41.142	45.835
Magnetite	%	0.410	0.319	0.848	1.099	1.747	0.148	0.743	0.419	0.390	0.922	1.150	0.900
Hematite	%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ilmenite	%	0.558	0.358	0.586	0.730	0.723	0.736	1.095	0.753	0.736	1.907	1.327	1.201
Apatite	%	0.243	0.218	0.246	0.346	0.367	0.378	0.495	0.372	0.324	0.569	0.713	0.868
SUM	%	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

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	Tn 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. *$^{40}Ar/^{39}Ar$ and K-Ar dates from the Donlin Creek area, Alaska* [a]

Prospect Area Sample ID	Rock Type	Mineral Dated	Plateau Age (Ma)[b]	Comm ents
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	$^{40}Ar/^{39}Ar$ 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_2O 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_2O very low. Miller & Bundtzen (1994).

[a]Dates via $^{40}Ar/^{39}Ar$ method and analyzed by UAF Geochronology Lab unless noted otherwise, 1 sigma analytical error on ages.
[b]Plateau Age is Best Interpreted Age.
[c]Isochron Age (Ma) = Interpreted Age for more complex or disturbed samples.

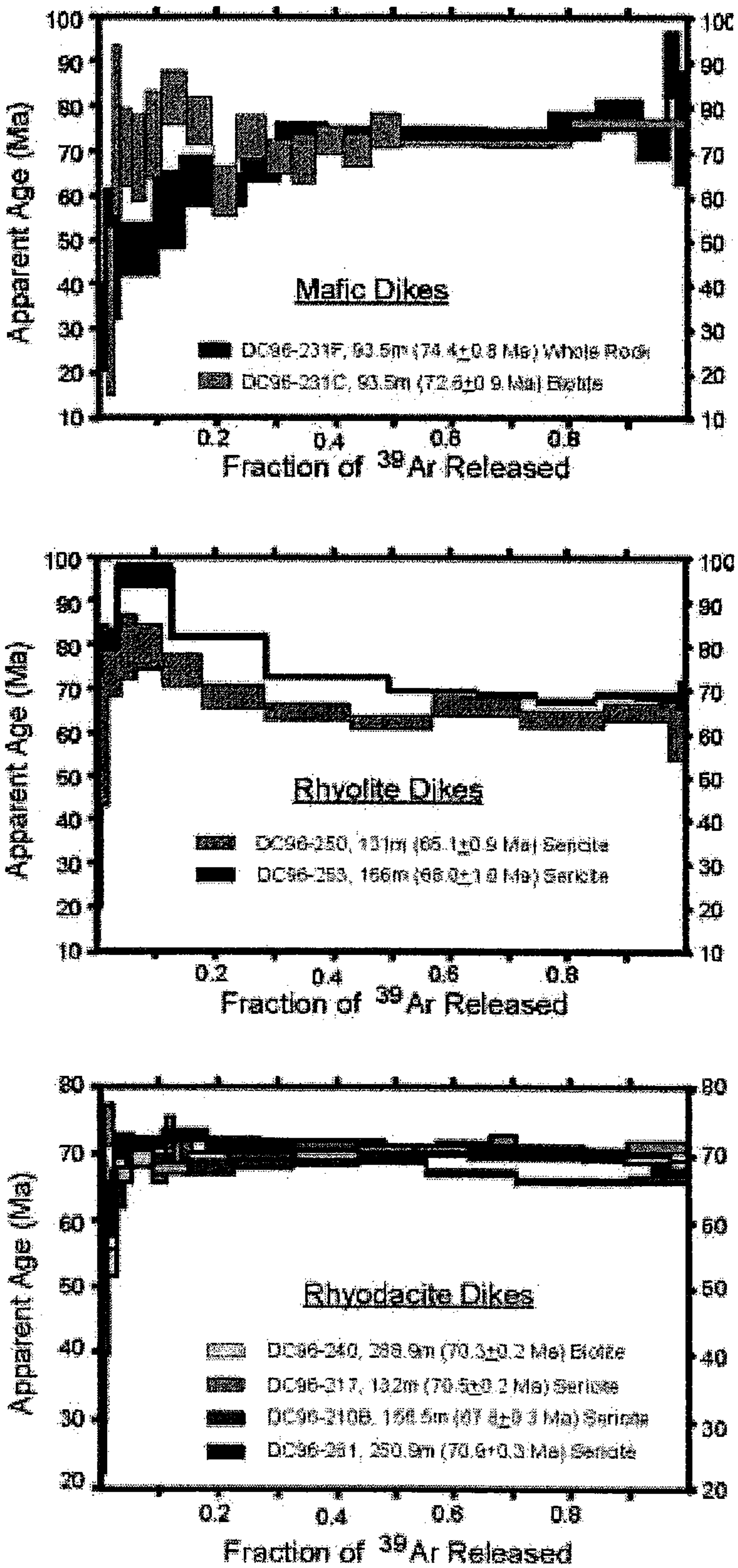


Figure 4. *$^{40}Ar/^{39}Ar$ spectra for sericite and biotite from Donlin Creek igneous rocks. Mafic dike data are slightly erratic, but yield fair plateaus. Rhyolite samples from Dome show a downstepping plateau, with a mini plateau. Biotite and sericite from rhyodacite samples yield good plateaus.*

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 micro-fracturing 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 ± illite ± kaolinite ± carbonates ± 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 indepen-dent of sericite alteration intensity.

Silicic alteration is weak to absent at Donlin Creek, and confined to weak replacement of porphyry and graywacke matrix material. Areas of strong pervasive silicic alteration are localized, and present only in rare areas of strong stockwork silica veining.

Altered mafic dikes are bleached to a cream color. Alteration of mafic dikes is dominated by carbonate, with local almost complete carbonate replacement. Carbonate fracture fillings are also very common. Bright green fuchsite (chrome-bearing mica) is a distinctive alteration mineral confined to mafic dikes.

Very fine-grained graphite is pervasive throughout most intrusive rocks as disseminated grains in a volume percentage range of 0.5 to 3 percent and represented by up to 12 percent carbon in chemical analyses (unpublished Placer Dome data). The graphite is thought to be a hydrothermal alteration product, but it is not clear whether graphite is a separate alteration event or part of the sericite and carbonate alteration events. Graphite is common and occurs in open spaces or high porosity areas, often with coarse sericite or as fine, isolated, shred-like fragments, wisps and grains. Graphite content in rhyodacite commonly increases near faults/shears and sedimentary contacts. An increase in graphite, along with an increase in finely disseminated sulfides, imparts a distinct blue-gray color to the typical gray-colored rhyodacite. Coarse graphite clots up to 1.1 in (3 cm) in diameter occasionally occur in rhyodacite units. The genesis of the graphite clots is not clear. It is unlikely that the clots are melted Kuskokwim Group sedimentary rock because rhyolite composition magmas are not hot enough to melt carbon and quartz (major constituents of the sedimentary rocks). The graphite clots may be condensed methane (Rainer Newberry, written commun.). Methane could have formed by decomposition of organic materials in the surrounding sedimentary rocks at depth (essentially a contact metamorphic phenomenon). The rising methane would have cooled, oxidized, and eventually condensed as graphite.

Wall-rock alteration is not megascopically visible in the Kuskokwim Group sedimentary rocks even in close proximity to highly altered intrusive rocks. However, where intrusive sills terminate along strike there is a thin (0.5–3 inch [1.2–8 cm] wide) envelope of black clay or gouge. No contact metamorphic effects were noted in wallrocks except at the Dome and Duqum prospects.

MINERALIZATION

ORE MINERALS

Ore mineralogy at Donlin Creek is dominated by simple sulfide assemblages. The most common ore minerals are pyrite, arsenopyrite, and stibnite. Other ore minerals include marcasite, realgar, orpiment, and limonite, with lesser amounts of native arsenic, native gold, cinnabar, covellite, chalcopyrite, galena, pyrrhotite, malachite, sphalerite, scorodite, molybdenite, stibiconite?, kermesite?, and hematite. Trace amounts of enargite were seen in thin section enclosed in an arsenopyrite grain, and trace amounts of fine-grained gersdorffite were found in mafic dike samples (John McCormack, 1996, unpublished petrographic report for Placer Dome).

Pyrite is common and appears to be the earliest sulfide phase. Pyrite is ubiquitous in the rhyodacite phases and occurs as disseminated grains and as microfracture fillings. Disseminated pyrite is generally absent within the siliciclastic section. Disseminated pyrite in the sedimentary rocks occurs as fine to coarse grains (up to 0.2 in [5 mm] across) preferentially concentrated near igneous contacts. Most, if not all, of the pyrite is believed to be epigenetic in origin. Pyrite is also common in areas of strong quartz–carbonate veining in both igneous and sedimentary rocks. Relative abundance of pyrite is not an indicator of gold grade.

Arsenopyrite is the dominant gold-bearing mineral at Donlin Creek. Arsenopyrite is deposited later than pyrite and commonly replaces pyrite in all cases examined petrographically. Arsenopyrite occurs as fine to very fine grains disseminated in intrusive rocks and as fracture/vein fillings. Fine-grained arsenopyrite is difficult to distinguish from disseminated graphite in hand specimen and visual estimates may vary widely in accuracy. Marcasite is found as coatings on fine- and coarse-grained arsenopyrite.

Native arsenic occurs as dark gray, granular massive to reniform masses and grains commonly associated with stibnite in dolomite veinlets. Stibnite commonly occurs as disseminated grains and masses within carbonate veins and occasionally as interlocking needles up to 0.08 by 1 in (2 mm by 2–3 cm) in size in open spaces within quartz–carbonate veins and on fracture surfaces. Stibnite replaces arsenopyrite in at least some cases and stibnite-dominant mineralization is most common in sedimentary rock-hosted veins.

Sphalerite occurs as rare, scattered grains associated with stibnite in carbonate veins. Galena, tetrahedrite, and sphalerite are found in sedimentary heavy mineral concentrates (Chryssoulis and others, 1996). Realgar and orpiment occur as vein and fracture fillings in late, crosscutting structures (±quartz) and locally replace sericite casts of feldspar phenocrysts. Graphite may be deposited last because it typically fills open spaces and fractures, but there is not a clear relationship to other mineralization.

Gold mineralization at Donlin Creek is refractory, with arsenopyrite as the dominant gold-bearing mineral. Geochemical results indicate the affinity of gold with arsenic and antimony. Metallurgical tests indicate that 95–98 percent of the gold in the Lewis area is contained in arsenopyrite. Fine-grained arsenopyrite (<20 mm diameter) contains 5–10 times more gold than coarse-grained arsenopyrite (Chryssoulis and others, 1996). Visible gold is extremely rare at the Donlin Creek property and has only been found at the Far Side prospect in association with thin quartz veins cutting rhyodacite porphyry. Gold observed in polished thin sections occurs as 1 to 3 mm blebs with no clear paragenetic relationship to other minerals (John McCormack, 1996, unpublished petrographic report for Placer Dome).

MINERALIZATION ZONES

Gold mineralization at Donlin Creek occurs over a remarkable 4-mi-long (6.5-km-long) area with a northeast–southwest trend. Mineralization is open at depth and to the northeast and west. Figure 1 shows 12 prospects, mostly aligned in a northeast-southwest direction along a rhyodacite dike system. Most prospect names refer to the creek immediately north of the ridge on which they occur. From north to south, the prospect names are Far Side (formerly known as Carolyn or Wheetie), Dome, Duqum, Quartz, Snow, Queen, Lewis (further subdivided into Northeast, Southeast, Southwest, Vortex, and Rochelieu areas), 400 Area, and ACMA. The bulk of recent exploration work has been conducted in the Queen, Lewis, and ACMA areas.

Gold mineralization at Donlin Creek is lithologically and structurally controlled. Ore mineralization in igneous rocks is controlled by disseminated arsenopyrite, shear/fracture coatings, and sulfide (pyrite, arsenopyrite, and/or stibnite) ± quartz ± carbonate veinlets. Structurally controlled mineralization typically occurs in the Kuskokwim sedimentary rocks proximal to dike and sill contacts. Quartz–carbonate–sulfide (pyrite, stibnite, and arsenopyrite) veins are the primary mineralized features, but gold mineralization also occurs in thin, discontinuous veinlets and fracture fillings. Veinlets seldom exceed 0.5 in (1 cm) in diameter and most fracture fills are just thin sulfide coats on fracture surfaces. Realgar and orpiment with local high gold values occur as late-stage fracture filling in sediments and intrusive rocks crosscutting other mineralized structures. Realgar and orpiment are locally disseminated in rhyodacite.

Mineralization is open to depth and along strike in the Lewis/Rochelieu area. Figure 5 is a cross-section through the Northeast Lewis and Rochelieu areas. The ore zones are concentrated near rhyodacite bodies, but there is not a one-to-one correlation. Ore zones are offset and discontinuous along portions of their strike length due to faults, shearing, and local rock competency differences. Mineralization occurs in two main structural domains within the Queen to ACMA areas (the main bulk mineable resource). A series of north-northeast-trending dikes and faults with a subordinate northwest fabric occurs in the Northeast Lewis/Rochelieu area whereas north-northeast-trending structures crosscutting northwest-trending dikes, sills, and structures dominate the Southeast and Southwest portions of the Lewis areas and the ACMA area.

In the Rochelieu area, three mineralized zones over a 1,000-ft-wide (300-m-wide) area can be traced for 2,000 ft (600 m) in a northeast direction. The zones are 35 to 70 ft (10–20 m) thick, dip 45°–60° to the southeast and average 0.058 to 0.12 oz/ton (2–4 g/tonne) gold. Mineralized zones are hosted in graywacke, shale, rhyodacite with sheared margins, and a rhyodacite dike.

The Northeast Lewis area contains four mineralized zones controlled by normal faults having minor displacement that can be traced for approximately 1,600 ft (500 m) in a northeast direction. The ore zones vary in strike from 355° to 045° and dips range from vertical to -50°, both to the east and west. The ore zones are similar in thickness to zones described at Rochelieu, with the addition of a zone of variable thickness that is controlled by a low-angle fault subparallel to a rhyodacite/sedimentary rock contact. Factors that apparently controlled gold deposition include the presence of porphyry dikes or thick graywacke units and possibly flexures in structure orientations.

Mineralization at the Queen prospect is associated with northeast-trending rhyodacite dikes and north-northeast-trending faults that dip steeply to the southeast. Igneous lithologies are continuous from Northeast Lewis, and the known mineralization at Queen occurs over a 1,300 ft (400 m) strike length.

The south Lewis area has multiple controls on gold mineralization, with northeast-trending shear zones like those present at the north Lewis and Queen areas, as well as northwest-trending sills and faults. A cross-section of the south Lewis area is shown in figure 6. These multiple controls lead to discontinuous, discrete mineralization zones. Some of the thicker zones of mineralization appear to be southwest dipping. The thickest and highest-grade drill intercepts occur where north-northeast-trending structures intersect northwest-trending sills.

Several gold soil anomalies (>0.5 parts per million gold) occur over a 2.5 mi (4 km) strike length to the west of Lewis ridge in an area without rock exposure. Drilling in this area to the west of the Rochelieu area encountered several igneous bodies as well as several drill intercepts that assayed between 0.088 and 0.15 oz/ton (3–5 g/tonne) gold. Drilling proved that dikes occur west of the main Lewis Ridge and that gold mineralization also occurs within that area.

Rhyodacite bodies were exposed during trenching and excavation of road building materials in the 400 Area. These bodies are southwest of the Lewis area and approximately 2,600 ft (800 m) from previously known igneous rocks. These rhyodacite bodies have northwest strikes (~300°) and appear to be 30 to 70 ft (10–20 m) thick. Sericite-altered rhyodacite porphyry locally contains up to 0.23 oz/ton (8 g/tonne) gold. Drilling encountered significant gold mineralization hosted in quartz–pyrite–arsenopyrite–carbonate veinlets and local realgar veinlets within altered rhyodacite and immediate wallrocks.

Gold and arsenic have a fairly strong positive correlation, reflecting the occurrence of gold as sub-micron particles in the crystal lattice of arsenopyrite. Mercury and antimony correlate with gold to a lesser degree. There is a general inverse relationship between gold and sodium. Sodium loss is directly related to an increase in sericite alteration, and geochemical data from the Donlin Creek property indicate that gold values increase with increasing sericite alteration. Based on

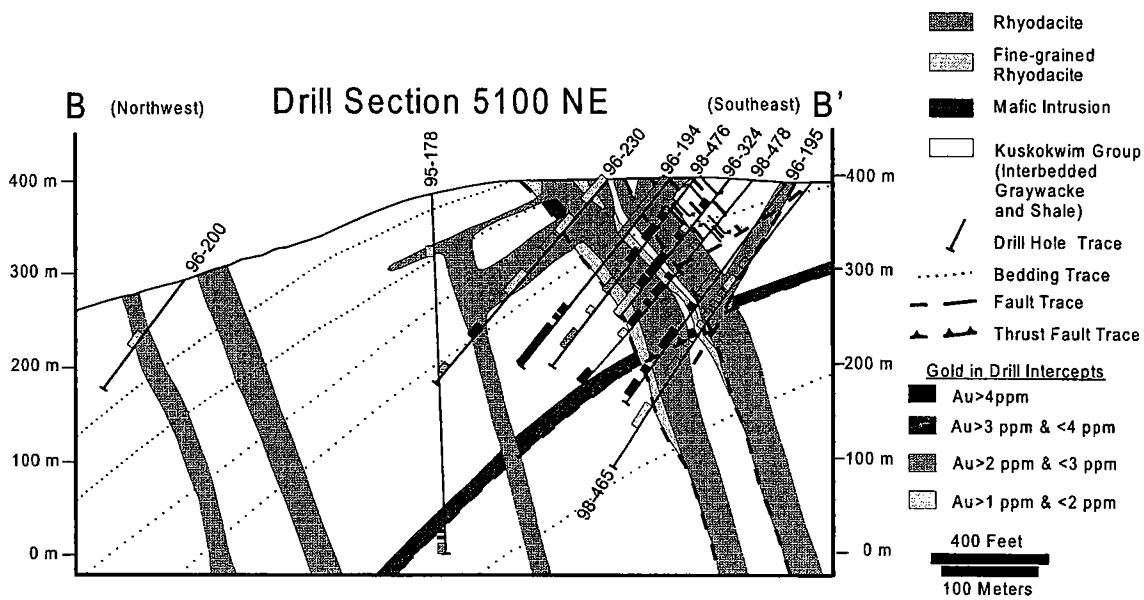


Figure 5. *Geologic cross-section through Lewis and Rochelieu prospects. Note the abundant dikes and high-grade gold intercepts associated with faults in the dikes.*

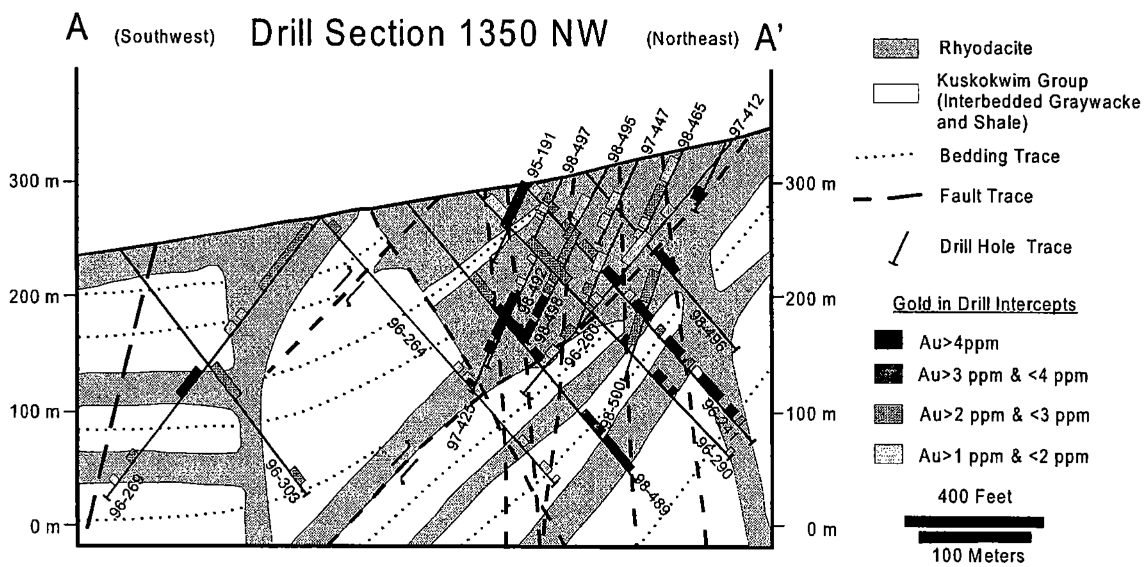


Figure 6. *Geologic cross-section through the Southeast and Southwest Lewis prospects. Note that rhyodacite occurs as both dikes and sills and most high-grade gold intercepts occur within faulted rhyodacite.*

silver:gold ratios and copper:gold ratios, it is inferred that a progressively deeper expression of a hydrothermal system is exposed from south (Lewis area) to north (Dome area).

Gold mineralization (especially ≥0.1 oz/ton [≥ 3 g/tonne] gold) at the Donlin Creek deposit is structurally controlled and, in the northeastern Lewis area, localized within a post-intrusion, small-displacement, normal fault system. Individual faults within this extensional system strike between 000° and 030° and dip predominantly toward the east, reflecting a syn-mineralization east-west extensional event. The majority of mineralization is hosted within an irregular swarm of rhyodacitic and subordinate mafic to intermediate sills and dikes of variable thickness and orientation. Mineralization is hosted, to a lesser degree, within massive graywacke.

Fault orientations commonly change as faults propagate through rock types of varying competence and composition (Ramsay and Huber, 1987). Faults dip more shallowly in incompetent units and steepen abruptly in more competent units. Dilation zones are created around the steeper segments of the faults. At Donlin Creek, dips of the normal faults may change from relatively shallow to relatively steep as the fault propagates from shale to rhyodacite or graywacke. A dilation zone and possible ore shoot may form as a result of this geometry.

Resultant high-grade ore shoots may be localized along these normal faults, where they steepened and dilated as they cut through more competent rock types such as rhyodacite and graywacke. Figure 7 depicts an idealized fault geometry and mineralization pattern. However, the inherent variability of a small-displacement fault system combined with the highly irregular geometries of a dike swarm will create a large degree of variability in the orientation of ore shoots, and likely relatively low degrees of continuity.

A model for structural control of gold mineralization at Donlin Creek is given in figure 7. Competency differences between various rock units are important factors in localization of gold mineralization. The brittle response of igneous rocks and graywacke to stress allows for more fracturing and creation of space for movement of ore fluids. Shale and siltstone tend to act more ductilely under stress and absorb stress by bedding plane movements, restricting the amount of open space for later fluid flow. Shale horizons may have acted more ductilely than the interbedded graywacke and magmatic fluids flowed along shale horizons to produce sills capped by thick shale units.

FLUID INCLUSIONS

A systematic fluid inclusion study at Donlin Creek has not been conducted, but observations have been made on three occasions on separate sets of samples. Results are consistent among sample sets and significant to understanding more about the deposit's origin. Table 3 summarizes observations made during these fluid inclusion studies. Measured vapor phase homogenization temperatures for two-phase, liquid-rich, primary fluid inclusions in vein quartz range from 150° to 260°C (Roberts, 1993; table 3). Crushing tests reveal abundant vapor bubble expansion, indicating a minimum of 0.1 mole percent CO_2 (Roberts, 1993). Porphyry and epithermal attributes (vein textures and various phases within fluid inclusions) were identified (Roberts, 1993), but the fluid inclusions were generally too small for microthermometric work.

Jim Reynolds (Fluid Inc., Denver) conducted preliminary qualitative fluid inclusion work in 1996 for Placer Dome Exploration Inc. Secondary fluid inclusions in igneous quartz phenocrysts are interpreted to broadly record temperature and fluid characteristics associated with hydrothermal fluids responsible for pervasive sericitic alteration. Pervasive sericitic alteration of rhyodacite porphyry at Lewis, Rochelieu and Queen is interpreted to form from dilute fluids in a hydrothermal system with temperatures probably between 200° and 350°C (table 3). Shallow, late quartz ± carbonate ± stibnite ± realgar veinlets, with local associated high gold values, have an inconsistent fluid inclusion population with abundant necking and few reliable primary fluid inclusions, features common in epithermal quartz (Bodnar and others, 1985). No daughter minerals were observed and temperatures of homogenization were estimated at below 200°C.

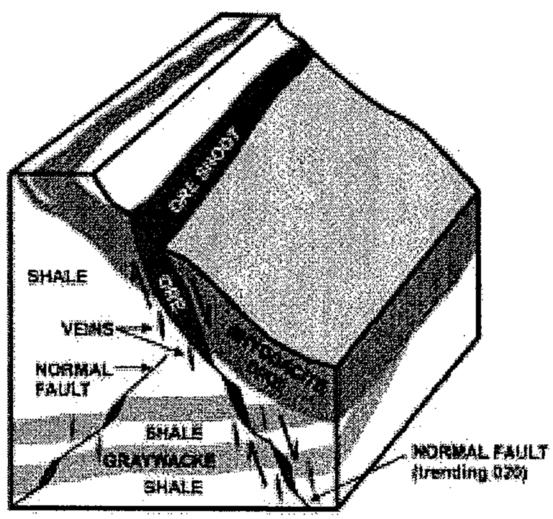


Figure 7. *Model for development of mineralization zones at Donlin Creek. Ore shoots developed in dilation zones along normal faults as the faults steepened in rocks such as rhyodacite and graywacke, which are more competent than the shale units.*

Table 3. *Donlin Creek fluid inclusion data*

Prospect sample no.	Sample description	Texture	%FIs	FI[a] sizes avg/max	FI[a] origin	FI shape	Number of phases	Estimated Temp (°C)	Measured[b] Temp (°C)	Interpretation	Reference[c]
Far Side TR-CT1-20m	*Breccia vein at least 5 cm wide in feldspar–quartz porphyry with vein margin of prismatic quartz (1–2 mm wide). Vein matrix is very fine-grained quartz.*										1
	host wallrock	euhedral quartz "eyes" in dike	2	<1/10	S	irregular–smooth	2 l+v-rich and 3+multi-solid	?			
	fragments in vein	euhedral prismatic quartz with growth zones	20	<3	P	irregular–smooth	2 l-rich	<200	147–196		
	long, thin brecciated shards in breccia vein	plumose-textured quartz	25	<3	S	irregular–smooth	2 l-rich, rare 3+multisolid	<200	220 (270 multi-solid inclusions decrepitate)	hydrothermal fluid from an early, deep? event	
	breccia-vein matrix	euhedral clear quartz (recrystallized?)	<1	<1	P	irregular	2	<200			
	opaque fragment in breccia vein	microcrystalline quartz	?	?	S?	?	?	<160			
Snow TR-ST-5m	*Breccia vein over 7 cm wide with breccia fragments of stibnite-rich, angular quartz matrix and quartz porphyry.*										1
	grains interlocked with anhedral quartz and as cockade texture around porphyry rock fragments	plumose quartz (?after amorphous silica or chalcedony?)	10	10/25	S	smooth	2 l+v-rich and 3+multi-solid	?	216–260 (multi-solid inclusions decrepitate at >300)	early, saline (minimum 23 eq. wt percent NaCl) fluid	
	broken fragments of earlier vein event	anhedral quartz	2	<3	S	irregular	2 l-rich	?	?		
	infilling around breccia fragments	prismatic, euhedral quartz	2	<3	P	irregular–smooth	2 l-rich	~200	153		
Lewis TR-LT18-225m	*Thin (1–2 mm wide), translucent gray quartz vein cutting gray feldspar–quartz porphyry.*										1
	resorbed and broken phenocrysts, FI's along fractures	quartz "eyes" in porphyritic wallrock	10	6/30	PS/S	smooth	2 l+v-rich and rare 3+multi-solid, rare 3-phase CO_2-rich inclusions	?			
		quartz breccia fragments in wallrock	1	<1	PS?	irregular	?	<200			
		prismatic quartz in vein	<1	<1	P	irregular	?	<200			
	FIs along fractures	late, subhedral quartz vein infill	2–20	<3	PS/S	irregular–smooth	2 l-rich	<200			
Lewis TR-LT26-146m	*Highly iron-stained breccia vein over 10 cm wide, with fragments of pale green, feldspar–quartz porphyry and clear to translucent quartz.*										1
	resorbed and broken phenocrysts, FIs along fractures	quartz "eyes" in porphyritic wallrock	25	3/15	PS/S	smooth	2 l+v-rich and 3+multi-solid	?			
	fragments in vein breccia	anhedral, broken quartz crystals	5–15	<3	S	irregular–smooth	2 l-rich and 3-phase solid present	?	~220	formed at 1–3 km depth?	
	matrix of breccia vein	late, euhedral, comb-textured, drusy quartz	<1	<1	P	irregular, & irregular l-v ratios	2 l-rich	<200			
	FIs along fractures	subhedral quartz vug fill	5	<1	S	irregular, & irregular l-v ratios	2 l-rich	<200	93–101		
Rochelieu DC96-210B, 156.5 m	sericite-altered rhyodacite	igneous quartz phenocrysts	scarce	--	S	?	l-rich	275–300		dilute fluids in hydrothermal system	2
Queen DC96-240, 82.9 m	sericite-altered rhyodacite	igneous quartz phenocrysts	scarce	--	S	?	l-rich	275–300		dilute fluids in hydrothermal system	2
Southwest Lewis DC96-260, 148.6 m	sericite-altered rhyodacite	igneous quartz phenocrysts	scarce	--	S	?	l-rich	275–300		dilute fluids in hydrothermal system	2

Prospect sample no.	Sample description	Texture	%FIs	FI[a] sizes avg/max	FI[a] origin	FI shape	Number of phases	Estimated Temp (°C)	Measured[b] Temp (°C)	Interpretation	Reference[c]
Lewis DC96-261, 251 m	sericite-altered rhyodacite	igneous quartz phenocrysts	scarce	–	S	?	l-rich	275–300		dilute fluids in hydrothermal system	2
Southeast Lewis DC96-244, 82.9 m & 92.5 m, DC96-248, 148.6 m	sericite-altered rhyodacite with quartz ± carbonate ± stibnite ± realgar veinlets and high gold grades	abundant necking-down of FIs, few reliable primary FIs	inconsistent			irregular	no daughter minerals	<200		dilute, heated groundwater	2
Dome DC96-250, 131 m	sericite-altered rhyolite	igneous quartz phenocrysts with multiple microfractures	abundant		S		l-rich, v-rich, v-rich w/ hypersaline l	>400–450		formed close to magmatic fluid source	2
Dome DC96-251, 62.5 m	sericite-altered rhyolite with quartz stockworks						l+v-rich	>400–450		formed in zone near (typically above) a magmatic source	2
Dome ?(USGS)	sericite-altered rhyolite with quartz stockworks	low salinity, vapor-rich inclusions with significant CO_2+CH_4					2		350–400	represents early magmatic fluid	3
	sericite-altered rhyolite with quartz stockworks	high salinity, l-rich with 1 or 2 daughter minerals, halite melts above 450°–550°C					2–3		350–400	represents early magmatic fluid	3

[a]FI=fluid inclusion, l=liquid, v=vapor, P=primary, PS=pseudosecondary, S=secondary.
[b]Measured temperature is measured microthermometric homogenization by vapor-phase disappearance and represents the **minimum** estimated trapping temperature.
[c](1) Roberts, 1993, (2) Arribus, written communication, 1996, (3) McCoy and others, 1999.

Sericitized rhyolite with hydrothermal quartz stockwork mineralization from the Dome prospect has vastly different fluid inclusion characteristics. Fluid inclusions are abundant and present along multiple microfractures crosscutting quartz phenocrysts in all directions. Fluid inclusions at the Dome prospect consist of a vapor-rich CO_2-bearing type co-existing with a high-salinity, liquid-rich, halite-bearing type, with liquid–vapor homogenization for both types at 340–380°C (McCoy and others, 1999). Similar fluid inclusions are less common throughout the rest of the Donlin Creek property (preliminary results) and homogenize at 220–300°C. These fluid inclusions are interpreted to be similar to fluid inclusions found in the core zone of porphyry-type deposits. On the basis of observations of porphyry-type deposits, these fluid inclusions would form very close to magmatic fluid sources where both high-temperature hypersaline and vapor-rich inclusions often coexist due to phase separation of a residual aqueous magmatic fluid.

STABLE ISOTOPE STUDIES

Nine sericite samples from sericite-altered feldspar phenocrysts in rhyodacite were collected from across the Donlin Creek property for oxygen and hydrogen isotope analyses (table 4). Figure 8 shows the isotopic composition of calculated hydrothermal fluids responsible for sericite formation and the relationships between those fluids and magmatic and Alaskan Cretaceous–Tertiary meteoric waters. The temperature used for calculation of fractionation factors between water and illite (the main mineral in the sericite collected for analysis) is 300°C on the basis of secondary fluid inclusion observations in igneous quartz phenocrysts from the same samples. Given the higher temperature documented at Dome, water-illite fractionation factors for Dome are plotted at 400°C.

Fluids responsible for sericite alteration (and at least part of the mineralization) at Donlin Creek likely formed by mixing of magmatic water and meteoric water. The mixing trend is evident in figure 8. The largest apparent magmatic component of the stable isotope data is found in samples from the southern Lewis area as well as from Dome. On the basis of the available data, hydrothermal fluids at the Snow prospect are interpreted to have a larger meteoric water component than the south Lewis areas. Fluids from the Queen and Rochelieu prospects are intermediate between the other two groups.

The data are too limited to draw any more conclusions. It is unclear whether the Dome and Lewis prospects are part of the same hydrothermal system or separate systems. No fundamental isotopic differences are apparent between the Dome and Lewis prospects and the calculated hydrothermal fluids and alteration intensities are broadly similar. The geochemical signatures at Donlin Creek are like a classic phyllic zone of a porphyry-type deposit, with some features at the Dome prospect similar to the potassic zone (Zaluski and others, 1994). Further sampling at Donlin Creek within the mineralized system(s) and beyond the system(s) might help to define gradients within the paleo-hydrothermal system as well as the boundaries of one or more systems.

Several oxygen, hydrogen, and sulfur isotope analyses were obtained from samples of stibnite- and pyrite-bearing quartz veins in rhyodacite dikes and

Table 4. *Donlin Creek oxygen and hydrogen isotope compositions of sericite samples and calculated isotope ratios of associated water*

No.	Sample Number	Location	$\delta^{18}O$	δD	$\delta^{18}O_{H2O}$	δD_{H2O}
1	DC96-251@238m	Dome	+ 8.9	- 126	+ 5.4	- 101
2	DC96-250@131m	Dome	+ 4.5	- 144	+ 1.0	- 119
3	Snow (surface)	Snow	+ 5.8	- 151	+ 2.3	- 126
4	DC96-240@71m	Queen	+ 8.3	- 136	+ 4.8	- 111
5	DC96-266@411m	North Lewis	+ 6.6	- 143	+ 3.1	- 118
6	DC96-210B@156.5m	Rochelieu	+ 8.4	- 147	+ 4.9	- 122
7	DC96-204@174.5m	W. of Rochelieu	+ 5.8	- 146	+ 2.3	- 121
8	DC96-261@250.9m	SE Lewis	+ 11.3	- 117	+ 7.8	- 92
9	DC96-238@195m	SW Lewis	+ 12.5	- 106	+ 9.0	- 81
10[c]	USGS, Gray and others (1997)	Snow Gulch	+ 24.9, + 24.5	-181 (d)		

[a]Samples collected by Antonio Arribas, Jr., and analyzed by Geochron Laboratories (Cambridge, Massachusetts), except for #10. Analytical precision reported as better than ± 0.2 per mil ($\delta^{18}O$) and ± 5 per mil (δD).
[b]H_2O calculated for T = 300°C for all samples, except Dome = 400°C. Fractionation factors for sericite (illite/muscovite-water) from Sheppard and Gilg (1996).
[c]$\delta^{18}O$ values for quartz and dickite (d).

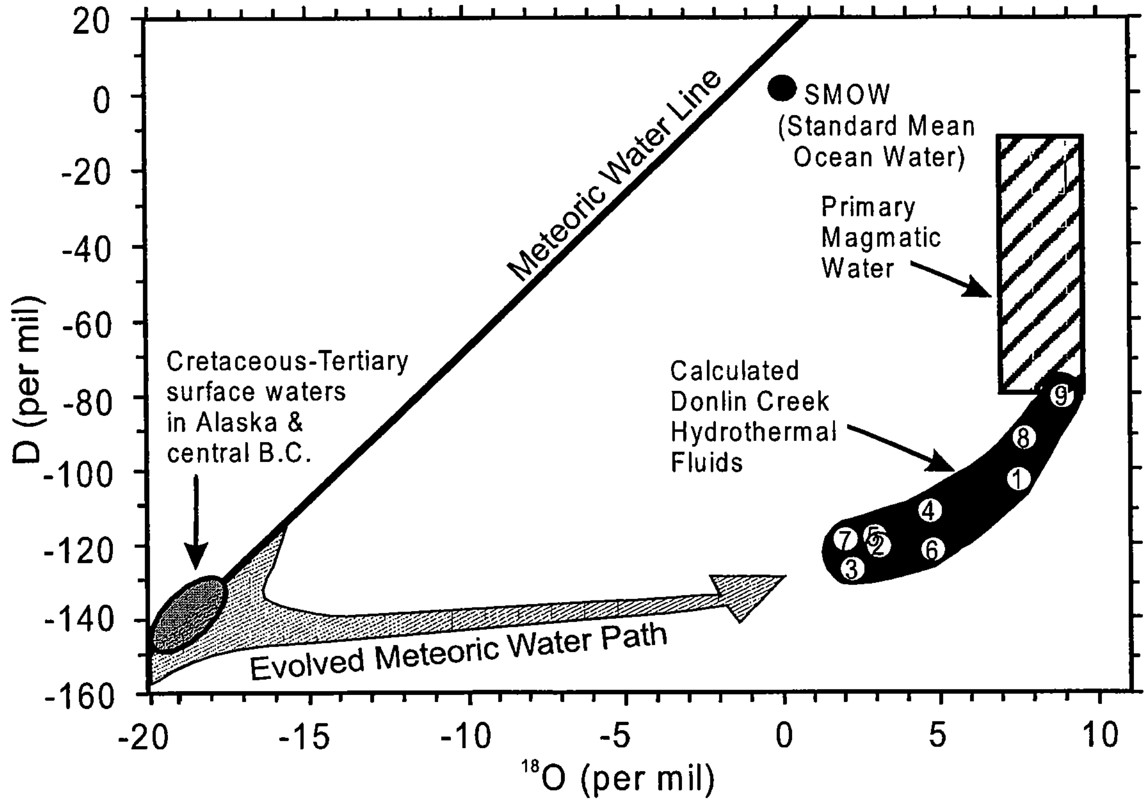


Figure 8. *A δD versus δ¹⁸O plot depicting stable isotope geochemistry of calculated Donlin Creek hydrothermal fluids. Numbers in circles correspond to samples listed in table 4. The stable isotope geochemistry of the Donlin Creek ore fluids can be formed by the interaction of evolved meteoric water with primary magmatic water. Diagram adapted from Taylor (1979) and primary magmatic water is defined somewhat arbitrarily as the calculated water isotopic composition in equilibrium with "normal" igneous rocks or magmas at temperatures greater than or equal to 700°C (Taylor, 1979). Field for Cretaceous–Tertiary surface waters in Alaska and central British Columbia from Zaluski and others (1994).*

graywacke and shale wallrock (Gray and others, 1997; Goldfarb and others, 1990). The heavy oxygen and light hydrogen isotope values are similar to whole rock oxygen isotope results from Kuskokwim Group samples (Gray and others, 1997). The authors concluded that hydrothermal fluids were derived from multiple sources and may be partially derived by the dehydration of surrounding sedimentary rocks. Values of $\delta^{18}O$ from sulfide-bearing quartz veins at Donlin Creek range from 11 to 25 per mil, and the isotopically heaviest values are associated with later, lower temperature sulfide stages (McCoy and others, 1999). The $\delta^{34}S$ values for sulfides from all ore stages are -10 to -20 per mil, with late stibnite values as light as -25 per mil, suggesting that at least some sulfur is derived from clastic sedimentary rocks (McCoy and others, 1999).

Preliminary carbon isotope data from Donlin Creek was obtained from a graphite bleb in rhyodacite porphyry exposed in a Southeast Lewis trench. The graphite had a $\delta^{13}C$ value of -22.8 per mil, similar to a $\delta^{13}C$ value of -21.9 per mil, from a felsic dike with graphite spots in the Sleetmute D-4 Quadrangle (Rich Goldfarb, 1997, written commun.). These carbon isotope values are consistent with reduced carbon (that is, graphite) $\delta^{13}C$ values in igneous rocks, but overlap with values of biogenic carbon (Faure, 1986). The isotope results are inconclusive as to whether the carbon is derived from inorganic or organic sources.

OTHER DONLIN CREEK PROSPECTS

Intrusion/sedimentary rock contact relationships and hydrothermal alteration and mineralization are roughly similar for the ACMA, 400 Area, Rochelieu, Lewis, Queen, Snow, Far Side, and Quartz prospects. The Dome and Duqum prospects share similar characteristics that are different from the above prospects.

FAR SIDE PROSPECT

The Carolyn prospect of WestGold was renamed the Far Side prospect by Placer Dome Exploration. The Far Side prospect is the northernmost prospect on the Donlin Creek property. It is near Quartz Gulch and is off-trend from other prospects. Bedrock exposures are limited to a placer cut in Quartz Gulch and shallow, slumped trenches. The only visible gold seen on the Donlin Creek property is present in quartz veins exposed in trenches and in core at the Far Side prospect. Soil samples collected by WestGold averaged 943 parts per billion gold, with a maximum value of 19.3 parts per million gold. Rhyodacite dikes mapped at the prospect by WestGold have northwest trends, unlike the northeast trend of dikes seen at most Donlin Creek prospects. Drilling by WestGold defined a northeast-trending mineralized zone at least 650 ft (200 m) long and up to 100 ft (30 m) wide, with a calculated gold resource of 38,400 oz (1,194 kg) (Retherford and others, 1989). Placer Dome drilled three core holes on the Far Side prospect during 1996 to test intersecting northwest-trending rhyodacite dikes, north-northeast-trending structures, and coincident strong gold anomalies in soil samples. Spotty, thin, high-grade gold intercepts were encountered in rhyodacite.

WestGold mapped a steeply dipping (approximately 84°) rhyodacite dike 80 ft (25 m) thick and trending 310° azimuth in the immediate lower Far Side area. A 50-ft-thick (15-m-thick) rhyodacite dike with a 40° east plunge occurs south of the above dike. Most mineralization and the only visible gold occur in the southern dike. Other dikes in the southwest portion of the Far Side prospect appear to trend east-west, but the dikes are thin and discontinuous. Sedimentary rocks in this area strike 110° and dip moderately shallowly to the northeast.

Shears noted in trenches and drill logs are semi-pervasive throughout the Far Side prospect. Also, left-lateral offset of the larger, more northerly rhyodacite dike and the dike orientation immediately south suggest an east-west trend to the tectonic fabric of the area. This shearing may have provided a weakened avenue for the smaller porphyry and mafic dikes to follow and could also explain the spotty higher gold values.

SNOW PROSPECT

Soil sampling by WestGold identified an extensive gold soil anomaly (average of 464 parts per billion gold in soils) along the northwest flanks of Snow Ridge (fig. 1). Trenching and shallow reverse-circulation drilling by WestGold in 1989 identified similar geology and mineralization to that found at Queen and Lewis to the southwest. WestGold identified a drill-indicated, kriged resource of 44,000 contained oz (1,368 kg) of gold with an average grade of 0.1 oz/ton (3.59 g/tonne gold) (Retherford and others, 1989). Both rhyodacitic dikes and sills are present and crosscut by north- and northeast-trending mineralized structures. Dikes have northeast trends and southeast dips. Northwest-trending sills containing anomalous gold values crop out to the north. Mineralization appears to be restricted to narrow high-grade structures. The Snow prospect contains the only oxidized ore resource found to date on the Donlin Creek property.

400 AREA PROSPECT

Mineralized rhyodacite at this prospect was discovered in 1996 at several material pits while excavating material for the Lewis Ridge–American Ridge main road and the Lewis Ridge–Snow Gulch road. The 400 Area Prospect straddles these two roads constructed in mostly wetlands without outcrop (fig. 1).

Structurally controlled gold mineralization is found along low-angle, northwest-striking, moderately southwest-dipping sills and bedding plane shears. A complex zone of layer-parallel shearing was intersected in American Creek during drilling. The bedding and structure relationships are consistent with deformational features identified as D1 in the Donlin Creek area. In the 400 Area Prospect, the main mineralized unit is a rhyodacite sill. This sill is proximal to the American Creek fault, and most of the unit is logged as sheared or with abundant mineralized fractures (although it is unresolved if shearing is really from this particular fault). Mineralized veins strike north-northeast with steep dips both to the northwest and southeast. Although veins trend north-northeast, the mineralized package appears to closely follow the sill, probably due to competency contrasts in this area of high shearing. The sill is projected to intersect the surface just north of the American Ridge–Lewis road and, appears to branch down-dip into multiple thin sills to the south, still containing gold values, below the American Creek fault.

Numerous, generally thin (<15 ft [<4.5 m] wide) rhyodacite units found by drilling are not as well constrained as the main 400 Area Prospect sill. Drilling along the American Creek–Snow Gulch road penetrated what appears to be a northwest-trending rhyodacite dike, with a sill-like appendage. High-grade gold mineralization hosted in graywacke in drillhole intercepts is possibly due to a nearby mineralized rhyodacite sill not encountered in drilling. Mafic rocks encountered during drilling in the 400 Area Prospect are mostly thin sills that are generally unmineralized. However, a 65-ft-thick (20-m-thick), well-mineralized mafic dike with a northwest strike and moderate northeast dip was encountered in one drillhole.

AMERICAN CREEK MAGNETIC ANOMALY (ACMA) AREA

The American Creek Magnetic Anomaly (ACMA) area occurs on the south slopes of Lewis Ridge (fig. 1). The ACMA area measures 1 mi by 1,750 ft, or 0.33 mi ^{2} (1,700 m by 530 m, or 0.9 km ^{2}), with the long axis aligned nearly parallel to American Creek.

Airborne-magnetic data in conjunction with soil sampling data discovered and delineated mineralization in the ACMA area. Drilling in the area intersected sericite-altered rhyodacite porphyry (RDX) with up to 2 percent disseminated graphite. The dominant strike direction of bedding in the ACMA area is 125° with dips to the southwest and northeast. A map based on strike and dip direction of bedding on a hole-per-hole basis suggests an antiformal structure trending 290° or sub-parallel to American Creek. Sills are the dominant igneous style in ACMA and drilling has encountered two thick (in excess of 300 ft [100 m]) south-southwest-dipping sill packages formed by multiple sill-within-sill intrusions. Sills decrease in thickness to the east-southeast. Three dikes (north-northeast trending), up to 80 ft (25 m) thick, were also documented within the ACMA area.

Gold mineralization is associated with north-northeast-trending quartz–arsenopyrite–pyrite veinlets, fracture coatings of realgar, quartz–stibnite veinlets, and local disseminated acicular arsenopyrite hosted mainly within rhyodacite. Gold mineralization is structurally controlled by north-northeast striking structures with moderate southeast dips. The thickest ore zones occur where northerly structures crosscut rhyodacite.

DOME PROSPECT

The Dome prospect is the northeasternmost prospect on the property along the northeast trend of the Donlin Creek dike swarm (fig. 1), on the ridge between Quartz and Dome creeks. WestGold conducted soil sampling and trenching, but never drilled the Dome prospect. Placer Dome Exploration drilled the Dome prospect in 1996 and 1997. Drill targets were in one of the largest untested gold soil anomalies on the Donlin Creek property. Soil anomalies average 270 parts per billion gold, with a high value of 1,541 parts per billion gold (with coincident arsenic and mercury anomalies). Rock chip samples from trenches contained up to 10 parts per million gold.

The geology of the Dome prospect is distinct from most other Donlin Creek prospect areas. Kuskokwim Group sedimentary rocks have been hornfelsed to intermixed biotite hornfels and greenish gray calc-silicate hornfels adjacent to porphyritic rhyodacite and rhyolite. Some of the hornfels may be intermixed volcanoclastic units. The dominant igneous rock is a light gray to cream colored, quartz-eye rhyolite. Secondary biotite (potassic alteration) is present in the rhyolite dike in addition to ubiquitous sericite alteration. Igneous breccias and equigranular granodiorite are also present (observed only in core). Dikes exposed on the surface and in drill core at the Dome prospect do not appear to have enough volume to have hornfelsed the Kuskokwim Group sedimentary rocks. This observation suggests that there may be a more extensive plutonic body at depth.

Copper mineralization in the form of disseminated chalcopyrite and quartz–chalcopyrite veinlets occurs in altered intrusive rock and hornfels and appears correlative with elevated silver values. Disseminated pyrrhotite is common in both igneous and contact metamorphosed sedimentary units. Elevated gold values appear to be associated with disseminated and vein-controlled arsenopyrite and occur over broad zones (McCoy and others, 1999). Gold mineralization is "porphyry style" and hosted in both igneous and metamorphic/sedimentary rock types. Fluid inclusions from quartz veins indicate filling temperatures in excess of 400°C, suggesting a magmatic source for fluids and a porphyry-style setting for mineralization.

Much of the available geologic and geochemical data indicate that Dome prospect gold mineralization is part of the 4-mi-long (6.5-km-long) system extending northward from the Lewis prospect. Based on silver:gold ratios, it can be inferred that a progressively deeper expression of a hydrothermal system is exposed from south (Lewis areas) to north (Dome). Homogenization temperatures from fluid inclusion studies also indicate that the Dome prospect may be the deeper, hotter portion of the Donlin Creek hydrothermal system. Alternatively, it may be indicative of lateral fluid flow with Dome being closer to the hotter part of the hydrothermal system. Nevertheless, other evidence, such as the presence of younger rhyolite dikes and a hornfels aureole, suggests that the Dome prospect may be part of a different hydrothermal system, or a slightly younger, magmatic ± hydrothermal event has been superimposed on the Lewis–Dome system.

DUQUM PROSPECT

The Duqum prospect is the southwestern extension of the Dome prospect into Quartz Creek. The geology and mineralization styles are similar to the Dome prospect. Auger soil samples from this area contained up to 7 parts per million gold. Coincident gold, arsenic, and mercury soil anomalies and aeromagnetic anomalies in the Duqum area were drill-tested in 1997.

DONLIN CREEK DEPOSIT GEOCHRONOLOGY AND MODEL

Pervasive sericitic alteration occurs within rhyodacite intrusive rocks over a 4.3-mi by 1-mi (7-km by 1.5-km) area. This large area of alteration is evidence that an unusually large magmatic-hydrothermal system was active in the Donlin Creek area. Dike and sill emplacement and alteration are contemporaneous within limits of radiometric dating methods. It is possible that alteration occurred as a magmatic degassing event as the igneous bodies were emplaced near the paleosurface.

The Donlin Creek dikes represent a bimodal (felsic and mafic) assemblage. This assemblage, along with the general orientation of the dikes sub-parallel to north-northeast-trending normal faults, strongly suggests an extensional setting for magma emplacement. The morphology of igneous rocks at Donlin Creek as a dike swarm instead of the much more common Kuskokwim volcanoplutonic complex also suggests a relationship between extension and magmatism at Donlin Creek (R.J. Newberry, written commun., 1999).

Despite intrinsic mineralization variability, a positive one-to-one correlation has been established between fault density, alteration intensity, gold tenor, and intrusive rock thickness. Specifically, the thicker the intrusive body, the greater the fault density. The greater the fault density, the higher and more consistent the grade, and the more intense the alteration. It appears that the thickest intrusions are cut by the largest number of faults, resulting in the widest ore zones and most intense alteration zones.

Age dating, crosscutting relationships, and mappable features present in core and trenches suggest the following geologic and metallogenic chronology at Donlin Creek:

1. Deposition of Kuskokwim Group sediments in an elongate basin formed by wrench fault tectonics and lithification of these sediments during the mid-Cretaceous.
2. Lithification of the Kuskokwim Group rocks was followed by a major deformation event characterized by northward stratigraphic imbrication along south-dipping thrust faults.
3. Emplacement of intermediate to mafic dikes and sills (oldest), fine-grained rhyodacitic porphyry dikes, and rhyodacitic dikes and sills (youngest) in the Late Cretaceous/Early Tertiary, near the end of the major deformation event. Rhyolite dikes in the Dome area may be part of this igneous event or a slightly later, separate igneous event. Dikes likely followed structures subparallel to the regional grain.
4. Crystallization of rhyodacitic rocks was closely followed by sericite and carbonate alteration accompanied by pyrite–arsenopyrite–gold mineralization. Mineralization occurred almost contemporaneously with emplacement of the intrusions as a magmatic-hydrothermal system concentrated gold within a volatile-rich magma. The hydrothermal system led to pervasive sericite alteration of the intrusions and deposition of gold–arsenic mineralization.
5. East-west extension and development of north-trending normal faults occurred during and after emplacement of the intrusive units.
6. Mixed magmatic and meteoric fluids remobilized and deposited gold accompanied by graphite and arsenopyrite in shears.
7. The latest mineralization event deposited gold + stibnite + realgar + native arsenic ± quartz ± carbonate in open spaces within igneous and sedimentary rocks.
8. Faulting occurred throughout the deposit history, but significant post-mineralization faulting is not recognized in the Lewis area of the Donlin Creek property.

ACKNOWLEDGMENTS

The authors are grateful to Placer Dome Exploration Inc. for permission to publish this paper. The data presented in this paper are the result of many people from Placer Dome, Calista Corporation, and The Kuskokwim Corporation working together on the Donlin Creek project. Thanks are especially extended to Rich Moses, Darren O'Brien, and David Barnett for insightful discussions and careful analysis of the plethora of data generated during exploration efforts at Donlin Creek. Placer Dome Exploration's research group provided gold resource calculations. All of the geologists who logged drill core over the years at Donlin Creek are thanked for their consistently detailed observations. Roland Bartch and Mark O'Dea of Steffen, Robertson and Kirsten provided critical structural observations and interpretations. Thanks also are due to Rainer Newberry and Melanie Werdon for their technical reviews that significantly improved the final version of this paper.

REFERENCES

Bodnar, R.J., Reynolds, T.J., and Kuehn, C.A., 1985, Fluid inclusion systematics in epithermal systems, *in* Berger, B.R., and Bethke, P.M., eds., Geology and geochemistry of epithermal systems: Reviews in Economic Geology, v. 2, p. 73–97.

Bundtzen, T.K., and Gilbert, W.G., 1983, Outline of geology and mineral resources of upper Kuskokwim region, Alaska, *in* Proceedings of the 1982 symposium on western Alaska geology and resource potential: Journal of Alaska Geological Society, v. 3, p. 101–117.

Chryssoulis, Stephen, Kafritsa, Gina, and Wong, Clarissa, 1996, Deportment of gold in the Donlin Creek ores: unpublished Advanced Mineral Technology Laboratory (London, ON, Canada) report 96/11, 34 p.

Decker, John, Bergman, S.C., Blodgett, R.B., Box, S.E., Bundtzen, T.K., Clough, J.G., Coonrad, W.L., Gilbert, W.G., Miller, M.L., Murphy, J.M., Robinson, M.S., and Wallace, W.K., 1994, Geology of Southwestern Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska, The Geology of North America: Boulder, Colorado, Geological Society of America, v. G-1, p. 285–310.

Faure, Gunter, 1986, *Principles of Isotope Geology:* New York, John Wiley and Sons, 589 p., ISBN 0-471-86412-9.

Goldfarb, R.J., Gray, J.E., Pickthorn, W.J., Gent, C.A., and Cieutat, B.A., 1990, Stable isotope systematics of epithermal mercury–antimony mineralization, southwestern Alaska, *in* Goldfarb, R.J., Nash, J.T., and Stoeser, J.W., eds., Geochemical Studies in Alaska by the U.S. Geological Survey, 1989: U.S. Geological Survey Bulletin 1950, p. E1–E9.

Gray, J.E., Gent, C.A., Snee, L.W., and Wilson, F.H., 1997, Epithermal mercury–antimony and gold-bearing vein lodes of southwestern Alaska, *in* Goldfarb, R.J, and Miller, L.D., eds., Mineral Deposits of Alaska: Economic Geology Monograph 9, p. 287–305.

Gray, J.E., Goldfarb, R.J., Snee, L.W., and Gent, C.A., 1992, Geochemical and temporal conditions for the formation of mercury–antimony deposits, southwestern Alaska: Geological Society of America Abstracts with Programs, v. 24, no. 5, p. 28.

McCoy, D.T., Dodd, S.P., Arribas, Jr., Antonio, Miller, M.L. Goldfarb, R.J., and Szumigala, D.J., 1999, Geology and geochemistry of the Donlin Creek gold deposit, southwestern Alaska (abs): GSA Cordilleran Section Centennial, Geological Society of America Abstracts with Programs, v. 31, no. 6, p. A-78.

McCoy, D.T., Newberry, R.J, Layer, P.W., DiMarchi, J.J., Bakke, A.A., Masterman, J.S., and Minehane, D.L., 1997, Plutonic-related gold deposits of Interior Alaska, *in* Goldfarb, R.J, and Miller, L.D., eds., Mineral Deposits of Alaska: Economic Geology Monograph 9, p. 191–241.

Miller, M.L., and Bundtzen, T.K., 1994, Generalized geologic map of the Iditarod quadrangle, Alaska, showing potassium–argon, major-oxide, trace-element, fossil, paleocurrent, and archaeological sample localities: U.S. Geological Survey Miscellaneous Field Studies Map 2219-A, 48 p., 1 sheet, scale 1:250,000.

Miller, M.L., and Bundtzen, T.K., 1988, Right-lateral offset solution for the Iditarod–Nixon Fork fault, western Alaska, *in* Galloway, J.P., and Hamilton, T.D., eds., Geologic Studies in Alaska by the U.S. Geological Survey during 1987: U.S. Geological Survey Circular 1016, p. 99–103.

Moll-Stalcup, E.J., 1994, Latest Cretaceous and Cenozoic magmatism in mainland Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska, The Geology of North America: Boulder, Colorado, Geological Society of America, v. G-1, p. 589–620.

Newberry, R.J., McCoy, D.T., and Brew, D.A., 1995, Plutonic-hosted gold ores in Alaska; igneous vs. metamorphic origins, in Ishihara, Shunso, and Czamanske, G.K., eds., Proceedings of the Sapporo international conference on mineral resources of the Northwest Pacific Rim, Shigen Chishitsu: Resource Geology Special Issue No. 18, p. 57–100.

O'Dea, M., 1997, Structural controls on gold mineralization at the Donlin Creek deposit, southwest Alaska: unpublished Etheridge Henley Williams Geoscience Consultants report, 59 p., 22 figs., 19 trench maps, 3 sheets.

Patton, W.W., Jr., Box, S.E., Moll-Stalcup, E.J., and Miller, T.P., 1994, Geology of west-central Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska, the Geology of North America: Boulder, Colorado, Geological Society of America, v. G-1, p. 241–269.

Ramsay, J.G., and Huber, M.I., 1987, *The techniques of modern structural geology, Volume 2, Folds and fractures*: London, U.K, Academic Press Ltd., 462 p. ISBN: 0-12-576902-4.

Retherford, R.M., Graff, P., and Hinderman, T.K., 1989, Donlin Creek project (Alaska) 1989 exploration program final report: unpublished Western Gold Exploration and Mining Company Ltd. report, 186 p., 7 appendices, 52 sheets, various scales.

Roberts, Paul, 1993, Report on trench mapping and sampling, Donlin Creek Project: unpublished Teck Exploration Ltd. report, 37 p., 4 sheets.

Sheppard, S.M.F., and Gilg, H.A., 1996, Stable isotope geochemistry of clay minerals; the story of sloppy, sticky, lumpy and tough: Clay Minerals, v. 31, no. 1, p. 1–24.

Streckeisen, A.B., and LeMaitre, R.W.L., 1979, A chemical approximation to the modal QAPF classification of the igneous rocks: Neues Jahrbuch für Mineralogie Abhandlungen., v. 136, no. 2, p. 169–206.

Szumigala, David J. 1997, Donlin Creek Project—1996 summary report of exploration activities: unpublished Placer Dome Exploration Inc. report, 2 vols., 5 sheets, 114 p.

Szumigala, D.J., 1996, Gold mineralization related to Cretaceous–Tertiary magmatism in west-central Alaska—A geochemical model and prospecting guide for the Kuskokwim region, *in* Coyner, A.R., and Fahey, P.L., eds., Geology and ore deposits of the American Cordillera: Reno, Nevada, Geological Society of Nevada Symposium Proceedings, p. 1317–1340.

Szumigala, D.J., 1993, Gold mineralization related to Cretaceous–Tertiary magmatism in the Kuskokwim Mountains of west-central and southwestern Alaska: University of California, Los Angeles, Ph.D. dissertation, 301 p.

Taylor, H.P., Jr., 1979, Oxygen and hydrogen isotopes in hydrothermal mineral deposits, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits: New York, John Wiley & Sons, 798 p., ISBN 0-471-05056-3.

Zaluski, Gerard, Nesbitt, Bruce, and Muehlenbachs, Karlis, 1994, Hydrothermal alteration and stable isotope systematics of the Babine porphyry Cu deposits, British Columbia—implications for fluid evolution of porphyry systems: Economic Geology, v. 89, no. 7, p. 1518–1541.