

GOLD-SULPHIDE ENRICHMENT PROCESSES IN MESOTHERMAL VEINS OF THE SIXTYMILE RIVER AREA, YUKON TERRITORY, CANADA

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ABSTRACT

The upper Sixtymile River area is located approximately 128 km west of Dawson City, Yukon. Lithology in this area consists of Precambrian to Paleozoic metamorphic rocks, Paleozoic ultramafic rocks, Middle Jurassic pegmatite and aplite dykes, Late Cretaceous porphyritic dykes and volcanic rocks with intercalated sedimentary rocks, Quaternary alkaline basaltic dykes and Quaternary alluvial sediments.

Gold bearing, mesothermal quartz-(carbonate)-sulphide veins which trend NNE-SSW are hosted by metamorphic rocks north and south of Sixtymile River.

The mesothermal quartz-(carbonate)-sulphide veins are surrounded by successive envelopes of sericitic, K-feldspar and propylitic alteration. Two stages of vein mineralization are recognized in the northern part of the area, and three stages are recognized in the south part.

In the northern veins, pyrite, arsenopyrite, pyrrhotite and quartz are intergrown and formed first. These minerals are fractured and healed by second stage minerals, which include galena, sphalerite, chalcopyrite, pyrite, carbonate and minor quartz.

Stage I mineralization in the southern veins is represented by quartz, and pyrite containing inclusions of other sulphides. Stage II is the main stage of precious metal enrichment, represented by arsenopyrite and galena which contain tetrahedrite, miagryrite and polybasite exsolutions. Stage I and II minerals are tectonically fractured, and healed by pyrite, sphalerite, chalcopyrite, freibergite and quartz of stage III. In both vein systems, gold enrichment is associated with arsenopyrite and silver enrichment is associated with galena. The evolution of hydrothermal fluids in the northern area is characterized by decreasing temperature (330°C to 280°C), salinity (12.8% wt.-% to 6 wt.-% NaCl equiv.), oxygen activity ($\log a(O_2) = -30$ to $\log a(O_2) = -35$), and sulphur activity ($\log a(S_2) = -10$ to $\log a(S_2) = -12$), as well as a slight increase in pH range (from $>3.1 - <5.2$ to $>3.3 - <5.4$).

In the southern vein system the fluid evolution characterized by a decrease in temperature (330°C to 150°C), salinity (18.3 wt.-% to 10 wt.-% NaCl equiv.), oxygen activity ($\log a(O_2) = -29$ to $\log a(O_2) = -52$), and sulphur activity ($\log a(S_2) = -9$ to $\log a(S_2) = -18$), as well as a slight increase in pH range ($>3.2 - <5.3$ to $>4.1 - <5.9$).

The following conclusions can be drawn about the fluid composition and mineral enrichment process in the fossil geothermal system of the Sixtymile River area. Deep seated fluids which circulated in the metamorphic rocks were characterized by high temperatures (above 300°C), high salinities (about 18 wt.-% NaCl equiv.) and pH values between 3.1 and 5.2. These fluids are similar to alkaline chloride fluids of active geothermal systems. Arsenic was transported as $H_2AsO_3^-$, gold as $Au(HS)_2^-$ and lead, zinc, iron, copper as $MeCl_2^0$ complexes. The first stage mineralization resulted from reaction of these deep-seated fluid with the wall rock. Second and third stage mineralization is believed to result from the mixing of two fluids with different physico-chemical characteristics.

RÉSUMÉ

La région du cours supérieur de la rivière Sixtymile est située approximativement à 128 km à l'ouest de Dawson City au Yukon. La lithologie de cette région consiste en roches métamorphiques précambriennes à paléozoïques, en roches ultramafiques paléozoïques, en dykes pegmatitiques et aplitiques du Jurassique moyen, en dykes porphyriques et roches volcaniques avec roches sédimentaires intercalaires du Crétacé supérieur, en dykes basaltiques alcalins quaternaires et en sédiments alluviaux quaternaires.

Les filons aurifères «mésothermaux» avec quartz-(carbonate)-sulfures qui sont orientées NNE-SSW se trouvent dans les roches métamorphiques au nord et au sud de la rivière Sixtymile.

Les filons «mésothermaux» avec quartz-(carbonate)-sulfures sont entourés d'enveloppes successives d'altération séricitique, feldspatho-potassique et propylitique. Deux stades de minéralisation filonienne sont reconnus dans la partie septentrionale de la région et trois stades sont reconnus dans la partie méridionale.

Dans les filons septentrionaux, la pyrite, l'arsénopyrite, la pyrrhotine et le quartz sont enchevêtrés et se sont formés les premiers. Ces minéraux sont fracturés et ont été soudés les uns aux autres par les minéraux du deuxième stade incluant la galène, la sphalérite, la chalcopryrite, la pyrite, le carbonate et des quantités mineures de quartz.

Le premier stade de minéralisation des filons méridionaux est caractérisé par le quartz et la pyrite qui renferment des inclusions d'autres sulfures. Le deuxième stade est le principal stade d'enrichissement en arsénopyrite et en galène avec exsolutions de tétrahédrite, de miagyrite et de polybasite. En raison de mouvements tectoniques, les minéraux du minerai et de la gangue des stades I et II sont fracturés et ont été de nouveaux soudés les uns aux autres par de la pyrite, de la sphalérite, de la chalcopryrite, de la freibergite et du quartz du stade III. Dans les deux réseaux de filons l'enrichissement en arsénopyrite coïncide avec l'enrichissement en or et l'enrichissement en galène avec celui en argent.

L'évolution des fluides hydrothermaux dans la région septentrionale est caractérisée par une température (de 330 à 280 °C), une salinité (12,8 % à 6 % d'équivalent de NaCl en poids) une activité de l'oxygène ($\log a(O_2) = -30$ à $\log a(O_2) = -35$) et une activité du soufre ($\log a(S_2) = -10$ à $\log a(S_2) = -12$) à la baisse ainsi que par une légère augmentation de la plage des pH (de $> 3,1 - < 5,2$ à $> 3,3 - < 5,4$).

Dans le réseau méridional de filons, l'évolution des fluides hydrothermaux en fonction du temps est caractérisée par une température (de 330 à 150 °C), une salinité (18,3 % à 10 % d'équivalent de NaCl en poids) une activité de l'oxygène ($\log a(O_2) = -29$ à $\log a(O_2) = -52$) et une activité du soufre ($\log a(S_2) = -9$ à $\log a(S_2) = -18$) à la baisse ainsi que par une légère augmentation de la plage des pH (de $> 3,2 - < 5,3$ à $> 4,1 - < 5,9$).

L'on peut formuler les conclusions suivantes quant à la composition des fluides et quant au processus d'enrichissement en minéraux dans le réseau géothermal fossile dans la région de la rivière Sixtymile. Les fluides profonds sont caractérisés par des températures élevées (supérieures à 300 °C), une salinité élevée (environ 18 % d'équivalent de NaCl en poids) et des valeurs du pH comprises entre 3,1 et 5,2. Ces fluides sont similaires aux chlorures alcalins des réseaux géothermaux actifs. De l'arsenic a été transporté sous forme de $H_2AsO_4^-$, de l'or sous forme de $Au(HS)_2^-$ et du plomb, du zinc, du fer ainsi que du cuivre sous forme de complexes $MeCl_2$.

La précipitation des minéraux pendant le premier stade d'enrichissement a été causée par l'interaction des fluides avec la roche encaissante. Le processus d'enrichissement qui a suivi le premier stade de minéralisation dans les filons aurifères avec quartz-(carbonate)-sulfures de type «mésothermal» été déterminé par le mélange de deux fluides aux caractéristiques physiques et chimiques différentes.

INTRODUCTION

The upper Sixtymile River area (here referred to as Sixtymile River area) is located approximately 128 km (80 miles) west of Dawson City, Yukon, at an average latitude 64°00'N and longitude 141°45'W on N.T.S. map sheets 116C/2 and 115N/15 (Fig. 1). The area encompasses four tributaries of the Sixtymile River, as well as parts of Glacier and Little Gold Creek (Fig. 2). From southwest to northeast, the tributaries are Bedrock Creek, Mosquito Creek (south side), Miller Creek and Big Gold Creek.

At Miller Creek, Glacier Creek, Little Gold Creek and south of Mosquito Creek, NNE-SSW trending gold bearing quartz-(carbonate)-sulphide veins (MINFILE 116C 082, 116C 146, 116C 166 and 116N 39) are hosted by metamorphic rocks. At the mouth of Big Gold Creek and Miller Creek in the Sixtymile River valley, gold-bearing disseminated, stockwork and vein-type sulphide mineralization occurs in Carmacks Group volcanics (MINFILE 116C 153, 115N 041)(Glasmacher and Friedrich, 1985).

The occurrence of two types of gold-bearing mineralization in the area prompted a detailed study of the

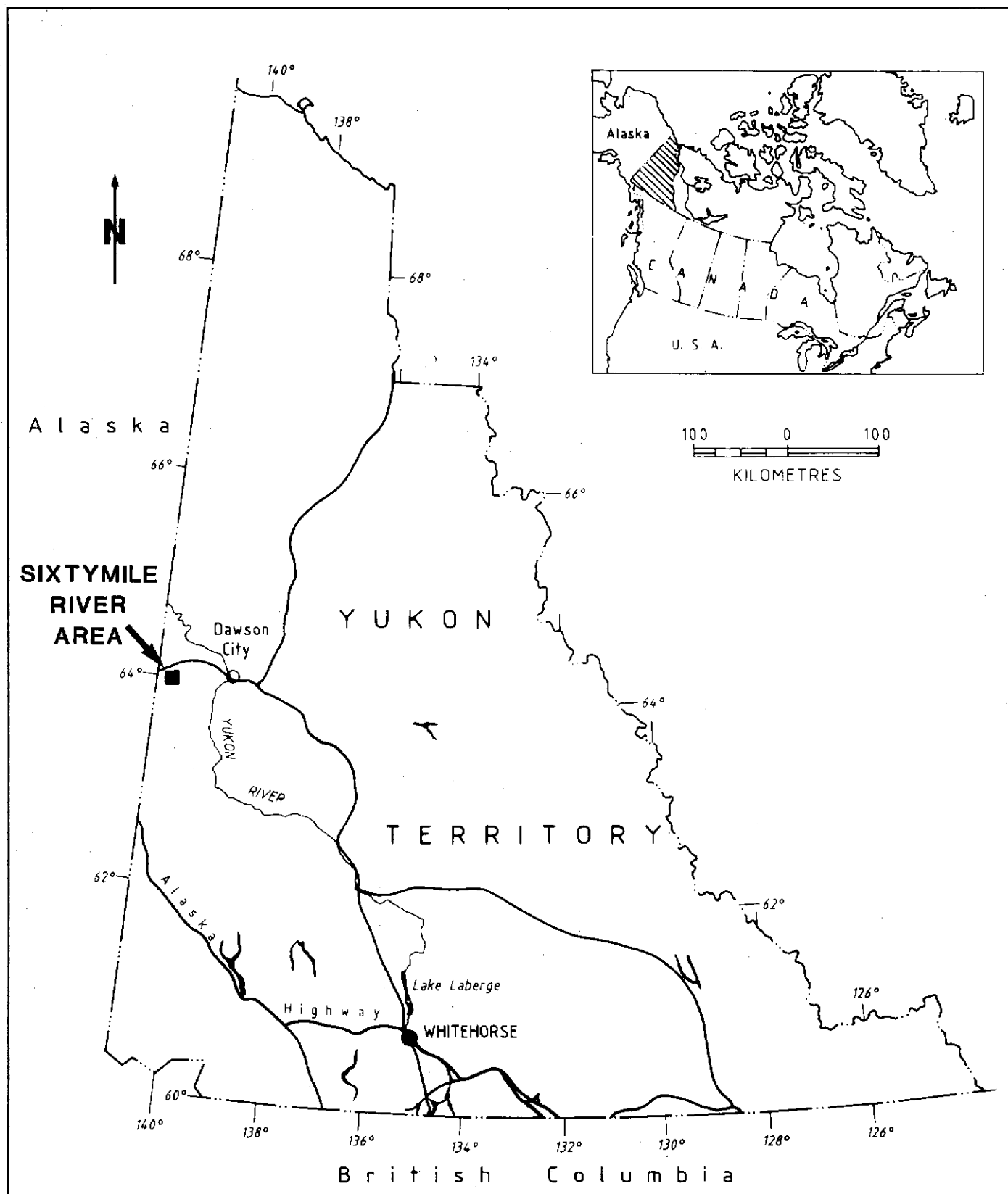


Figure 1. Location of the Sixtymile River area.

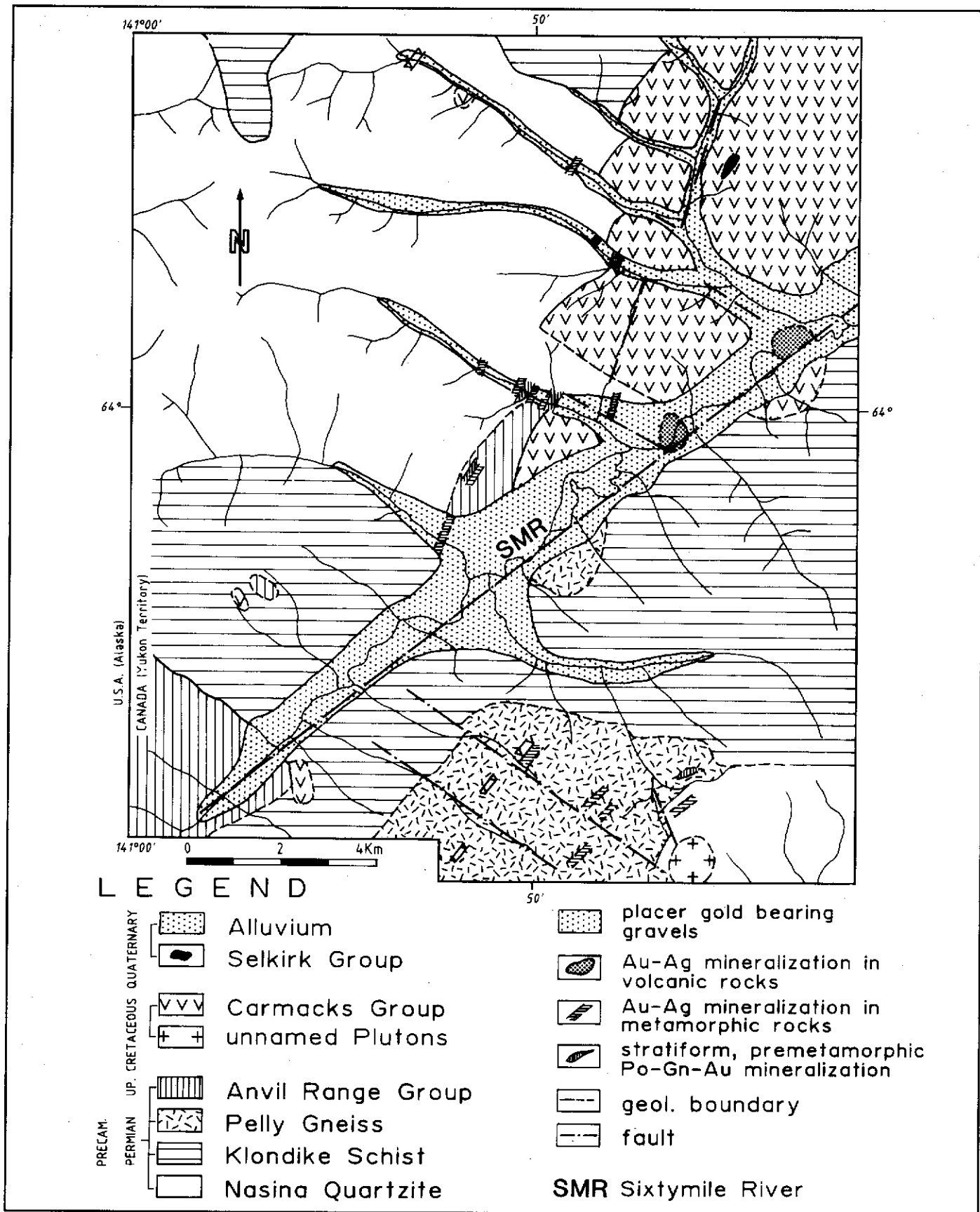


Figure 2. Geological map of the Sixtymile River area (partly compiled after Cockfield, 1921).

enrichment processes, using ore petrology, fluid inclusion and isotope studies. The field work was carried out as part of the Canada/Germany Science and Technology Exchange Program.

The chemical compositions of ore, gangue and alteration minerals were obtained by using an ARL-SEM-Q electron microprobe. Natural and synthetic sulphides, oxides and silicates were used as standards. Full details of the analytical technique are given in Glasmacher (1991). On-line data reduction used a modified Magic IV (Colby, 1968). Detailed mineral compositions are reported in Glasmacher (1991). Names of gangue and alteration minerals follow the classification scheme of Deer et al. (1979).

Microthermometric data was obtained using a Chaixmeca (MIM 85) heating/freezing stage. The determination of pH ranges is based on thermodynamic calculations presented in Henley et al. (1984).

Stability fields of ore minerals in $\log a(\text{O}_2)$ - pH and $\log a(\text{S}_2)$ - $\log a(\text{O}_2)$ diagrams were calculated for the physico-chemical conditions of the different enrichment stages. Thermodynamic data bases are described in Barton (1969), Barton and Skinner (1979), Craig and Barton (1973), Haas and Robbie (1973), Helgeson (1969, 1979), Henley et al. (1984), King et al. (1973), Rau et al. (1973a, 1973b), Richardson and Jeffers (1952), Toulmin and Barton (1964), and Schneeberg (1973). By analogy with similar hydrothermal mineralization (Creede, Colorado, Roedder et al., 1963, Baron et al., 1977) and active geothermal systems (Henley and Hedenquist, 1986, Mann et al., 1986) a total sulphur concentration of $\Sigma\text{S}=0.02\text{M}$ was assumed.

GEOLOGY

The Precambrian to Paleozoic metamorphic basement in the Sixtymile River area is interpreted as part of the Yukon Tanana Terrane (Monger, 1984; Fig. 3). Based on the tectonic features of the metamorphic basement south of Tintina Fault, Tempelman-Kluit (1974; 1976; 1979) assigned part of Yukon Tanana Terrane and Stikine Terrane to "Yukon Cataclastic Complex". During Upper Cretaceous and Lower Tertiary, the crustal evolution of the Stikine and Yukon Tanana Terranes was influenced by subduction processes further to the southwest (Monger et al., 1972; Monger et al., 1982). Tholeiitic calcalkaline and shoshonitic magmas were generated above a northeast-dipping subduction zone, (Armstrong, 1988). High local heat flow caused by these magmatic activities initiated the development of hydrothermal systems.

Today, gold and sulphides precipitated from these fossil geothermal systems occurs in mesothermal gold-bearing quartz-(carbonate)-sulphide veins hosted by metamorphic rocks and gold-bearing skarns (Meinert, 1986) or in gold-bearing epithermal mineral occurrences hosted by volcanic rocks (Morin and Stroschein, 1987; Sinclair, 1986; Fig. 4). Regionally, most Yukon gold occurrences appear to be located

in areas which are underlain by allochthonous terranes (Morin and Downing, 1984).

Due to tectonic and lithostratigraphic differences, the Sixtymile River area has been divided into a northern and a southern part. The boundary is represented by the Sixtymile River fault zone, which strikes east-northeast.

Lithologic units in the northern area comprise Precambrian to Paleozoic metamorphic rocks, Paleozoic ultramafic rocks, Middle Jurassic pegmatitic and aplitic dykes, Upper Cretaceous porphyry dykes and volcanic rocks with intercalated sedimentary rocks, Quarternary alkaline basaltic dykes and Quarternary alluvial sediments (Glasmacher and Friedrich, 1985, Hughes and Morison, 1986; Fig. 2; Table 1). Metasedimentary rocks with minor metavolcanic layers are assigned to the Nasina Series, and metavolcanic rocks with minor metasedimentary layers are assigned to the Klondike Schist. Biotite-amphibole orthogneiss of unknown age is discordant to the Nasina Series and Klondike Schist. Serpentinized ultramafic rocks occur along thrust faults (Mortensen, personal communication) and are possibly linked to the Anvil Range Group.

Muscovite from one of the northeast-southwest trending pegmatitic to aplitic dykes yielded a K/Ar age of 180 Ma (Mortensen, 1988), the same age as rocks of the Klotassin Suite. Calcalkaline volcanic rocks of intermediate composition are intruded by a quartz-feldspar porphyry plug dated at 68 ± 0.3 Ma, (Mortensen, 1988), and are assigned to the Upper Cretaceous Carmacks Group. They are intercalated with sedimentary rocks. Northwest-southeast trending andesitic dykes are possible feeders to the Carmacks Group volcanics. Quarternary alkaline olivine basalts are the youngest igneous rocks in the area.

Metamorphic rocks in the southern area are similar to those in the northern area with the exception of the Pelly Gneiss (Late Devonian-Early Mississippian; Mortensen, 1988). This stratigraphic unit comprises mainly biotite augen gneiss with minor lenses of quartzite and garnet-mica schist. Magmatic rocks in the southern area include a calcalkaline, I-type biotite granodiorite intrusion and northeast-southwest trending andesite to dacite dykes. These dykes are possibly related to Carmacks Group volcanics in the northern area. Quarternary alluvial sediments occur in all valleys.

MINERALIZATION

Northern Area

Gold bearing quartz-carbonate veins in the northern area are hosted by metamorphic rocks and occur along north-northeast trending faults. The veins are lensoid, average 50 cm thick, and are often discontinuous. In the underground placer mine on Miller Creek, quartz-carbonate veins occur along the same structures as the Late Cretaceous volcanic rocks.

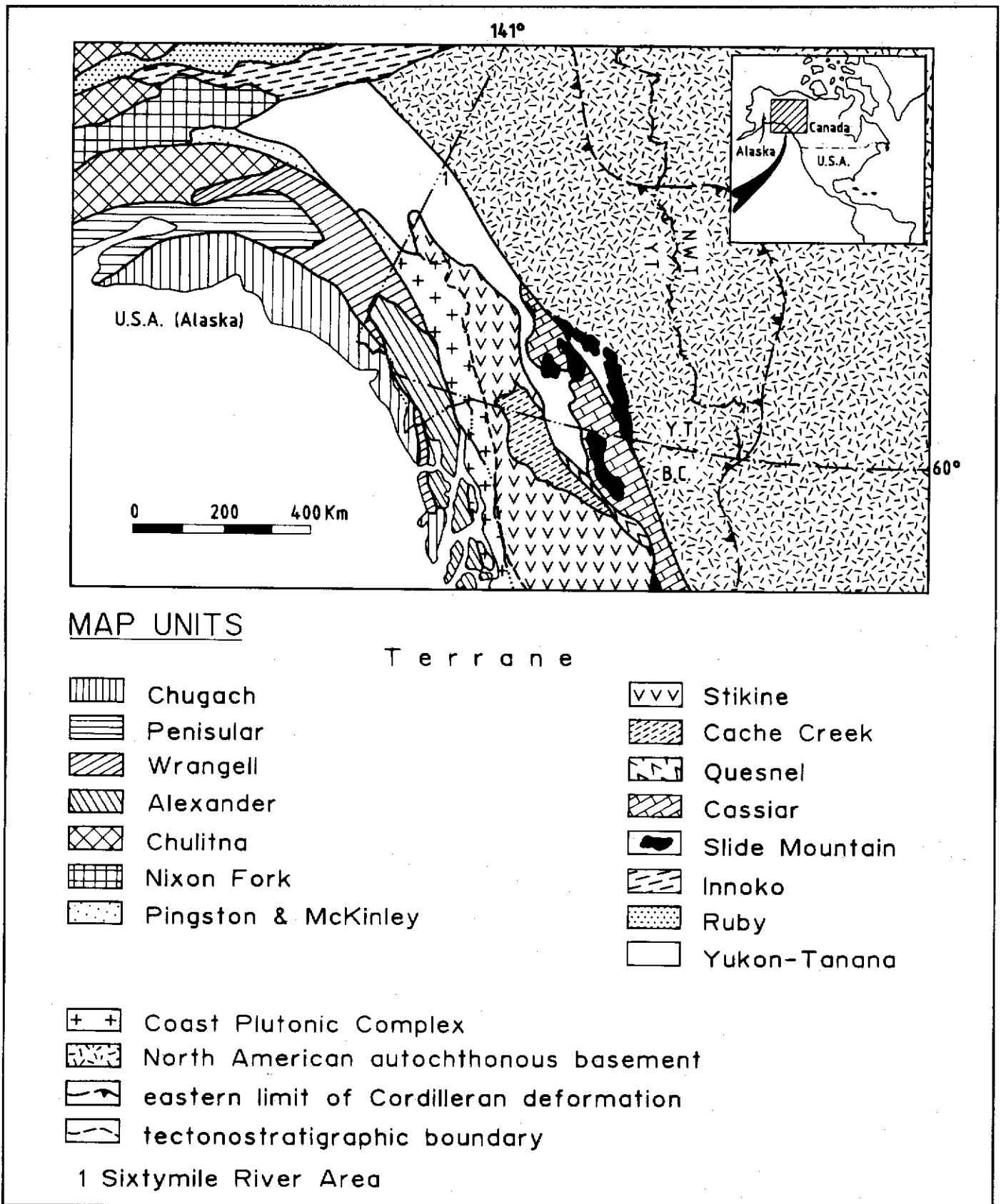


Figure 3. Recent distribution of terranes in the northern Cordillera and adjacent parts of Alaska (compiled after Coney, 1980; Tempelman-Kluit, 1981; Monger, 1984).

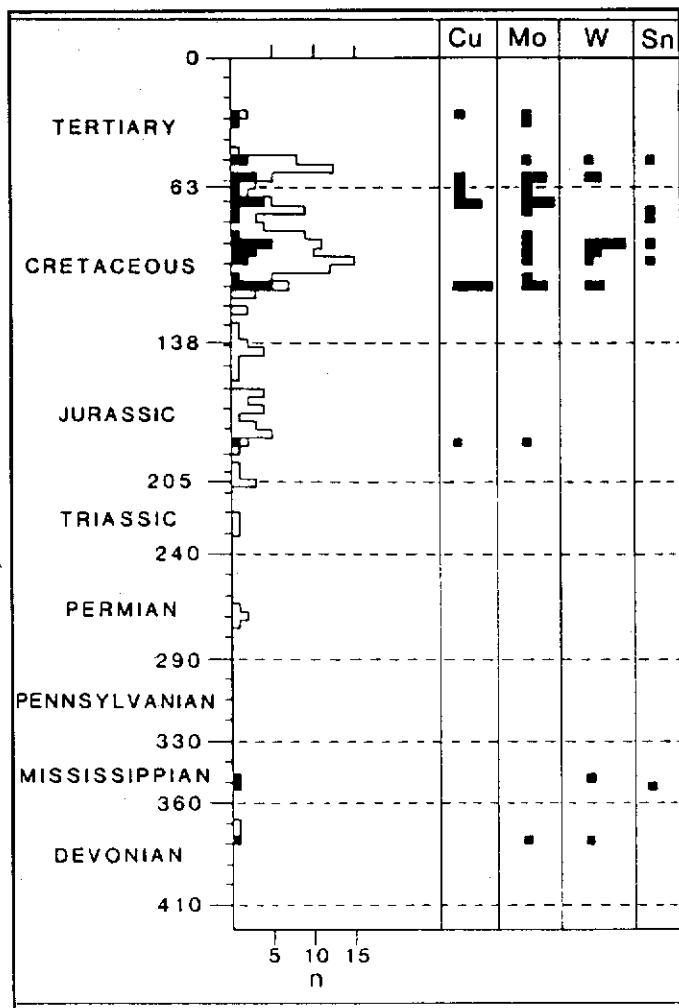


Figure 4. Radiometric ages of granitoid rocks in the northern Cordillera and adjacent parts of Alaska. Shaded areas represent the ages of intrusions with associated mineral deposits; unshaded areas are ages of intrusions unrelated to any known deposits. The ages of Cu, Mo, W and Sn mineralization are inferred from the ages of associated intrusions (after Sinclair, 1986).

Petrology and mineral composition

Based on structural features of and intergrowth relationships of the vein minerals, the paragenetic sequence has been subdivided into two enrichment stages (Table 2). Intergrown pyrite, arsenopyrite, pyrrhotite and quartz formed during the first stage. Stage I minerals are fractured and healed by Stage II galena, sphalerite, chalcopyrite, pyrite and carbonate and minor quartz. Stage I pyrite replaces magnetite in the wall rock and is surrounded by Stage II pyrite. Gold is detectable only by geochemistry and is confined to stage I. High gold content is related to high arsenic content in quartz-carbonate-sulphide samples.

Pyrite in both the veins and in the wall rock contained no gold above detection limit (DL = 0.06 wt.-%). Pyrite of

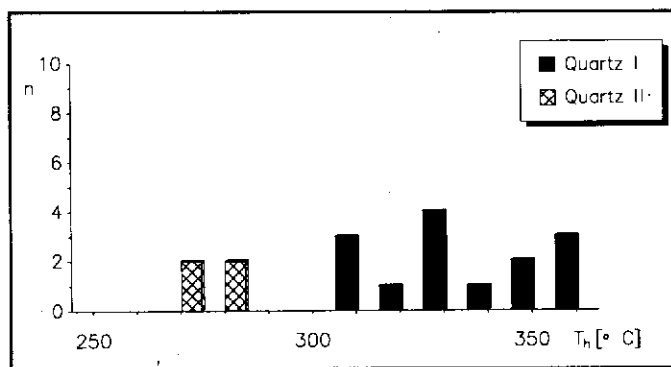


Figure 5. Histogram showing the frequency distribution of homogenization temperatures of fluid inclusions in quartz (gold bearing quartz-carbonate-sulphide veins in the northern area).

Stage I is enriched in cobalt (0.15-0.64 wt.-%) and nickel (0.08 - 0.16 wt.-%) relative to the wall rock, and is intergrown with arsenopyrite. It contains up to as 0.50 wt.-% As.

The average arsenic content of arsenopyrite is 30.25 at.-% As. The proportions of cobalt (<0.08 wt.-%) and nickel (<0.06 wt.-%) are low. Microprobe analyses along a traverse across arsenopyrite grains did not reveal any distinct zonation. Arsenic ranges from 29.45 to 31.20 at.-% and cobalt and nickel range from 0.03 to 0.05 at.-%. Work by Kretschmar and Scott (1976) suggests that a local fluctuation in sulphur and arsenic activity or disequilibrium between arsenopyrite, pyrite and pyrrhotite during their growth can cause this type of variation.

In galena, bismuth (0.16 to 1.3 wt.-%) and silver (0.07 to 0.54 wt.-%) are the only trace elements above detection limit (0.03 wt.-% Sb).

Sphalerite is characterized by high FeS (21.71 - 23.46 mol.-%) and manganese (0.46 - 0.85 wt.-%) as well as low cadmium content (0.17 - 0.35 wt.-%). Erratic copper distribution is caused by small chalcopyrite inclusions.

Siderite, magnesio-siderite, ferromagnesite and ankerite are the main gangue minerals of stage II. The trace element content of ankerite shows a distinct variation which depends on the galena/sphalerite ratio in the veins. Where galena is the main sulphide component, ankerite contains an average of 1.29 wt.-% PbO and a 1.25 wt.-% MnO. ZnO and SrO are below detection limit. Where sphalerite is the major mineral, the ankerite has a lower lead and manganese content (<0.05 wt.-% PbO; avg: 0.81 wt.-% MnO) a higher zinc and strontium content: (up to 0.43 wt.-% ZnO; avg: 0.12 wt.-% ZnO and up to 0.15 wt.-% SrO). Because the Stage II minerals crystallized simultaneously, these results suggest that manganese has a stronger affinity for sphalerite and/or siderite (which may contain up to 11 wt.-% MnO) than for ankerite.

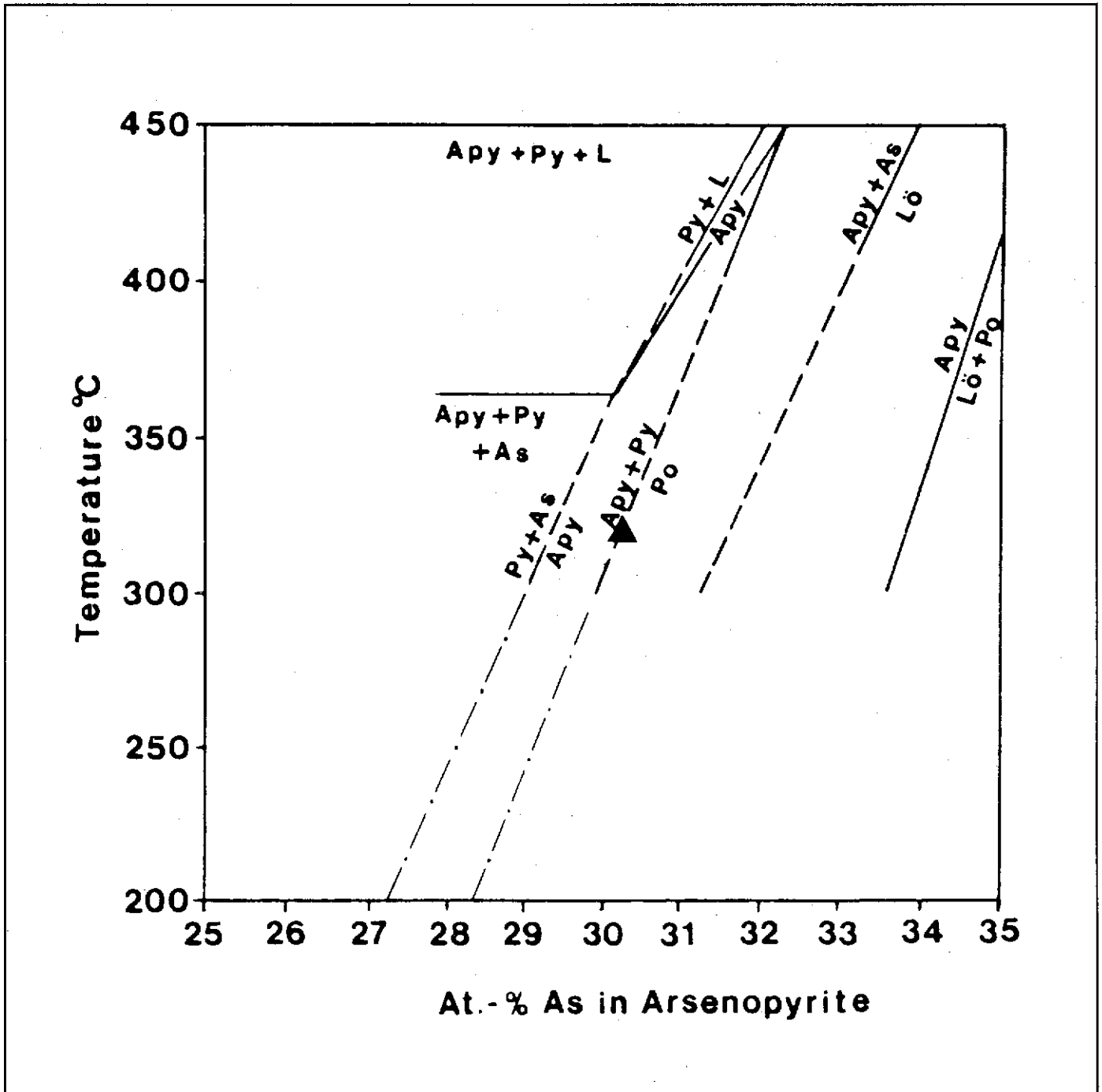


Figure 6. Arsenopyrite composition as a function of temperature and bulk composition (▲ arsenopyrite of the gold bearing quartz-carbonate-sulphide veins in the northern area; stability fields after Kretschmar and Scott, 1976).

Wall rock alteration and mineral composition

Each quartz-carbonate-sulphide vein is surrounded by an irregular zone of sericitic alteration which grades outwards into an alteration zone dominated by K-feldspar (Table 3). In the sericitic alteration zone, pyrite replaces magnetite, and sericite and quartz replace K-feldspar. In the K-feldspar zone, sericite, quartz and minor K-feldspar replace epidote and chlorite. An outer propylitic zone, which is also irregular in

shape, is characterized by pyrite and chlorite replacement of biotite, epidote and sericite replacement of plagioclase, and as epidote and chlorite replacement of amphibole.

Microthermometry

Microthermometric studies were carried out on fluid inclusions in quartz crystals of both enrichment stages. Stage I quartz contains both primary and secondary inclusions,

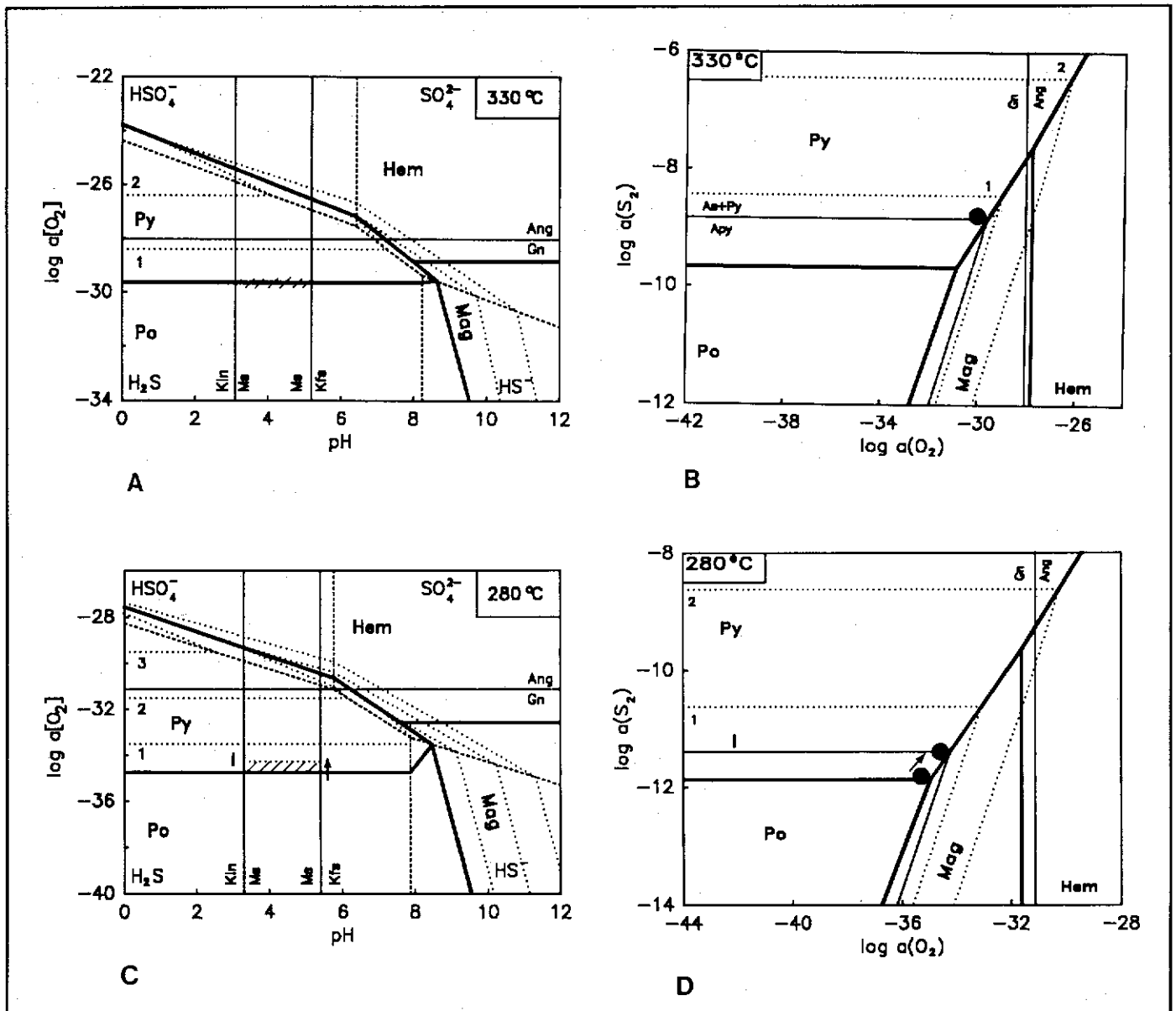


Figure 7. Log $a(\text{O}_2)$ -pH and log $a(\text{S}_2)$ -log $a(\text{O}_2)$ diagrams of the mineralization stages in the gold bearing quartz-carbonate-sulphide veins in the northern area (//// field of enrichment; ---> direction of change in physico-chemical conditions, I = sphalerite containing 24 mol.-% FeS; Mineral abbreviations follow Kretz, 1983).

whereas Stage II quartz contains only primary inclusions. Stage I inclusions gave homogenization temperatures between 308°C and 353°C with a maximum at 325°C and a salinity of 12.8 wt.-% NaCl-equivalent (Fig. 5). Fluid inclusions along microfractures in Stage I quartz yielded homogenization temperatures similar to fluid inclusions in Stage II quartz, which homogenize between 270°C and 280°C and have a salinity of 6 wt.-% NaCl equivalent.

Physical and chemical conditions

Based on the mineral paragenesis arsenopyrite-pyrite-pyrrhotite (stage I) and the arsenopyrite thermometer of Kretschmar and Scott (1976), the arsenic content (30.25 at.-%)

of arsenopyrite indicates an average temperature of 320°C (Fig. 6). This temperature is close to the homogenization temperature (325°C) of primary fluid inclusions in Stage I quartz. Calculations of pH, log $a(\text{O}_2)$ and log $a(\text{S}_2)$ conditions during Stage I are based on an assumed formation temperature of 330°C, although the actual temperature may have been higher. Because of the tectonic fracturing between Stage I and Stage II it is possible that the fluid pressure during stage II was hydrostatic rather than lithostatic. If so, only a small pressure correction would be necessary to calculate the true formation temperature. Based on this assumption, and the measured homogenization temperatures of fluid inclusions in Stage II quartz (270°C - 280°C), the physico-chemical

conditions during the second stage were calculated assuming a formation temperature of 280°C.

Using the equilibrium between K-feldspar and muscovite, and also between muscovite and kaolinite, the formation temperature, molarity and the mineral paragenesis of alteration zone III the pH range was calculated as:

Stage I	$3.1 < \text{pH}_{330^\circ\text{C}} < 5.2$	neutral $\text{pH}_{330^\circ\text{C}} = 5.7$
Stage II	$3.3 < \text{pH}_{280^\circ\text{C}} < 5.4$	neutral $\text{pH}_{280^\circ\text{C}} = 5.6$

The mineral paragenesis of Stage I is consistent with an oxygen activity of $\log a(\text{O}_2) \approx -30$ and a sulphur activity of about $\log a(\text{S}_2) \approx -10$ (Fig. 7A; Fig. 7B). The Stage II mineral paragenesis indicates that oxygen activity during stage II decreased from $\log a(\text{O}_2) = -35$ to $\log a(\text{O}_2) = -34$ and sulphur activity decreased from $\log a(\text{S}_2) = -12$ to $\log a(\text{S}_2) = -11$ (Fig. 7C; Fig. 7D).

Southern area

Gold bearing mesothermal quartz veins in the southern area are hosted by metamorphic rocks of the Pelly Gneiss unit and occur along north-northeast trending faults. These veins are often discontinuous and lenticular in shape and have an average thickness of about 70 cm. Some characteristic features of the veins include alternating quartz-sulphide bands, open-space fillings and idiomorphic zoned quartz crystals intergrown with sulphide minerals. Some of the veins show evidence of several phases of mineralization.

Petrology and mineral composition

Three stages of mineral enrichment have been distinguished (Table 4). Stage I minerals include quartz and pyrite with inclusions of bornite, galena with matildite exsolutions, chalcocopyrite with mackinawite ex-solutions, cubanite, native bismuth, pyrrhotite, sphalerite, tetrahedrite and quartz.

Stage II coincides with the main enrichment of arsenopyrite and galena with tetrahedrite, miagyrite and polybasite exsolutions. Quartz, and pyrite containing arsenopyrite and galena inclusions (with matildite exsolutions) occur in subordinate amounts. Gold enrichment is associated with the arsenopyrite, and silver enrichment is associated with the galenat. Both the Stage I and Stage II minerals are fractured as a result of tectonic movements which preceded Stage III mineralization. The fractures are healed by Stage III pyrite, zoned sphalerite (iron poor core - iron rich rim), chalcocopyrite, freibergite and quartz.

Gold was not detected in pyrite in any of the three stages (detection limit 0.06 wt.-% Au), but Stage II pyrite contains more arsenic (up to 2 wt.-%) than pyrite of stage I or stage III.

Arsenopyrite inclusions, which occur only in pyrite II, contain 27.66 at.-% arsenic, and return low trace element values (0.04 wt.-% Co, Ni, Sb; <0.11 wt.-% Cu; <0.04

wt.-% Ag). Arsenopyrite II, which is intergrown with pyrite and pyrrhotite, contains an average 29.03 at.-% As and a higher trace element content (<0.43 wt.-% Co; 0.09 wt.-% Ni; <0.34 wt.-% Cu; <0.50 wt.-% Sb).

High bismuth (<7.86 wt.-%) and silver (4.35 wt.-%) values in galena inclusions in pyrite I and II are caused by matildite exsolutions. In addition to the matildite ex-solutions, galena inclusions in pyrite II are characterized by high arsenic content (<1.21 wt.-%). Trace element variations (<0.49 wt.-% Bi; <0.78 wt.-% Ag; <1.79 wt.-% Sb) of galena II are caused by tetrahedrite, miagyrite and polybasite exsolutions.

From Stage I to Stage III there was a decrease in the iron content of sphalerite, from 20.22 mol.-% to 3.46 mol.-% FeS, and a decrease in manganese content from 0.20 wt.-% to 0.04 wt.-%. The iron content increased slightly to 5.77 mol.-% FeS during stage III. Cadmium content increased, from 0.34 wt.-% to 0.84 wt.-% between Stage I and Stage III, but decreased slightly to 0.66 wt.-% at the end of Stage III. Whereas the copper content of sphalerite I and II is below detection limit (0.04 wt.-%) sphalerite III contains significant copper (up to 0.42 wt.-%).

Wall rock alteration and mineral composition

Veins showing evidence of one, two or three mineral enrichment stages are surrounded by similar envelopes of wall rock alteration. Adjacent to the quartz-sulphide veins is a zone of sericitic alteration, where quartz is recrystallized, and K-feldspar is replaced by sericite and quartz (Table 5). Between the sericite alteration zone and the unaltered biotite augen gneiss is a zone of quartz-K feldspar-sericite alteration, followed by a zone of propylitic alteration. The quartz-K feldspar-sericite zone is characterized by the replacement of plagioclase and chlorite by sericite and quartz. In the propylitic zone, pyrite and rutile replace magnetite, biotite and muscovite replace chlorite and sericite replaces plagioclase.

Microthermometry

The cores of idiomorphic and zoned quartz crystals consist of Stage I quartz I, and the rims consist of Stage II quartz. Quartz of stages I and II is fractured, and healed by Stage III quartz. Primary fluid inclusions in Stage I quartz homogenize at about 275°C and indicate a salinity of 18.3 wt.-% NaCl equivalent (Fig. 8). Homogenization temperatures of primary fluid inclusions in Stage II quartz are about 205°C and the salinity of the fluid is 12 wt.-% NaCl equivalent. Primary inclusions in Stage III quartz and secondary inclusions in Stage I and II quartz return homogenization temperatures of about 145°C and salinity values of about 10 wt.-% NaCl equivalent.

Physico-chemical conditions

Based on studies done by Kojima and Sugaki (1985), Sugaki et al. (1982) and Yund and Kullerud (1966), the presence of chalcocopyrite-pyrrhotite, cubanite-pyrrhotite and cubanite-chalcocopyrite-pyrrhotite as inclusions in pyrite of stage I are consistent with formation temperatures above 325°C and $334 \pm 17^\circ\text{C}$, respectively. The difference between this

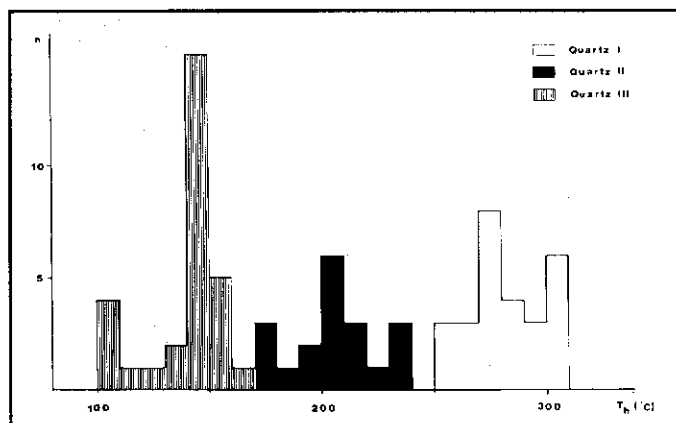


Figure 8. Histogram showing the frequency distribution of homogenization temperatures of fluid inclusions in quartz of the gold bearing quartz-sulphide veins in the southern area.

mineral formation temperature and the 275°C homogenization temperature of Stage I inclusions suggests a minimum fluid pressure of about 500 bar, based on the work of Potter (1977).

According to the studies of Scott and Barnes (1971), Scott and Kissin (1973) and Browne and Lovering (1973), the iron content (15 mol.-% FeS) of sphalerite II intergrown with pyrite indicates a formation temperature above 248°-260°C for the second stage mineralization. Following the same reasoning as the paragraph above, the minimum pressure for hydrothermal fluids of stage II is also about 500 bar. Evidence of tectonic fracturing between stage II and stage III suggests that the fluid pressure may have been hydrostatic at some point.

Using temperatures of 330°C for stage I, 280°C for stage II and 150°C for stage III, and with the additional assumption that the same mineral alteration occurred during each stage of mineralization, pH, log $a(\text{O}_2)$ and log $a(\text{S}_2)$ of mineral enrichment were calculated. The following pH ranges were obtained:

stage I	3.2 < pH _{330°C} < 5.3	neutral pH _{330°C} = 5.7
stage II	3.2 < pH _{280°C} < 5.2	neutral pH _{280°C} = 5.6
stage III	4.1 < pH _{150°C} < 5.9	neutral pH _{150°C} = 5.8

The change in mineral paragenesis during stage I from sphalerite (21 mol.-% FeS)-pyrrhotite-pyrite to native bismuth-pyrrhotite-pyrite indicates a decrease in oxygen activity from log $a(\text{O}_2) = -29$ to log $a(\text{O}_2) = -30$ and a decrease in sulphur activity from log $a(\text{S}_2) = -9$ to log $a(\text{S}_2) = -10$ (Fig. 9A; Fig. 9B).

Oxygen and sulphur activity continued to decrease during stage II. Early arsenic-bearing pyrite with arsenopyrite and galena inclusions was followed by the crystallization of sphalerite (15 mol.-% FeS)-pyrite-pyrrhotite and pyrite-pyrrhotite, indicating a change from log $a(\text{O}_2) = -31$ to log $a(\text{O}_2) = -35$ and log $a(\text{S}_2) = -11$ to log $a(\text{S}_2) = -12$ (Fig. 9C;

Fig. 9D).

The mineral paragenesis sphalerite (6 mol.-% FeS)-pyrite of stage III is consistent with an oxygen activity of log $a(\text{O}_2) = -53$ and a sulphur activity of log $a(\text{S}_2) = -18$ (Fig. 9E; Fig. 9F).

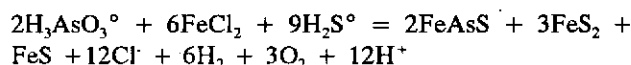
MINERAL ENRICHMENT PROCESS

Northern area

Although the physical and chemical conditions of both mineral enrichment stages lie within the stability fields of arsenopyrite, galena and sphalerite, arsenopyrite and gold enrichment occurred during stage I and galena, sphalerite and silver were deposited during stage II. Either the hydrothermal fluids of stage I were depleted in lead, zinc and silver, and the fluids of stage II in arsenic and gold, or these elements were transported as complexes with different stability conditions.

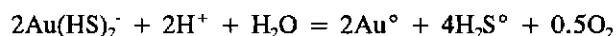
Heinrich and Eadington (1986) and Ballantyne and Moore (1988) described the transport of arsenic in hydrothermal solutions in terms of hydroxide ($\text{H}_3\text{AsO}_3^\circ$ and/ or $\text{H}_3\text{AsO}_4^\circ$) or bisulphide (HAsS_2°) complexes. Due to the physico-chemical conditions prevalent in most active hydrothermal systems, arsenic is transported as the $\text{H}_3\text{AsO}_3^\circ$ -complex. Transport of arsenic as a bisulphide complex is only possible at sulphur concentrations above $\Sigma\text{S} = 0.1\text{m}$. At very low pH and high salinities, arsenic is transported as a chloride complex.

Based on the assumptions above, an equilibrium reaction can be written which describes the coprecipitation of arsenopyrite, pyrite and pyrrhotite (**reaction 1**):



The solubility of arsenopyrite at a particular temperature depends on the oxygen and sulphur activity and pH (Fig. 10). Decreased oxygen activity, or increased pH and sulphur activity, cause precipitation of arsenopyrite.

In active hydrothermal systems under similar physico-chemical conditions, gold is transported as a gold-thio complex ($\text{Au}(\text{HS})_2^-$) up to a temperature of about 300°C (Seward, 1973; Seward, 1982; Henley et al., 1984; Henley and Brown, 1985). Above this temperature, the gold-chloride complex predominates (Henley, 1973). An equilibrium reaction describing the precipitation of gold can be written as follows (**reaction 2**):



As this reaction shows, the solubility of gold as a gold-thio complex increases with increasing pH and oxygen activity.

Seward (1976), Barnes (1979), Henley et al. (1984), Seward (1984), and Henley and Brown (1985), have described the transport of lead, zinc, copper and silver in active hydrothermal systems as a metal-chloride complex

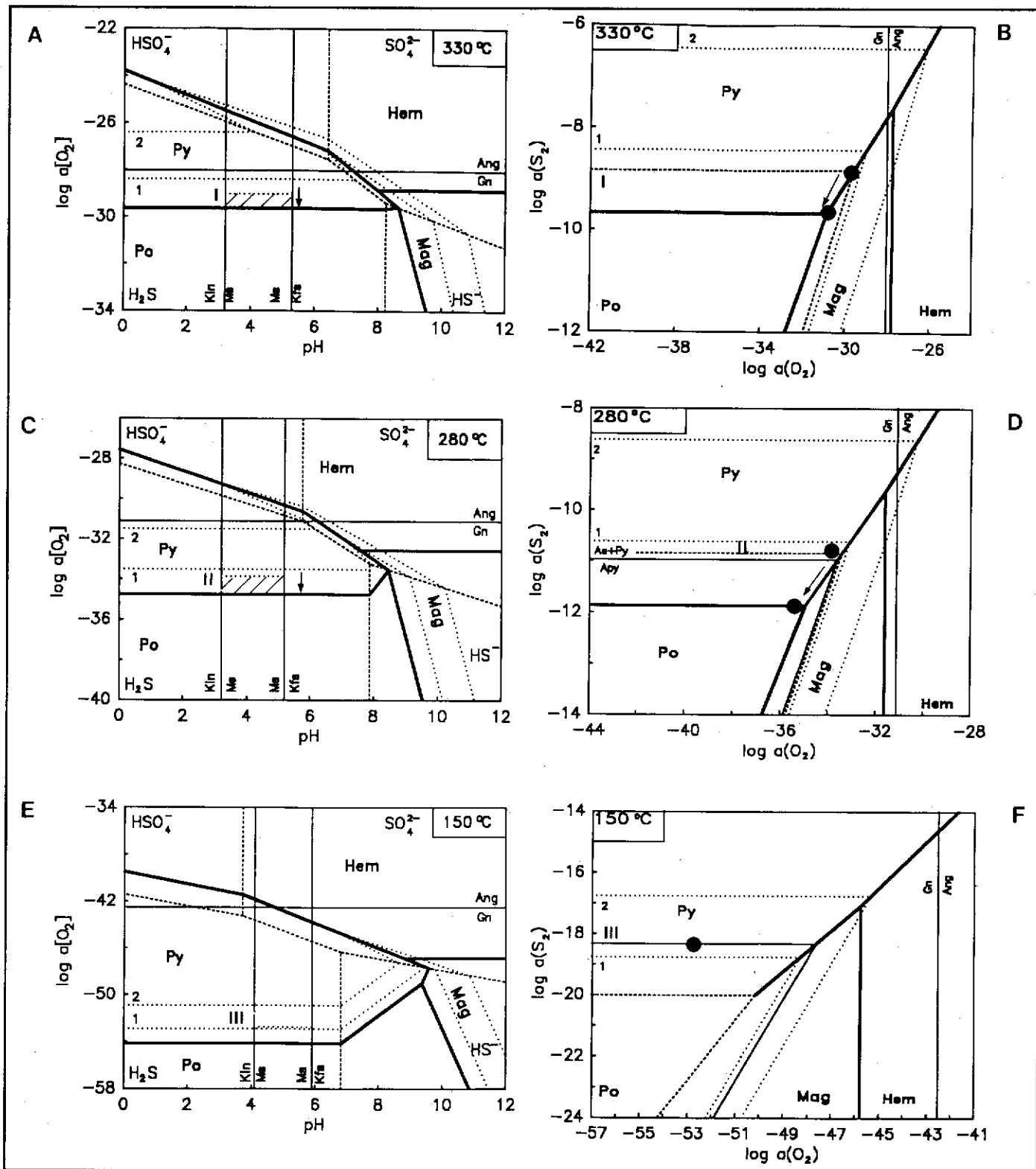
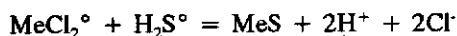


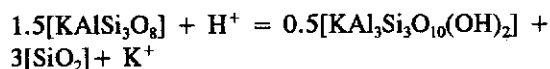
Figure 9. $\log a(\text{O}_2)$ -pH and $\log a(\text{S}_2)$ - $\log a(\text{O}_2)$ diagrams of the mineralization stages in the gold bearing quartz-sulfide veins in the southern area (legend as described in Figure 7; I = sphalerite containing 21 mol.-% FeS; II = sphalerite containing 15 mol.-% FeS; III = sphalerite containing 6 mol.-% FeS; Mineral abbreviations after Kretz, 1983).

(reaction 3):



Above 200°C, these metal-chloride complexes are the prevalent transport mechanism. Increasing the sulphur activity and pH, or decreasing the activity of chlorine, causes the precipitation of sulphides.

In the Sixtymile area, fluid-wall rock interaction during the first stage of mineralization caused the replacement of K-feldspar by muscovite (**reaction 4**):



This alteration reaction would have increased the pH of the hydrothermal solutions during the first enrichment stage, probably causing the precipitation of arsenopyrite, pyrite and pyrrhotite by reaction 1. The crystallization of arsenopyrite, pyrite and pyrrhotite causes a decrease in pH and sulphur activity, and an increase in oxygen activity. The decrease in pH and sulphur activity as a result of reaction 1 predominates over the change in oxygen activity and probably control the precipitation of gold by reaction 2. On the other hand, an increase in Cl⁻ activity as a result of reaction 1 would favour the formation of metal-chloride complexes (reaction 3) and may have suppressed the formation of lead, zinc and copper sulphides during stage I.

The decrease in both temperature and salinity from stage I to stage II suggests mixing of two fluids with different physical and chemical characteristics. Decreased Cl⁻ activity can cause the precipitation of galena, sphalerite, chalcopyrite and silver as a result of reaction 3. The mixing of two fluids with contrasting oxygen activities would increase the oxygen activity of the initial fluid and counteract the deposition of arsenopyrite and gold and possibly dissolve arsenopyrite. The replacement of arsenopyrite I by galena of stage II might have been caused by this process.

Southern area

Physical and chemical conditions of hydrothermal fluids during the three stages of mineralization were within the stability field of galena and arsenopyrite, but whereas galena formed during both Stage I and Stage II, arsenopyrite enrichment is confined to Stage II. Assuming that fluid-wall rock interaction during Stage I caused the alteration of K-feldspar to muscovite by reaction 4, the pH of the fluids must have increased. Depending on the element saturation of the hydrothermal fluids, this pH increase could cause minerals to precipitate as a result of reaction 3. If the arsenic concentration in the fluid were low the change in pH would not cause a precipitation of arsenopyrite by reaction 1.

The decrease in temperature and salinity from Stage I to Stage III suggests mixing of two hydrothermal fluids with different physical and chemical characteristics. Assuming that

the element transport and enrichment during stage II occurred as described by reactions 1 to 4, the precipitation of minerals could have been caused by decreasing temperature, Cl⁻ and oxygen activity between stage I and II.

The absence of arsenopyrite and galena during stage III is indicative of low concentrations of arsenic and lead in the Stage III hydrothermal fluid.

CONCLUSIONS

Gold-bearing, mesothermal quartz-(carbonate)-sulphide veins in the northern and southern areas are believed to have formed in the deeper parts of the same fossil geothermal system, and are probably related to a Late Cretaceous magmatic event. The following conclusions about the fluid composition and mineral enrichment process can be made:

- (1) The fluids which circulated at depth in the metamorphic rocks are characterized by high temperatures (above 300°C), high salinities (about 18 wt.-% NaCl equiv.) and pH values in the range 3.1 to 5.2. These fluids are similar to alkaline chloride fluids of active geothermal systems.
- (2) Arsenic was transported as a $\text{H}_3\text{AsO}_3^\circ$ complex, gold as $\text{Au}(\text{HS})_2^-$ and lead, zinc, copper and iron as MeCl_2° complexes.
- (3) Stage I mineralization resulted directly from fluid-wall rock interaction.
- (4) Subsequent (second and third stage) mineralization resulted from the mixing of two fluids with different physical and chemical characteristics.

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Table 1. Lithostratigraphic units of Sixtymile River area.

SYSTEM	FORMATION	LITHOLOGY NW Area	LITHOLOGY SE Area
QUATERNARY		alluvial sediments	alluvial sediments
	Selkirk Group	alkaline-olivine basalt	
LATE CRETACEOUS	Carmacks Group	andesite, dacite, andesite-dacite dykes, pyroclastic rocks, fluvial sediments	andesite and dacite dykes
	Unnamed plutons		biotite granodiorite
	Klotassin Suite	pegmatite, aplite	
MIDDLE JURASSIC			
PERMIAN	?	orthogneiss	
	Anvil Range Group	ultramafic rocks	
	Pelly Gneiss		augen gneiss garnet-mica schist, gneiss
	Klondike Schist	chlorite schist, mica schist	chlorite schist mica schist
	Nasina Series	paragneiss, quartzite, quartz-mica schist, mica schist, graphite schist, marble	quartzite, quartz- mica schist, mica schist
PRE-PERMIAN (DEVONO- MISSISSIPPIAN AND ? OLDER)			

Table 2. Paragenetic sequence and physico-chemical conditions of the gold-bearing mesothermal quartz-carbonate-sulphide veins in the northern area.

	Stage I	Stage II
Arsenopyrite (at.-% As)	30.25	
Pyrite		
Pyrrhotite		
Galena		Ag-Bi
Sphalerite (mol.-% FeS)		23
Chalcopyrite		
Quartz		
Ankerite		
Siderite		
		→ t
Temp. (°C) :	330	280
Salin. (wt.-% NaCl equiv.) :	12.8	6
log a(K ⁺) :	-1.4	-1.5
pH :	>3.1 = >5.2	>3.3 = >5.4
log a(O ₂) :	≈-30	-35 ← -34
log a(S ₂) :	≈-10	-12 ← -11

Table 3. Mineral paragenesis of the quartz veins and the alteration zones encasing the gold-bearing mesothermal quartz-carbonate-sulphide veins in the northern area.

	Wall rock	Zone I	Zone II	Zone III	Qtz.-S. Veins
Plagioclase		---			
K feldspar					
Quartz					
Biotite		---			
Amphibole		---			
Sericite		---			
Chlorite					
Epidote					
Magnetite					
Sulphides					

Table 5. Mineral paragenesis of the sulphide veinlets and the alteration zones encasing the gold-bearing mesothermal quartz-carbonate-sulphide veins in the southern area.

	Bio-K-Gneiss	Zone I	Zone II	Zone III	Qtz.-S. Veins
Plagioclase			---		
K feldspar				---	
Quartz					
Biotite		---			
Muscovite		---			
Sericite			---	---	---
Chlorite					
Magnetite					
Sulphides		---	---	---	---

Table 4. Paragenetic sequence and physico-chemical conditions of the gold-bearing mesothermal quartz-carbonate-sulphide veins in the southern area.

	Stage I	Stage II	Stage III
Pyrite (wt.-% As)		> 1	
Sphalerite (mol.-% FeS)	≈20	≈15	≈6
Chalcopyrite	—	—	
Mackinawite	—		
Cubanite	—		
Bornite	—		
Pyrrhotite	—	—	
nat. Bismuth	—		
Arsenopyrite (at.-% As)		27.66 29.03	
Galena	Ag-Bi	*As Sb-Ag-Bi	
Matildite	—		
Tetrahedrite	—		
Miagyrite		—	
Polybasite		—	
Gold		—	
Freibergite (wt.-% Ag)			≈22
Quartz			
			→ t
Temp. (°C)	330	280	150
Salin. (wt.-% NaCl equiv.)	18.3	12	10
log a(K ⁺)	-1.5	-1.3	-1.6
pH	>3.2 = >5.3	>3.2 = >5.2	>4.1 = >5.9
log a(O ₂)	-29 → -30	-31 → -35	-53
log a(S ₂)	-9 → -10	-11 → -12	-18