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DEPARTMENT OF NATURAL RESOURCES

DIVISION OF GEOLOGICAL AND GEOPHYSICAL SURVEYS

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Report of Investigations 87-5

GEOLOGY OF ZINC-LEAD SKARN DEPOSITS IN THE TIN CREEK AREA, McGRATH B-2 QUADRANGLE, ALASKA

By

D.J. Szumigala

STATE OF ALASKA
Department of Natural Resources
DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS

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GEOLOGY OF ZINC-LEAD SKARN DEPOSITS IN THE TIN CREEK AREA, MCGRATH B-2 QUADRANGLE, ALASKA

By
D.J. Szumigala[1]

ABSTRACT

Several copper-zinc-lead-silver skarn and replacement bodies occur in a 500-km^2 area near Farewell, Alaska. One of the major mineralized areas, the upper Tin Creek area, has been studied in detail.

Host rocks for skarns are mid-Paleozoic sedimentary rocks that have undergone contact metamorphism and are folded, faulted, and overlain and intruded by Tertiary igneous rocks. Skarns in the Tin Creek area are small, discontinuous bodies (up to 3 m wide) of exoskarn along dike contacts and of endoskarn within the dikes. Skarns also form mantos in marble and irregular bodies along thrust and high-angle faults. Semimassive to massive sulfide mantos occur in calc-silicate hornfels. Many dikes do not have skarn along their contacts; others have skarn along only one margin. These relationships indicate that dikes and faults are structural conduits for later metasomatic fluids and are not directly responsible for skarn formation.

Skarn deposits are dominantly of two types: 1) pyroxene (Hd_{15-66}) skarns with sphalerite and minor chalcopyrite ± pyrite and 2) garnet (Ad_{12-100}) skarns with chalcopyrite and minor sphalerite. Locally, the dominant skarn minerals are amphibole or epidote or both, although generally endoskarn is epidote rich. Pyroxene-dominant skarns exhibit textural and compositional zoning: along the marble front the pyroxene is coarse and iron-manganese rich, and near the intrusion the pyroxene is finer grained and magnesium rich. Garnet is also compositionally zoned with magnesium-rich metamorphic cores rimmed by progressively more iron-rich metasomatic garnet. Zoning occurs on a larger scale with pyroxene-sphalerite-dominant skarns distal to and garnet-chalcopyrite-dominant skarns proximal to centers of dike swarms.

Skarn prospects in the Tin Creek area compare favorably with other zinc-lead skarns and can be classified with zinc-lead skarns that form near dikes. The deposits have features, such as structural control of metasomatic fluids and textural and compositional zoning, common to zinc-lead skarns worldwide.

INTRODUCTION

The study area is near the upper reaches of Tin Creek in rugged mountains of the northwest flank of the Alaska Range. It is approximately 16 km southeast of Farewell, a Federal Aviation Agency station, in the McGrath B-2 Quadrangle (fig. 1). Elevations range from 670 m in the Tin Creek drainage to 1,765 m along the ridge line that defines the western boundary of the study area. Most of the site is above timberline and generally has excellent

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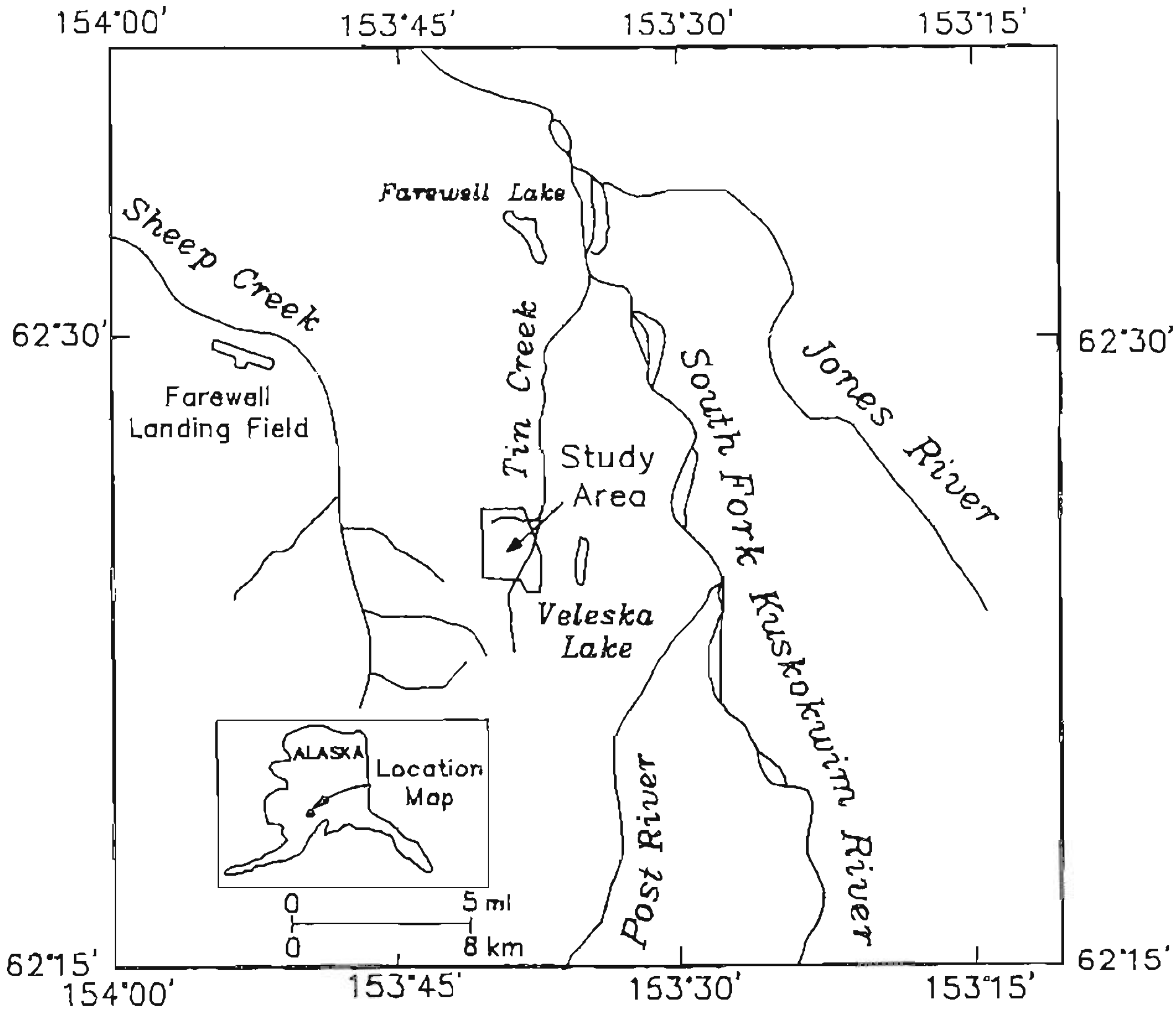

Figure 1. Location map showing study area (sheet 1) in McGrath B-2 Quadrangle, Alaska.

bedrock exposures. The area is accessible by helicopter or by floatplane to Veleska Lake 1 mi to the east.

This investigation is related to thesis work for a Master of Science degree at the University of Alaska, Fairbanks. I spent 43 days from mid-June to mid-August 1983 mapping and sampling skarn deposits in the Tin Creek area. Fieldwork was augmented with examination of thin and polished sections, X-ray diffraction analyses, and electron-microprobe analyses. Geochemical analyses were performed at the Alaska Division of Geological and Geophysical Surveys' (DGGS) laboratory and Chemex Labs, Ltd., Vancouver, B.C.

ACKNOWLEDGMENTS

Many people helped make this project possible. I especially thank R.J. Newberry (University of Alaska, Fairbanks) for his guidance throughout this project; T.K. Bundtzen (DGGS) and R.E. Kell (Anaconda Minerals Company) for sharing their extensive knowledge of the McGrath region; C.L. Allegro (DGGS) for her electron-microprobe analyses; and DGGS and Anaconda Minerals Company for their logistical support. I also thank T.K. Bundtzen, M.S. Robinson, V.L. Reger, and K.E. Adams (DGGS) for reviewing this manuscript. Funding for thin sections, polished sections, geochemical and major-oxide analyses, and K-Ar ages was provided by DGGS.

PREVIOUS WORK

Reed and Elliott (1968) discovered several geochemical anomalies in stream sediments in the Tin Creek area, but they did not find the source of these anomalies. Rob Kell (Anaconda) discovered significant mineralization along Tin Creek in 1980, and detailed work by Anaconda within the Farewell area continued until 1984. Bundtzen and others (1982) mapped the geology of the McGrath B-2 Quadrangle.

REGIONAL GEOLOGY

The Farewell fault, a major right-lateral, strike-slip feature, is the westernmost extension of the Denali fault system in the Alaska Range and has a right-lateral displacement of at least 60 km since mid-Tertiary time (Reed and Lamphere, 1974) North of the study area, the Farewell fault juxtaposes younger, undeformed, shallow-water carbonates of Devonian age to the northwest against polydeformed basin-and-slope deposits of early to mid-Paleozoic age to the southeast (Bundtzen and others, 1982).

The section south of the Farewell fault is composed of stratified rocks of Early Ordovician to Late Pennsylvanian age. The Ordovician section, approximately 100 to 250 m thick, consists of shale, siltstone, black chert, and thin volcaniclastic-sand intervals (Bundtzen and others, 1982). Overlying the Ordovician sequence is a 1,500-m-thick sequence of Silurian clastic rocks. The Silurian sequence consists of rhythmically layered shale, siltstone, laminated limestone, and medium- to coarse-grained sandstone that grade upward into shale and fine-grained siltstone (Bundtzen and others, 1982). Units of the Silurian clastic sequence are the oldest units mapped in the Tin Creek area. Interbedded with the Silurian clastic sequence is a structurally thickened sequence of mid-Silurian (Wenlockian; T.K. Bundtzen, written commun., 1984) limestones with some shale. This limestone sequence hosts the skarns in the Tin Creek area. The Silurian carbonate-clastic sequence is overlain by a Devonian-Pennsylvanian sequence that consists of algal limestone, shale, chert, and clastic rocks (Bundtzen and others, 1982). The general stratigraphic sequence suggests that shallow platform carbonates prograded over a deeper shelf margin during mid-Paleozoic time (Bundtzen and Gilbert, 1983).

Igneous rocks in the McGrath B-2 Quadrangle range in age from Late Cretaceous to mid-Tertiary (Bundtzen and others, 1982). Intrusive rocks range in size from dikes to small plutons of dominantly intermediate compositions. As in the Tin Creek area, dike swarms are complexly intertwined with hornfelsed sedimentary rocks of Paleozoic age. Two volcanic complexes also occur in the McGrath B-2 Quadrangle. The Veleska Lake volcanic complex, dominantly of dacite composition, defines the western edge of the study area.

STRUCTURE

The Farewell fault is the major structural feature in the Farewell area. South of the Farewell fault, sedimentary rocks of Paleozoic age were deformed by three folding events (Kell, 1980). The earliest event (F_1), associated with regional thrust faulting, resulted in isoclinal recumbent folds. The second event (F_2) produced upright fold structures, including the Tin Creek synclinorium and the adjacent Sheep Creek anticlinorium. The last major deformational event (F_3) was caused by drag along the Farewell fault and produced broad, regional warping. The deformational sequence is similar to that worked out by Bundtzen and others (1982) and Gilbert and others (1982).

GEOLOGY OF SKARN DEPOSITS

Silurian Clastic-carbonate Unit

Silurian clastic-carbonate rocks (Smp) compose the oldest unit mapped within the study area (sheet 1). Most of the clastic-carbonate sequence in the Tin Creek area has been metamorphosed to banded calc-silicate hornfels (Tch). Small outcrops of the relatively unmetamorphosed clastic-carbonate rocks are exposed along Tin Creek and consist of interbedded lithic sandstone, gray phyllitic siltstone, and minor amounts of gray laminated marble. The contact between the interbedded clastic-carbonate rocks and undifferentiated marble to the west is obscured, but the thrust fault exposed in lower Tin Creek should extend between these units. The beds strike north-northeast and dip approximately 50° NW.

Silurian Marble Units

Although seven marble units were defined during geologic mapping (sheet 1), most units are not traceable for more than 100 m along strike because of poor exposure and complex structure. Each marble unit probably does not represent a separate entity, but rather metamorphosed equivalents or local facies changes.

The most commonly exposed marble units are those with silt partings (Sms) and garnet bands (Smg) (sheet 1). (Locally, where the marble unit with silt partings contains shaley interbeds, it was mapped as a separate unit [Smss]). The unit with silt partings is more common at lower elevations and is farther from the most concentrated area of igneous dikes than the unit with garnet bands. On the west side of Tin Creek, the unit with silt partings lies in thrust-fault contact with the banded calc-silicate hornfels (Tch). The marble with silt partings is gray, medium to thick bedded, highly fractured, and folded. The folds are generally asymmetric and very tight. Fracture sets dip more steeply than bedding attitudes, which indicates that the marble unit is right-side up. The prevalent beds strike north-northeast and dip moderately to steeply northwest.

The marble unit with garnet bands, the most areally extensive marble unit, represents a higher metamorphic stage than the marble unit with silt partings. The original silty layers within the marble with garnet bands were metamorphosed to light-green bands of garnet. The unit with garnet bands is especially prevalent in areas where igneous dikes are abundant, including the margin of dikes where the marble with garnet bands grades into the marble with silt partings.

Most marble in the study area weathers easily to form scree slopes, which were mapped as undifferentiated marble talus (Smu). Other marble units recognized within the Tin Creek area (sheet 1) include black, fine-grained marble with calcite veinlets (Sbm), black marble with shaley interbeds (Sbms), and gray, silty marble that has been metamorphosed in part to siliceous hornfels (Tmh). Another unit included with the marble units is a gray to dark-gray, fine- to medium-grained, calcareous siltstone (Scs) that weathers olive green and contains local graded beds.

Tertiary Igneous Rocks

Veleska Lake volcanic complex

The ridge on the western boundary of the study area is capped by the Veleska Lake volcanic complex (TKvu), which is underlain by the Silurian marble units (sheet 1). The base of the complex consists of tuff breccia (0.5 m thick), lapilli breccia (6 to 10 m thick), white to green-gray andesitic ash-fall tuff (about 80 m thick), and a green-gray quartz latite flow (undetermined thickness). Locally black mudstone that contains abundant plant debris is interbedded with the basal volcanics. Overlying the lower sequence are massive dacite flows and sills (>200 m thick) that compose most of the volcanic complex.

Igneous dikes

Igneous dikes that intrude sedimentary, metasedimentary, and volcanic units generally trend N. 60° W. to east-west, dip moderately to steeply north, and are more prevalent in the northern part of the study area. Dikes range in thickness from <1 m to about 50 m and change in texture from porphyritic near the margins to aphanitic near the centers.

Normative mineral ratios of igneous dikes in the Tin Creek area were calculated from major-oxide analyses (fig. 2). The dikes are primarily of two compositional types: 1) dacite (granodiorite-tonalite) and 2) andesite (monzodiorite-diorite).

Granodiorite porphyry dikes

Granodiorite porphyry (Tgp) is the most abundant dike type in the Tin Creek area (sheet 1). Fresh granodiorite porphyry dikes are generally gray white to gray. Plagioclase constitutes approximately 50 percent of the total phenocrysts and occurs as rectangular or equilateral phenocrysts up to 1 cm long. Hornblende constitutes 35 percent of the total phenocrysts, ranges from black to dark green, and occurs as phenocrysts up to 1 cm long. Biotite content varies considerably among dikes, ranging from 0 to 15 percent of the total phenocrysts. Quartz generally constitutes 5 to 10 percent of the total phenocrysts and usually occurs as phenocrysts about 1 mm diam. Some granodiorite porphyry dikes contain xenoliths of porphyritic, fine-grained quartz monzodiorite.

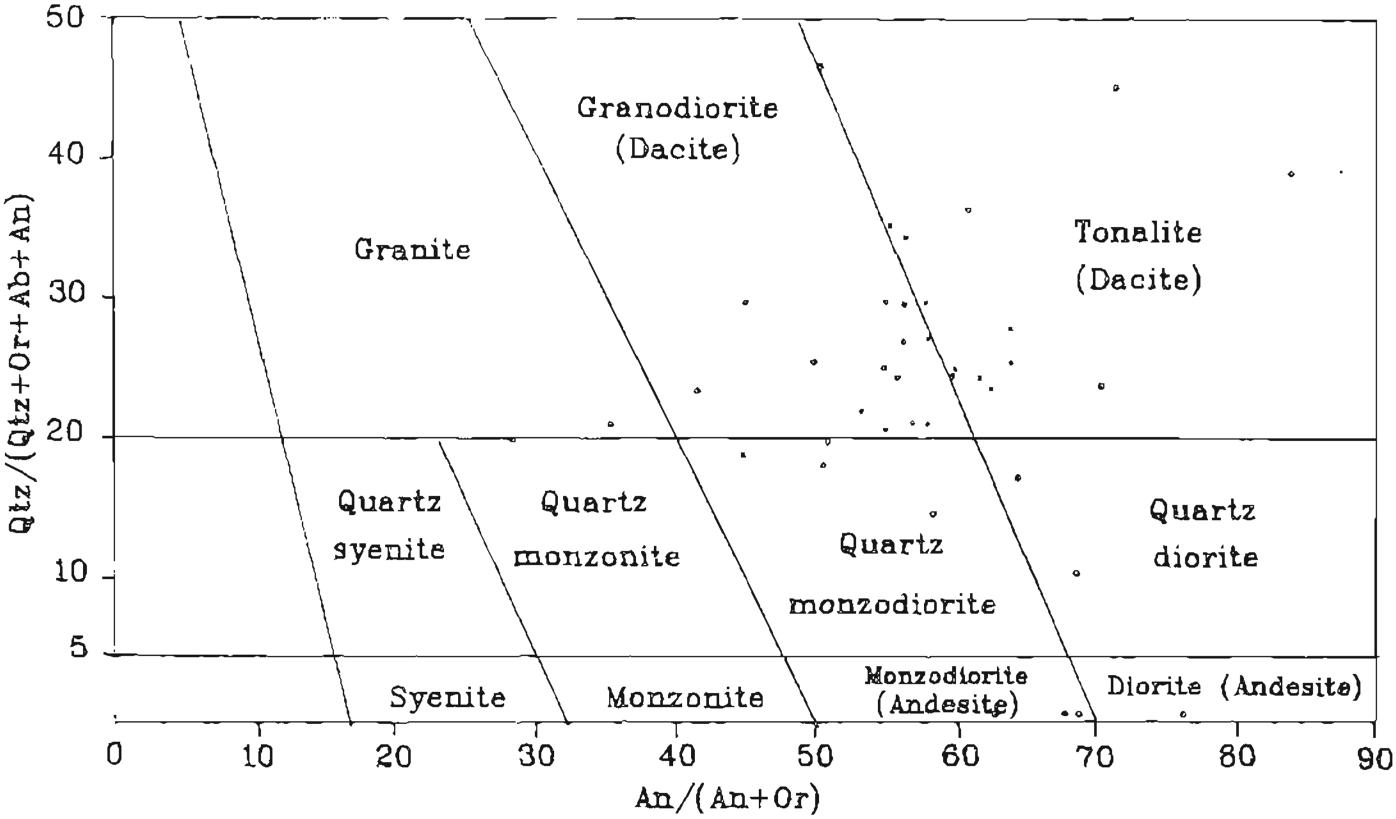

Figure 2. Normative mineral ratios of igneous dikes in the Tin Creek area, Alaska, based on major oxide analyses.

Porphyritic dacite dikes and porphyritic hornblende-rich dacite dikes

When the normative mineral ratios of the porphyritic dacite dikes (Td) and porphyritic hornblende-rich dacite dikes (Thd) are plotted, they fall into the same range as the granodiorite porphyry dikes (fig. 2). However, the dacite dikes and hornblende-rich dacite dikes are significantly different in texture than the granodiorite porphyry dikes. Porphyritic dacite dikes consist of a gray, aphanitic groundmass with phenocrysts of plagioclase, hornblende, biotite, and quartz. Plagioclase constitutes 70 to 80 percent of the total phenocrysts, hornblende 15 to 25 percent, and biotite and quartz up to 5 percent each. Some porphyritic hornblende-rich dacite dikes contain two distinctly different types of hornblende: 1) short, equilateral, black phenocrysts and 2) longer, rectangular, green phenocrysts.

Many dikes (Td and Tgp) are propylitically altered; thus, the groundmass has a green cast with white ghost alteration of former plagioclase phenocrysts. In addition, some dikes are altered to sericite, and mafic minerals are generally partially to completely altered to epidote, chlorite, and calcite. All dikes contain pyrite ± pyrrhotite, which occur in clots that replace the mafic minerals.

Andesite dikes

A minor percentage of the dikes in the Tin Creek area consist of andesite (Ta) and are not traceable farther than 25 m along strike (sheet 1). These dikes are probably older than the dacite (Td and Thd) and granodiorite (Tgp) dikes because the andesitic dikes have been altered, and sometimes silicified, by the dacite and granodiorite dikes. Fresh andesite varies from green to dark green, but the andesite dikes are usually altered and contain ghost phenocrysts of plagioclase and chloritized mafic minerals. Some dikes contain up to 15 percent sulfides as needles or in clots that appear to be replacing original mafic minerals. The sulfides are dominantly composed of pyrrhotite with minor pyrite and traces of chalcopyrite. Weathering of sulfide-bearing andesite dikes produces conspicuous red-stained outcrops.

Igneous-matrix breccia dikes

Igneous-matrix breccia dikes (Tibx), the youngest dikes identified within the study area, crosscut skarn bodies and crosscut and occasionally envelop the termini of intermediate-composition dikes (sheet 1). Igneous-matrix breccia dikes have a white, aphanitic matrix that contains quartz phenocrysts and lithic clasts. The clasts are rounded to angular, up to 5 cm diam, and are mostly metasedimentary hornfels with granodiorite porphyry and marble. Some dikes also contain clasts of mineralized skarn.

Metamorphic and Metasomatic Units

Banded calc-silicate hornfels

Silurian clastic-carbonate rocks have been transformed into banded calc-silicate hornfels (Tch) by contact metamorphism. These hornfels have been bimetosomatically altered; that is, a net transfer has occurred between two adjacent unlike lithologies, but there has not been a net transfer of chemical components with the surrounding environment. The banded calc-silicate hornfels consists of alternating gray-green and dark-brown, fine-grained, compact layers that primarily consist of garnet + pyroxene and quartz + biotite, respectively. The upper 7 to 10 m of the calc-silicate hornfels unit has bands that average 2 to 3 cm thick; the rest of the unit has bands that range from 5 to 50 cm thick.

As mentioned by Bundtzen and others (1982), some primary sedimentary structures of the Silurian clastic-carbonate sequence are preserved, including Bouma intervals, graded bedding, and cross-bedding. The orientation of graded bedding and cross-bedding indicates that the section is right-side up with stratigraphic tops facing northwest. Remnant bedding attitudes are consistent in the banded calc-silicate hornfels; the beds strike almost due north and dip steeply west-southwest.

Hornfels

The hornfels unit (Th) consists of metamorphosed siliceous rocks that generally occur as interbeds within the marble sequence. The unit is not banded and is composed of very fine grained, compact rock that usually breaks with a conchoidal fracture.

Skarnoid

Skarnoid is a rock formed by both metamorphic and metasomatic processes in which neither process is dominant, although in the Tin Creek area, metamorphic processes have probably been slightly overprinted by metasomatic processes. The actual origin of skarnoids, therefore, is uncertain or complex (Einaudi and Burt, 1982), but some transfer of components occurs through fluids or volatile gases or both. Several areas of skarnoid occur in the Tin Creek area as a grayish-brown rock that weathers brown or sometimes green (shown as part of Ts unit on sheet 1). In most areas, however, skarnoid outcrops are too small to be shown on the map. The majority of the skarnoid is composed of fine-grained clinopyroxene with epidote, chlorite, quartz, medium-grained clinopyroxene, and calcite in subequal amounts. Pods of calcite up to 5 cm diam occur in the skarnoid, and some veinlets of pyrite with coarse clinopyroxene, quartz, and calcite crosscut the skarnoid.

Endoskarn

Endoskarn is formed by the calc-silicate replacement of intrusive rocks through metasomatic fluid interaction. Dikes in the Tin Creek area display varying degrees of endoskarn development. Generally, endoskarn development is minor in dikes and absent in the Veleska Lake volcanic complex (TKvu). Dikes in the northern part of the study area typically contain pink clinozoisite that replaces plagioclase and calcite + chlorite that replace mafic minerals. Epidote, chlorite, clinopyroxene, and quartz are common minerals that occur within all endoskarn. Endoskarn is not thoroughly developed in the dikes; typically only the edges of some dikes have been replaced. Unlike skarn in the Tin Creek area, endoskarn is devoid of appreciable ore mineralization.

Skarn

Skarn, as used here, is formed by large-scale transfer of components between hydrothermal fluids of magmatic input and predominantly carbonate rocks (Einaudi and Burt, 1982). Skarns (Ts) occur throughout the study area (sheet 1), but are generally too small to be mapped. Skarns in the Tin Creek area have a zoned distribution pattern, with garnet-dominant skarns near the center of the Tin Creek dike system and pyroxene-dominant skarns peripheral to the garnet skarns. The occurrence of calc-silicate minerals in skarns depends on the composition of the lithology that is metasomatized. The southern part of the Tin Creek area is dominated by pyroxene-rich skarns within calcareous rocks, whereas adjacent areas are dominated by garnet-rich skarns within siliceous calc-silicate hornfels.

Epidote-clinozoisite occurs in most skarns. In some areas, epidote occurred as a late event and formed the dominant skarn mineral (fig. 3). Chlorite, quartz, and calcite are abundant in almost every thin section examined. Amphibole, as a retrograde product of the coarser grained clinopyroxene, occasionally occurs as shredded grains or mats with clinopyroxene cores.

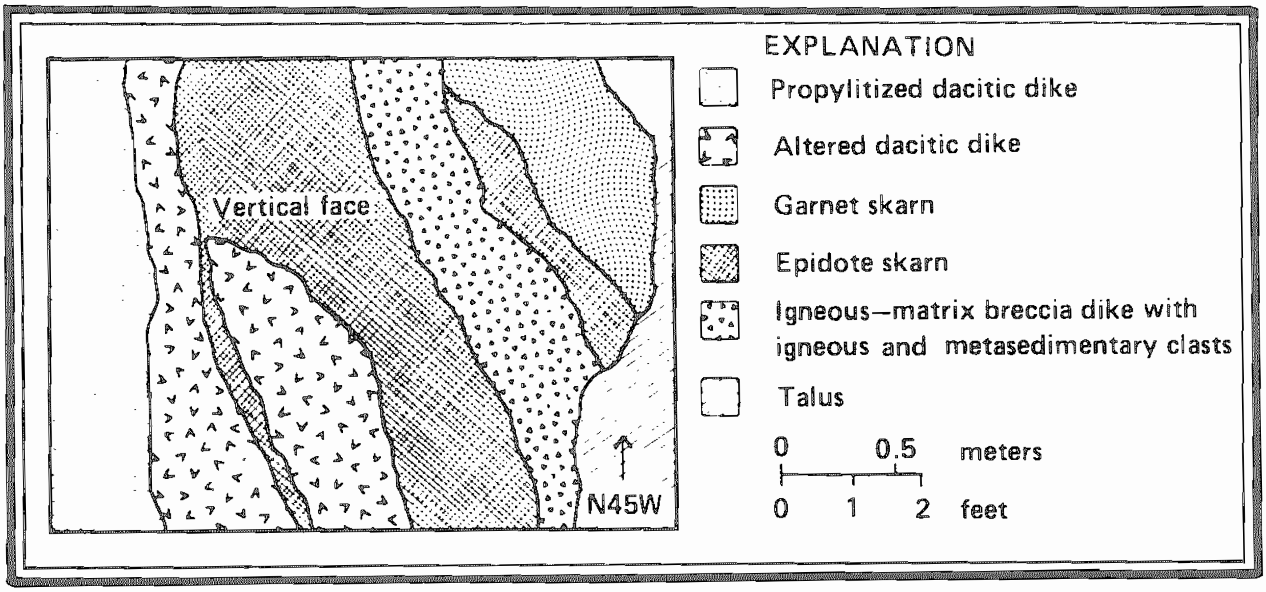

Figure 3. Geologic map of the vertical face of an epidote-rich skarn zone in the Tin Creek area, Alaska. (See site 2, sheet 1, for specific locality.)

Skarn bodies are up to 5 m wide and are traceable for up to 35 m along trend. These bodies are discontinuous and commonly pinch out or widen along structural features and dikes. A geologic map of the vertical face of a typical skarn zone in the Tin Creek area is shown in figure 4.

Skarn forms along marble contacts with granodiorite porphyry dikes, porphyritic dacite dikes, and porphyritic hornblende-rich dacite dikes. Some dikes have skarn developed along one side of their margin only, and many dikes do not have any skarn development. No local metamorphic aureoles were formed around individual dikes, because the dikes in the Tin Creek area are too small to have had a significant heating effect on the surrounding rocks.

Skarn mineralization is also controlled by faults that are clearly exposed along Tin Creek. The thrust fault (lower right corner of geologic map, sheet 1) that juxtaposes marble over banded calc-silicate hornfels has pyroxene-dominant skarn discontinuously developed along its length. A high-angle fault west of the thrust fault also has skarn developed along it. This skarn appears to have been retrograded to chlorite + calcite + quartz with sphalerite + pyrite + chalcopyrite.

Pyroxene skarn

Pyroxene-dominant skarns exhibit textural and compositional zoning. Iron-rich salite occurs along the marble front, but clinopyroxene becomes finer grained and more magnesium rich near the intrusive contact. Where skarn is in contact with marble, hedenbergitic pyroxene can occur as green prismatic crystals up to 7 cm long. Most pyroxene occurs as fine to extremely fine grained masses that produce hard, compact outcrops.

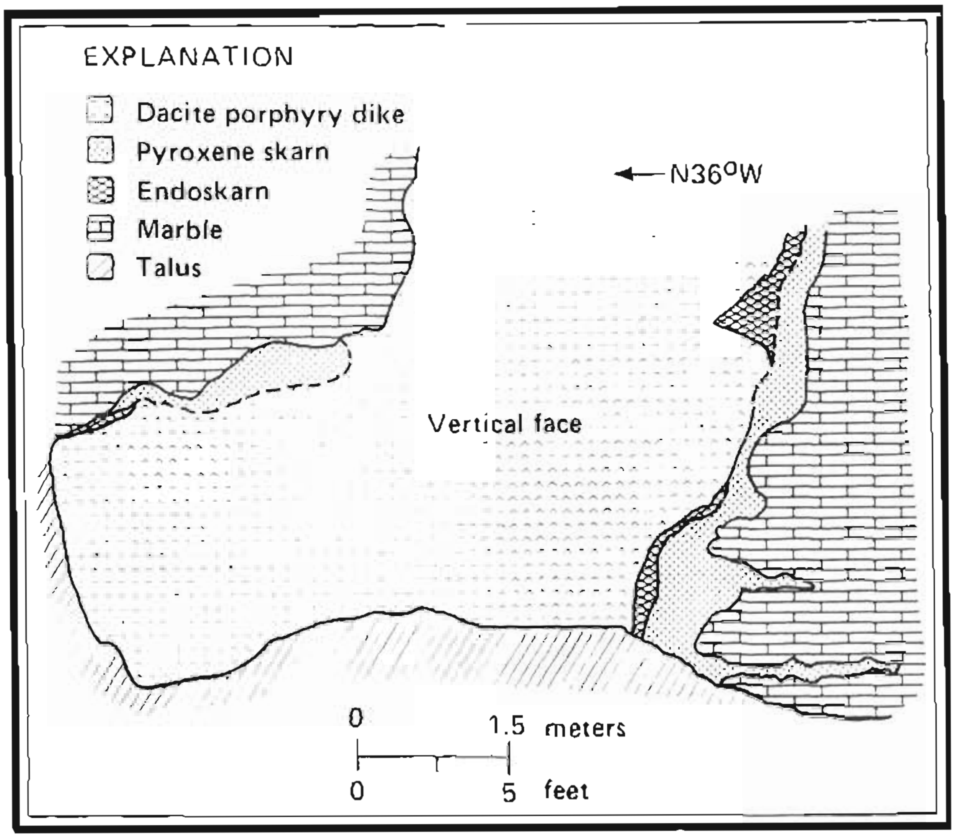

Figure 4. Geologic map of the vertical face of a typical skarn zone in the Tin Creek area, Alaska. Endoskarn and skarn are irregularly developed along a dacite dike in contact with marble. Skarn manto bodies develop where metasomatic fluids have infiltrated along bedding in the marble. (See site 1, sheet 1, for specific locality.)

Pyroxene compositions from skarn samples in the Tin Creek area are shown in figure 5. Pyroxenes range from 12 to 83 mole percent hedenbergite. As the composition increases in johannensite, there is a corresponding increase in hedenbergite. Maximum percentages of hedenbergite and johannensite occur in the coarse-grained salite along the marble front. Pyroxene analyses show an iron-manganese enrichment through time whereby coarse-grained hedenbergitic pyroxene overprinted fine-grained diopsidic pyroxene.

Garnet skarn

Garnet-dominant skarns are restricted to the center of the Tin Creek system. Garnet skarns weather red brown to brown, and fresh surfaces are green. Small garnet faces are visible throughout these skarns.

Garnet compositions show an even more systematic change through time than the pyroxenes. Garnet compositions (fig. 6), like pyroxenes, show iron enrichment during evolution of the metasomatic system. The composition of

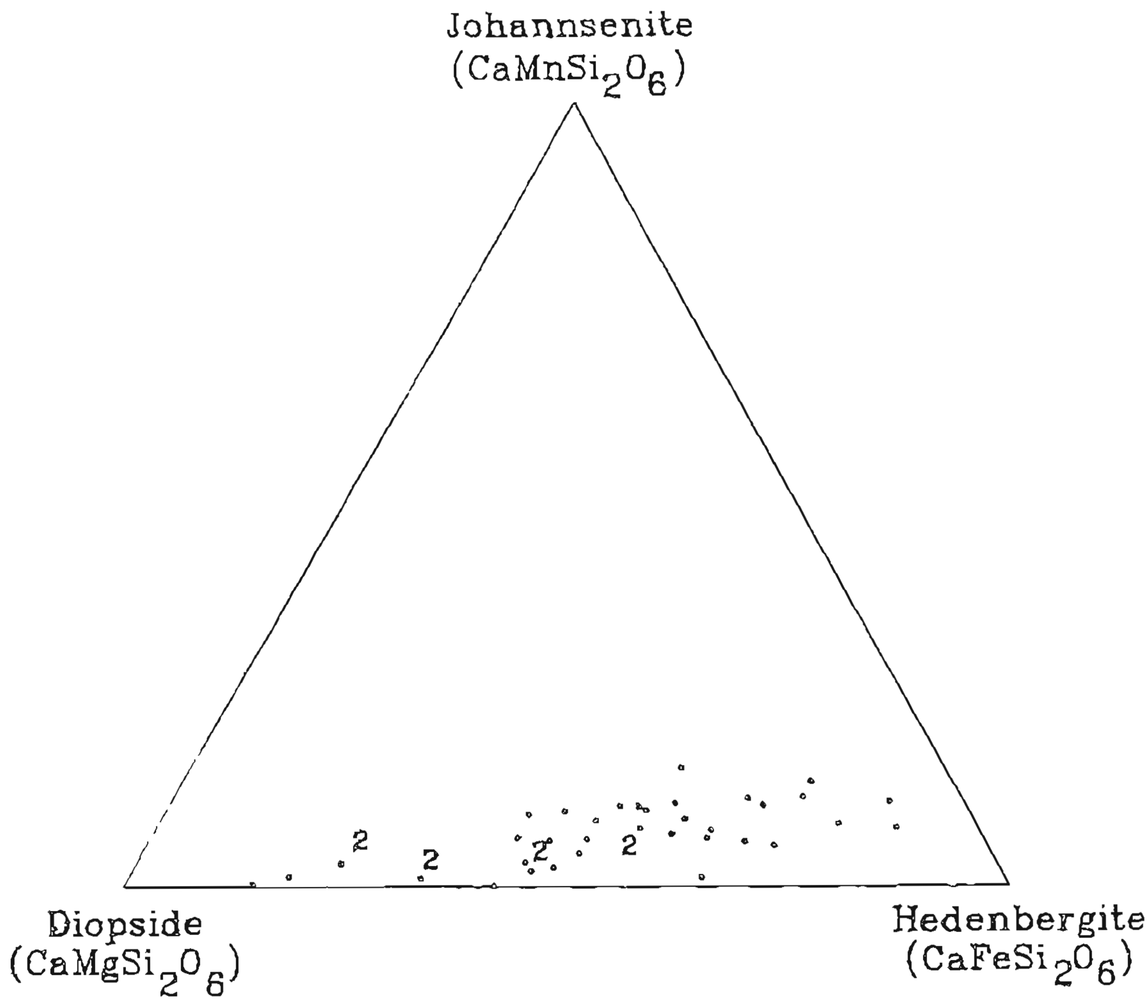

Figure 5. Pyroxene compositions from skarns in the Tin Creek area, Alaska. Compositions are expressed as mole percents of end members based on electron-microprobe analyses. Numbers refer to the number of analyses at that point.

garnets from the Tin Creek area is restricted to grossular-andradite with a maximum of 6 percent spessartine + almandine. Metamorphic garnet was the first to form; it is grossular rich with an average andradite content of 12 percent. Clear metasomatic garnet, which formed after and generally rims metamorphic garnet, has an average composition of 18 mole percent andradite. The latest garnet formed is brown and has a large range in composition with an average of 58 mole percent andradite. The brown garnet probably represents a long period of skarn formation because individual garnet grains exhibit several periods of chemical reversals during garnet growth. For example, iron-rich, brown garnet formed before less iron-rich, brown garnet; then the process repeated itself. Figure 7 summarizes the evolution of garnet compositions based on electron-microprobe analyses.

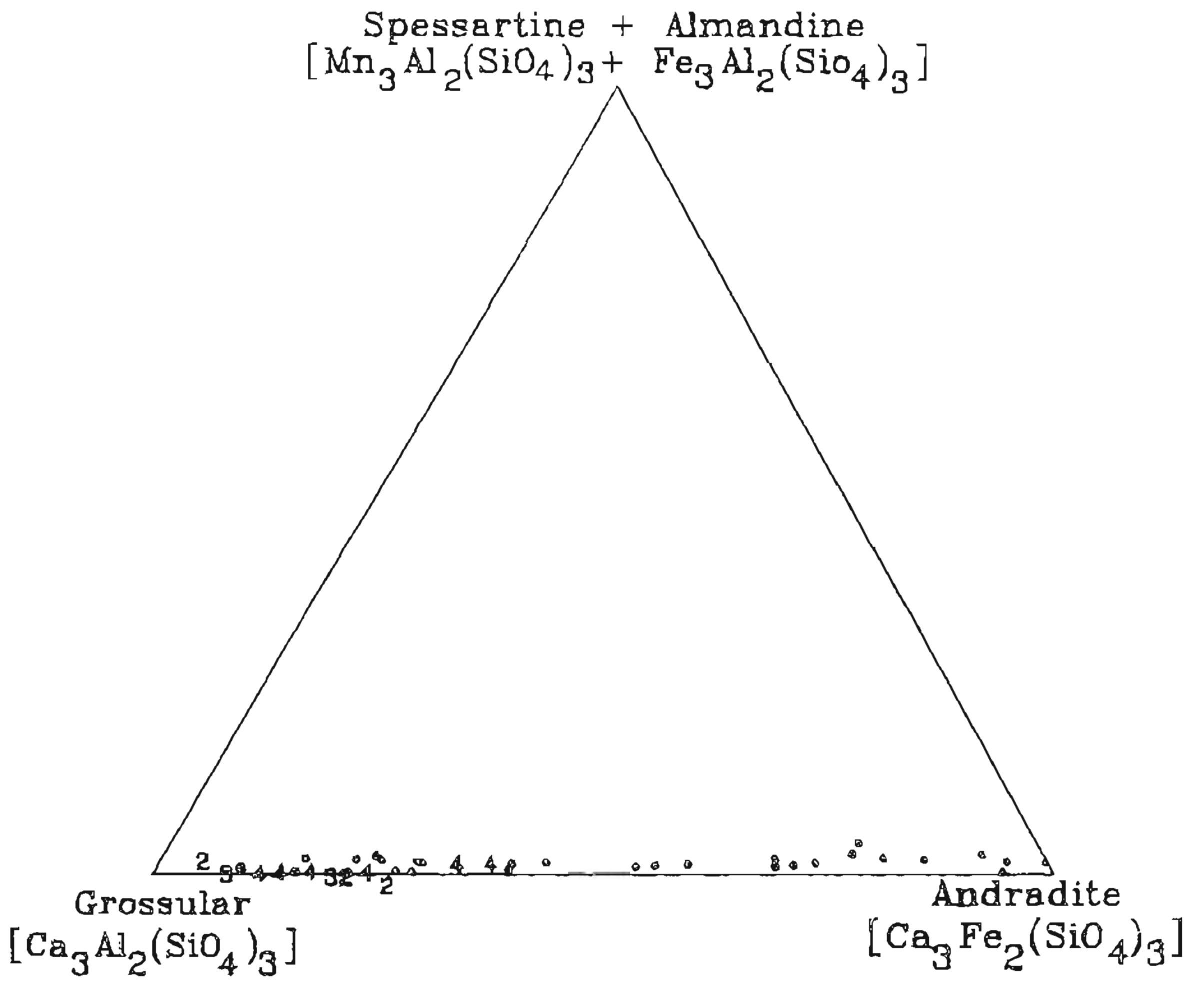

Figure 6. Garnet compositions from skarns in the Tin Creek area, Alaska. Compositions are expressed as mole percents of end members. Numbers refer to the number of analyses at that point.

Mineralization

Mineralization consists predominantly of massive to disseminated sphalerite and chalcopyrite with minor amounts of galena, pyrite, and pyrrhotite, and rare arsenopyrite, covellite, chalcocite, and magnetite. Silver occurs as an ore mineral, but its form and localization have not yet been determined. Sulfides occur as fine to coarse grains that are generally associated with calc-silicate assemblages. Ore minerals occur in skarn bodies, as sulfide mantos within the calc-silicate hornfels, as mineralized skarn clasts in the igneous-matrix breccia dikes, and as minor veins with quartz and calcite in the calc-silicate hornfels.

Semimassive to massive sulfide mantos are the only significant mineralization within the banded calc-silicate hornfels and the only significant mineralization that is not hosted by skarns. Mineralization within the hornfels occurs immediately below the thrust fault exposed in Tin

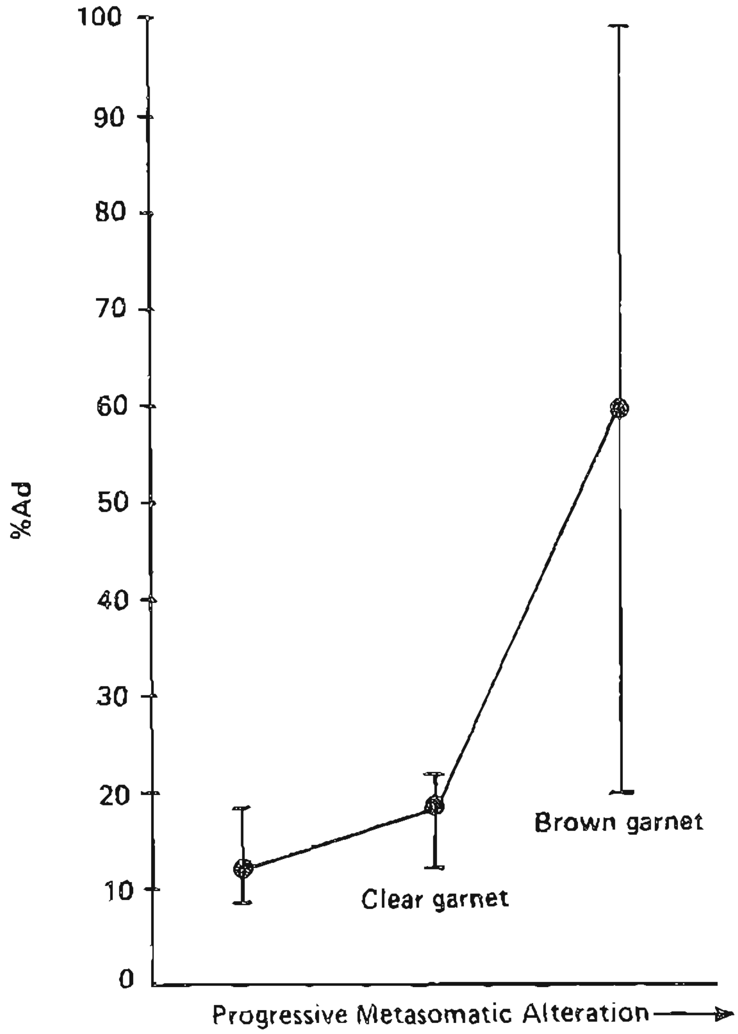

Figure 7. Evolution of the composition of garnets from skarns in the Tin Creek area, Alaska, based on electron-microprobe analyses. Percentage of andradite in the garnets is plotted vs. progressive metasomatic alteration.

Creek. About a dozen mineralized layers, conformable to banding (relic bedding), are exposed over a stratigraphic distance of 6 m. Individual mantos vary in thickness from 2 cm to 1 m. They are composed dominantly of sphalerite and pyrite with chalcopyrite and galena in association with sparry calcite and some quartz. Sulfide mantos may have replaced the original thin limestone beds within the metasiliceous clastic unit.

Sulfide deposition is intimately associated with the skarn calc-silicates. Petrographic studies of altered rocks in the Tin Creek area have suggested the paragenetic model that is summarized in figure 8. Metamorphic grossularitic garnet and diopsidic pyroxene form without any sulfide phases. Early metasomatic garnet and pyroxene, however, are accompanied by minor amounts of sphalerite and chalcopyrite. Overall, skarn-mineral formation and sulfide deposition are not contemporaneous in most skarn bodies studied.

In almost every case where ore minerals occur in skarns, the nearby calc-silicate minerals are partially to completely destroyed. The main period of sulfide crystallization is contemporaneous with the waning formation of garnet and pyroxene. Sulfides, commonly accompanied by quartz and calcite, replace garnet and pyroxene and occur in calcite-dominant veins and pods throughout many of the examined skarns. The dominant ore minerals that occur in the Tin Creek skarns are sphalerite and chalcopyrite. Even though sphalerite and chalcopyrite may occur with pyroxene and garnet, the sulfides and metasomatic calc-silicates usually have a preferential association: hedenbergitic pyroxene is commonly replaced by sphalerite, whereas andraditic garnet is preferentially replaced by chalcopyrite. Copper-zinc ratios increase from the distal pyroxene-sphalerite-dominant skarns toward the proximal garnet-chalcopyrite-dominant skarns. Maximum copper-zinc ratios occur at the center of the exposed metasomatic system, where garnet skarns are associated with chalcopyrite and magnetite.

Retrograde alteration of garnet and pyroxene to epidote and amphibole with quartz is sometimes postdated by sulfide formation. Unlike the main sulfide-deposition event, where much of the sulfide has replaced the calc-silicates, late sulfide deposition occurs as crosscutting veins. Where galena occurs in skarns, it is commonly associated with calcite in veins that crosscut all earlier features. Sphalerite and chalcopyrite occur as veins that crosscut amphibole and epidote, although these occurrences are minor due to the low retrograde alteration of the skarns.

PORPHYRY-COPPER SYSTEM

Skarn prospects in the Tin Creek area may overlie a porphyry-copper deposit. This hypothesis is difficult to prove because of the lack of exposure of any stock. Additionally, no deep drilling has been completed in the prospect area. However, the porphyry-copper hypothesis is supported by four observations (1 through 4, below) and negated by five others (5 through 9, below):

1. The metamorphic aureole probably resulted from a hidden stock. The stock may have porphyry-copper mineralization because some exposed dikes contain disseminated sulfides.
2. The quartz stockwork is intensely veined at the center of the Tin Creek area (Anaconda Minerals Company, written commun., 1983).
3. Actinolite(?)-bearing veins occur in hornfels near the center of the Tin Creek area, and actinolite-bearing veins are absent in skarn not associated with potassium-silicate altered stocks.
4. There are many examples in literature (for example, Einaudi and others, 1981) in which zinc-lead skarns are peripheral to porphyry-copper systems.

METAMORPHIC	METASOMATIC
Pyroxene (diopside) →	Pyroxene (hedenbergite) + minor Sphalerite → massive Sphalerite + Galena + Quartz + Calcite + Epidote + Amphibole
Garnet (grossular) →	Garnet (andradite) + minor Chalcopyrite → massive Chalcopyrite + Calcite + Quartz + Epidote

Figure 8. Generalized paragenetic model based on petrographic studies showing skarn formation and sulfide deposition of altered rocks in the Tin Creek area, Alaska.

5. Metal ratios of igneous rocks in the Tin Creek area are not like metal ratios of igneous rocks that are associated with porphyry-copper systems. Figure 9 compares metal ratios of intrusive rocks in the Tin Creek area with the average metal ratio for the porphyry-copper system in the Kalamazoo deposit, Arizona (Chaffee, 1982).
6. The molybdenum mineralization that commonly occurs with porphyry-copper systems does not occur in the Tin Creek area.
7. Significant porphyry-copper mineralization has not been found in exposed igneous plutons of intermediate compositions in the Tin Creek area.
8. Skarns in the Tin Creek area are usually not retrograded, whereas porphyry-copper-related skarns have strong retrograde alteration (Einaudi and others, 1981).
9. Igneous dikes in the Tin Creek area do not have the intense alteration assemblages characteristic of porphyry-copper systems. Igneous rocks in the study area are mostly propylitically altered with very minor sericitic alteration.

The question of whether a hidden porphyry-copper system exists in the Tin Creek area is relatively unimportant, economically, at this time. Silver grades will determine whether these prospects are economically feasible given the present conditions.

COMPARISON OF SKARN DEPOSITS IN THE TIN CREEK AREA WITH OTHER ZINC-LEAD SKARN DEPOSITS

Skarn deposits are classified according to the dominant economic metal present. Six general subclasses exist: iron-gold, tungsten, copper, zinc-lead-silver, molybdenum, and tin. Zinc and silver are the dominant economic metals in the Tin Creek area. Variations within these subclasses are a function of magma type, environment of emplacement, and composition of the host rock (Einaudi and others, 1981). Einaudi and others (1981) further divided zinc-lead skarns by proximity to plutonic bodies. For comparative purposes, table 1 lists some characteristics of calcic zinc-lead skarns, table 2 summarizes the similarities between skarns in the Tin Creek area and other zinc-bearing skarns, and table 3 lists some zinc-lead skarns that formed near dikes.

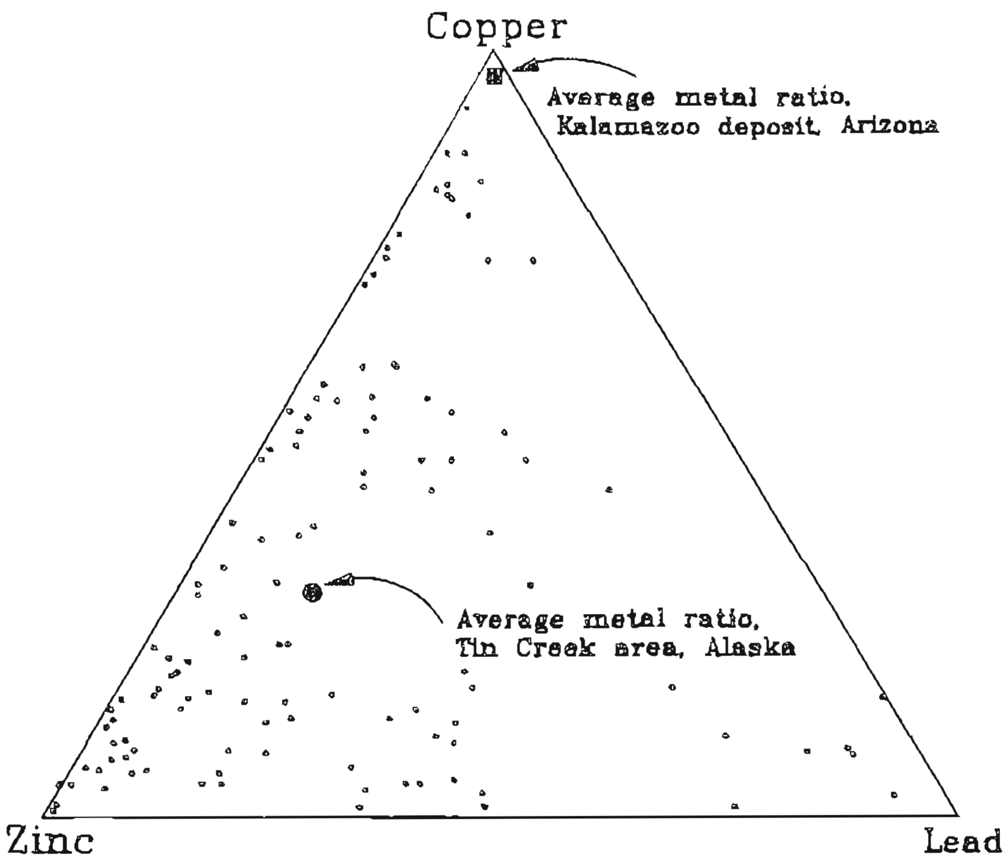

Figure 9. Comparison of metal ratios of intrusive rocks in the Tin Creek area, Alaska, with the average metal ratio for the porphyry-copper system in the Kalamazoo deposit, Arizona (Chaffee, 1982).

Skarn prospects in the Tin Creek area are some of the best explored areas in the McGrath Quadrangle, yet there has been limited drilling and detailed geologic mapping. Estimates of grade and tonnage of potentially mineable skarn deposits in the area are tentatively based on local knowledge, but estimates can also be postulated by extrapolating data from zinc-lead skarn deposits throughout the world (table 4). An inherent assumption is that the Tin Creek area contains a skarn deposit(s) that is similar in size and quality to the average zinc-lead skarn deposit.

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Table 1. Some characteristics of calcic zinc-lead skarns. From Einaudi and others, 1981.

Typical size: 0.2 - 3 million tons

Typical grade: 9% Zn, 6% Pb, 5 oz/ton Ag

Metal association (minor metals): Zn, Pb, Ag (Cu, W)

Tectonic setting: Continental margin, synorogenic to late orogenic

Associated igneous rocks: Granodiorite to granite; diorite to syenite

Co-genetic volcanic rocks: Absent or uncommon

Intrusive texture: Coarse grained to aphanitic, equigranular to porphyritic

Intrusive morphology: Large stocks or dikes

Intrusive alteration: Local, but intense endoskarn; epidote-pyroxene-garnet

Mineralogy

Prograde: Johannsenitic pyroxene, andraditic garnet, bustamite, local idocrase

Retrograde: Mn-actinolite, ilvaite, epidote, chlorite, dannemorite (amphibole)

Ore: Sphalerite, galena, chalcopyrite, arsenopyrite

Table 2. Similarities between skarns in the Tin Creek area, Alaska, and other zinc-bearing skarns.

Skarns are associated with structural pathways.

Skarns contain distinctive manganese and iron-rich calc-silicate minerals.

Skarnoid stages are absent.

Skarns contain a relatively minor degree of retrograde alteration.

Pyroxene is usually a dominant prograde calc-silicate mineral.

Dominant ore sulfides are associated with pyroxene.

Calc-silicate minerals contain significant amounts of pyroxenes (ferrous iron) and garnet (ferric iron).

The iron-sulfide mineralogy of the skarn is simple: sphalerite and galena with minor chalcopyrite and rare pyrite, pyrrhotite, and magnetite.

The iron-sulfide content in sphalerite is 12 to 20 mole percent iron sulfide (compare to Tin Creek's 14 to 20 mole percent iron sulfide in sphalerite).

Table 3. Examples of zinc-lead skarns that formed near dikes. Modified from Einaudi and others, 1981.

Locality	Metals (minor)	Tonnage grade	Host rocks	Intrusive rock	Prograde[a] minerals	Retrograde minerals	Opaque minerals	Skarn morphology	Alteration in intrusive
Groundhog mine, Central mining district, N. Mex.	Zn, Pb (Cu, Ag)	3 m.t.[b] 12% Zn 4% Pb 1% Cu 2 oz Ag/ton	Carboniferous limestone	Tertiary(?) granodiorite porphyry dikes	$Pyx(Hd_{40-45}$, $Jo_{30-50})$, Gar (Ad_{80-100}), bustamite	Ilvaite, cummingtonite, amphibole, chlorite	Sphalerite, galena, chalcopyrite, pyrite, magnetite	Along dike and other lithologic contacts	Extensive epidote-chlorite endoskarn
San Antonio mine, Chihuahua, Mexico	Pb, Zn (Cu, Sn, Ag)	3 m.t. grades unknown	Cretaceous limestone	Tertiary(?) rhyolite dikes	$Pyx(Hd_{64}Jo_{16})$, andraditic garnet	Epidote, cummingtonite, ilvaite, fluorite	Galena, sphalerite, chalcopyrite, magnetite, cassiterite	Along contacts and distal to rhyolite dikes	Sericite, [illegible]
Santa Eulalia mine, Chihuahua, Mexico	Zn, Pb, Ag	3.2 m.t. 11% Zn 10% Pb 6 oz Ag/ton	Cretaceous limestone underlain by evaporites	Rhyolite dikes and sills underlain by quartz monzonite stock	$Olv(Fa_{75}Tp_{0-25})$, hedenbergitic pyroxene, rhodonite	Ilvaite, amphibole, chlorite	Sphalerite, galena, pyrite, chalcopyrite, magnetite, pyrrhotite, arsenopyrite	Along fault and dike contacts; in chimneys	Minor sericite
Naica mine, Chihuahua, Mexico	Zn, Pb, Ag (Cu, W)	10 m.t. 10% Zn 13% Pb 13 oz Ag/ton	Cretaceous limestone, shale	Tertiary(?) rhyolite dikes	$Gar(Ad_{20-98}$, $Sp_{2-7})$ $Pyx(Hd_{40}$, $Jo_{40})$, wollastonite, idocrase, bustamite	Fluorite, chlorite, amphibole	Sphalerite, galena, chalcopyrite, pyrite, arsenopyrite, pyrrhotite, magnetite, molybdenite	Along dike and fault contacts	Garnet-idocrase endoskarn
Frisco mine, Chihuahua, Mexico	Zn, Pb, Ag (Cu)	0.5 m.t. 8% Zn 5% Pb 0.6% Cu 5 oz Ag/ton	Cretaceous shale	Tertiary(?) rhyolite dikes	Pyroxene	Amphibole ilvaite, epidote, fluorite	Sphalerite, galena, chalcopyrite, pyrite, arsenopyrite	Veins cutting shale	
Hildago mine, Santa Barbara district, Chihauhua, Mexico	Zn, Pb, Ag, Cu	? 10% Zn 15% Pb 2% Cu 8 oz Ag/ton	Cretaceous limestone, shale	Tertiary(?) rhyolite dikes	Garnet, pyroxene, idocrase(?)	Fluorite, epidote	Sphalerite, galena, chalcopyrite, pyrite, arsenopyrite	Along fault and dike contacts	Clay after feldspar

[a]Pyroxene (Pyx) composition expressed as mole percent hedenbergite (Hd) and johannsenite (Jo); remainder is diopside. Garnet (Gar) composition expressed as mole percent andradite (Ad) and spessartine (Sp); remainder is grossularite. Olivine (Olv) composition expressed as mole percent fayalite (Fa) and tephroite (Tp); remainder is forsterite.
[b]Tonnage represents estimate of total ore, or yearly production, in millions of tons (m.t.).

Table 4. Grade and tonnage for samples from 47 zinc-lead skarn deposits throughout the world. From Singer and Mosier, 1983.

	10th percentile[a]	50th percentile[b]	90th percentile[c]
Tonnage (millions of tons)	18.0	2.1	0.25
Zinc grade (%)	14.0	5.8	2.8
Copper grade (%)	1.2	0.079	---
Lead grade (%)	11.0	3.6	0.54
Silver grade (g/ton)	390.0	98.0	---

[a] Minimum grades or tonnage for 90% of the lead-zinc skarns examined.
[b] Mean or average.
[c] Minimum grades or tonnage for 10% of the lead-zinc skarns examined.