North Korea, that magnesian Au-bearing skarn may show dolomite followed by marble bearing kotoite [$Mg_3(BO_3)_2$] and ludwigite [$(Mg,Fe^{2+})_2Fe^{3+}BO_5$]; a narrow fluoborite [$Mg_3(BO_3)(F,OH)_3$]-bearing reaction zone marking the contact between skarn and marble; a marked concentration of native gold, bismuth, chalcopyrite, pyrrhotite, and cubanite just inside the reaction zone; diopside; clinohumite; and, finally, diopside partly replaced by phlogopite—all zones developed across 25–35 cm. At the Surprise, Nevada, gold skarn, limonite, fine-grained quartz, copper oxide(s), and calcite occur interstitial to massive garnet; garnet is crosscut and replaced by veins of limonite and chlorite (Schmidt and others, 1988). In this deposit, gold is present as electrum in limonite (fig. 8) associated with quartz, calcite, and secondary copper minerals. The only sulfides remaining in extensively oxidized high-grade ore currently (1989) exposed at the Surprise Mine are pyrite remnants in limonite and tiny blebs of various sulfides encapsulated in late, euhedral quartz crystals. The Buffalo Valley, Nevada, gold skarn shows widespread development of nontronite throughout much of the exposed ore.

Structural Setting

Gold-bearing skarn may occur in the immediate vicinity of, or relatively distal from, weakly mineralized intrusive rocks, commonly where wallrocks are extensively brecciated or faulted (fig. 4). On a local scale, gold-enriched dikes and small plutons astride hinge regions of broad anticlinal arches seem to have been an important structural control (Madrid, 1987). The Bau Mining District, Malaysia, lies along the axis of a major anticline flanked by synclinal basins (Wolfenden, 1965).

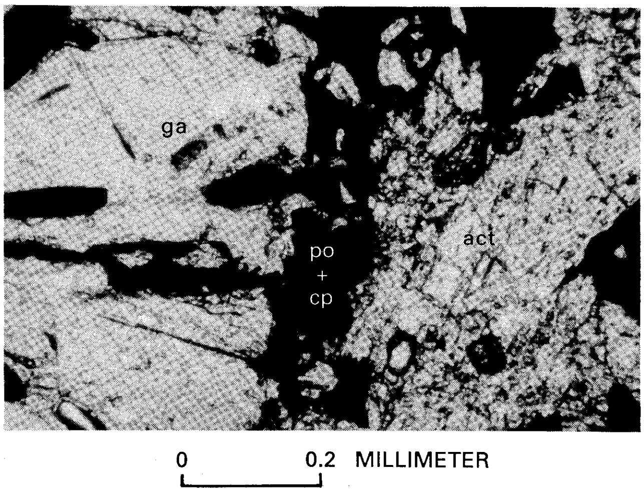

Figure 12. Photomicrograph showing massive garnet (ga), partly replaced by pyrrhotite (po) and chalcopyrite (cp) and separated from a pod of actinolite (act) grains by pyrrhotite; Fortitude Mine, Nevada.

Dimensions of Ore in Typical Deposits

Overall dimensions of ore in Au-bearing skarn are highly variable; dimensions possibly increase with distance from the genetically associated intrusive rock and as grade decreases. Geologic configuration of such deposits is largely a function of respective geometries of mineralizing magma and premineralization structures, favorable replacement sequences, and impermeable barriers to fluid flow, if present. However, eventual configuration of economic dimensions of deposits results from cut-off grades that are influenced highly by factors such as pre-mining topography (R.G. Russell, written commun., 1989).

Dimensions of Alteration or Distinctive Haloes

Alteration haloes that surround Au-bearing skarn are highly variable in size, from very restricted to as much as several kilometers from inferred loci of mineralizing systems. In some systems, the overall size of the alteration zone has been enhanced by the presence of premineralization structures that channeled fluid flow. Nonetheless, in a largely carbonate terrane, the Au-bearing skarns are almost always found within the outer limit of conversion of carbonate sequences to marble.

Effect of Weathering

The economic limits of some deposits are entirely within the oxide zone. In fact, gold grade is commonly higher in the oxide zone than in the equivalent sulfide zone. The oxide zone in some deposits includes coarsely crystalline vivianite along fractures in areas showing limited overall amounts of iron oxide development and limited amounts of subjacent iron sulfide(s) (R.G. Benson, written commun., 1988). At the McCoy, Nevada, Au-skarn, samples from the 5,080-ft bench show some extremely small, micrometer-sized crystals of greenockite (CdS) concentrated at interfaces between chalcopyrite and chalcocite. In this deposit, some chalcocite also appears to be associated paragenetically with a silver-selenide mineral, possibly $Ag_2(S, Se)$. Nontronite layers are commonly interbedded with some garnet skarn and locally concentrated along fractures in some deposits. At Browns Creek, Australia, gold-bearing nontronite was the major target of mining activity inasmuch as it typically contained greater than 10 g/t gold (Creelman and others, 1988). The term "nontronite" is used as a field term for iron-rich, yellow-green montmorillonite that swells upon treatment with ethylene glycol; a Mössbauer spectrometic study of one such clay from skarn in the Harmony Formation near the Surprise Mine shows that nearly all of the iron present in the sample is ferric iron. Thus, nontronite is the main component of the clay layer there. Clay layers include quartz and calcite and may include relict skarn silicates (pyroxene, garnet, and epidote). Oxidized karst-collapse breccia developed in marble as a result of marble reacting with acidic ground water at Red Dome (Torrey and others, 1986). At this deposit, acidic ground water probably resulted from breakdown of sulfides in the surrounding pyritic halo of the Au-skarn.

Effect of Metamorphism

Gold-bearing skarn systems could undergo regional metamorphism to yield gneiss-hosted Au deposits with a resultant loss of most contact-metasomatic features. The Tumco deposit, California, which has been metamorphosed to amphibolite grade and is provisionally included by us with Au-bearing skarn (Smith and Graubard, 1987; Tosdal and Smith, 1987), may be an example of such a process. However, some relatively extensive tin-tungsten-base-metal skarns in Alaska show readily recognizable prograde and retrograde contact-metasomatic assemblages through a superposed greenschist dynamothermal event (Newberry and others, 1986). In these Sn skarns, strain is confined largely to 1-m-wide zones at the margins of skarn where calc-silicate porphyroclastic mylonite is present. Skarn away from the contact shows some kinked chalcopyrite-bornite exsolution lamellae, but no cleavage or foliation. The Falun deposit in Sweden is hosted by Proterozoic granite, amphibolite, and quartz porphyry (Grip, 1978). Greenstone-hosted Au-Ag-W-As deposits in the Southern Cross greenstone belt of western Australia may represent Archean analogues of Phanerozoic gold skarn deposits (Mueller, 1988).

Geochemical Signatures

Geochemical signatures for Au-bearing skarn include anomalous gold primarily in an environment of retrograde-altered, sulfidized skarn. The associated pyrite in some Au-skarn deposits is reported to contain 0.1 to 250 ppm Au (Vakhrushev, 1972). At Bau, Malaysia, anomalous antimony (in stibnite) and arsenic (in scorodite) are present with gold in wollastonite-bearing skarn assemblages and in colloform-banded quartz and jasperoid, all distal to quartz- and calcite-flooded, calc-silicate gold ore (Wolfenden, 1965; W.C. Bagby, oral commun., 1987). In other Au-bearing skarn systems, quartz-calcite veins contain anomalous gold. In addition, gold mineralization and highly anomalous concentrations of gold in some skarn systems (Akshiryak Range, U.S.S.R.) are found mostly in fine-grained, gray to light-gray, highly silicified sequences of rock in carbonate beyond the outer limit of established skarn (Dolzhenko, 1974). Many Au-bearing skarns in British Columbia contain elevated abundances of arsenic, bismuth, and tellurium (Ray and others, 1987b; Ettlinger and Ray, 1989). The bismuth minerals reported from some Au-skarns include native bismuth, bismuthinite, wittichenite, hedleyite, maldonite, and Bi-bearing galena (Meinert, 1988b). Theodore and others (1989) report major-element and trace-element data for garnet skarns associated with gold mineralization at Copper Basin, Nevada, including low-grade, oxidized ore from the Surprise Mine (29 ppb Au, 6 ppm Ag, $<$10 ppm Bi, 57 ppm As, 4 ppm Sb, 3 ppm Co, 25 ppm Cu). Finally, surface expression of some Au-skarn systems (Red Dome, Australia; Surprise, Nevada) includes relatively abundant, fracture-controlled secondary copper minerals (Torrey and others, 1986; Schimdt and others, 1988).

The Au/Ag ratio in rock apparently increases laterally outward (away from the center of the associated intrusion) in some productive copper-bearing calcic skarn systems toward ore (Fortitude, Nevada) that is approximately 0.6 km from the exposed, genetically associated intrusion. The Fortitude Au-skarn is close to a relatively sharp boundary between marble and sulfidized calc-silicates (Blake and others, 1984; Theodore and others, 1986; Wotruba and others, 1987a, b; Myers and Meinert, 1988). In other Au-skarn systems that are predominantly zoned vertically close to the related intrusive rocks (Red Dome, Australia), much of the gold ore is near the original intrusion-wallrock contact and interior to massive magnetite developed at the calc-silicate-marble interface (Torrey and others, 1986). Surrounding rocks in many systems typically show high local thresholds for many associated base and ferrous metals and, for some deposits, arsenic, bismuth, selenium, and tellurium values in particular may be relatively high both within and peripheral to the Au-bearing skarn (Ray and others, 1987b).

Zonation of gold in Au- and Pb-Zn-bearing skarn (Ban Ban, Australia; Thanksgiving, Philippines; Tomboy-Minnie, Nevada) seems to show inconsistent patterns. At Ban Ban, gold in unreported trace abundances may coincide with known distribution of silver, which varies directly with lead and zinc concentrations that are, in turn, constrained tightly to the central part of associated garnet skarn (Ashley, 1980). At Thanksgiving, irregularly distributed sphalerite-pyrite pods that replace andradite skarn show higher gold contents than pyrite-magnetite replacement pods (Callow, 1967). At Tomboy-Minnie, local metal zoning of the gold orebodies shows high concentrations of gold (more than 0.05 troy oz/ton or more than 1.7 g/t); these high concentrations of gold show increased abundances of zinc and silver (more than 500 ppm and more than 0.1 troy oz/ton, or more than 3.4 g/t respectively) on the granodiorite side of the gold orebody. Such metal-zoning relations constitute a local reversal of the district-wide zoning from Cu+Au+Ag, through Au+Ag, to finally Pb+Zn+Ag (Theodore and others, 1986).

Zonation of gold in some Fe-skarn systems that contain byproduct gold (Benson Lake, British Columbia) seems to be related directly to the abundance of sulfide