(1967) presented an andradite analysis for brown garnet in garnet-clinozoisite skarn at the Thanksgiving Mine in the Philippines. Late, coarse, zoned andradite (Ad_{85} to Ad_{100}) is reported as the latest skarn mineral in some Au-bearing skarn from the Altai-Sayan region (Vakhrushev, 1972). The wider range of compositions reported for more recent (1980's) studies reflects data acquired by electron microprobe, wherein compositional data for different grains and different zones within a grain can be obtained, whereas much of the earlier data represents wet chemical analysis of a garnet separate.

Many recent studies have examined garnet zoning patterns and protolith effects on garnet composition for gold-mineralized skarn systems (for example, Beddoe-Stephens and others, 1987; Hammarstrom *in* Theodore and others, 1989; Ettlinger and Ray, 1989; Brooks and others, 1989). These studies show that (1) garnets commonly remain stable throughout extensive retrograde alteration processes, (2) TiO_2 contents of a few weight percent are typical of many garnets, especially those formed from impure carbonates or noncarbonates, and (3) although the normal zoning trends (core to rim increases in andradite content) typical of copper and base-metal skarn garnets are observed, aluminous zones and aluminous rims may be a feature peculiar to gold-mineralized systems. Ettlinger and Ray (1989) suggest that the deposition of Al-rich zones in both garnets and pyroxenes (see below) in precious-metal-enriched skarns reflects changes in availability or solubility of aluminum in the system. Alternatively, fluctuations in ferric iron-aluminum availability in the system could reflect changes in sulfidation state (J. Hemley, oral commun., 1989); that is, ore minerals (predominantly iron sulfides) could effectively deplete the iron available at silicate-hydrothermal fluid interfaces, resulting in growth of relatively aluminous zones.

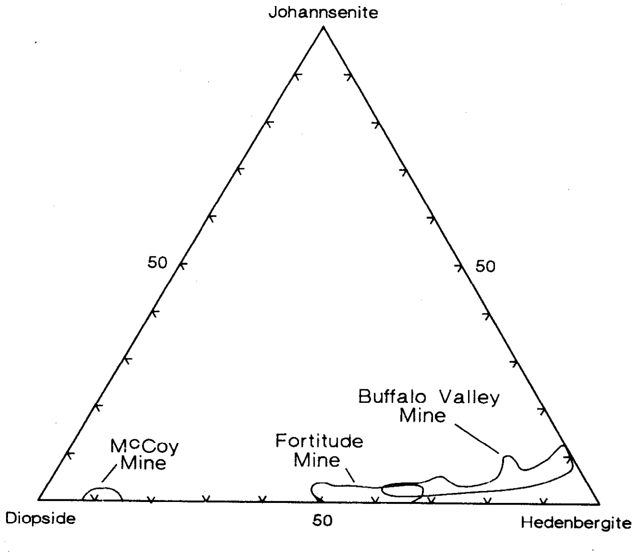

Figure 11. Ranges of pyroxene compositions for representative samples from three Au-bearing skarn systems in north-central Nevada.

Pyroxene in Au-bearing skarns is typically a diopside-hedenbergite solid solution having low manganese contents. Vakhrushev (1972) described diopside (pure to Hd_{20}) as the characteristic pyroxene of the Altai-Sayan gold skarns. Pyroxene in garnet skarn at the middle Tertiary McCoy deposit is diopside-rich (Hd_{10} to Hd_{50}, <3 percent johannsenite). Pyroxene coexisting with massive pyrrhotite, other sulfides, and late garnet at the Fortitude deposit is more iron-rich (Hd_{40} to Hd_{60}) whereas pyroxene in pale-green garnetite skarn from the 5,770-ft bench of the Buffalo Valley Mine is nearly pure hedenbergite (Hd_{80} to Hd_{92}) (table 7; fig. 11). Skarn mineral assemblages in the gold-enriched part of the Marn property, Yukon, contain iron-rich pyroxene (Hd_{40} to Hd_{80}) (Brown and Nesbitt, 1987). Brooks and others (1989) noted the presence of narrow aluminous zones in pyroxenes from the McCoy deposit. Ettlinger and Ray (1989) recognized similar zones in pyroxenes in precious-metal-enriched skarns from British Columbia and suggested that (1) the presence of high Al_2O_3+TiO_2 (>1.25 weight percent) in skarn pyroxene may be an indication of precious-metal potential, and (2) the presence of very iron rich (>26.0 weight percent FeO) or very iron poor (<3.5 weight percent FeO) pyroxenes may indicate a low precious-metal potential for a given skarn.

Amphibole typically replaces pyroxene as pseudomorphs in Au-skarns and is present with sulfides; reported compositions include actinolite, tremolite, ferro-tremolite, and hornblende. Representative amphibole compositions for some Nevada gold skarns are given in table 6, along with data for other minerals. In sulfidized skarn at the Fortitude deposit, ferro-actinolite (low fluorine, as much as 1 percent MnO, 2 percent Al_2O_3) is intergrown with or replaces pyroxene; pyroxene is present adjacent to massive garnet that is replaced partly by pyrrhotite and chalcopyrite (fig. 12). Actinolite is present with epidote and chlorite in sulfidized retrograde skarn at the Northeast Extension Mine, and in pyrite in garnet skarn at the Carissa Mine.

Wallrock Alteration

Metasomatic, anhydrous calcic (or magnesian) skarn assemblages in Au-bearing skarn are typically superposed on preceding contact-metamorphic assemblages and followed paragenetically in most deposits by hydrous assemblages with abundant sulfide(s) and (or) magnetite. Some deposits (Bau, Malaysia) show lateral gradation and subsequent replacement by jasperoid (Wolfenden, 1965; W.C. Bagby, oral commun., 1987). Calcic Au-bearing skarns typically are zoned from marble, wollastonite, diopside-hedenbergite, and finally grossular-andradite with or without retrograde tremolite-actinolite-epidote-chlorite assemblages. Watanabe (1943) reported in his study of the Suian Mining District, 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).

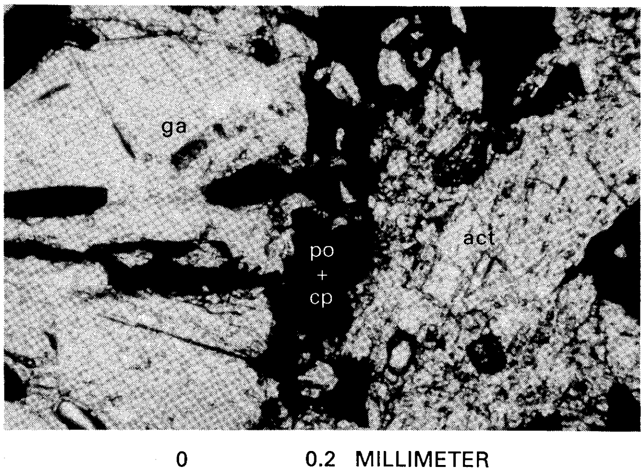

Figure 12. Photomicrograph showing massive garnet (ga), partly replaced by pyrrhotite (po) and chalcopyrite (cp) and separated from a pod of actinolite (act) grains by pyrrhotite; Fortitude Mine, Nevada.

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