

## Skarn Deposits

This text is based on the review papers of Meinert (1992) and Einaudi and Burt (1982). Much of the text is a simplified and shortened version of an updated version of the work of Meinert (1992) presented by himself in internet. Additional literature is listed in the references.

**Definition:** There are many definitions and usages of the word “skarn”. Skarns can form during regional or contact metamorphism and from a variety of metasomatic processes involving fluids of magmatic, metamorphic, meteoric, and/or marine origin. They are found adjacent to plutons, along faults and major shear zones, in shallow geothermal systems, on the bottom of the seafloor, and at lower crustal depths in deeply buried metamorphic terrains. What links these diverse environments, and what defines a rock as skarn, is the mineralogy. This mineralogy includes a wide variety of calc-silicate and associated minerals but usually is dominated by garnet and pyroxene.

Skarns can be subdivided according to several criteria. Exoskarn and endoskarn are common terms used to indicate a sedimentary or igneous protolith, respectively. These terms relate to the spatial position of the skarn body relative to an intrusion. The endoskarn bodies constitute the former igneous rocks changed by metasomatic processes into a skarn, while the exoskarns developed outside of an intrusion, in the surrounding wall rocks. A problem arises when the rocks that were changed into a skarn were chemically and mineralogically similar to the intrusion, for example, a granite body intruding into acid volcanic rocks. In such case, this type of exoskarn may also be called the “silicate skarn”.

Magnesian and calcic skarn can be used to describe the dominant composition of the protolith and resulting skarn minerals. Such terms can be combined, as in the case of a magnesian exoskarn which contains forsterite-diopside skarn formed from dolostone.

Calc-silicate hornfels is a descriptive term often used for the relatively fine-grained calc-silicate rocks that result from metamorphism of impure carbonate units such as silty limestone or calcareous shale. They represent an end-member in the skarn evolution, description, and terminology. Reaction skarns can form from isochemical metamorphism of thinly interlayered shale and carbonate units where metasomatic transfer of components between adjacent lithologies may occur on a small scale (perhaps centimetres). Skarnoid is a descriptive term for calc-silicate rocks which are relatively fine-grained and iron-poor. Genetically, skarnoid is intermediate between a purely metamorphic hornfels and a purely metasomatic, coarse-grained skarn.

**Geographic and age distribution:** Magmatic rocks which intrude into sedimentary and volcanic sequences can initiate and cause significant metasomatic overprint of these rocks, that is, the formation of a skarn. That means that skarns are located where such geological event took place. The formation of skarns then requires the emplacement of an igneous body into shallow crustal levels. A consequence of these statements is that skarns occur in orogenic belts where sufficient magmatic volumes were produced and, because of the formation at shallow levels in the crust, these are commonly geologically young. The geologically older skarns were often eroded away, although Proterozoic examples are also known. A slide below shows that skarn bodies described by Einaudi and Burt (1982) and their concentration in the Pacific rim of fire.

**Ore-bearing skarns:** Not every skarn body must necessarily carry ore minerals, even in small amounts. The definition of the skarn simply states that these rocks originated by metamorphic or metasomatic processes and their mineralogy is dominated by Ca-Fe silicates. Those bodies which contain economic ore mineralization are simply called skarn deposits. In rare cases, it is also possible that skarn deposits

originated by metamorphism of pre-existing deposits. The best examples of such deposits are Franklin, New Jersey, USA, and Broken Hill, Australia.

**Tectonic settings and geometry:** The vast majority of skarn deposits are associated with magmatic arcs related to subduction beneath continental crust. Plutons range in composition from diorite to granite although differences among the main base metal skarn types appear to reflect the local geologic environment (depth of formation, structural and fluid pathways) more than fundamental differences of petrogenesis.

Some skarns are not associated with subduction-related magmatism. These skarns may be associated with S-type magmatism following a major period of subduction or they may be associated with rifting of previously stable cratons. Plutons are granitic in composition and commonly contain primary muscovite and biotite, dark gray quartz megacrysts, miarolitic cavities, greisen-type alteration, and anomalous radioactivity. Associated skarns are rich in tin or fluorine although a host of other elements are usually present and may be of economic importance. This evolved suite includes W, Be, B, Li, Bi, Zn, Pb, U, F, and REE.

Calcic Fe-Cu skarn deposits are virtually the only skarn type found in oceanic island-arc terranes. Many of these skarns are also enriched in Co, Ni, Cr, and Au. In addition, some economic gold skarns appear to have formed in back arc basins associated with oceanic volcanic arcs. Some of the key features that set these skarns apart from those associated with more evolved magmas and crust are their association with gabbroic and dioritic plutons, abundant endoskarn, widespread sodium metasomatism, and the absence of Sn and Pb. Collectively, these features reflect the primitive, oceanic nature of the crust, wall rocks, and plutons.

Skarns formed at greater depths can be seen as a narrow rim of small size relative to the associated pluton and its metamorphic aureole. In contrast, host rocks at shallow depths will tend to deform by fracturing and faulting rather than folding. In many of the shallow skarn deposits, intrusive contacts are sharply discordant to bedding and skarn cuts across bedding and massively replaces favorable beds, equalling or exceeding the (exposed) size of the associated pluton. The strong hydrofracturing associated with shallow level intrusions greatly increases the permeability of the host rocks, not only for igneous-related metasomatic fluids, but also for later, possibly cooler, meteoric fluids. The influx of meteoric water and the consequent destruction of skarn minerals during retrograde alteration is one of the distinctive features of skarn formation in a shallow environment.

**Mineralogy of skarns:** As stated above, skarns are dominated by Ca-Fe silicates, of these especially garnets and pyroxenes. Here, we briefly review the classification of these minerals, noting some minerals which are usually not introduced during the basic mineralogy courses, but which are very important for the mineralogy of the skarn bodies. The typical minerals of the various skarn types are listed in Table 1.

<b>Garnets</b> are divided into two groups, that is, the ugrandite and the pyralspite group. Both groups derive their names from the initial letters of the garnet minerals and are therefore easy to remember. To recall these minerals and their formula, see the following table:			
ugrandite		pyralspite	
uvarovite	$\text{Ca}_3\text{Cr}_2(\text{SiO}_4)_3$	pyrope	$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$
grossular	$\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$	almandine	$\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$
andradite	$\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$	spessartite	$\text{Mn}_3\text{Al}_2(\text{SiO}_4)_3$

It is important to notice that the ugrandite garnets mix among each other and the pyralspite garnets mix among each other. Mixing between the two groups is limited (see Fig. 1, in this box). The composition of a garnet is often given as molar per cent of the components, for example,  $\text{And}_{80}\text{Gr}_{20}$ . Such abbreviations are used in Table 1.

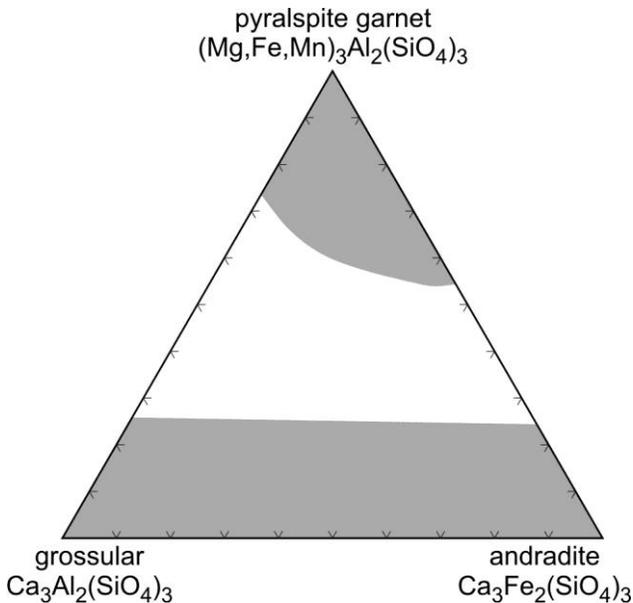
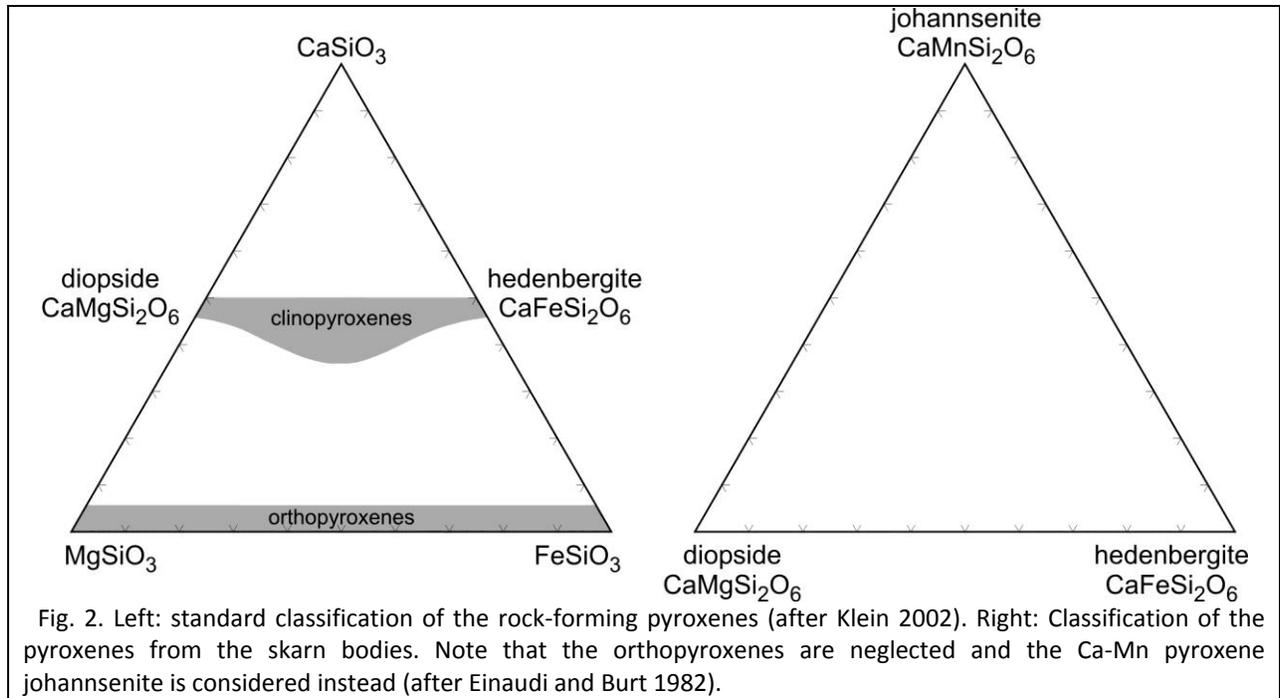


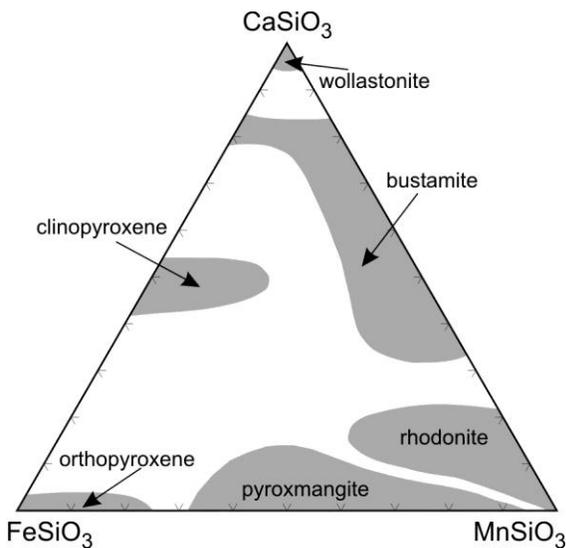
Fig. 1. The extent of solid solutions and miscibility of pyralspite and ugrandite garnets. The shaded fields show the possible composition of solid solutions of the garnet end-member components (after Klein 2002).

Naturally, skarns as bodies rich in Ca-Fe silicate contain garnets predominantly the andradite component, with some grossular component. Uvarovite component is negligible. Some skarns, especially the Pb-Zn ones, are manganese-rich, and their garnet may have elevated content of the spessartite component. Variation in the chemical composition of garnets in different types of skarns is shown in triangular diagrams in the slides.

Another group of minerals important for the skarns are the **pyroxenes**. The usual classification of pyroxenes is shown in Fig. 2 (left). For the skarns, the Ca-poor orthopyroxenes are not important at all. Actually, only the calcium-rich compositions are relevant for the discussion here. Because, as with the garnets, some skarns are manganese-rich, another pyroxene end-member is used and the composition of the pyroxenes in skarn bodies is presented in triangular diagrams diopside-hedenbergite-johannsenite (Fig. 2 right). Diagrams with the typical composition of pyroxenes for different types of skarns can be found in the slides.



The last group of silicate minerals common for the skarns are the **pyroxenoids**. These minerals, as their name suggests, are structurally and chemically related to pyroxenes, but not the same. One of the pyroxenoids can be seen in Fig. 2 (left) – the mineral wollastonite with the composition  $\text{CaSiO}_3$ . The other pyroxenoids typical for skarns are the manganese silicates rhodonite and bustamite. The compositional fields of these minerals are plotted in Fig. 3.



**Classification.** Skarn deposits are classified on the basis of the dominant metal (see Table 1). This table lists not only the most important metals but also the associated igneous rocks, tectonic settings, and the silicate and ore mineralogy of the skarns. We see a systematic relationship between the skarn type and the igneous rocks. There is also a very characteristic variation in the composition of the important rock-forming minerals; these variations are shown in the slides, taken from Einaudi and Burt (1982).

The largest skarn deposits are the iron skarns. Calcic iron skarns in oceanic island arcs are associated with iron-rich plutons of intermediate to basic rocks intruded into limestone and volcanic wall rocks. In some deposits, the amount of endoskarn may exceed exoskarn. We must stress, however, that many skarns may develop small-volume iron-rich zones with abundant magnetite which may have been mined locally. Such deposits, however, are not the typical iron skarns.

Tungsten skarns are found on most continents in association with calc-alkaline plutons in major orogenic belts. As a group, tungsten skarns are associated with coarse-grained, equigranular batholiths (with pegmatite and aplite dikes) surrounded by large, high-temperature, metamorphic aureoles. These features are collectively indicative of a deep environment. The tungsten skarns were further divided into two groups: reduced and oxidized types, based on host rock composition (carbonaceous versus hematitic), skarn mineralogy (ferrous versus ferric iron), and relative depth (metamorphic temperature and involvement of oxygenated groundwater).

Copper skarns are perhaps the world's most abundant skarn type. They are particularly common in orogenic zones related to subduction, both in oceanic and continental settings. Most copper skarns are associated with I-type, magnetite series, calc-alkaline, porphyritic plutons, many of which have co-genetic volcanic rocks, stockwork veining, brittle fracturing and brecciation, and intense hydrothermal alteration. These are all features indicative of a relatively shallow environment of formation. Most copper skarns form in close proximity to stock contacts with a relatively oxidized skarn mineralogy dominated by andraditic garnet. A number of copper skarn bodies are spatially, temporally, and genetically related to porphyry-copper deposits and their igneous rocks.

Most Pb/Zn skarns occur in continental settings associated with either subduction or rifting. Related igneous rocks span a wide range of compositions from diorite through high-silica granite. They also span diverse geological environments from deep-seated batholiths to shallow dike-sill complexes to surface volcanic extrusions. Besides their Zn-Pb-Ag metal content, Pb/Zn skarns can be distinguished from other skarn types by their distinctive manganese- and iron-rich mineralogy, by their occurrence along structural and lithologic contacts, and by the absence of significant metamorphic aureoles centered on the skarn. Almost all skarn minerals in these deposits can be enriched in manganese including garnet, pyroxene, olivine, pyroxenoid, amphibole, chlorite, and serpentine. For a number of Pb/Zn skarns, the associated igneous body has not been found or recognized, perhaps because it is too far away from the skarn itself. The mineralogy of these skarns, however, distinguishes such Pb/Zn ores clearly from other Pb/Zn deposits (for example, Mississippi-type valley ores).

Tin skarns are almost exclusively associated with high-silica granites generated by partial melting of continental crust. There is a common thread linking the several types of tin skarn deposits and that is the characteristic suite of trace elements (Sn, F, B, Be, Li, W, Mo, and Rb) in the ore and in associated igneous rocks. This suite distinguishes tin skarns from all other skarn types. Many tin skarn deposits develop a greisen alteration stage which is superimposed upon the intrusion, early skarn, and unaltered carbonate. Greisen alteration is characterized by high fluorine activities and the presence of minerals like fluorite, topaz, tourmaline, muscovite, grunerite, ilmenite, and abundant quartz. In many cases this greisen-stage alteration completely destroys earlier alteration stages. Of particular importance, greisen-style alteration is absent from all other skarn types.

Table 1. Classification and typical properties of skarn deposits. Simplified and modified after Einaudi and Burt (1982). For the abbreviation and nomenclature of garnets and pyroxenes, see the section Mineralogy in this text. Mt = millions of tons.

Type of skarn deposit	Iron	Tungsten	Copper	Zinc-lead	Tin-tungsten
typical size	5-200 Mt	0.1-2 Mt	1-100 Mt	0.2-3 Mt	0.1-3 Mt
typical grade	40 % Fe	0.7 % WO <sub>3</sub>	1-2 % Cu	9 % Zn, 6 % Pb, 150 g Ag/t	0.1-0.7 % Sn
metals (or elements) associated	Fe (Cu,Co,Au)	W,Mo,Cu (Zn,Bi)	Cu (Mo,Zn,W)	Zn,Pb,Ag (Cu,W)	Sn,F,W (Be,Zn)
tectonic settings	oceanic island arc; rifted continental margins	continental margin, syn- to late orogenic	continental margin, syn- to late orogenic	continental margin, syn- to late orogenic	continental; late to postorogenic or anorogenic
associated igneous rocks	gabbro to syenite, diorite	quartz diorite	granodiorite	plutons commonly absent; if present, granite to diorite	granite
pluton morphology	large to small stocks, dikes	large plutons, batholiths	small stocks, dikes, breccia pipes	if present, stocks and dikes	stocks, batholiths
early minerals	pyroxene (Hd <sub>20-80</sub> ), garnet (And <sub>20-95</sub> ), epidote, magnetite	pyroxene (Hd <sub>60-90</sub> , Jo <sub>5-20</sub> ), garnet (And <sub>10-50</sub> ), vesuvianite, wollastonite	garnet (And <sub>60-100</sub> ), diopside pyroxene (Hd <sub>5-50</sub> ), wollastonite	Mn-rich hedenbergite (Hd <sub>30-90</sub> , Jo <sub>10-40</sub> ), garnet (And <sub>20-100</sub> , Sps <sub>2-10</sub> ), bustamite, rhodonite	vesuvianite, spessartite-rich garnet, Sn-containing garnets, danburite, datolite
late minerals	amphibole, chlorite	garnet (Sps <sub>5-35</sub> , And <sub>5-40</sub> ), biotite, hornblend, plagioclase	actinolite, chlorite	Mn actinolite, chlorite, rhodochrosite	amphibole, mica, tourmaline, chlorite, fluorite
ore minerals (only main minerals are listed)	magnetite (chalcopyrite, cobaltite, pyrrhotite)	scheelite, molybdenite, chalcopyrite	chalcopyrite, pyrite, hematite, magnetite	sphalerite, galena, pyrrhotite, pyrite, magnetite	cassiterite, wolframite

**Zonation of skarns:** Zonation of skarn bodies is one of their distinct features and may be used in exploration and exploitation of skarn deposits. Endoskarns show mineral zoning that reflect the addition of calcium to the protolith, that is, to the igneous rocks affected by metasomatic processes. Under reducing conditions, the zones involve the minerals biotite – amphibole – pyroxene – garnet. The biotite zone is the closest one to the igneous body (located within the igneous body) whereas the pyroxene and garnet zones are further away, between the igneous body and the carbonate (limestone) wall rocks. Note that in this sequence (from left to right), the amount of water (or hydrogen) decreases and the amount of calcium increases. K-feldspar is present only in the biotite zone but plagioclase remains an important mineral throughout. Under oxidizing conditions, the assemblage epidote-quartz will be preferred over pyroxene-plagioclase and garnets tend to be more abundant.

The zoning in exoskarns involves typically garnet – pyroxene – wollastonite – calcite, where the calcite zone corresponds to the rock called marble.

**Genetic model:** Skarns, as mentioned several times here, usually originate as metasomatic products owing to fluid and element exchange between igneous rocks and the surrounding sedimentary or volcanic rocks. The fluids have high salinity, carrying massive amount of metals in the form of chlorides out of the intrusion and carrying elements into the intrusion from the wall rocks. Most garnet and

pyroxene fluid inclusions in iron skarns have homogenization temperatures of 370-700 °C and 300-690 °C, respectively, with salinities up to 50 wt. % NaCl equivalent, whereas retrograde epidote and crosscutting quartz veins have homogenization temperatures of 245-250 °C and 100-250 °C, respectively, with salinities of less than 25 wt. % NaCl equivalent. Stable isotopic investigations are consistent with fluid inclusion and mineral equilibria studies which demonstrate that most large skarn deposits form from diverse fluids, including early, high temperature, highly saline brines directly related to crystallizing magma systems.

**Exploration for skarn deposits:** Even though skarn metal contents are quite variable, anomalous concentrations of pathfinder elements in distal skarn zones can be an important exploration guide. Geochemical studies of individual deposits have shown that metal dispersion halos can be zoned from proximal base metal assemblages, through distal precious metal zones, to fringe Pb-Zn-Ag vein concentrations. Anomalies of 10s to 100s of ppm for individual metals can extend for more than 1000 meters beyond proximal skarn zones. Comparison of geochemical signatures among different skarn classes suggests that each has a characteristic suite of anomalous elements and that background levels for a particular element in one skarn type may be highly anomalous in other skarns.

Some skarns have a strong geophysical response. Almost all skarns are significantly denser than the surrounding rock and therefore may form a gravitational anomaly or seismic discontinuity. This is particularly evident in some of the large iron skarns which may contain more than a billion tons of magnetite (specific gravity of 5.18). In addition, both skarns and associated plutons may form magnetic anomalies.

Electrical surveys of skarns need to be interpreted carefully. Either disseminated or massive sulfide minerals may give strong IP, EM, or magnetotelluric responses in skarn. However, metasomatism of carbonate rock necessarily involves the redistribution of carbon. The presence of carbonaceous matter, especially if in the form of graphite, can strongly effect electrical surveys. Such carbon-induced anomalies may be distant from or unrelated to skarn ore bodies.

## Deposits related to skarns

There are a few deposits related to skarns although their origin is not quite clear. These are most likely metamorphosed pre-existing ore deposits where the protolith is difficult to define and describe. The best known examples of this type are the famous deposits in Franklin, New Jersey, USA, and Langban in Sweden. They are famous because of the large number of minerals that were described from there. An additional example is Broken Hill in Australia.

The deposit Franklin, NJ, USA was investigated for a long time, for example by Frondel and Baum (1974) and more recently Johnson and Skinner (2003). The latter authors used extensive data on regional geology, mineralogy, and isotopic composition of the ores to argue that the deposit was formed by almost isochemical metamorphism of a calcite-iron-oxide protolith. This protolith is similar to modern ferruginous exhalates in the Red Sea and is assumed to occur also in the Swedish and Australian deposits of the same type prior to the metamorphism. Furthermore, the protolith is isotopically similar to some banded iron formation ores.

The origin of the banded iron formation is not clear so far; the presence of zinc and, to some extent, manganese, is a further mystery. Johnson and Skinner (2003) propose that zinc was deposited from oxidizing fluids (in the stability field of sulfate) in the form of zinc-rich carbonates or oxides instead of a

sulfide (sphalerite). Metal precipitation in the form of carbonates or oxides can be seen as a consequence of insufficient bacterial sulfate reduction or insufficient supply of organic matter. Both possibilities could have delivered enough reduction power to reduce sulfate to sulfide and cause the precipitation of sphalerite. These metal accumulations were later metamorphosed in the sillimanite zone, causing major textural, mineralogical and some geochemical changes.

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