Lithophile-element mineralization associated with Late Cretaceous two-mica granites in the Great Basin

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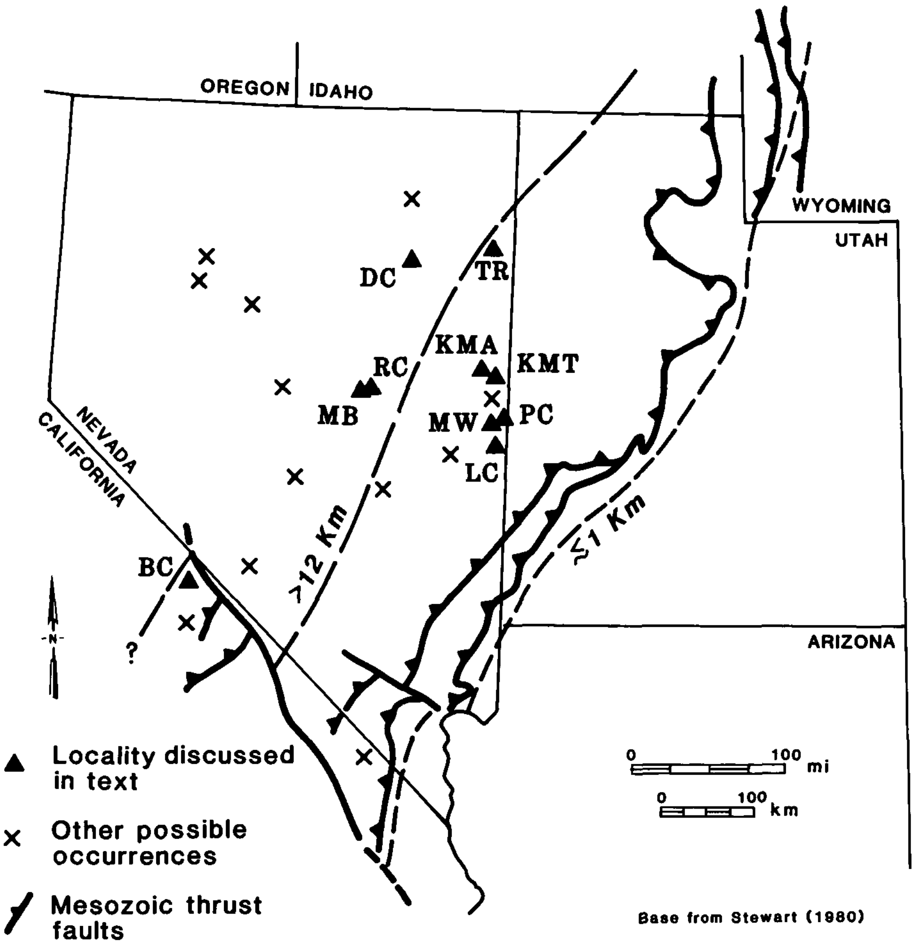
ABSTRACT

Late Cretaceous two-mica granitoids in the Great Basin are closely associated with a characteristic style of lithophile-element (Be, F, W, Mo, Sn, and Zn) mineralization. Previously undescribed in the western United States, this kind of deposit is characterized by greisenlike zones in the intrusions, distinctive F- and Al-rich skarns in carbonate rocks, F-deficient quartz veins in clastic rocks, and distal metal-bearing, quartz-carbonate veins. Mineralization can be extensive, locally reaching economic grades. These occurrences resemble greisen-type ore deposits found in other parts of the world; collectively, they constitute a new metallogenic province in the western United States.

INTRODUCTION

Although prominent in many parts of the world, lithophile-element (Be, F, Li, Mo, Sn, U, and W) mineral deposits associated with peraluminous granitoids are little known in western North America outside Alaska and northwestern Canada (Mitchell and Garson, 1981; Taylor, 1979). It has been recognized for some time, however, that peraluminous granitoids extend in a fairly continuous belt from Alaska through Canada and the United States into northern Mexico (Armstrong, 1987; Miller and Bradfish, 1980). Most of these plutons were emplaced during the Late Cretaceous and early Tertiary (Barton et al., 1987). The apparent paucity of lithophile-element mineralization associated with two-mica granites of the western United States presents a metallogenic puzzle—part of the motivation for this study.



Base from Stewart (1980)

Figure 1. Locations of two-mica granite-related lithophile-element mineralization. Also shown are foreland thrust belt and approximate isopachs on Paleozoic and latest Proterozoic sediments of Cordilleran miogeocline. BC = Birch Creek, White Mountains; DC = Dawley Canyon, Ruby Mountains; KMA = Antelope district, Kern Mountains; KMT = Tungstonia area, Kern Mountains; LC = Lexington Creek, Snake Range; MB = McCullough Butte, Fish Creek Range; MW = Mt. Wheeler Mine area, Snake Range; PC = Pole Canyon, Snake Range; RC = Rocky Canyon, Fish Creek Range; TR = Toana pluton, Toana Range.

Be, W, and F provinces spanning a variety of ages and deposit types have been recognized in the Great Basin (Griffiths, 1964; Kerr, 1946; Shawe, 1976). Most exploited Be and F deposits occur with Tertiary high-silica, commonly topaz-bearing, rhyolites, whereas exploited W deposits occur with Mesozoic granitoids. Published studies document regional distribution but do not deal with the specific timing or petrogenesis of mineralization. Moreover, only in a few areas has mineralization of any type been linked with peraluminous magmatism. New field work and a compilation of published data demonstrate that distinctive lithophile-element mineralization is associated with at least 7 to perhaps 20 or more Late Cretaceous two-mica granitic intrusions in the Great Basin (Fig. 1, Table 1, Appendix 1[1]). These occurrences are distributed approximately along the axis of the Cordilleran miogeocline ranging from east-central California to northeastern Nevada, an area closely corresponding to the belt of two-mica granites.

Several of these areas have been mined on a small scale for tungsten or explored for other commodities. The lack of attention stems in part from the fact that these occurrences appear to be lower grade than similar deposits elsewhere in the world, but it is also partly a matter of recognition. Several of the occurrences may be quite significant. The skarn at McCullough Butte (Fig. 1) contains >110 million tons of material with >10% CaF_2 and considerable but, so far, noneconomic concentrations of Zn, W, Be, Mo, and Sn. It is thus one of the world's largest fluorite resources. Exploration of Be-W-F-Sn miner-

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[1] Appendix 1, Geological Society of America Supplementary Material 8716, containing a synopsis of geologic, geochronological, petrological, and geochemical data for the identified localities in Figure 1, is available from Documents Secretary, Geological Society of America, P.O. Box 9140, Boulder, CO 80301.

Note: Additional material for this article is Supplementary Material 8716, available on request from the GSA Documents Secretary (see footnote 1).

alization at the Mt. Wheeler Mine (Fig. 1) has outlined what may be the second largest Be resource in the United States (A. M. Buranek, 1985, personal commun.) in only a small fraction of the total mineralized area (>>10^5, possibly >10^7, tons containing ~0.7% BeO, ~0.5% WO_3, and ~20% CaF_2).

This paper summarizes some geologic and geochemical features of the Great Basin occurrences and gives a synoptic geologic model for the deposit type along with a brief comparison with other deposits.

DESCRIPTION

Four components are common to the occurrences: polyphase two-mica granitoid intrusions; early-formed thermal aureoles; complex, proximal F- and Al-rich metasomatism; and distal metal-bearing quartz-carbonate veins. Several F-rich metasomatic mineral associations that occur in some or all of the areas distinguish this deposit type from others. Rather than discuss each locality, the following discussion is general. Information on individual areas is summarized in Table 1 and Appendix 1 (see footnote 1).

Medium- to coarse-grained, in places porphyritic, muscovite-biotite monzogranites and granodiorites compose the bulk of the larger intrusions. Protoclastic textures in the intrusions, locally intense deformation in adjacent country rocks, and large-scale concordance of plutons with intruded strata indicate forceful emplacement of the better-exposed plutons (e.g., Tungstonia—Best et al., 1974; Birch Creek—Nelson and Sylvester, 1971). Aplites, pegmatites, and strongly porphyritic granites crosscut the main phase and commonly extend into the country rocks.

Quartz veins, greisens, and albitized rocks formed last in the intrusions. Hydrothermal alteration is most extensive in the smaller plutons and near the margins, particularly within or near late intrusive phases. Commonly, dikes near pluton margins are pervasively muscovitized, usually to muscovite + clinozoisite + albite + quartz + K-feldspar ± fluorite, but also to muscovite + quartz ± fluorite (greisen). Abundant quartz veins range from millimetre to metre width; they commonly have greisenized, argillized, or bleached envelopes. In other cases, pegmatites grade into feldspathic quartz veins. Albitization is prominent at Dawley Canyon and has been recognized at McCullough Butte. Secondary K-feldspar has not been found. Metallization within the intrusions is limited to sparse wolframite, molybdenite, beryl, columbite, and base metal sulfides in some of the quartz/greisen veins and pegmatites.

Thermal metamorphism preceded metasomatism in the country rocks. In some areas, thermal aureoles overprint earlier deformation and metamorphism. Marbles and spatially zoned, low-Fe, calc-silicate assemblages form in purer carbonate rocks (forsterite/diopside/tremolite/talc in dolomite, or wollastonite/diopside/tremolite in limestone). Calc-silicate and pelitic hornfelses of variable mineralogy are well developed in suitable protoliths. Aureoles typically extend a few hundred metres to >1000 m from the contact regardless of the area of igneous rocks exposed.

Six metasomatic mineral associations constitute a suite that is at least partially represented in all occurrences (Table 1). These include four types of F-rich skarn in carbonate rocks, F-bearing quartz veins in clastic rocks, and Ag-, base metal–bearing, F-poor, quartz-carbonate veins in all hosts. The four associations in the extensively developed stockwork skarns show consistent temporal and spatial relations; they almost always consist of texturally and mineralogically distinct vein assemblages within metasomatic envelopes. Earliest is the garnet association (G) which consists of grossularitic ($Gr_{95}Ad_5$ to $Gr_{50}Ad_{45}$) to subcalcic (>40 mol% Alm+Sp) garnet + hedenbergitic clinopyroxene (Hd_{40-95}) ± fluorite ± idocrase ± quartz ± wollastonite ± humite ± scheelite ± pyrite. Only garnet, quartz, pyrite, and idocrase occur in veins of this association. The other minerals are restricted to vein envelopes or veinlike skarn zones lacking a texturally distinct central assemblage. Early magnesian skarns at Birch Creek contain humite + calcite and small amounts of spinel, magnetite, diopside, and andraditic (>Ad_{90}) garnet (not necessarily coexisting).

The plagioclase association (P) cuts G skarns and is characterized by plagioclase (An_{0-30}) + fluorite veins in fluorite + amphibole (actinolite-hornblende) + epidote + chlorite envelopes. Also present are idocrase, clinozoisite, biotite, apatite, muscovite, talc, quartz, magnetite, beryl, scapolite, biotite, pyrrhotite, sphalerite, pyrite, scheelite, molybdenite, chalcopyrite, and bismuthinite. Sulfides are most abundant in this association. Idocrase and epidote dominate skarns transitional from the G to P associations. In dolomitic hosts, chlorite and clinozoisite are much more prominent, sometimes to the exclusion of plagioclase.

The P veins grade into a later muscovite association (M) characterized by quartz-free muscovite + fluorite veins. Biotite (generally phlogopite), fluorite, and pyrite dominate the M-vein envelopes. Talc, actinolite, carbonates, clinozoisite, scheelite, sphalerite, beryl, phenakite, bertrandite, and cassiterite also occur. Fluorite ranges from 10% to 95%, averaging ~40% of the vein envelopes of the P and M associations; the modes and textures suggest neutralization of acid fluoride species to form fluorite and silicates. Al_2O_3 content of originally Al_2O_3-poor host rocks (determined by X-ray fluorescence) can exceed 20 wt% and average ~10 wt% in the M and P associations. Quartz association (Q) veins cut all the other F-rich skarn associations. Fluorite and muscovite are minor constituents of Q veins; silicified and/or fluoritized vein envelopes are minor or absent. Accessory minerals include pyrite, sphalerite, carbonates, and Be minerals.

In addition to a consistent temporal relation, the skarns/veins have a regular spatial distribution; later associations are progressively more widespread. Where later veins crosscut earlier assemblages, retrograde reactions occur, including garnet to epidote/clinozoisite; pyroxene to amphibole ± chlorite; and calcic plagioclase to muscovite, clinozoisite, and albite. These and other reactions produce assemblages compatible with those formed where the later veins cut fresh carbonate. Noncarbonate rocks have much simpler metasomatic mineral associations, pri-

TABLE 1. SUMMARY OF DATA ON GREAT BASIN LITHOPHILE-ELEMENT DEPOSITS

	BC	DC	KM	LC	MB	MW	PC	RC
Age (Ma)	80 ± 4	84 ± 2	75 ± 9*	86 ± 2	84 ± 2	?	79 ± 1	84 ± 2
Igneous rocks†	GAP	GPA	GAP	GAP	D_mA	D_f	GAP	D_m
Igneous exp. (km^2)	~15	~10	~90	~6	<0.01	<0.01	~10	0§
Host rocks**	DSL	MG	L?SL	L?SQ	LDQ	LSQ	LSQ	SD?L?
Alteration types††	TGP MQV	T?A	TgGP MQV	gGPQ	TDgAG PMQV	MDQV	TgGP MQ	TgGQ
Introduced elements of economic interest	F,Be,W, Zn,Pb,Ag	Be,Nb,Ta	F,W,Ag, Cu,Be	F,W(?)	F,Be,W,Zn, Mo,Sn,Ag	Be,W,F, Sn,Ag	F,Be,Mo	F,W,Mo

Note: BC = Birch Creek, White Mountains; DC = Dawley Canyon, Ruby Mountains; KM = Kern Mountains; LC = Lexington Creek, Snake Range; MB = McCullough Butte, Fish Creek Range; MW = Mt. Wheeler Mine area, Snake Range; PC = Pole Canyon, Snake Range; RC = Rocky Canyon, Fish Creek Range.

* Alteration at Tungstonia may be Oligocene as indicated by recent Ar-Ar dates (P.B. Gans, 1986, personal commun.). The apparent restriction of mineralization to areas within or near the Tungstonia pluton and the characteristic alteration support a Cretaceous origin, but further work is required.

† G = two-mica granite or granodiorite; P = pegmatite; A = aplite; D = porphyritic felsite (D_f) or two-mica granite (D_m) dikes. Listed in order of abundance.

§ Intrusive rocks are seen only in drill core.

** D = dolomite; L = limestone; S = shale; Q = quartzite; G = granitoid; M = schist or gneiss. Listed in order of abundance.

†† T = thermal metamorphism; D = dolomitization; g = greisen/quartz veins; G = garnet; P = plagioclase; M = muscovite; Q = Quartz; A = albitization (in granite); V = Ag-base-metal veins.

marily quartz veins containing minor muscovite, fluorite, and pyrite, and rare beryl, scheelite, and calcite.

F-poor, quartz-carbonate veins that contain variable amounts of silver and base-metal sulfides compose the last and most extensive of the metasomatic rock types. These Ag–base-metal veins are not unequivocally related to the magmatic events; however, they usually occur around the plutons and some occurrences have small amounts of probable magmatic components such as F and W.

PETROLOGICAL AND GEOCHEMICAL CONSTRAINTS

Some petrological and geochemical results are available for the granites and their associated alteration. Considerable data are available for many of the granites (e.g., Lee et al., 1981; Lee and Christensen, 1983; Appendix 1, see footnote 1). Of the skarns, only McCullough Butte has been intensively studied (Barton, 1982a, and in prep.).

Major-element and O, Nd, and Sr isotopic data indicate that the granites are crustal in origin and have a considerable (meta)sedimentary component (Appendix 1, see footnote 1; Farmer and DePaolo, 1983). The granites are peraluminous; normative corundum ranges from 0.5 to 5.7 wt% (averaging 2.5 wt%). Oxygen isotope compositions are uniformly heavy, ranging from 9.1‰ to 13.4‰ (whole rock). Epsilon Nd values are all less than -9. Initial Sr ratios are elevated, ranging from 0.711 to 0.737 (median = 0.713). On the other hand, low Rb/Sr (averaging 0.25); strong light-rare-earth enrichments; small to absent Eu anomalies; and other trace-element characteristics require a relatively unevolved source and little upper crustal magmatic differentiation.

Phase equilibrium considerations, oxygen-isotope partitioning, and fluid-inclusion observations indicate that the F-rich skarns at McCullough Butte formed from moderate- to low-salinity fluids with $X_{CO_2} < 0.10$ at temperatures from $\geqslant 450$ °C for the G association to $\leqslant 350$ °C for the M and Q associations. Similar conditions can be inferred for the other skarns on the basis of mineral assemblages and fluid inclusions. Alteration within the intrusions appears to have formed over a like temperature range. The garnet and pyroxene compositions indicate oxygen fugacities near CH_4-CO_2. Consistent with this, magmatic iron oxides are rare to absent (Appendix 1, see footnote 1; Lee et al., 1981). Magnetite is reported from only two of the plutons; it may be deuteric in both cases. Pressures of formation estimated from stratigraphic reconstruction and phase equilibria range from about 1.5 to >3 kbar, compatible with emplacement at 5–12 km depth.

At McCullough Butte, O, C, H, and Sr isotopic data on the F-rich skarn and the intrusion-hosted alteration are consistent with mixing between fluids with a magmatic signature and the carbonate host rocks. Only the F-poor, quartz-carbonate veins and distal, late skarns have significant meteoric water signatures.

MODEL

The broad geologic observations outlined above can be synthesized in a simple model. This is facilitated by the different levels of exposure in the various mineralized areas, as indicated by the extent of plutonic exposure. Figure 2 schematically shows the geologic relations about an ideal pluton with speculative levels of exposure for the occurrences listed in Table 1. Metasomatic alteration is strongly concentrated near the tops of the plutons. Thermal metamorphism is more evenly distributed. At shallow exposure levels, extensive F-rich skarns occur with small, highly altered dikes. Thermal contact metamorphism is approximately as extensive as the skarns; Ag–base-metal veins form in a much wider zone. At deeper erosional levels, larger plutonic exposures contain abundant late intrusive phases along with attendant quartz veins and greisen. Lesser amounts of skarn occur well within the thermal aureole, but the Ag–base-metal veins remain extensive. At the deepest relative levels, alteration of all kinds is sparse and occurs within the thermal aureoles of plutons with less abundant late intrusive phases.

The geochemical data indicate that the mineralization is a direct consequence of the emplacement of reduced, crustally derived peraluminous magmas. The overall sequence of events is similar to the general model for skarn formation presented by Einaudi et al. (1981). Early heating during forceful emplacement of the plutons led to thermal metamorphism in the host, concurrent with local development of cataclastic fabrics in the country rock and intrusions. Partial separation and subsequent crystallization of the residual liquid fraction led to development of aplites, pegmatites, and hydrothermal alteration within the intrusions. Outside the plutons, the hydrothermal fluids caused F-rich alteration (mainly skarns) primarily by neutralization reactions with the host rocks, although cooling and mixing may have played a role. Meteoric fluids remained at the fringes during these events, where they were involved principally in the formation of the Ag–base-metal veins, collapsing in on the pluton only in the waning stages of the hydrothermal system.

The distinctive Al+F enrichment of these rocks can be rationalized from the characteristics of peraluminous magmas. A necessary requirement for fluorine enrichment in late-stage magmatic fluids is low mafic and calcium content. Otherwise, fluorine will be fixed in the form of fluoride in mafic minerals or fluorite (Barton,

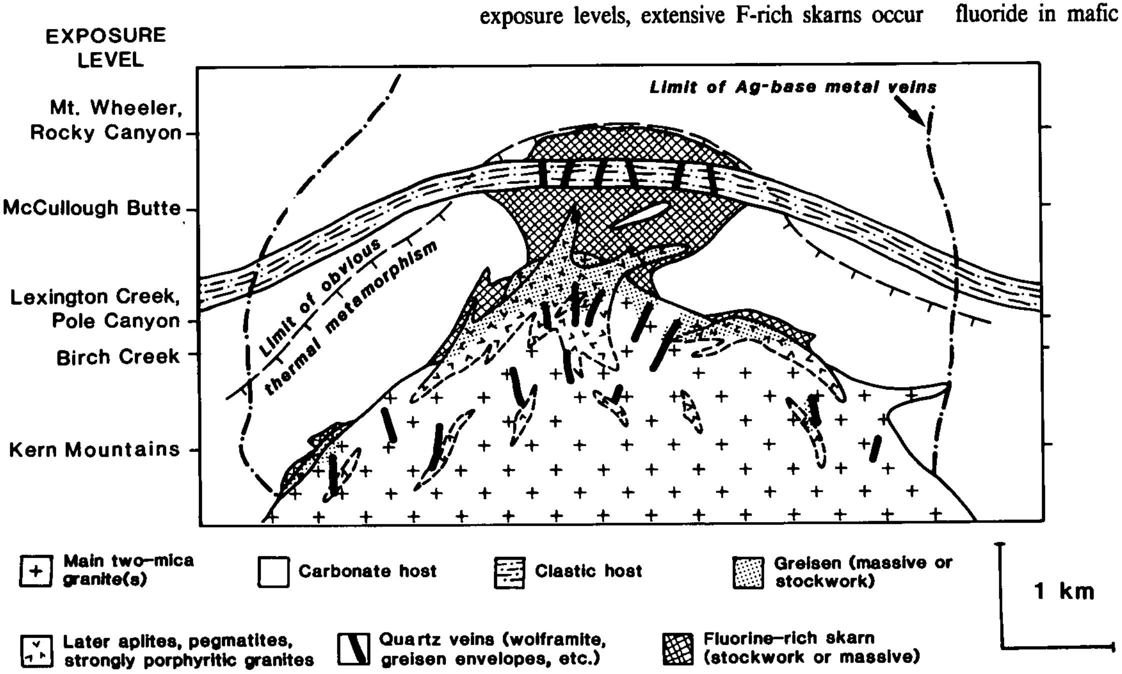

Figure 2. Schematic distribution of alteration and metamorphism about Great Basin two-mica granite. Inferred relative levels of exposure are shown for localities in Figure 1 and Table 1.

1982b). The leucocratic two-mica granites of the Great Basin meet this requirement, as do many other kinds of intrusions. High Al mobilities, however, are observed only in peraluminous systems. Experiments in progress demonstrate that F effectively complexes Al at magmatic temperatures; more than 0.1% Al goes into solution under geologically reasonable conditions. Furthermore, simple thermodynamic calculations demonstrate that the solubility of Al will be one to three orders of magnitude higher in aqueous fluids equilibrated with a peraluminous melt than with typical metaluminous melts. Thus, F- *and* Al-rich metasomatism should be restricted to peraluminous systems.

COMPARISON WITH OTHER MAGMATIC-HYDROTHERMAL DEPOSITS

The Great Basin lithophile-element occurrences differ from other western U.S. mineral deposits by their metal content, extensive stockwork skarns, igneous association, and combined F and Al enrichment. The mineralization, however, shares many characteristics with Sn-W deposits in other parts of the world.

Described skarn deposits in the western United States are predominantly of the Cu, W, Zn, or Fe types (Einaudi et al., 1981; Meinert et al., 1980). Alteration in genetically related intrusions is variably developed; it ranges from intense, as in porphyry Cu-Mo deposits, to virtually absent. Intrusion-hosted, F-rich alteration occurs in porphyry Mo(-Cu) systems of the Climax and "quartz monzonite" types. Only the quartz monzonite systems contain greisen-type alteration similar to that in the peraluminous systems; however, the Mo deposits differ by having abundant K-feldspathization (Shaver, 1984). None of the other skarn types are associated with two-mica granitoids, although many of the intrusions are weakly peraluminous. Other western U.S. lithophile-element mineralization, such as Mo- and W-rich skarn and porphyry deposits, generally lacks the combined Be, F, and Sn anomalies found in the two-mica occurrences. F-enrichments occur in few other skarns; most common are polymetallic W skarns (Einaudi et al., 1981). These polymetallic W skarns are commonly associated with quartz monzonite–type porphyry Mo mineralization; in many respects they appear to be transitional between porphyry Cu-Mo deposits and the deposits described in this paper. Large quantities of Al are mobilized along with Fe in the two-mica systems. In contrast, Al-enrichments in the other systems (e.g., some W skarns) probably reflect the lack of introduced Fe rather than an exceptional mobility of Al (Newberry and Einaudi, 1981).

The areally extensive, stockwork nature of the lithophile-element skarns is another distinguishing feature. For example, skarn underlies >5 km^2 at both McCullough Butte and the Mt. Wheeler Mine. Most other skarns tend to be fairly massive and restricted, commonly along intrusive contacts or favorable horizons. Stockwork veins may preferentially form in F-rich skarns because the formation of fluorite from carbonate results in a decrease in volume, whereas the formation of calc-silicates results in an increase in volume (conserving Ca). Thus, fracture permeability could be preferentially enhanced in F-rich systems.

The conditions of formation also distinguish the lithophile-element deposits from many others. Although the temperature and X_{CO_2} ranges coincide with those reported from other skarns, pressures of formation are higher than all but W skarns, the fluids were more reduced and less saline than most, and meteoric waters appear to have played a less significant role in most of the alteration events (see Einaudi et al., 1981, for data on other skarns).

Although the characteristics outlined above are distinctive for western U.S. mineral deposits, they resemble those of some greisen-type deposits (see Shcherba, 1970; Taylor, 1979). These deposits share strong enrichments in the lithophile elements (especially Be, F, W, Sn), associations with peraluminous granites, alteration associations (e.g., greisenization in the intrusions, evidence for high Al mobilities), and broadly similar conditions of formation. Outside the Great Basin, such deposits are of considerable economic importance. Greisen-type deposits, however, show great variation (Shcherba, 1970), and to lump them all into a single category is misleading. For example, the Great Basin occurrences lack boron minerals, topaz, and significant tin, whereas these features are abundant in many other greisen-type deposits. Such differences may ultimately be related to differences in the sources and subsequent evolution of the ore-forming magmas (Reynolds and Keith, 1982). Consistent with this are the comparatively unevolved trace-element content of the Great Basin two-mica granites.

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