Late Cretaceous Two-Mica Granites and Lithophile-Element Mineralization in the Great Basin

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Introduction

Two-mica granitoids of Late Cretaceous age are widespread along the Cordilleran miogeoclone in the Great Basin. Associated with these granitoids is a characteristic suite of lithophile elements (Be, F, Mo, Sn, W, Zn) in skarns and veins of distinctive mineralogy (Barton, 1987). Late Cretaceous magmatic and metallogenic characteristics can be rationalized in the larger context of systematic changes in Cretaceous magmatism and metallogeny (Barton, 1989).

These occurrences have been little studied, although they have much in common with mineralized, strongly peraluminous granitoids elsewhere in the world (Mitchell and Garson, 1981; Taylor, 1979). This paper presents an overview of ongoing field, petrological, and geochemical studies of the Great Basin localities.

Two-Mica Granites

More than 20 Late Cretaceous (65-105 Ma, mostly 75-90 Ma) biotite + muscovite granites and granodiorites occur along a broad belt from northeastern Nevada to east-central California (Fig. 1; Table 1; Lee et al., 1981; Barton, 1989; Miller and Barton, 1989). This zone roughly coincides with the axis of the Cordilleran miogeoclone, and lies between the main belt of Cretaceous batholiths to the west and the foreland thrust belt to the east. The zone is part of a longer belt of strongly peraluminous magmatism and Mesozoic regional metamorphism that lies inboard of the coastal batholiths along much of western North America (Miller and Bradfish, 1980; Armstrong, 1982, 1989).

The intrusions share many petrological and structural features; they differ principally in the texture and abundance of their various intrusive phases. The presence of magmatic muscovite in one or more volumetrically abundant phases (i.e., not solely in aplites or pegmatites) characterizes these rocks. In most cases, the muscovite is demonstrably igneous. Several areas where the muscovite may be secondary are also included in Table 1; these intrusions tend to be along the western margin of the miogeoclone. They are tentatively included with the indisputable two-mica granites because these occurrences have other features in common with the general picture. Whole-rock compositions are all peraluminous (molecular Al₂O₃/(CaO + Na₂O + K₂O) > 1), and most are strongly peraluminous (Al/CNK > 1.1). The plutons typically contain abundant pegmatitic and aplitic phases. Major internal contacts have been recognized where detailed mapping has been done, as at Birch Creek.
# Table 1.
## Lithophile-Element Mineralization and Two-Mica Granites

<table>
<thead>
<tr>
<th>Abbr</th>
<th>Name &amp; Location</th>
<th>Igneous rocks</th>
<th>Age (Ma)</th>
<th>Alteration types</th>
<th>Selected References</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCN</td>
<td>Birch Creek, Toiyabe Range, NV</td>
<td>B±M(?), G, A, P</td>
<td>89</td>
<td>ign: Q host: GQ</td>
<td>Stewart et al., 1977; D. L. Smith, pers. comm., 1987</td>
</tr>
<tr>
<td>CM</td>
<td>Clark Mountain, CA</td>
<td>none exposed</td>
<td>—</td>
<td>host: MQ</td>
<td>Carlisle, 1958; Crosby and Hoffman, 1951</td>
</tr>
<tr>
<td>DC</td>
<td>Dawley Canyon, Ruby Mountains, NV</td>
<td>B±M G, P, A</td>
<td>84</td>
<td>ign: AQ</td>
<td>Olson and Hinrichs, 1960; Kistler et al., 1981; Barton, 1987</td>
</tr>
<tr>
<td>KD</td>
<td>Klondyke district, Esmeralda Co., NV</td>
<td>altered M(?), G</td>
<td>104</td>
<td>ign: G host: GQB</td>
<td>Bonham and Garside, 1979; M. D. Barton, unpubl. data</td>
</tr>
<tr>
<td>LC</td>
<td>Lexington Creek, Snake Range, NV</td>
<td>B±M Gr</td>
<td>79</td>
<td>ign: GQ host: GMQ</td>
<td>Lee et al., 1981; Lee and Christiansen, 1983; Barton, 1987</td>
</tr>
<tr>
<td>MB</td>
<td>McCullough Butte, Fish Creek Range, NV</td>
<td>B+M porph. G dikes, A, P</td>
<td>84</td>
<td>ign: AOG host: DGMQB</td>
<td>Barton, 1982, 1987; Barton et al., 1982</td>
</tr>
<tr>
<td>PF</td>
<td>Papoose Flat, Inyo Range, CA</td>
<td>B±M G, A, P</td>
<td>80</td>
<td>ign: GQ host: G</td>
<td>Sylvester et al., 1978; Brigham and O'Neil, 1985; M. D. Barton, unpubl. data</td>
</tr>
<tr>
<td>PS</td>
<td>Pipe Spring pluton, Toquima Range, NV</td>
<td>B±M(?), G, A</td>
<td>80</td>
<td>ign: G host: M</td>
<td>Shaw et al., 1986; Kleinhampel and Zinyo, 1984; Tingley and Maldonado, 1983</td>
</tr>
<tr>
<td>RC</td>
<td>Rocky Canyon, Fish Creek Range, NV</td>
<td>porph. B±M G dikes</td>
<td>84</td>
<td>ign: G host: GPQ</td>
<td>Barton, 1987</td>
</tr>
<tr>
<td>RM</td>
<td>Round Mountain, Toquima Range, NV</td>
<td>B±M A, P, dikes</td>
<td>80</td>
<td>ign: G host: Q</td>
<td>Shaw et al., 1986</td>
</tr>
<tr>
<td>TO</td>
<td>Tura pluton, Tura Range, NV</td>
<td>B±M G</td>
<td>76</td>
<td>D</td>
<td>Lee et al., 1981</td>
</tr>
<tr>
<td>TR</td>
<td>Troy District, Grant Range, NV</td>
<td>B±M G, A, P</td>
<td>70</td>
<td>ign: D host: GQ</td>
<td>Kleinhampel and Zinyo, 1984; Fryxell, 1988</td>
</tr>
<tr>
<td>TU</td>
<td>Tungstonia, Kern Mtns, NV</td>
<td>B±M G, A, P</td>
<td>72</td>
<td>ign: GQ host: GPMQB</td>
<td>Best et al., 1974; Barton, 1987; Trim and Barton, this volume; Miller et al., 1988</td>
</tr>
</tbody>
</table>

1 Rock types listed in order of abundance: G = granite/granodiorite [containing: B = biotite and/or M = muscovite (queried if of uncertain origin)], A = aplite, P = pegmatite.

2 In igneous rocks: A = albite, G = greisen, Q = greisen-absent quartz veins. In sedimentary rocks: D = dolomitization, G = garnet/humite associations, P = plagioclase association, M = muscovite association, Q = quartz association, B = base-metal precious-metal association.
Fig. 2. Geologic maps of the Birch Creek area, southern White Mountains, California. A. Simplified regional geology showing the major suites of the Birch Creek granite and the overall distribution of F-rich (magmatic/hydrothermal) and F-poor (meteoric/hydrothermal) alteration associations. B. Detailed map of the northwestern portion of the Birch Creek system showing intrusive phases, aplite abundances, and limits of specific alteration associations (cf. Fig. 5).
Fig. 3. Geologic cross-section of the McCullough Butte area, Eureka County, Nevada showing the distribution of dolomitization and F-rich metasomatic rocks. Drill holes are widely spaced, some are as much as 1000 m (3100 ft) from the plane of the section.

California (Fig. 2). Metaluminous and(or) more mafic intrusive phases are absent. Margins of the larger intrusions, which probably represent more deeply exposed bodies, tend to exhibit protoclastic deformation, commonly with ductile thinning in the adjacent host rocks and other signs of forceful emplacement (e.g., the Birch Creek (CA), Papoose Flat, and Tungstonia plutons). In systems where only the upper portions of intrusions are exposed (e.g., McCullough Butte, Fig. 3), the granites tend to be strongly porphyritic and generally dike rather than ductily deform their host rocks.

Petrological and geochemical (isotope and trace element) data indicate that these are reduced intrusions that were derived largely or entirely from continental crust with a substantial metasedimentary component (Kistler et al., 1981; Farmer and DePaolo, 1983; Barton, 1989). In most intrusions, Fe-Ti oxide minerals (principally ilmenite) are scarce or absent and biotites are iron-rich (molecular Fe/[Fe + Mg] ≥ 0.6). The Birch Creek (CA) granite is unusual in that it contains about one-half percent magnetite and atypically magnesian biotite (Fe/[Fe + Mg] ~ 0.5), characteristics reflected in the relatively oxidized and iron-rich nature of the associated mineralization (see below). Uniformly low εNd (< -9), high ⁸⁷Sr/⁸⁶Sr initial (> 0.710), and high δ¹⁸O NW (whole rock ≥ 10 per mil) in these granites require crustal sources. The heavy oxygen isotopic compositions, and the paucity of metaluminous or weakly peraluminous parents from which the strongly peraluminous rocks might have differentiated require a large source component of weathered material (e.g., metasedimentary rocks). Initial Sr ratios determine on the multiple phases of the Birch Creek (CA) pluton (Fig. 2) are quite uniform and indicate effective mixing of an isotopically homogeneous source (0.7112 ± 0.0005 on 7 samples).

Although dominated by crustal components, Great Basin and many other Cordilleran two-mica granitoids have less evolved compositions than collision-related strongly peraluminous granitoids (e.g., lower K, O/Na, O, Sr/initial, δ¹⁸O; higher CaO, MgO; numerous trace element characteristics; Reynolds and Keith, 1982; Harris et al., 1986). These differences could reflect different modes of origin: massive crustal assimilation into mantle-derived magmas for the Cordilleran granitoids and crustal anatexis without a deeper component for the collisional granitoids (Barton, 1989).

Alteration and Mineralization

Nearly all the areas listed in Table 1 have associated thermal metamorphism and metasomatic alteration. Table 2 lists generalized mineral associations for the
Table 2.

<table>
<thead>
<tr>
<th>Timing</th>
<th>Granite</th>
<th>Limestone</th>
<th>Host Lithology</th>
<th>Classic rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late metasomatic (F-poor)</td>
<td>--</td>
<td>Base-metal</td>
<td>Qz + Cc + Gt + Sl</td>
<td>Base-metal</td>
</tr>
<tr>
<td>Late Quartz</td>
<td>Qz + Mu + Py/—</td>
<td>Qz + Py + Mt + Fl</td>
<td>Dtt + Bt + Sh/</td>
<td>Quartz</td>
</tr>
<tr>
<td>Greisen</td>
<td>Mu + Py + Zt + Be + Tp</td>
<td>Mu + Fl + Be</td>
<td>Bt + Cc + Sl</td>
<td>Muscovite</td>
</tr>
<tr>
<td>Ab + Mt + Fl + Py</td>
<td>Vz + Py + Mt + Sl + Sh/</td>
<td>Fl + Bt + Gt</td>
<td>Cc + Sl +</td>
<td>Fl + Bt + Sh</td>
</tr>
<tr>
<td>Early Quartz</td>
<td>Qz + Kf + Mt + Bt + Ox/—</td>
<td>Gr + Qz + Vz + Py</td>
<td>Ht + Gt + Cc + Sl</td>
<td>Humeite</td>
</tr>
<tr>
<td>Early metasomatic (F-poor)</td>
<td>--</td>
<td>Subsolidus deformation</td>
<td>Mororization, low-Fe</td>
<td>Hornfels and phyllicite</td>
</tr>
<tr>
<td>Thermal</td>
<td>--</td>
<td>Dolomitization</td>
<td>Do ± Tc</td>
<td>--</td>
</tr>
</tbody>
</table>

*Based largely on Birch Creek (CA), McCullough Butte, Mount Wheeler, and Tungsten mine. See text for discussion.

Alteration association names are shown in italics. Minerals listed in approximate order of abundance. "/" separates vein minerals (preceding) from envelope minerals (following).

"D" indicates absence of alteration. Mineral abbreviations: Ab = albite, Be = beryl, Bi = biotite, Cc = calcite, Cl = chloride, Cq = chlorite, Cm = clinozoisite, Di = diopside, Do = dolomite, Ep = epidote, Fl = fluorspar, Fo = forsterite, Gt = garnet, Ht = hornblende, Hu = humite, Kf = K-feldspar, Mt = magnetite, Mu = muscovite, Ox = Fe-Ti oxides, Pn = perovskite, Py = pyrite, Qtz = quartz, Sa = salteil, Sp = spinel, Tc = talc, Td = tremolite, Tr = tremolite, Vp = veins, Wf = wolframite, Ws = wollastonite.

alteration and their typical sequence. Significantly different assemblages at some localities (e.g., the Mount Washington district) can be rationalized in terms of specific geological variations.

The earliest metamorphic event, represented in most areas, is isothermal (except volatiles) dymotothermal contact metamorphism. Thermally metamorphosed rocks contain low-variance, low-iron calc-silicate suites in carbonate rocks (forsterite- and wollastonite-bearing assemblages represent the highest grades obtained) and non-distinctive albite-epidote-hornfels or hornblende-

hornfels assemblages in clastic rocks. Near the larger granite exposures, penetrative fabrics commonly formed during thermal metamorphism. In some areas ductile deformation continued during early hydrothermal events indicating continued magma emplacement after vapor saturation (e.g., at Birch Creek (CA), and Papoose Flat).

Most metasomatic alteration associated with the two-mica granites falls in three broad classes: (1) quartz veins and greisen-style alteration in igneous and clastic rocks; (2) distinctive, proximal F- and Al-rich skarns in carbonate rocks; (3) distal, low-grade, Ag + Zn + Pb ± Cu ± Au-

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Fig. 4. Geologic map of the vertical cut at the portal of the Mount Wheeler mine, Mount Washington district, Nevada showing veins and replacement zones in the carbonate beds of the Cambrian Pioche Shale. The replacement zones occur directly above prominent sets of quartz veins that cut the underlying clastic rocks.
bearing quartz-carbonate veins and replacements. Early F-
poor metasomatic events present in a few districts include
dolomitization of limestone and formation of oxidized
iron-rich skarns. The F-poor features are non-differenti-
ate and can be interpreted as reflecting second-order differ-
ences in geochemistry or geologic setting.

Veins are ubiquitous in most intrusions, although
their abundance and paragenesis varies considerably.
Early quartz + K-feldspar + muscovite ± biotite ± oxide
veins are gradational with pegmatitic and aplitic dikes.
Although these veins represent porassic alteration in a
general sense, hydrothermal K-feldspar rarely replaces
igneous plagioclase. Later quartz veins commonly con-
tain muscovite + pyrite ± fluorite and rare molybdenite,
woolramite, and topaz. These late veins have greisen
envelopes (muscovite[after feldspar] + quartz ± fluorite)
and intergrade with quartz-absent greisen veins
(muscovite + pyrite ± fluorite). Greisenization can be perva-
sive, rarely covering areas upwards of 100 m across.
Albitic alteration (albite[after K-feldspar and plagioclase]
+ muscovite ± quartz ± fluorite) is recognized in several
localities preceding the greisen stage; it is prominent
although volumetrically minor (<1% of exposures) at
dawny Canyon and Birch Creek (CA). Most F-bearing
veins in elastic rocks are mineralogically simple: quartz
± muscovite ± pyrite ± fluorite. Feldspar, beryl, wol-
framite, scheelite, and base-metal sulfides occur spar-
ingly in these elastic-rock-hosted, high-temperature
vein assemblages.

Fluorine- and Al-rich stockwork skarns occur in
many localities and distinguish the two-mica-related
systems from other igneous-related deposits in the Great
Basin (Barton, 1989). The skarn mineral associations
change from early garnet- or humite-rich anhydrous
skarns through a consistent sequence of fluorite-rich
hydrous skarn associations (Table 2; details for selected
localities are given in Barton, 1987, Appendix I). The
hydrus skarn associations are characterized (and named)
by their dominant minerals. They are found in many
areas, always in the sequence of plagioclase/chloroiso-
to muscovite- to quartz-dominated veins and skarns.
Systematic differences between calcic and magnesian
hosts are subdued and reflected mainly in the relative
abundance of magnesian sheet silicates. In massive car-
bonate hosts, the skarns are typically vein stockworks
and can extend several kilometers from the nearest
igneous rocks (Figs. 2 and 3).

Mineralization in the Mount Washington district

![Diagram](image)

**Fig. 6.** Metasomatic garnet and pyroxene compositions for
three skarn systems. The arrows indicate compositional changes
with time. Birch Creek is Birch Creek (CA).
has a distinctly lower-temperature set of assemblages. There, siliceous replacement bodies form where quartz + muscovite + pyrite ± beryl ± wolframite veins cutting clastic rocks reach the stratigraphically lowest Cambrian carbonates (Fig. 4). Early quartz + scheelite + Fe-Mn-carbonate assemblages give way to fluorite + adularia + quartz + phenakite + bertrandite and then muscovite + fluorite + beryl ± quartz ± carbonate ± wolframite/scheelite assemblages. This sequence resembles the Fe-Mn-silicate (relatively F-poor) to Al-rich silicate (F-rich) changes of the garnet to plagioclase to muscovite assemblages found in proximal skarns at many of the other localities. The difference may reflect far transport of fluids through non-reactive (clastic) rocks at Mount Washington before reaching a chemically favorable, but much cooler horizon.

The third alteration suite consists of F-poor, sulfide-bearing quartz veins and/or siliceous replacements. These veins occur in both clastic and carbonate rocks; they are typically peripheral to the skarns (e.g., Fig. 2A). In clastic rocks, the veins may have silicate gangue (feldspar, muscovite, or chlorite), and they appear to be partly correlative with skarn formation in the carbonates. In carbonate rocks, the quartz-rich alteration lacks silicate minerals and always appears to be later than nearby skarn assemblages. Sulfides, particularly pyrite, are common. Lead and precious metals are concentrated in the late veins and replacements, whereas Zn and the other metals appear to be concentrated in the silicate-bearing assemblages.

The alteration associations show systematic relationships in time and space. The higher temperature (and, at any given point, earlier) associations are more restricted to the vicinity of the intrusions than the lower temperature associations. The intensively studied Birch Creek (CA) system illustrates many of these relationships (Fig. 2). There, the magmatic history can be related to fluid evolution and associated alteration by cross-cutting relationships (Fig. 5). Progressive deformation during crystallization and fluid release, and multiple generations of mappable aplitic and pegmatitic dikes establish reliable time lines. Early, anhydrous calcic and magnesian skarns are related to fluid release during crystallization of the Border Suite. Later hydrous skarn assemblages can be tied directly to fluid release from the Central Suite and to subsequent greisenizing events (related to deeper, unexposed intrusive phases?). Early stages of the peripheral F-poor vein assemblages locally can be found grading into distal portions of the F-rich system.

Field, petrological, and geochemical data indicate that the igneous-hosted and skarn mineralization is dominated by magmatic components, whereas distal mineralization is dominated by meteoric fluids. Skarn silicate assemblages reflect the generally reduced, Fe-poor, Al-rich characteristics of the intrusions. Most garnet and pyroxene compositions (Fig. 6) indicate low-oxidation states, similar to many tin-tungsten skarns worldwide (Einaudi et al., 1981). An exception is the early andradite garnet at Birch Creek (CA), which is consistent with the atypically oxidized character of that intrusion. In many of the locations (e.g., at McCullough Butte, Fig. 3), no plausible non-magmatic source exists for many of the major skarn components (e.g., Al and F). Oxygen, hydrogen, and carbon isotope data for four locations (McCullough Butte, Birch Creek (CA), Tungstona, Dawley Canyon) demonstrate that the early skarn-forming events were dominated by magmatic compositions. Later, and especially peripheral events,
Fig. 8. Schematic interpretive summary of the Cretaceous magmatic, metallogenic, and metamorphic evolution of the miogeoclone (from Barton, 1989). Increasing temperature and progressive regional metamorphism are indicated by increasingly dark shading.

have meteoric isotopic signatures. This is nicely seen at McCullough Butte where the late F-poor veins and the peripheral, late F-bearing skarns record a meteoric hydrothermal system that was stacked above a magmatic system (Fig. 7). In the Kern Mountains, skarns associated with the Tungstone granite appear to be related to its emplacement, but geologic and stable isotope data indicate that Oligocene hydrothermal circulation remobilized Cretaceous metals forming granite-hosted quartz-wolframite veins (Trim and Barton, this volume).

These areas have some resource potential, although grades tend to be low. The McCullough Butte area contains \( >10^4 \), possibly \( >10^6 \) tons of material with \( >5\% \) CaF, and significant amounts of Zn, Be, W, and Mo. The Mount Wheeler mine area (Mount Washington district) has \( >10^5 \), possibly as much as \( 10^7 \) tons of material with 1-30% CaF, 0.2-2.0% BeO, 0.1-2.0% WO, and minor Sn. The low grades, compared to metallogenetically similar mineralization elsewhere in the world, may reflect systematic differences in the magma compositions and salinities of evolved fluids (Barton, 1987).

Fig. 9. Schematic distribution of alteration and metamorphism around a Great Basin two-mica granite. Inferred relative levels of exposure are indicated for several of the localities listed in Table 1. Modified from Barton (1987).
Regional and Temporal Context

The Late Cretaceous, two-mica granite-related, lithophile-element deposits are part of a magmatic and metallogenic continuum in the Cretaceous (Fig. 8; Barton, 1989). Sparse, Early Cretaceous plutons are biotite + hornblende quartz diorites and monzonites and have associated porphyry Cu mineralization (e.g., Ely, NV). Mid-Cretaceous plutons are mainly biotite granodiorites and monzogranites with associated Mo-Cu porphyry mineralization and polymetallic W skarn and replacement mineralization (e.g., Eureka, NV, Monte Cristo, NV). Finally in the Late Cretaceous, two-mica monzogranites and granodiorites predominate, with their distinctive F- and Al-rich alteration and lithophile suite of metals. Geochemical data on the igneous rocks indicate that this trend reflects an increasing crustal component with time (Barton, 1989).

The Cretaceous magmatic evolutionary patterns in the eastern Cordilleran metamorphic belt (Armstrong, 1982) in the hinterland of the Cretaceous foreland fold and thrust belt (Fig. 1) can be interpreted in several ways. One possibility is that crustal thickening in the Late Cretaceous led to thermal relaxation of the lower crust and anatexic melting, producing the two-mica granites. This mechanism does not account for the systematic magmatic changes with time, nor does it rationalize why faulting in the foreland thrust belt (in central Utah) was roughly coeval with lateral magmatism (Late Cretaceous, Heller et al., 1986) rather than earlier as required by thermal relaxation models. Also, as noted earlier, Great Basin two-mica granites differ from collision-related (more clearly anatetic) strongly perruminous granites. Available geochronometry is compatible with a Late Cretaceous metamorphic culmination (e.g., Miller et al., 1987) pointing to a Cretaceous thermal event that is reflected in upper crustal metamorphism. and that perhaps weakened the crust sufficiently to promote extensive shortening. A long-lived, deep-seated Cretaceous heat source (subduction-related mantle uprise?) better fits the geologic, geochronometric, and thermal constraints (Barton, 1989). The Cretaceous shift from mantle-dominated to crust-dominated magmatism with late, but concomitant metamorphic culmination and crustal shortening is interpreted as a consequence of long-term lithospheric warming with or without the effects of crustal thickening.

Synopsis

Combining the information from all the localities leads to a synoptic view of the idealized Late Cretaceous two-mica granite system (Fig. 9). Composite, forcefully emplaced two-mica granite plutons have extensive, equidimensional thermal aureoles. Florine-rich alteration in the intrusions (quartz veins, greisen) and the host rocks (Al-rich skarns, some quartz veins) is concentrated near the tops of the intrusions and can be tied by field and geochemical relationships to magmatic fluid sources. Late, F-poor vein and replacement deposits peripheral to the intrusions were dominated by meteoric waters. Variations in parageneses and in the distribution and intensity of alteration can be attributed to level of exposure and to specific differences in magmatic compositions and the local geologic environment. The lithophile-element deposits belong to a broader metallogenic and magmatic history in the Cretaceous, one in which metamogenesis follows changing magmatic patterns, that in turn reflect the evolving thermal and tectonic history of the Great Basin.

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