Gahnite (ZnAl$_2$O$_4$)

**Crystallography**

- **System:** Isometric
- **Class:** m3m (4/m bar3 2/m) – Hexoctahedral
- **Space Group:** Fd3m \{F4$_1$/d bar3 2/m\}
- **Cell Parameters:** $a = 8.062\text{Å}$
- **Morphology:** crystals usually octahedral
Gahnite (ZnAl$_2$O$_4$)

Physical Properties

- **Lustre:** Vitreous
- **Colour:** Dark blue-green, yellow, brown, black
- **Hardness (Mohs):** 7.5-8
- **Tenacity:** Brittle
- **Fracture:** Irregular/Uneven, Conchoidal
- **Density:** 4.62 g/cm$^3$
- **Cleavage:** indistinct
Previous Studies


- Boardman (1971): Gahnite reported in the Sedalia, Turret, Independence, and Ace High and Jackpot deposits.
- Knight (1981): Gahnite reported in the Sedalia and Bon Ton deposits.
- Ririe (1981): Described gahnite in the Green Mountain and Cotopaxi deposits and the Grape Creek district near Canyon City and noted the intimate association between gahnite and sphalerite and the possibility that gahnite formed by desulfidation of sphalerite.
- Salotti (1965): Analyzed magnesian gahnite from the Cotopaxi deposit.
- Ririe & Foster (1984): the Zn:Fe ratio of gahnite in sillimanite-bearing gneisses increases with proximity to the Cotopaxi deposit and suggested that this ratio could be used as an exploration guide to ore elsewhere.
Regional Geology

- **General map of western Colorado** showing the extent of Proterozoic rocks (grey shaded pattern; after Sheridan & Raymond 1984), terrane boundaries (after Shaw & Karlstrom 1999), and the zincian spinel localities.

1. Bon Ton deposit,
2. Cinderella deposit,
3. Sedalia deposit,
4. Ace High – Jackpot deposit,
5. Independence deposit,
6. Betty (Lone Chimney) deposit,
7. Green Mountain deposit,
8. Cotopaxi deposit,
9. Marion deposit,
10. Amethyst prospect,
11. Unnamed prospect,
12. Evergreen zone of hydrothermal alteration,
13. Caprock deposit.

MF: Mazatzal Deformation Front (Shaw & Karlstrom 1999).
Regional Geology

- The area that contains the zincian-spinel-bearing metamorphosed massive sulfides occurs in a **sequence of Proterozoic metasedimentary and metavolcanic rocks** that extends from the Wet Mountains, in the south, to the Independence Mountains, near the Colorado–Wyoming border.

- Several geochronological techniques applied to these rocks (Shaw & Karlstrom 1999) yielded **ages of formation of ~1.8 Ga** (Tweto 1980), whereas the main period of deformation and metamorphism occurred at ~1,775 to 1,700 Ma (Hedge *et al.* 1967, 1968).
Geology of Zincian Spinel Locations and The Origin of Massive Sulfide Deposits in Colorado

- **Zincian spinel occurs** in and adjacent to more than twenty occurrences of Proterozoic Cu–Zn sulfides in central and northern Colorado.
- **Metallic minerals in these deposits**: pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena, with lesser amounts of zincian spinel, magnetite, ilmenite, hematite, and rutile; Molybdenite and scheelite are locally abundant.
- **Most deposits occur in rocks metamorphosed to the upper amphibolite facies** (sillimanite zone), although those in the Wet Mountains (Amethyst, Marion, and unnamed prospect) reached the **lower granulite facies** (Sheridan & Raymond 1984).
- **Host rocks to the sulfide deposits** consist mainly of sillimanite–biotite gneiss, amphibolite, calc-silicate rock, biotite–muscovite schist, and nodular sillimanite rock.
- **Common mineralized rock-types**: garnet – biotite – muscovite schists, garnet gneisses, chlorite schists, nodular sillimanite rocks, calc-silicate rocks, iron formation, quartz garnetite, and **rocks consisting almost entirely of zincian spinel**, amphiboles (actinolite, anthophyllite, gedrite), or chlorite. **Zincian spinel is found in most of these rocks.**
<table>
<thead>
<tr>
<th>Deposit</th>
<th>Grades, reserves, past production, metallic minerals</th>
<th>Metamorphic grade, structure</th>
<th>Country rocks</th>
<th>Mineralized rocks</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ace High – Jackpot</td>
<td>Unknown grade, best sample from dump: 10% Cu, 0.4% Zn, 198 g/Ag, cp, sp, sp, mgt</td>
<td>Upper amphibolite, NS-trending isotnal folds;</td>
<td>Bi-qz gneiss, amphibolite, bi schist, nodular sil schist</td>
<td>Nodular sil-grt schist, gln-plgms-chl gneiss, grt-bit-py gneiss, mgt-bbd gneiss, aht-glm schist, cud-alt-glmms-rock</td>
<td>Van Alstine (1969), Boardman (1971)</td>
</tr>
<tr>
<td>Amethyst</td>
<td>Unknown production, sp, cp, gn, py, and po</td>
<td>Upper amphibolite-granulite</td>
<td>Amp-bit gneiss, granite</td>
<td>Spr-amp rock, spl-amp rock, spr-qz-fl-nms rock, spr-cld-plgms-rock, spr-cld-plgms-bit rock</td>
<td>Raymond et al. (1980)</td>
</tr>
<tr>
<td>Betty (Lone Chimney)</td>
<td>Past production: 3,060 g Cu, 1,680 kg Pb, 1,680 kg Zn, 4,76 kg Ag, 32 kg Au, py-cp, sp, gn, py, po, br, bn, ilm, mgt, hem</td>
<td>Upper amphibolite, shear and fault have disrupted the orebody</td>
<td>Bi gneiss, qz-ms schist, qz-cld-sil gneiss, amphibolite</td>
<td>Qz-cld-sil gneiss, nodular sil gneiss, calc-silicate gneiss, cud-alt rock, ghn rock, act-bit rock, aht rock, qz-cld rock</td>
<td>Heinrich (1981)</td>
</tr>
<tr>
<td>Bon Tim</td>
<td>Unknown grade, best sample from dump: 1.9% Cu, 6.4% Zn, 47 g/Ag, sp, cp, po</td>
<td>Upper amphibolite, complex, folds, three events of deformation</td>
<td>Psp-bt-qz-pg gneiss, amphibolite, felicicarbonate, quartzite, qz-fsp-m-sall gneiss, bt-qz-fsp-lbd gneiss, qz-fsp-bit gneiss</td>
<td>Nodular sil gneiss, iron formation, bt-schist, quartzite, ms schist</td>
<td>Knight (1981)</td>
</tr>
<tr>
<td>Caprock</td>
<td>0.9 Mt of 8% (Zn+Pb) projected reserves; sp, gn, py, po</td>
<td>Upper amphibolite, three events of folding, NS-trending thrust faults</td>
<td>Qz-fsp-sil-bt gneiss, nodular bt-sil-qz gneiss</td>
<td>Spl-aln-bit gneiss, nodular sil-nms rock, spl rock</td>
<td>Klipfel (1992)</td>
</tr>
<tr>
<td>Cinderella</td>
<td>Unknown grade, best sample from dump: 1.9% Cu, 6.4% Zn, 47 g/Ag, sp, cp, gn, py</td>
<td>Upper amphibolite, complex, folds, three events of deformation</td>
<td>Sil-qz-ms-ma gneiss, qz-koep gneiss, amphibolite, grt gneiss</td>
<td>Calc-silicate rock, nodular sil gneiss, bt-schist, bt-gneiss, ms schist, aht rock, quartzite</td>
<td>Heinrich (1981)</td>
</tr>
<tr>
<td>Cotopaxi</td>
<td>Past production: 0.01 Mt, with at least 1,177 tonnes Zn, 83 tonnes Cu, 71 tonnes Pb, 301 kg Ag, 4.5 kg Au, sp, cp, gn, po, py, mgt, tt, ilm, nhd, cp, mgt</td>
<td>Upper amphibolite, evently hosted in monocline</td>
<td>Qz-bt-fsp sil gneiss, nodular sil-schist, bhd gneiss, bt schist, calc-silicate gneiss, granite gneiss, pegmatite</td>
<td>Gln-adt rock, nodular sil-bit schist, aht-bit gneiss, gln-qz-grt rock, pegmatite gln-bit rock, chl schist, qz-bt garnetite</td>
<td>Lindgren (1908), Heinrich &amp; Sallot (1959), Stobbe (1975), Ririe (1984)</td>
</tr>
<tr>
<td>Evergreen</td>
<td>No production, sp, cp, po</td>
<td>Upper amphibolite</td>
<td>Sil-m-s-qz-aln gneiss, ged-aln-crd gneiss, amphibolite, calc-silicate rock</td>
<td>Ged-aln-crd gneiss, nodular sil-m-s rock</td>
<td>Gable &amp; Sims (1969), Heinmann et al. (2002)</td>
</tr>
<tr>
<td>Independence</td>
<td>Unknown grade but best sample from dump: 3.3% Cu, 1.5% Zn, 1.8 g/Ag, sp, cp, po, py, mgt, ilm, mgt</td>
<td>Upper amphibolite, NE-trending isoclinal folds</td>
<td>Bi-qz gneiss, granite, qz-cld-bt gneiss, pegmatite, bt-ms schist</td>
<td>Gln-adt rock, marble, nodular sil-m-s-qz gneiss</td>
<td>Lindgren (1908), Boardman (1971), Heinrich (1981)</td>
</tr>
<tr>
<td>Green Mountain</td>
<td>Best drill-hole intersection: 18.1% Cu and 4.3% Zn, over 1.5 m, cp, py, sp, gn, mo, po, ilm, hem, n</td>
<td>Upper amphibolite, broad NE-SE-trending folds</td>
<td>Qz-fsp gneiss, qz-cld-bt gneiss, migmaitite, ged-cld rock, sil gneiss, bhd-cld-bt gneiss, amphibolite</td>
<td>Nodular sil-cld-grt rock, qz-cld-grt rock, aht-glm rock, grt amphibolite, grt sil gneiss, qz gneiss, ged-hgb gneiss, ged-bt garnetite, ged-bt garnetite, ged-bt garnetite, ged-bt garnetite</td>
<td>Ririe (1981)</td>
</tr>
<tr>
<td>Marion</td>
<td>Unknown production, sp, cp, gn, py, po, sp, mgt, ilm, mgt, rt</td>
<td>Upper amphibolite-granulite</td>
<td>Amp-bearing gneiss, calc-silicate gneiss, impure marble, granite, migmaitized gneiss</td>
<td>Spr-amp-sil-bit rock</td>
<td>Boyer (1963), Heinrich (1981), Raymond et al. (1980)</td>
</tr>
<tr>
<td>Sedalia</td>
<td>1.2 Mt &amp; 3.3% Cu, 5.6% Zn, 2.3 g/Ag, 5.25 g Au, sp, cp, gn, cv, py, mgt, po, mgt, gln, ilm, native gold, native silver</td>
<td>Middle amphibolite, shallow to moderately plunging anticline</td>
<td>Feldsparic gneiss, biorex schist, amphibolite, ged-cld amphibolite gneiss, ged-bit schist, pegmatite</td>
<td>Cud-alt-sil-grt gneiss, rimor calc-silicate rocks, nodular sil-land schist, mgt-chl-aln rocks, bt-qz-cld-sil-pl rock, acl rock, tr-pl rock, tr-chl rock</td>
<td>Lindgren (1908), Boardman (1971), Heinrich (1981), Knight (1981)</td>
</tr>
<tr>
<td>Unnamed prospect</td>
<td>Unknown production, sp, cp, gn, py, po, cp, ilm, mgt, rt</td>
<td>Upper amphibolite to granulite</td>
<td>Amp-opx gneiss, calc-silicate gneiss, marble</td>
<td>Spr-amp-opx-sil-bit rock, spr-opx-sil-bit rock</td>
<td>Raymond et al. (1980)</td>
</tr>
</tbody>
</table>
Skarns or Metamorphosed Volcanic Deposits

- Lindgren (1908), Boyd (1934), and Lovering & Goddard (1950): The Proterozoic sulfide deposits of central Colorado are magmatic-hydrothermal in origin.
- Sheridan & Raymond (1977, 1984): The deposits formed on the ocean floor by volcanic-exhalative processes and were subsequently metamorphosed.
- Heinrich (1981): Cu–Zn deposits are skarns (a metamorphic zone developed in the contact area around igneous rock intrusions when carbonate sedimentary rocks are invaded by and replaced with chemical elements that originate from the igneous rock mass nearby), in large part on the basis of “skarn-like” assemblages of minerals and the presence of tungsten skarns in central Colorado. Previously, Salotti (1965) considered the Cotopaxi Cu–Zn deposit to be a skarn.
- There is however evidence to suggest that the Cu–Zn deposits are metamorphosed volcanogenic deposits rather than skarns.
Geology of Zincian Spinel Locations and The Origin of Massive Sulfide Deposits in Colorado
398 analyses of zincian spinel were obtained, along with >1,100 compositions of silicates and oxides in 114 zincian-spinel bearing rocks.

Representative compositions of spinel-group minerals and coexisting minerals.

1. Gahnite, Bon Ton
2. Spinel, Cinderella
3. Gahnite, Cinderella
4. Hercynite, Sedalia
5. Gahnite, Ace High
6. Hercynite, Independence
7. Gahnite, Independence
8. Hercynite, Betty
9. Gahnite, Betty
10. Hercynite, Green Mountain
11. Gahnite, Green Mountain
12. Spinel, Cotopaxi
13. Gahnite, Cotopaxi
14. Spinel, Marion
15. Spinel, Amethyst
16. Spinel, Unnamed Prospect (West of Amethyst)

<table>
<thead>
<tr>
<th>Table 2. Representative Compositions of Zincian Spinel from Colorado</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>SiO₂ wt.%</td>
</tr>
<tr>
<td>Al₂O₃</td>
</tr>
<tr>
<td>MnO</td>
</tr>
<tr>
<td>MgO</td>
</tr>
<tr>
<td>ZnO</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Si, Al, Fe₂⁺, Fe³⁺, Mn, Mg, Zn.
### TABLE 3. REPRESENTATIVE COMPOSITIONS OF SILICATES AND ILMENITE COEXISTING WITH ZINCIAN SPINEL FROM COLORADO

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chm 1</th>
<th>Ann 2</th>
<th>Phil 3</th>
<th>Chl 4</th>
<th>St 5</th>
<th>Ilm 6</th>
<th>Phil 7</th>
<th>Chu 8</th>
<th>Spr 9</th>
<th>En 10</th>
<th>Chu 11</th>
<th>Alm 12</th>
<th>Ath 13</th>
<th>Fo 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ wt.%</td>
<td>22.93</td>
<td>35.20</td>
<td>39.35</td>
<td>28.10</td>
<td>26.73</td>
<td>0.11</td>
<td>35.90</td>
<td>39.34</td>
<td>13.67</td>
<td>51.80</td>
<td>34.34</td>
<td>38.36</td>
<td>57.41</td>
<td>39.43</td>
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<tr>
<td>TiO₂</td>
<td>0.02</td>
<td>0.71</td>
<td>0.69</td>
<td>0.08</td>
<td>0.24</td>
<td>0.57</td>
<td>0.19</td>
<td>1.45</td>
<td>0.04</td>
<td>0.12</td>
<td>1.79</td>
<td>0.03</td>
<td>1.03</td>
<td>0.00</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>25.19</td>
<td>19.85</td>
<td>17.47</td>
<td>23.55</td>
<td>55.30</td>
<td>0.12</td>
<td>17.74</td>
<td>0.01</td>
<td>62.08</td>
<td>0.10</td>
<td>21.18</td>
<td>0.75</td>
<td>0.00</td>
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<tr>
<td>FeO</td>
<td>30.28</td>
<td>20.88</td>
<td>6.32</td>
<td>5.73</td>
<td>11.97</td>
<td>38.62</td>
<td>16.88</td>
<td>4.23</td>
<td>6.31</td>
<td>9.66</td>
<td>6.03</td>
<td>20.21</td>
<td>6.82</td>
<td>13.71</td>
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<tr>
<td>MnO</td>
<td>0.75</td>
<td>0.26</td>
<td>0.06</td>
<td>0.05</td>
<td>0.30</td>
<td>5.36</td>
<td>0.04</td>
<td>0.30</td>
<td>0.06</td>
<td>0.19</td>
<td>0.14</td>
<td>12.94</td>
<td>4.58</td>
<td>4.04</td>
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<tr>
<td>ZnO</td>
<td>0.44</td>
<td>0.38</td>
<td>0.50</td>
<td>0.89</td>
<td>2.52</td>
<td>4.84</td>
<td>0.35</td>
<td>0.02</td>
<td>0.00</td>
<td>0.17</td>
<td>0.00</td>
<td>0.19</td>
<td>0.19</td>
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<tr>
<td>MgO</td>
<td>9.03</td>
<td>8.73</td>
<td>22.43</td>
<td>28.70</td>
<td>1.58</td>
<td>0.15</td>
<td>12.63</td>
<td>54.56</td>
<td>17.46</td>
<td>31.48</td>
<td>53.13</td>
<td>5.47</td>
<td>25.90</td>
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<td>CaO</td>
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<td>0.08</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.14</td>
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<td>0.08</td>
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<td>Na₂O</td>
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<td>0.26</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.48</td>
<td>0.00</td>
<td>0.03</td>
<td>0.05</td>
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<td>0.10</td>
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<td>K₂O</td>
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<td>7.87</td>
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<td>9.52</td>
<td>0.00</td>
<td>0.02</td>
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<td>F</td>
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<td>0.53</td>
<td>0.76</td>
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<td>0.47</td>
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<td>0.61</td>
<td>0.26</td>
<td>6.24</td>
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<td>Cl</td>
<td>0.13</td>
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<td>0.08</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
<td>0.11</td>
<td>0.05</td>
<td>0.03</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
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<tr>
<td>Total</td>
<td>88.87</td>
<td>95.67</td>
<td>96.29</td>
<td>87.17</td>
<td>99.02</td>
<td>100.00</td>
<td>96.14</td>
<td>102.83</td>
<td>100.35</td>
<td>99.17</td>
<td>102.01</td>
<td>100.36</td>
<td>97.59</td>
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<td>Oxygen atoms</td>
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<td>14</td>
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<td>Si apfu</td>
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<td>3.080</td>
<td>6.037</td>
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<td>0.974</td>
<td>0.225</td>
<td>0.092</td>
<td>0.003</td>
<td>0.121</td>
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<td>0.003</td>
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<tr>
<td>Al</td>
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<td>3.588</td>
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<td>3.150</td>
<td>0.001</td>
<td>8.680</td>
<td>0.231</td>
<td>0.111</td>
<td>3.928</td>
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<td>0.459</td>
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<td>0.825</td>
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<td>0.626</td>
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<td>0.452</td>
<td>2.660</td>
<td>0.791</td>
<td>0.29</td>
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<td>0.033</td>
<td>0.008</td>
<td>0.004</td>
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<td>0.011</td>
<td>1.725</td>
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<td>0.043</td>
<td>0.052</td>
<td>0.063</td>
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<td>0.001</td>
<td>0.000</td>
<td>0.011</td>
<td>0.000</td>
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<td>0.681</td>
<td>0.006</td>
<td>2.837</td>
<td>6.853</td>
<td>3.088</td>
<td>1.667</td>
<td>7.105</td>
<td>12.84</td>
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<td>1.628</td>
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<td>Ca</td>
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<td>0.013</td>
<td>0.004</td>
<td>0.004</td>
<td>0.007</td>
<td>0.000</td>
<td>0.005</td>
<td>0.013</td>
<td>0.005</td>
<td>0.003</td>
<td>0.000</td>
<td>0.357</td>
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<td>0.000</td>
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<tr>
<td>Na</td>
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<td>0.076</td>
<td>0.201</td>
<td>0.000</td>
<td>0.003</td>
<td>0.000</td>
<td>0.141</td>
<td>0.000</td>
<td>0.007</td>
<td>0.003</td>
<td>0.000</td>
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<td>K</td>
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<td>1.713</td>
<td>1.421</td>
<td>0.004</td>
<td>0.002</td>
<td>0.001</td>
<td>1.829</td>
<td>0.000</td>
<td>0.003</td>
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<tr>
<td>F + Cl</td>
<td>0.023</td>
<td>0.268</td>
<td>0.361</td>
<td>0.000</td>
<td>0.321</td>
<td>0.003</td>
<td>0.252</td>
<td>0.735</td>
<td>0.235</td>
<td>0.031</td>
<td>1.781</td>
<td>0.013</td>
<td>0.307</td>
<td>0.002</td>
</tr>
</tbody>
</table>

- 1, 2: Bon Ton
- 3, 4: Ace High
- 5, 6: Independence
- 7: Green Mountain
- 8: Marion
- 9: Amethyst
- 10, 11: Unnamed prospect
- 12, 13, 14: Caprock
Figure 4 is a plot of spinel compositions from the thirteen locations studied here in terms of gahnite, hercynite, and spinel components.
• Zincian spinel has been known in Colorado for over 100 years.

• It occurs in massive sulfides and associated Fe–Al-rich rocks (Bon Ton, Independence, and Sedalia deposits), Mg–Ca–Al-rich rocks (Ace High, Amethyst, and Marion deposits) and in both Fe–Al-rich and Mg–Ca–Al-rich rocks (Cotopaxi, Cinderella, Caprock and Betty).

• In Fe–Al-rich rocks, zincian spinel occurs in contact with sillimanite, zincian staurolite, with up to 2.4 wt. % ZnO, biotite, garnet, and sphalerite.
Zoning

- **Compositional zoning** observed in spinel grains from the Ace High – Jackpot, Independence, Betty, and Green Mountain deposits shows weak to moderate enrichment of the gahnite component and a corresponding depletion in spinel and hercynite components from the center to the edge of grains. It indicates that gahnite formed during the prolonged metamorphic history.
Gahnite associated with Metamorphosed Massive Sulfide Deposits

- Figure 6. This triangular plot of spinel compositions in terms of Zn, Fe, and Mg from 106 sulfide-free and sulfide-bearing locations, is an attempt to distinguish zinc-bearing spinel associated with metamorphosed massive sulfide deposits from that found in marbles, granitic pegmatites, and aluminous metasedimentary rocks.

(1) Marbles,
(2) metamorphosed massive-sulfide deposits
(3) granitic pegmatites,
(4) aluminous metasedimentary rocks
(after Spry & Scott 1986a)
Metamorphic Grade

- Zincian spinel associated with metamorphosed massive sulfide deposits contains 55–90 mole % ZnAl2O4, 10–40 mole % FeAl2O4, and 5–20 mole % MgAl2O4. Spry (2000) the dependence of zincian spinel compositions on temperature.
- Green zincian spinel that coexists with minor galena and chalcopyrite in metapelites and quartzites subjected to the granulite facies at Orangefontein, South Africa (Hicks et al. 1985) is highly enriched in the spinel component, whereas blue zincian spinel in the same rocks, but associated with a retrograde greenschist-facies event, is enriched in the gahnite component.
- Hercynite (eqm with quartz) is stable at granulite-facies conditions \(\Rightarrow\) amphibolite-greenschist-facies conditions by addition of Zn. (Shulters & Bohlen 1989)
- Examples:
  - Low proportion of gahnite in some zincian samples from Mamandur deposit in India, which formed during granulite-facies condition.
  - High proportion of gahnite in samples from Orangefontein, South Africa. (greenschist-facies).
- Spinel-group minerals in metamorphosed massive sulfide deposits hosted by hydrothermally altered aluminous metasedimentary and metavolcanic units exhibit the following compositional range: Gah45–90Hc0–45Spl0–25. This range of zincian spinel compositions is considered to be useful as a guide to ores in Fe–Al-rich rocks.
The relationship between bulk-rock composition and the composition of zincian spinel

- samples of zincian spinel enriched in the **spinel** component (i.e., field 1 in Fig. 4) coexist with silicates with compositions that fall close to the **MgO–Al2O3** join. (Mg- and Mg–Ca-rich rocks from the Cotopaxi, Marion, Amethyst and Caprock deposits)
- those enriched in the **gahnite or hercynite** components generally coexist with silicates less enriched in Mg and more **enriched in Fe**. (spinel compositions in field 2 occur in Fe–Al-rich rocks in the Bon Ton, Betty, Sedalia, Green Mountain, and Independence deposits, as well as some rocks from the Cotopaxi and Caprock deposits.)
Zincian-spinel-forming reactions

- The **gahnite** component of zincian spinel in parts of the Bon Ton, Green Mountain, Cotopaxi, and Caprock deposits was likely a **product of sulfidation–oxidation reactions** of the type (Spry & Scott 1986a, Spry 2000):

\[
\begin{align*}
\text{ZnS} + \text{Al}_2\text{SiO}_5 + \frac{1}{2}\text{O}_2 & = \text{ZnAl}_2\text{O}_4 + \text{SiO}_2 + \frac{1}{2}\text{S}_2 \\
\text{sphalerite} & \quad \text{sillimanite} & \quad \text{gahnite} & \quad \text{quartz}
\end{align*}
\]

\[
\begin{align*}
\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12} + \text{ZnS} + \text{S}_2 & = \text{ZnAl}_2\text{O}_4 + 3\text{FeS} + 3\text{SiO}_2 + \text{O}_2 \\
\text{almandine} & \quad \text{sphalerite} & \quad \text{gahnite} & \quad \text{pyrrhotite} & \quad \text{quartz}
\end{align*}
\]

- The replacement of sillimanite by gahnite from the Bon Ton deposit is supportive of a desulfidation mechanism, although a **sulfur-free reaction of the type** (Segnit 1961):

\[
\begin{align*}
2\text{Al}_2\text{Si}_2\text{O}(\text{OH})_4 + \text{ZnO} & = \text{ZnAl}_2\text{O}_4 + \text{Al}_2\text{Si}_2\text{O}_5 + 3\text{SiO}_2 + 4\text{H}_2\text{O} \\
\text{kaolinite} & \quad \text{zincite} & \quad \text{gahnite} & \quad \text{sillimanite} & \quad \text{quartz}
\end{align*}
\]

may have also been responsible for the formation of coexisting gahnite and sillimanite in sulfide-free rocks,

- It is also likely that other zincian-spinel-forming reactions occurred in and adjacent to each of the sulfide deposits. These reactions could involve

- **(1) the breakdown of Zn-bearing biotite at the Green Mountain deposit,**
- **(2) the breakdown of zincian staurolite at the Independence deposit,** and
- **(3) the precipitation from a metamorphic hydrothermal solution** in pegmatitic veins and metamorphic segregations in the Cotopaxi deposit. Textural evidence and mass-balance considerations indicate that hercynite from Evergreen, which occurs in corona and symplectite textures along with cordierite, corundum,
Conclusion

- Zincian spinel [(Zn,Fe,Mg)Al₂O₄] is an accessory mineral in a variety of rock types, in particular, metamorphosed massive sulfide deposits, pegmatites, aluminous metasedimentary rocks, skarns, marbles, and sulfide-bearing granulites.

- The composition of zincian spinel in rocks is controlled by a variety of physical and chemical parameters: \( f(O_2) \), \( f(S_2) \), pressure, temperature, the composition of the host rocks, and the ability of minerals in the host rock, other than spinels and sulfides, to incorporate Zn in their structures.

- The gahnite-to-hercynite ratio of zincian spinel is higher at low metamorphic grades (e.g., upper greenschist facies) than at high metamorphic grades (e.g., granulite facies), and at high \( f(O_2) \) and \( f(S_2) \) conditions.

- Nearly all occurrences of zincian spinel in and adjacent to metamorphosed massive-sulfide deposits are hosted by hydrothermally altered aluminous metasedimentary and metavolcanic rocks and have the following compositional range: Gahnite_{45–90} Hercynite_{0–45} Spinel_{0–25}.

- However, zincian spinel in zones of unusually Mg-rich (and Ca-rich) alteration spatially associated with metamorphosed massive-sulfide deposits, as observed for example in Colorado, are more enriched in the spinel component and show a markedly different compositional range: Gahnite_{0–65} Hercynite_{0–50} Spinel_{25–90}.

- The gahnite component of zincian spinel in parts of the Bon Ton, Green Mountain, Cotopaxi, and Caprock deposits was likely a product of sulfidation–oxidation reactions: gahnite was a product of the retrograde breakdown of zincian biotite.

- The Zn:Fe ratio of gahnite in sillimanite-bearing gneisses increases with proximity to the Cotopaxi deposit and suggested that this ratio could be used as an exploration guide to ore elsewhere.