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GEOLOGICAL SURVEY

# GEOCHEMISTRY OF LARAMIDE AND MIDDLE TERTIARY PLUTONS IN THE AJO MINING DISTRICT, PIMA COUNTY, ARIZONA

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Geochemistry of Laramide and Middle Tertiary Plutons
in the Ajo Mining District, Pima County, Arizona

The Ajo Mining District comprises the Ajo porphyry copper deposit and various small vein deposits in the Little Ajo Mountains of western Pima County, Arizona. The New Cornelia Mine, developed on the Ajo deposit by Phelps Dodge Corporation has produced 2.5 million tonnes of copper since it was opened in 1917. Ajo is the westernmost deposit of a large cluster of porphyry Cu-Mo deposits in southern Arizona and, although molybdenum is recovered from parts of the deposit, it most closely matches the porphyry Cu-Au model of Cox(1986).

The geology of the Ajo 15 minute quadrangle and the New Cornelia Mine was described by Gilluly (1946), and of the surrounding region by Gray and others (1988). Precambrian gneiss and granite and felsic volcanic rocks of possible Mesozoic age are intruded by granitic rocks of quartz diorite to monzogranite composition which he called the Cornelia quartz monzonite. Copper mineralization is related to a granodiorite porphyry phase of this pluton.

Analyses of 19 rock samples from the Ajo district are presented in table 1 and 2 and their locations are shown on figure 1. They illustrate the differences and similarities between rocks of the Cornelia pluton (Gilluly, 1946), located around the New Cornelia Mine and on Camelback Mountain, and the pluton of Cardigan Peak, lying to the west of Gibson Arroyo (see Fig. 2). The first has K-Ar ages clustered around 61 Ma and the second has K-Ar and incomplete U-Pb ages of approximately 25 Ma (McDowell, 1980; Hagstrum and others, 1987). The two rock units are similar in appearance and major-element chemistry and were considered by Gilluly (1946) to be parts of the same intrusion.

The rock samples are grouped by age on tables 1 and 2: four samples belong to the Cornelia pluton; one sample of uncertain age and affinity closely resembles quartz diorite of the Cornelia pluton but crops out on the west margin of the Cardigan Peak pluton; 12 samples are from the Cardigan Peak pluton; and two samples represent porphyritic dikes intruding the Cardigan Peak pluton and the Cornelia pluton on Camelback Mountain.

X-ray spectroscopic analyses of major element oxides and Nb were made by A. J. Bartel, Kathleen Stewart, and J. E. Taggart in Lakewood Colorado, and L. F. Espos in Menlo Park, California. Determination of FeO, $H_20$, $CO_2$, Cl, and F were made by D. V. Vivit in Menlo Park. Be, Co, Cr, Cu, Ga, Ni, Pb, and V were determined by emission spectrograph by Judith Kent and R. L. Lerner in Menlo Park. Sn, and Nb were determined colorimetrically by J. S. Kane and M. W. Doughten in Reston, Virginia, respectively. Remaining elements in table 2 were determined by instrumental neutron activation analysis by J. Storey, J. R. Budahn, R. J. Knight, S. Danehey, and R. B. Vaughn in Lakewood.

Rocks of the Cardigan Peak pluton are indistinguishable from those of the Cornelia pluton with respect to major elements and most trace elements. The Peacock index ( 57, see Figure 3) is the same for both plutons; they are calc-alkalic. The Cardigan Peak rocks differ in their higher content of thorium, hafnium, and zirconium (Fig. 4a-c), and rare earth elements (Fig. 4d-f and Fig. 5a-d). In plots of these elements against $SiO_2$, sample 516 of quartz diorite (KT?fd) from the undated western margin of the Cardigan Peak pluton consistently falls within the cluster of Cornelia pluton samples. This suggests that this quartz diorite unit is the same age as the quartz diorite (KTfd) on Camelback Mountain to which it bears a close resemblance (Cox and Ohta, 1984.

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**Table 1. Major element chemistry of rocks from the Ajo district, Arizona**

[Values in percent]

| | Cornelia Pluton (61 Ma) | | | | Unknown age | Cardigan Peak Pluton (25 Ma) | | | | | | | | | | | | Dike rocks | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | 214 | 540 | 805 | 806 | 516 | 436 | 434 | 264 | 44 | 278 | 289 | 270 | 101 | 252 | 24 | 315 | 311 | 503 | 517 |
| SiO2 | 59.7 | 64.4 | 64.5 | 65.7 | 61.1 | 59.6 | 63.2 | 66 | 67.4 | 70.1 | 67.1 | 70.4 | 71.5 | 76.7 | 77.5 | 73 | 77.5 | 64.3 | 63.1 |
| Al2O3 | 16.8 | 16.3 | 15.6 | 15.4 | 16.1 | 16 | 16.4 | 15.9 | 15.4 | 14.8 | 15.5 | 14.8 | 14.4 | 12.6 | 12.1 | 14.1 | 12.2 | 16 | 16.2 |
| Fe2O3 | 3 | 2.09 | 2.1 | 2.29 | 2.44 | 2.48 | 2.02 | 2.16 | 1.52 | 1.18 | 1.661 | 1.28 | 1.42 | 0.154 | 0.492 | 0.304 | 0.364 | 2.06 | 2.45 |
| FeO | 2.43 | 1.71 | 1.68 | 1.57 | 2.03 | 3.19 | 1.5 | 1.23 | 1.46 | 0.38 | 1.25 | 0.89 | 0.44 | 0.05 | 0.07 | 0.32 | 0.05 | 1.63 | 1.36 |
| MgO | 3.05 | 1.69 | 1.6 | 1.79 | 3.06 | 3.85 | 2.31 | 1.53 | 1.47 | 0.95 | 1.45 | 0.79 | 0.63 | 0.14 | 0.17 | 0.57 | 0.14 | 1.81 | 1.93 |
| CaO | 4.8 | 3.96 | 3.27 | 3.43 | 4.94 | 5.63 | 4.65 | 3.03 | 2.89 | 2.58 | 3 | 2.07 | 1.73 | 0.75 | 0.36 | 1.45 | 0.53 | 3.45 | 4.05 |
| Na2O | 4.31 | 4.31 | 4 | 3.98 | 3.88 | 3.47 | 3.91 | 3.78 | 3.62 | 3.57 | 3.63 | 3.37 | 3.35 | 3.28 | 3.11 | 2.95 | 3.38 | 4.06 | 3.88 |
| K2O | 2.42 | 2.98 | 3.42 | 3.1 | 2.92 | 3.18 | 3.68 | 3.97 | 4.14 | 4.46 | 4.17 | 4.65 | 4.85 | 4.8 | 5.23 | 5.54 | 4.74 | 3.52 | 4.03 |
| TiO2 | 0.87 | 0.57 | 0.54 | 0.57 | 0.57 | 0.79 | 0.67 | 0.43 | 0.44 | 0.34 | 0.44 | 0.28 | 0.23 | 0.12 | 0.1 | 0.21 | 0.1 | 0.51 | 0.59 |
| P2O5 | 0.28 | 0.23 | 0.2 | 0.21 | 0.22 | 0.38 | 0.29 | 0.19 | 0.18 | 0.14 | 0.18 | 0.1 | 0.09 | <0.05 | <0.05 | 0.07 | <0.05 | 0.23 | 0.24 |
| MnO | 0.09 | 0.05 | 0.03 | 0.06 | 0.04 | 0.09 | 0.03 | 0.04 | 0.05 | <0.02 | 0.03 | 0.03 | 0.04 | <0.02 | <0.02 | <0.02 | <0.02 | 0.03 | 0.02 |
| H2O+ | 1.1 | 0.59 | 1.11 | 0.67 | 0.93 | 0.5 | 0.38 | 0.46 | 0.31 | 0.32 | 0.39 | 0.08 | 0.35 | 0.19 | 0.08 | 0.25 | 0.44 | 0.88 | 0.61 |
| H2O- | 0.12 | 0.12 | 0.16 | 0.16 | 0.27 | 0.09 | 0.14 | 0.2 | 0.17 | 0.17 | 0.16 | 0.16 | 0.18 | 0.08 | 0.14 | 0.22 | 0.03 | 0.22 | 0.18 |
| CO2 | 0.1 | 0.07 | 0.64 | 0.03 | 0.18 | 0.03 | 0.08 | 0.07 | 0.04 | 0.05 | 0.15 | 0.11 | 0.03 | 0.03 | 0.03 | 0.07 | 0.11 | 0.08 | 0.1 |
| Cl | 0.02 | 0.02 | 0.012 | 0.02 | 0.033 | 0.07 | 0.05 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.03 | 0.04 | 0.02 | 0.02 | <0.02 | 0.034 | 0.033 |
| F | 0.03 | 0.02 | 0.04 | 0.04 | 0.08 | 0.07 | 0.09 | 0.06 | 0.06 | 0.05 | 0.07 | 0.05 | 0.05 | <0.02 | <0.02 | 0.04 | <0.02 | 0.05 | 0.23 |
| Sum | 99.12 | 99.11 | 98.90 | 99.02 | 98.79 | 99.42 | 99.40 | 99.08 | 99.18 | 99.12 | 99.20 | 99.08 | 99.32 | 98.93 | 99.40 | 99.11 | 99.58 | 98.86 | 99.00 |

**Table 2. Trace element chemistry of rocks from the Ajo district, Arizona**
[Values in parts per million]

| | Cornelia Pluton (61 Ma) | | | | Unknown age | Cardigan Peak Pluton (25 Ma) | | | | | | | | | | | | Dike rocks | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample No. | 214 | 540 | 805 | 806 | 516 | 436 | 434 | 264 | 44 | 278 | 289 | 270 | 101 | 252 | 24 | 315 | 311 | 503 | 517 | |
| Be | 1.9 | 2 | 1.8 | 1.7 | 2 | 2.4 | 3.1 | 3 | 3.3 | 3.6 | 2.8 | 2.4 | 2.1 | 3.9 | 2.8 | 2.5 | 7.1 | 2.2 | 2.4 | Be |
| Co | 19 | 13 | 9 | 12 | 14 | 16 | 12 | 9.3 | 9.7 | 4.3 | 7 | 5.4 | 4.3 | 1.8 | 3.8 | 2.9 | 3.2 | 12 | 9.9 | Co |
| Cr | 31 | 19 | 17 | 14 | 110 | 89 | 49 | 22 | 23 | 11 | 15 | 10 | <10 | <10 | <10 | <10 | <10 | 30 | 39 | Cr |
| Cu | 32 | 17 | 60 | 7.8 | 7.1 | 50 | 71 | 12 | 14 | 1.6 | 18 | 6.3 | 21 | 2.3 | 7.9 | 130 | 1.5 | 15 | 6.2 | Cu |
| Ga | 26 | 25 | 20 | 18 | 21 | 21 | 24 | 21 | 22 | 21 | 19 | 20 | 19 | 17 | 19 | 18 | 21 | 19 | 20 | Ga |
| Ni | 18 | 10 | 9 | 9.2 | 46 | 44 | 30 | 17 | 17 | 10 | 13 | 8.5 | 6.3 | 2.5 | 4.8 | 5.7 | 3.2 | 18 | 19 | Ni |
| Pb | 18 | 18 | 20 | <10 | 16 | 14 | 15 | 16 | 23 | | 26 | 22 | 35 | <10 | 13 | <10 | 16 | 18 | <10 | Pb |
| V | 140 | 100 | 83 | 81 | 84 | 120 | 110 | 66 | 71 | 48 | 48 | 45 | 31 | 19 | 33 | 29 | 29 | 64 | 68 | V |
| Y | 16 | 16 | 14 | 13 | 19 | 26 | 25 | 21 | 24 | 19 | 20 | 21 | 19 | <10 | 10 | 23 | 12 | 19 | 19 | Y |
| Zr | 150 | 99 | 120 | 93 | 240 | 210 | 200 | 160 | 190 | 160 | 140 | 180 | 150 | 53 | 86 | 130 | 65 | 220 | 280 | Zr |
| Sn | 1.5 | 1.2 | 1.6 | 2.8 | 1.2 | 1.3 | 1.9 | 1.8 | 2 | 1.2 | 1.6 | 2.3 | 2.6 | 1.1 | 2.1 | 1.4 | 2 | 1.9 | 1.3 | Sn |
| Nb | 1 | 12 | 12 | 13 | 10 | 13 | 16 | 14 | 15 | 15 | 15 | 12 | 12 | 17 | 15 | 15 | 25 | 15 | 16 | Nb |
| U | 1.19 | 3.72 | 3.49 | 3.28 | 2.12 | 2.71 | 3.81 | 3.66 | 4.6 | 4.57 | 4.89 | 3.07 | 6.12 | 6.08 | 6.94 | 6.17 | 8.19 | 2.21 | 2.29 | U |
| Ba | 836 | 927 | 973 | 846 | 1240 | 1450 | 1270 | 1600 | 1460 | 1380 | 1450 | 1440 | 1180 | 420 | 512 | 1080 | 90 | 1260 | 1610 | Ba |
| Co | 16.5 | 8.95 | 7.45 | 9.53 | 11 | 18.9 | 8.73 | 7.14 | 7.27 | 2.2 | 6.82 | 4.03 | 3.05 | 0.278 | 0.826 | 1.6 | 0.5 | 8.97 | 7.21 | Co |
| Cr | 28.3 | 13.6 | 12.6 | 12.3 | 111 | 97.3 | 41 | 20.5 | 19.4 | 8.5 | 17 | 8 | 4.61 | 0.69 | 0.25 | 2.79 | 0.5 | 24.8 | 34.2 | Cr |
| Cs | 1.83 | 1.43 | 2.59 | 1.47 | 0.491 | 0.938 | 0.666 | 1.69 | 1.87 | 0.704 | 1.7 | 2.1 | 5.11 | 0.621 | 0.994 | 1.07 | 3.97 | 2.3 | 0.548 | Cs |
| Hf | 4.06 | 3.96 | 3.65 | 3.64 | 4.9 | 6.24 | 8.07 | 6.69 | 7.16 | 5.92 | 7.09 | 5.04 | 4.47 | 3.15 | 3.93 | 5 | 4.44 | 5.03 | 6.23 | Hf |
| Rb | 58.8 | 77.9 | 94.7 | 73.8 | 49.9 | 81 | 81.3 | 111 | 128 | 99.3 | 125 | 164 | 174 | 92.9 | 136 | 149 | 195 | 88.5 | 76.8 | Rb |
| Sb | 0.302 | 0.108 | 1.66 | 0.232 | 0.151 | 0.133 | 0.105 | 0.184 | 0.159 | 0.1 | 0.1 | 0.107 | 0.102 | 0.181 | 0.318 | 0.083 | 0.804 | 0.722 | 0.211 | Sb |
| Sr | 790 | 680 | 560 | 620 | 920 | 1040 | 903 | 723 | 669 | 603 | 660 | 385 | 344 | 186 | 105 | 270 | <75 | 710 | 880 | Sr |
| Ta | 0.426 | 0.751 | 0.826 | 0.82 | 0.553 | 0.793 | 0.983 | 0.977 | 1.09 | 1.17 | 1.04 | 0.995 | 1.02 | 1.5 | 1.89 | 1.38 | 2.31 | 0.729 | 0.797 | Ta |
| Th | 3.68 | 7.2 | 7.99 | 8.43 | 6.42 | 11.3 | 16.3 | 17.1 | 19.8 | 27.8 | 19.7 | 19.3 | 25.4 | 29.9 | 40 | 24.8 | 45.4 | 10 | 10.7 | Th |
| Zn | 59.1 | 27.2 | 28.5 | 26.8 | 17.7 | 54 | 56 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | Zn |
| Zr | 139 | 136 | 124 | 124 | 172 | 241 | 321 | 252 | 259 | 202 | 265 | 180 | 170 | 89 | 110 | 151 | 83.2 | 198 | 267 | Zr |
| Sc | 10.7 | 6.67 | 6.29 | 6.49 | 9.79 | 13.9 | 8.54 | 5.99 | 5.56 | 3.5 | 5.55 | 3.36 | 2.32 | 0.547 | 0.423 | 2.89 | 0.738 | 6.67 | 7.29 | Sc |
| La | 28.6 | 30.9 | 27.7 | 29.5 | 43.4 | 58.2 | 52.6 | 60 | 59.5 | 60.9 | 64.2 | 50.8 | 45.8 | 9.85 | 21.3 | 32.2 | 26.4 | 44.9 | 53.4 | La |
| Ce | 57.4 | 61.6 | 56.2 | 59.3 | 73 | 120 | 120 | 110 | 111 | 110 | 116 | 89.4 | 79.5 | 17.5 | 36.2 | 58.2 | 40.7 | 81.6 | 95.5 | Ce |
| Nd | 24.1 | 23.7 | 22.7 | 24.7 | 26.3 | 49.9 | 47.3 | 34.9 | 37.2 | 32.8 | 39.5 | 29.4 | 25.5 | 8.98 | 11.5 | 20.5 | 10.5 | 32.1 | 32.9 | Nd |
| Sm | 4.52 | 4.62 | 4.14 | 4.24 | 4.58 | 8.01 | 7.07 | 5.25 | 5.53 | 4.78 | 5.58 | 4.19 | 3.83 | 1.21 | 1.7 | 3.94 | 1.27 | 4.66 | 5.39 | Sm |
| Eu | 1.36 | 1.2 | 1.05 | 1.12 | 1.14 | 1.85 | 1.67 | 1.17 | 1.2 | 1 | 1.02 | 0.873 | 0.759 | 0.344 | 0.31 | 0.726 | 0.141 | 1.24 | 1.23 | Eu |
| Gd | 3.51 | 3.24 | 2.98 | 2.98 | 3.67 | 6.6 | 5.69 | <2.0 | <2.0 | <2.0 | <2.0 | <2.0 | <2.0 | <2.0 | <2.0 | <2.0 | <2.0 | 3.75 | 3.59 | Gd |
| Tb | 0.492 | 0.445 | 0.401 | 0.452 | 0.482 | 0.824 | 0.765 | 0.547 | 0.575 | 0.466 | 0.561 | 0.483 | 0.415 | 0.109 | 0.132 | 0.512 | 0.138 | 0.508 | 0.528 | Tb |
| Dy | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | 5.1 | 4.4 | 3.3 | 3.4 | 2.9 | 3.5 | 2.9 | 2.5 | 0.7 | 0.9 | 3.5 | 1 | <0.1 | <0.1 | Dy |
| Tm | 0.197 | 0.188 | 0.19 | 0.203 | 0.232 | 0.358 | <0.5 | 0.26 | 0.29 | 0.265 | 0.27 | 0.255 | 0.241 | <0.5 | <0.5 | 0.37 | <0.5 | 0.239 | 0.229 | Tm |
| Yb | 1.06 | 1.17 | 1.09 | 1.15 | 1.44 | 2.12 | 2.13 | 1.67 | 1.81 | 1.66 | 1.74 | 1.58 | 1.55 | 0.546 | 0.561 | 2.38 | 1.2 | 1.44 | 1.51 | Yb |
| Lu | 0.158 | 0.179 | 0.167 | 0.178 | 0.221 | 0.301 | 0.29 | 0.24 | 0.27 | 0.24 | 0.26 | 0.234 | 0.225 | 0.09 | 0.088 | 0.35 | 0.21 | 0.214 | 0.23 | Lu |

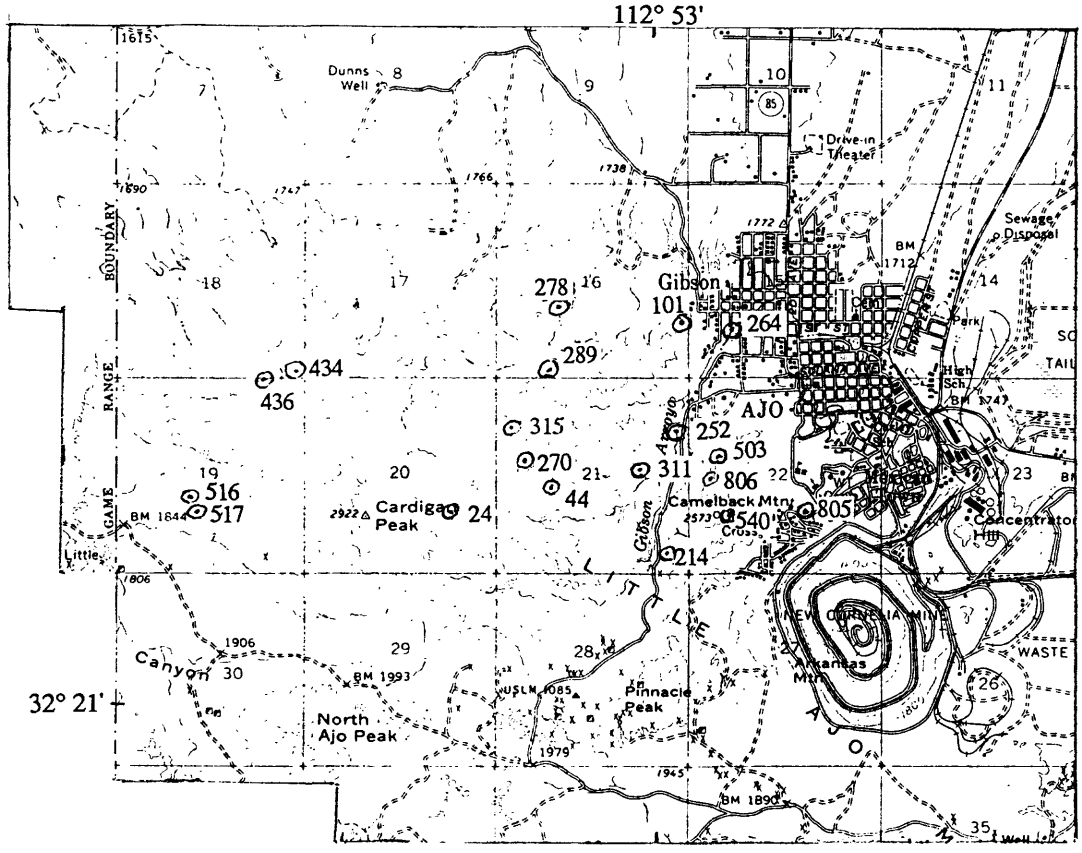


Figure 1, Locations of analyzed rock samples in the Ajo district, Arizona
Base from U.S. Geological Survey, Ajo, 15 minute Quadrangle,
scale 1:62,500, 1963

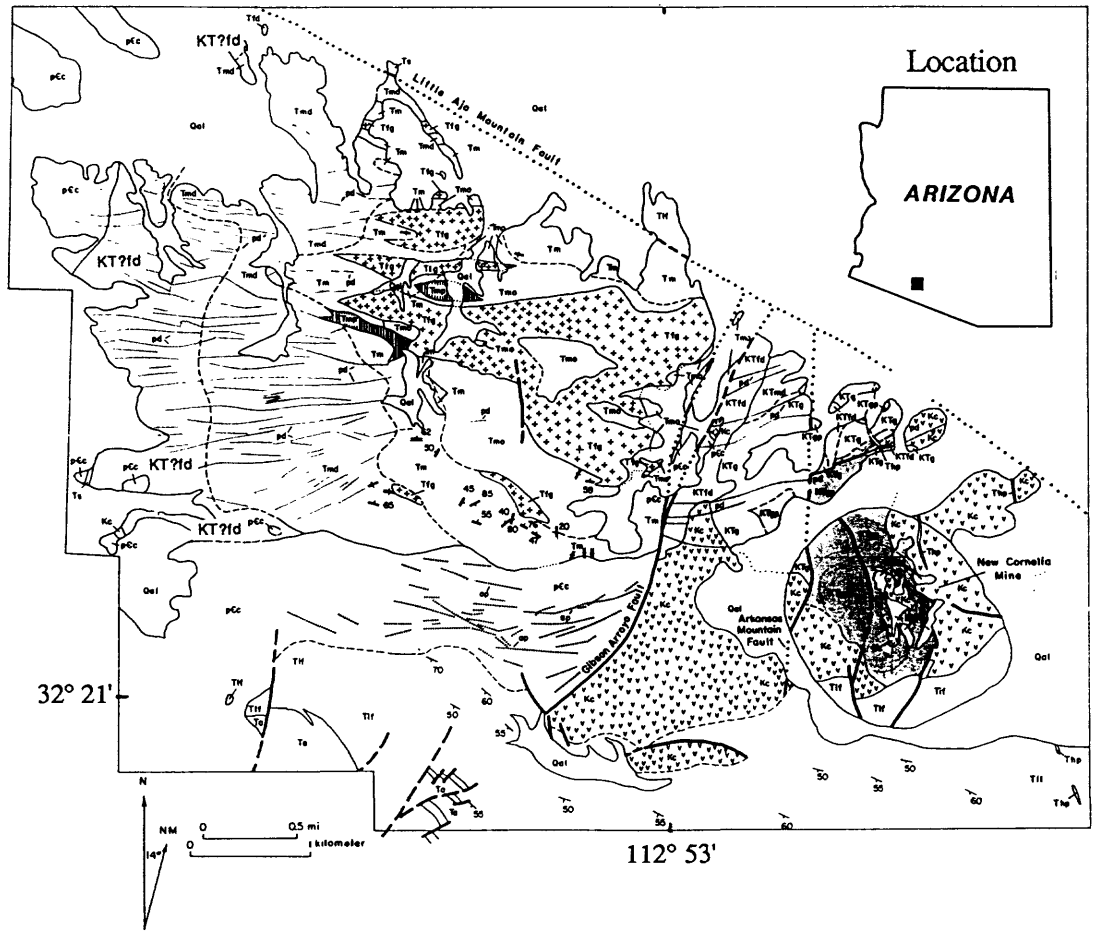


Figure 2, Geologic map of the Ajo district, Arizona modified from Cox and Ohta (1984)

## Explanation for Figure 2

| | | |
|---|---|---|
| Qal | Alluvium and mine waste, undifferentiated, Quaternary | |
| Thp | Hospital porphyry | Tertiary |
| Ts | Sneed Andesite | |
| Ta | Ajo Volcanics | |
| Tlf | Locomotive Fanglomerate | |
| pd | Feldspar porphyry and hornblende andesite dikes | |
| ap | Andesite porphyry dikes | |
| Tmp, Tfg, Tmo, Tm, Tmd | Pluton of Cardigan Peak: Monzogranite porphyry, Tmp; fine-grained granite, Tfg; monzogranite, Tm, and monzogranite with oikocrystic quartz and K-feldspar, Tmo; and quartz monzodiorite, Tmd | |
| KT?fd | Fine-grained diorite and quartz diorite, age uncertain | |
| KTgp, KTg, KTmd, KTfd | Cornelia pluton: Granodiorite porphyry, KTgp; granodiorite, KTg; quartz monzodioite, KTmd; and fine grained diorite and quartz diorite, KTfd | Late Cretaceous and early Tertiary |
| Kc | Concentrator Volcanics, Cretaceous (?) | |
| pЄc | Cardigan gneiss and Chico Shuni Quartz Monzonite, Proterozoic | |

| | |
|---|---|
| 60 | Strike and dip of beds |
| 40 | Strike and dip of monzogranite porphyry dikes |
| ——– | Geologic contact, dashed where uncertain |
| —— - | Fault, dashed where uncertain |

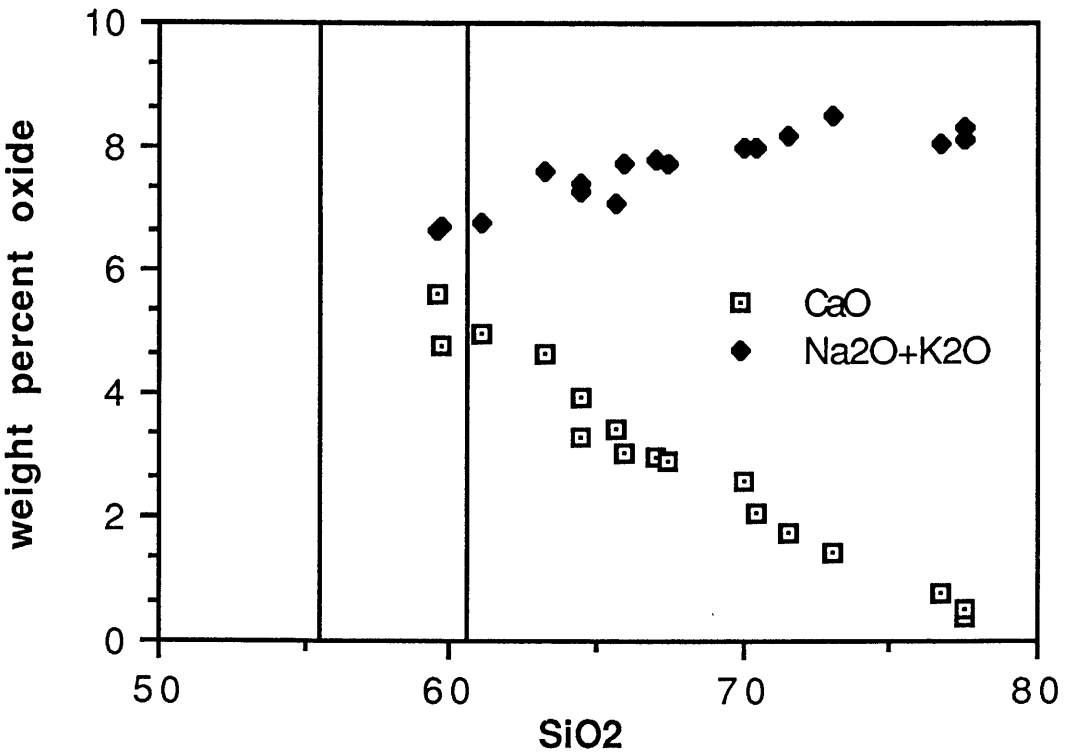


Figure 3. Weight percent CaO and $Na_2O+K_2O$ plotted against $SiO_2$ for all pluton samples in the Ajo mining district, Arizona. Peacock indices for calc-alkalic rocks fall between vertical lines.

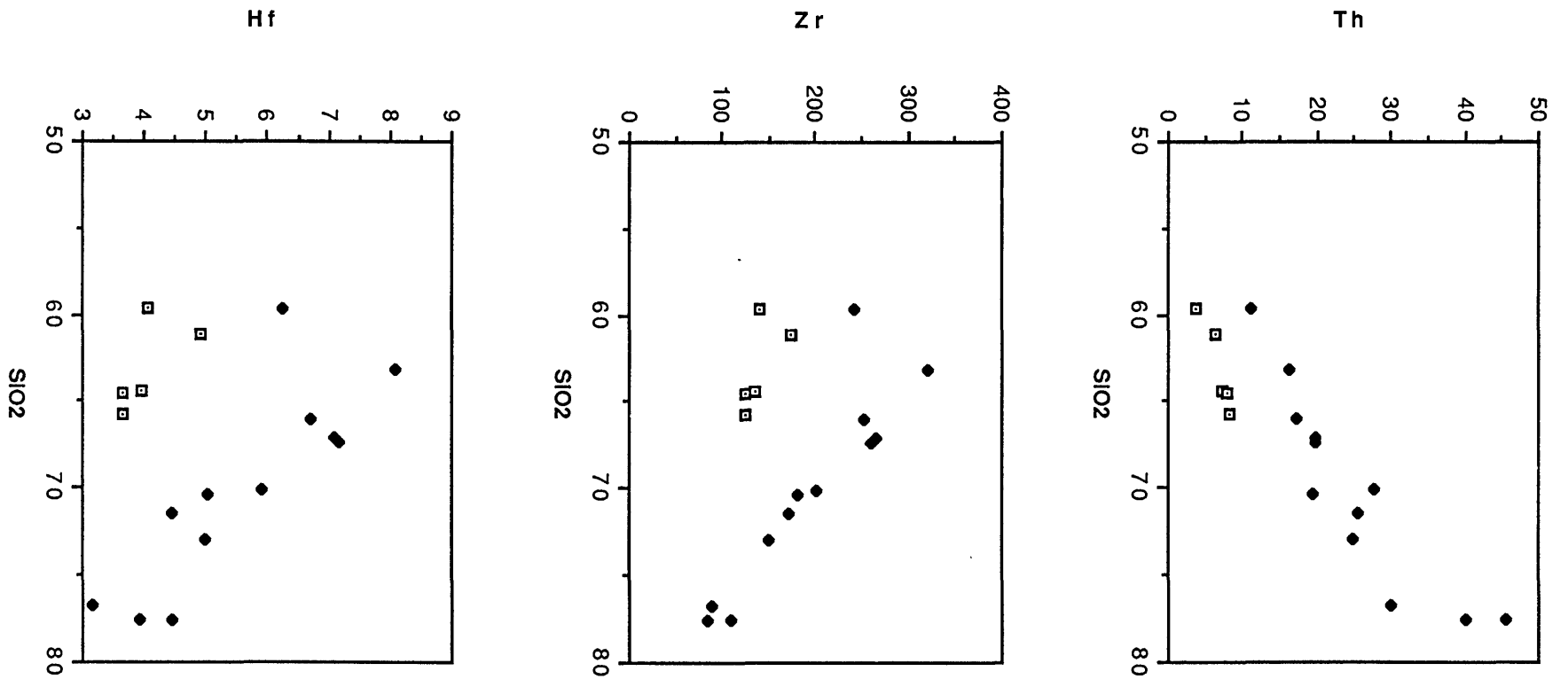


Figure 4a-c. Thorium, zirconium, and hafnium (in parts per million, ppm)plotted against weight percent $SiO_2$. Closed symbols represent samples from Cardigan peak pluton; open symbols, Cornelia pluton

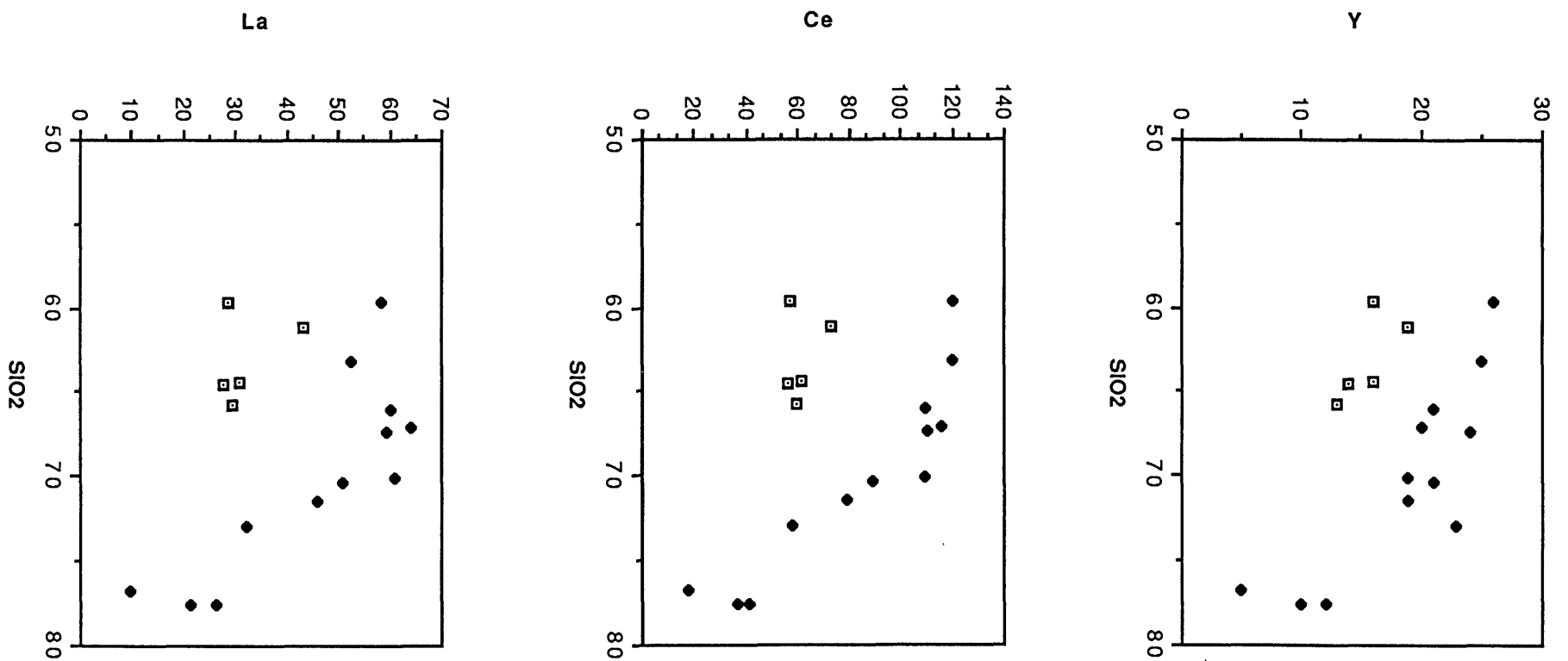


Figure 4d-f. Lanthanum, cerium, and yttrium (ppm) plotted against weight percent $SiO_2$. Closed symbols represent samples from Cardigan peak pluton; open symbols, Cornelia pluton

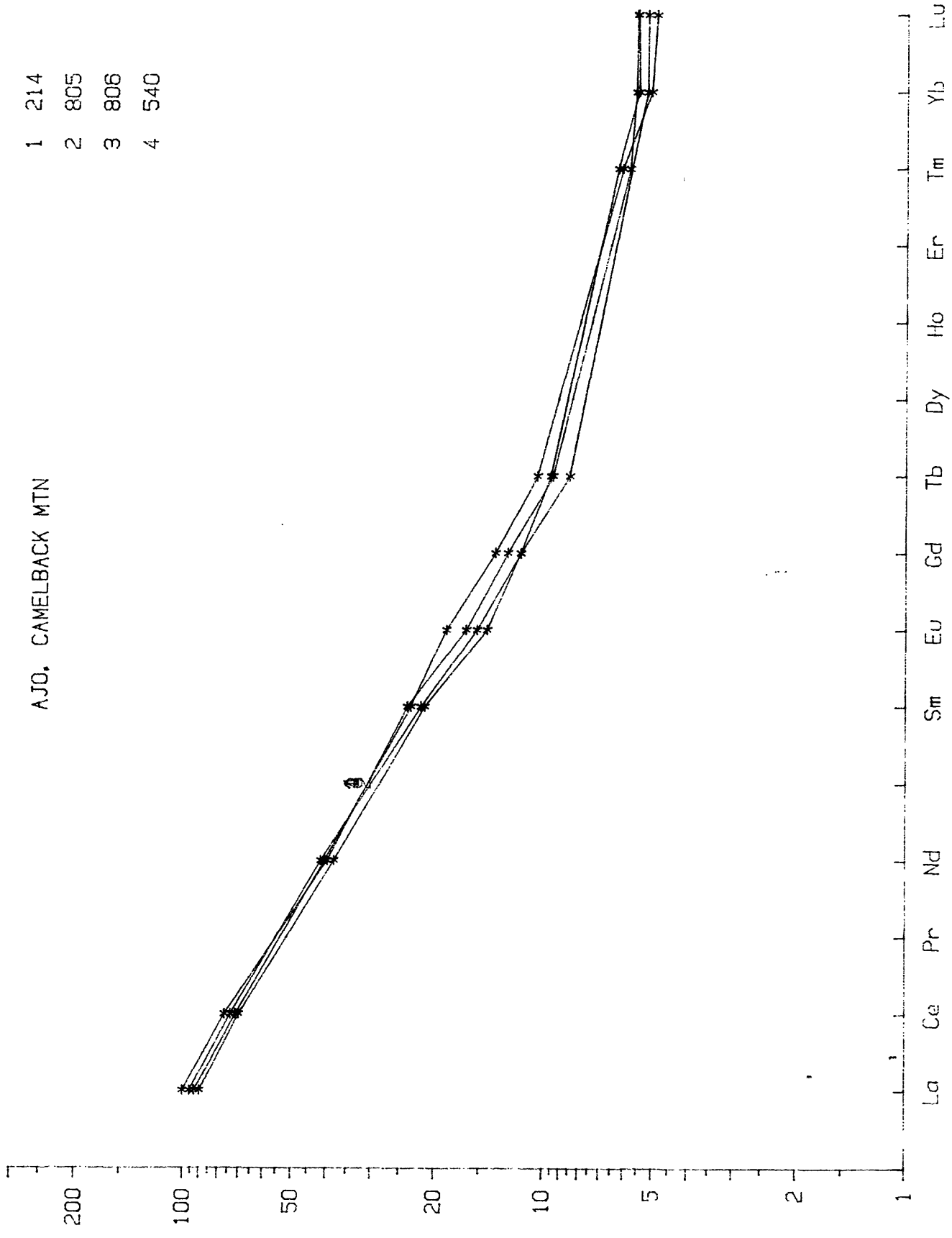


Figure 5a. Chondrite-normalized rare-earth element abundances for 4 samples from the Cornelia pluton.

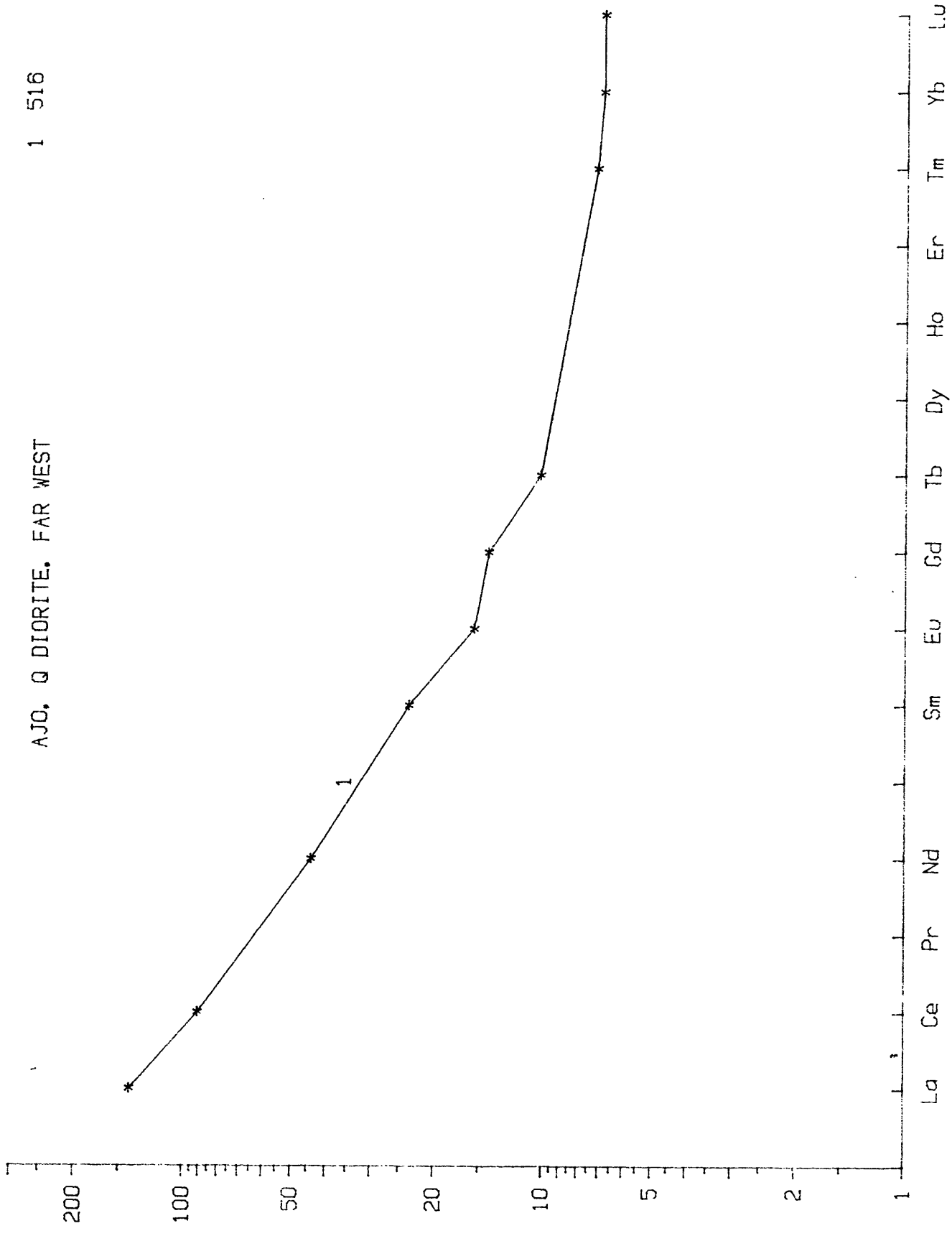


Figure 5b. Chondrite-normalized rare-earth element abundances for sample 516 from the western margin of the Cardigan Peak pluton.

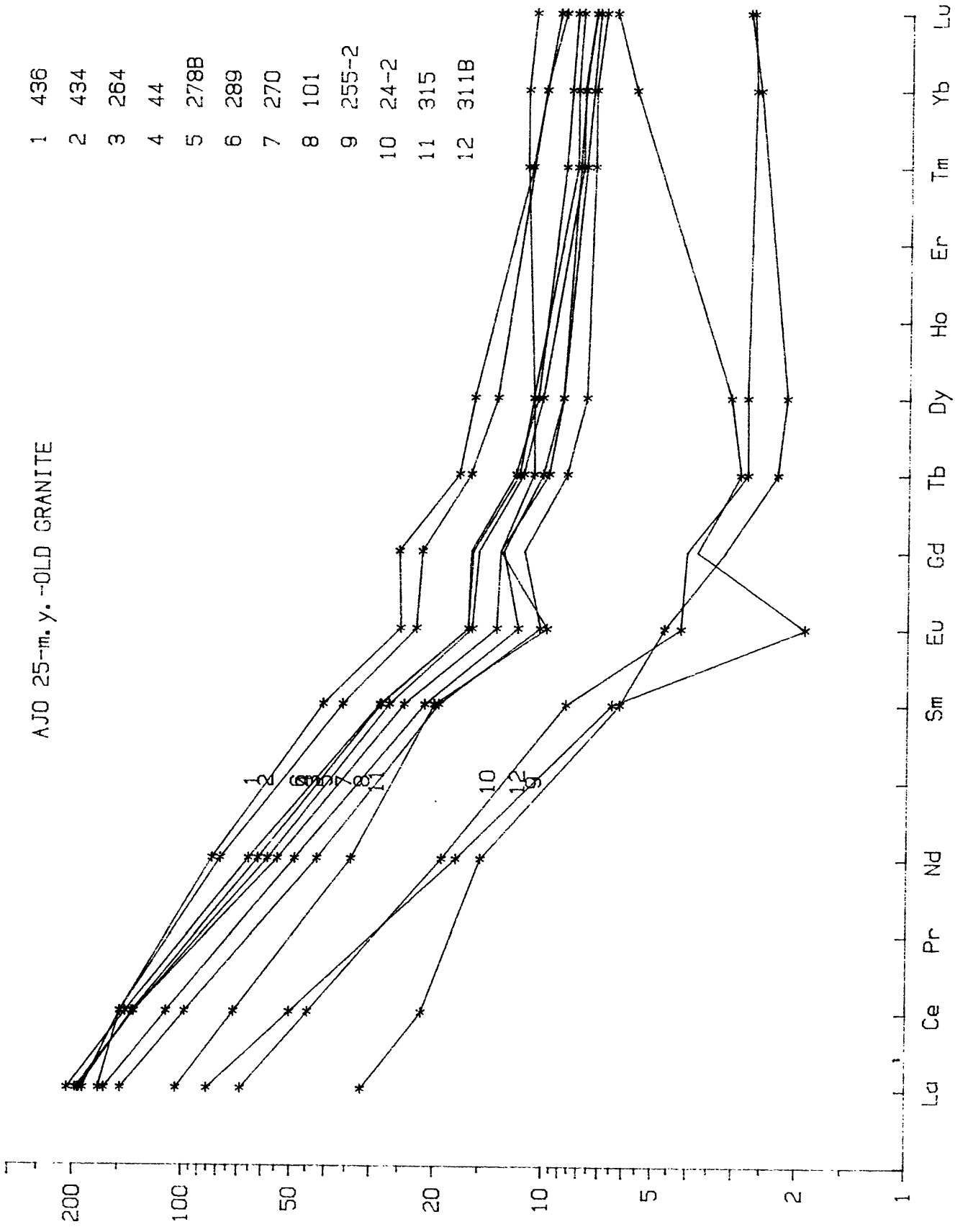


Figure 5c. Chondrite-normalized rare-earth element abundances for 12 samples from the Cardigan Peak pluton.

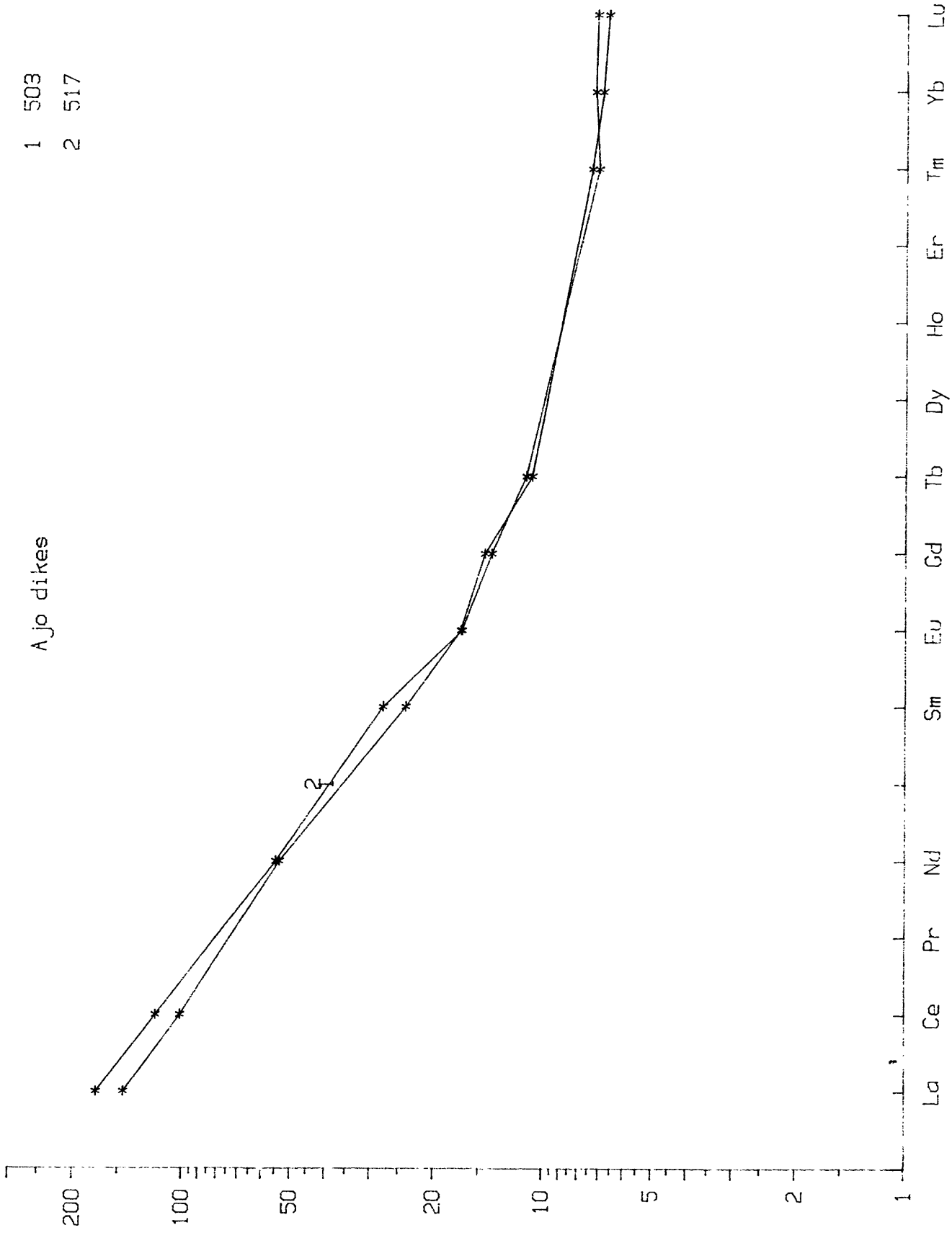


Figure 5d. Chondrite-normalized rare-earth element abundances for 2 dike rocks intruding the Cornelia pluton and Cardigan Peak pluton.