

# Partition coefficients for Ni, Cu, Pd, Pt, Rh and Ir between monosulphide solid solution and sulphide liquid and the implications for the formation of compositionally zoned Ni-Cu sulphide bodies by fractional crystallization of sulphide liquid

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## Introduction

Many nickel-copper sulphide ore bodies are compositionally zoned. In most cases some parts of the ore body are enriched in Fe, Os, Ir, Ru and Rh, while other parts are enriched in Cu, Pd, Pt and Au. Nickel concentrations are similar throughout the bodies. The presence of Au and Pt makes the Cu-rich ore more valuable than the Fe-rich ore and understanding how this zonation arises could help in developing exploration models for the Cu-rich ore.

One model for the origin of this zonation is that at temperatures greater than 1200°C the ore body was a homogeneous sulphide liquid. The first mineral to crystallize from this liquid was  $\text{Fe}_{(1-x)}\text{S}$  (monosulphide solid solution, or MSS). It is possible that Os, Ir, Ru, Rh and to a lesser extent Ni substitute for Fe in the MSS. Fractional crystallization of the sulphide liquid produced an MSS cumulate rich in these elements and a liquid rich in the elements excluded from MSS (Cu, Pt, Pd and Au).

## Results

Using this model we have calculated the partition coefficients of the metals into the MSS from various Ni-Cu sulphide ore deposits (Noril'sk, Sudbury, Alexo, Agnew, Delta, Hosanger, Erterilen, Flat and Faooy). The compositions of the silicate rocks associated with the sulphides range from komatiite to tholeiite. The calculated partition coefficients into the MSS of 2 to 5 for Ir; 1 to 3 for Rh; 0 to 0.8 for Pd; 0 to 1 for Pt; 0.1 to 0.6 for Cu; 0.4 to 1.6 for Ni.

In order to test the model further the partition coefficients of the metals into MSS need to be determined experimentally. The partition coefficients for Ni and Pd may be calculated from the 40 published experimental runs (Karup-Møller and Makovicky, 1993; Makovicky and Karup-Møller, 1993; Fleet *et al.*, 1993) and 13 new runs (Table 1). The experimental partition coefficients vary from 0.2 to 1.5 for Ni and 0.001 to 0.3 for Pd. Our preliminary work indicates that the partition coefficients for Cu are 0.1 to 0.4; Pt 0.1 to 0.2; Rh 0.2 to 4; Ir 1 to 10 (Table 1). There is a positive correlation between the partition coefficients and the S content of the MSS and the S content of liquid. We interpret this as the influence of S fugacity on the partition coefficients, therefore, when using the partition coefficients in modelling of ore bodies the S content of the system should be considered. The similarity between the partition coefficients calculated from natural examples and the experimentally determined partition coefficients supports the idea that the zonation observed in the ore bodies is due to crystal fractionation of MSS from the sulphide liquid.

## References

- Fleet M.E., Chrysosoulis, S.L., Stone, W.E. and Weisener, C.G. (1993) *Contrib. Mineral. Petrol.*, **115**, 36–44.
- Karup-Møller, S. and Makovicky, E. (1993) *Econ. Geol.*, **88**, 1261–8.
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TABLE 1. Experimental results for metal partition coefficients between sulphide liquid and monosulphide solid solution

| Run #                        | T °C | S wt% | Fe    | Cu    | Ni    | Pd     | Pt     | Rh     | Ir     |
|------------------------------|------|-------|-------|-------|-------|--------|--------|--------|--------|
| Run Compositions             |      |       |       |       |       |        |        |        |        |
| 11-1                         | 1100 | 31.89 | 49.85 | 5.04  | 4.98  | 2.08   | 2.12   | 2.08   | 1.97   |
| 11-2                         | 1100 | 36.91 | 44.96 | 4.96  | 4.99  | 2.11   | 2.10   | 1.94   | 2.04   |
| 11-3                         | 1100 | 41.01 | 40.95 | 5.02  | 4.95  | 1.96   | 2.02   | 2.04   | 2.05   |
| 10-1                         | 1000 | 31.45 | 49.16 | 5.00  | 4.93  | 2.09   | 3.48   | 1.95   | 1.95   |
| 10-2                         | 1000 | 36.96 | 44.91 | 4.96  | 5.08  | 1.96   | 2.12   | 1.98   | 2.04   |
| 10-3                         | 1000 | 40.95 | 40.95 | 5.04  | 4.96  | 2.05   | 2.01   | 2.06   | 2.00   |
| Pd-10-14                     | 1000 | 32.33 | 58.55 | 6.55  |       | 4.62   |        |        |        |
| Pd-10-15                     | 1000 | 34.21 | 47.38 | 7.07  |       | 11.35  |        |        |        |
| Pd-10-16                     | 1000 | 42.10 | 50.51 | 2.69  |       | 4.68   |        |        |        |
| Pd-9-6                       | 900  | 53.84 | 23.13 | 10.39 |       | 12.64  |        |        |        |
| Pd-9-7                       | 900  | 55.68 | 33.79 | 5.27  |       | 5.27   |        |        |        |
| Pd-9-8                       | 900  | 37.02 | 45.38 | 6.05  |       | 11.55  |        |        |        |
| Pd-9-9                       | 900  | 39.83 | 44.33 | 4.07  |       | 11.76  |        |        |        |
| Sulphide Liquid Compositions |      |       |       |       |       |        |        |        |        |
| 11-1                         | 1100 | 34.52 | 52.20 | 6.12  | 4.79  | 2.09   | < 0.20 | 1.4    | 0.22   |
| 11-2                         | 1100 | 36.48 | 42.48 | 8.56  | 5.43  | 3.78   | 3.42   | 0.77   | 0.5    |
| 11-3                         | 1100 | 37.39 | 42.59 | 8.52  | 5.03  | 2.89   | 3.21   | 0.99   | 0.67   |
| 10-1                         | 1000 | 30.86 | 41.88 | 12.14 | 9.34  | 5.17   | < 0.20 | 2.3    | < 0.20 |
| 10-2                         | 1000 | 32.11 | 28.25 | 16.96 | 5.48  | 7.56   | 10.85  | 0.33   | < 0.20 |
| 10-3                         | 1000 | 34.61 | 31.08 | 16.79 | 3.71  | 7.77   | 7.47   | < 0.20 | < 0.20 |
| Pd-10-14                     | 1000 | 31.48 | 59.19 | 8.51  |       | 2.55   |        |        |        |
| Pd-10-15                     | 1000 | 31.34 | 38.53 | 13.44 |       | 17.61  |        |        |        |
| Pd-10-16                     | 1000 | 30.51 | 23.24 | 14.48 |       | 33.79  |        |        |        |
| Pd-9-6                       | 900  | 31.89 | 27.06 | 18.55 |       | 22.31  |        |        |        |
| Pd-9-7                       | 900  | 33.38 | 30.55 | 18.31 |       | 17.98  |        |        |        |
| Pd-9-8                       | 900  | 31.54 | 29.67 | 13.09 |       | 26.38  |        |        |        |
| Pd-9-9                       | 900  | 32.39 | 29.22 | 9.34  |       | 30.21  |        |        |        |
| Monosulphide Solid Solution  |      |       |       |       |       |        |        |        |        |
| 11-1                         | 1100 | 36.97 | 58.76 | 2.14  | 1.04  | < 0.20 | < 0.20 | 0.69   | 0.2    |
| 11-2                         | 1100 | 38.21 | 49.96 | 2.39  | 4.01  | 0.64   | 0.35   | 2.93   | 2.64   |
| 11-3                         | 1100 | 38.46 | 47.91 | 2.12  | 3.91  | 0.46   | 0.55   | 3.94   | 4.09   |
| 10-1                         | 1000 | 37.49 | 59.77 | 1.88  | 1.91  | < 0.20 | < 0.20 | 0.56   | < 0.20 |
| 10-2                         | 1000 | 37.05 | 41.73 | 4.42  | 6.17  | 1.33   | 1.65   | 6.9    | 2.12   |
| 10-3                         | 1000 | 38.91 | 46.45 | 4.37  | 4.78  | 1.92   | 1.34   | 2.55   | 1.09   |
| Pd-10-14                     | 1000 | 37.24 | 63.34 | 0.82  |       | < 0.20 |        |        |        |
| Pd-10-15                     | 1000 | 38.08 | 56.61 | 3.40  |       | 1.98   |        |        |        |
| Pd-10-16                     | 1000 | 39.96 | 53.86 | 2.78  |       | 4.84   |        |        |        |
| Pd-9-6                       | 900  | 37.99 | 48.77 | 5.85  |       | 5.72   |        |        |        |
| Pd-9-7                       | 900  | 38.85 | 49.59 | 5.35  |       | 5.47   |        |        |        |
| Pd-9-8                       | 900  | 38.01 | 50.29 | 4.15  |       | 6.45   |        |        |        |
| Pd-9-9                       | 900  | 38.46 | 49.82 | 3.25  |       | 8.24   |        |        |        |
| Partition Coefficients       |      |       |       |       |       |        |        |        |        |
| 11-1*                        | 1100 |       |       | 0.350 | 0.217 | < 0.10 |        | 0.493  | 1      |
| 11-2                         | 1100 |       |       | 0.279 | 0.738 | 0.169  | 0.102  | 3.80   | 5.28   |
| 11-3 +                       | 1100 |       |       | 0.249 | 0.777 | 0.159  | 0.171  | 3.98   | 6.10   |
| 10-1*                        | 1000 |       |       | 0.155 | 0.204 | 0.002  |        | 0.243  |        |
| 10-2                         | 1000 |       |       | 0.261 | 1.126 | 0.176  | 0.152  | 20.9   | > 10   |
| 10-3 +                       | 1000 |       |       | 0.260 | 1.288 | 0.247  | 0.179  | > 10.4 | > 5.04 |
| Pd-10-14*                    | 1000 |       |       |       | 0.096 |        | < 0.10 |        |        |
| Pd-10-15                     | 1000 |       |       | 0.253 |       | 0.112  |        |        |        |
| Pd-10-16 +                   | 1000 |       |       | 0.192 |       | 0.143  |        |        |        |
| Pd-9-6 +                     | 900  |       |       | 0.315 |       | 0.256  |        |        |        |
| Pd-9-7 +                     | 900  |       |       | 0.292 |       | 0.304  |        |        |        |
| Pd-9-8                       | 900  |       |       | 0.317 |       | 0.245  |        |        |        |
| Pd-9-9                       | 900  |       |       | 0.348 |       | 0.273  |        |        |        |

\*Alloy present; + Sulphur present