

full responsibility for the conclusions. Financial support was supplied by a National Science Foundation fellowship (1960-1961) and by fellowships and research assistanceships from The Johns Hopkins University (1961-1963). The experimental investigation was supported by NSF grant no. G-19033. The writer is deeply indebted to his mother, Mrs. John S. French, for additional financial assistance.

The original dissertation (French, ms) and the present manuscript have benefited greatly from the critical reviews and suggestions of H. P. Eugster, D. R. Wones, J. S. Huebner, J. R. Weidner, and Mary-Hill French.

REFERENCES

- Allen, R. C., and Barrett, L. P., 1915, Geology of the Marenisco Range: Michigan Geol. Survey Pub. 18, p. 65-85.
- Anderson, C. T., 1934, The heat capacities of magnesium, zinc, lead, manganese, and iron carbonates at low temperatures: Am. Chem. Soc. Jour., v. 56, p. 849-851.
- Bank, C. A., and Verdurmen, E. A. Th., 1963, Oxygen exchange between CO and CO_2 : Jour. Inorg. Nuclear Chemistry, v. 25, p. 667-675.
- Bank, C. A., Verdurmen, E. A. Th., de Vries, A. E., and Monterie, F. L., 1961, Oxygen exchange between CO and O_2 : Jour. Inorg. Nuclear Chemistry, v. 17, p. 295-301.
- Berner, R. A., 1969, Goethite stability and the origin of red beds: Geochim. et Cosmochim. Acta, v. 33, p. 267-273.
- Bonnicksen, B., ms, 1968, General geology and petrology of the metamorphosed Biwabik iron formation, Dunka River area, Minnesota: Ph.D. dissert., Univ. of Minnesota, 240 p.
- Bradner, J. D., and Urey, H. C., 1945, Kinetics of the isotopic exchange reaction between carbon monoxide and carbon dioxide: Jour. Chem. Physics, v. 13, p. 351-362.
- Buddington, A. F., and Lindsley, D. H., 1964, Iron-titanium oxide minerals and synthetic equivalents: Jour. Petrology, v. 5, p. 310-357.
- Burchard, E. F., 1924, Bauxite associated with siderite: Geol. Soc. America Bull., v. 35, p. 437-448.
- Burnham, C. W., and Jahns, R. H., 1962, A method for determining the solubility of water in silicate melts: Am. Jour. Sci., v. 260, p. 721-745.
- Butler, P., 1969, Mineral compositions and equilibria in the metamorphosed iron formation of the Gagnon region, Quebec: Jour. Petrology, v. 10, p. 56-101.
- Carozzi, A. V., 1960, Microscopic sedimentary petrography: New York, John Wiley & Sons, 485 p.
- Coughlin, J. P., 1954, Heats and free energies of formation of inorganic oxides: U. S. Bur. Mines Bull. 542, 80 p.
- Deer, W. A., Howie, R. A., and Zussman, J., 1962, Rock-forming minerals, v. 5, Non-silicates: New York, John Wiley & Sons, 371 p.
- Ernst, W. G., 1962, Synthesis, stability relations, and occurrence of riebeckite and riebeckite-arfvedsonite solid solutions: Jour. Geology, v. 70, p. 689-736.
- Eugster, H. P., 1957, Heterogeneous reactions involving oxidation and reduction at high pressures and temperatures: Jour. Chem. Physics, v. 26, p. 1760-1761.
- 1959, Reduction and oxidation in metamorphism, in Abelson, P. H., ed., Researches in geochemistry: New York, John Wiley & Sons, p. 397-526.
- Eugster, H. P., and Skippen, G. B., 1968, Igneous and metamorphic reactions involving gas equilibria, in Abelson, P. H., ed., Researches in geochemistry, v. 2: New York, John Wiley & Sons, p. 492-520.
- Eugster, H. P., and Wones, D. R., 1962, Stability relations of the ferruginous biotite, annite: Jour. Petrology, v. 3, p. 82-125.
- Fabian, H. J., Mueller, G., and Roese, K. L., 1957, Eine sideritisch-sideroplesitische Vererzung in einer Zechstein-Bohrung des Erdgasfeldes Rehden (krs. Diepholz): Neues Jahrb. Geologie Palaeontologie, Abh., v. 105, no. 2, p. 205-209.
- Fisher, G. W., 1967, Fe-Mg olivine solid solutions: Carnegie Inst. Washington Year Book 65, p. 209-217.
- Ford, W. E., 1917, Studies in the calcite group: Conn. Acad. Arts Sci. Trans., v. 22, p. 211-248.

- French, B. M. ms, 1964, Stability of siderite, FeCO_3 , and progressive metamorphism of iron formation: Ph.D. dissert., Johns Hopkins Univ., 357 p.
- _____, 1965, Synthesis and stability of siderite, FeCO_3 [abs.]: Am. Geophys. Union Trans., v. 46, p. 103.
- _____, 1966, Some geological implications of equilibrium between graphite and a C-H-O gas at high temperatures and pressures: Rev. Geophysics, v. 4, p. 223-253.
- _____, 1968, Progressive contact metamorphism of the Biwabik iron-formation, Mesabi Range, Minnesota: Minnesota Geol. Survey Bull. 45, 103 p.
- _____, 1970, Stability relations of siderite (FeCO_3), determined in controlled- f_{O_2} atmospheres: NASA Document X-644-70-102, 61 p.
- French, B. M., and Eugster, H. P., 1962, Stability of siderite, FeCO_3 [abs.]: Geol. Soc. America Spec. Paper 73, p. 155-156.
- _____, 1965, Experimental control of oxygen fugacities by graphite-gas equilibria: Jour. Geophys. Research, v. 70, p. 1529-1539.
- French, B. M., and Rosenberg, P. E., 1965, Siderite (FeCO_3): thermal decomposition in equilibrium with graphite: Science, v. 147, p. 1283-1284.
- Garrels, R. M., 1960, Mineral equilibria at low temperature and pressure: New York, Harper and Bros., 254 p.
- Garrels, R. M., and Christ, C. L., 1965, Solutions, minerals, and equilibria: New York, Harper and Row, 450 p.
- Gates, R. M., 1959, Bedrock geology of the Roxbury quadrangle, Connecticut: U. S. Geol. Survey Quad. Map GQ 121.
- Goldsmith, J. R., 1959, Some aspects of the geochemistry of carbonates, in Abelson, P. H., ed., Researches in geochemistry: New York, John Wiley & Sons, p. 336-358.
- Goldsmith, J. R., Graf, D. L., Witters, J., and Northrop, D. A., 1962, Studies in the system CaCO_3 - MgCO_3 - FeCO_3 : 1. Phase relations; 2. A method for major-element spectrochemical analysis; 3. Compositions of some ferroan dolomites: Jour. Geology, v. 70, p. 659-688.
- Goodwin, A. M., 1962, Structure, stratigraphy, and origin of iron formations, Michipicoten area, Algoma district, Ontario, Canada: Geol. Soc. America Bull., v. 73, p. 561-586.
- Graf, D. L., 1961, Crystallographic tables for the rhombohedral carbonates: Am. Mineralogist, v. 46, p. 1283-1316.
- Greenwood, H. J., 1961, The system $\text{NaAlSi}_2\text{O}_6$ - H_2O -Argon: total pressure and water pressure in metamorphism: Jour. Geophys. Research, v. 66, p. 3923-3946.
- Gruner, J. W., 1946, The mineralogy and geology of the taconites and iron ores of the Mesabi Range, Minnesota: St. Paul, Minn., Office Commissioner Iron Range Resources and Rehabilitation, 127 p.
- Gundersen, J. N., and Schwartz, G. M., 1962, The geology of the metamorphosed Biwabik iron-formation, Eastern Mesabi district, Minnesota: Minnesota Geol. Survey Bull. 43, 139 p.
- Gustafson, J. K., 1933, Metamorphism and hydrothermal alteration of the Homestake gold-bearing formation: Econ. Geology, v. 28, p. 123-162.
- Haas, J. L., ms, 1968, On the equilibria, magnetite-hematite-vapor (O_2): U. S. Geol. Survey Interim Rept., April 1968, 13 p.
- Haendler, H. M., and Bernard, W. J., 1951, The reaction of fluorine with cadmium and some of its binary compounds. The crystal structure, density, and melting point of cadmium fluoride: Am. Chem. Soc. Jour., 73, p. 5218-5219.
- Harker, R. I., and Hutton, J. J., 1956, The stability of smithsonite: Econ. Geology, v. 51, p. 375-381.
- Harker, R. I., and Tuttle, O. F., 1955a, Studies in the system $\text{CaO}-\text{MgO}-\text{CO}_2$. I. Thermal dissociation of calcite, dolomite, and magnesite: Am. Jour. Sci., v. 253, p. 209-224.
- _____, 1955b, Studies in the system $\text{CaO}-\text{MgO}-\text{CO}_2$. II. Limits of solid solution along the binary join CaCO_3 - MgCO_3 : Am. Jour. Sci., v. 253, p. 274-282.
- Holland, H. D., 1959, Some applications of thermochemical data to problems of ore deposits. I. Stability relations among the oxides, sulfides, sulfates, and carbonates of ore and gangue metals: Econ. Geology, v. 54, p. 184-233.
- _____, 1965, Some applications of thermochemical data to problems of ore deposits. II. Mineral assemblages and the composition of ore-forming fluids: Econ. Geology, v. 60, p. 1101-1166.
- Huebner, J. S., 1969, Stability relations of rhodochrosite in the system manganese-carbon-oxygen: Am. Mineralogist, v. 54, p. 457-481.