Manganoan fayalite [(Fe,Mn)₂SiO₄]: A new occurrence in rhyolitic ash-flow tuff, southwestern Nevada, U.S.A.

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Abstract

Manganoan fayalite is usually found associated with sedimentary iron-manganese ore deposits. Phenocrysts of manganoan fayalite were recently discovered in high-silica rhyolite pumice fragments from the Ammonia Tanks Member of the Timber Mountain Tuff in the Southwestern Nevada Volcanic Field. Twenty-one electron microprobe analyses (major-element oxides, NiO, BaO) are reported for the newly discovered phenocrysts. The slightly zoned phenocrysts range in composition from $Fa_{63}Fo_{0}Te_{37}La_{0.2}$ to $Fa_{72}Fo_{0.2}Te_{28}La_{0.1}$.

Introduction

Manganoan fayalite, a member of the Fe_2SiO_4-Mn_2SiO_4 solid solution series, was originally thought to be restricted in its paragenesis, occurring almost exclusively in iron-manganese ore deposits (Deer et al., 1982). Rare occurrences of manganoan fayalite as a primary igneous phase have been reported in the literature. These occurrences include manganoan fayalite in nordmarkite at Shefford Mountain, Quebec (Frisch, 1972), and in a pegmatite located in the Fukushima Prefecture, Japan (Omori et al., 1950; Omori and Hasegawa, 1951). A compilation of the more notable occurrences of manganoan fayalite is given in Table 1.

Fayalitic olivine has been noted in the rhyolitic portions of several ash-flow tuffs (cf. Bacon et al., 1981). Deer et al. (1982) suggested that many of the reported fayalite samples in igneous rocks are actually Mn-rich fayalite. Reexamination by Mills and Rose (this paper)

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of analytical data for some of the iron fayalite specimens reported by other workers (Warshaw and Smith, 1988; Mahood, 1981; Carmichael, 1967), revealed that several of them are Mn- and Mg-enriched fayalite, whereas the remainder of the phenocrysts lack significant Mn or Mg and are near end-member fayalite in composition.

In this paper we report a new occurrence and chemical analyses for manganoan fayalite phenocrysts in high-silica rhyolite pumice fragments from the Ammonia Tanks Member of the Timber Mountain Tuff, southwestern Nevada.

Geologic setting

The Ammonia Tanks Member of the Timber Mountain Tuff is a large-volume (approximately 900 km³) compositionally zoned ash-flow sheet that formed from eruption of the Timber Mountain caldera complex approximately 11.1 Ma (Fig. 1) (Byers et al., 1976; Broxton et al., 1989). Compositionally, the pumice fragments within the Ammonia Tanks Member range from trachyandesite (58 wt% SiO_2) to high-silica rhyolite (78 wt%

Table 1. Reported occurrences of manganoan fayalite

| Locality	Deposit type or host rock	Reference
East Ghat, Andkra Pradesh, India	manganese ore belt, nonvolcanogenic calc-granulite, garnetiferous quartzite	Bhattacharyya, 1986
Broken Hill, Australia	Cu-Pb-Zn sulfides and carbonates	Birch, 1984
New Broken Hill Claim, Australia	Cu-Pb-Zn sulfides and carbonates	Hodgson, 1975
Bluebell Mine, Kootenay, British Columbia	massive sulfide, Fe-Pb-Zn, Precambrian limestone, Pb-Zn massive sulfide and limestone	Gunning, 1936
North Vancouver Island, British Columbia	unknown	Gunning, 1936
Dannemora, Tunaberg, Dalekarlia, Sweden	skarn	Gunning, 1936
Santa Eulalia, Mexico	skarn(?), Lower Cretaceous limestone	Gunning, 1936
Primorye, USSR	Fe-Pb-Zn massive sulfide in Mesozoic sandstones + siltstones	Kazachenko et al., 1979
Kaso Mine, Japan	rhodonite veins intruded into rhodocrosite ore	Yoshimura, 1939
Kyurazawa, Japan	unknown	Watanabe and Kato, 1957
Tochigi Prefecture, Japan	pegmatite	Omori et al., 1950
Hakozaki Mine, Japan	unknown	Nambu et al., 1966
Hijikuza Mine, Japan	bedded manganese ore associated with Jurassic quartzite	Keankeo et al., 1986
Shefford Mountain, Quebec	normardkite	Frisch, 1972
Lewisian area, Scotland	manganiferous schists and sandy carbonate	Tilley, 1938
Tamworth, New South Wales, Australia	metasediments	Segnit, 1962
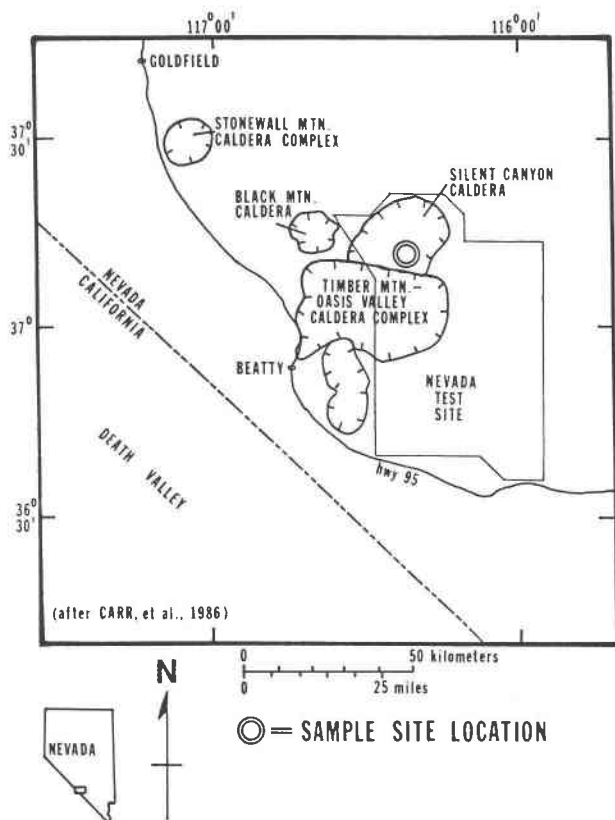
Fig. 1. Location map of the Timber Mountain–Oasis Valley caldera complex, southwestern Nevada, and the sampling site where manganoan fayalite–bearing pumice fragments from the Ammonia Tanks Member of the Timber Mountain Tuff were collected.

TABLE 2. Representative chemical compositions and mole proportions of manganoan fayalite grains, whole pumice, and whole pumice glass in the Ammonia Tanks Member of the Timber Mountain Tuff, southwestern Nevada

Sample	A21-18	A5-3	A5-3	A5-3
Grain no.	4	8	glass	pumice
Analysis no.	23	13	14	15
Position*	C	E	—	—
Oxide (wt%)				
SiO_2	30.25	30.41	72.97	75.87
TiO_2	0.05	0.06	0.19	0.13
Al_2O_3	0.04	0.02	12.32	11.80
FeO**	42.47	49.28	0.72	0.56
MgO	†	0.08	0.10	†
CaO	0.11	0.08	0.39	0.35
Na_2O	†	†	3.85	3.17
K_2O	†	0.02	5.34	5.35
MnO	24.46	18.89	0.13	0.08
NiO	†	0.04	‡	‡
BaO	0.04	†	0.13	0.01
Total	97.42	98.88	96.18	97.33
Mole proportions				
Fa	63.17	71.90	—	—
Fo	0.0	0.21	—	—
Te	33.63	27.75	—	—
La	0.21	0.15	—	—

* E = grain edge, C = grain core.
** FeO = FeO + Fe_2O_3.
† Not detected.
‡ Not analyzed.

SiO$_2$) (Mills et al., 1987; Rose, 1988). Manganoan fayalite occurrences are limited strictly to the high-silica rhyolite pumice fragments that are most commonly found near the base of the ash-flow sheet, but it may occur throughout the ash-flow sheet both vertically and laterally. Based on previous studies of ash-flow tuffs, it is generally accepted that high-silica rhyolite magmas occur in the extreme upper portion of magma chambers because of their low densities and high volatile contents (cf. Smith, 1979; Hildreth, 1981). These magmas are most likely formed by fractional crystallization of a more mafic parent magma (i.e., dacite) or partial melting of crustal material (cf. Hyndman, 1982).

MINERAL ASSEMBLAGE

Thin sections of pumice fragments and microprobe analyses of grain mounts for two samples, A5-3 and A21-18, revealed similar mineral assemblages. The phenocryst assemblages in order of decreasing modal abundance are sanidine, plagioclase, quartz, biotite, magnetite, ilmenite, titanite, zircon, chevkinite, and manganoan fayalite.

CHEMISTRY

Analytical techniques

The manganoan fayalite phenocrysts were initially found and identified with an electron microprobe while compositional studies on phenocrysts from pumice fragments of the Ammonia Tanks Member (samples A5-3 and A21-18) were being performed. The manganoan fayalite phenocrysts were separated from glassy pumice fragments by hand crushing the pumice in a ceramic mortar and pestle and sieving the resulting powders. The mesh fraction of −60 to +140 was then concentrated into light and heavy mineral fractions by bromoform heavy-liquid separation. Manganoan fayalite phenocrysts were concentrated in the heavy fraction along with biotite, magnetite, ilmenite, and titanite fragments. The heavy mineral fractions were mounted in standard metallurgical epoxy disks for microprobe analysis. Hand separation of the grains was not possible because of the small modal percentage of manganoan fayalite present in the pumice fragments, the small size of the grains (<0.2 mm), and the difficulty of visual identification.

Manganoan fayalite chemical compositions were determined by an automated JEOL 733A Superprobe at the Lawrence Livermore National Laboratory. Operating parameters for the microprobe beam were 15 KeV, 15 nA, and a beam size of 100 μm^2. The system was calibrated periodically with the oxide and silicate mineral standards. The Bence-Albee correction procedure was applied to all quantitative analyses (Bence and Albee, 1968).

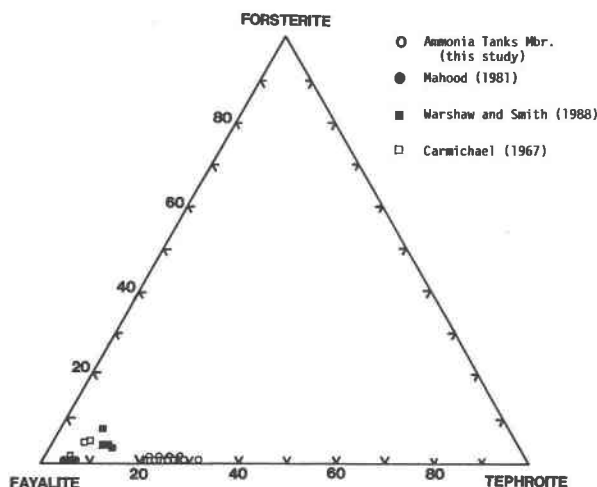To date, phenocrysts of manganoan fayalite have not

Fig. 2. Plot of compositions of olivine from the Ammonia Tanks Member of the Timber Mountain Tuff, southwestern Nevada (this study), and those of olivine from other high-silica rhyolites reported in the literature. (See text for references to data sources.)
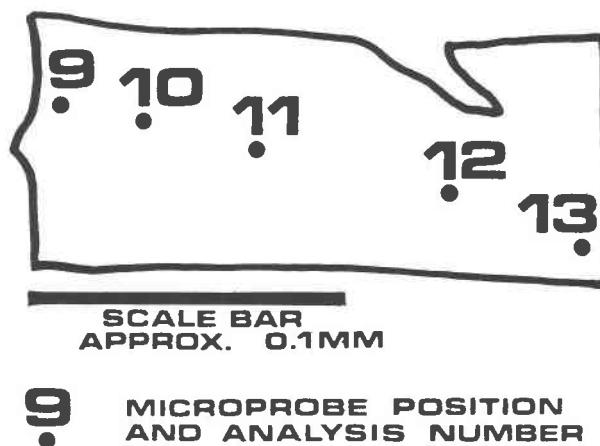

Fig. 3. Location of electron microprobe analyses on a chemically zoned (with respect to FeO, MnO, and CaO) manganoan fayalite phenocryst (sample A5-3).

been positively identified in thin section owing to the small size of the host pumice fragments and the corresponding paucity of manganoan fayalite grains. Several potential phenocrysts have been located that have similar optical properties to those noted by Henriques (1956, 1957), but they are too small for any further determinative analyses on a petrographic microscope.

RESULTS

Representative chemical analyses of the manganoan fayalite grains, pumice fragments, and pumice glass separates are reported in Table 2. Analyses of the manganoan fayalite samples cluster in the Fe_2SiO_4-Mn_2SiO_4 field (Fig. 2). The compositional range of the grains is from $Fa_{63}Fo_0Te_{37}La_{0.2}$ to $Fa_{72}Fo_{0.2}Te_{28}La_{0.1}$.

Low analytical totals for the glass and pumice fragment analyses are probably due to secondary hydration of the pumiceous glass that was produced during periods of ground-water saturation or surface weathering. Deer et al. (1982) reported that manganoan fayalite may contain significant concentrations of H_2O^+ and CO_2. Since H_2O^+ and CO_2 were not included in our analyses, this may account for the low totals on some of the analyses. Alternatively, partial oxidation of Fe^{2+} to Fe^{3+} could also account for the low analytical totals; however, backscattered electron imaging is not capable of distinguishing between Fe^{2+} and Fe^{3+}. Thus it is not clear whether this process has occurred. More detailed chemical analyses need to be performed to resolve this problem. Significant concentrations of ZnO (1.54 wt%) have been reported by Stillwell (in Deer et al., 1982) in manganoan fayalite at the Broken Hill lode, New South Wales, Australia. Other manganoan fayalite samples at the Broken Hill lode however, con-

tained up to 8.2 wt% ZnO, which was shown by Mason (1973) to be the result of sphalerite inclusions. Although ZnO was not determined for the manganoan fayalite samples that were analyzed during this study, Ni (up to 0.43 wt% NiO, analysis 10) and Ba (up to 0.17 wt% BaO, analysis 22) were detected (Table 2). Evidence of inclusions or possible exsolved phases was not observed in manganoan fayalite grains from the Ammonia Tanks ash-flow sheet during backscattered electron imaging.

Chemical analyses of the high-silica pumice fragments that are hosts to the manganoan fayalite grains show them to be Mg poor (<0.01 wt%) with moderate amounts of Fe (Fe^{2+} and Fe^{3+} reported as FeO_{tot}) (0.56 to 0.72 wt%), MnO (0.08 wt%), and CaO (0.35 to 0.41 wt%). Analyses of glass separates from the pumice fragments are slightly higher in MgO, FeO, MnO, and CaO relative to the pumice fragment analyses. This is most likely due to the absence of feldspar and quartz phenocrysts that cause a decrease in these elemental concentrations in the analyses of the pumice fragments. Pumice fragment and glass-separate alkali and Fe concentrations were most likely affected by secondary hydration and probably do not reflect preeruptive magmatic concentrations (Lipman, 1965; Noble, 1965, 1967). Although FeO_{tot} and MnO concentrations are low in the host rhyolite when compared to enrichments in iron-manganese ore bodies where manganoan fayalite is most commonly found, the enrichment in volatile phases such as H_2O and CO_2 in the high-silica rhyolitic magma (T. Vogel, personal communication) may have contributed to the stability of manganoan fayalite.

Of the grains analyzed, only grains no. 1 and 8 (complete data set available from authors) in sample A5-3 were large enough for zoning studies. Grain no. 1 exhibits negligible zoning, whereas grain no. 8 is zoned with respect to FeO (47.71 wt% to 50.03 wt%), MnO (20.63 wt% to 19.48 wt%), and CaO (0.08 wt% to 0.05 wt%), as measured from the edge to the center of the grain. The crystallographic orientation of this grain could not be deter-
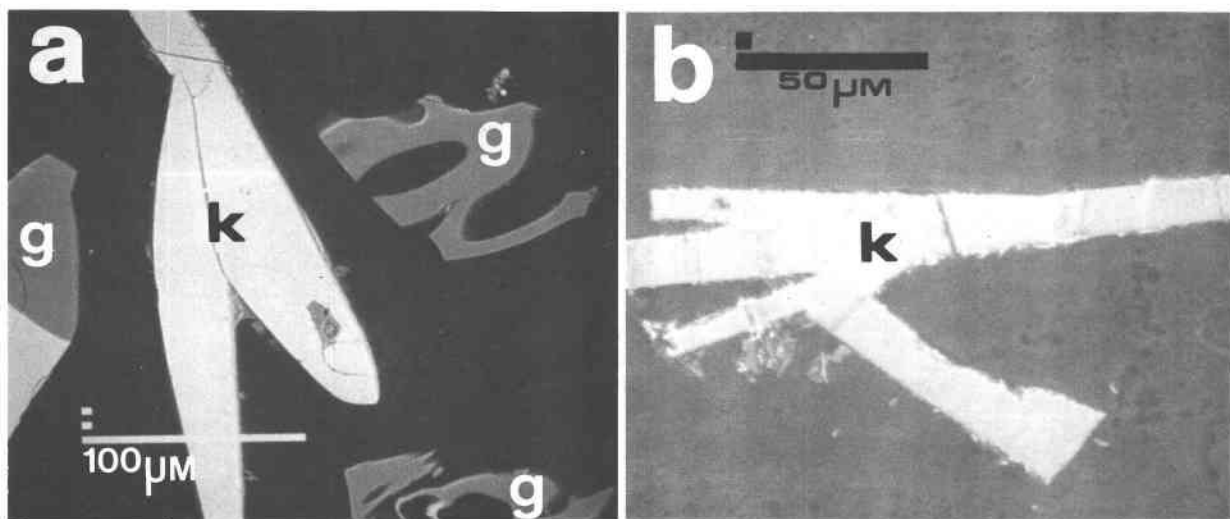
Fig. 4. Backscattered electron photomicrographs (a and b) of manganoan fayalite phenocrysts from samples A5-3 and A21-18. Note difference in scale bar size. Labels are g = glass, k = manganoan fayalite.

mined, but a sketch of the grain orientation and electron microprobe traverse is shown in Figure 3. Because of the random nature of the cut through the manganoan fayalite grain, the range of chemical zonation in grain no. 8 should be considered a minimum, as it is uncertain whether the actual core of the grain was analyzed. Backscattered electron (BSE) photographs of representative grains are presented in Figure 4. Comparison of the BSE photographs and Figures 4a and 4b of Mossman and Pawson (1976, pages 484 and 485) reveal similar grain morphologies.

DISCUSSION

The manganoan fayalite phenocrysts are interpreted by us to be primary magmatic phases that crystallized within the Timber Mountain magmatic system. The occurrence of manganoan fayalite as a xenocrystic phase can be rejected because of the lack of other xenocrystic phases or rock fragments in the pumice fragments (Rose, 1988). The use of whole pumice fragments as opposed to whole-rock tuff samples to study magmatic compositions in the Ammonia Tanks Member of the Timber Mountain Tuff is based partly upon this condition (see Schuraytz et al., 1986, and Schuraytz et al., 1989, for a detailed discussion of sample analyses of pumice vs. whole-rock tuff). Other xenocrystic phases should be present if the magma had partially assimilated or mechanically incorporated metasomatized country rock containing manganoan fayalite. Although Paleozoic carbonate forms a cover 1–2 km thick in the southern Nevada region, there is no evidence of manganese-bearing sulfide deposits in the area.

Fayalite may be present in highly evolved silicic ash-flow tuffs. Several analyses taken from the literature are plotted in Figure 3. The fayalite found in silicic ash-flow tuffs has a composition of approximately $Fa_{94}Fo_1Te_5$ (Carmichael, 1967; Mahood, 1981). Fayalite from other rhyolitic tuffs ranges in composition from $Fa_{88}Fo_6Te_6$

(Carmichael, 1967) to $Fa_{85}Fo_9Te_6$ (Warshaw and Smith, 1988). This suggests that many of the reported occurrences of fayalite by workers in high-level silicic magmatic systems may in fact have a significant proportion of the manganoan component present. The manganoan fayalite of the Ammonia Tanks Member, however, is more enriched in Mn than any other fayalitic olivine thus far documented by workers in silicic magmatic systems.

ACKNOWLEDGMENTS

REFERENCES CITED

Bacon, C.R., Macdonald, R., Smith, R.L., and Baedecker, P.A. (1981) Pleistocene high-silica rhyolites of the Coso Volcanic Field, Inyo County. Journal of Geophysical Research, 86, 10223–10241.

Bence, A.E., and Albee, A.L. (1968) Empirical correction factors for the electron microanalyses of silicates and oxides. Journal of Geology, 76, 382–403.

Bhattacharyya, S. (1986) Mineral chemistry and petrology of the manganese silicate rocks of Vizianagaram manganese belt, Andhra Pradesh. Journal Geological Society of India, 27, 169–184.

Birch, W.D. (1984) Roepperite from Broken Hill (New South Wales) is ferroan tephroite. Mineralogical Magazine, 48, 137–139.

Broxton, D.E., Warren, R.G., Byers, F.M., Jr., and Scott, R.B. (1989) Chemical and mineralogic trends within the Timber Mountain–Oasis Valley caldera complex, Nevada: Evidence for multiple cycles of chemical evolution in a long-lived silicic magma system. Journal of Geophysical Research, 94, 5961–5986.

Byers, F.M., Jr., Carr, W.J., Orkild, P.P., Quinlivan, W.D., and Sargent, K.A. (1976) Volcanic suites and related cauldrons of Timber Mountain–Oasis Valley caldera complex, southern Nevada. U.S. Geological Survey Professional Paper 919.

Carmichael, I.S.E. (1967) The iron-titanium oxides of salic volcanic rocks

and their associated ferromagnesian silicates. Contributions to Mineralogy and Petrology, 14, 36–64.

Carr, W.J., Byers, F.M., Jr., and Orkild, P.P. (1986) Stratigraphic and volcano-tectonic relations of Crater Flat Tuff and some older volcanic units, Nye county, Nevada. U.S. Geological Survey Professional Paper 1323.

Deer, W.A., Howie, R.A., and Zussman, J. (1982) Olivine group. In Rock-forming minerals, vol. 1A: Orthosilicates (2nd edition), p. 1–375. Longman, London.

Frisch, T. (1972) Iron knebelite from the nordmarkite of Shefford Mountain, Quebec. Canadian Mineralogist, 11, 552–553.

Gunning, H.C. (1936) Knebelite at Bluebell Mine, Kootenay Lake, B.C. Transactions Royal Society of Canada, Section IV, 19–22.

Henriques, C.A. (1956) Optical and physical properties of knebelite. Arkiv foer Mineralogi och Geologi, 2, 255–269.

—— (1957) The effect of cations on the optical properties and the cell dimensions of knebelite and olivine. Arkiv foer Mineralogi och Geologi, 2, 303–312.

Hildreth, W. (1981) Gradients in silicic magma chambers: Implications for lithospheric magmatism. Journal of Geophysical Research, 86, 10153–10192.

Hodgson, C.J. (1975) The geology and geological development of the Broken Hill lode, in the New Broken Hill Consolidated Mine Australia: Part II, mineralogy. Journal of the Geological Society of Australia, 22, 33–50.

Hyndman, D.W. (1982) Petrology of igneous and metamorphic rocks, 768 p. McGraw-Hill, New York.

Kazachenko, V.T., Narnov, G.A., Chubarov, Zh.A. Shcheka, and Romanenko, I.M. (1979) Manganese silicates from a polymetallic deposit in Primorye, U.S.S.R. Neues Jahrbuch für Mineralogie Abhandlungen, 137, 20–41.

Keankeo, W., Kitamura, T., and Tanida, K. (1986) Tephroite and knebelite from Hijikuzu Mine, Iwate Prefecture, Japan. Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists, 81, 341–347.

Lipman, P.W. (1965) Chemical comparison of glassy and crystalline volcanic rocks. Geological Society of America Special Paper 82, 260–261.

Mahood, G.A. (1981) A summary of the geology and petrology of the Sierra La Primavera, Jalisco, Mexico. Journal of Geophysical Research, 86, 10137–10152.

Mason, B. (1973) Manganese silicate minerals from Broken Hill, New South Wales. Journal of the Geological Society of Australia, 20, 397–404.

Mills, J.G., Jr., Schuraytz, B.C., Flood, T.P., Rose, T.P., and Vogel, T.A. (1987) Evolution of a zoned magmatic system in the southwestern Nevada volcanic field. Geological Society of America Abstracts with Programs, 19, 773.

Mossman, D.J., and Pawson, D.J. (1976) X-ray and optical characterization of the forsterite-fayalite-tephroite series with comments on kne-

belite from Bluebell Mine, British Columbia. Canadian Mineralogist, 14, 479–486.

Nambu, M., Tanida, K., and Kitamura, T. (1966) Mineralogical study of manganese silicate ores in northeastern Japan (I). Knebelite from Hakozaki mine, Iwate Prefecture. Bulletin. Research Institute of Mineral Dressing and Metallurgy, Tohoku University, 22, 63–75.

Noble, D.C. (1965) Ground-water leaching of sodium from quickly cooled volcanic rocks (abs.). American Mineralogist, 50, 289.

—— (1967) Sodium, potassium, and ferrous iron contents of some secondarily hydrated natural silicic glasses. American Mineralogist, 52, 280–286.

Omori, K., and Hasegawa, S. (1951) A new find of iron knebelite from a pegmatite in Iizaka village, Fukushima Prefecture. Tohoku University, Science Reports, series C, 4, 29–32.

Omori, K., Hasegawa, S., and Ishii, M. (1950) A new occurrence of iron-knebelite from a pegmatite in Iizaka village, Fukushima Prefecture. Journal of the Japanese Association of Mineralogists, 34, 107–113.

Rose, T.P. (1988) A model for the origin of the chemically zoned Ammonia Tanks Member of the Timber Mountain Tuff due to crystal fractionation. M.S. thesis, Michigan State University, East Lansing, Michigan.

Schuraytz, B.C., Vogel, T.A., and Younker, L.W. (1986) Geochemical gradients in the Topopah Spring Member of the Paintbrush Tuff: Evidence for eruption across a magmatic interface. Lawrence Livermore National Laboratory Report, UCRL-53698, 59.

—— (1989) Evidence for dynamic withdrawal from a layered magma body: The Topopah Spring Tuff, southwestern Nevada. Journal of Geophysical Research, 94, 5925–5942.

Segnit, E.R. (1962) Manganese deposits in the neighbourhood of Tamworth, New South Wales. Proceedings, Australian Institute of Mining and Metallurgy, 202, 47–61.

Smith, R.L. (1979) Ash-flow magmatism. In C.E. Chapin and W.E. Elston, Eds., Ash-flow tuffs. Geological Society of America Special Paper 180, 5–27.

Tilley, C.E. (1938) Cummingtonite-bearing rocks from the Lewisian. Geological Magazine, 75, 76–81.

Warshaw, C.M., and Smith, R.L. (1988) Pyroxenes and fayalites in the Bandelier Tuff, New Mexico: Temperatures and comparison with other rhyolites. American Mineralogist, 73, 1025–1037.

Watanabe, T., and Kato, A. (1957) A new occurrence of pyrosmalite in the Kyurasawa mine, Tochigi Prefecture, Japan. Mineralogical Journal, 2, 180–186.

Yoshimura, T. (1939) Studies on the minerals from the manganese deposit of Kaso mine, Japan. Journal Faculty Science Hokkaido University, series IV, 4, 313–451.