NIEDERSÄCHSISCHE STAATS- UND
UNIVERSITÄTSBIBLIOTHEK GÖTTINGEN

Werk

Jahr: 1986
Kollektion: fid.geo
Signatur: 8 Z NAT 2148:60
Digitalisiert: Niedersächsische Staats- und Universitätsbibliothek Göttingen
Werk Id: PPN1015067948_0060
PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948_0060

LOG Id: LOG_0017
LOG Titel: Magnetic properties and oxidation experiments with synthetic olivines (Fe□Mg□□□)□SiO□, 0□x□1
LOG Typ: article

Übergeordnetes Werk

Werk Id: PPN1015067948
PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948
OPAC: http://opac.sub.uni-goettingen.de/DB=1/PPN?PPN=1015067948

Terms and Conditions

The Goettingen State and University Library provides access to digitized documents strictly for noncommercial educational, research and private purposes and makes no warranty with regard to their use for other purposes. Some of our collections are protected by copyright. Publication and/or broadcast in any form (including electronic) requires prior written permission from the Goettingen State- and University Library.
Each copy of any part of this document must contain there Terms and Conditions. With the usage of the library's online system to access or download a digitized document you accept the Terms and Conditions.
Reproductions of material on the web site may not be made for or donated to other repositories, nor may be further reproduced without written permission from the Goettingen State- and University Library.

For reproduction requests and permissions, please contact us. If citing materials, please give proper attribution of the source.

Contact

Niedersächsische Staats- und Universitätsbibliothek Göttingen
Georg-August-Universität Göttingen
Platz der Göttinger Sieben 1
37073 Göttingen
Germany
Email: gdz@sub.uni-goettingen.de

J Geophys (1986) 60:41–46

Journal of Geophysics

Magnetic properties and oxidation experiments with synthetic olivines $(Fe_xMg_{1-x})_2SiO_4$, $0 \leqq x \leqq 1$

V. Hoffmann and H.C. Soffel

Institut für Allgemeine und Angewandte Geophysik der Universität,
Theresienstrasse 41, D-8000 München 2, Federal Republic of Germany

Abstract. Olivines with the composition of $(Fe_xMg_{1-x})_2SiO_4$ with $x = 0.1$, 0.3, 0.5, 0.7, 0.9, and 1.0 have been synthesized using a modification of the method by Hoye and O'Reilly (1972). The structural and magnetic properties of the olivines have been tested with X-ray powder pattern studies and the measurement of the magnetic susceptibility and its variation with temperature. The specific susceptibility X_g at room temperature, the Curie constant C_g and the asymptotic Curie temperature θ_a, the Néel temperature T_N, and the transition temperature T_t were found to vary systematically with x thus confirming and extending the results obtained by Hoye and O'Reilly (1972). The oxidation experiments were done in air at various temperatures up to 700° C and heating times up to 70 h. The resulting ferrimagnetic phases in the olivines have been identified with magnetic measurements and X-ray studies.

Key words: Rock magnetism – Olivine – Oxidation – Magnesioferrite – Paleomagnetism

Introduction

Many natural silicates contain inclusions of ferrimagnetic minerals which alter their magnetic properties from paramagnetism to antiferromagnetism or even weak ferrimagnetism. Due to these ferrimagnetic inclusions a remanent magnetization can be produced in these rocks which is often related to a metamorphic event. If the generation of the ferrimagnetic inclusions occurred at appreciably lower temperatures than the blocking temperatures, the thus formed remanence is generally called a chemical remanent magnetization (CRM). In cases where higher temperatures are involved, a partial thermoremanent magnetization (PTRM) or even a thermoremanent magnetization (TRM) may result. Due to the often extremely small size of the ferrimagnetic phases they can generally not be observed with reflected-light microscopes and often not by X-ray powder diffraction methods as well. Electron microscope studies, Mössbauer spectroscopy, and magnetic measurements are reliable methods to identify these phases.

An essential prerequisite for the generation of ferrimagnetic inclusions in silicates by oxidation processes is the presence of iron, either as a principle constituent in the minerals or as an accessory cation. Therefore, such frequently occurring minerals like pyroxenes (Evans et al., 1968; Evans and Wayman, 1970), biotite (Wu et al., 1974), hornblende (Wu et al., 1974), and even some feldspars (Hargraves and Young, 1969; Murthy et al., 1971; Wu et al., 1974) have been reported to carry stable remanent magnetization components due to ferrimagnetic inclusions of submicroscopic size.

The olivines are generally described as a solid solution between the two end members forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). In natural olivines the composition is generally close to the forsterite side, and natural olivines with compositions close to the fayalite are rarely found. Furthermore, other naturally occurring cations in olivines like chromium, manganese, and others could eventually lead to complicated ferrimagnetic exsolution products. It was therefore decided to make synthetic olivines for our oxidation experiments with given compositions to avoid problems of uncertain chemistry and to get representative compositions along the forsterite-fayalite line.

Synthesis and structural control of the olivines

The olivines of our study have been sintered using a modification of the method by Hoye and O'Reilly (1972). It consists of a solid-state reaction in a self-buffered system to generate the appropriate oxygen partial pressure. The constituents which have been used for the synthesis are: MgO (99.99%), Fe_2O_3 (99.99%), Fe (99.9%), and SiO_2 (99.999%). The SiO_2 powder was heated at 1,000° C for 48 h to remove all water. The mixture of the constituents for 5 g of olivine was milled for 30 min in acetone for homogenization and reduction of the grain size, sealed into quartz tubes, heated for 120 h at 1,000° C and quenched to room temperature. After the first run the X-ray powder patterns still showed lines of enstatite, cristobalite, magnetite, or wuestite. After a second run under the same conditions homogeneous olivines of white or light-olive color were able to be obtained. The sintering time of 10 h (after Hoye and O'Reilly, 1972) turned out to be insufficient for the production of homogeneous phases.

The exact composition of the olivines and the quality of the specimens were tested by X-ray powder diffraction using the $d(130)$ line which depends on the fayalite content x. Schwab and Küstner (1977) have set up a calibration curve, where x is given by the nonlinear equation:

$$x = 7.522 - 14.9071 * (3.0199 - d(130))^{0.5}.$$

Offprint requests to: H.C. Soffel

According to this calibration curve the fayalite content x of our specimens was always slightly smaller (up to 3 mol%) than the theoretical value. This is explained by a diffusion of some Fe into the quartz tubes.

The Fe^{3+}/Fe^{2+} ratio was determined by wet chemical analyses. The ratio never exceeded 3%, which is also observed for natural olivines (Schwab, 1967).

The paramagnetic specific susceptibility X_g at room temperature can also be used to test the purity of the synthetic olivines. Eventually occurring exsolutions of ferrimagnetic phases (mainly magnetite) can be detected because of the very large specific susceptibility of magnetite (0.1–1.0 $cm^3\ g^{-1}$). However, as will be discussed in detail in the next section, the values of X_g were always on the order of 10^{-5}–10^{-4} $cm^3\ g^{-1}$, which is in good agreement with the expected values for purely paramagnetic substances and the olivines specifically (Hoye and O'Reilly, 1972).

Magnetic properties of the synthetic olivines

Hoye and O'Reilly (1972) have determined some magnetic properties of the olivines at room temperature for the solid-solution series between forsterite and fayalite. Forsterite (Mg_2SiO_4) is diamagnetic because it contains no paramagnetic cations. Its specific diamagnetic susceptibility is $X_g = -0.31 * 10^{-6}\ cm^3\ g^{-1}$. With increasing fayalite (Fe_2SiO_4) content the paramagnetic specific susceptibility X_g increases according to Fig. 1. The dashed line gives the values determined by Hoye and O'Reilly (1972), crosses are data from this paper. The value for a natural olivine is shown by a circle. The data set can be approximated by the following curve of second degree:

$$X_g = 2.6 + 161.4x - 71.6x^2 \quad \text{for } 0.1 \le x \le 1.0.$$

The olivines are not paramagnetic in the strictest sense. A plot of the reciprocal specific susceptibility, $1/X_g$ versus the absolute temperature, T, shows in fact a weak antiferromagnetic interaction with a straight line intersecting the temperature axis at negative values (asymptotic Curie temperature, θ_a). This is shown in Fig. 2 for an olivine of the composition $Fa_{30}Fo_{70}$. θ_a varies linearly with the fayalite content x, as shown in Fig. 3. The data can be approximated by the following relationship:

$$\theta_a = -0.45 - 102.4x \quad \text{for } 0.1 \le x \le 1.0.$$

In the theory of antiferromagnetism (Néel, 1948) the slope of the $1/X_g$ vs T curve determines the Curie constant C_g according to the following equation:

$$1/X_g = (T - \theta_a)/C_g.$$

C_g varies with the fayalite content x as shown in Fig. 4. The data can be approximated by the following nonlinear relationship:

$$C_g = 5.1x - 1.51x^2 \quad \text{for } 0 \le x \le 1.$$

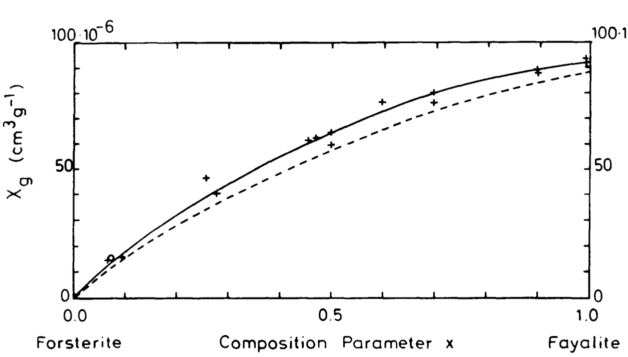

Fig. 1. Dependency of the specific susceptibility X_g of olivines on the fayalite content x. Dashed curve, values from Hoye and O'Reilly (1972); crosses, our data; circle, a natural olivine. The solid line is a best fit of a polynomial of the second degree

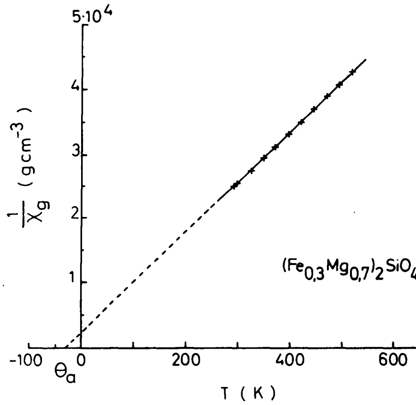

Fig. 2. Plot of the reciprocal specific susceptibility $1/X_g$ versus the absolute temperature T for a synthetic olivine of the composition Fa_{30} and the definition of the asymptotic Curie temperature θ_a

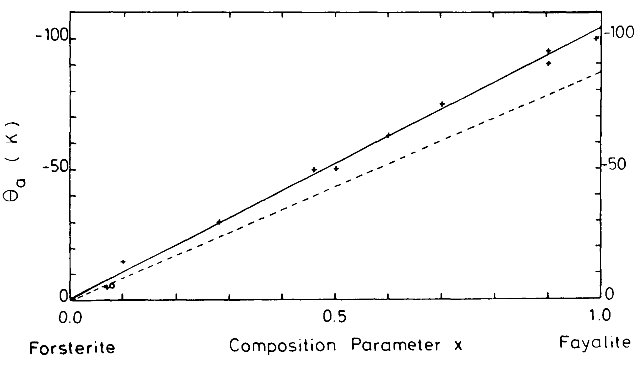

Fig. 3. Dependency of the asymptotic Curie temperature θ_a on the fayalite content x in olivines. For symbols see legend of Fig. 1. The line is a linear least square fit

Because of technical reasons it was not possible to observe the $1/X_g$ vs T curves down to temperature close to $t = 0$ and to determine the Néel temperature T_N, above which the antiferromagnetic ordering disappears, and the temperature T_t, below which spin canting occurs instead of a collinear spin arrangement (Fuess et al., 1983). Santoro et al. (1966) determined simple relationships between θ_a, T_N and T_t which are given by:

$$T_N/\theta_a = 0.68; \quad T_t/T_N = 0.29.$$

The relationships between θ_a, T_N, T_t, and the fayalite content x are shown in Fig. 5 (dashed lines, data from Hoye and O'Reilly, 1972; solid lines, calculation of this paper). According to Hoye and O'Reilly (1972) any magnetic order-

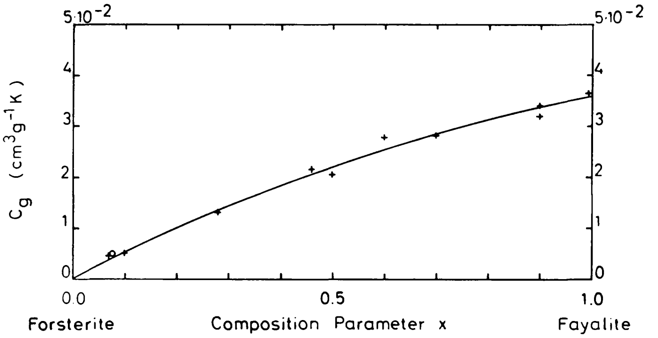

Fig. 4. Dependency of the Curie constant C_g of olivines on the favalite content x. Crosses, our data; circle, a natural olivine. The line is a best fit by a polynomial of the second degree

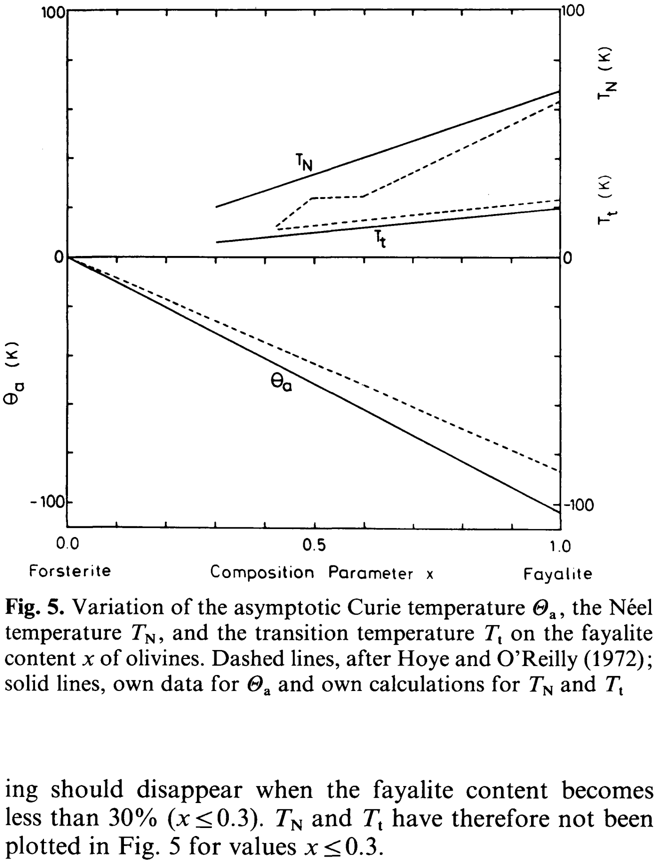

Fig. 5. Variation of the asymptotic Curie temperature Θ_a, the Néel temperature T_N, and the transition temperature T_t on the fayalite content x of olivines. Dashed lines, after Hoye and O'Reilly (1972); solid lines, own data for Θ_a and own calculations for T_N and T_t

ing should disappear when the fayalite content becomes less than 30% ($x \leq 0.3$). T_N and T_t have therefore not been plotted in Fig. 5 for values $x \leq 0.3$.

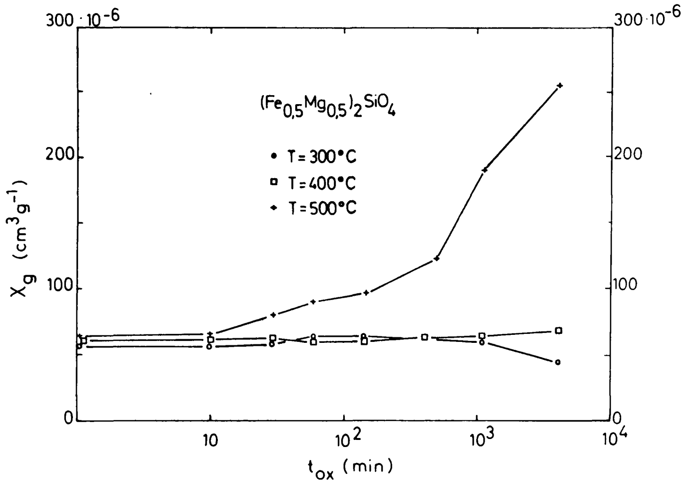

Fig. 6. Oxidation experiment with Fa_{50} heated at 300°, 400°, and 500° C. A drastic change of the specific susceptibility X_g with the logarithm of the heating time t in minutes occurs at the heating temperature of 500° C indicating the formation of a ferrimagnetic phase in the olivine

Table 1. Chemical, structural, and some magnetic properties of the synthetic olivines. d, composition determined with X-ray powder diffraction methods; c, composition determined by wet chemical analysis

Sintering products		Color	$d(130)$ in Å	Susceptibility in 10^{-6} cm³ g⁻¹
Theoretical composition	Real composition			
$Fa_{10}Fo_{90}$	d, $Fa_{10}Fo_{90}$ c, $Fa_{09}Fo_{91}$	white	2.7719	20.2
$Fa_{30}Fo_{70}$	d, $Fa_{28}Fo_{72}$ c, $Fa_{28}Fo_{72}$	white	2.7835	40.7
$Fa_{50}Fo_{50}$	d, $Fa_{47}Fo_{53}$ c, $Fa_{49}Fo_{51}$	light olive	2.7964	60.6
$Fa_{70}Fo_{30}$	d, $Fa_{70}Fo_{30}$ c, $Fa_{68}Fo_{32}$	light olive	2.8101	76.5
$Fa_{90}Fo_{10}$	d, $Fa_{90}Fo_{10}$ c, $Fa_{88}Fo_{12}$	light olive	2.8241	88.2
Fayalite	d, $Fa_{100}Fo_{0}$ c, $Fa_{100}Fo_{0}$	light olive	2.8263	94.0

Oxidation experiments with synthetic olivines

The synthetic olivine specimens were first milled in acetone to a grain size of 0.5 μm and then heated in air in a sintered Al_2O_3 crucible within a quartz tube furnace at temperatures up to 700° C between 10 and 4,200 min (70 h) and quenched to room temperature within a few minutes. The upper temperature limit was chosen to simulate oxidation conditions occurring in nature during weathering, hydrothermal, and deuteric alteration. The color of the olivines gives a first indication for the onset of oxidation. According to Koltermann (1962) the following colors are indicative for the oxidation state:

– white to light olive	unoxidized (depending on Fa content)
– olive to dark olive	partial oxidation of Fe^{2+} to Fe^{3+}
– dark olive to dark grey and black	almost complete oxidation of Fe^{2+} to Fe^{3+}, generation of hematite or spinel phases
– reddish brown	complete oxidation, decomposition of the olivine, generation of hematite

Besides this qualitative scale the following quantitative methods have been used for the identification and quantification of the oxidation products:

- specific magnetic susceptibility,
- X-ray powder diffraction, $d(130)$ line, and
- saturation magnetization J_s vs temperature T, Curie temperature.

Because of the limited quantities of synthetic olivines only 50–100 mg of material was used for the oxidation experiments.

Table 2. Oxidation experiments with synthetic olivines Fa_{10}, Fa_{30}, Fa_{50} (two runs for 500° C), Fa_{70}, and Fa_{100}. T(°C), heating temperature; unox, unoxidized specimen; t(min), heating time in minutes; color, color of the olivine after the heating experiment (w, white; lo, light olive; o, olive; do, dark olive; lb, light brown; b, brown; dark brown; gb, grey brown; dg, dark grey; bk, black); X_g specific susceptibility in 10^{-6} cm^3 g^{-1}; d(130), d(130) line in Å; X-ray, composition of the olivine and other phases after heating determined from powder pattern analysis; T_C, Curie temperature of exsolved ferrimagnetic phases; no T_C, no ferrimagnetic phases detectable in $J_s(T)$ curves; He, hematite present; Mt, magnetite present; S, spinel phase present; Fa, fayalite; Fo, forsterite

Table 2a. Experiments with Fa_{10}

T(°C)	t(min)	Color	X_g	d(130)	X-ray	T_C(°C)
unox.	0	w	20.2	2.7719	Fa_{10}	
200	4,320	w	19.8	2.7719	Fa_{10}	no T_C
unox.	0	w	18.1	2.7719	Fa_{10}	
300	10	w	15.7			
300	30	w	15.6			
300	60	w	15.0	2.7719		
300	150	w	23.3			
300	1,080	w	19.5			
300	4,200	w	18.5	2.7719	Fa_{10}	
unox	0	w	20.2	2.7719	Fa_{10}	
400	10	w	14.6			
400	30	w	14.4			
400	60	w	14.7			
400	150	lo	17.8			
400	420	lo	25.5			
400	1,080	lo	21.0			
400	4,200	lo	26.6	2.7705	Fa_{07}	550°
unox.	0	w	18.1	2.7700	Fa_{07}	
500	10	lo	24.4			
500	30	lo	30.3			
500	60	lo	32.1			
500	150	lo	39.8			
500	480	lo	40.5			
500	1,080	lo	42.7			500°(?)
500	4,200	lo	43.1	2.7656	Fo	500°
unox.	0	w	20.2	2.7719	Fa_{10}	
600	4,200	lb	244.4	2.7655	Fo	360°, 570°

Table 2b. Experiments with Fa_{30}

T(°C)	t(min)	Color	X_g	d(130)	X-ray	T_C(°C)
unox.	0	w	40.7	2.7835	Fa_{28}	
200	4,320	w	41.2	2.7824	Fa_{26}	no T_C
unox.	0	w	40.7	2.7835	Fa_{28}	
300	10	w	39.2			
300	30	w	40.0			
300	60	lo	38.1			
300	150	lo	40.2			
300	420	lo	43.3			
300	1,080	lo	43.5			
300	4,200	lo	42.3	2.7814	Fa_{24}	
unox.	0	w	40.7	2.7835	Fa_{28}	
400	10	lo	40.6			
400	30	lo	43.6			
400	60	lo	39.9			
400	150	lo	38.3			
400	420	o	43.1			
400	1,080	o	36.2			
400	4,200	o	38.4	2.7782	Fa_{19}	no T_C
unox.	0	w	40.7	2.7835	Fa_{28}	
500	10	lo	40.3			
500	30	o	39.3			
500	60	o	37.9			
500	150	o	40.7	2.7814	Fa_{24}	
500	420	o	48.3			
500	1,080	o	57.4			
500	4,200	o	103.4	2.7719	Fa_{10}	360°
unox.	0	w	40.7	2.7835	Fa_{28}	
600	4,200	b	337.0	2.7657	Fo, S	360°

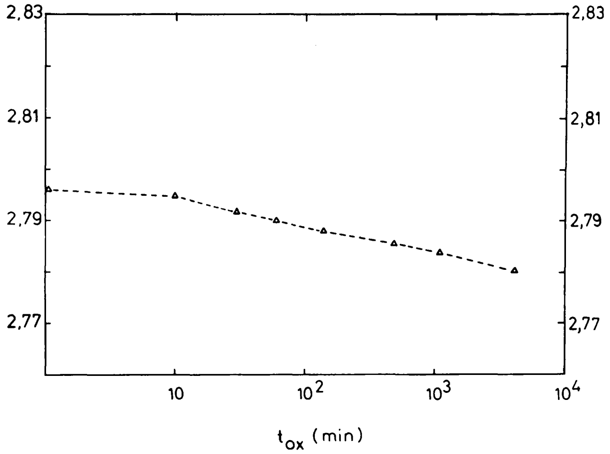

Fig. 7. Example for an oxidation experiment with Fa_{50} heated at 500° C. Change of the d(130) line with the logarithm of the heating time t indicating the variation of the composition of the olivine toward a phase less rich in Fe

Similar to the experiments by Hoye and Evans (1975) we used the following oxidation times: 10, 30, 60, 150, 420, (480), 1080, 4200, and (4,320) min. The specimens were put in a ceramic crucible and placed into the preheated furnace. According to Hoye and Evans (1975) they reach their maximum temperature within less than 3 min. This heating time was included in the total heating time. After the heating experiment the powder was quickly filled into a quartz tube and cooled under running water within 2–3 min to room temperature to avoid further oxidation. Olivines of the composition Fa_{10}, Fa_{30}, and Fa_{50} were studied in more detail than the other compositions due to their more frequent occurrence in nature. Special attention was also given to pure fayalite, Fa_{100}, because it contains no magnesium. Table 2 describes the results of the heating experiments, while Table 3 gives a description of the ferrimagnetic exsolution products in the olivines.

Ferrimagnetic phases as a result of the oxidation

It is interesting to see from Table 3 that the heat treatment of up to 4,320 min was not able to produce ferrimagnetic phases in the olivines with a fayalite content of less than Fa_{70} at temperatures lower than 300° C. The main effects occur at temperatures higher than 400° C. In fayalite the ferrimagnetic phase is predominantly hematite; magnetite is also formed to a lesser degree. During the heating experiment amorphous quartz is also formed but cannot be identified by X-ray methods. In all Mg-rich olivines a Mg$-$Fe spinel has been identified, mainly from the Curie temperature measurements. According to Nagata (1961) the Curie

Table 2c. Experiments with Fa_{50}

T(°C)	t(min)	Color	X_g	d(130)	X-ray	T_C(°C)
unox.	0	lo	62.4	2.7951	Fa_{46}	
200	4,320	lo	61.9	2.7951	Fa_{46}	no T_C
unox.	0	lo	62.8	2.7959	Fa_{47}	
300	10	lo	61.0			
300	30	lo	60.5			
300	60	lo	61.7			
300	150	o	60.1			
300	1,080	o	60.9			
300	4,200	o	44.2	2.7951		no T_C
unox.	0	lo	62.4	2.7940	Fa_{44}	
400	10	o	63.5			
400	30	o	61.6			
400	60	o	60.1			
400	150	o	60.2			
400	420	o	63.4			
400	1,080	o	63.6			
400	4,200	do	67.5	2.7930	Fa_{42}	no T_C
unox.	0	lo	62.8	2.7959	Fa_{47}	
500	10	lo	65.2	2.7947	Fa_{45}	
500	30	o	80.5	2.7915	Fa_{40}	
500	60	do	90.9	2.7898	Fa_{37}	
500	150	do	97.8	2.7877	Fa_{34}	
500	480	do	122.8	2.7853	Fa_{30}	360°
500	1,080	do	189.2	2.7835	Fa_{27}	
500	4,200	do	253.9	2.7803	Fa_{22}, S	360°
unox.	0	lo	60.6	2.7964	Fa_{50}	
500	30	o	79.2	2.7932	Fa_{42}	
500	60	o	85.0	2.7913	Fa_{39}	
500	150	do	90.8	2.7888	Fa_{35}	
500	420	do	116.5	2.7870	Fa_{33}	360°
500	1,080	do	132.2	2.7858	Fa_{32}	360°
500	4,200	do	160.6	2.7803	Fa_{21}, S	360°
unox.	0	lo	62.8	2.7959	Fa_{47}	
600	4,200	db	489.0	2.7655	Fo, S	360°

Table 2d. Experiments with Fa_{70}

T(°C)	t(min)	Color	X_g	d(130)	X-ray	T_C(°C)
unox.	0	lo	76.5	2.8101	Fa_{70}	
500	10	db	182.4	2.8047	Fa_{61}	360°
500	30	dg	197.0			
500	60	dg	198.3			
500	150	bk	189.8			360°
500	420	bk	203.2	2.7824	Fa_{26}, S	
500	1,080	bk	253.0			360°
500	4,200	bk	241.0	2.7782	Fa_{19}, S	360°

Table 2e. Experiments with Fa_{100} fayalite

T(°C)	t(min)	Color	X_g	d(130)	X-ray	T_C(°C)
unox.	0	lo	93.9	2.8263	Fa_{100}	
300	10	b	91.7			
300	30	b	91.5			
300	60	b	92.0			
300	150	b	91.3			
300	1,080	gb	91.9	2.8252		
300	4,200	gb	86.6	2.8242		680°
unox.	0	lo	93.9	2.8263	Fa_{100}	
500	10	dg	85.6			
500	30	dg	76.4			
500	60	bk	71.3	2.8112	Fa_{71}, He	680°
500	150	bk	71.3			
500	480	bk	58.6			
500	1,080	bk	54.7	2.7856	Fa_{31}, He	
500	4,200	bk	45.6	2.7761	Fa_{16}, He	680°
unox.	0	lo	93.9	2.8263	Fa_{100}	
700	10	bk	51.1	2.8176	Fa, He	680°
700	30	bk	84.8			
700	60	bk	82.1	2.8292	Fa, He, Mt	
700	150	bk	328.9			
700	1,080	bk	621.5		He, Mt	570°, 680°

Table 3. Ferrimagnetic exsolutions in synthetic olivines after heat treatment in air for 4,200 min. Maximum heating temperature in °C. Curie temperatures are also given in °C. He, hematite; Mt, magnetite; MFS, Mg–Fe spinel; n.ex., no exsolution could be observed under the above-mentioned conditions; n.m., not measured

T(°C)	Fa_{10}	Fa_{30}	Fa_{50}	Fa_{70}	Fa_{100}
200°	n.ex.	n.ex.	n.ex.	n.m.	n.m.
300°	n.ex.	n.ex.	n.ex.	MFS, 360°	He, 680°
400°	MFS, 550°	n.ex.	n.ex.	n.m.	n.m.
500°	MFS, 500°	MFS, 360°	MFS, 360°	MFS, 360°	He, 680°
600°	MFS, 360° Mt, 570°	MFS, 360°	MFS, 360°	n.m.	n.m.
700°	n.m.	n.m.	n.m.	n.m.	Mt, 570° He, 680°

temperatures of the solid-solution series Mg-Fe spinel (MFS) to magnetite (Mt) vary between around 320° C for MFS and 570° C for Mt. curie temperatures around 360° C are normally attributed to titanomagnetites in the Curie temperature analysis of basaltic rocks. The absence of any titanium in the synthetic olivines demands another interpretation. As the lattice parameters of the observed Mg–Fe spinel are not very different from those of pure magnetite (ASTM Charts, 1969), the actual composition of this spinel may have been misinterpreted by previous authors because most investigators speak of magnetite exsolution in olivines during oxidation experiments (Koltermann, 1962).

Table 2 shows that the growth of the ferrimagnetic phases reduces the nominal fayalite content of the remaining olivine phase. This is revealed by a shift in the d(130) line toward compositions which are less rich in Fe. Table 2c (500° C) gives a good example of this effect.

Kinetics of the oxidation process

One of the aims of this study has been the determination of the kinetics of the oxidation of olivines. The results for the heat treatment are listed in detail in Table 2 and in Figs. 6 and 7.

Figure 6 shows the variation of the specific susceptibility X_g with the logarithm of heating time t. There is a more or less linear increase in X_g with log t, which can of course not be extrapolated to geological times because the process comes to an end when all the Fe in the olivines has been consumed for the formation of first a Mg–Fe spinel and later for hematite when the oxidation goes on. Similarly, the composition of the remaining olivine phase changes due to the concentration of part of the Fe in the iron oxides. This is revealed by the shift in the $d(130)$ line toward compositions less rich in Fe. This shift follows also a log/normal law as shown in Fig. 7.

Conclusions

Our results confirm to a large degree those of Hoye and O'Reilly (1973). Heating temperatures around 300° C are necessary to start the oxidation process under laboratory conditions. Depending on the availability of magnesium either Mg-poor or Mg-rich Mg−Fe spinels are formed. While Hoye and O'Reilly (1973) report also the generation of pure magnetite under these conditions – Champness (1970) reports even the formation of hematite – we only found Mg−Fe spinels. Only at oxidation temperatures above 600° C did we discover magnetite as a ferrimagnetic phase. The situation is completely different for the fayalite, which contains no Mg. Here, hematite is formed already at low heating temperatures, and magnetite appears at temperatures above 700° C.

The ferrimagnetic ore grains were found to be submicroscopic. They are presumably in the size range between superparamagnetism and the single-domain state. This is revealed by a strong magnetic viscosity of the material. With increasing oxidation time there seems to be a tendency for further crystal growth of the ferrimagnetic inclusions leading to first more single-domain and later even multidomain grains. The identification of Mg−Fe spinels in the olivines indicates that at least part of the remanent magnetization of altered mafic and ultramafic rocks may be carried by this not so intensively studied magnetic mineral.

Acknowledgements. We thank Prof. Dr. G. Huckenholz, Dr. T. Fehr, Dipl. Min. R. Hochleitner, and Dipl. Chem. T. Dorfner from the Mineralogical Institute of our university for their help in the preparation of the synthetic olivines and for the possibility to use their equipment. Thanks are also due to Priv. Doz. Dr. E. Schmidbauer for many helpful discussions.

References

ASTM Charts. Powder Diffraction File, Amer. Soc. for Testing and Materials, Philadelphia, USA, 1969

Champness, P.E.: Nucleation and growth of iron oxides in olivines, $(Mg, Fe)_2SiO_4$. Mineral. Mag., **37**, 790–800, 1970

Evans, M.E., Wayman, M.L.: An investigation of small magnetic particles by means of electron microscopy. Earth Planet. Sci. Letters, **9**, 365–370, 1970

Evans, M.E., McElhinny, M.W., Gifford, A.C.: Single domain magnetite and high coercivities in a gabbroic intrusion. Earth Planet. Sci. Letters, **4**, 142–146, 1968

Fuess, H., Lottermoser, W., Müller, R.: Magnetische Eigenschaften der synthetischen Olivine Tephroit und Fayalit. Fortschr. Min. **61**, Beiheft **1**, 134–136, 1983

Hargraves, R.B., Young, W.M.: Source of stable remanent magnetism in Lambertville diabase. Amer. J. Sci., **267**, 1161–1177, 1969

Hoye, G.S., Evans, M.: Remanent Magnetisations in Oxidized Olivine. Geophys. J., **41**, 139–151, 1975

Hoye, G.S., O'Reilly, W.: A magnetic study of ferromagnesian olivines, $(Fe_xMg_{1-x})_2SiO_4$, $0 \leq x \leq 1$. J. Phys. Chem. Solids, **33**, 1827–1834, 1972

Hoye, G.S., O'Reilly, W.: Low-temperature oxidation of ferromagnesian olivines – a gravimetric and a magnetic study. Geophys. J., **33**, 81–92, 1973

Koltermann, M.: Der thermische Zerfall fayalithaltiger Olivine bei hohen Temperaturen. N. Jb. f. Mineral., Monatshefte, 181–192, 1962

Murthy, G.S., Evans, M.E., Gough D.I.: Evidence of single-domain magnetite in the Michikamau anorthosite. Can. J. Earth Sci., **8**, 361–370, 1971

Nagata, T.: Rock Magnetism. Maruzen Comp. Ltd. Tokyo, Japan, 1961

Néel, L.: Magnetic properties of ferrites: ferrimagnetism and antiferromagnetism. Ann. Phys., **3**, 137–198, 1948

Santoro, R.P., Newnham, R.E., Nomura, S.: Magnetic properties of Mn_2SiO_4 and Fe_2SiO_4. J. Phys. Chem. Solids., **27**, 655–666, 1966

Schwab, R.: Die Bedeutung und die experimentelle Beherrschung des Sauerstoffpartialdruckes bei der Synthese und Untersuchung Fe^{2+}-haltiger Silikate. N. Jb. Mineral. Monatsh., 244–254, 1967

Schwab, R., Küstner, D.: Präzisionsgitterkonstantenbestimmung zur Festlegung röntgenographischer Bestimmungskurven für synthetische Olivine der Mischkristallreihe Forsterit-Fayalit. N. Jb. Mineral. Monatsh., 205–215, 1977

Wu, Y.T., Fuller, M., Schmidt, V.A.: Microanalysis of N.R.M. in a granodiorite intrusion. Earth Planet. Sci. Letters, **23**, 275–285, 1974

Received January 31, 1986; revised version June 13, 1986
Accepted July 8, 1986