

ROCK-FORMING MINERALS

Vol. 1 Ortho- and King Silicates

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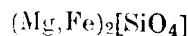
OLIVINE GROUP	1
Olivine	2
Tephroite, Knebelite	34
Monticellite	41
HUMITE GROUP	47
Norbergite, Chondrodite	48
Humite, Clinohumite	49
ZIRCON	59
SPHENE	69
GARNET GROUP	77
Almandine	85
Andradite	89
Grossular	93
Pyrope	97
Spessartine	99
Uvarovite	101
Hydrogrossular	104
VESUVIANITE	113
SILLIMANITE	121
ANDALUSITE	129
KYANITE	137
TOPAZ	145
STAUROLITE	151
CHLORITOID	161
DATOLITE	171
SAPPHIRINE	176
EPIDOTE GROUP	183
Zoisite	185
Clinzoisite, Epidote	193
Piemontite	194
Allanite	211
LAWSONITE	221
PUMPELLYITE	227
MELILITE GROUP	236
Gehlenite, Melilite, Åkermanite	236
BERYL	256
CORDIERITE	268
TOURMALINE	300
AXINITE	320
INDEX	329

OLIVINE GROUP

The olivine group includes a number of closely related minerals which crystallize with orthorhombic symmetry. The structures of all the minerals of the group consist of independent $[\text{SiO}_4]$ tetrahedra linked by divalent atoms in six-fold coordination. As is common in other orthosilicate minerals silicon is not replaced by aluminium, and the octahedral positions in the structures are occupied almost exclusively by divalent atoms; the common trivalent atoms Al and Fe^{+3} are either absent, or present in very small amounts. In the (Mg,Fe)-olivines there is a continuous series between the two end-members Mg_2SiO_4 (forsterite) and Fe_2SiO_4 (fayalite): the fayalite-knebelite (FeMnSiO_4)-tephroite (Mn_2SiO_4) series also shows complete solid solution. In the forsterite-fayalite series, however, manganese occurs only in small amounts, and the low content of manganese in this series is probably related to the small amounts of manganese in the magmas and rocks in which they crystallized. A few occurrences of magnesium-rich tephroite, picrotephroite, have been reported. The CaMgSiO_4 orthosilicate (monticellite) does not vary greatly from the ideal composition, and members of the forsterite-fayalite series in general do not contain appreciable amounts of calcium. The iron analogue of monticellite, kirschsteinite, CaFeSiO_4 , is known from slags, but has not been reported from a natural occurrence, and a magnesium-rich kirschsteinite containing 69 per cent. CaFeSiO_4 is the most iron-rich mineral of the Fe_2SiO_4 - CaFeSiO_4 series yet reported. Glaucochroite (CaMnSiO_4) is a rare olivine, and minerals intermediate in composition between CaMgSiO_4 and CaMnSiO_4 are unknown. Larsenite (PbZnSiO_4) has normally been included in the olivine group; a recent determination of the cell size and space group, however, has shown that it is not isostructural with the olivine group. Single-crystal X-ray investigation of larsenite from Franklin, New Jersey, gave a 8.23 Å, b 18.94 Å, c 5.06 Å (a and b are approximately double the values for olivine), space group $Pnam$ or Pna , $Z=8$ (Layman, 1957). The minerals of the olivine group are very susceptible to alteration by hydrothermal and weathering processes and are often pseudomorphed by minerals of low temperature paragenesis.

The (Mg,Fe)-olivines are common and important rock-forming minerals, and are particularly characteristic of the basic and ultrabasic igneous rocks; often their composition is a useful indication of the differentiation stage of the parent magmas in which they crystallized. Monticellite is not a common mineral but occurs in some ultrabasic rocks and in limestone contacts with basic and acid intrusions. The other olivine minerals are rare and have a very restricted paragenesis.

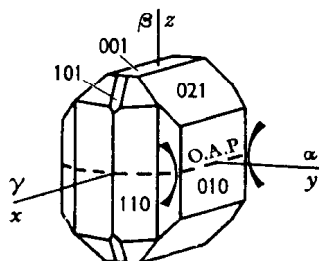
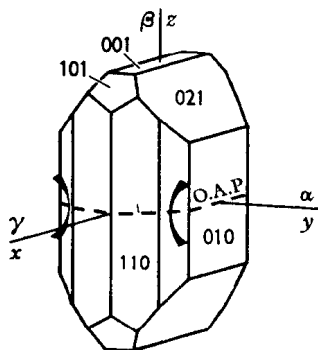
Olivine



ORTHORHOMBIC (+)(-)

Forsterite
 Mg_2SiO_4

Fayalite
 Fe_2SiO_4



α^*	1.635	1.827
β	1.651	1.869
γ	1.670	1.879
δ	0.035	0.052
$2V_\gamma$	82°	134°
$\alpha=y, \beta=z, \gamma=x, \text{O.A.P. (001)}$.		$\alpha=y, \beta=z, \gamma=x, \text{O.A.P. (001)}$.
Dispersion:	$r > v$	$r > v$
D†	3.222	4.392
H	7	$6\frac{1}{2}$
Cleavage:	{010}, {100} imperfect.	{010} moderate, {100} weak.
Twinning:	{100}, {011}, {012}	{100}
Colour:	Green, lemon-yellow; colourless in thin section.	Greenish yellow, yellow-amber; pale yellow in thin section.
Pleochroism:	—	$\alpha=\gamma$ pale yellow β orange yellow
Unit cell: †	a 4.756 Å b 10.195 Å c 5.981 Å $Z=4$	a 4.817 Å b 10.477 Å c 6.105 Å Space group $Pbnm$

Gelatinizes in HCl,

* Values of refractive indices, birefringence and $2V$ refer to end-members, between which there is continuous variation.

† Values for synthetic forsterite and fayalite (Yoder & Sahama, 1957).

The magnesium-rich olivines are common constituents of ultrabasic and basic rocks. The iron-rich members crystallize in small quantities in some acid and alkaline plutonic and volcanic rocks. Magnesium-rich olivines also occur in thermally metamorphosed impure dolomitic limestones, *e.g.* forsterite marble. The iron-rich varieties occur as a product of regional metamorphism in eulysites and other metamorphosed iron-rich sediments. Although the two atomic pairs MgFe^{+2} and Fe^{+2}Mn show complete diadochy, the (Mg,Fe)-olivines rarely contain appreciable amounts of Mn. The Mg-olivine, forsterite, is named after J. Forster, founder of the Heuland Cabinet, and the Fe-olivine, fayalite, after Fayal Island in the Azores where it was believed to have occurred in a local volcanic rock, but it was probably obtained from slag carried as ship's ballast (Palache, 1950). The names forsterite and fayalite are restricted to the compositions Fo_{100-90} and Fo_{10-0} respectively; the nomenclature of the intermediate members of the series is given in Fig. 11. The clear gem quality olivine is known as peridot.

STRUCTURE

The olivine structure was determined by Bragg and Brown (1926) on a mineral of composition $\text{Fo}_{90}\text{Fa}_{10}$, the cell dimensions of which are a 4.755 Å, b 10.21 Å, c 5.985 Å. The structure consists of individual silicon-oxygen tetrahedra linked by magnesium atoms each of which has six nearest oxygen neighbours. The oxygens lie in sheets parallel to the (100) plane and are

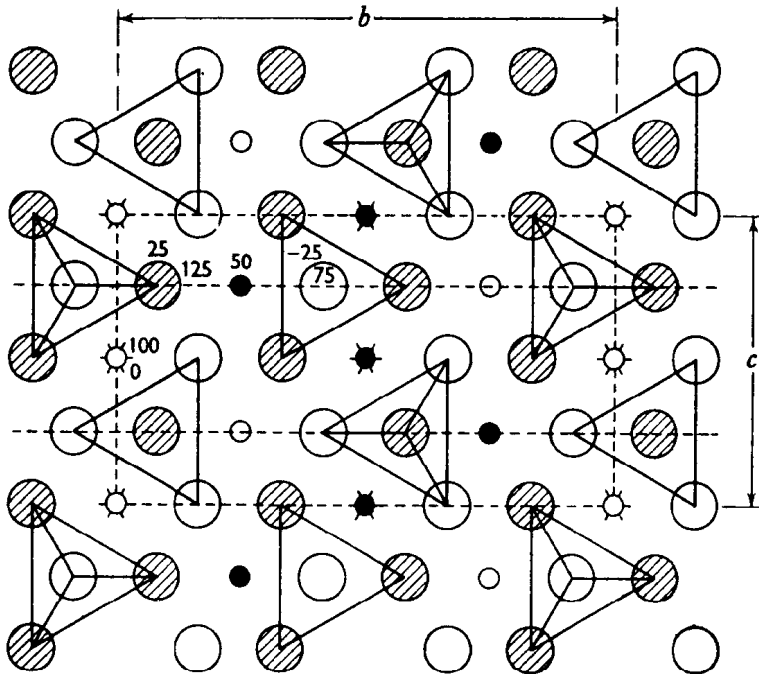


FIG. 1. Olivine structure parallel to (100) plane. Si atoms are at the centres of the tetrahedra and are not shown. Small open circles \circ Mg atoms at $x = 0$; small solid circles \bullet Mg atoms at $x = \frac{1}{2}$ (after Bragg and Brown, 1926).

arranged in approximate hexagonal close packing. In accordance with full orthorhombic symmetry the silicon-oxygen tetrahedra point alternately either way along both the x and y directions. The magnesium atoms do not occupy one set of equivalent lattice positions: half are located at centres of symmetry and half on reflection planes (Fig. 1), the former having as nearest neighbours two oxygens from two adjacent tetrahedra, the latter, two oxygens from one adjacent tetrahedron. In the olivine series the cell dimensions increase with the increasing replacement of the smaller magnesium atom by the larger iron atom. X-ray powder diffraction data for synthetic forsterite and synthetic fayalite have been determined by Yoder and Sahama (1957) and may be used to estimate the composition of the (Mg,Fe)-olivines. The equation of the determinative curve is:

$$\text{Fo (Mol. per cent.)} = 4233.91 - 1494.59d_{130}$$

and the fictive end points are forsterite $d_{130} = 2.7659$ and fayalite $d_{130} = 2.8328$. Depending on the olivine composition the determination is subject to an error of 3 to 4 mol. per cent. (Fig. 2).¹ Tables showing the variation in d values, cell dimensions and density across the olivine series are given by Eliseev (1957). Some cell determinations of members of the olivine group are listed in Table 1.

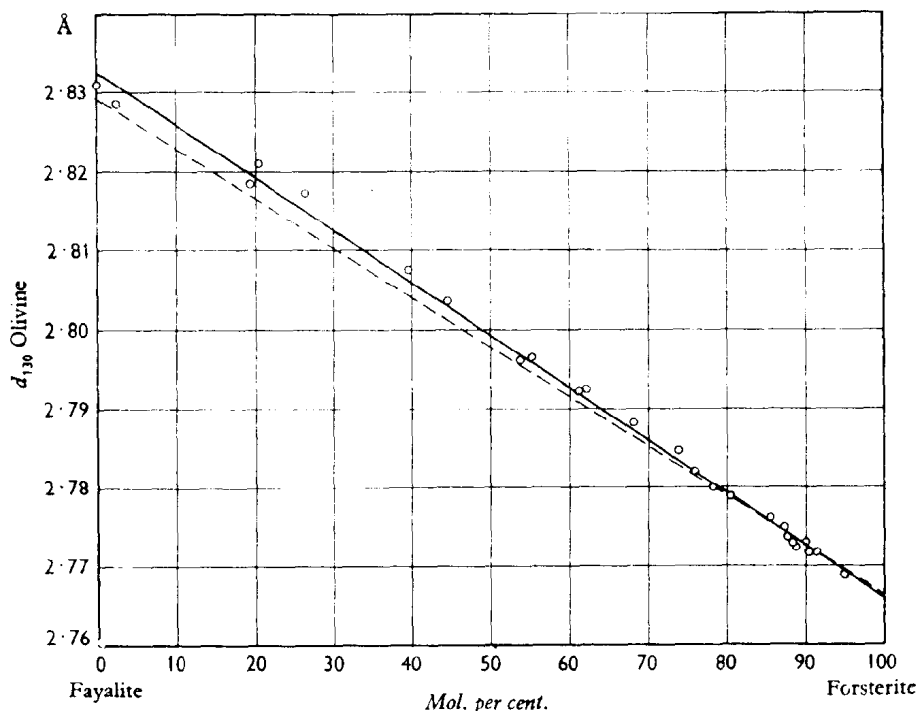


FIG. 2. Olivine X-ray determinative curve (solid line). Circles represent average d_{130} values of analysed specimens used in constructing the curve. Dashed line is assumed linear variation of d_{130} for synthetic olivines using experimentally determined end points (after Yoder and Sahama, 1957).

¹ An alternative curve for determining Mg-rich olivines to ± 0.4 mol. per cent., using 20 062, has been published (Jackson, E. D., 1960, *U.S. Geol. Surv. Prof. Paper 400B*, p. 432).

Table 1. CELL PARAMETERS OF OLIVINES

	<i>a</i> (Å)	<i>b</i> (Å)	<i>c</i> (Å)	
Fo ₁₀₀	4.76	10.20	5.99	Swanson & Tatge, 1953.
Fo ₁₀₀	4.756	10.225	5.982	Eliseev, 1957.
Fo ₁₀₀	4.756	10.195	5.981	Yoder & Sahama, 1957.
Fa ₉₆	4.812	10.565	6.085	Eliseev, 1957.
Fa ₁₀₀	4.817	10.477	6.105	Yoder & Sahama, 1957.

CHEMISTRY

The composition of olivines varies from forsterite, Mg_2SiO_4 , to fayalite, Fe_2SiO_4 , there being complete diadochy between Mg and Fe^{+2} (Table 2). In most natural crystals, and particularly in the iron-rich members of the series, there is a little replacement of (Mg, Fe^{+2}) by Mn and Ca. At the magnesium-rich end of the series Cr and Ni, generally in small amounts, are usually present. For ten olivines examined by Egorova (1938), in which the MgO content varies between 46.72 and 55.74 wt. per cent., the range of NiO is 0.00 to 0.41. Grigoriev (1937) synthesized a nickel olivine by fusing NiO and SiO_2 with 3 per cent. CaF_2 , and the small substitution of (Mg, Fe^{+2}) by Ni in natural olivine is controlled by the small amounts of this ion in the magmas and rocks in which the olivines crystallized. Ferric iron is reported in many olivine analyses. The investigation of the $FeO-SiO_2$ system (Bowen and Schairer, 1932) showed that at compositions near Fe_2SiO_4 2.25 per cent. Fe_2O_3 was present in the liquid, and in some olivines small amounts of Fe^{+3} may be primary. The not infrequent dendritic minute octahedra and opaque plates and wedges oriented

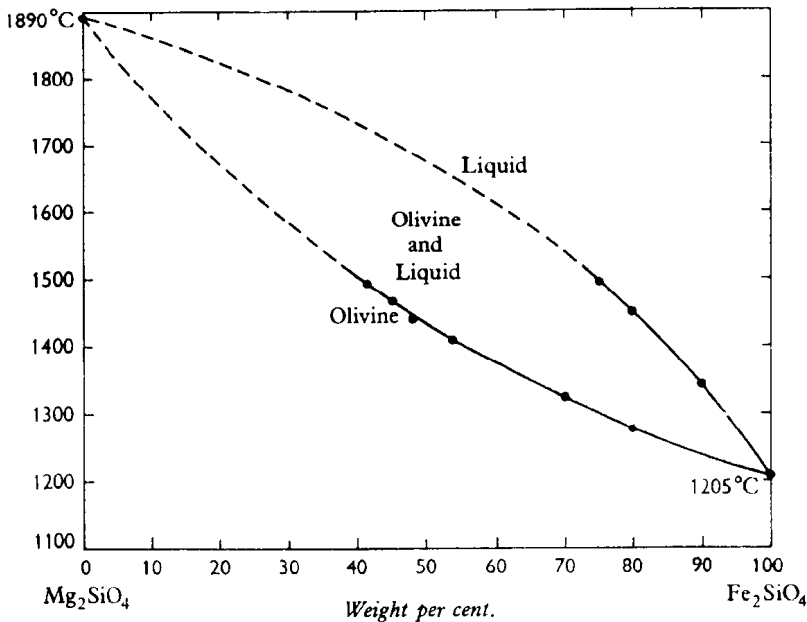


FIG. 3. Equilibrium diagram of the system $Mg_2SiO_4-Fe_2SiO_4$ (after Bowen and Schairer, 1935).

parallel to the (001) or (100) planes of the olivine host in some examples have been shown to be magnetite, chromium-rich magnetite, or chromite, and these growths are probably due to the exsolution on cooling of very small amounts of ferric and chromic oxides. In other olivines, and in all those with relatively high values of Fe^{+3} , the ferric iron is an oxidation product formed by alteration of the olivine. The alumina and alkalis reported in some olivine analyses are due most probably to impurities in the analysed samples.

The synthetic olivines form a complete solid solution series, the pure magnesium mineral melting at 1890°C . and the pure iron olivine at 1205°C . (Fig. 3). The thermal relationship between forsterite and fayalite illustrates the effect on melting temperatures in a diadochic series of replacing an ion of smaller by one of larger radius. The cation-oxygen bonds are weaker for the larger cation of the same charge, and as more of the larger cations enter the structure there is a progressive reduction in the melting points of intermediate compositions. Thus the first olivines to separate from a liquid of given composition are richer in Mg than those of later crystallization, and in consequence the larger Fe^{+2}

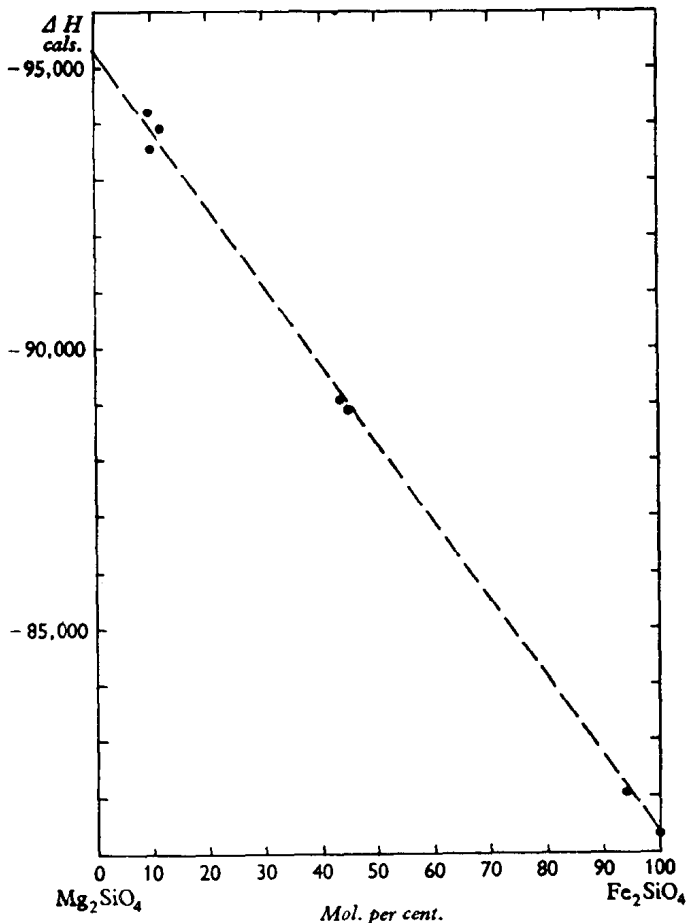


FIG. 4. Heats of solution in hydrofluoric acid of the (Mg,Fe)-olivines (after Sahama and Torgeson, 1949).

ions are concentrated in the residual liquids. The perfection of the diadochic replacement of magnesium by ferrous iron in the olivine structure has been substantiated by the measurement of the heats of solution, by solution calorimetry, of a number of olivines varying in molar composition from $\text{Fo}_{90.6}\text{Fa}_{9.4}$ to $\text{Fo}_{0.0}\text{Fa}_{100.0}$ (Sahama and Torgeson, 1949). The heats of solution range from the extrapolated value for forsterite of $-95,380$ cal./mole to $-81,330$ cal./mole for synthetic fayalite, and are a linear function of the molar composition (Fig. 4). Thus during the replacement $\text{Mg} \rightleftharpoons \text{Fe}^{+2}$ perfect thermal equilibrium is maintained, and the heat of isomorphous mixing is zero. The heat of solution of intermediate members of the series may be obtained from the equation:

$$\Delta H \text{ (cal./mol.)} = -81,330 - 140.5X_{\text{Mg}}$$

where X_{Mg} is the mole per cent. Mg_2SiO_4 .

Mg-olivines. Magnesium olivines have been synthesized frequently during the investigation of a large number of artificial systems. Many of these studies are of considerable interest and importance in the interpretation of the phase

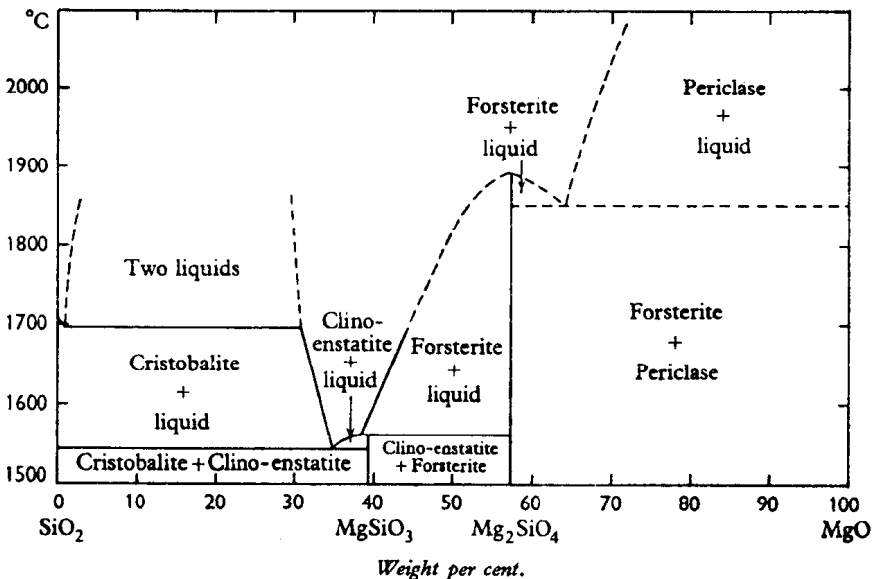
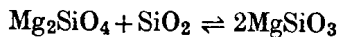


FIG. 5. Equilibrium diagram of the system MgO-SiO_2 (after Bowen and Schairer 1935).

relationships of olivine in natural rocks. In the system MgO-SiO_2 (Fig. 5) the metasilicate MgSiO_3 , as well as forsterite and SiO_2 , crystallizes and forsterite shows an incongruent melting reaction:



The reaction between olivine crystals and liquid in the system forsterite-silica also occurs in the two ternary systems anorthite-forsterite-silica (Andersen, 1915) and diopside-forsterite-silica (Bowen, 1914) and is confirmed by many natural occurrences. The discontinuous reaction relationship of forsteritic olivine to the magma from which it precipitated is recorded in resorbed crystals and in the reaction rims of peripheral orthopyroxene. Magnetite is sometimes

across the bridge R_3 to some convenient value, such as 1.00 or 3.00 volts, which appears on the voltmeter V . This should have a 0–3-volt range; though even a cheap 3-inch meter suffices for most work, a meter such as the Triplet Model 725 (The Triplet Electrical Instrument Co., Bluffton, Ohio), which has a 6.4-inch mirror scale, is much more accurate and easy to read. If the polarograph is to be used for the measurement of half-wave

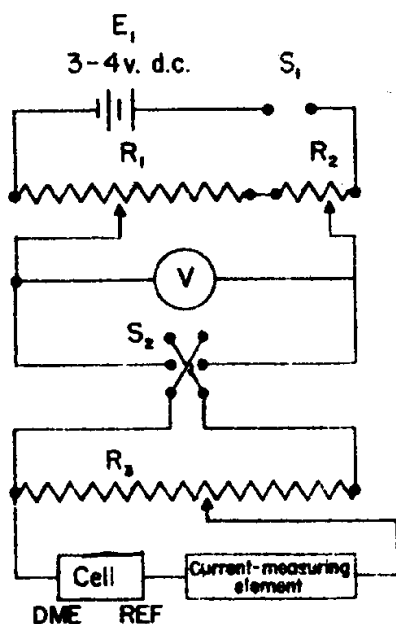


Figure 2. Schematic diagram of manual polarograph. S_1 : SPST toggle switch; S_2 : DPDT toggle switch; R_1 : 500-ohm linear taper potentiometer; R_2 : 10-ohm linear taper potentiometer; R_3 : voltage divider (see text); V : 0–3 v. d.c. voltmeter.

potentials, the voltmeter must be checked against a precision potentiometer; if very accurate half-wave potential data are required, the mean potential drop across the cell at each point on the c.-v. curve must be measured directly with a precision potentiometer.

The bridge R_3 is used to apply a known fraction of the voltage across it to the portion of the circuit containing the cell and the current-measuring element. So that R_3 will function as an accurate linear voltage divider, its resistance must be very much

when the composition of the liquid is 43.5 wt. per cent. anorthite, 49 per cent. diopside and 7.5 per cent. forsterite (Fig. 7). Spinel crystallizes from some compositions in this system but is a transient phase only, and under equilibrium conditions with falling temperature it is dissolved.

Forsterite has been synthesized from stoichiometric mixtures of its oxides in the presence of water vapour at temperatures of 500°C. and above, at pressures between 2000 and 40,000 lb./in.². Forsterite is a prominent phase in the ternary system MgO-SiO₂-H₂O (Bowen and Tuttle, 1949). The lowest temperature curve of the *P-T* diagram of this system is of particular paragenetic interest in showing that brucite, serpentine, forsterite and vapour are in equilibrium at temperatures of approximately 400°C. Just above 400°C. at low pressure, and

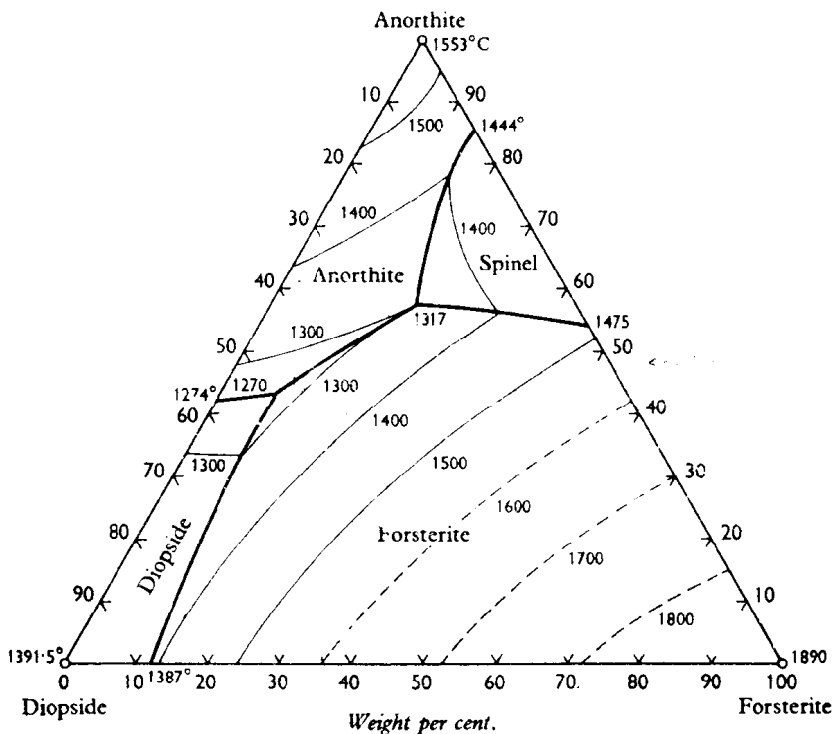


FIG. 7. Equilibrium diagram of the system diopside-forsterite-anorthite. Boundary curves in heavy lines, isotherms in light lines (after Osborn and Tait, 1952).

somewhat higher than 400°C. at higher pressures, forsterite is stable in the presence of water vapour. That the reaction:



is one of reversible equilibrium has been demonstrated by the serpentinization (formation of brucite and serpentine) of a forsterite crystallized from an anhydrous melt at high temperatures. The replacement of Mg by Fe⁺² reduces the temperature at which serpentinization takes place, thus in an olivine with 10 mol. per cent. Fe₂SiO₄ the reaction took place at 340°C. (water vapour pressure = 15,000 lb./in.²), while an olivine with 52 mol. per cent. Fe₂SiO₄ was not serpentinized at 295°C. and 15,000 lb./in.² water vapour pressure.

Investigations of the quaternary system $MgO-Al_2O_3-SiO_2-H_2O$ (Yoder, 1952; Roy and Roy, 1955) have confirmed the main results of the above ternary system, forsterite crystallizing from powdered mixes and glasses of appropriate composition at approximately $430^\circ C.$ and under excess water vapour pressure. In this system two sets of equilibrium associations have been recognized, (a) phase associations in equilibrium in the presence of excess water, (b) associations in equilibrium under "water deficient" conditions, *i.e.* those in which there is insufficient water to convert all the phases to hydrates. Forsterite in equilib-

Table 2. OLIVINE ANALYSES

	1.	2.	3.	4.	5.
SiO ₂	41.72	41.07	40.70	41.29	40.96
TiO ₂	—	0.05	tr.	tr.	0.01
Al ₂ O ₃	—	0.56	0.60	0.27	0.21
Fe ₂ O ₃	—	0.65	1.60	0.22	0.00
FeO	1.11	3.78	4.47	7.09	7.86
MnO	—	0.23	0.32	0.42	0.13
MgO	57.83	54.06	51.84	51.07	50.45
CaO	—	0.00	tr.	0.13	0.15
Na ₂ O	—	—	tr.	—	0.01
K ₂ O	—	—	tr.	—	0.00
H ₂ O ⁺	—	0.05	} 0.51	—	0.29
H ₂ O ⁻	—	0.00		—	—
Total	100.66	100.45	100.04	100.49	100.35

α	—	—	1.649	—	—
β	—	—	—	1.664	—
γ	—	—	1.689	1.685	—
$2V_\gamma$	86° 20'	—	86°	87°	—
D	3.22	—	3.187	3.22	3.313

NUMBERS OF IONS ON THE BASIS OF 4 OXYGENS

Si	0.978	0.979	0.983	0.996	0.996
Al	—	0.016	0.017	0.007	—
Ti	—	0.001	—	—	—
Fe ⁺³	—	0.012	0.030	0.004	—
Mg	2.021	1.920	1.867	1.836	1.828
Fe ⁺²	0.022	0.075	0.090	0.143	0.160
Mn	—	0.005	0.007	0.009	0.003
Ca	—	—	—	0.003	0.004

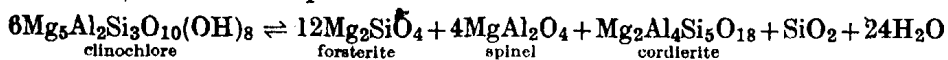
Atomic ratios

Mg	98.9	96.2	95.4	92.8	92.0
Fe ⁺²	1.1	3.8	4.6	7.2	8.0

1. Forsterite, crystalline limestone, Mogok Mining District, Burma (Adams and Graham, 1926).
2. Olivine, with clinohumite in limestone, Ojama, Finland (Sahama, 1953).
3. Olivine, forsterite-mica-magnetite rock, Vostochny mine, Ensky, U.S.S.R. (Sobolev, 1947).
4. Olivine, tuff, Alban Hills, Italy (Fornaseri, 1951).
5. Olivine, dunite, Dun Mountain, New Zealand (Ross *et al.*, 1954). Anal. M. D. Foster (Includes Cr₂O₃ 0.02, CoO 0.01, NiO 0.25).

* Includes Ni 0.005.

rium with cordierite and spinel can co-exist at water vapour pressures above 15,000 lb./in.² and a temperature of 680°C.



Forsterite has also been crystallized from gels precipitated from solutions of Na₂SiO₃ and MgCl₂ (Sabatier, 1950).

Table 2 contd. OLIVINE ANALYSES

	6.	7.	8.	9.	10.
SiO ₂	40.84	40.30	39.12	40.21	39.87
TiO ₂	0.04	0.15	0.09	0.00	0.03
Al ₂ O ₃	0.19	0.25	0.58	—	0.00
Fe ₂ O ₃	0.13	0.00	1.69	—	0.86
FeO	8.18	10.26	10.76	12.57	13.20
MnO	0.17	0.09	0.16	—	0.22
MgO	50.27	48.60	46.51	47.49	45.38
CaO	—	0.07	0.48	0.20	0.25
Na ₂ O	—	0.04	0.15	—	0.04
K ₂ O	—	0.03	0.06	—	0.01
H ₂ O ⁺	0.37	}0.33	0.21	—	0.33
H ₂ O ⁻	—		0.07	—	0.10
Total	100.38	100.56	99.95	100.47	100.30
α	1.649	—	1.656	—	1.6628
β	1.666	—	1.674	—	—
γ	1.684	—	1.695	—	1.6990
2V _γ	—	—	89°	—	90°
D	3.30	3.349	3.33	3.38	3.44
NUMBERS OF IONS ON THE BASIS OF 4 OXYGENS					
Si	0.994	0.990	0.975	0.993	0.997
Al	0.005	0.007	0.016	—	—
Ti	0.001	0.003	0.002	—	0.001
Fe ⁺³	0.002	—	0.031	—	0.016
Mg	1.824	1.779	1.728	1.748	1.692
Fe ⁺²	0.177	0.211	0.224	0.260	0.276
Mn	0.004	0.002	0.003	—	0.005
Ca	—	0.002	0.013	0.005	0.007
Atomic ratios					
Mg	91.1	89.4	88.5	87.1	86.0
Fe ⁺²	8.9	10.6	11.5	12.9	14.0

6. Olivine, dunite, Little Castle Creek, California (Hawkes, 1946). Anal. M. Fleischer (Includes Ni 0.19).
7. Olivine, nodules in basalt, Ichinomegata, Japan (Ross *et al.*, 1954). Anal. M. D. Foster (Includes NiO 0.41, Cr₂O₃ 0.03).
8. Olivine, melilite basalt, Spiegel river, Cape Province (Mathias, 1949). Anal. Geochemical Laboratories (Includes P₂O₅ 0.07).
9. Olivine, pallasite meteorite, Huckitta, central Australia (Madigan, 1939). Anal. A. R. Alderman.
10. Olivine, allivalite, Rhum, Scotland (Brown, 1956). Anal. G. M. Brown (Includes P₂O₅ 0.01, Cr₂O₃ trace).

† Includes Ni 0.004.

‡ Includes Na 0.002, K 0.001, Ni 0.008, Cr 0.001.

§ Includes Na 0.007, K 0.002.

|| Includes Na 0.002.

Table 2 contd. OLIVINE ANALYSES

	11.	12.	13.	14.	15.
SiO ₂	39.31	37.33	38.11	34.96	34.04
TiO ₂	0.06	0.09	tr.	0.00	0.43
Al ₂ O ₃	1.68	0.18	0.00	0.00	0.91
Fe ₂ O ₃	---	1.60	0.15	0.00	1.46
FeO	19.84	21.58	31.48	36.77	40.37
MnO	0.17	0.27	0.22	0.52	0.68
MgO	37.74	38.13	30.50	27.04	20.32
CaO	0.87	0.38	0.02	0.00	0.81
Na ₂ O	---	0.03	---	---	---
K ₂ O	---	0.05	---	---	---
H ₂ O	---	0.17	---	---	0.09
H ₂ O ⁻	---	0.04	---	---	---
Total	99.67	99.94	100.48	100.58	99.11
α	1.675	1.683	1.710	1.721	1.742
β	1.694	1.704	1.733	1.750	---
γ	1.712	1.722	1.748	1.765	---
2V _Y	90°	95°	101°	95°	102°-104°
D	---	3.53	3.69	---	---
NUMBERS OF IONS ON THE BASIS OF 4 OXYGENS					
Si	1.010	0.979	1.026	0.989	0.990
Al	0.051	0.005	---	---	0.032
Ti	0.001	0.002	---	---	0.009
Fe ⁺³	---	0.031	0.003	---	0.032
Mg	1.446	1.491	1.226	1.140	0.881
Fe ⁺²	0.427	0.474	0.709	0.870	0.983
Mn	0.004	0.006	0.005	0.012	0.017
Ca	0.024	0.011	0.006	---	0.025
Atomic ratios					
Mg	77.2	75.9	63.3	59.7	47.3
Fe ⁺²	22.8	24.1	36.7	40.3	52.7

11. Olivine, basalt, Buffalo Buttes, Colorado (Larsen *et al.*, 1936). Anal. F. A. Gonyer.
 12. Olivine, melilite basalt, Klaasvoogds, Cape Province (Mathias, 1949). Anal. Geochemical Laboratories (Includes P₂O₅ 0.09).
 13. Olivine, hypersthene-olivine gabbro, Kangerdlugssuaq, east Greenland (Deer and Wager, 1939). Anal. W. A. Deer.
 14. Hyalosiderite, gabbro, Black Cascade, Trip pyramid Mountain, New Hampshire (Chapman and Williams, 1935). Anal. F. A. Gonyer.
 15. Olivine, olivine gabbro, Camas Mòr, Muck, Scotland (Tilley, 1952). Anal. J. H. Scoon.

‡ Includes Na 0.001, K 0.001.

Table 2 contd. OLIVINE ANALYSES

	16.	17.	18.	19.	20.	21.
SiO ₂	31.85	30.42	30.15	29.83	29.75	29.87
TiO ₂	0.01	1.20	0.20	—	—	0.08
Al ₂ O ₃	tr.	0.50	0.07	—	0.00	—
Fe ₂ O ₃	0.11	0.00	0.43	—	0.83	12.07
FeO	58.64	57.62	65.02	69.48	66.10	54.88
MnO	0.85	—	1.01	0.28	3.20	0.02
MgO	8.49	8.17	1.05	—	—	2.54
CaO	0.18	1.32	2.18	—	—	0.20
Na ₂ O	—	—	—	—	—	0.71
K ₂ O	—	—	—	—	—	0.08
H ₂ O ⁺	—	0.18	—	0.34	0.19	—
H ₂ O ⁻	—	0.21	—	0.04	—	—
Total	100.13	99.62	100.11	99.97	100.07	100.45

α	1.788	1.787	1.827	1.8235	—	1.870
β	1.828	1.821	1.869	1.8649	—	—
γ	1.840	1.838	1.879	1.8770	—	1.908
2V _Y	122°	—	132°	130°	—	131°
D	4.15	—	—	4.215	—	4.1

NUMBERS OF IONS ON THE BASIS OF 4 OXYGENS

Si	1.007	0.971	1.002	1.011	1.010	0.962
Al	—	0.019	0.003	—	—	—
Ti	—	0.029	0.005	—	—	0.002
Fe ⁺³	0.002	—	0.011	—	0.020	0.292
Mg	0.400	0.389	0.052	—	—	0.122
Fe ⁺²	1.552	1.539	1.808	1.970	1.877	1.479
Mn	0.023	—	0.028	0.008	0.092	0.001
Ca	0.006	0.045	0.078	—	—	0.007

Atomic ratios

Mg	20.5	20.2	2.8	0.0	0.0	—
Fe ⁺²	79.5	79.8	97.2	100.0	100.0	—

16. Olivine, ferrohorthonolite ferrogabbro, Kangerdlugssuaq, east Greenland (Deer and Wager 1939). Anal. W. A. Deer.
17. Olivine, iron-rich diabase, Beaver Bay, Minnesota (Muir, 1954). Anal. I. D. Muir.
18. Olivine, fayalite ferrogabbro, Kangerdlugssuaq, east Greenland (Deer and Wager, 1939). Anal. W. A. Deer.
19. Fayalite, metamorphosed iron-rich sediments, Brocken, Harz, Germany (Ramdohr, 1927). Anal. J. Jakob.
20. Fayalite, Rockport, Massachusetts (Bowen *et al.*, 1933a). Anal. E. Posnjak.
21. Talasskite, pegmatite, Talassa Valley, Siberia (Nikitin, 1936).

** Includes Na 0.045, K 0.002.