American Ceramics Society

Phase Diagrams

2021

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PHASE EQUILIBRIUM DIAGRAMS OF OXIDE SYSTEMS

Revised and Redrawn by

E.F. OSBORN AND ARNULF MUAN

College of Mineral Industries
The Pennsylvania State University

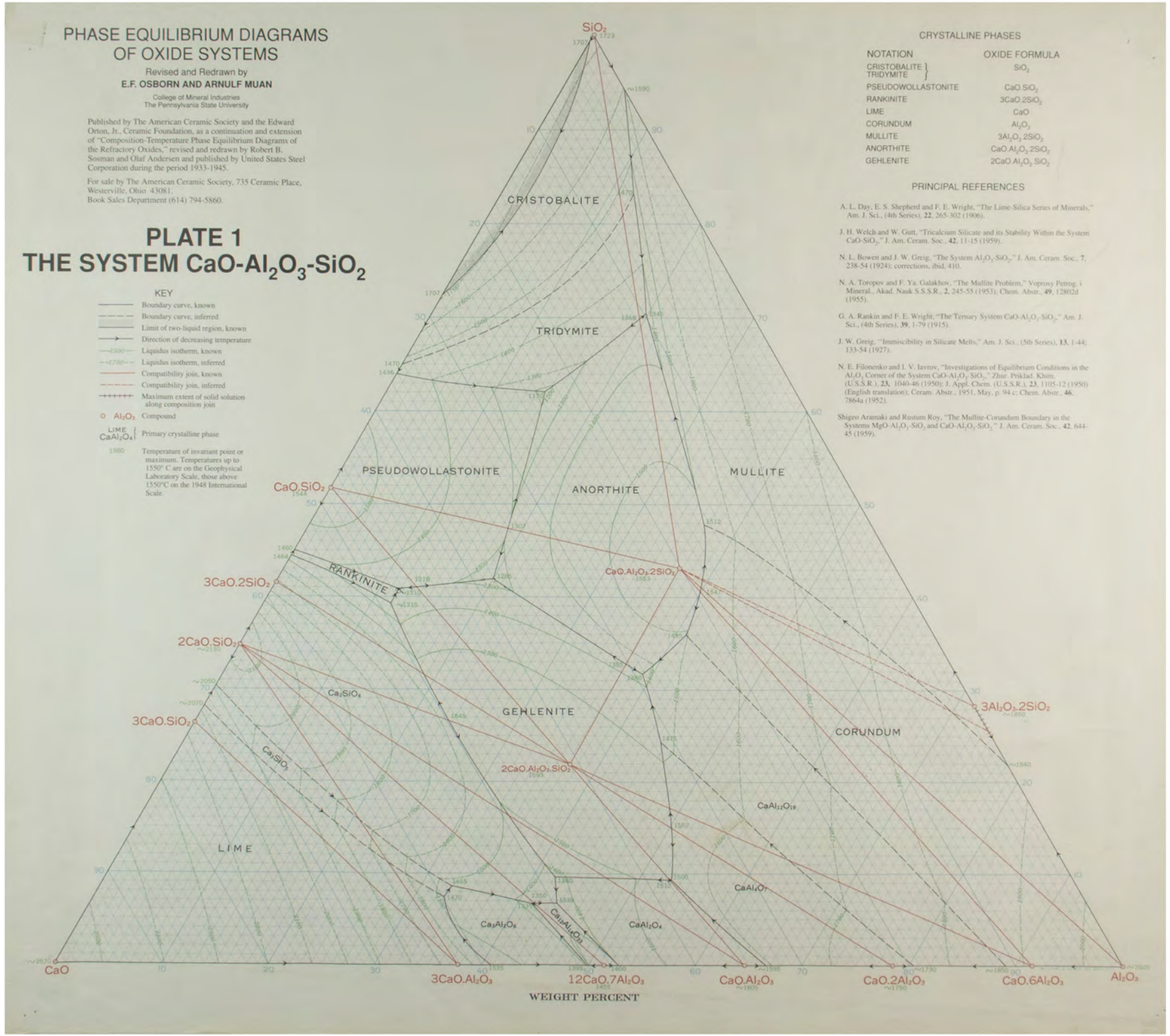
Published by The American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, as a continuation and extension of "Composition-Temperature Phase Equilibrium Diagrams of the Refractory Oxides," revised and redrawn by Robert B. Sosman and Olaf Andersen and published by United States Steel Corporation during the period 1933-1945.

For sale by The American Ceramic Society, 735 Ceramic Place, Westerville, Ohio 43081.
Book Sales Department (614) 794-5860.

PLATE 1
THE SYSTEM CaO-Al_2O_3-SiO_2

KEY

- Boundary curve, known
- Boundary curve, inferred
- Limit of two-liquid region, known
- Direction of decreasing temperature
- 1500 Liquidus isotherm, known
- 1700 Liquidus isotherm, inferred
- Compatibility join, known
- Compatibility join, inferred
- Maximum extent of solid solution along composition join
- Al_2O_3 Compound
- LIME, $CaAl_2O_4$ Primary crystalline phase
- 1380 Temperature of invariant point or maximum. Temperatures up to 1550° C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.



CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE, TRIDYMITE	SiO_2
PSEUDOWOLLASTONITE	$CaO.SiO_2$
RANKINITE	$3CaO.2SiO_2$
LIME	CaO
CORUNDUM	Al_2O_3
MULLITE	$3Al_2O_3.2SiO_2$
ANORTHITE	$CaO.Al_2O_3.2SiO_2$
GEHLENITE	$2CaO.Al_2O_3.SiO_2$

PRINCIPAL REFERENCES

A. L. Day, E. S. Shepherd and F. E. Wright, "The Lime-Silica Series of Minerals," Am. J. Sci., (4th Series), **22**, 265-302 (1906).

J. H. Welch and W. Gutt, "Tricalcium Silicate and its Stability Within the System CaO-SiO_2," J. Am. Ceram. Soc., **42**, 11-15 (1959).

N. L. Bowen and J. W. Greig, "The System Al_2O_3-SiO_2," J. Am. Ceram. Soc., **7**, 238-54 (1924); corrections, ibid, 410.

N. A. Toropov and F. Ya. Galakhov, "The Mullite Problem," Voprosy Petrog. i Mineral., Akad. Nauk S.S.S.R., **2**, 245-55 (1953); Chem. Abstr., **49**, 12802d (1955).

G. A. Rankin and F. E. Wright, "The Ternary System CaO-Al_2O_3-SiO_2," Am. J. Sci., (4th Series), **39**, 1-79 (1915).

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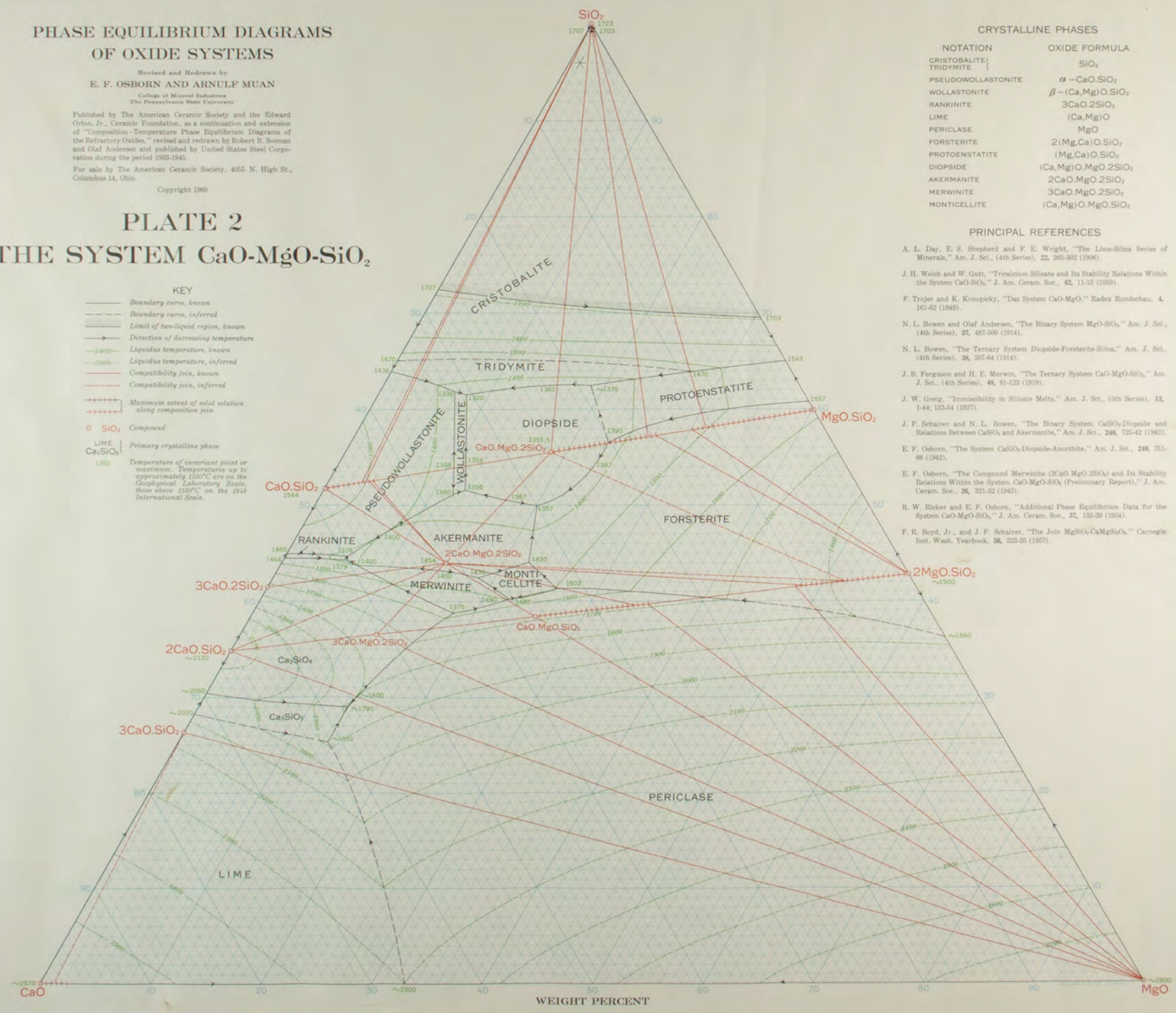
PLATE 2
THE SYSTEM CaO-MgO-SiO_2

KEY

- *Boundary curve, known*
- *Boundary curve, inferred*
- *Limit of two-liquid region, known*
- *Direction of decreasing temperature*
- 1400 *Liquidus temperature, known*
- 2000 *Liquidus temperature, inferred*
- *Compatibility join, known*
- *Compatibility join, inferred*
- *Maximum extent of solid solution along composition join*
- SiO_2 *Compound*
- LIME Ca_3SiO_5 *Primary crystalline phase*
- 1360 *Temperature of invariant point or maximum. Temperatures up to approximately 1550°C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.*



CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE, TRIDYMITE	SiO_2
PSEUDOWOLLASTONITE	$\alpha - CaO.SiO_2$
WOLLASTONITE	$\beta - (Ca,Mg)O.SiO_2$
RANKINITE	$3CaO.2SiO_2$
LIME	(Ca,Mg)O
PERICLASE	MgO
FORSTERITE	$2(Mg,Ca)O.SiO_2$
PROTOENSTATITE	$(Mg,Ca)O.SiO_2$
DIOPSIDE	$(Ca,Mg)O.MgO.2SiO_2$
AKERMANITE	$2CaO.MgO.2SiO_2$
MERWINITE	$3CaO.MgO.2SiO_2$
MONTICELLITE	$(Ca,Mg)O.MgO.SiO_2$

PRINCIPAL REFERENCES

A. L. Day, E. S. Shepherd and F. E. Wright, "The Lime-Silica Series of Minerals," Am. J. Sci., (4th Series), **22**, 265-302 (1906).

J. H. Welch and W. Gutt, "Tricalcium Silicate and Its Stability Relations Within the System $CaO-SiO_2$," J. Am. Ceram. Soc., **42**, 11-15 (1959).

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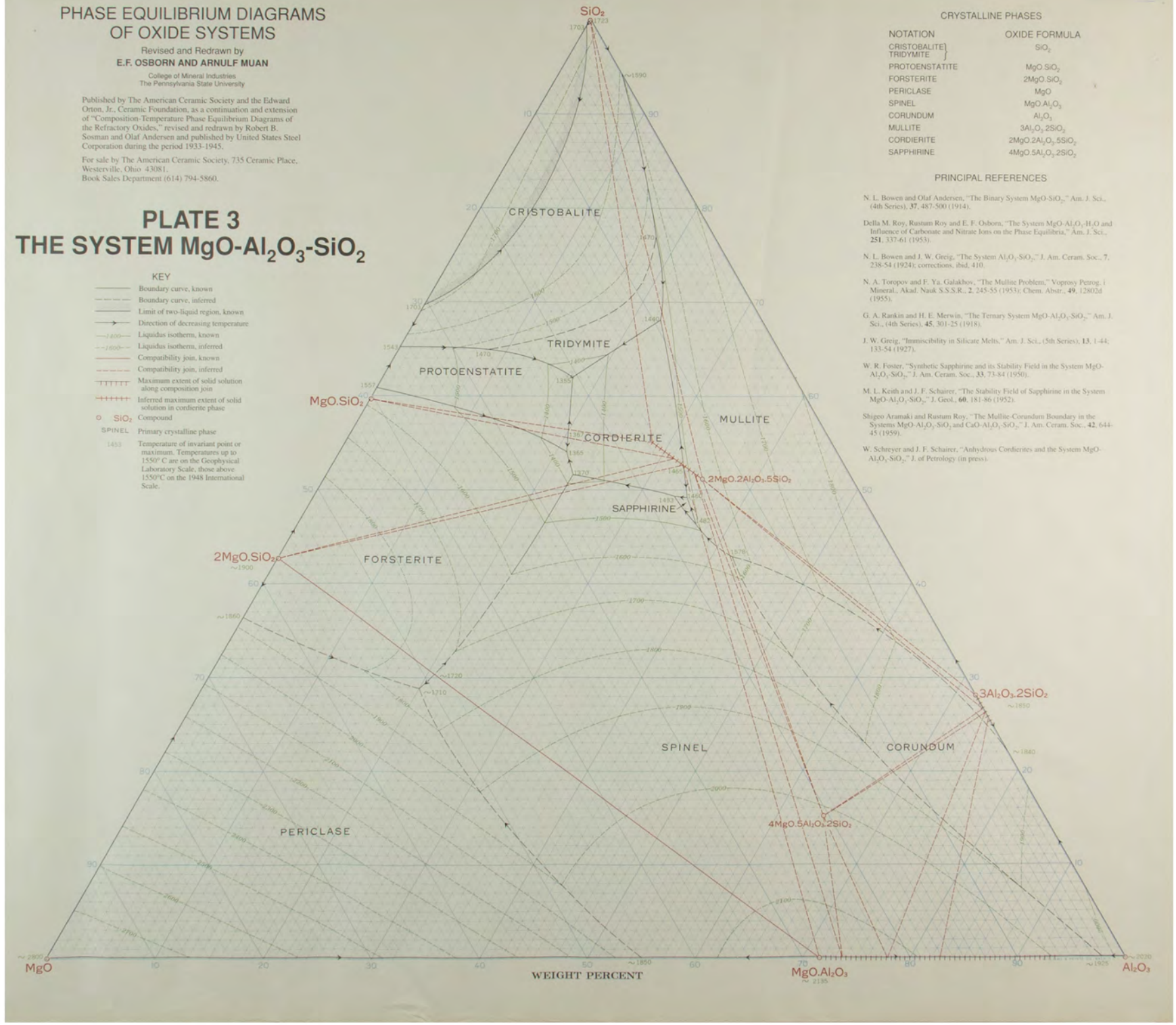
PLATE 3
THE SYSTEM MgO-Al_2O_3-SiO_2

KEY

- Boundary curve, known
- Boundary curve, inferred
- Limit of two-liquid region, known
- Direction of decreasing temperature
- 1400 Liquidus isotherm, known
- 1600 Liquidus isotherm, inferred
- Compatibility join, known
- Compatibility join, inferred
- Maximum extent of solid solution along composition join
- Inferred maximum extent of solid solution in cordierite phase
- SiO_2 Compound
- SPINEL Primary crystalline phase
- 1453 Temperature of invariant point or maximum. Temperatures up to 1550°C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.



CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE, TRIDYMITE	SiO_2
PROTOENSTATITE	$MgO.SiO_2$
FORSTERITE	$2MgO.SiO_2$
PERICLASE	MgO
SPINEL	$MgO.Al_2O_3$
CORUNDUM	Al_2O_3
MULLITE	$3Al_2O_3.2SiO_2$
CORDIERITE	$2MgO.2Al_2O_3.5SiO_2$
SAPPHIRINE	$4MgO.5Al_2O_3.2SiO_2$

PRINCIPAL REFERENCES

N. L. Bowen and Olaf Andersen, "The Binary System MgO-SiO_2," Am. J. Sci., (4th Series), **37**, 487-500 (1914).

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PLATE 4
THE SYSTEM Na_2O-Al_2O_3-SiO_2

KEY

- Boundary curve, known
- Boundary curve, inferred
- Direction of decreasing temperature
- 1400 Liquidus isotherm, known
- 1600 Liquidus isotherm, inferred
- Compatibility join, known
- Compatibility join, inferred
- Maximum extent of solid solution along composition join, excluding carnegieite phase.
- Inferred maximum extent of solid solution in carnegieite phase
- SiO_2 Compound
- ALBITE / $Na_2Si_3O_8$ Primary crystalline phase
- 768 Temperature of invariant point or maximum. Temperatures up to 1550°C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.

CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE / TRIDYMITE / QUARTZ	SiO_2
BETA-ALUMINA	$Na_2O.11Al_2O_3$
CORUNDUM	Al_2O_3
MULLITE	$3Al_2O_3.2SiO_2$
ALBITE	$Na_2O.Al_2O_3.6SiO_2$
NEPHELINE / CARNEGIEITE	$Na_2O.Al_2O_3.2SiO_2$

PRINCIPAL REFERENCES

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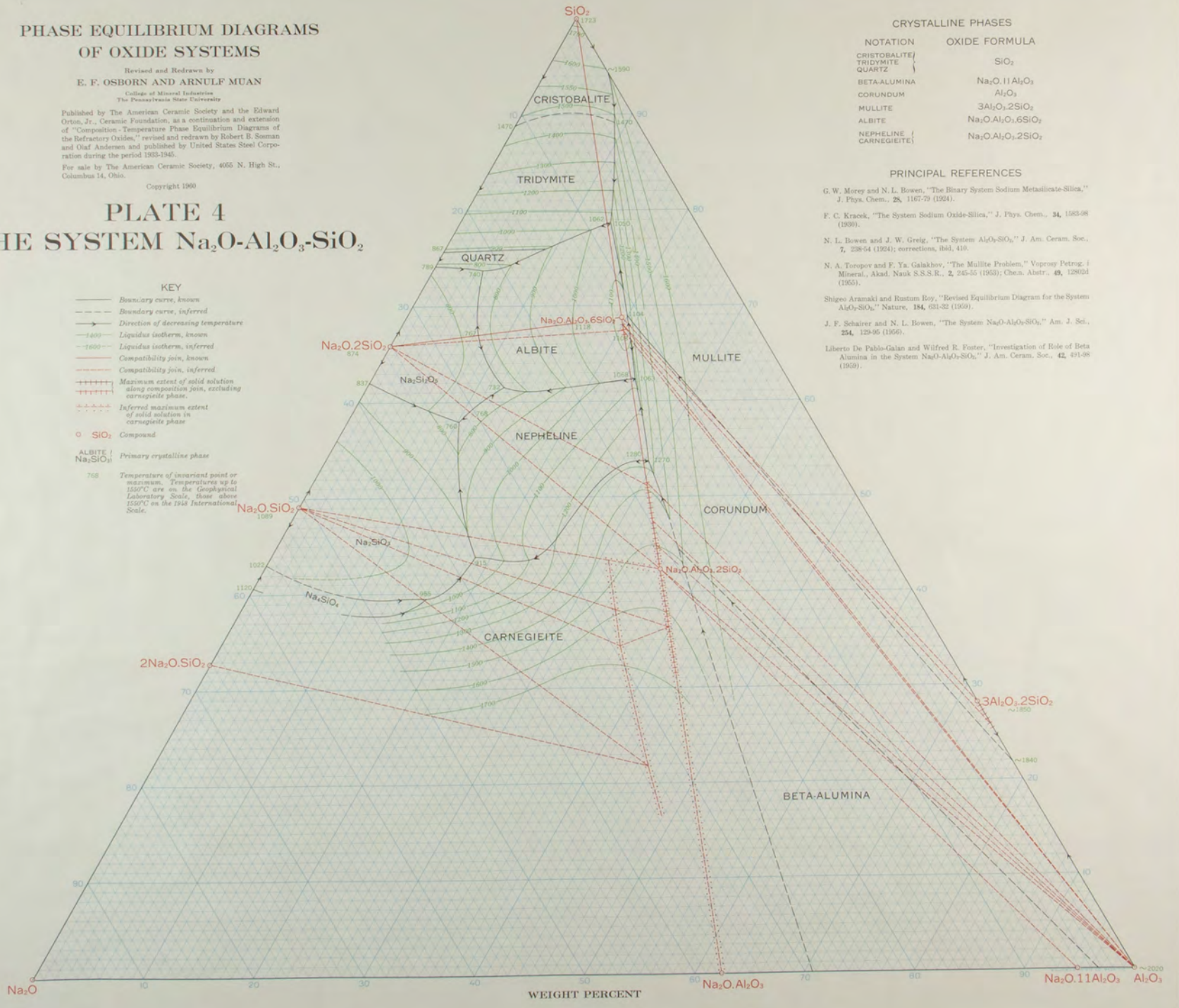

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PLATE 5
THE SYSTEM K_2O-Al_2O_3-SiO_2

KEY

- Boundary curve, known
- Boundary curve, inferred
- Direction of decreasing temperature
- —1200— Liquidus isotherm, known
- --1700-- Liquidus isotherm, inferred
- Compatibility join, known
- Compatibility join, inferred
- Maximum extent of solid solution along composition join
- SiO_2 Compound
- MULLITE / $K_2Si_4O_{11}$ Primary crystalline phase
- 918 Temperature of invariant point or maximum. Temperatures up to 1550° C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.

CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE, TRIDYMITE, QUARTZ	SiO_2
CORUNDUM	Al_2O_3
MULLITE	$3Al_2O_3.2SiO_2$
POTASH FELDSPAR	$K_2O.Al_2O_3.6SiO_2$
LEUCITE	$K_2O.Al_2O_3.4SiO_2$

PRINCIPAL REFERENCES

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N. A. Toropov and F. Ya. Galakhov, "The Mullite Problem," Voprosy Petrog. i Mineral., Akad. Nauk S.S.S.R., **2**, 245-55 (1953); Chem. Abstr., **49**, 12802d (1955).

Shigeo Aramaki and Rustum Roy, "Revised Equilibrium Diagram for the System Al_2O_3-SiO_2," Nature, **184**, 631-32 (1959).

J. F. Schairer and N. L. Bowen, "The System K_2O-Al_2O_3-SiO_2," Am. J. Sci., **253**, 681-746 (1955).

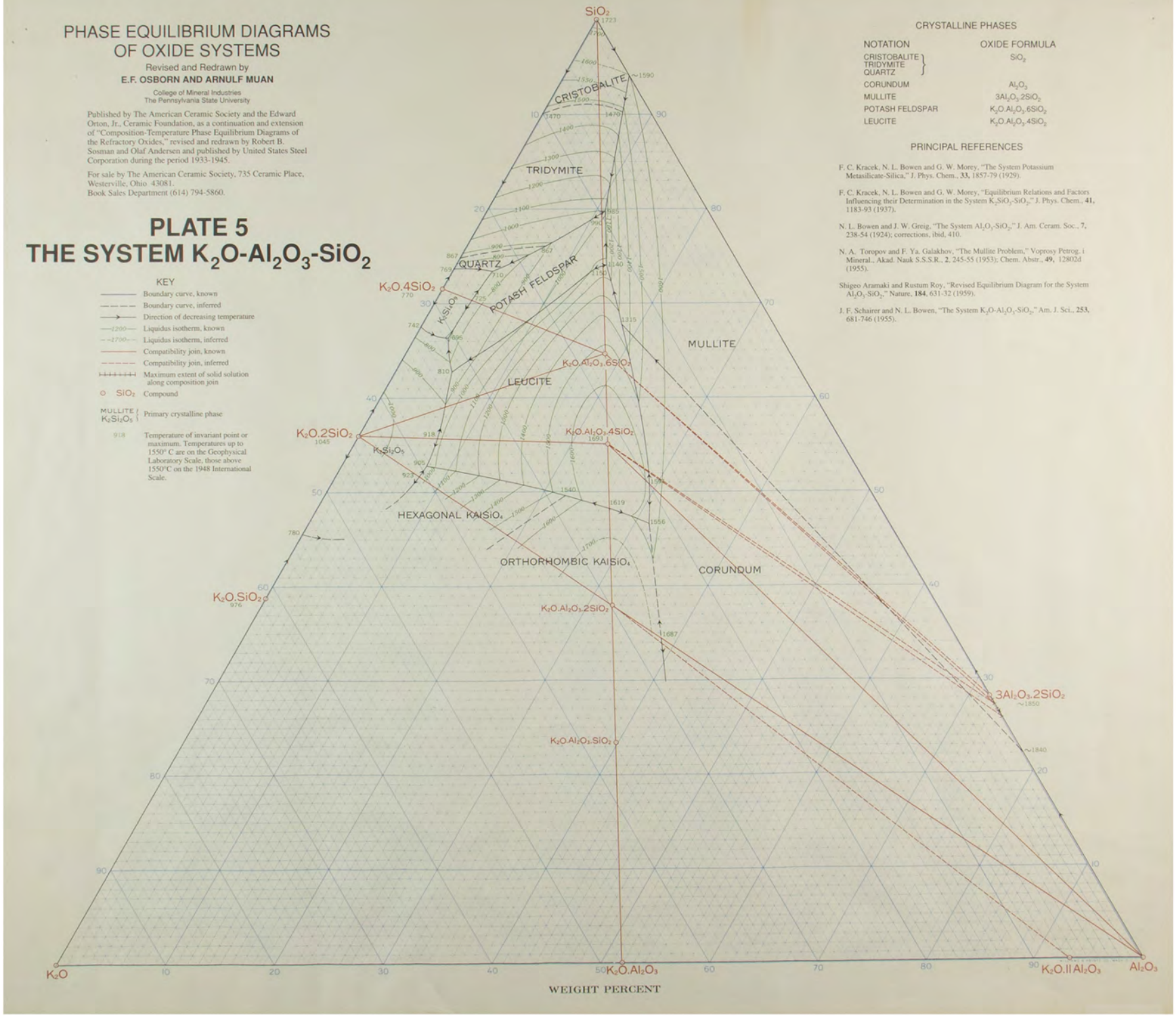

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PLATE 6

THE SYSTEM FeO-Fe_2O_3-SiO_2

KEY

- Boundary curve, known
- Boundary curve, inferred
- Limit of two-liquid region, inferred
- Direction of decreasing temperature
- 1200 — Liquidus temperature, known
- 1300 — Liquidus temperature, inferred
- Compatibility join
- Maximum extent of solid solution along composition join
- Lines of equal oxygen partial pressure (atm.) of gas phase at liquidus temperatures
- Fe_2O_3 — Compound or composition point
- WÜSTITE — Primary crystalline phase
- 1178 — Temperature of invariant point or maximum. Temperatures up to 1550°C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.

CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE, TRIDYMITE	SiO_2
FAYALITE	$2FeO.SiO_2$
WÜSTITE	"FeO"
MAGNETITE	$FeO.Fe_2O_3$
HEMATITE	Fe_2O_3

PRINCIPAL REFERENCES

N. L. Bowen and J. F. Schairer, "The System FeO-SiO_2," Am. J. Sci., (5th Series), **24**, 177-213 (1932).

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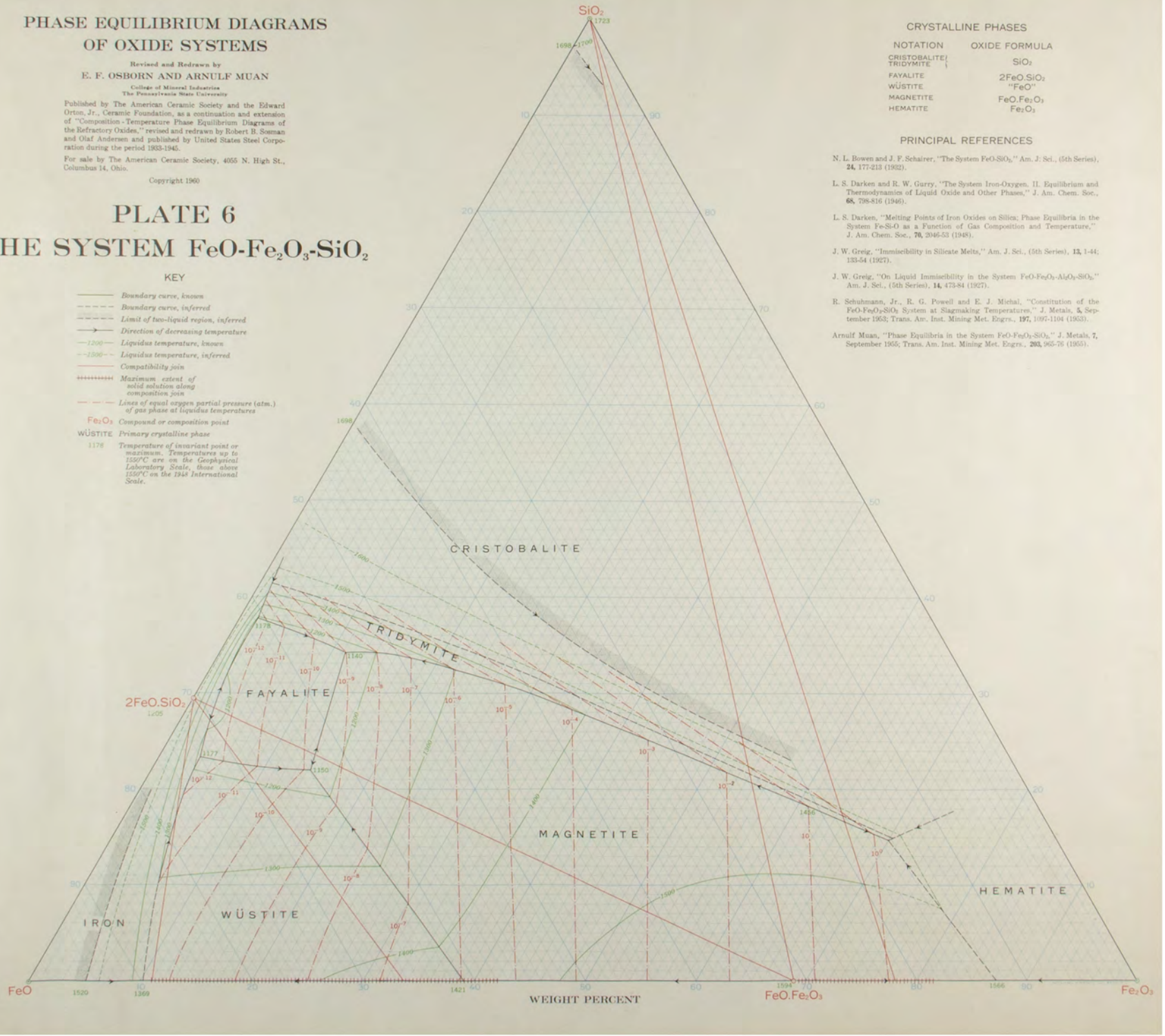

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PLATE 7

THE SYSTEM CaO-"FeO"-SiO_2

(OXIDE PHASES IN EQUILIBRIUM WITH METALLIC IRON)

KEY

- Boundary curve, known
- Boundary curve, inferred
- Direction of decreasing temperature
- Limit of two-liquid region, inferred
- 1400 Liquidus isotherm, known
- 1600 Liquidus isotherm, inferred
- Compatibility join, known
- Compatibility join, inferred
- Maximum extent of solid solution along composition join
- SiO_2 Compound or composition point
- OLIVINE / Ca_2SiO_4 Primary crystalline phase
- 1544 Temperature of invariant point, maximum or minimum. Temperatures up to 1550°C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.

CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE / TRIDYMITE	SiO_2
PSEUDOWOLLASTONITE	α – CaO.SiO_2
WOLLASTONITE	β – (Ca,Fe)O.SiO_2
RANKINITE	3CaO.2SiO_2
OLIVINE	2(Fe,Ca)O.SiO_2
LIME	(Ca,Fe)O
WÜSTITE	"(Fe,Ca)O"

PRINCIPAL REFERENCES

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G. A. Rankin and F. E. Wright, "The Ternary System CaO-Al_2O_3-SiO_2," Am. J. Sci., (4th Series), **39**, 1-79 (1915).

J. H. Welch and W. Gutt, "Tricalcium Silicate and its Stability Within the System CaO-SiO_2," J. Am. Ceram. Soc., **42**, 11-15 (1959).

N. L. Bowen and J. F. Schairer, "The System FeO-SiO_2," Am. J. Sci., (5th Series), **24**, 177-213 (1932).

J. W. Greig, "Immiscibility in Silicate Melts," Am. J. Sci., (5th Series), **13**, 1-44; 133-54 (1927).

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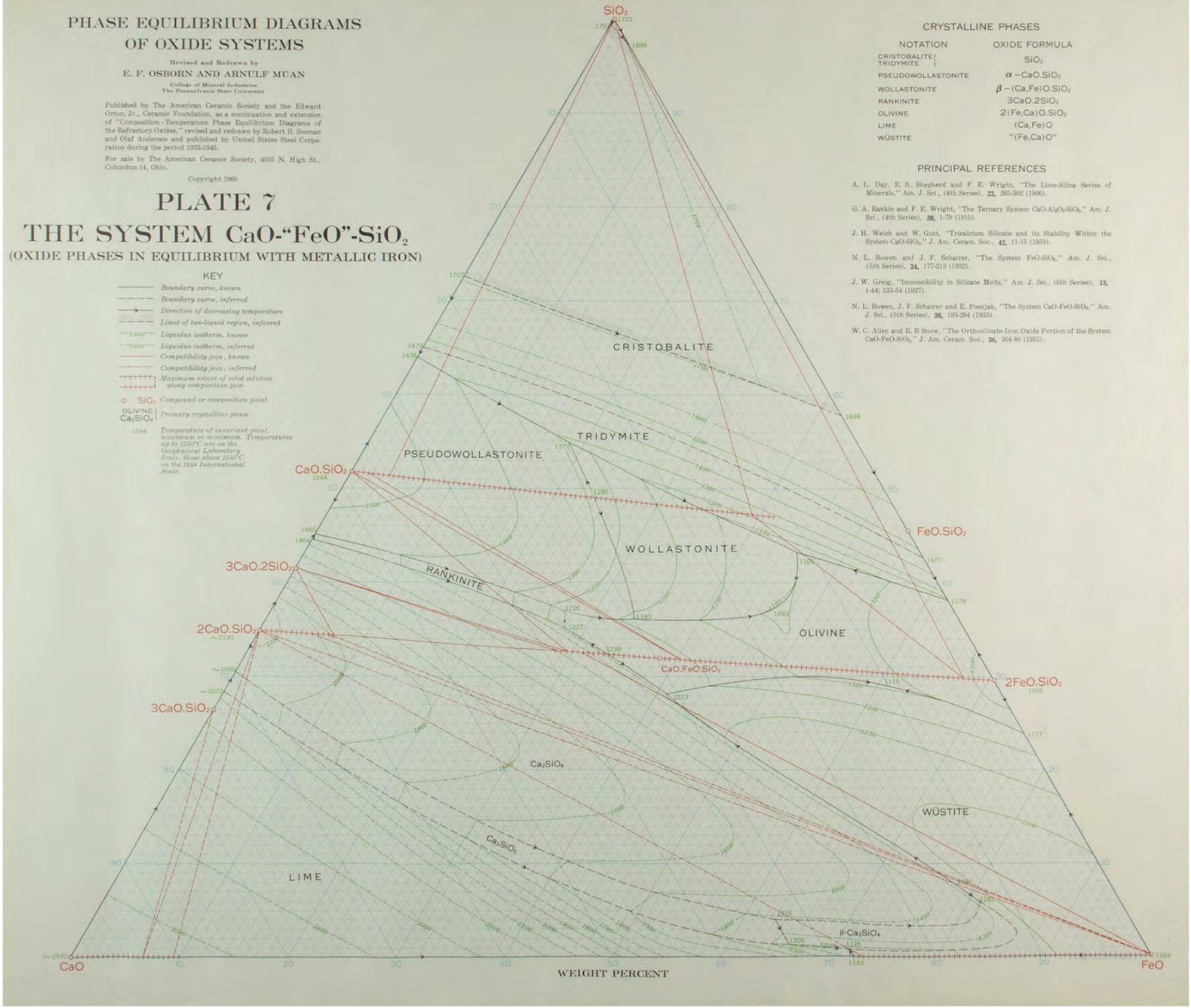

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PLATE 8
THE SYSTEM MgO-"FeO"-SiO_2
(OXIDE PHASES IN EQUILIBRIUM WITH METALLIC IRON)

KEY

- Boundary curve, known
- Boundary curve, inferred
- Limit of two-liquid region, inferred
- Direction of decreasing temperature
- 1900 Liquidus isotherm, known
- 1900 Liquidus isotherm, inferred
- Compatibility join
- Maximum extent of solid solution along composition join
- SiO_2 Compound or composition point
- OLIVINE Primary crystalline phase
- 1478 Temperature of invariant point or maximum. Temperatures up to 1550°C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.

CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE } TRIDYMITE }	SiO_2
PYROXENE	$(Mg,Fe)O.SiO_2$
OLIVINE	$2(Mg,Fe)O.SiO_2$
MAGNESIOWÜSTITE	$(Mg,Fe)O$

PRINCIPAL REFERENCES

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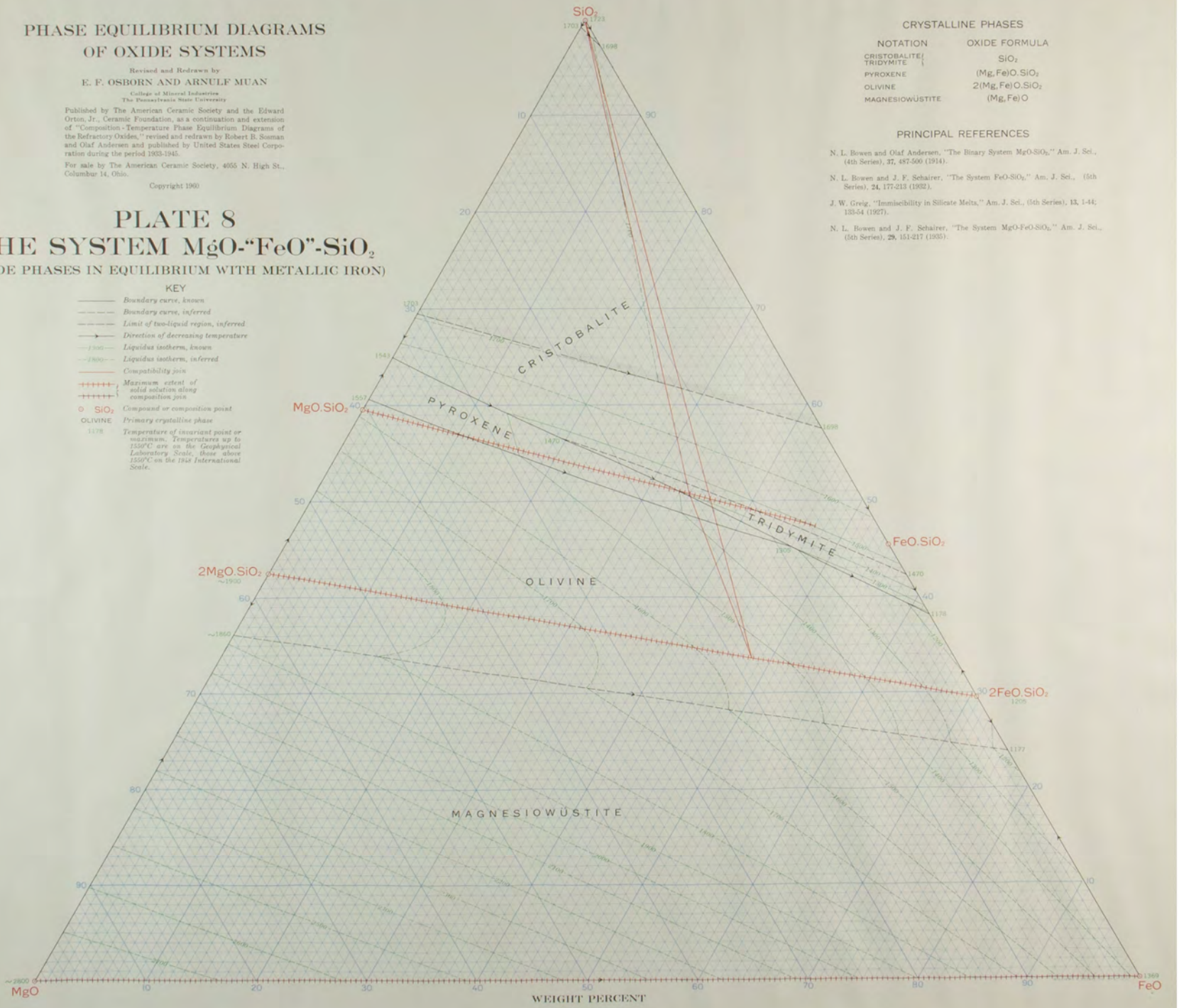


PHASE EQUILIBRIUM DIAGRAMS OF OXIDE SYSTEMS

Revised and Redrawn by

E. F. OSBORN AND ARNULF MUAN

College of Mineral Industries
The Pennsylvania State University

Published by The American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, as a continuation and extension of "Composition - Temperature Phase Equilibrium Diagrams of the Refractory Oxides," revised and redrawn by Robert B. Sosman and Olaf Andersen and published by United States Steel Corporation during the period 1933-1945.

For sale by The American Ceramic Society, 4055 N. High St., Columbus 14, Ohio.

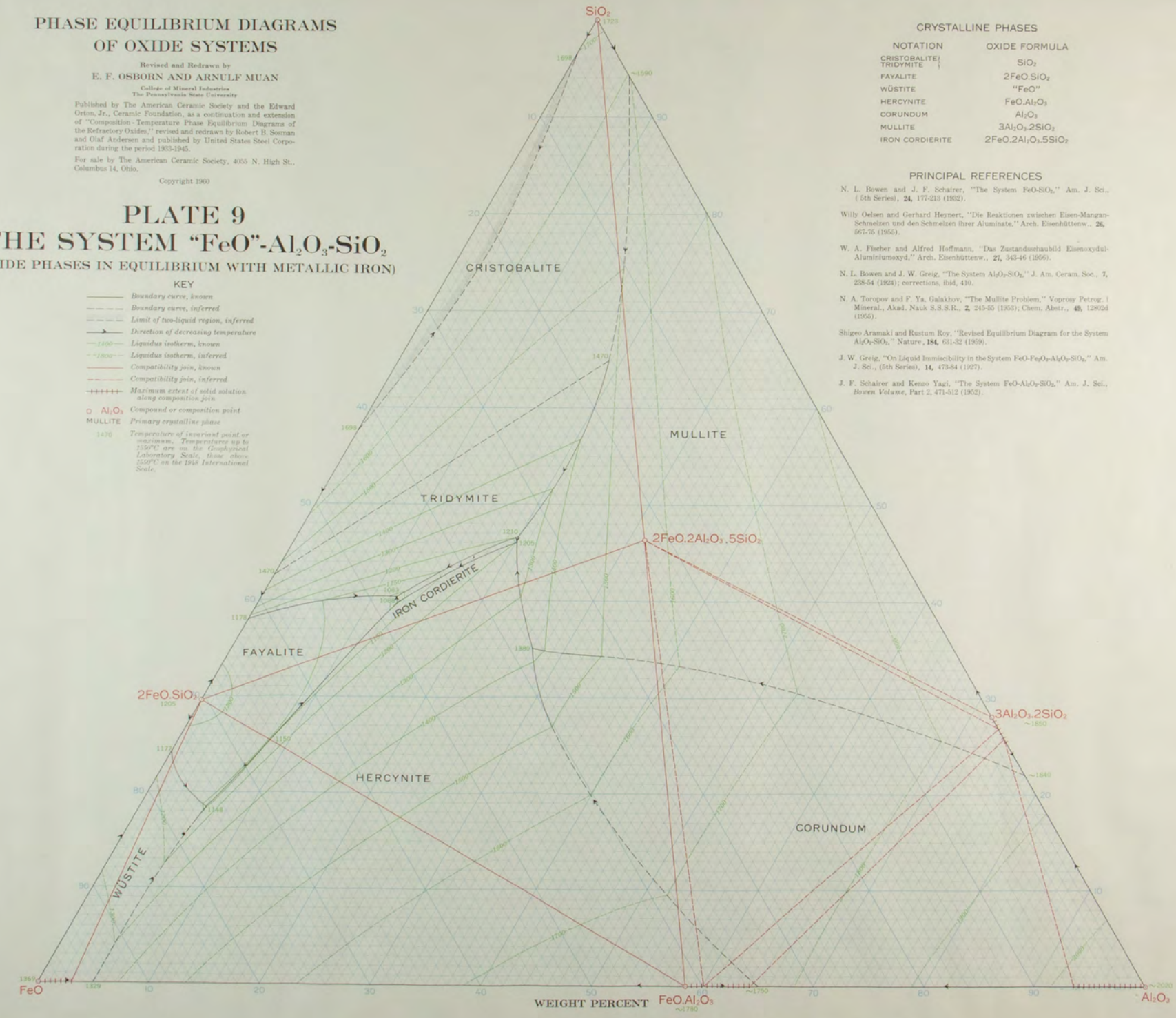
PLATE 9

THE SYSTEM "FeO"-Al_2O_3-SiO_2

(OXIDE PHASES IN EQUILIBRIUM WITH METALLIC IRON)

KEY

- Boundary curve, known
- Boundary curve, inferred
- Limit of two-liquid region, inferred
- Direction of decreasing temperature
- 1400 Liquidus isotherm, known
- ~1800 Liquidus isotherm, inferred
- Compatibility join, known
- Compatibility join, inferred
- Maximum extent of solid solution along composition join
- Al_2O_3 Compound or composition point
- MULLITE Primary crystalline phase
- 1470 Temperature of invariant point or maximum. Temperatures up to 1550°C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.



CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE / TRIDYMITE	SiO_2
FAYALITE	$2FeO.SiO_2$
WÜSTITE	"FeO"
HERCYNITE	$FeO.Al_2O_3$
CORUNDUM	Al_2O_3
MULLITE	$3Al_2O_3.2SiO_2$
IRON CORDIERITE	$2FeO.2Al_2O_3.5SiO_2$

PRINCIPAL REFERENCES

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PLATE 10

THE SYSTEM CaO-"Fe_2O_3"-SiO_2

(CONDENSED PHASES IN EQUILIBRIUM WITH AIR)

KEY

- Boundary curve, known
- Boundary curve, inferred
- Limit of two-liquid region, inferred
- Direction of decreasing temperature
- Liquidus isotherm, known
- Liquidus isotherm, inferred
- Compatibility join
- Maximum extent of solid solution in magnetite
- SiO_2 Compound
- LIME Ca_3SiO_5 Primary crystalline phase
- 1470 Temperature of invariant point or maximum. Temperatures up to 1550°C are on the Geophysical Laboratory Scale, those above 1550°C on the 1948 International Scale.

CRYSTALLINE PHASES

NOTATION	OXIDE FORMULA
CRISTOBALITE / TRIDYMITE	SiO_2
PSEUDOWOLLASTONITE	$CaO.SiO_2$
RANKINITE	$3CaO.2SiO_2$
LIME	CaO
HEMATITE	Fe_2O_3
MAGNETITE	$FeO.Fe_2O_3$

PRINCIPAL REFERENCES

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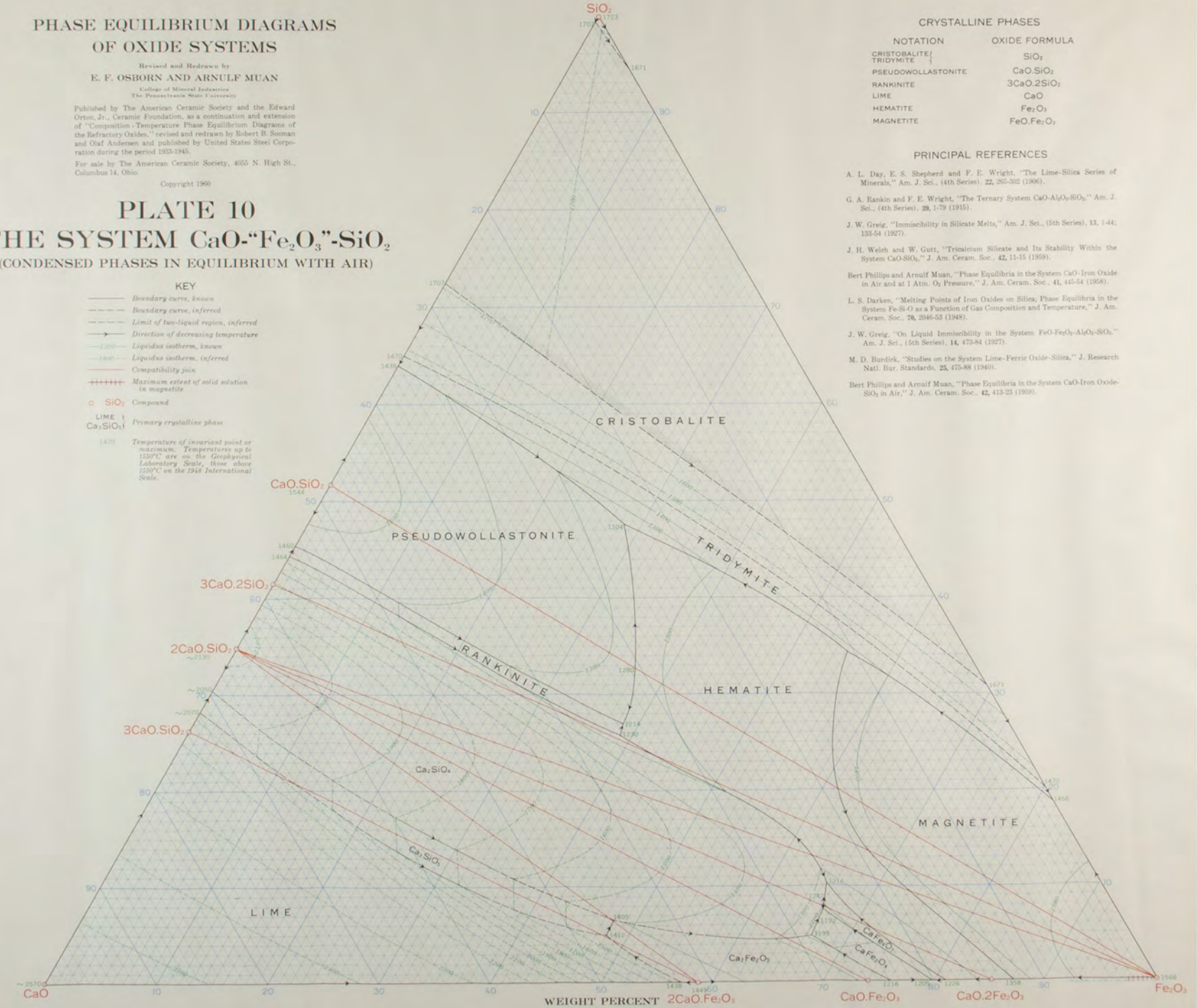

PHASE EQUILIBRIUM DIAGRAMS OF OXIDE SYSTEMS

DAVID W. JOHNSON AND F. A. HUMMEL

Ceramic Science Section, Materials Science Department
The Earth and Mineral Science College
The Pennsylvania State University

Published by the American Ceramic Society and the Lead Industries Association, Inc.; the research to develop this information was sponsored by the International Lead Zinc Research Organization, Inc. This series is a continuation and extension of "Phase Equilibrium Diagrams of Oxide Systems," Plates 1 through 10, by E. F. Osborn and Arnulf Muan, published by the American Ceramic Society in 1960.

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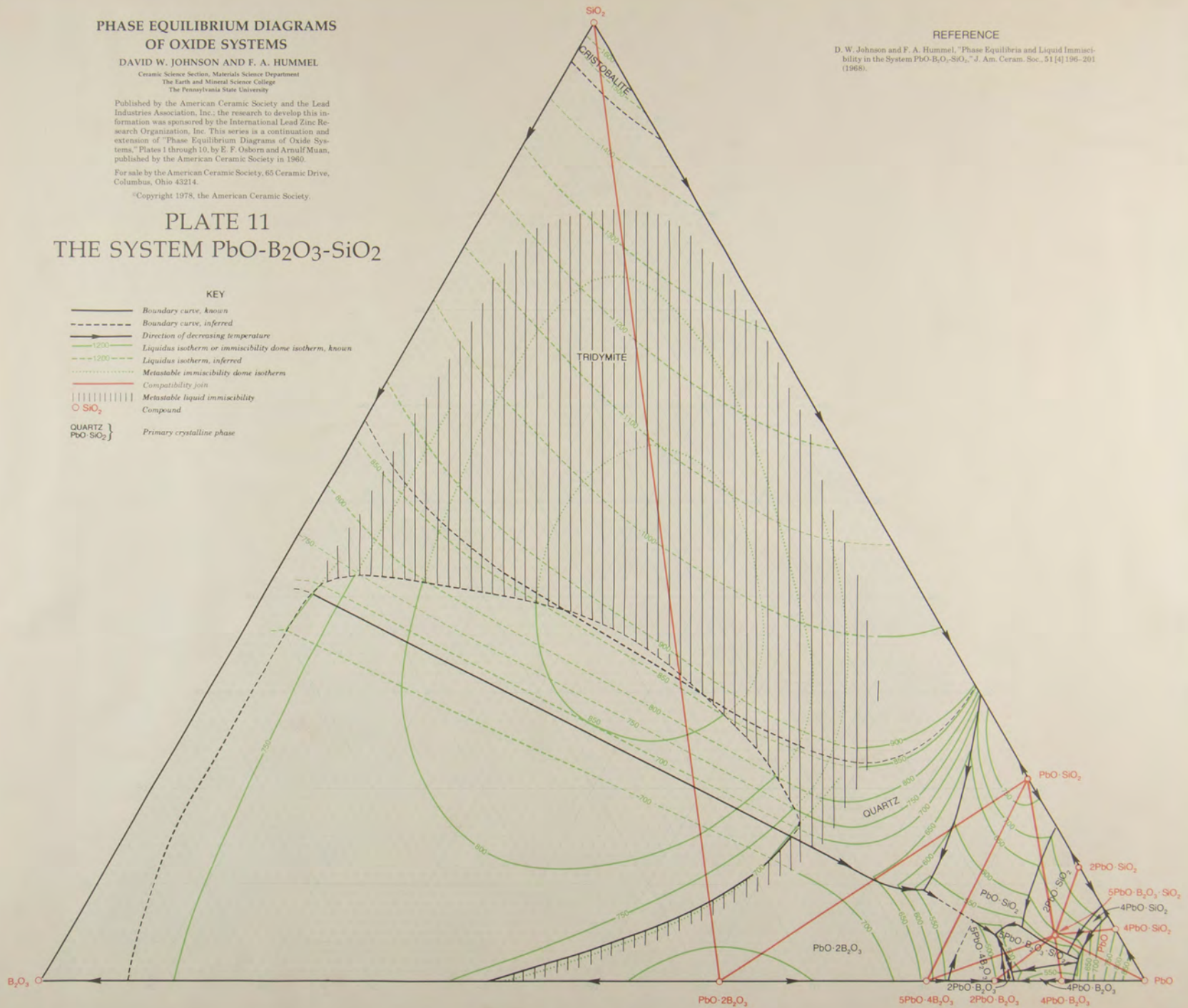
PLATE 11
THE SYSTEM PbO-B_2O_3-SiO_2

KEY

- *Boundary curve, known*
- *Boundary curve, inferred*
- *Direction of decreasing temperature*
- 1200 *Liquidus isotherm or immiscibility dome isotherm, known*
- 1200 *Liquidus isotherm, inferred*
- *Metastable immiscibility dome isotherm*
- *Compatibility join*
- *Metastable liquid immiscibility*
- SiO_2 *Compound*
- QUARTZ, $PbO \cdot SiO_2$ *Primary crystalline phase*

REFERENCE

D. W. Johnson and F. A. Hummel, "Phase Equilibria and Liquid Immiscibility in the System PbO-B_2O_3-SiO_2," J. Am. Ceram. Soc., 51 [4] 196–201 (1968).



WEIGHT PERCENT

PHASE EQUILIBRIUM DIAGRAMS OF OXIDE SYSTEMS

S. C. SAMANTA AND F. A. HUMMEL

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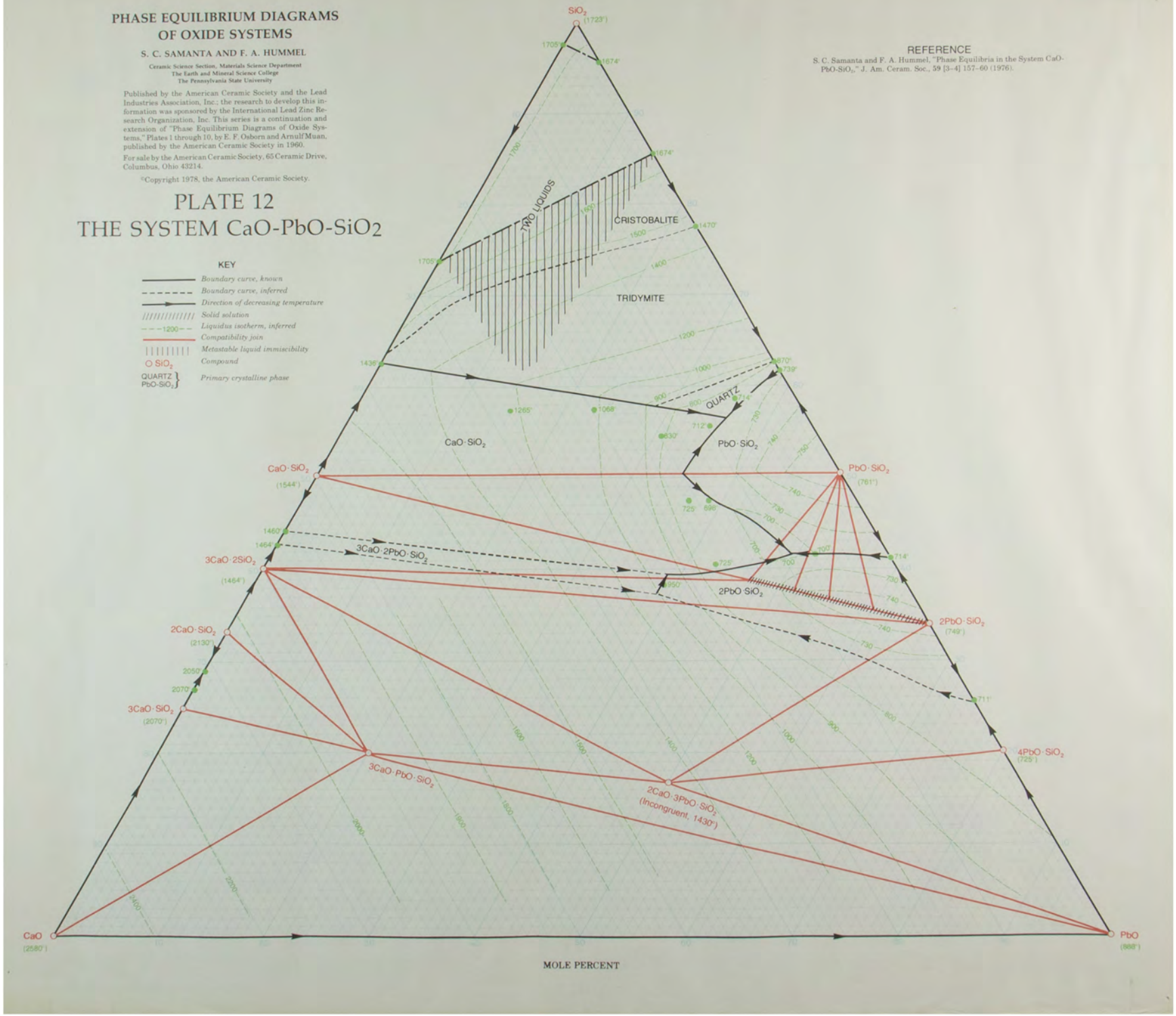
PLATE 12
THE SYSTEM CaO-PbO-SiO_2

KEY

- Boundary curve, known
- Boundary curve, inferred
- Direction of decreasing temperature
- Solid solution
- 1200 Liquidus isotherm, inferred
- Compatibility join
- Metastable liquid immiscibility
- SiO_2 Compound
- QUARTZ, $PbO\text{-}SiO_2$ Primary crystalline phase

REFERENCE

S. C. Samanta and F. A. Hummel, "Phase Equilibria in the System CaO-$PbO\text{-}SiO_2$," J. Am. Ceram. Soc., 59 [3–4] 157–60 (1976).



PHASE EQUILIBRIUM DIAGRAMS OF OXIDE SYSTEMS

S. C. SAMANTA AND F. A. HUMMEL

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PLATE 13
THE SYSTEM SrO-PbO-SiO_2

KEY

- Boundary curve, known
- Boundary curve, inferred
- Direction of decreasing temperature
- Solid solution
- -1200- Liquidus isotherm, inferred
- Compatibility join
- Metastable liquid immiscibility
- ○ SiO_2 Compound
- QUARTZ, $PbO\text{-}SiO_2$ } Primary crystalline phase

REFERENCE

S. C. Samanta and F. A. Hummel, "Phase Equilibria in the System SrO-PbO-SiO_2," J. Am. Ceram. Soc., 59 [5–6] 244–48 (1976).