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MASTER

THE FUSION OF SOILS

Prepared by

J. L. Post
University of New Mexico

SANDIA LABORATORIES



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THE FUSION OF SOILS

J. L. Post*
Research Associate Engineer
The University of New Mexico

July 1967

ABSTRACT

A method is provided which can be used to predict the melt ranges of soils with ensuing vapor and gas losses; previously determined soil mineral fusion data are correlated; test soils are selected which are representative of predominant and extreme soil types of the world with their mineralogical analyses and melt range predictions given; and the results of nine soil fusion tests are included.

* The work on this report was done at the Eric H. Wang Civil Engineering Facility which is operated for the U.S. Air Force Weapons Laboratory by the University of New Mexico, Albuquerque.

SUMMARY

One of the consequences of launching a space isotope power supply is that it may eventually return to earth and become buried in the soil. Since such a system is thermally hot, it may well melt and release its inventory of radioactive fuel. In order to predict what happens, more information is needed about soils that exist throughout the world, particularly regarding their high temperature behavior. This report presents some of the initial investigations into high temperature soil properties.

This investigation consists of three interrelated sections: the melt-temperature range of soils with respect to their composition; the determination of soils for testing which are representative of the predominant, and extreme, soil types comprising the surface of the earth; and the soil mineralogy and estimated melt-temperature range of soil samples which have been chosen for testing.

Basic data have been compiled from literature about the behavior of soils at high temperatures to enable the prediction of phase changes and melt ranges for the mineral combinations that exist in soils. These data include: a list of the predominant constituent oxides that occur in soils, their reaction and melt temperatures; a list of common clay and non-clay minerals, with basic compositions, atomic proportions, and melt points; dehydration and degassing curves for soil minerals; and a method for using the presented data, including 14 ternary phase diagrams to predict soil melt range temperatures.

Common soil types of the world are listed in a condensed table with the classification, percent of total world land area, stage of weathering, predominant mineralogy, and common constituent characteristics for each soil. Effects of the many soil variables on thermally induced reactions and melt ranges are discussed.

Nine soils are proposed for thermal tests with justifications given for choice of these soils, which are considered to be typical of world soils, and their expected reactions and melt ranges are given.

X-ray diffraction analyses of soil samples and mineral assemblages by the spectrometric powder technique are described, X-ray diffraction data are presented for 17 soils, including all the soils selected for the SNAP-27 Capsule Burial Tests.

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THE FUSION OF SOILS

SECTION I

Melt-Temperature Range of Soils

Introduction

Soils may be defined as the weathered surface of the earth. The engineer who is concerned with soil mechanics may have to consider any portion of the soil horizon from the surface to the unweathered rock strata underlying the soil.

The entire soil horizon consists of in-situ weathered rock or transported material. The soil consists of certain mineralogical suites, which are primarily determined by source material, climate, and topography. There are ordinarily two or three colloidal-size minerals which predominate in a soil and are dependent on the weathering stage of the soil.

The silicate minerals form the predominant portion of most soils, along with lesser amounts of carbonates, sulfates, sulfides, and oxides. These soil minerals may all be described in terms of constituent oxides when considering the melt point of any soil complex. These oxides are listed in Table I.

TABLE I

Predominant Soil Constituent Oxides

<u>Oxide</u>	<u>Name</u>	<u>Melt point (°C)</u>
Al_2O_3	Corundum	2020
CaO	Lime	2570
FeO	Wüstite	1369
Fe_2O_3	Hematite $\rightarrow \text{Fe}_3\text{O}_4$ @	1390
Fe_3O_4	Magnetite	1594
H_2O	Water	0
K_2O	Potash	350 decomp.
MgO	Periclase	2800
Na_2O	Soda	1275 subl.
SiO_2	Silica	1723
TiO_2	Rutile	1830

Certain components of soils were first investigated during the latter part of the 19th century by ceramists in order to determine their fluxing properties. The soil components of primary interest to the ceramists were clays and feldspars, especially kaolinite and microcline. During this time research was also conducted on the high-temperature physical characteristics of silica-alumina refractory bricks for use in metallurgical processes.

Most of the soil mineral investigations undertaken in agriculture and mineralogy involved reactions at ambient temperatures. The study of the formation and alteration of rocks and minerals at high temperatures and pressures has been undertaken primarily in geochemistry and geophysics. This study is far from completion. Much work has also been done with the high-temperature phase relations of metals, alloys, and oxides in metallurgy.

Solid Phase Reactions

A soil mass consists of a network of solid particles enclosing voids which are filled with water and air. The solid particles may be comprised of many different minerals some of which contain water as an integral part of their crystal lattice structure (water of hydration). Most solid particles also hold surface water layers by means of molecular attraction (adsorption). The solid particles may contain carbonates and sulfates which means that gases are also included in the crystalline structure of some soil minerals.

The clay minerals, i.e., hydrous layered silicates, may also contain layers of water which are bound by residual negative charges existing in the clay particles. This bound water requires considerable heat energy to be separated from the solids.

The following figures show the common soil minerals which suffer a significant weight loss when the minerals are heated through their solid phase ranges. Figures 1, 2, and 3 show weight losses for seven of the more common clay minerals and Figures 4 and 5 show weight losses for three of the more common hydrous non-clay soil minerals.

When the temperature of the soil mass is first increased the free interstitial water is driven off, then the adsorbed water is driven off. The bound water held by the clay minerals may not be completely and irreversibly driven off until many of the hydrated soil minerals, e.g., gypsum, goethite, and gibbsite, are also dehydrated.

As the soil mass is heated further the hydration water is driven off and new minerals are formed having different crystalline morphologies. Often several solid-state phase changes may ensue, the hydration water being driven off in stages, then the anhydrous minerals going through several phase changes.

At higher temperatures the carbonate soil minerals begin to break down, as shown in Figure 7. The partial pressure of the carbon dioxide increases rapidly in calcite above 700°C and at higher temperatures a solid-state phase of calcium oxide results (Figure 8).

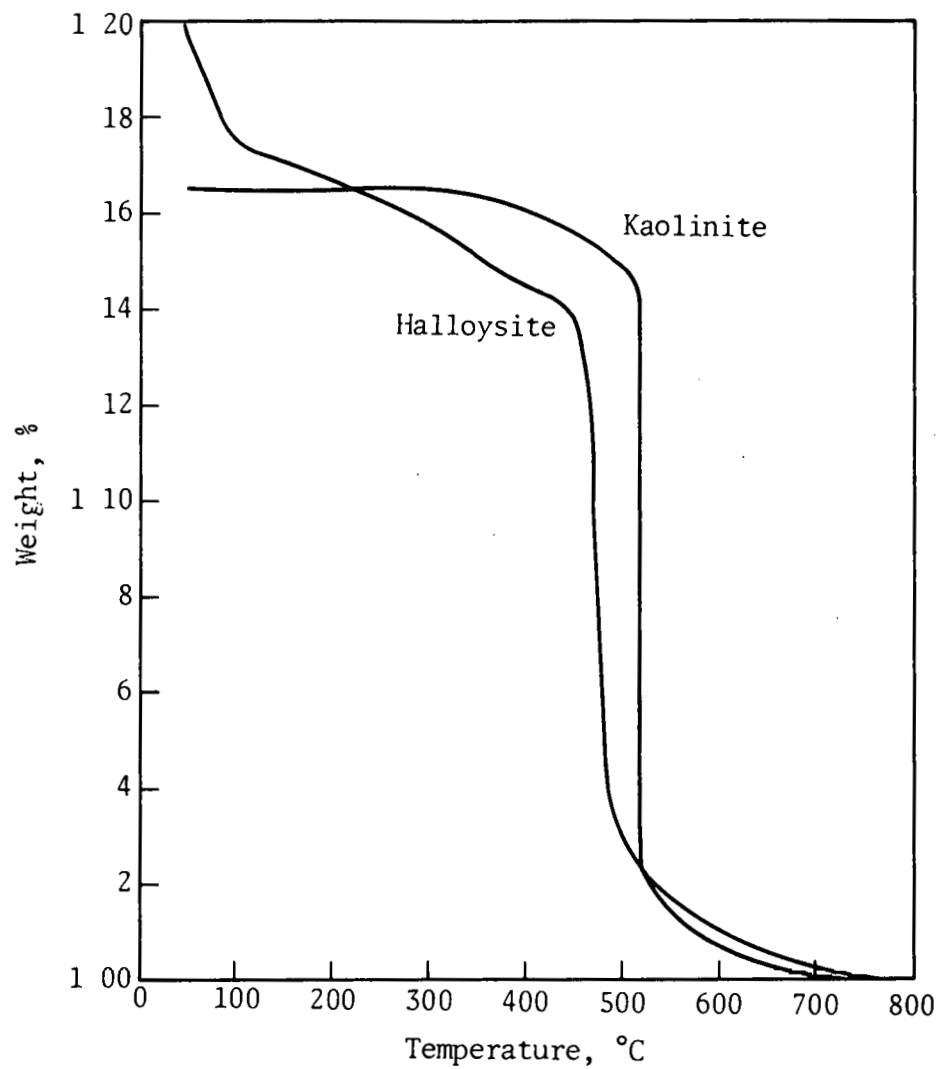


Figure 1. Dehydration curves for halloysite and kaolinite
(Grim, Clay Mineralogy, p. 191, 1953)

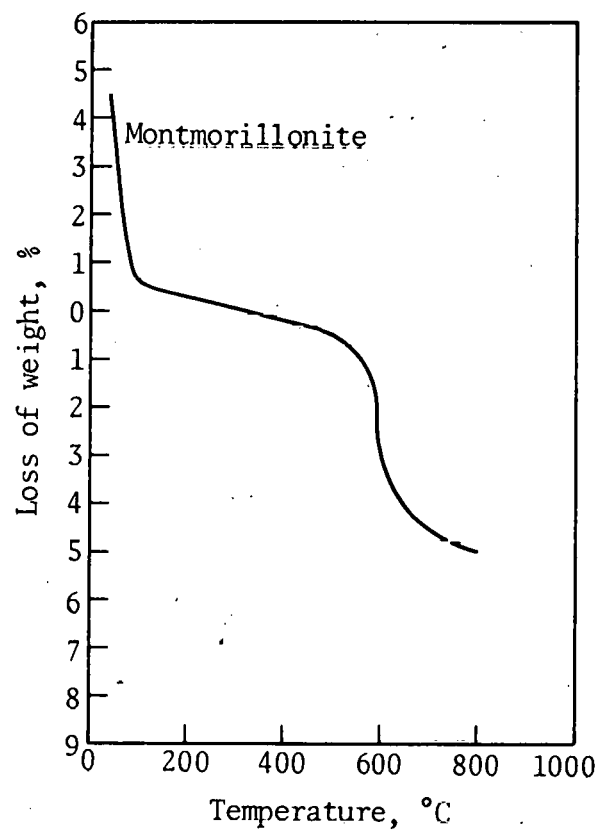


Figure 2. Dehydration curve for montmorillonite from Belle Fourche, South Dakota (partially derived from Grim, Clay Mineralogy, p. 194, 1953)

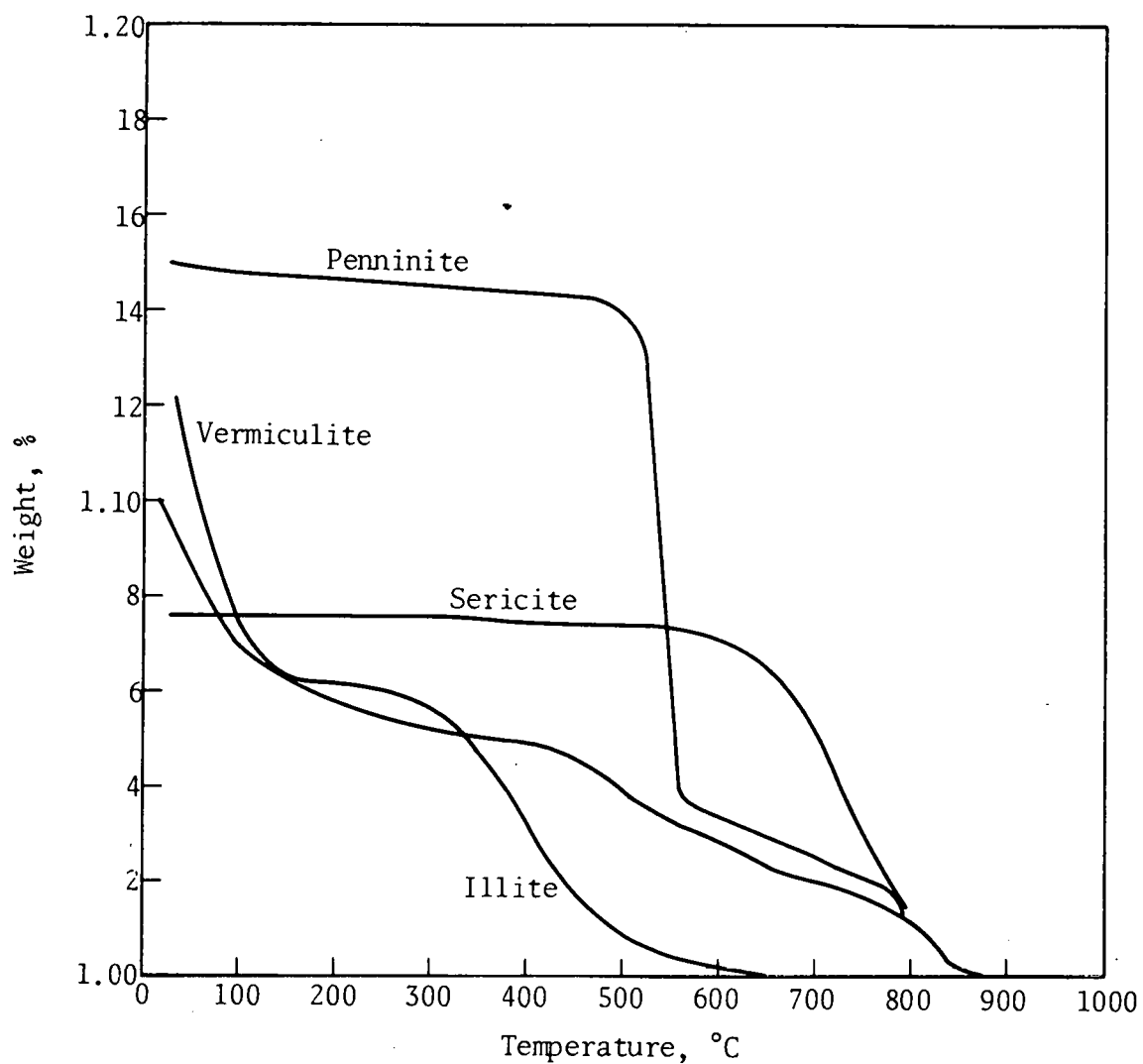


Figure 3. Dehydration curves for four clay minerals
(Grim, Clay Mineralogy, p. 192, 1953)

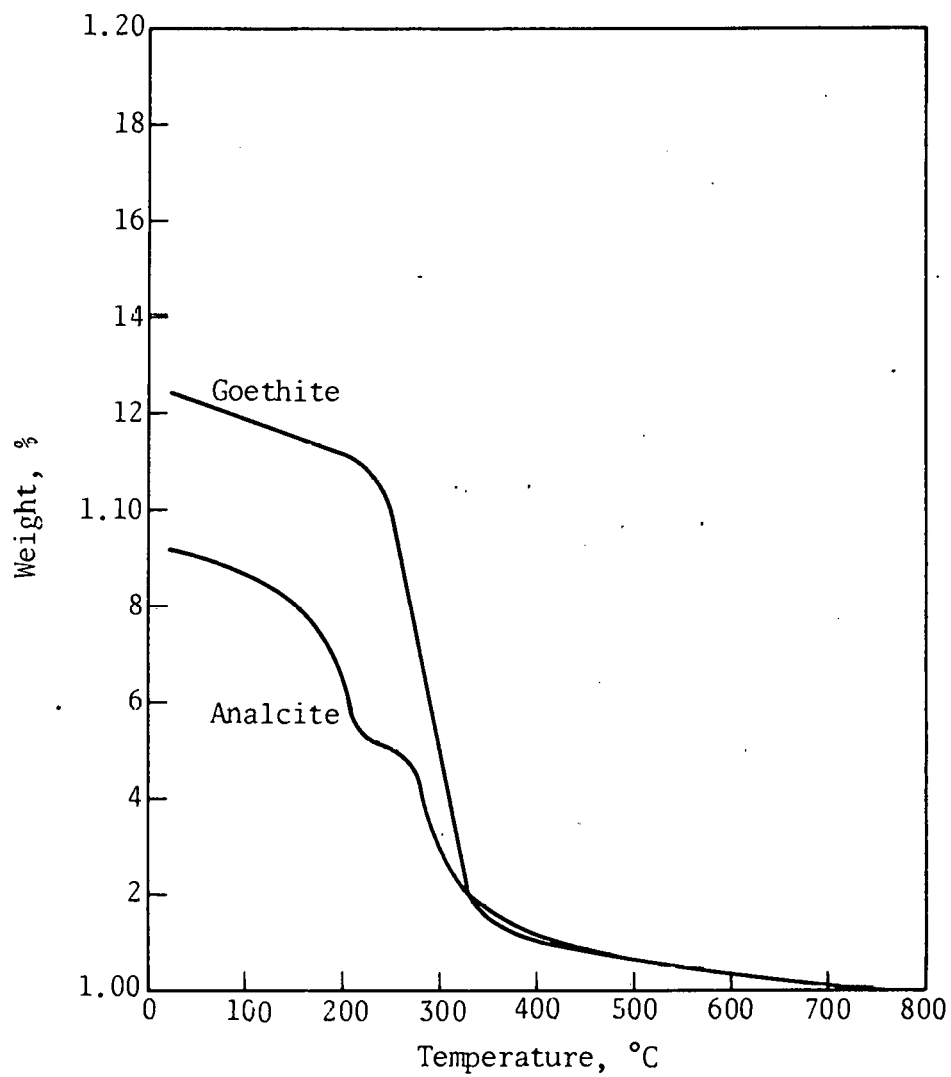


Figure 4. Dehydration curves for analcite and goethite (Nutting, Some Standard Thermal Dehydration Curves of Minerals, p. 204, 1943)

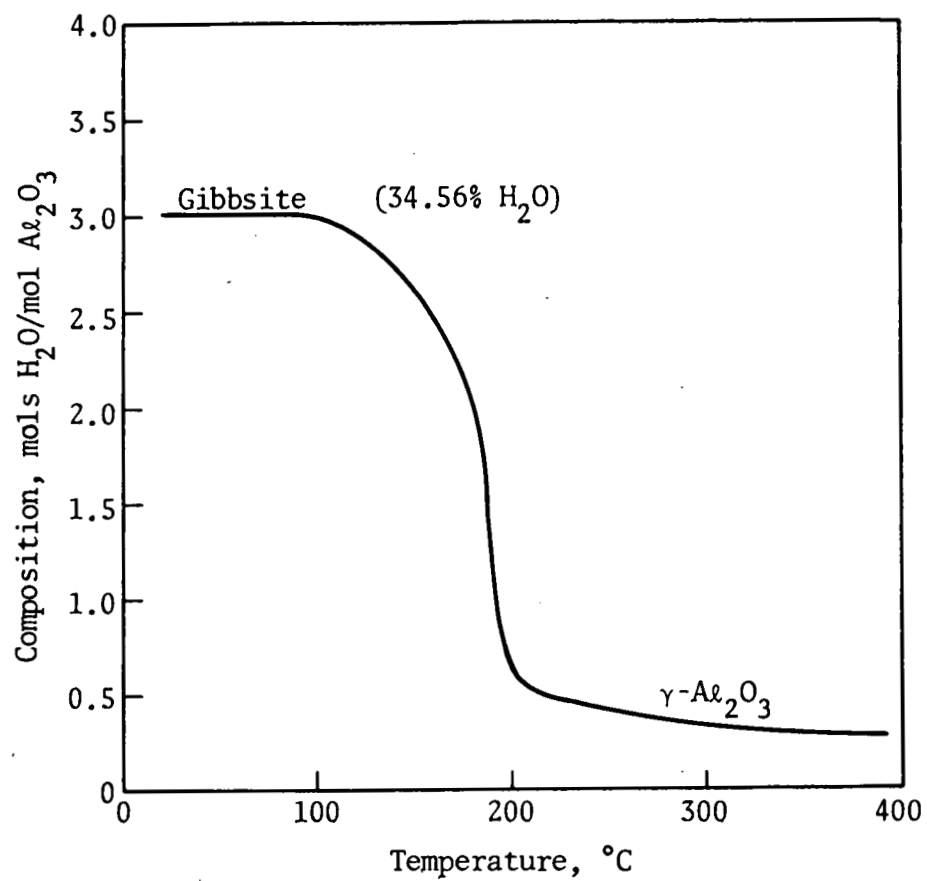


Figure 5. Dehydration isobar for synthetic gibbsite (Brown, The X-ray Identification of Clay Minerals, p. 361, 1961)

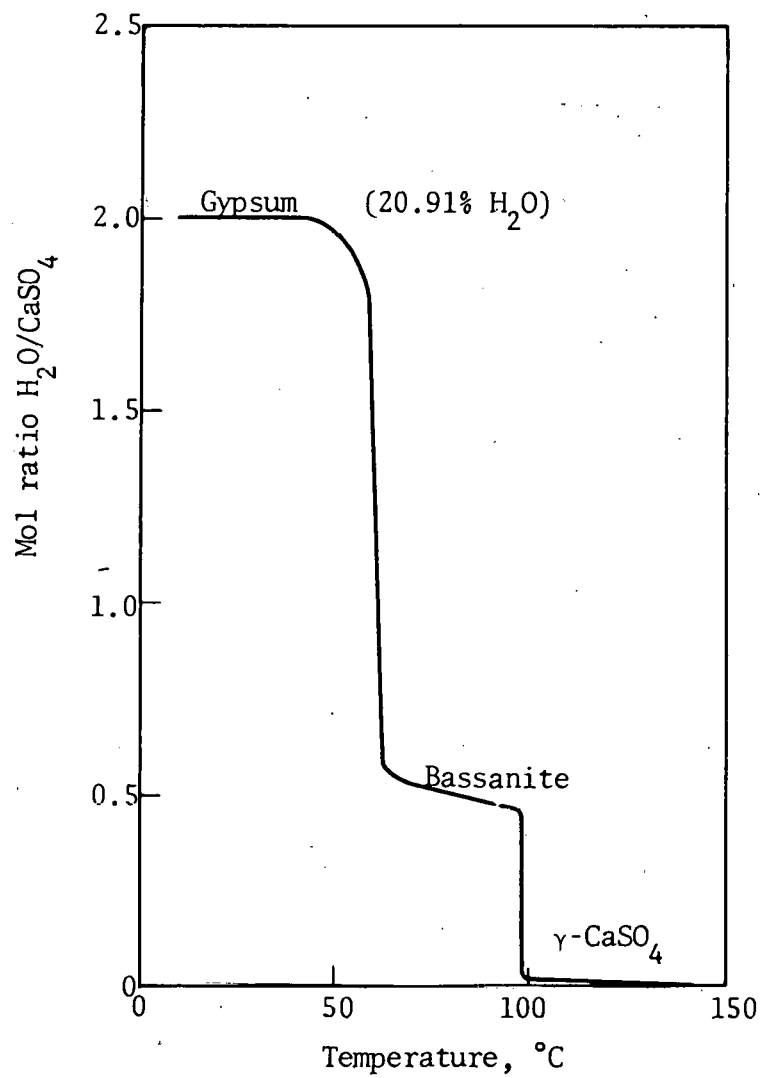


Figure 6. Isobaric hydration state of gypsum with respect to temperature (Deer et al., Rock Forming Minerals, Vol. 5, p. 207, 1962)

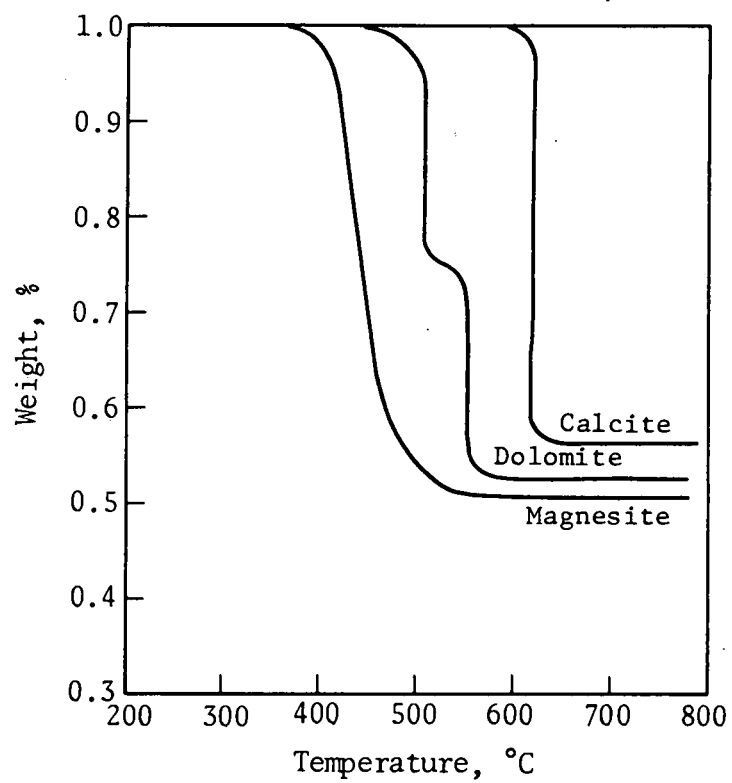


Figure 7. Thermal decomposition curves for three carbonates (Nutting, Some Standard Thermal Dehydration Curves of Minerals, p. 216, 1943)

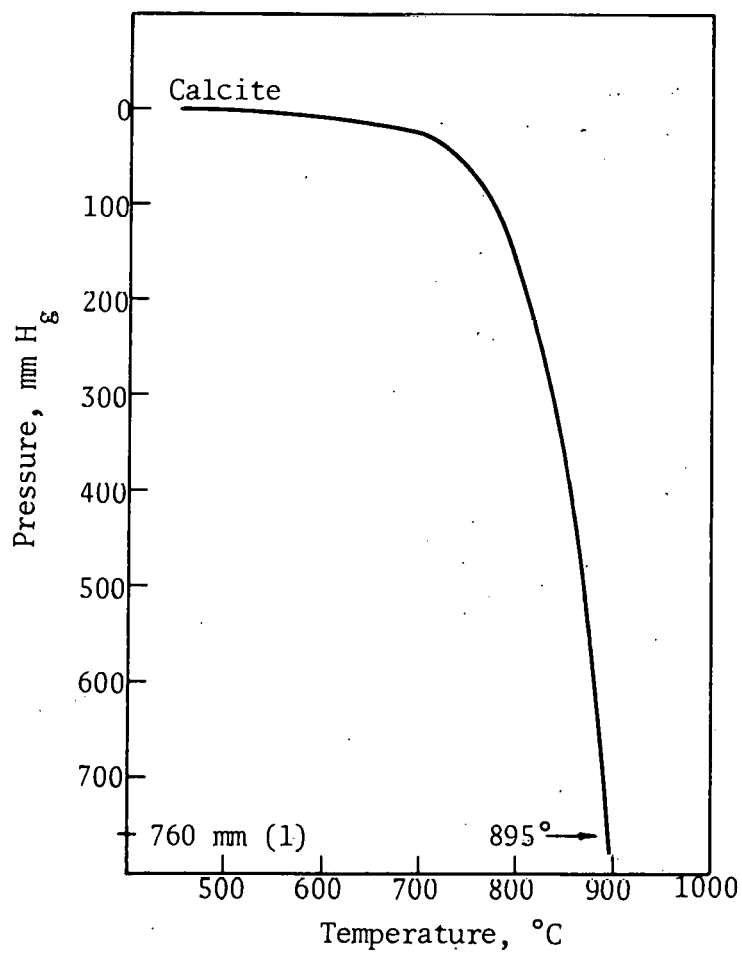


Figure 8. Partial pressure of carbon dioxide in calcite at varying temperatures (Bogue, Chemistry of Portland Cement, p. 122, 1955)

The chlorides, sulfides, and sulfates are metastable when heated in air. The sulfides tend to become sulfates and will melt without oxidizing when forming a predominant part of the soil mass. If a large part of the surface area of the soil mass is exposed to air the chlorides and sulfates will eventually oxidize with a resultant loss of chlorine and sulfur dioxide. Of the chlorides and sulfates, halite and gypsum are the only two common soil minerals which may be encountered in soils and these minerals seldom comprise a predominant part of soil masses.

Figures 1 through 7 may be used to estimate weight losses in soil masses which are heated. The weight loss of the minerals are shown for varying temperatures and it is only necessary to know the quantitative mineralogy of the soil mass to estimate the weight loss of the soil for any temperature.

Most soil masses are comprised largely of quartz and feldspars and thus when heated will suffer weight losses mainly from the gassing of free pore water and adsorbed water.

Liquid Phase

The melt point of a compound is the temperature at which the liquid phase of the compound is in equilibrium with the solid phase. When there is more than one compound present, each with different melt points, the mixture will melt incongruently. Most soils consist of mixtures of minerals and (hence) oxides, and therefore will exhibit incongruent melt points or ranges.

A mixture of two or more solid compounds, when heated to the eutectic temperature, produces a certain amount of liquid by interaction or fusion, but the upper melt point of the combination of minerals will depend on the mixture ratio. A eutectic mixture will melt congruently.

The phase change from solidus to liquidus is dependent on several soil parameters. These parameters include the grain size, packing arrangement, gas-phase conditions, hydrated and adsorbed water, and the rate of heating.

Melt-Point Determination

As the temperature of a soil is increased, the hydrated and adsorbed water will be driven off. At a temperature of about 500°C the adsorbed water on the clay particles will be driven off irreversibly, and by 900°C the CO₂ will be driven off the calcium carbonate. Most of the SO₃ of the sulfates, along with the organics of the soil, will also be driven off. The organics may cause a reducing action when being burned off.

The more common soil minerals are listed in Tables II and III. The general compositions of the minerals are shown along with their atomic proportions. The estimated and observed melt points are also given. In the clay minerals, which are generally hydrous-layered silicates, the basic compositions and more common crystal lattice substitutions are given.

The most common minerals which form the rocks of the outer mantle of the earth are feldspars, quartz, micas, amphiboles, and pyroxenes, the feldspars comprising more than 60 percent of this combination. Because the soils are derived from the earth's rock mantle, a large portion of soils will consist of feldspar, quartz, and micas, the amphiboles and pyroxenes being more susceptible to weathering. The clay minerals are largely of diagenetic origin, and they may be formed in-situ or be detrital. Kaolinite, illite, and montmorillonite are the most common of the clay minerals.

To estimate the melt range for any soil, the mineral constituents of the soil must be identified and the amount of each mineral present must be ascertained. These soil constituents may be expressed as oxides, as in Tables II and III, and their atomic proportions may then be easily computed.

After the soil mineral composition is determined, a summation of the more predominant oxides must be made. The upper melt range of the soil may be determined from the fourteen metal oxide ternary phase diagrams in the appendix. In general there will be only two or three predominant oxides in the soil. When more than three oxides are present, an interpolation must be made between phase diagrams. This interpolation may be considered linear in nature for purposes of estimating the soil melt range because a slight depression in melt point is produced by the addition of another oxide. This melt-temperature depression is given by Raoult's law.

The most common phase system encountered in the study of ceramics is the silica-alumina binary phase system, Figure 9. This system includes the most common clay minerals. Refractory bricks are made from these clays and are in this binary phase system, given in Figure 10. A direct comparison may be made between estimated and observed melt temperatures for different silica-alumina ratios. The less common MgO-SiO_2 binary phase diagram is given in Figure 11.

The most common rock minerals, the feldspar suite, contain a continuous solid-state series of mineral compositions which consist of lime, soda, and potash feldspars. Minor amounts of some other oxides may be present in the feldspars but are not common. Figure 12 shows the feldspar ternary phase diagram. It should be noted that the potassium and sodium feldspars, as well as the potassium and sodium oxides, have similar melt ranges except for the formation of leucite from potash feldspar when more than about 75 percent of potash feldspar is present.

The fusion ranges for the potash feldspar-kaolin-flint ternary phase system were determined, as shown in Figure 13. Soda feldspar gives melt ranges similar to the potash feldspars, so that the phase diagram may be used to estimate the melt ranges of mixtures when albite or perthite are used instead of the microcline.

Phase diagrams are given in the appendix for all of the more common soil oxides which may be encountered. The phase diagrams will give the maximum melt points for pure mineral systems in each case. Because there are always minor constituents and trace elements in the soils, the melt ranges for soils will always be lower than those indicated by the ternary phase diagrams. As an example, the fusion temperatures given in Figure 5 are generally about 100°C below those given by the comparable $\text{Al}_2\text{O}_3\text{-K}_2\text{O-SiO}_2$ ternary phase diagram. Some metal oxides, such as Na_2O , greatly depress the melt point of oxide mixtures, even when present in small quantities.

TABLE II
Common Soil Minerals (non-clay)

Mineral	Basic composition	Lattice substitutions	Atomic proportions	Estimated melt point (°C)	Observed melt point (°C)
<u>Quartz</u>	SiO ₂	--	1.000	--	1720
<u>Feldspars:</u>					
Albite	Na ₂ O·Al ₂ O ₃ ·6SiO ₂	--	0.118 0.195 0.687	--	1120
Oligoclase	Na ₂ O·Al ₂ O ₃ ·6SiO ₂	Na ₂ O→CaO to 20%	0.093 0.036 0.192 0.679	--	1335
Andesine	Na ₂ O·Al ₂ O ₃ ·6SiO ₂	Na ₂ O→CaO to 40%	0.070 0.070 0.190 0.670	--	1420
Microcline (orthoclase)	K ₂ O·Al ₂ O ₃ ·6SiO ₂	--	0.169 0.184 0.647	--	1150-1530
Anorthoclase	[Na _{.67} K _{.33}] ₂ O·Al ₂ O ₃ ·6SiO ₂	--	0.077 0.059 0.191 0.673	--	1050
<u>Amphiboles:</u>					
Hornblende	2CaO·5(Mg, Fe)O·8SiO ₂ ·H ₂ O	To 10% Al ₂ O ₃	Mg 0.141 0.253 0.606 Fe 0.118 0.378 0.504	1425 1400	-- 1180-1220
<u>Pyroxenes:</u>					
Enstatite	MgO·SiO ₂	--	0.400 0.600	1500	1380-1500
Augite	(Mg, Ca, Fe)O·SiO ₂	Si-Al avg 3%	(Ca, Mg) 0.483 0.517 Fe 0.545 0.455	1350 1500	1150 --
<u>Carbonates:</u>					
Calcite (aragonite)	CaO·CO ₂	CO ₂ ↑ 898°C	1.000		2570
Dolomite	(Ca, Mg)O·CO ₂	--	0.600 0.400	2350	2100
<u>Sulphates:</u>					
Gypsum	CaO·SO ₃ ·2H ₂ O	SO ₃ ↑ 1250-1300°C	1.000	--	2570
Anhydrite	CaO·SO ₃	SO ₃ ↑ 1250-1300°C	1.000	--	2570

TABLE II (cont)
Common Soil Minerals (non-clay)

Mineral	Basic composition	Lattice substitutions	Atomic proportions	Estimated melt point ($^{\circ}\text{C}$)	Observed melt point ($^{\circ}\text{C}$)
<u>Zeolites:</u>					
Analcite (Na)	$\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Na→Ca	0.153 0.252 0.595	1150	--
<u>Iron Oxides:</u>					
Hematite (maghemite)	Fe_2O_3	$\text{Fe}_2\text{O}_3 \rightarrow \text{Fe}_3\text{O}_4$ @ 1390	1.000	--	1594
Goethite (lepidocrocite)	$\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$	$\text{Fe}_2\text{O}_3 \rightarrow \text{Fe}_3\text{O}_4$ @ 1390	1.000	--	1594
Magnetite	$\text{FeO} \cdot \text{Fe}_2\text{O}_3$	--	0.310 0.690	--	1594
<u>Aluminum oxides:</u>					
Gibbsite	$\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	$\text{H}_2\text{O} \uparrow 250^{\circ}\text{C}$	1.000	--	2035
Diaspore (boehmite)	$\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$	$\text{H}_2\text{O} \uparrow 250^{\circ}\text{C}$	1.000	--	2035
Corundum	Al_2O_3	--	1.000	--	2035
Anatase (rutile)	TiO_2	Ti→Fe to 5%	1.000	--	1900
Halite	NaCl	--	1.000	--	801

TABLE III

Common Clay Minerals

Mineral	Basic composition	Lattice substitutions	Atomic proportions	Estimated melt point (°C)	Observed melt point (°C)
Kandites:					
Kaolinite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	$\text{Al} \rightarrow (\text{Ti}, \text{Mg}, \text{Fe})$ to 0.5%	0.459 0.541	1810	1785
Halloysite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	$\text{Al} \rightarrow (\text{Ti}, \text{Mg}, \text{Fe})$ to 0.5%	0.459 0.541	1810	1775
Smectites:					
Montmorillonite	$\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$	$\text{Al}^{+3} \rightarrow \text{Mg}^{+2}$ (to 30%), $\text{Si}^{+4} \rightarrow \text{Al}^{+3}$ (to 15%)	0.017 0.315 0.669	1750	1310 @ 90%
Beidellite	$\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$	----	0.298 0.702	1775	--
Nontronite	$\text{FeO} \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$	$\text{Fe}^{+2} \rightarrow \text{Al}^{+3}$ (to 10%), $\text{Si}^{+4} \rightarrow \text{Al}^{+3}$ (to 15%)	0.375 0.625	1600	--
Saponite	$\text{MgO} \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$	$\text{Mg}^{+2} \rightarrow \text{Al}^{+3}$ (to 10%), $\text{Si}^{+4} \rightarrow \text{Al}^{+3}$ (to 15%)	0.250 0.750	1700	--
Micas:					
Muscovite	$\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	----	0.124 0.403 0.473	To 20% Mg 1400-1650	1255-1290
Phlogopite	$\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	$\text{Al}^{+3} \rightarrow \text{Mg}^{+2}$ to 20%	Mg 0.118 0.502 0.128 0.452	1450	--
Biotite	$\text{K}_2\text{O} \cdot 6(\text{Fe}^{+2}, \text{Mg}^{+2})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	----	Fe 0.095 0.438 0.105 0.364	1300	1155-1240
Illite	$\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	$\leq 5\% \text{K}^+, \text{Al}^{+3} \rightarrow (\text{Mg}^{+2}, \text{Fe}^{+3})$ to 5%	0.050 0.437 0.513	1650	--
Vermiculite	$\text{MgO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$	$\text{Mg}^{+2} \rightarrow \text{Fe}^{+3}$ (to 50%), $\text{Si}^{+4} \rightarrow \text{Al}^{+3}$ (to 10%)	0.187 0.152 0.055 0.626	1500	--
Chlorite (typical)	$5\text{MgO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$	$[\text{Mg}_{11}\text{Al}]$ to $[\text{Mg}_8\text{Al}_4]$, $[\text{Si}_{17}\text{Al}]$ to $[\text{Si}_4\text{Al}_4]$	0.415 0.211 0.374	1400	--
Sepiolite	$\text{MgO} \cdot \text{SiO}_2$	to enstatite	0.400 0.600	1550	1380-1500
Attapulgit	$\text{MgO} \cdot \text{SiO}_2$	@ 800°C	$\text{Mg}^{+2} \rightarrow \text{Fe}^{+3}$ to 5%	1550	1330-1500
Bentonite	Random mixed-layer swelling clays		----	1400-1600	--

Note: Kaolinite may adsorb to 0.5% Ca^{+2} , Na^+ , K^+ ions by weight.

Montmorillonite may adsorb to 1% Na^+ and 3% Ca^{+2} ions.

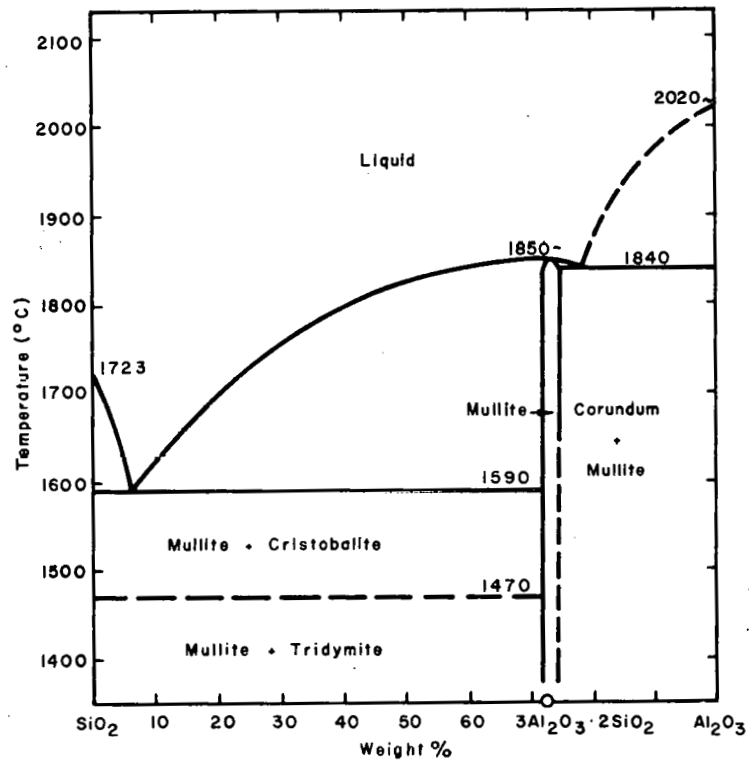


Figure 9. Al_2O_3 - SiO_2 Binary Phase Diagram

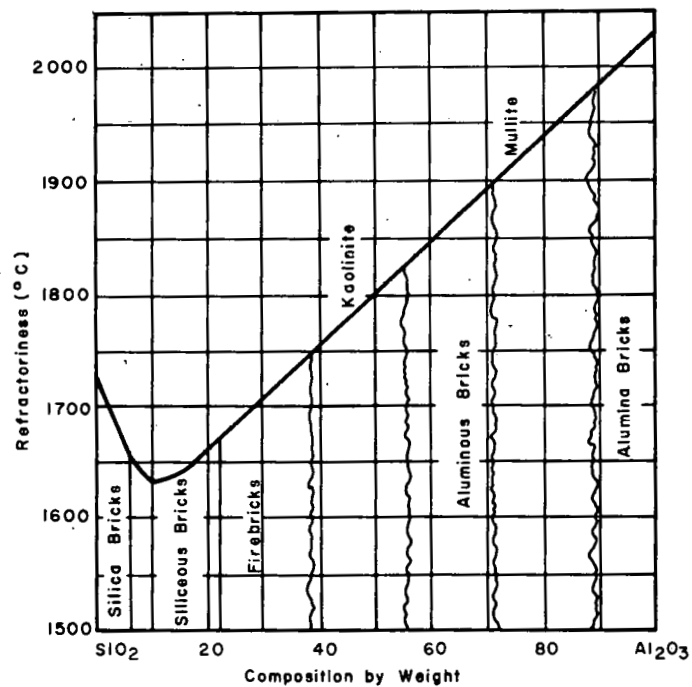


Figure 10. Silica-Alumina Refractory Diagram

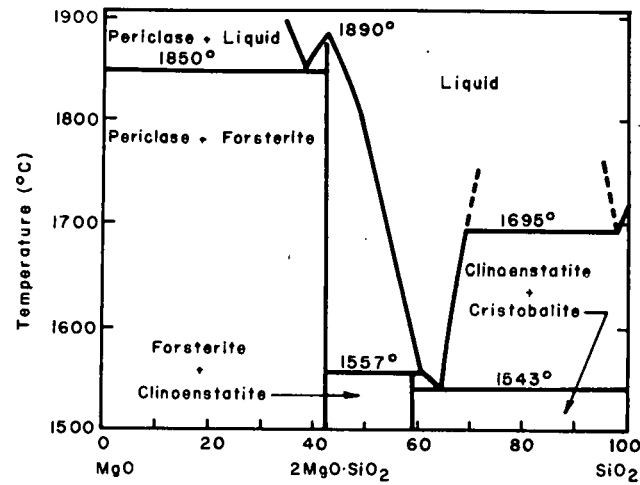


Figure 11. MgO-SiO₂ Binary Phase Diagram
(Courtesy of American Ceramic Society)

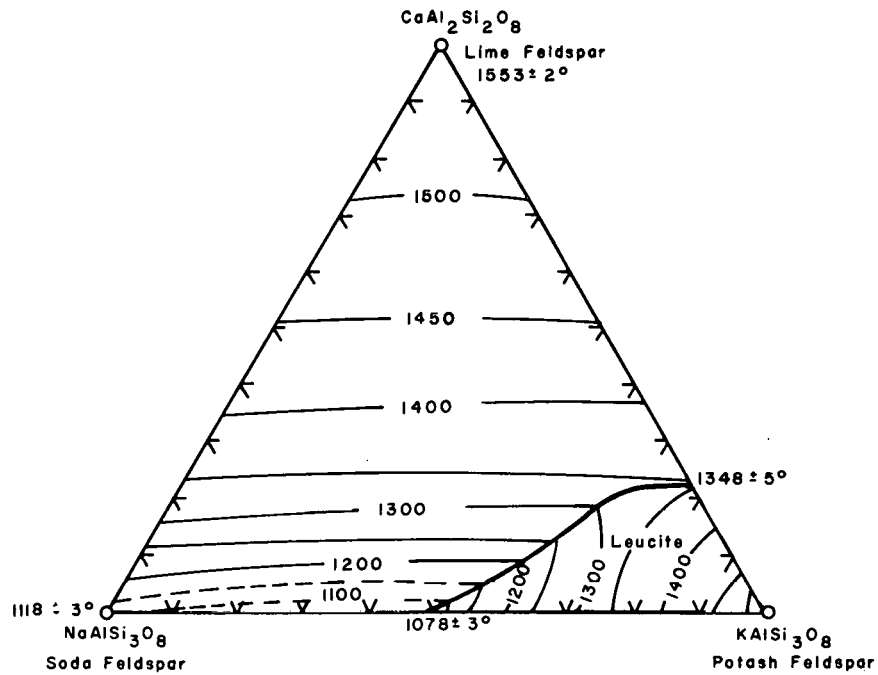


Figure 12. Soda-Potash-Lime Feldspar Ternary Phase Diagram

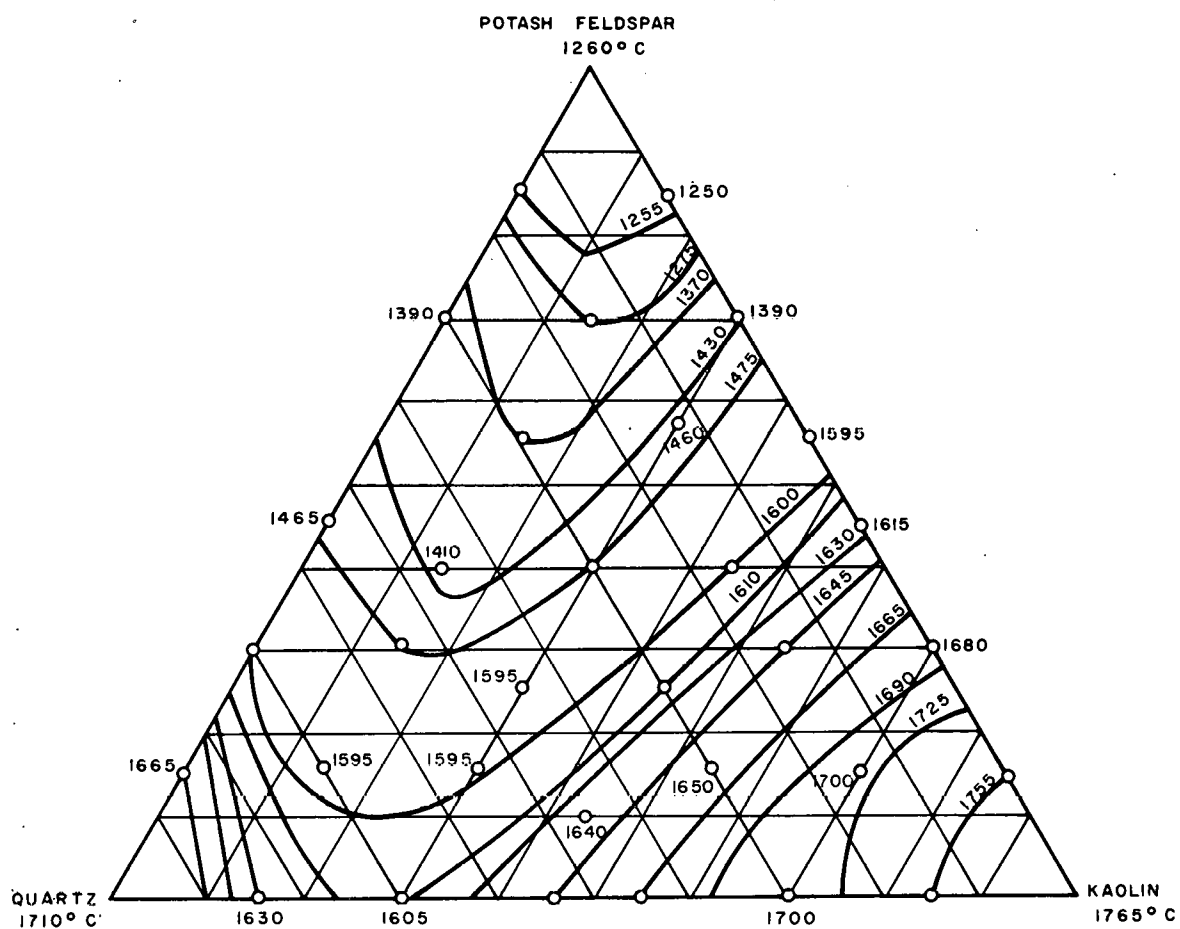


Figure 13. Feldspar-Kaolin-Quartz Ternary Phase Diagram

The ternary phase diagram, Figure 13, includes many of the common pedalfer soils of the humid temperate and subtropical zones of the world, potash-soda feldspars being considered in common. The upper melt range of the quartz-potash feldspar-kaolin mixtures may be computed in the following manner, if one considers a mixture of 25 percent K-feldspar, 50 percent kaolin, and 25 percent quartz:

25% K-Feldspar

Formula	K_2O	Al_2O_3	$6SiO_2$	
Atomic weight	94	102	360	→ 556
Atomic proportion	0.163	0.184	0.647	
A.P. x 25%	4.2%	4.6%	16.2%	

50% Kaolin

Formula		Al_2O_3	$2SiO_2$	
Atomic weight		102	120	→ 222
Atomic proportion		0.459	0.541	
A.P. x 50%		22.9%	27.1%	

25% Quartz

Formula			SiO_2	
Atomic weight			60	→ 60
Atomic proportion			1.000	
A.P. x 25%			25.0%	

Oxide ratio	Σ	4.2%	27.5%	68.3%	→ 100.0%
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The estimated and observed melt temperatures are given in Table IV for different proportions of feldspar, kaolin, and quartz, comprising artificial soil mixtures.

TABLE IV

Determination of Artificial Soil Melt Ranges
(Data from the Al_2O_3 - K_2O - SiO_2 phase diagram and Figure 13)

<u>K-feldspar (%)</u>	<u>Kaolin (%)</u>	<u>Quartz (%)</u>	<u>Estimated melt point (°C)</u>	<u>Observed melt point (°C)</u>
25	25	50	1605	1525
25	50	25	1710	1640
50	25	25	1600	1415

It should be noted that the minerals used to produce the data for Figure 13 were not chemically pure, and therefore a lower melt range is to be expected. The high viscosity of the melted feldspar, the low rate of solution of the quartz, and the slow diffusion of the partially mixed and partially melted batch materials hinder the attainment of equilibrium and of homogeneity, so that the constituents not only differ from the equilibrium phases but the composition varies throughout the mixture.

An example of the determination of the melt range of a calcareous silty-sand soil from the Rio Grande basin is presented in Table V. Note that the clays are treated as a pure smectite silica-alumina system and the system must be adjusted for CO_2 loss. The water in the system is considered to have been lost below melt-temperature ranges. (The in-situ moisture is about 2 percent of the dry weight of the soil.)

With this Al_2O_3 - SiO_2 ratio the Na_2O - K_2O oxides give approximately the same melt ranges and will be treated together.

4.3 percent (Na_2O - K_2O)- Al_2O_3 - SiO_2 melt point of 1050°C .

8.4 percent (CaO)- Al_2O_3 - SiO_2 melt point of 1450°C .

By using a linear interpolation, the soil will melt incongruently from 1050°C (perthite) to 1315°C .

The soil mineral was analyzed by X-ray diffraction procedures except for the carbonates which were determined by means of quantitative chemical analysis.

The surface soil at Trinity site in the Jornada del Muerto is similar in composition to the soil of the Rio Grande basin and displays a comparable melt range. The soil at Trinity site was melted to a maximum depth of about 1 inch for about a 1500-foot radius from the nuclear explosion. Considering the mineralogical composition of the soil, it probably melted incongruently between about 1000°C (perthite) and 1320°C .

The X-ray diffraction analyses of the slag (trinitite) indicate that while the surface was completely melted the lower portion of the slag layer still contains much unmelted quartz, the feldspars having melted incongruently.

Estimated and observed melt-temperature data are listed in Table VI for soil mineral components. The estimated data are derived largely from the ternary phase diagrams which are included in the appendix. Little melt-temperature data are available on soil mineral aggregates. Some available data are listed in Table VII.

TABLE V
Determination of Calcisol Melt Range

<u>Constituent</u>		<u>Estimated (%)</u>				
Albite		20				
Microcline		10				
Quartz		40				
Calcite		13				
Micas		5				
Smectite		5				
Random mixed-layer clays		5				
Trace minerals		2				
		100				
		K ₂ O	Na ₂ O	CaO	Al ₂ O ₃	SiO ₂
Ab	20%		<u>0.118</u>		<u>0.195</u>	<u>0.687</u>
			2.4%		3.9%	13.7%
Or	10%	<u>0.169</u>			<u>0.184</u>	<u>0.647</u>
		1.7%			1.8%	6.5%
Qtz	40%					<u>1.000</u>
						40.0%
Smectite	17%				<u>0.298</u>	<u>0.702</u>
					5.1%	11.9%
CaO	8%			<u>1.000</u>		
				8.0%		
CO ₂	<u>5%</u>					
	100%	<u>1.7%</u>	<u>2.4%</u>	<u>8.0%</u>	<u>10.8%</u>	<u>72.1% = 95.0%</u>
Solids Σ =		1.8%	2.5%	8.4%	11.4%	75.9% = 100.0%

TABLE VI

Soil Mineral Melt-Temperature Data

<u>Material</u>	<u>Formula</u>	<u>Occurrence in soil</u>	<u>Estimated melt point (°C)</u>	<u>Observed melt point (°C)</u>
Albite	$\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	Very common	1118	1120-1220
Analcite	$\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Common	1150	--
Anatase (rutile)	TiO_2	Uncommon	1830	1700
Andalusite	$\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$	Rare	1845	1770
Anorthite	$\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	Uncommon	1553	1532
Apatite	$\text{CaF}_2 \cdot 3\text{Ca}_3(\text{PO}_4)_2$	Uncommon	1630	1270-1300
Asbestos (actinolite)	$\text{Ca}_2(\text{Mg, Fe})_5(\text{OH})_2(\text{Si}_4\text{O}_{11})_2$	Very rare	--	1285-1310
Attapulgite	$\text{MgO} \cdot \text{SiO}_2$	Uncommon	1550	1380-1500
Augite	$(\text{Mg, Ca, Fe})\text{O} \cdot \text{SiO}_2$	Uncommon	--	1145-1150
Baddeleyite	ZrO_2	Very rare	--	2700
Barite	BaSO_4	Very rare	--	1580
Bauxite	$\text{Al}_2\text{O}_3 \cdot (1-3)\text{H}_2\text{O}$	Common	2020	1730-1850
Beidellite	$\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$	Uncommon	1775	--
Beryl	$\text{Al}_2\text{O}_3 \cdot 3\text{BeO} \cdot 6\text{SiO}_2$	Very rare	--	1410-1430
Biotite	$\text{K}_2\text{O} \cdot 6(\text{Fe, Mg})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Very common	1300	1155-1240
Borax	$\text{Na}_2\text{O} \cdot 2\text{B}_2\text{O}_3 \cdot 10\text{H}_2\text{O}$	Uncommon	--	878
Brucite (magnesia)	$\text{MgO} \cdot \text{H}_2\text{O}$	Uncommon	--	2500-2800

TABLE VI (continued)

Soil Mineral Melt-Temperature Data

<u>Material</u>	<u>Formula</u>	<u>Occurrence in soil</u>	<u>Estimated melt point (°C)</u>	<u>Observed melt point (°C)</u>
Calcite	CaCO_3	Very common	--	2570
Chlorite (typical)	$5\text{MgO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$	Very common	1400	--
Chromite	$\text{FeO} \cdot \text{Cr}_2\text{O}_3$	Uncommon	1770	1850-2180
Corundum	Al_2O_3	Uncommon	--	2020
Cristobalite	SiO_2	Common	--	1720
Cryolite	$3\text{NaF} \cdot \text{AlF}_3$	Very rare	--	977
Diaspore	$\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$	Common	2020	2035
Dickite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Uncommon	1810	1785
Diopside	$(\text{Ca}, \text{Mg})\text{O} \cdot 2\text{SiO}_2$	Rare	--	1391
Dolomite	$(\text{Ca}, \text{Mg})\text{O} \cdot \text{CO}_2$	Very common	2350	2100-2500
Enstatite	$\text{MgO} \cdot \text{SiO}_2$	Common	1550	1380-1500
Epidote	$4\text{CaO} \cdot 3(\text{Al}, \text{Fe})_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$	Uncommon	--	1250
Fayalite	$2\text{FeO} \cdot \text{SiO}_2$	Very rare	1205	1210
Fluorite	CaF_2	Rare	--	1361
Forsterite	$2\text{MgO} \cdot \text{SiO}_2$	Very rare	1890	1910

TABLE VI (continued)
Soil Mineral Melt-Temperature Data

<u>Material</u>	<u>Formula</u>	<u>Occurrence in soil</u>	<u>Estimated melt point (°C)</u>	<u>Observed melt point (°C)</u>
Gehlenite	$2\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{SiO}_2$	Very rare	1593	1570
Gibbsite	$\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Very common	2020	2035
Goethite	$\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$	Common	1594	--
Grossularite (garnet)	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$	Uncommon	1265	1150-1250
Gypsum	$\text{CaO} \cdot \text{SO}_3 \cdot 2\text{H}_2\text{O}$	Very common	--	2570
Halite	NaCl	Common	--	810
Halloysite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Very common	1810	1775
Hematite	Fe_2O_3	Common	--	1594
Hornblende	$2\text{CaO} \cdot 5(\text{Mg}, \text{Fe})\text{O} \cdot 3\text{SiO}_2 \cdot \text{H}_2\text{O}$	Common	1400-1425	1180-1220
Ilmenite	$\text{FeO} \cdot \text{TiO}_2$	Common	--	1400
Illite	$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Very common	1650	--
Kaolinite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Very common	1810	1745-1790
Lepidolite	Lithium mica	Very rare	--	925-945
Leucite	$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$	Uncommon	1530	1320-1370
Magnesite	$\text{MgO} \cdot \text{CO}_2$	Uncommon	--	2800

TABLE VI (continued)
Soil Mineral Melt-Temperature Data

<u>Material</u>	<u>Formula</u>	<u>Occurrence in soil</u>	<u>Estimated melt point (°C)</u>	<u>Observed melt point (°C)</u>
Magnetite	$\text{FeO} \cdot \text{Fe}_2\text{O}_3$	Common	--	1594
Microcline	$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	Very common	1530	1150-1530
Montmorillonite	$\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$	Very common	1750	--
Muscovite	$\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Very common	1400-1650	1255-1290
Nacrite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Rare	1810	1785
Nepheline	$(\text{Na}, \text{K})_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	Uncommon	1526-1675	1225-1525
Nontronite	$\text{FeO} \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$	Uncommon	1600	--
Olivine	$2(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$	Uncommon	--	1700-1910
Orthoclase	$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	Very common	--	1150-1530
Periclase	MgO	Very rare	--	2800
Phlogopite	Magnesium mica	Uncommon	1450	--
Quartz	SiO_2	Very common	--	1720
Rhodonite	$\text{MnO} \cdot \text{SiO}_2$	Rare	--	1210

TABLE VI (continued)

Soil Mineral Melt-Temperature Data

<u>Material</u>	<u>Formula</u>	<u>Occurrence in soil</u>	<u>Estimated melt point (°C)</u>	<u>Observed melt point (°C)</u>
Saponite	$\text{MgO} \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$	Common	1700	--
Sepiolite	$\text{MgO} \cdot \text{SiO}_2$	Uncommon	1550	1380-1500
Sillimanite	$\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$	Rare	--	1816
Spinel	$\text{MgO} \cdot \text{Al}_2\text{O}_3$	Uncommon	--	2135
Spodumene	$\text{Li}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$	Very rare	--	1380
Titanite (sphene)	$\text{CaO} \cdot \text{TiO}_2 \cdot \text{SiO}_2$	Rare	--	1200--1300
Tourmaline	$3\text{Al}_2\text{O}_3 \cdot 2\text{B}_2\text{O}_3 \cdot 8\text{SiO}_2 \cdot 11\text{H}_2\text{O}$	Uncommon	--	1000-1100
Vermiculite	$\text{MgO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$	Common	1500	--
Wollastonite	$\text{CaO} \cdot \text{SiO}_2$	Rare	--	1540
Zircon	$\text{ZrO}_2 \cdot \text{SiO}_2$	Uncommon	--	2550

TABLE VII

Soil Mineral-Aggregate Melt-Temperature Data

	Observed melt range (°C)	Average melt point (°C)
Basalt (and gabbro)	---	1140
Bentonite (90% montmorillonite, 5% quartz, 5% feldspar)	1340	--
Clays (samples from 17 areas of North America)	1582-1796	1660
Clays (aluminous)	1800-1880	1840
Clays (carboniferous)	1605-1675	1640
Granite (and rhyolite)	800-1100	950
Kaolins (southern)	1645-1785	1715
Silica sand	1700-1750	1725

Pyrometric Cone Evaluations

<u>Natural soils</u>	Estimated melt range (°C)	Observed approximate melt range (°C)	
		<u>Trial 1</u>	<u>Trial 2</u>
Estancia Playa soil	850-900	vol. 1220	dec. 1260
Hayes, Kansas, soil	1250-1500	1280	1235-1285
Magnesian soil	1450-1475	1310	vol. 1260
Granitic Detrital soil	1200-1320	vol.	1310-1335
Rio Salado dune sand	1300-1400	1310	1330-1340
<u>Artificial soils</u>			
Calcareous soil	1300-1325	1235	vol. 1300
Clayey soil	1300-1390	1310	vol. 1340
Organic calcareous soil	1275-1300	vol. 1220	--

NOTES: Fusion tests conducted by R. W. Foster, New Mexico Bureau of Mines and Mineral Resources (July 1967).

Trial 1 observed by optical pyrometer, trial 2 observed by P. C. E. (vol. = volatilization, dec. = decrepitation).

P. C. E. furnace draft appears to have sintered the Estancia Playa soil.

Calcareous soil (25% calcite, 15% kaolinite, 30% perthite, 30% quartz)
Clayey soil (10% calcite, 30% kaolinite, 30% perthite, 30% quartz)
Organic calcareous soil (22.5% calcite, 13.5% kaolinite, 27% perthite, 27% quartz, 10% carbon)

All cones for the P. C. E. tests were fabricated from material ground to -60 size; gum tragacanth was used as the cone binder. No heat treatment was given any cones prior to testing.

SECTION II

World Soil Types

Common Soil Constituents

The predominant soils which comprise the surface of the earth have been classified in terms of land form, weathering stage, and grain-size distribution. These classifications are very general and not always consistent. Although moisture content, grain-size distribution, and density are important parameters in the investigation of the fusion and heat conductance of soils, the mineralogical composition of soils is by far the most important factor in the determination of soil-fusion temperatures and reaction products.

The determination of soil samples which are characteristic of the majority of the land area of the world was made by correlating the soil classification, weathering stage, and predominant mineralogy of the soil types and observing their common constituent characteristics, Table VIII. The soil type is primarily dependent on source material, topography, and climate while the weathering stage is primarily dependent on topography and climate.

It should be observed, Table VIII, that the first five of the fourteen soil types have common constituent characteristics which comprise 46.7 percent of the total land area of the world. The next three soil types comprise another 9 percent of the world's land area and they differ little in mineral content from the first five. It can be seen from these data that the mineralogical composition of a soil is largely dependent on source materials and, generally, only dependent on weathering where windy, hot, or humid or all three conditions prevail.

Clarke, in Data of Geochemistry, 1916, has estimated the percent of composition of the crust of the earth to be approximately as follows: SiO_2 , 59.8; Al_2O_3 , 14.9; Fe_2O_3 , 2.7; FeO , 3.4; MgO , 3.7; CaO , 4.8; Na_2O , 3.2; K_2O , 3.0; H_2O , 2.0; TiO_2 , 0.8; CO_2 , 0.7; P_2O_5 , 0.3; remainder, 0.7.

The list of proposed representative soils which are to be investigated are comprised of common soil minerals which include the twelve most common oxides of the crust of the earth in various discrete combinations. The majority of soil minerals are silicates, many of which contain significant amounts of alumina. Of the remaining oxides, sodium and potassium tend to give low soil-melt ranges, as in granitic soils; and calcium and magnesium tend to give high soil-melt ranges, as in limestones. Iron, aluminum, and titanium oxides tend to give intermediate-to-high melt ranges, as do the clay minerals.

TABLE VIII
Common Soil Types of World

<u>Symbol</u>	<u>Soil classification¹</u> <u>Type</u>	<u>%</u>	<u>Weathering</u> <u>stage²</u>	<u>Predominate mineralogy</u>	<u>Common constituent characteristics</u>
	Lithosol	23.9	1	Quartz, feldspars, micas, amphiboles, pyroxenes, carbonates	Clastic material from granite (acidic) to gabbro (basic) sources, also sedimentary and metamorphic sources; includes soils derived from detrital granite-rhyolite to gabbro-basalt, calcite-dolomite, phyllite, and quartzite
J	Tundra plains	4.1	2-4	Quartz, feldspars, micas, chlorite, amphiboles, pyroxenes, carbonates	
C	Arid to semi- arid topography	7.3	2	Quartz, feldspars, micas, calcite, chlorite, gypsum, smectites, amphiboles, pyroxenes, halite	
E	Upland plateaus	7.7	2-4	Quartz, feldspars, micas, chlorite, carbonates, kan- dites, amphiboles, pyroxenes	
D	Upland plains	3.7	3-5	Quartz, feldspars, micas, chlorite, carbonates, kan- dites, amphiboles, pyroxenes	
Total		46.7			

TABLE VIII (continued)

Common Soil Types of World

Symbol	Soil classification ¹ Type	%	Weathering stage ²	<u>Predominate mineralogy</u>	<u>Common constituent characteristics</u>
F	River flood plains	2.7	4-8	Quartz, feldspars, micas, chlorite, kaolinite, illite, iron oxides	Same as above with the more basic source materials altered and mostly leached out; considerably less carbonate soils
I	Lake, stream, estuary beds	2.3	5-8	Quartz, feldspars, kaolinite, chlorite, calcite, illite, organics	
K	Coastal, alluvial, lake beds	4.0	7-9	Quartz, feldspars, kaolinite, illite, chlorite, halite	
	Total	9.0			
L	Swamps, marshes	2.6	6-9	Quartz, feldspars, kaolinite, chlorite, calcite, illite, organics	Filled lake, stream, and estuary beds
	Total	2.6			
H	Clay aggre- gations	1.3	7-10	Quartz, iron oxides, chlorite, illite, kaolinite, montmorillonite	Clayey lowland delta soils and lake beds
	Total	1.3			

TABLE VIII (continued)
Common Soil Types of World

<u>Symbol</u>	<u>Soil classification¹</u> <u>Type</u>	<u>%</u>	<u>Weathering</u> <u>stage²</u>	<u>Predominant mineralogy</u>	<u>Common constituent characteristics</u>
A	Sand dunes	7.1	Arenaceous	Quartz, feldspars	Detrital soils which may include amphiboles, pyroxenes, and volcanic ash
B	Loessial plains	7.0	Arenaceous	Quartz, feldspars	
	Total	14.1			
G	Laterites	10.1	11-13	Quartz, bauxite, hematite, kaolinite, halloysite	Indurated lateritic soils and ironstone
	Total	10.1			

¹Goldberg, J. M., Fosberg, F. R., Sachet, M. H., and Reimer, A., "World Distribution of Soil, Rock, and Vegetation," U.S.G.S. Pub. TEI 865, June 30, 1965.

²Jackson, M. L., Tyler, S. A., Willis, A. L., Bourbeau, G. A., and Pennington, R. P., "Weathering Sequence of Clay-Size Minerals in Soils and Sediments," Jour. of Physical and Colloidal Chem., Vol. 52, No. 7, 1948.

NOTE: These are general classifications with many exceptions in each class. Percentages are for total land area of world (16.2% perennial ice and snow, continuous permafrost, inland water).

List of Proposed Soils for Testing

Natural Soils

Calcareous Soil

- Possible Sources
1. Ideal Cement Plant, Tijeras Canyon, east of Albuquerque, N. Mex.
 2. Caliche of Upper Mesilla Valley, N. Mex.
- Justification
- Common to arid and semi-arid regions of world. CaO, one of 12 most plentiful oxides of the earth's crust, tends to have very high melting range and will cause gassing.

Coastal Clayey Soil

- Possible Sources
1. N. W. Montgomery County, Texas.
 2. Phoenix Basin, Phoenix, Ariz. (Agr. Exper. Sta., Univ. of Arizona, Tucson).
- Justification
- Typical of well-weathered soils, representative of about 15% of total land area of world. Soil may seal and build gas pressure when saturated.

Magnesian Soil

- Possible Sources
1. West flank of Ladron Mtns., central N. Mex.
 2. Fusselman dolomite, southeast N. Mex.
- Justification
- Representative of soils derived from gabbros, basalts, and dolomites. MgO is one of the 12 most plentiful oxides of the earth's crust.

Granitic Detrital Soil

- Possible Sources
1. McCormick Ranch Dry Lake, south of Albuquerque, N. Mex.
 2. West front of Sandia Mtns., east of Albuquerque, N. Mex.
- Justification
- These soils with a high-alkali feldspar content have a low-melting range. They are typical of many detrital soils, which comprise about a quarter of total land area of world.

Lateritic Soil

- Possible Sources
1. Kauai (Kunuweia series), USDA, SCS, Honolulu
 2. Southeast Asia; through Kirtland Air Force Base, N. Mex.
 3. Lower Bliss Formation, south central N. Mex.
- Justification
- Representative of tropical humid regions of world, comprising more than 10% of total land area of world. FeO and Fe₂O₃ are two of most plentiful oxides of the earth's crust.

Podzol Soil

Possible Sources	1. Bayfield County, Wisc. 2. Animas Valley above Durango, Colo.
Justification	Leached organic soils of woodland regions of temperate zones of world, which comprise about a quarter of total land area of world.

Special Soils

Dune Sand

Possible Sources	1. Rio Salado dunes, north of Socorro, N. Mex. 2. <u>Jornada del Muerto</u> dunes, southeast of Socorro, N. Mex.
Justification	Typical of barchan sand dunes of world, representative of about 7% of total land area of world. Consists largely of siliceous sand, SiO_2 comprising nearly 60% of oxides of the earth's crust.

Playa Salt Soil

Possible Sources	1. Estancia Basin playa (Dog Lake) southeast of Estancia, N. Mex. 2. Willcox playa, south of Willcox, Ariz.
Justification	Typical of very saline bolson playas of the world; most extreme chemical corrosive action upon heating.

Pure Mineral Standard

Ottawa Sand

Possible Source	Commercially available.
Justification	Used as standard material that has been previously investigated.

An investigation of the effect of calcite on a typical granitic soil, Figure 14, shows that the estimated melt temperature of such soil mixtures is not greatly affected unless the soil is more than half calcite, whereas small amounts of sodium salts lower the soil-melt range considerably. Gibbsite and brucite tend to act in a manner similar to calcite.

The soil samples were chosen to represent not only the typical world soils but also the most common oxides which comprise the surface of the earth. The playa soil is one of the most corrosive soils that will be encountered.

Soils are available in New Mexico which are representative of nearly every soil type of the world.

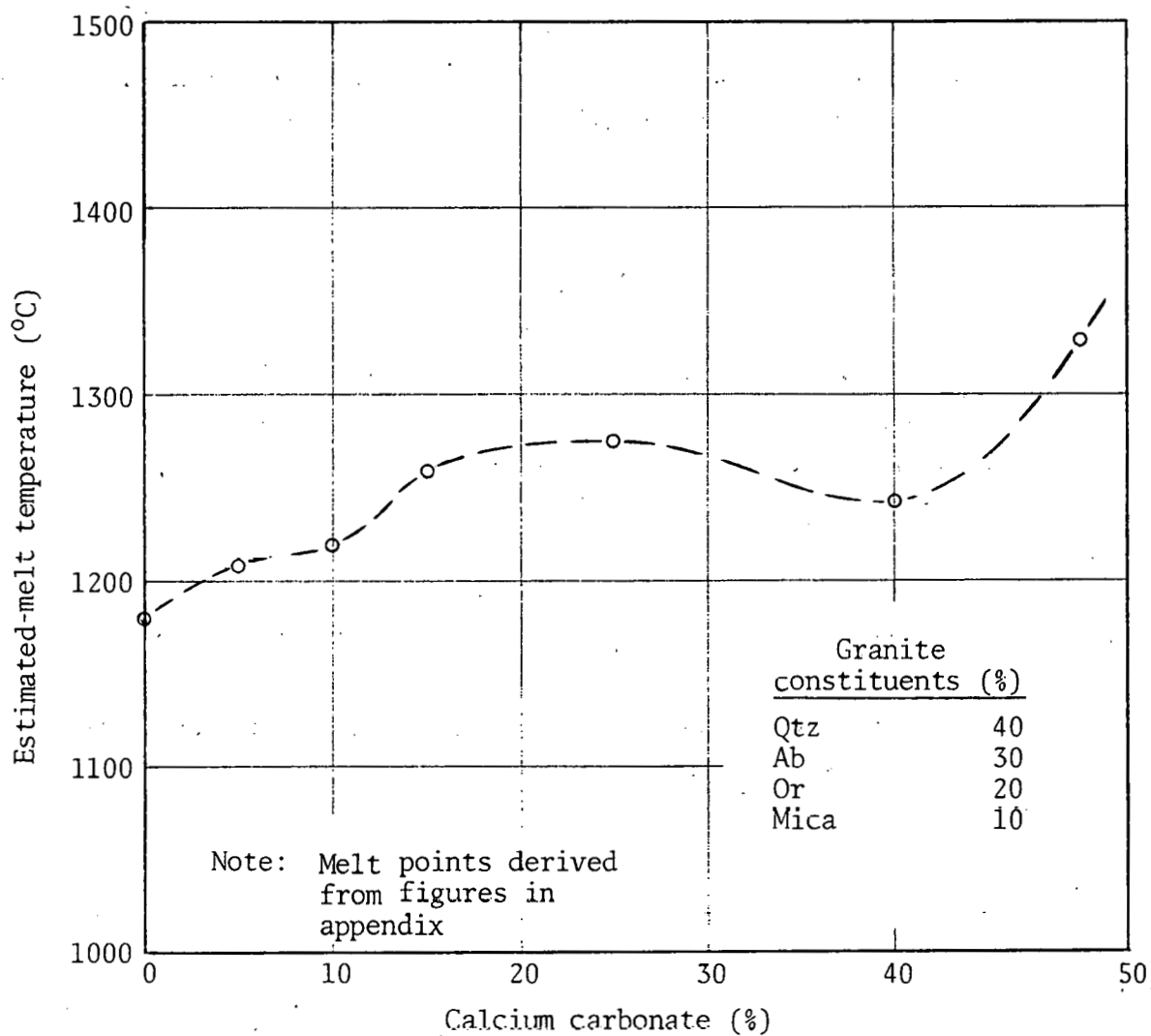


Figure 14. Effect of Calcium Carbonate on Melt Range of Granitic Soil

SECTION III

Soil Mineralogy

Analysis Procedure

The X-ray diffraction analyses of the seventeen soils and mineral assemblages were accomplished by the spectrometric powder technique. The soils were reduced in size to material passing a No. 140 sieve, and the mineral assemblages were reduced in size to material passing a No. 200 sieve.

The powder samples were prepared for analysis in such a manner as to secure random orientation of the sample particles. Random orientation was not achieved with the feldspar sample because of the perfect cleavage habits of pulverized feldspars.

The X-ray powder diffraction data which were used for the analyses of the soil samples were obtained mainly from the ASTM powder diffraction file. Many other data sources were used, including data published by the British Mineralogical Society, the American Mineralogist, the Mineralogical Magazine, and Geochimica et Cosmochimica Acta.

Ten of the diffraction patterns, which were used for mineral analyses, were made with a Siemens X-ray diffractometer; and one diffraction pattern of the feldspar sample was made with a Norelco X-ray diffractometer. Operational arrangements for producing the diffraction patterns were as follows:

THE SIEMENS X-RAY DIFFRACTOMETER

Tube power	35 KV @ 14 ma
Slits	1° source and 0.1° reception
X-ray source	Cu target and Ni filter
Count rate	1 x 10 ⁴ CPM and 2.0% sensitivity
Goniometer rate	2° 2 θ /min
Chart rate	1 cm/min

THE NORELCO X-RAY DIFFRACTOMETER

Tube power	40 KV @ 20 ma
Slits	1° source and 0.08° reception
X-ray source	Cu target and Ni filter
Count rate	500 CPS and TC = 2
Goniometer rate	24 and 96.2° 2 θ /min
Chart rate	K and M, 1 in/min

THE GENERAL ELECTRIC X-RAY DIFFRACTOMETER

Tube power	45 KV @ 10 ma
Slits	1° source and 0.1° reception
X-ray source	Fe target and Mn filter
Count rate	500 CPS and TC = 2
Goniometer rate	2° 2 θ /min
Chart rate	1 in/min

Six additional soil samples were analyzed with the GE X-ray diffractometer; five with a copper target and nickel filter using 35 KV at 23 ma, and one with a chromium target and zirconium oxide filter using 45 KV at 16 ma.

All X-ray diffraction data for quartz is from the Bibliography reference, Brown, 1961.

Summary

Most soils apparently exhibit a melt range that varies between 1250°C and 1850°C, the fat clay soils tending to melt at about 1800°C and the feldspar-rich soils tending to melt at about 1300°C. Soils with a high alumina or lime content tend to have a very high melt range, corundum melting at about 2000°C and calcite at about 2500°C. Soils consisting of detrital granite tend to have a very low melt range of about 1000°C because of the large proportion of potash and soda feldspars normally present in granite.

If the soil is heated in an open-air environment after it has completely melted, the melt consists of a homogeneous mixture of oxides derived from the original constituent minerals. At very high melt ranges, the partial pressure of potash and soda increases; and these oxides tend to sublime at ambient pressures.

List of Soils Tested

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Black Hills Bentonite	46
Diatomaceous Earth	48
Estancia Playa Soil, New Mexico	50
Georgia Kaolinite	52
Hayes, Kansas, Chernozem	54
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Magnesian Soil, New Mexico	58
Granitic Detrital Soil, McCormick Ranch Lake	60
Sodium Bentonite (No. 200 Volclay)	62
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Yellowstone Limestone	66
Calcareous Soil, Tijeras, New Mexico	68
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Rio Salado Dune Sand, Socorro, New Mexico	72
Podzol Soil, Wisconsin	74
Coastal Clayey Soil, Texas	76

ATTAPULGITE

X-ray Diffraction Data

Major peaks observed		Data for attapulgite			Additional constituents			
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	$d\text{\AA}$	I/I_1	hkl	Mineral
14.48	3	--	--	--	14.3	6	001	Chlorite
10.35	10	10.50	10	110				
7.24	2b	--	--	--	7.17	10	002	Chlorite
6.39	3	6.44	6	200				
5.37	1	5.42	5	130				
4.414	3	4.49	8	040				
4.227	3	--	--	--	4.26	3	100	Quartz
4.158	2	4.18	3	310				
4.027	1	--	--	--	4.028	8	20 $\bar{1}$	Andesine
3.637	2b	3.69	5	240	3.640	7	13 $\bar{1}$	Andesine
3.318	3	--	--	--	3.343	10	101	Quartz
3.206	3b	3.23	10	400				
3.195		--	--	--	3.195	10	040	Andesine
3.165		--	--	--	3.169	9	002	Andesine
3.129	2	--	--	--	3.134	7	220	Andesine
3.020	1	3.03	1	420				
2.990	1	--	--	--	2.999	6	13 $\bar{1}$	Andesine
2.873	1	--	--	--	2.867	6	005	Chlorite
2.769	1	2.76	--	350				
2.597	3b	2.61	8	440				
2.56		--	--	--	2.585	3	131	Chlorite
2.53		2.55	3	510	2.528	7	24 $\bar{1}$	Andesine
2.493		--	--	--	2.444	4	132	Chlorite
1.502	1	1.50	5	060				

Note: Peak at about 19 $\text{\AA}$ indicates presence of mixed-layer clay.

ATTAPULGITE (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Attapulgite	80
Quartz	5
Andesine (feldspar)	5
Chlorite	5
Mixed-layer clays	<u>5</u>
	100

Notes: The chlorite 002 peak and the attapulgite 110 peak may obscure kaolinite and vermiculite peaks.

The feldspar suite may include some microcline.

Soil-Melt Range

Estimated: 1400 to 1500°C incongruently

Melt Constituents (given):

	<u>%</u>		<u>%</u>
SiO ₂	68.0	P ₂ O ₅	1.0
Al ₂ O ₃	12.0	K ₂ O	1.0
MgO	10.5	TiO ₂	0.7
Fe ₂ O ₃	5.0	trace	0.1
CaO	1.7		

Note: The X-ray diffraction analysis indicates that Na₂O should be included.

BLACK HILLS BENTONITE

X-ray Diffraction Data

Major peaks observed		Data for montmorillonite			Additional constituents			
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	$d\text{\AA}$	I/I_1	hkl	Mineral
11.6	10	12.4	10	001	10.1	10	001	Biotite
4.438	9b	4.50	10	020	4.50	3	030	Biotite
4.019	2	--	--	--	4.016	8	201	Albite
3.335	6	--	--	--	3.37	10	003	Biotite
					3.343	10	100	Quartz
3.167	2b	--	--	--	3.179	10	040	Albite
					3.16	2	112	Biotite
3.066	1	3.07	2	005				
2.554	3b	2.55	4	201	2.561	6	241	Albite
2.520		--	--	--	2.52	4	004	Biotite
2.447		--	--	--	2.45	8	201	Biotite
2.410		2.41	4	203				
1.540	4	--	--	--	1.541	15	211	Quartz
1.536	4	--	--	--	1.54	8	060	Biotite
1.491	3b	1.50	4	060				

$d\text{\AA}$ Spacing After Treatment

Basal reflection	Oriented slide	Slide @ 325°C	Slide @ 550°C	"Glycolated" slide
001	11.60	9.90	9.80	17.45
002	--	--	--	8.70
003	--	--	--	5.75

BLACK HILLS BENTONITE (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Montmorillonite	80
Biotite (mica)	5
Quartz	5
Albite (feldspar)	5
Trace minerals	<u>5</u>
	100

Soil-Melt Range

Given: Fusion point = 1340°C

Estimated: 1300 to 1450°C incongruently

Melt Constituents (given):

	<u>%</u>		<u>%</u>
SiO_2	64.72	CaO	0.49
Al_2O_3	20.82	MgO	2.38
Fe_2O_3	3.44	Alkalies	2.92
TiO_2	0.14	Ignition loss	4.84

Note: The X-ray diffraction analysis indicates that the alkalies are predominantly Na_2O .

DIATOMACEOUS EARTH

X-ray Diffraction Data

Major peaks observed		Data for cristobalite			Additional constituents			
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	$d\text{\AA}$	I/I_1	hkl	Mineral
14.0	2b	--	--	--	Random mixed-layer clays			
4.04	10+	4.05	10	101				
3.32	1	--	--	--	3.343	10	101	Quartz
3.135	2	3.125	1	111				
2.838	1	2.841	1	102				
2.476	3	2.485	2	200				
2.030	1	2.019	1/2	202				
1.936	1/2b	1.929	1/2	113				
1.875	1/2b	1.870	1/2	212				
1.614	1/2	1.612	1/2	301				
1.543	1/2	1.533	1/2	311				
1.502	1/2	1.494	1/2	302				

Note: There appear to be some trace materials, but the paucity of diffraction peaks renders identification impossible.

DIATOMACEOUS EARTH (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Cristobalite	90
Random mixed-layer clays	5
Quartz	3
Trace minerals	<u>2</u>
	100

Soil-Melt Range

Estimated: 1700 to 1725°C congruently

Melt Constituents (estimated):

	<u>%</u>
SiO ₂	95+
Al ₂ O ₃	2
trace	3

ESTANCIA PLAYA SOIL (South End)

X-ray Diffraction Data

Major peaks observed		X-ray powder diffraction data			Predominant constituent
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	
7.56	10+	7.56	10	020	Gypsum
4.48	2	4.48	6	110	Mica-illite
4.26	2	4.26	4	100	Quartz
3.798	3	3.79	2	040	Gypsum
3.348	3	3.343	10	101	Quartz
3.246	1	3.258	1	111	Halite
3.195	1	3.198	10	20 $\bar{2}$	Oligoclase
3.030	5	3.035	10	104	Calcite
2.891	3	2.886	10	104	Dolomite
2.873	3	2.867	3	002	Gypsum
2.824	5	2.821	10	200	Halite
2.569	1	2.56	9	20 $\bar{2}$	Mica-illite
2.486	1	2.495	2	110	Calcite
2.279	2	2.285	2	113	Calcite
2.199	1	2.192	3	113	Dolomite
2.092	2	2.095	2	202	Calcite
1.994	4	1.994	6	220	Halite
1.910	2	1.913	2	108	Calcite
1.875	2	1.875	2	116	Calcite
1.821	1	1.817	2	112	Quartz
1.799	1	1.804	2	108	Dolomite
1.776	1	1.781	3	009	Dolomite
1.627	2	1.621	1	20 $\bar{4}$	Gypsum

ESTANCIA PLAYA SOIL (New Mexico)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Gypsum	31.5
Calcite	13.0
Dolomite	24.5
Quartz	7.5
Feldspar	5.0
Halite	7.5
Clays	5.0
Trace minerals	<u>6.0</u>
	100.0

Soil-Melt Range

Estimated: 1350 to 1400°C incongruently

Melt Constituents (estimated):

	<u>%</u>
CaSO ₄	41.6
CaO	24.3
MgO	8.1
SiO ₂	8.7
Na ₂ O	0.6
NaCl	11.3
Al ₂ O ₃	4.5
K ₂ O	<u>0.9</u>
	100.0

Note: The feldspar appears to be oligoclase.

GEORGIA KAOLINITE

X-ray Diffraction Data

Major peaks observed		Data for kaolinite			Additional constituents			
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	$d\text{\AA}$	I/I_1	hkl	Mineral
9.88	1	--	--	--	9.99	8	002	Muscovite
7.10	10	7.10	10+	001				
4.436	2	4.46	4	020	4.47	10	110	Muscovite
4.350	2	4.36	5	$\bar{1}\bar{1}0$				
4.149	2	4.18	5	$\bar{1}\bar{1}1$				
4.111	2	4.13	3	$\bar{1}\bar{1}\bar{1}$				
3.847	1	3.845	4	021				
3.728	1	3.741	2	021	3.72	6	023	Muscovite
3.705	1							
3.559	8	3.573	10+	002				
3.386	1	3.386	4	111				
3.324	2				3.32	10	006	Muscovite
1.538	< 1b	1.542	5b	$\bar{1}\bar{3}\bar{4}$				
1.485	1b	1.489	8	060	1.504	8	060	Muscovite

Notes: Mineral not scanned from 30 to 60° 2 θ .

Muscovite may be illitic.

GEORGIA KAOLINITE (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Kaolinite	95
Muscovite	<u>5</u>
	100

Soil-Melt Range

Given: 1785°C (pure kaolinite)

Estimated: 1700 to 1750°C

Melt Constituents (estimated):

	<u>%</u>
SiO ₂	54
Al ₂ O ₃	46
K ₂ O	trace

HAYES, KANSAS, CHERNOZEM

X-ray Diffraction Data

Major peaks observed		X-ray powder diffraction data			Predominant constituent
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	
14.24	2	15.4	10	001	Montmorillonite
10.16	1	10.0	8	001	Muscovite-illite
7.22	1	7.16	10	001	Kaolinite
4.436	2b	4.44	4	020	Clay minerals
4.247	3	4.26	3	100	Quartz
3.751	1	3.754	7	111	Oligoclase
3.645	1	3.651	6	13 $\bar{1}$	Oligoclase
3.330	10+	3.343	10	101	Quartz
3.235	3	3.240	10	040	Microcline
3.184	3	3.176	10	040	Oligoclase
2.580	1b	2.568	2	112	Microcline
2.540		2.545	6	24 $\bar{1}$	Oligoclase
2.520		2.530	3	240	Microcline
2.453	2	2.458	1	110	Quartz
2.276	1	2.282	1	102	Quartz
2.236	1	2.236	1	111	Quartz
2.122	2	2.128	1	200	Quartz
1.975	2	1.980	1	201	Quartz
1.818	2	1.817	2	112	Quartz
1.668	1	1.672	1	202	Quartz
1.538	2	1.541	2	211	Quartz
1.507	>1b	1.504	4	060	Muscovite-illite
1.491	>1b	1.489	8	060	Kaolinite

Notes: Trace minerals appear to include organics, amphiboles, iron oxides, chlorite, and calcite.

The 1.51 (060) peaks indicate trioctahedral and the 1.49 (060) peaks indicate dioctahedral clay lattice structures.

HAYES, KANSAS, CHERNOZEM (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Quartz	50
Oligoclase	10
Microcline	10
Montmorillonite	5
Muscovite-illite	5
Kaolinite	5
Mixed-layer clays	5
Trace minerals	<u>10</u>
	100

Soil-Melt Range

Estimated: 1250 to 1500°C incongruently

Melt Constituents (estimated):

	<u>%</u>
SiO ₂	79.7
Al ₂ O ₃	14.4
Na ₂ O	0.9
K ₂ O	2.3
MgO	2.3
CaO	0.4

HEMATITE

X-ray Diffraction Data

Major peaks observed		Data for hematite			Additional constituents			
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	$d\text{\AA}$	I/I_1	hkl	Mineral
7.90	1	--	--	--	7.91	< 1	101	Maghemite
7.15	4	--	--	--	7.16	10+	001	Kaolinite
3.683	4	3.66	3	012	3.73	< 1	210	Maghemite
3.575	2	--	--	--	3.573	10+	002	Kaolinite
2.970	2	--	--	--	2.95	3	220	Maghemite
2.777	1	--	--	--	2.78	2	221	Maghemite
2.700	10	2.69	10	104				
2.529	1	--	--	--	2.52	10	311	Maghemite
2.516	8	2.51	5	110				
2.206	3	2.201	3	113				
1.840	4	1.838	4	024				
1.694	4	1.690	6	116	1.70	1	422	Maghemite
1.599	1b	1.596	2	018	1.61	3	104	Maghemite
1.485	3	1.484	4	214	1.48	5	440	Maghemite
1.452	3	1.452	4	300				

Notes: Maghemite is $\gamma\text{-Fe}_2\text{O}_3$

The hematite contains other impurities besides kaolinite, indicated by small trace reflections at $4.06\text{\AA}$ and $2.44\text{\AA}$.

HEMATITE (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Hematite	70
Maghemite	15
Kaolinite	12
Trace minerals	<u>3</u>
	100

Soil-Melt Range

Estimated: 1525 to 1575°C congruently

Melt Constituents (estimated):

	<u>%</u>
Fe ₂ O ₃	85
Al ₂ O ₃	6
SiO ₂	6
trace	3

MAGNESIAN SOIL, NEW MEXICO

X-ray Diffraction Data

<u>Major peaks observed</u>		<u>X-ray powder diffraction data</u>			<u>Predominant constituent</u>
<u>dÅ</u>	<u>I/I₁</u>	<u>dÅ</u>	<u>I/I₁</u>	<u>hkl</u>	
14.02	10	14.3	6	001	Penninite
9.30	5	9.30	7	002	Talc
7.13	2	7.18	10	002	Penninite
4.766	1	4.79	10	003	Penninite
4.655	1	4.65	1	004	Talc
4.548	1	4.57	8	020	Talc
4.480	1	4.47	9	110	Muscovite
4.019	1	4.018	8	20 $\bar{1}$	Oligoclase
3.864	1	3.851	5	1 $\bar{1}$ 1	Oligoclase
3.751	1	3.754	7	111	Oligoclase
3.580	2	3.592	10	004	Penninite
3.463	1	3.481	5	11 $\bar{2}$	Oligoclase
3.354	1	3.355	5	1 $\bar{1}$ 2	Oligoclase
3.173	6	3.176	10	040	Oligoclase
3.108	4	3.10	7	006	Talc
3.020	2	3.035	10	104	Calcite
2.924	2	2.927	7	04 $\bar{1}$	Oligoclase
2.860	2	2.873	6	005	Penninite
2.473	1	2.48	10	132	Talc
1.527	1	1.52	7	060	Talc

MAGNESIAN SOIL (New Mexico) (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Talc	35
Penninite	30
Oligoclase	25
Calcite	5
Trace minerals	<u>5</u>
	100

Soil-Melt Range

Estimated: 1350 to 1435°C incongruently

Melt Constituents (estimated):

	<u>%</u>
SiO ₂	55.1
Al ₂ O ₃	12.2
MgO	27.0
CaO	3.4
Na ₂ O	<u>2.3</u>
	100.0

GRANITIC DETRITAL SOIL, McCORMICK RANCH LAKE (HEST site 4 at 20 to 25 feet depth)

X-ray Diffraction Data

<u>Major peaks observed</u>		<u>X-ray power diffraction data</u>			<u>Predominant constituent</u>
<u>dÅ</u>	<u>I/I₁</u>	<u>dÅ</u>	<u>I/I₁</u>	<u>hkl</u>	
14.5	2b	15.4	10	001	Montmorillonite
10.0	>1b	10.0	8	001	Muscovite
7.1	>1b	7.1	9	002	Chlorite
4.236	3	4.26	3	100	Quartz
3.330	10+	3.343	10	101	Quartz
3.235	3	3.240	10	040	Microcline
3.167	4	3.179	10	040	Albite
3.020	3	3.035	10	104	Calcite
2.482	1	2.495	1	110	Calcite
2.445	1	2.458	1	110	Quartz
2.276	1	2.282	2	102	Quartz
2.225	1	2.237	1	111	Quartz
2.120	1	2.128	1	200	Quartz
2.085	1	2.095	2	202	Calcite
1.975	1	1.980	1	201	Quartz
1.905	>1	1.913	2	108	Calcite
1.868	1	1.875	2	116	Calcite
1.812	2	1.817	2	112	Quartz
1.537	2	1.541	2	211	Quartz

GRANITIC DETRITAL SOIL, McCORMICK RANCH LAKE (HEST site 4 at 20 to 25 feet depth)
(continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Quartz	45
Albite	20
Microcline	10
Calcite	6
Montmorillonite	7
Illite-mica	3
Chlorite	3
Mixed-layer clays	4
Trace minerals	<u>2</u>
	100

Soil-Melt Range

Estimated: 1200 to 1320°C incongruently

Melt Constituents (estimated):

	<u>%</u>		<u>%</u>
SiO ₂	76.1	K ₂ O	2.3
Al ₂ O ₃	11.9	MgO	2.3
CaO	5.0		
Na ₂ O	2.4		

SODIUM BENTONITE (No. 200 Volclay)

X-Ray Diffraction Data

Major peaks observed		Data montmorillonite			Additional constituents			
<u>dÅ</u>	<u>I/I₁</u>	<u>dÅ</u>	<u>I/I₁</u>	<u>hkl</u>	<u>dÅ</u>	<u>I/I₁</u>	<u>hkl</u>	<u>mineral</u>
11.55	10b	12.4	10	001				
7.56	1	--	--	--	7.56	10	020	Gypsum
4.436	8b	4.50	10	020				
3.705	1	--	--	--	3.68	6	130	Oligoclase
3.336	5b	--	--	--	{ 3.33	9	220	Orthoclase
					{ 3.34	10	101	Quartz
3.218	2	--	--	--	3.22	10	002	Orthoclase
3.184	2	--	--	--	3.18	10	040	Oligoclase
3.111	5b	3.07	2	005				
2.996	1	--	--	--	2.99	8	131	Orthoclase
2.942	1	--	--	--	2.93	7	041	Oligoclase
2.891	1	--	--	--	2.89	1	022	Orthoclase
2.540	2b	2.55	4	201				
2.506		--	--	--	2.51	1	112	Oligoclase
2.479	3	--	--	--	2.47	3	241	Oligoclase
1.493	2	1.491	4	060				

Notes: Mineral not scanned from 40 to 60° 2θ.

Montmorillonite partially dehydrated.

SODIUM BENTONITE (No. 200 Volclay) (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Montmorillonite	80
Quartz	5
Orthoclase (feldspar)	4
Oligoclase (feldspar)	3
Gypsum	3
Trace minerals	<u>5</u>
	100

Soil-Melt Range

Estimated: 1600 to 1650°C

Melt Constituents (estimated):

	<u>%</u>
SiO ₂	70.0
Al ₂ O ₃	25.0
MgO	2.5
Na ₂ O	0.5
CaO	1.5
K ₂ O	0.5

WYOMING FELDSPAR (Perthite)

X-Ray Diffraction Data

Major peaks observed		Data for microcline			Data for oligoclase		
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	$d\text{\AA}$	I/I_1	hkl
6.46	2	6.47	2	020			
6.37	1	--	--	--	6.37	6	001
4.217	1	4.22	6	20 $\bar{1}$			
3.839	1	3.835	5	130			
3.775	1	--	--	--	3.754	7	111
3.705	1	3.701	4	1 $\bar{3}$ 0			
3.653	1	--	--	--	3.651	6	13 $\bar{1}$
3.587	1	3.577	2	1 $\bar{3}$ 1			
3.470	2	3.475	5	2 $\bar{2}$ 1	3.481	5	11 $\bar{2}$
3.367	2	3.370	5	220	3.355	5	1 $\bar{1}$ 2
3.281	2	3.287	4	20 $\bar{2}$			
3.241	10+	3.241	10	040			
3.190	5	--	--	--	3.176	10	040
3.020	1	3.023	4	131			
2.950	1	2.962	5	22 $\bar{2}$			
2.896	1	2.895	5	1 $\bar{3}$ 1			
2.157	2	2.158	5	060			
1.803	1	1.804	3	062	1.804	2	113

Note: Feldspar powder samples tend to assume a strongly preferred orientation.

WYOMING FELDSPAR (Perthite) (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Microcline	75
Oligoclase	<u>25</u>
	100

Soil-Melt Range

Estimated: As Feldspars - 1325 to 1350°C
 As Oxides - 1300 to 1350°C

Representative Melt Constituents (given):

	<u>%</u>
SiO ₂	68.3
Al ₂ O ₃	17.5
Na ₂ O	3.0
K ₂ O	10.4
CaO	0.7
Fe ₂ O ₃	0.1

YELLOWSTONE LIMESTONE

X-Ray Diffraction Data

Major peaks observed		Data for albite			Additional constituents			
<u>dÅ</u>	<u>I/I₁</u>	<u>dÅ</u>	<u>I/I₁</u>	<u>hkl</u>	<u>dÅ</u>	<u>I/I₁</u>	<u>hkl</u>	<u>Mineral</u>
6.40	>1	6.38	5	001				
4.25	1	--	--	--	4.24	8	20 $\bar{1}$	Orthoclase
4.19	1b	--	--	--	4.18	7	111	Nepheline
4.028	5	4.016	8	20 $\bar{1}$	4.05	10+	101	Cristobalite
3.914	1	--	--	--	3.94	3	111	Orthoclase
3.767	2	3.767	7	111	3.78	10	130	Orthoclase
3.660	1	3.660	8	13 $\bar{1}$				
3.601	1	--	--	--	3.62	4	13 $\bar{1}$	Orthoclase
3.437	1	--	--	--	3.46	8	11 $\bar{2}$	Orthoclase
3.336	1	--	--	--	3.33	9	220	Orthoclase
3.300	1	--	--	--	3.29	9	20 $\bar{2}$	Orthoclase
3.264	1	--	--	--	3.27	7	210	Nepheline
3.200	10+	3.193	10	20 $\bar{2}$	3.22	10	002	Orthoclase
2.971	1	2.952	7	1 $\bar{3}$ 1	2.99	8	131	Orthoclase
2.910	1	2.919	6	0 $\bar{4}$ 1	2.91	2	041	Orthoclase
2.882	1	2.856	6	131	2.88	7	300	Nepheline
2.829	1	--	--	--	2.841	1	102	Cristobalite
2.565	>1	2.561	6	24 $\bar{1}$	2.58	6	24 $\bar{1}$	Orthoclase
2.509	>1	2.509	3	1 $\bar{1}$ 2				
2.473	1	--	--	--	2.485	2	200	Cristobalite

Note: The orthoclase lattice structure appears to be somewhat distorted by some substitution of Na⁺ for K⁺ (anorthoclase).

YELLOWSTONE LIMESTONE (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Albite	60
Cristobalite	25
Orthoclase	8
Nepheline	5
Trace minerals	<u>2</u>
	100

Soil-Melt Range

Estimated: 1100 to 1150°C

Melt Constituents (estimated):

	<u>%</u>
SiO ₂	74.8
Al ₂ O ₃	15.3
Na ₂ O	8.2
K ₂ O	1.7

CALCAREOUS SOIL, TIJERAS, NEW MEXICO

X-ray Diffraction Data

<u>Major peaks observed</u>		<u>X-ray powder diffraction data</u>			<u>Predominant constituent</u>
<u>dÅ</u>	<u>I/I₁</u>	<u>dÅ</u>	<u>I/I₁</u>	<u>hkl</u>	
10.04	< 1	10.01	10	002	Muscovite
4.25	1	4.26	4	100	Quartz
4.037	< 1	4.018	8	20 $\bar{1}$	Oligoclase
3.839	2	3.86	1	102	Calcite
3.690	< 1	3.678	6	1 $\bar{3}$ 0	Oligoclase
3.504	< 1	3.481	5	11 $\bar{2}$	Oligoclase
3.348	2	3.345	10	101	Quartz
3.184	< 1	3.176	10	040	Oligoclase
3.03	10+	3.035	10	104	Calcite
2.838	1	2.845	> 1	006	Calcite
2.489	3	2.495	1	110	Calcite
2.460	< 1	2.458	1	110	Quartz
2.282	4	2.285	2	113	Calcite

Note: Some smectite clays present, indicated by small peaks appearing at 11.8 and 12.4 Å 'd' spacings.

CALCAREOUS SOIL (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Calcite	75
Montmorillonite	8
Quartz	8
Dolomite	3
Muscovite-illite	2
Goethite	1
Oligoclase	1
Trace minerals	<u>2</u>
	100

Soil-Melt Range

Estimated: 1950 to 2050°C

Melt constituents (given):

	<u>%</u>
SiO ₂	15.0
Al ₂ O ₃	2.5
Fe ₂ O ₃	1.0
MgO	0.7
SO ₃	0.1
Na ₂ O	0.05
K ₂ O	0.1
CaO	43.0

Note: Portland clinker is burned at a temperature range of 1350 to 1450°C
(grind size 50 to 90μ).

LATERITIC SOIL (Hawaii)

X-ray Diffraction Data

<u>Major peaks observed</u>		<u>X-ray powder diffraction data</u>			<u>Predominant constituent</u>
<u>dÅ</u>	<u>I/I₁</u>	<u>dÅ</u>	<u>I/I₁</u>	<u>hkl</u>	
4.843	10	4.85	10	020	Gibbsite
4.350	2	4.37	4	021	Gibbsite
4.325	1	4.31	2	041	Gibbsite
4.153	1b	4.18	10	110	Goethite
2.548	1	2.546	7	110	Ilmenite
2.517	1	2.514	10	313	Maghemite
2.450	2b	2.451	2	151	Gibbsite
2.420	1	2.422	1/2	080	Gibbsite
2.382	1	2.382	3	132	Gibbsite
2.236	1	2.244	1/2	220	Gibbsite
2.157	1	2.165	1	171	Gibbsite
2.042	1	2.042	2	241	Gibbsite
1.991	1	1.991	1	082	Gibbsite
1.802	1	1.801	1	222	Gibbsite

Notes: A Cr target was used with a ZrO filter, 45 KV/16 ma.

The goethite was very poorly crystallized; the equivalent Fe_2O_3 content was determined by chemical analysis.

LATERITIC SOIL (Hawaii) (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Goethite	55
Gibbsite	30
Magnetite	5
Maghemite	5
Ilmenite	<u>5</u>
	100

Soil-Melt Range

Estimated: 1900 to 1950°C

Melt Constituents (estimated):

	<u>%</u>
Al ₂ O ₃	20
Fe ₂ O ₃	70
TiO ₂	5
Trace oxides	<u>5</u>
	100

RIO SALADO DUNE SAND

X-Ray Diffraction Data

Major peaks observed		X-ray powder diffraction data			Predominant constituent
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	
6.43	1	6.37	6	001	Oligoclase
4.257	3	4.26	4	101	Quartz
4.037	1	4.018	8	20 $\bar{1}$	Oligoclase
3.758	2	3.754	7	111	Oligoclase
3.698	1	3.701	4	1 $\bar{3}$ 0	Microcline
3.34	10+	3.343	10	101	Quartz
3.241	3	3.240	10	040	Microcline
3.200	4	3.198	8	20 $\bar{2}$	Oligoclase
3.184	4	3.176	10	040	Oligoclase
3.020	2	3.037	4	131	Microcline
2.938	1	2.927	7	0 $\bar{4}$ 1	Oligoclase
2.456	3	2.458	1	110	Quartz
2.276	2	2.282	1	102	Quartz
2.233	1	2.237	<1	111	Quartz
2.125	2	2.128	1	200	Quartz
1.980	1	1.980	<1	201	Quartz
1.819	3	1.817	2	112	Quartz
1.671	2	1.672	1	202	Quartz
1.541	3	1.541	2	211	Quartz
1.454	1	1.453	<1	113	Quartz

Note: Small diffraction peaks at 3.02, 2.56, 2.51, 2.19 $\text{\AA}$ 'd' spacings indicate the presence of a clinopyroxene.

RIO SALADO DUNE SAND (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Quartz	60
Oligoclase	25
Microcline	10
Clinopyroxene	<u>5</u>
	100

Soil-Melt Range

Estimated: 1300 to 1450°C incongruently

Melt constituents (estimated):

	<u>%</u>
SiO ₂	86.1
Na ₂ O	2.3
K ₂ O	1.7
CaO	0.9
MgO	2.4
Al ₂ O ₃	6.6

PODZOLIC SOIL (Wisconsin)

X-Ray Diffraction Data

Major peaks observed		X-ray powder diffraction data			Predominant constituent
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	
14.24	2	14.1	5	001	Chlorite
7.08	1/2	7.08	10	002	Chlorite
6.46	1/2	6.47	2	020	Microcline
4.26	8	4.26	4	100	Quartz
4.037	1/2	4.02	8	20 $\bar{1}$	Albite
3.774	1/2	3.767	7	111	Albite
3.463	1	3.475	5	$\bar{2}21$	Microcline
3.345	10+	3.343	10	101	Quartz
3.241	7	3.240	10	040	Microcline
3.184	4	3.179	10	040	Albite
2.554	1b	2.54	9	201	Chlorite
2.453	4	2.458	1	110	Quartz
2.282	2	2.282	1	102	Quartz
2.241	1	2.237	1/2	111	Quartz
2.125	2	2.128	1	200	Quartz
1.980	2	1.980	1/2	201	Quartz
1.816	4	1.817	2	112	Quartz
1.668	2	1.672	1/2	202	Quartz
1.538	6	1.541	2	211	Quartz

Notes: The chlorite may be clinocllore.

The feldspar may be oligoclase.

PODZOLIC SOIL (Wisconsin) (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Quartz	60
Microcline	15
Albite	10
Chlorite	5
Hornblende	5
Trace Minerals	<u>5</u>
	100

Soil-Melt Range

Estimated: 1350 to 1450°C incongruently

Melt Constituents (estimated):

	<u>%</u>
SiO ₂	84.1
Al ₂ O ₃	8.0
K ₂ O	2.5
Na ₂ O	0.9
MgO	3.4
CaO	<u>1.1</u>
	100.0

COASTAL CLAYEY SOIL (Texas)

X-ray Diffraction Data

Major peaks observed		X-ray powder diffraction data			Predominant constituent
$d\text{\AA}$	I/I_1	$d\text{\AA}$	I/I_1	hkl	
15.4	3b	15.4	10	001	Montmorillonite
7.25	2h	7.18	10	001	Kaolinite
4.46	3	4.18	0	020	Kaolinite
4.26	8	4.26	4	100	Quartz
3.559	2b	3.573	10	002	Kaolinite
3.345	10+	3.343	10	101	Quartz
2.562	3b	2.565	8	20 $\bar{1}$	Kaolinite
2.460	4	2.458	1	110	Quartz
2.279	2	2.282	1	102	Quartz
2.234	1	2.237	1/2	111	Quartz
2.125	2	2.128	1	200	Quartz
1.980	1	1.980	1/2	201	Quartz
1.819	5	1.817	2	112	Quartz
1.671	1b	1.672	1/2	202	Quartz
1.541	3	1.541	2	211	Quartz
1.500	1b	1.503	6	060	Montmorillonite
1.490	1b	1.489	8	060	Kaolinite

COASTAL CLAYEY SOIL (Texas) (continued)

<u>Soil constituents</u>	<u>Estimated amount (%)</u>
Quartz	45
Kaolinite	25
Montmorillonite	25
Trace Minerals	<u>5</u>
	100

Soil-Melt Range

Estimated: 1600 to 1620°C

Melt Constituents (estimated):

	<u>%</u>
SiO ₂	78.5
Al ₂ O ₃	20.0
MgO	0.5

APPENDIX

Ternary Phase Diagrams

<u>System</u>	<u>Page</u>	<u>Figure</u>	<u>Page</u>
CaO-Al ₂ O ₃ -SiO ₂	80	630	219*
FeO-Al ₂ O ₃ -SiO ₂	81	696	241*
Fe ₃ O ₄ -Al ₂ O ₃ -SiO ₂	82	100	118†
K ₂ O-Al ₂ O ₃ -SiO ₂	83	407	156*
MgO-Al ₂ O ₃ -SiO ₂	84	712	246*
Na ₂ O-Al ₂ O ₃ -SiO ₂	85	501	181*
TiO ₂ -Al ₂ O ₃ -SiO ₂	86	85	100†
CaO-FeO-SiO ₂	87	586	204*
CaO-Fe ₂ O ₃ -SiO ₂	88	656	228*
CaO-MgO-SiO ₂	89	598	210*
CaO-MgO-SiO ₂ (10% Al ₂ O ₃)..	90	112	131†
CaO-MgO-SiO ₂ (20% Al ₂ O ₃)..	91	114	133†
MgO-FeO-SiO ₂	92	682	236*
MgO-Fe ₃ O ₄ -SiO ₂	93	94	112†

* Reprinted by permission from E. M. Levin, C. R. Robbins, and H. F. McMurdie, Phase Diagrams for Ceramists (1964). The American Ceramic Society, Columbus, Ohio.

† Reprinted by permission from A. Muan and E. F. Osborn, Phase Equilibria Among Oxides in Steel Making, 1965.

CaO-Al₂O₃-SiO₂

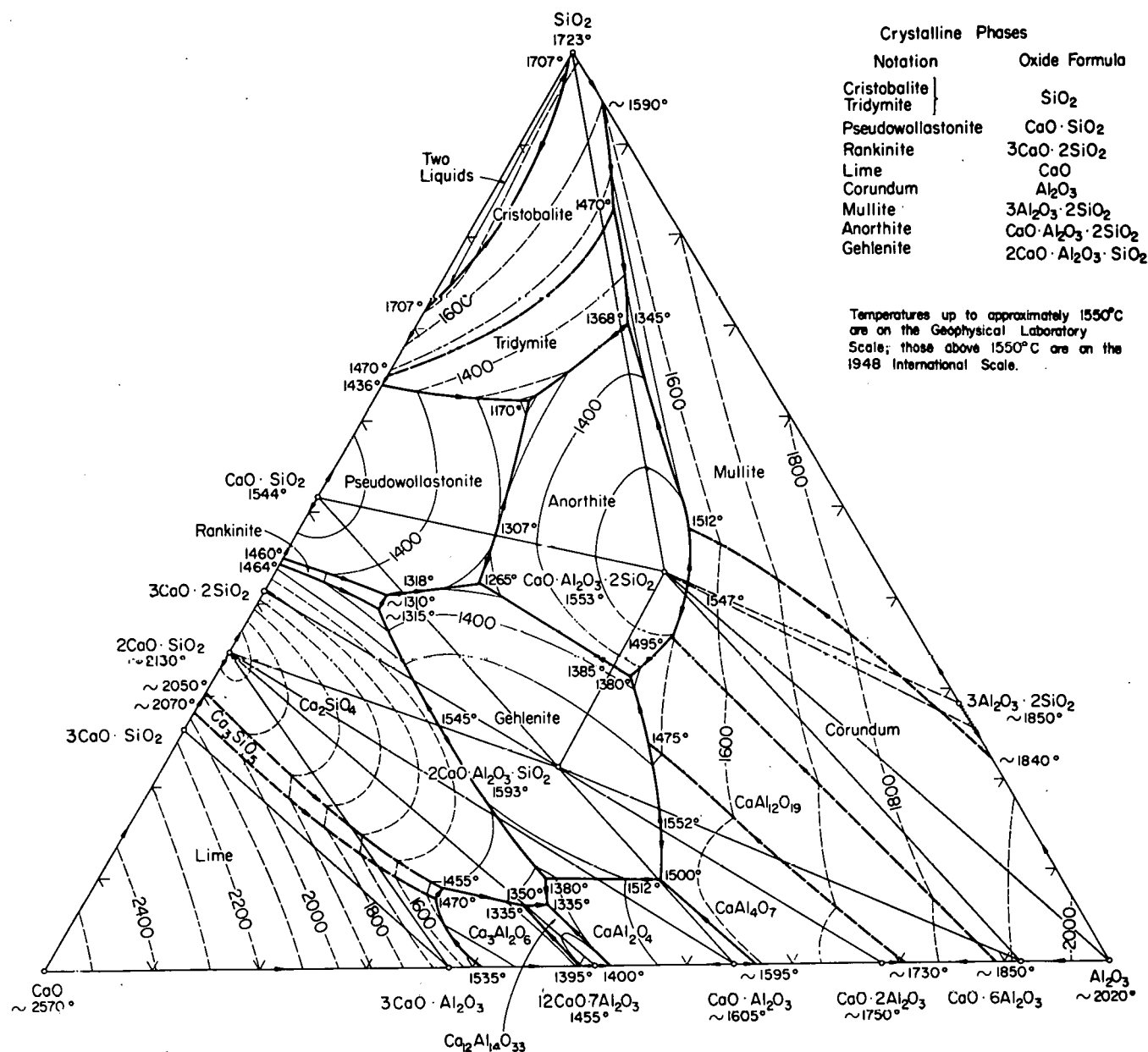


FIG. 630.—System CaO-Al₂O₃-SiO₂; composite.

E. F. Osborn and Arnulf Muan, revised and redrawn "Phase Equilibrium Diagrams of Oxide Systems," Plate 1, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

FeO-Al₂O₃-SiO₂

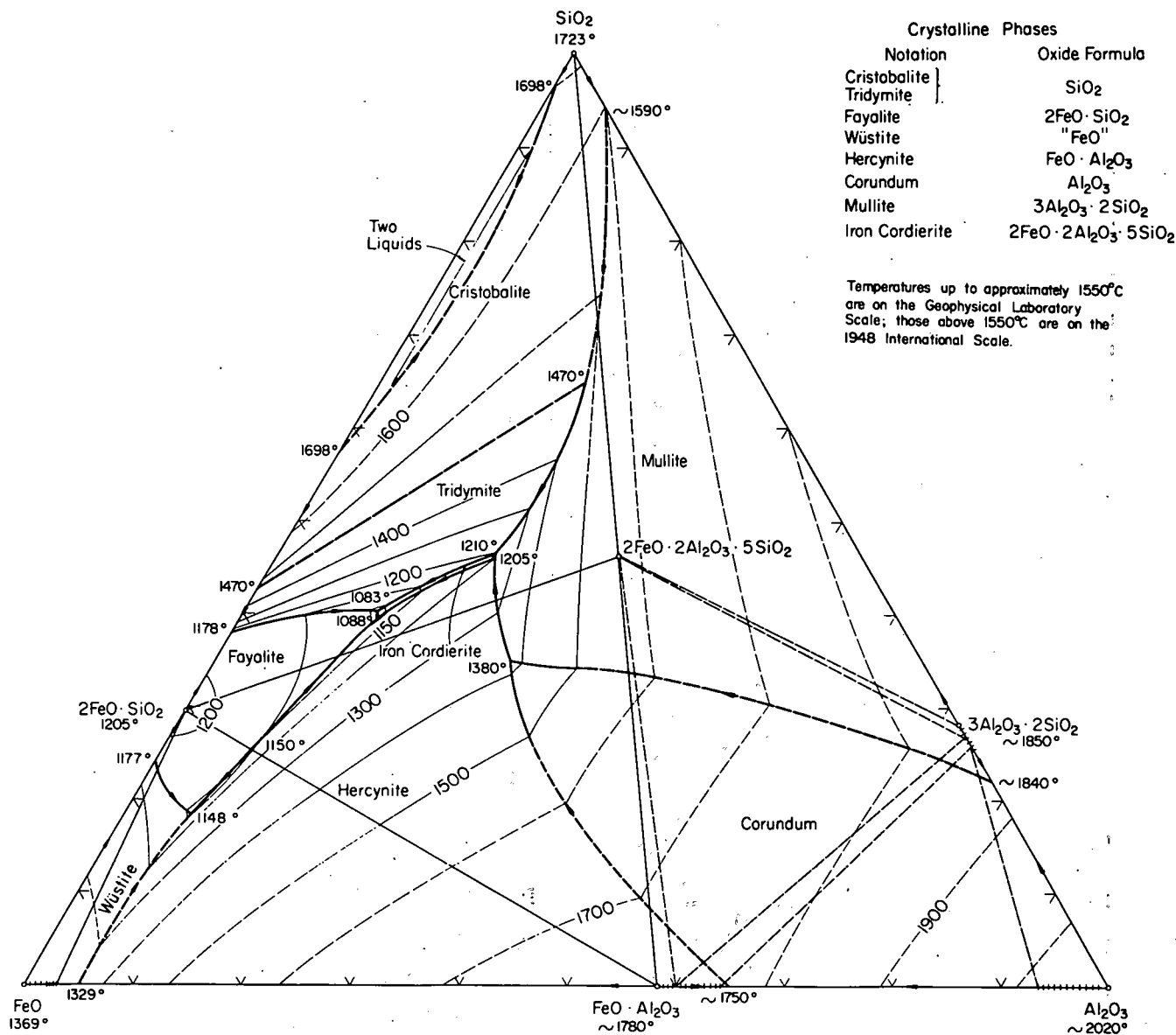


FIG. 696.—System "FeO"-Al₂O₃-SiO₂; composite. (Oxide Phases in Equilibrium with Metallic Iron).

E. F. Osborn and Arnulf Muan, revised and redrawn "Phase Equilibrium Diagrams of Oxide Systems," Plate 9, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

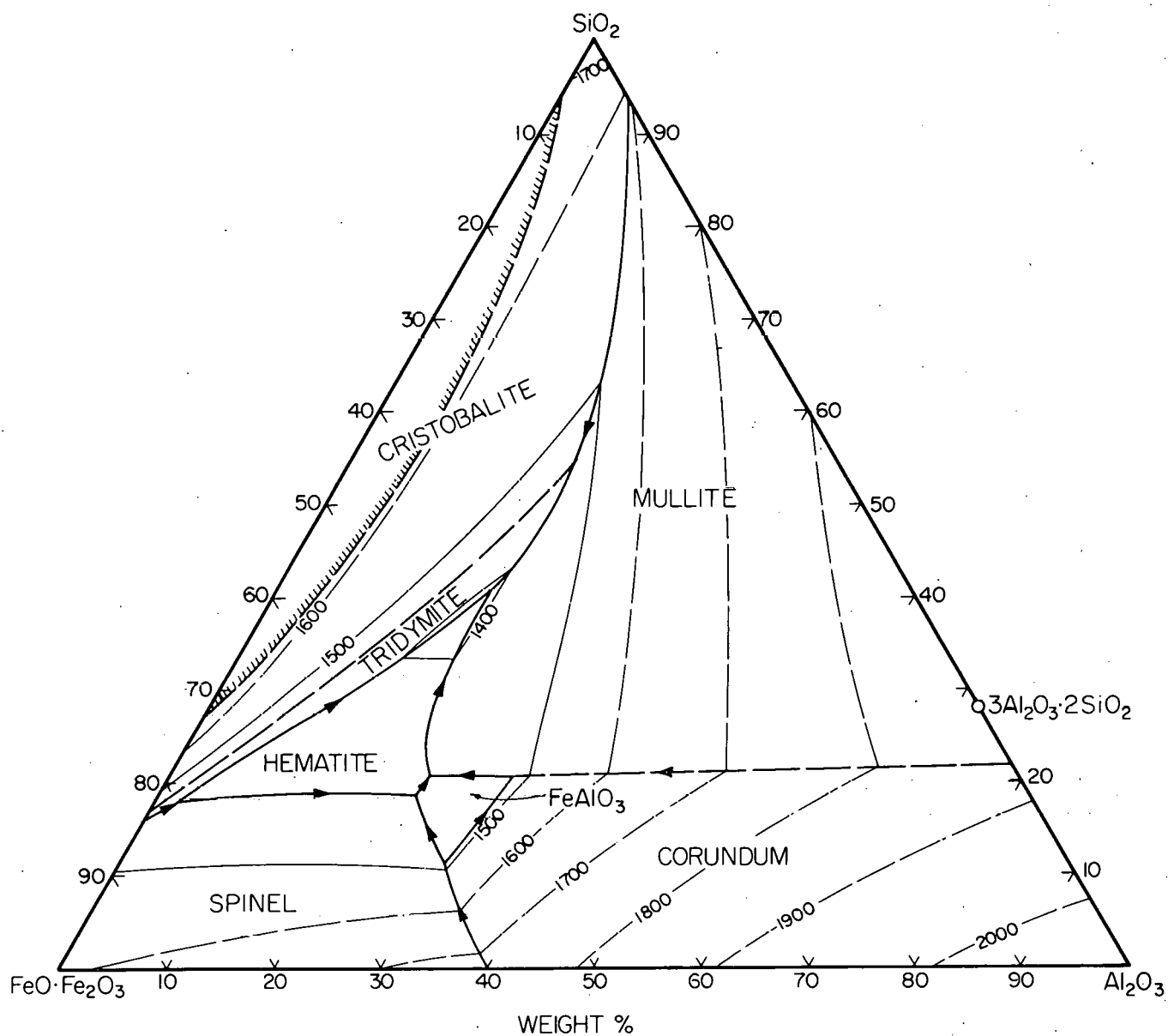


Fig. 100. Diagram showing phase relations at liquidus temperatures in the system iron oxide- Al_2O_3 - SiO_2 at 1 atm O_2 pressure, based mainly on data of Muan,⁽²⁷⁹⁾ with minor changes based on recent data for the system Al_2O_3 - SiO_2 .^(132,134) The system is not ternary. The method of projection is identical to that used in Fig. 94.

K₂O-Al₂O₃-SiO₂

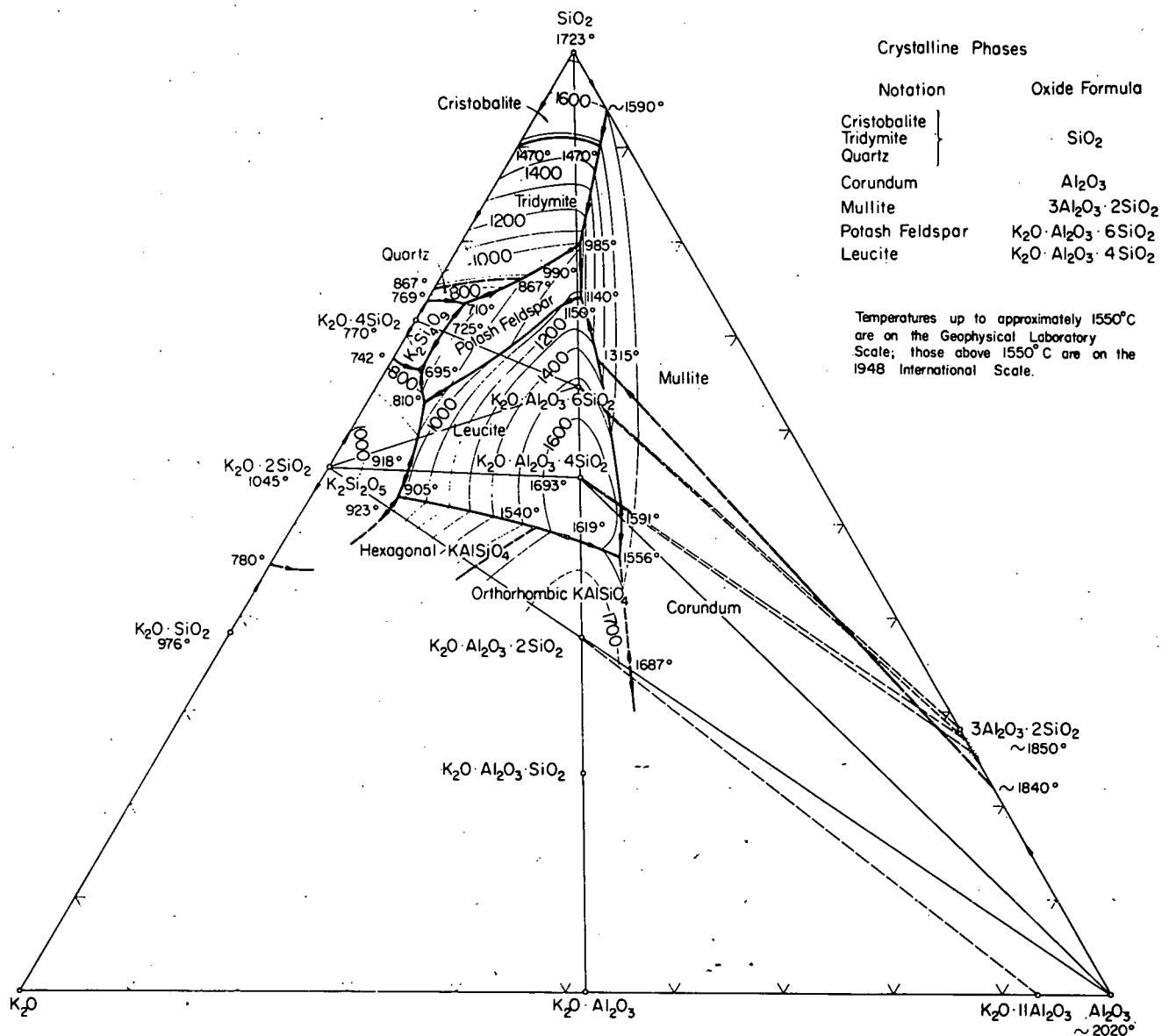


FIG. 407.—System K₂O-Al₂O₃-SiO₂; composite.

E. F. Osborn and Arnulf Muan, revised and redrawn "Phase Equilibrium Diagrams of Oxide Systems," Plate 5, Published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

MgO-Al₂O₃-SiO₂

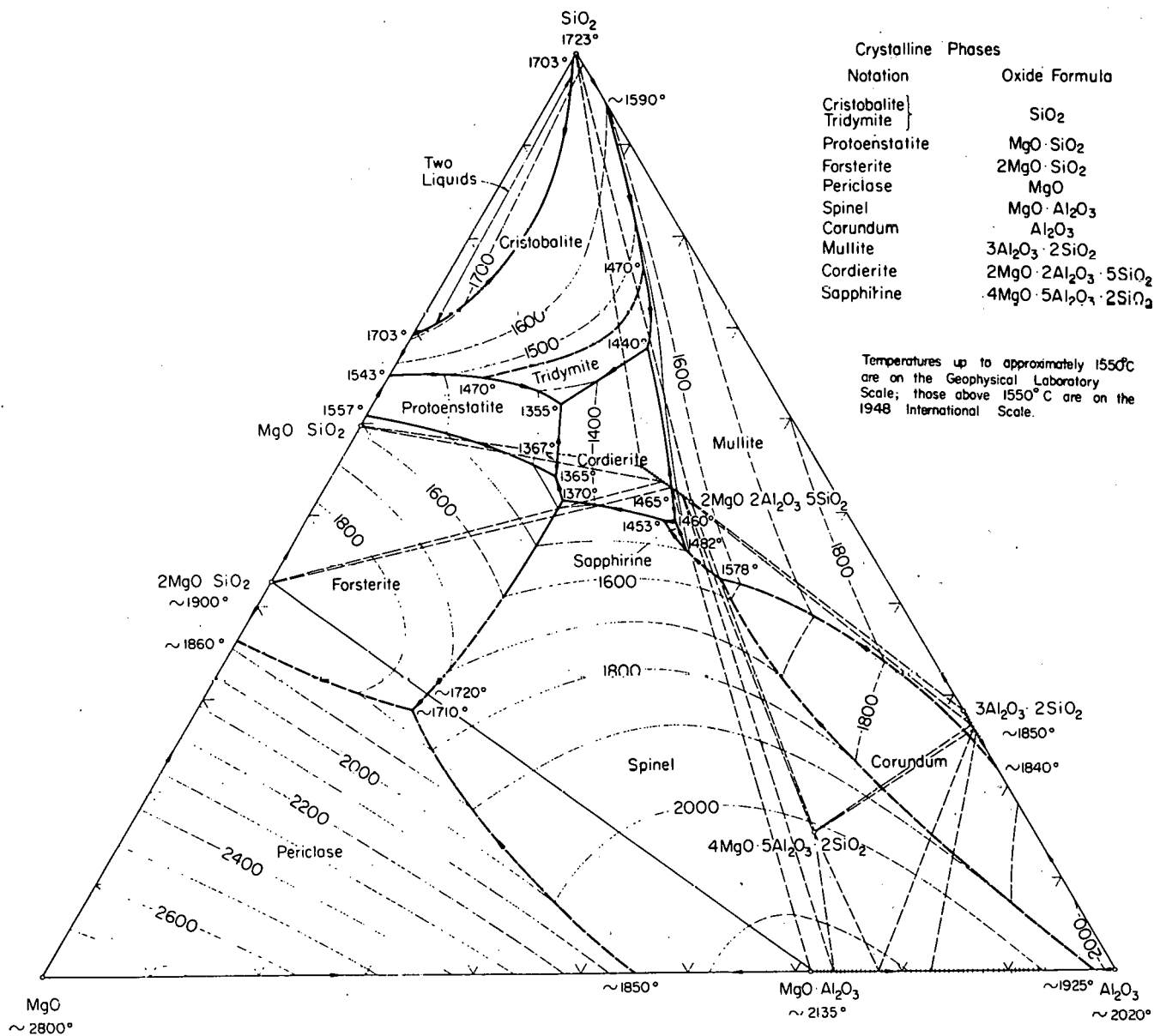


FIG. 712.—System MgO-Al₂O₃-SiO₂; composite.

E. F. Osborn and Arnulf Muan, revised and redrawn "Phase Equilibrium Diagrams of Oxide Systems," Plate 3, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

Na₂O-Al₂O₃-SiO₂

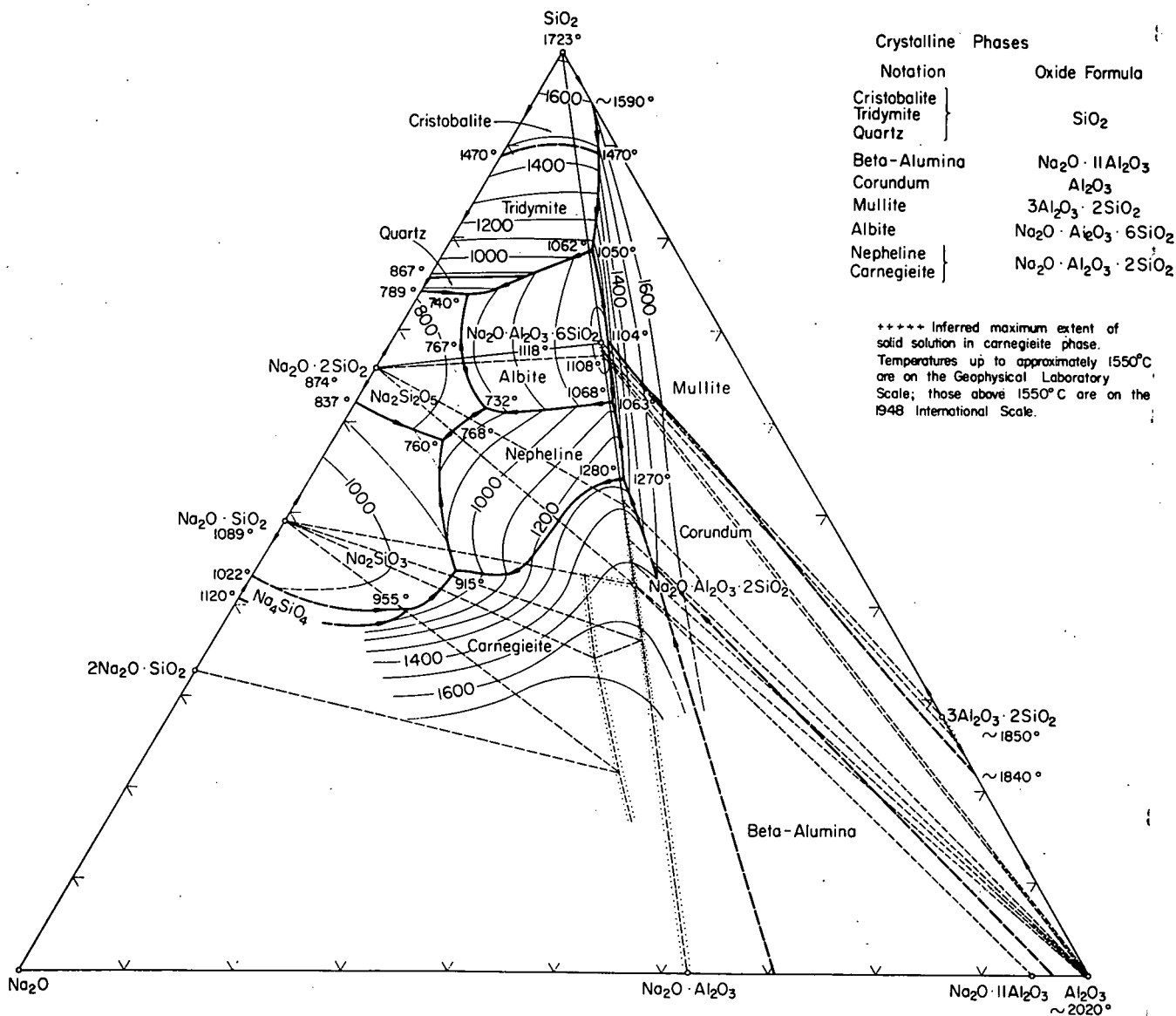


FIG. 501.—System Na₂O-Al₂O₃-SiO₂; composite.

E. F. Osborn and Arnulf Muan, revised and redrawn "Phase Equilibrium Diagrams of Oxide Systems," Plate 4, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

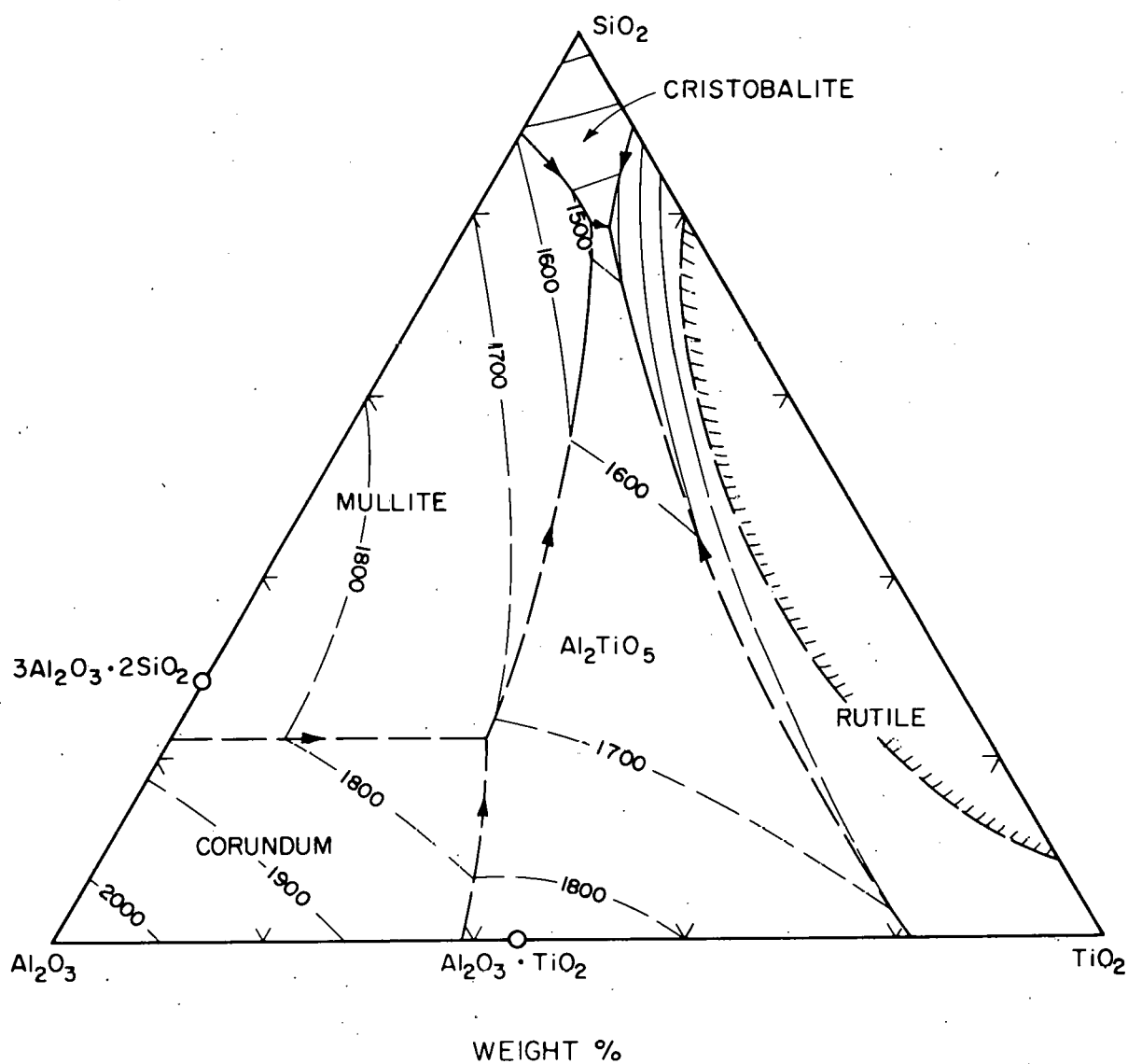


Fig. 85. Approximate phase diagram for the system $\text{Al}_2\text{O}_3\text{-TiO}_2\text{-SiO}_2$, sketched on the basis of data of Agamawi and White⁽²⁷⁰⁾ and of DeVries, Roy, and Osborn.⁽¹⁴⁵⁾

CaO-FeO-SiO₂

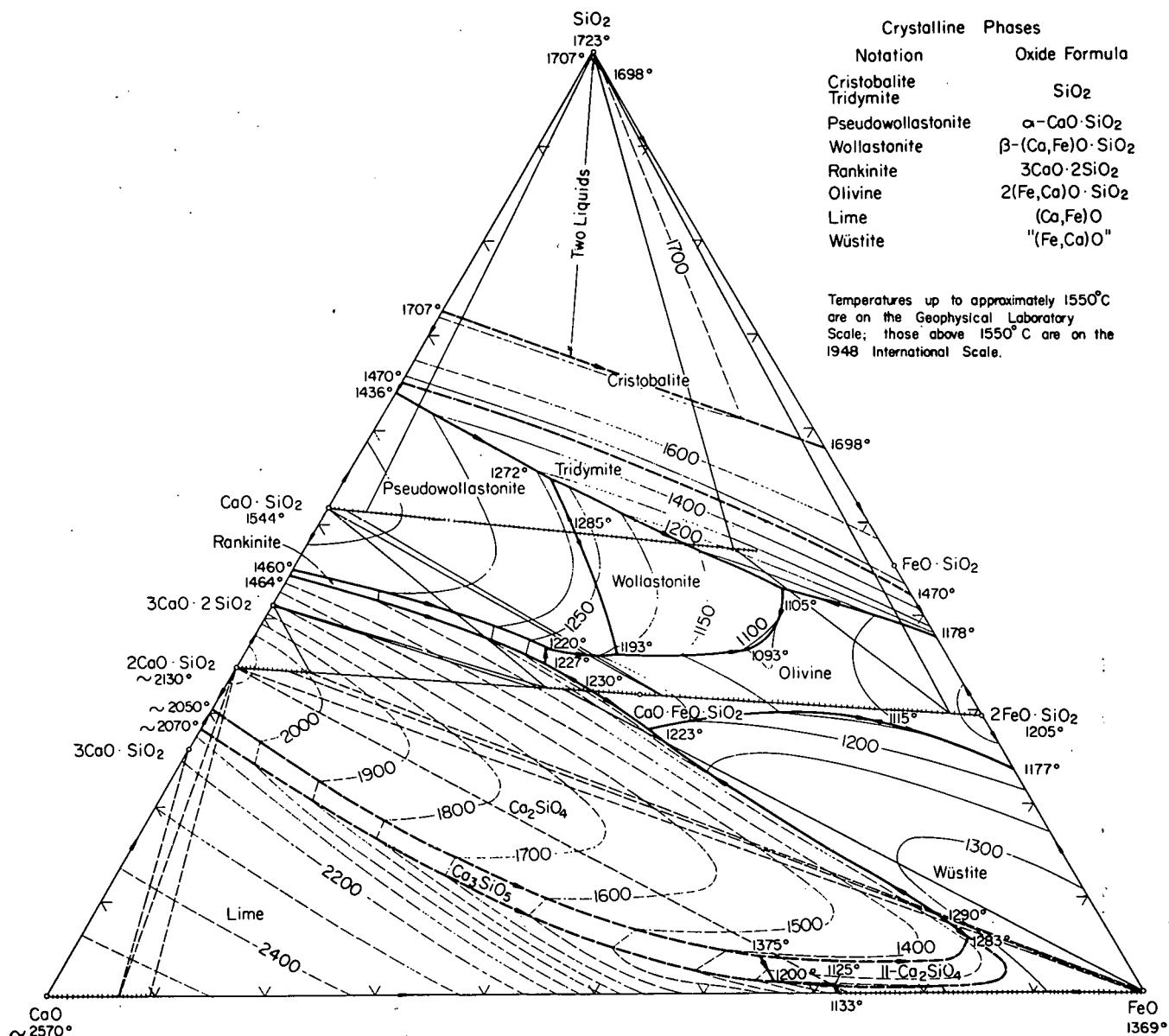


FIG. 586.—System CaO-“FeO”-SiO₂; composite. (Oxide Phases in Equilibrium with Metallic Iron)

E. F. Osborn and Arnulf Muan, revised and redrawn "Phase Equilibrium Diagrams of Oxide Systems," Plate 7, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

$\text{CaO}-\text{Fe}_2\text{O}_3-\text{SiO}_2$

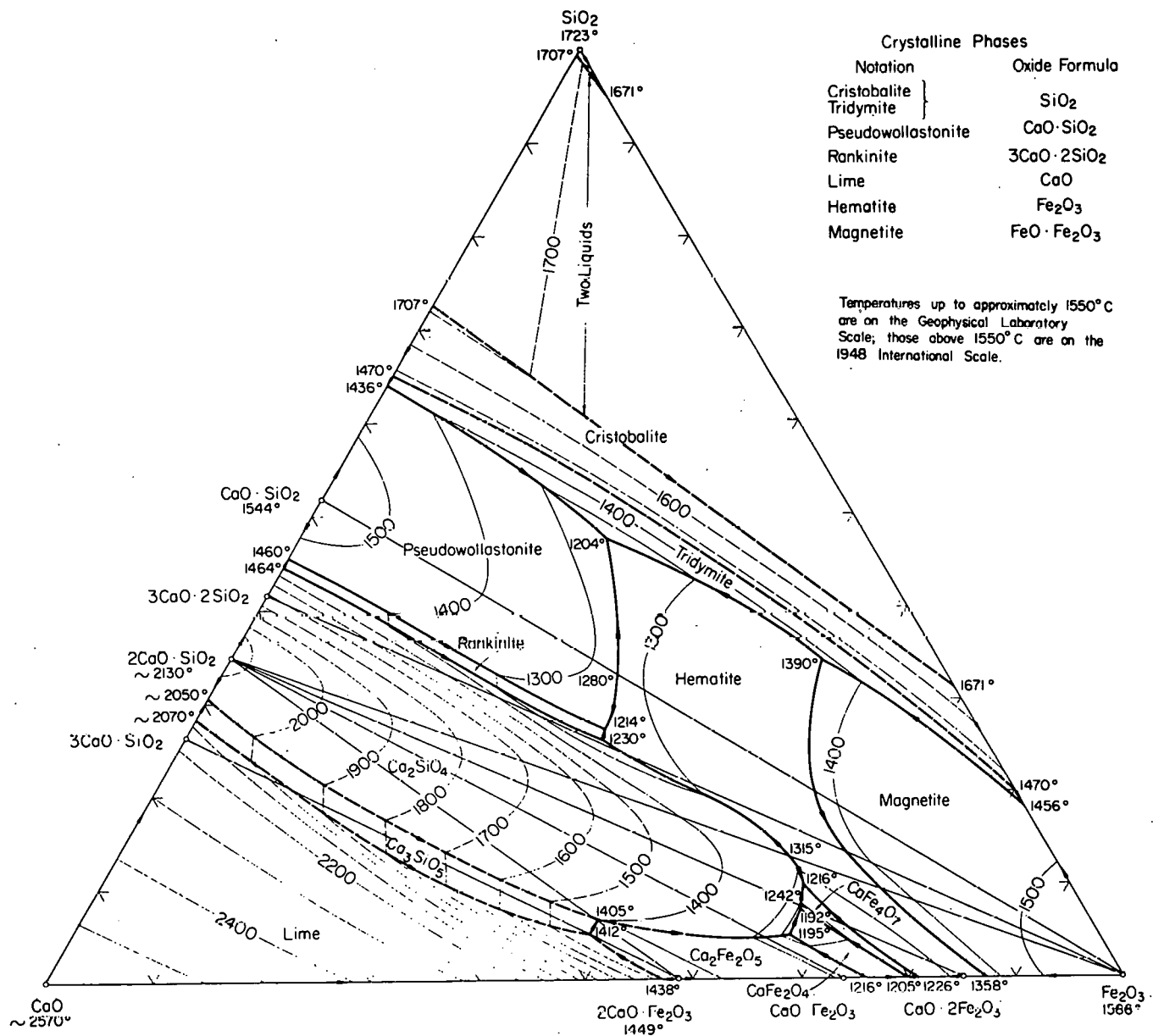


FIG. 656.—System $\text{CaO}-\text{Fe}_2\text{O}_3-\text{SiO}_2$; composite. (Condensed Phases in Equilibrium with Air).

E. F. Osborn and Arnulf Muan, revised and redrawn "Phase Equilibrium Diagrams of Oxide Systems," Plate 10, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

CaO-MgO-SiO₂

Temperatures up to approximately 1550°C are on the Geophysical Laboratory Scale; those above 1550°C are on the 1948 International Scale.

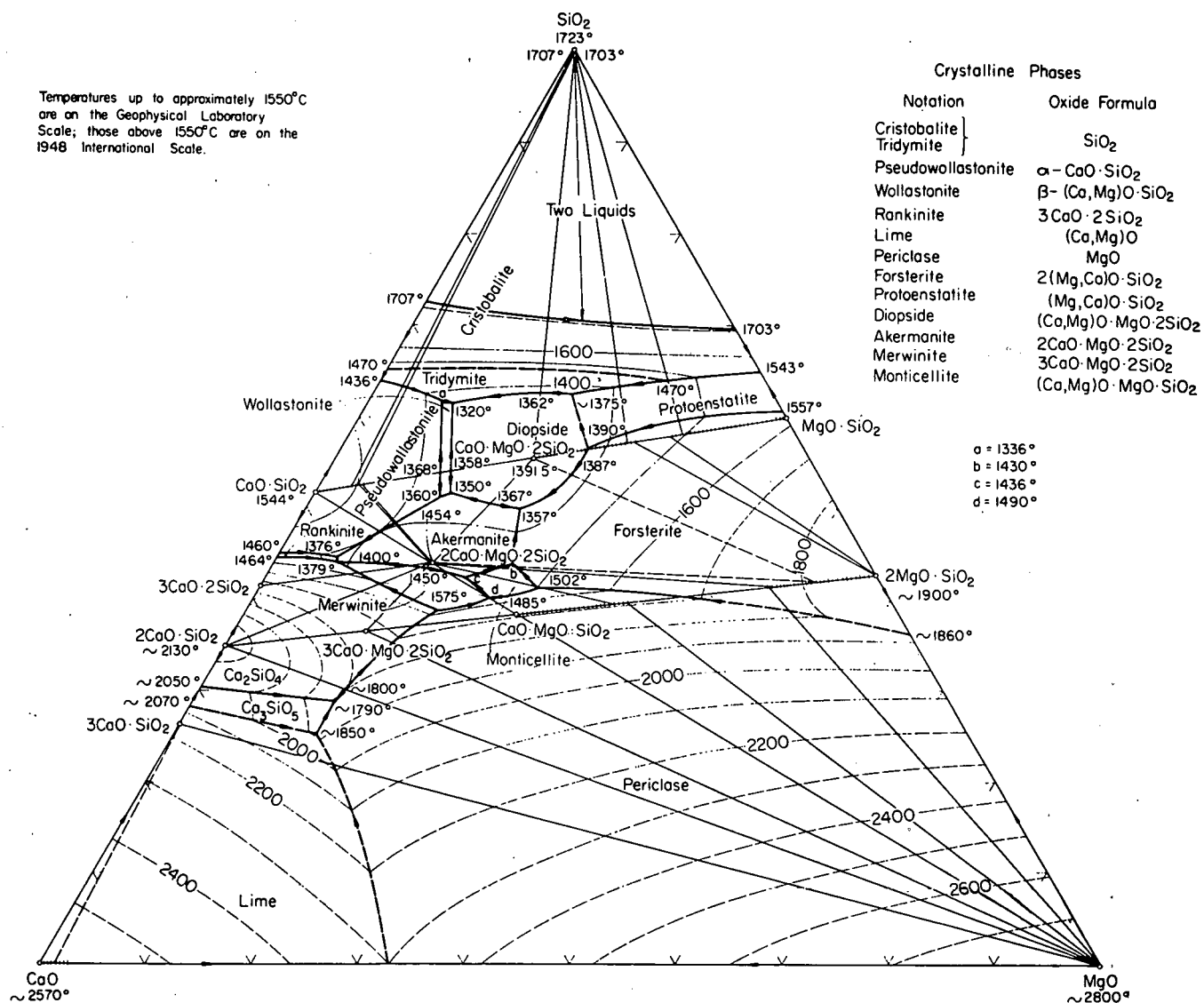


FIG. 598.—System CaO-MgO-SiO₂; composite.

E. F. Osborn and Arnulf Muan, revised and redrawn "Phase Equilibrium Diagrams of Oxide Systems," Plate 2, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

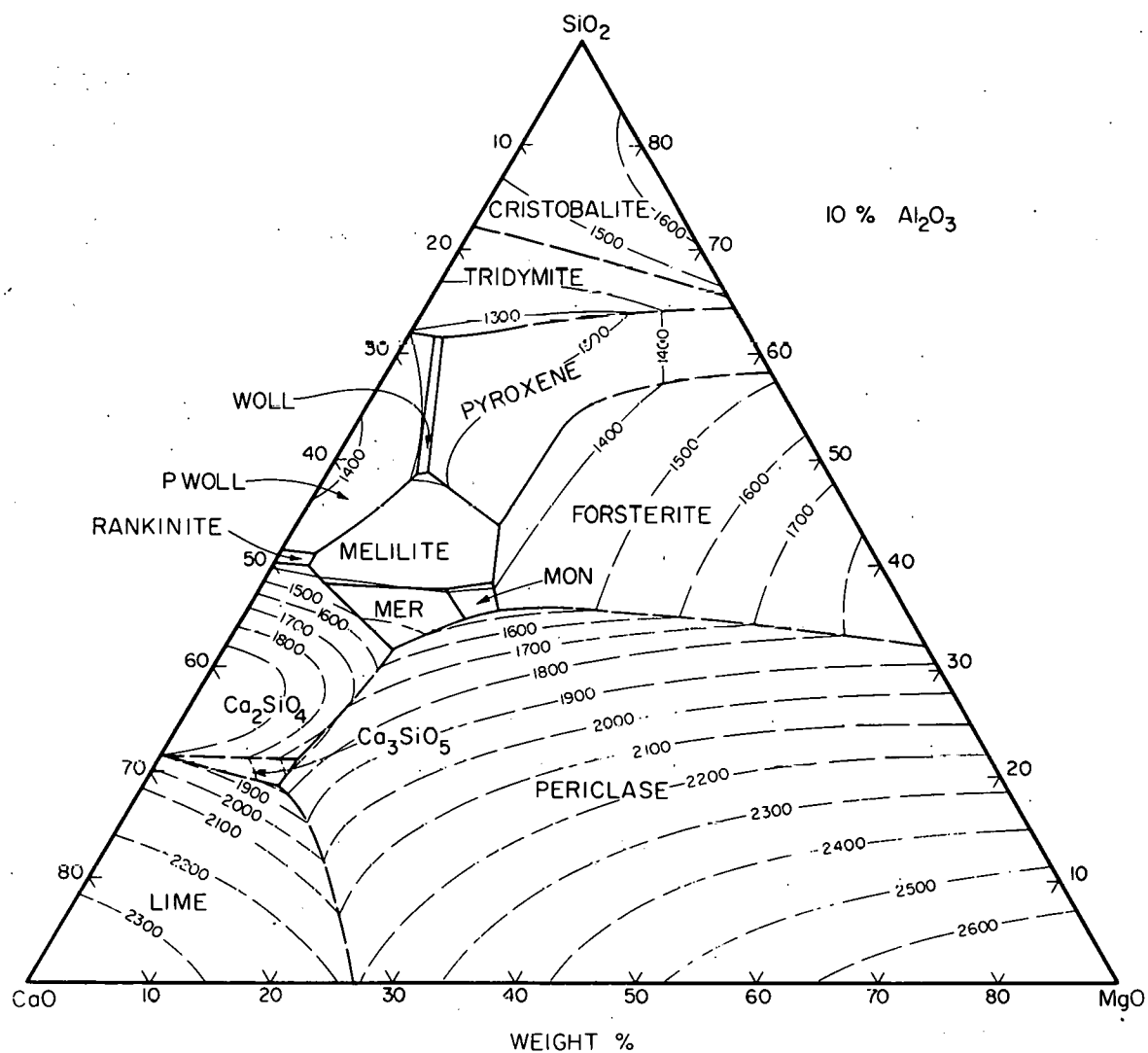


Fig. 112. Phase relations at liquidus temperatures in the 10% Al_2O_3 plane of the system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$, after Osborn, DeVries, Gee, and Kraner.⁽²⁹⁹⁾ Abbreviations used have the following meanings: Mer = merwinite, Mon = monticellite.

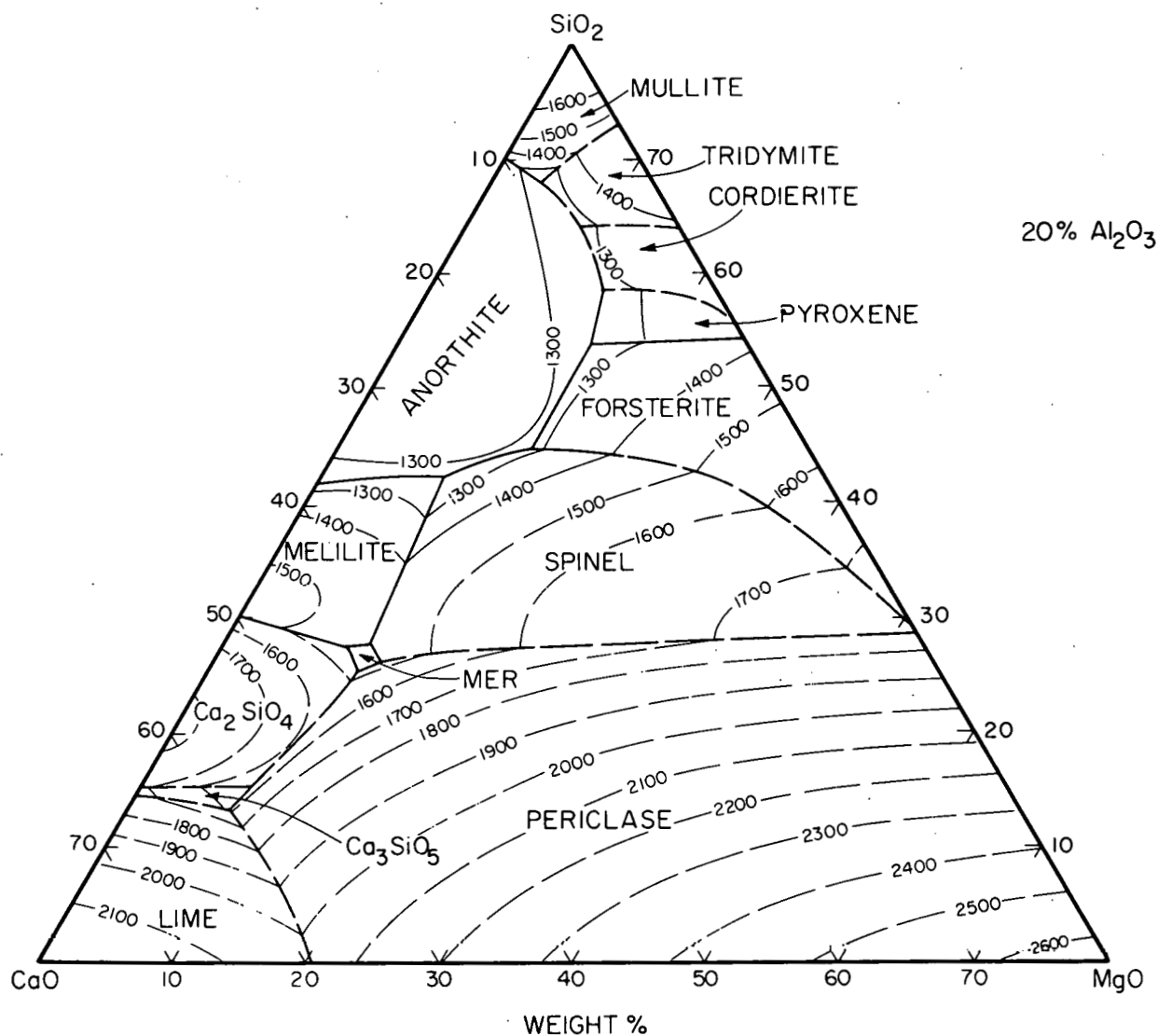


Fig. 114. Phase relations at liquidus temperatures in the 20% Al_2O_3 plane of the system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$, after Osborn, DeVries, Gee, and Kraner.⁽²⁹⁹⁾ Abbreviation used has the following meaning: Mer = merwinite.

FeO-MgO-SiO₂

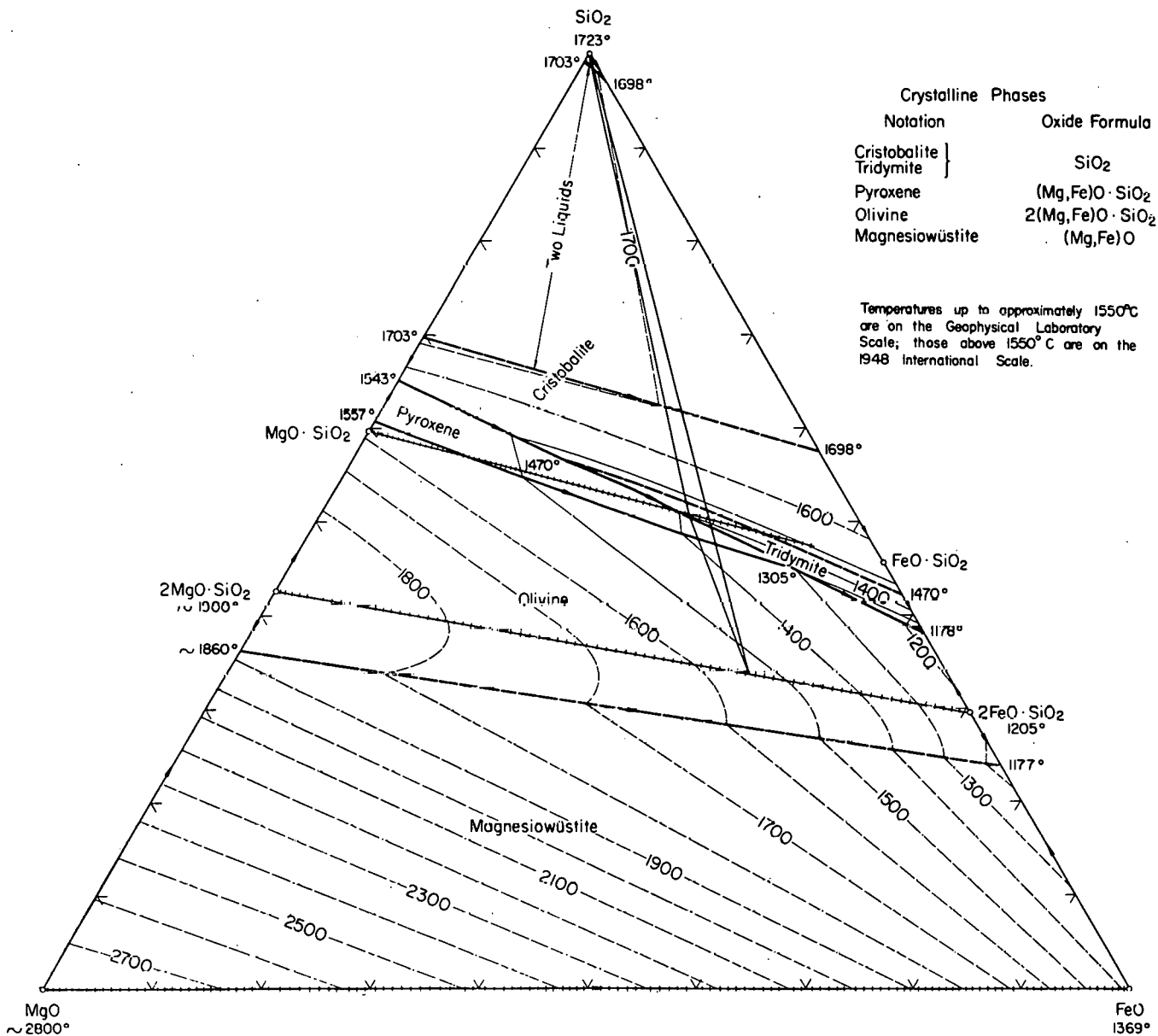


FIG. 682.—System MgO-“FeO”-SiO₂; composite. (Oxide Phases in Equilibrium with Metallic Iron).

E. F. Osborn and Arnulf Muan, revised and redrawn “Phase Equilibrium Diagrams of Oxide Systems,” Plate 8, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

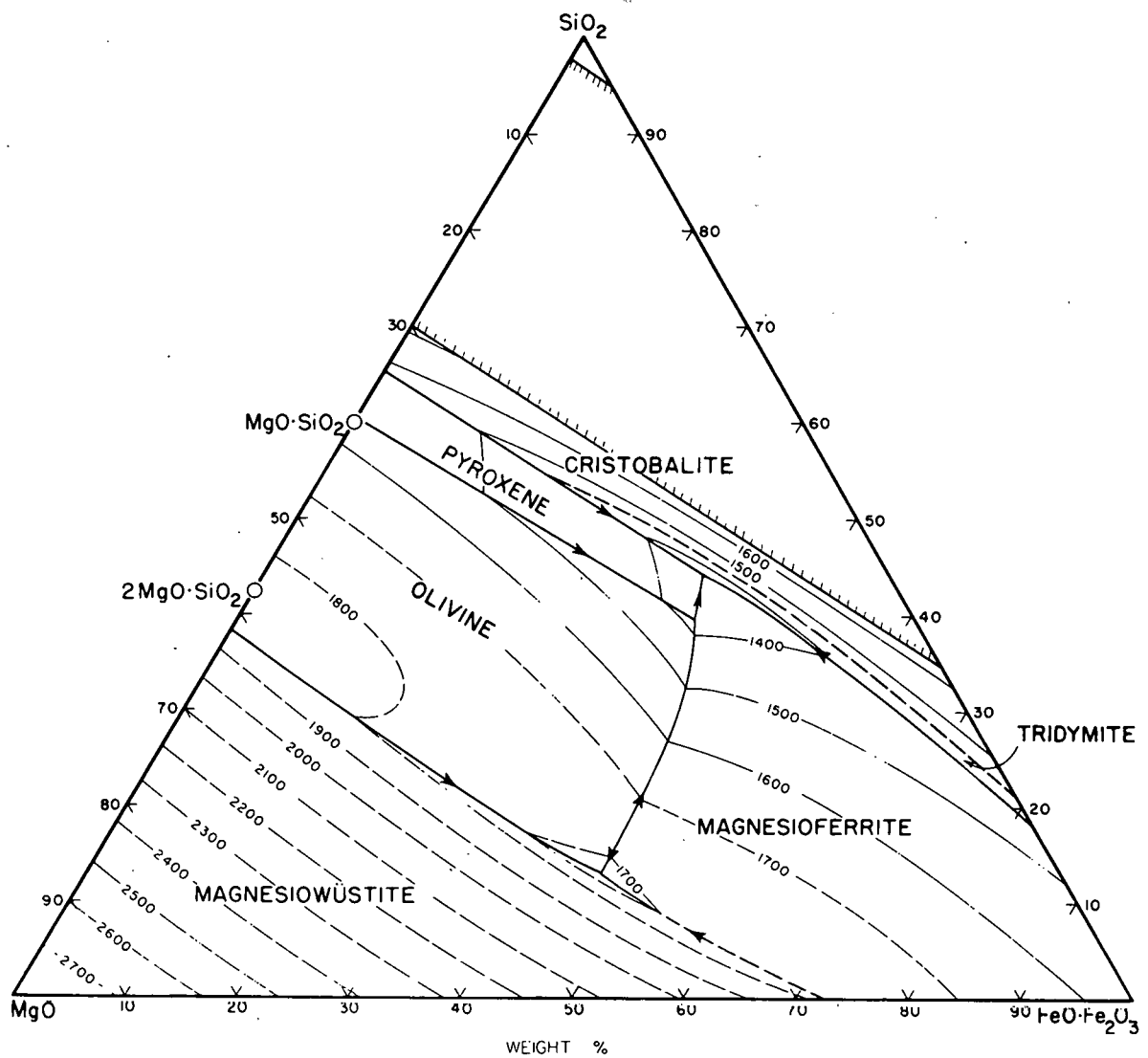


Fig. 94. Phase relations in the system MgO-iron oxide-SiO₂ in air, after Muan and Osborn.⁽²⁷²⁾ The system is not ternary. The method of projection used in order to obtain this diagram is explained in the text.

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