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- 4. NAME OF INSTITUTION: Southwest Center for Advanced Studies  
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Final Report for Contract DA-31-124-ARO-D-463

During the term of this contract (May, 1966 - September, 1970) the personnel has changed considerably, and this has resulted in a certain degree of disruption of the research program. One of the two original principal investigators, B.T.C. Davis, died in April, 1967. He was replaced by J.L. Carter. The other original principal investigator, I.D. MacGregor, is now chairman of the Department of Geology, University of California at Davis, Davis, California. His support was terminated in August, 1969. D.C. Presnall joined the project as a principal investigator in May, 1969.

Despite these changes in personnel, the goals of the research program have remained essentially the same, except that the emphasis has shifted from an earlier concentration on subsolidus studies to a later concentration on liquidus studies. This shift was in part a reflection of Presnall's interest in magma genesis from the earth's upper mantle but it was also a scientifically logical shift. The earlier subsolidus work helped to establish the pressure ranges within which various mineral assemblages are stable in the upper mantle (see papers by MacGregor [1966, 1970] supported by this contract). It was then of interest to investigate the kinds of liquids that could be generated as magmas from these various mineral assemblages

by partial fusion. First, it was necessary to establish a theoretical basis for such studies (see paper by Presnall [1969] supported by this contract). Subsequently, high pressure liquidus studies were carried out in the system  $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ . This system was chosen to model the composition of the upper mantle because (1) it contains all the major minerals thought to exist in the upper mantle and about 90 percent of the composition of the mantle can be represented by this system, and (2) it contains the maximum number of components that can be handled geometrically with complete rigor and generality.

Work that has been completed and published will not be mentioned further here. Projects that are in various stages of completion but are not yet published are as follows:

(1) A study of the liquidus and solidus surfaces of the system  $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$  at 15 kilobars. The experimental work is now close to completion and is being written up by H.C. Taylor as a M.S. thesis.

(2) A study of the liquidus and solidus surfaces in the system  $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$  at 7, 10, and 15 kilobars. The experimental work (being carried out by Presnall) is only partially completed.

(3) A study of the changes of electrical conductivity of a synthetic basalt during melting. This work has been carried out jointly by H. Porath of this department and Presnall. A preliminary study has been completed and submitted for publication. This work was undertaken in part to test the feasibility

of a more extensive program of conductivity measurements at high pressures and temperatures (see proposal to ARO-D submitted by Presnall and Carter).

(4) A study of the coexisting minerals in ultramafic nodules from kimberlite pipes in South Africa. This work is partially completed and is being carried out by Carter.

The remainder of the report consists of detailed accounts of projects (1), (2), and (4). The details of project (3) are contained in the preprint of the paper by Porath and Presnall that accompanies this report.

Project 1: Liquidus and Solidus Relationships in the System  
 $MgO-Al_2O_3-SiO_2$  at 15 kilobars

The system  $MgO-Al_2O_3-SiO_2$  contains several of the important mineral phases present in the upper mantle (forsterite, enstatite, spinel, pyrope) and the liquidus and solidus relationships have been determined at a pressure (15 Kb) representative of the spinel peridotite facies in the upper mantle (MacGregor, 1968, 1970). Pyrope is not stable on the liquidus surface at this pressure (Boyd and England, 1962).

The experiments were carried out in a single stage piston-cylinder apparatus as described by Boyd and England (1960). The phases produced in the experiments were identified from polished thin sections using a petrographic microscope and an electron microprobe.

Figure 1 shows the binary system  $Mg_2SiO_4-MgSiO_3$ . In agreement with the findings of Boyd, England, and Davis (1964), enstatite melts congruently at this pressure and the peritectic point between enstatite and forsterite at one atmosphere pressure has become a eutectic point. Stated differently, the primary phase field of forsterite contracts relative to that of enstatite as pressure increases, and partial fusion of a mixture of forsterite and enstatite will produce increasingly more mafic initial melts as pressure is increased. This trend closely

parallels similar relationships for more complex compositions that are closer approximations to the earth's upper mantle.

Figures 2 and 3 show liquidus and solidus relationships that have been determined in the ternary system  $\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$  at 15 kb. Crystalline phases that have been encountered are forsterite, enstatite, spinel, sapphirine, sillimanite, quartz, and corundum. Six invariant points have been determined in the ternary system together with the adjoining univariant lines which form the phase boundaries for the aforementioned mineral phases. Of the six invariant points, five are peritectics and only one is an entectic (point e, Figure 2). The single entectic point occurs at about  $1460^\circ\text{C}$  and is the lowest temperature on the liquidus surface. This entectic also defines the composition of the final liquid produced by fractional crystallization.

Figure 3 shows several important relationships regarding crystal-liquid equilibria for simplified upper-mantle compositions. Most notable is the contraction of the field of forsterite relative to the fields of both enstatite and spinel as pressure is increased (compare the dashed boundaries for the forsterite field at one atm. pressure). This means that simplified upper mantle compositions consisting of olivine, enstatite, and spinel will partially fuse to produce initial melts that are increasingly richer in forsterite and poorer in alumina

and silica as pressure is increased. This parallels the trend noted above for the simpler system  $Mg_2SiO_4$ - $MgSiO_3$ .

Another interesting feature of Figure 3 is the boundary line between forsterite and enstatite. One of the cornerstones of Bowen's reaction series was the incongruent melting of enstatite observed in the system  $MgO$ - $SiO_2$  at one atmosphere pressure. Because of this relationship, Bowen (1928) argued that silica enriched residual liquids could be produced by fractional crystallization of silica-undersaturated starting compositions. Boyd, England, and Davis (1964) found that the incongruent melting of enstatite disappears at pressures above 2.3 kb. From these data, they suggested that rocks showing the reaction relation olivine  $\rightarrow$  enstatite + liquid developed this relation at pressures less than 2.3 kb. They stated further that this reaction relation is not relevant to the development of magmas at greater depths. Figure 3 shows that the addition of  $Al_2O_3$  causes the boundary line b-c to curve across the aluminous enstatite compositions and the reaction relation is restored for aluminous enstatite, forsterite, and liquid. Thus, the reaction relation is indeed relevant to fractional crystallization of magmas at pressures at least as high as 15 kb and it is therefore possible to produce silica-saturated magmas from silica-undersaturated magmas at this pressure.

Another point of interest concerns the matter of "equilibrium thermal barriers" (Yoder and Tilley, 1962, p. 501). From subsolidus experiments, Yoder and Tilley (1962) showed that certain joins stable at low pressures are breached and replaced by new stable joins at high pressures. These stable joins were called "thermal barriers" across which liquids could not move during fractional crystallization. They used these changing "thermal barriers" to argue for the derivation of alkaline basalts at higher pressures and tholeiitic basalts at lower pressures. The liquidus relationships in Figure 3 show that in the absence of liquidus data it is not valid to consider a stable join as a thermal barrier. For example, aluminous enstatite and spinel form a stable join, yet it is quite possible for liquids to move across this join toward point b by precipitation of spinel and forsterite. This principle could be illustrated on many phase diagrams other than Figure 3, and the presence or absence of a subsolidus stable join is not related to the type of fractionation that can occur. Of particular interest here is the fact that silica enriched residual liquids can be derived at moderate pressures and it will be interesting to see the results of liquidus studies at still higher pressures. The contraction of the field of forsterite suggests that Yoder and Tilley were probably correct but not for the reason they stated.

Project 2: Liquidus and Solidus Relationships in the System  
 $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$  at 7, 10, and 15 kilobars

Work in the system  $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$  has been aimed toward a determination of the liquidus and solidus phase relations within the tetrahedron forsterite-silica-diopside-anorthite (Fig. 4). This is the tholeiitic portion of the "basalt tetrahedron" of Yoder and Tilley (1962) and is the region of the diagram in which the mantle minerals olivine, enstatite, diopside, spinel, and plagioclase are stable at liquidus temperatures. It is therefore of primary interest to an understanding of melting phenomena in the mantle and the relationships between basaltic magma and the mafic and ultramafic nodules which they bring to the earth's surface. Work is now in progress at 7, 10, and 15 kilobars on the joins forsterite-diopside-anorthite and enstatite-diopside-anorthite. Data on these two joins together with planned work on the join forsterite-silica-anorthite should allow the positions of the univariant lines and invariant points within each isobaric tetrahedron to be fixed.

The experiments have been carried out in a piston-cylinder apparatus similar to that described by Boyd and England (1960). Phase identification has been made from polished thin sections using reflected and transmitted light optical methods and also with an electron microprobe.

Figures 5-9 are preliminary phase diagrams, showing the work that has been completed so far. Figure 5 shows the liquidus surface of the join  $\text{MgSiO}_3$ - $\text{CaAl}_2\text{Si}_2\text{O}_8$  (enstatite-anorthite) at 7, 10, and 15 kb. It is seen that anorthite is not stable at liquidus temperatures anywhere along this join. The three primary phase fields of enstatite, spinel, and corundum intersect this join and the main effect of increased pressure is an increase in the liquidus temperatures. In particular, there appears to be very little change in the composition of the minimum between spinel and enstatite. This is in contrast to the decrease in size of the forsterite field relative to spinel as pressure increases in the system  $\text{MgO-Al}_2\text{O}_3$ - $\text{SiO}_2$  (see report on project 1).

Figures 6, 7, and 8 show the liquidus surfaces of the join  $\text{Mg}_2\text{SiO}_4$ - $\text{CaMgSi}_2\text{O}_6$ - $\text{CaAl}_2\text{Si}_2\text{O}_8$  (forsterite-diopside-anorthite) at 7, 10, and 15 kb. In addition to the expected increase of liquidus temperatures with pressure, the main feature of petrologic interest is the expansion of the diopside field at the expense of the forsterite field as pressure is increased. Also, the piercing point at which the fields of forsterite, spinel and diopside converge decreases in anorthite content and increases in forsterite content as pressure increases. A field of corundum occurs at the anorthite corner (Lindsley, 1967) but its limits have not yet been determined.

Figure 9 shows some of the liquidus relationships in the tetrahedron  $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$  at 15 kb and is compiled from several sources. Relationships on the left-hand face, forsterite-diopside-silica, are interpolated from Kushiro (1969). Data on the base,  $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ , are from the work of Taylor (see this report-project 1). The univariant lines within the tetrahedron (heavy lines with arrows) are based on data for the left hand and bottom faces plus data determined in this report for the join forsterite-diopside-anorthite (see Figure 8). A liquidus invariant point p occurs at which forsterite, enstatite, diopside, and spinel are in equilibrium with liquid. The exact position of this invariant point is not certain but it must be approximately as shown.

Several interesting conclusions are possible from the relationships shown in Figure 9. MacGregor (1968) has shown that at 15 kb, an upper mantle of peridotite composition will consist of the mineral assemblage olivine + enstatite + diopside + spinel. Thus, point p is a simplified analog of the composition of the first liquid formed on melting such a mantle, for as mentioned above, this liquid is in equilibrium with these four crystalline phases. Point p is a basaltic composition, and since it lies within the tetrahedron Fo-Di-En-An, it is analogous in composition to an olivine tholeiite. The data of

Taylor on the system  $MgO-Al_2O_3-SiO_2$  (this report) and Figures 6, 7, and 8 indicate that decreasing the pressure from 15 kb causes the field of forsterite to expand at the expense of the enstatite and diopside fields. Also, the peritectic a on the base of the tetrahedron moves to the right. Thus, as pressure is decreased, point p will move toward  $SiO_2$  and anorthite. This means that initial melts produced from a spinel peridotite mantle will change, as pressure decreases from 15 kb, toward high alumina basalt. At 7 kb, relationships are complicated by the fact that the subsolidus assemblage forsterite-diopside-enstatite-spinel is replaced by forsterite-enstatite-diopside-anorthite (MacGregor, 1968) and initial liquids derived by partial fusion would no longer lie at p. The data are incomplete at 7 kb but it is probable that initial liquids will lie within the tetrahedron  $SiO_2$ -En-Di-An (Figure 9) and would therefore be called quartz tholeiites.

Another interesting feature of Figure 9 is that p appears to be a peritectic point. The data at 15 kb are not conclusive, but at slightly lower pressures, the simultaneous movement of p toward anorthite and silica and the decrease in  $Al_2O_3$  content of enstatite and diopside will assure that p is a peritectic point. Thus, liquids at p in the olivine

tholeiite field can move generally toward anorthite and probably toward quartz into the quartz tholeiite field by crystallization of diopside, enstatite, and spinel. Green, Green, and Ringwood (1967) argued that quartz tholeiites could be derived from olivine tholeiites only at depths less than 15 km (pressures less than 4.5 kb). The preliminary data in Figure 9 suggests that this type of fractionation may be possible to considerably higher pressures.

The data in Figure 9 also bear on the depth of origin of high-alumina olivine tholeiite. Green, Green, and Ringwood (1967) suggested that such basalts were derived either by magma segregation or fractional crystallization at depths from 15-35 km (pressures from 4.5 to 9 kb). Point  $p$  is not quite rich enough in anorthite to correspond to a high-alumina olivine tholeiite but it was mentioned above that  $p$  moves toward anorthite with decreasing pressure. Thus, it appears likely that high-alumina olivine tholeiites could be derived by partial melting of a spinel peridotite mantle at pressures from 9 to 12 kb, a pressure range slightly higher than that proposed by Green, Green, and Ringwood (1967).

Project 4: Chemistry of Coexisting Minerals in Ultramafic  
Nodules from South African Kimberlite Pipes

Coexisting minerals consisting of various proportions of olivine, orthopyroxene, clinopyroxene, garnet, spinel and mica were handpicked from a suite of 270 ultramafic rocks (mainly dunites, harzburgites and lherzolites) occurring as inclusions in diamond-bearing kimberlites from Loewrencia (68 inclusions) (about 10 miles west of Gibeon; 25.09 S. Lat, 17.43 E. Long) and from the mines of Bultfontein (82 inclusions), DeBeer's (29 inclusions), Kamfersdam (29 inclusions) and Wesselton (24 inclusions) near Kimberly (28.45 S. Lat, 24.46 E. Long), South Africa (Figure 10). The grain mounts were analyzed with an electron microprobe to a precision generally better than 1%. The results are shown in Tables 1 and 2.

All minerals have been analyzed for silicon, aluminum and magnesium. With the exception of olivine, the coexisting minerals of inclusions from Loewrencia have been analyzed for silicon, aluminum, magnesium, iron, chromium, calcium, titanium and sodium (Table 2).

Figure 11 is a histogram of the fayalite content (mole ratio  $Fe/Fe + Mg$ ) of the olivine of inclusions from the various mines. The inclusions from Loewrencia have the highest average

fayalite content of the various suites. Even though the remaining suites are from the Kimberly area, there are subtle differences in the chemistry of the olivines. These subtle differences may reflect a difference in depth of the source area; a difference in the degree of partial fusion (Carter, 1966); or a difference in the degree of recrystallization and reequilibration (Rodgers and Brothers, 1969).

Figure 12 is a plot of the MgO content of orthopyroxenes versus the fayalite content of coexisting olivine from Loewrencia, Bultfontein and De Beer's. Even though there is much scatter to these data, there is a negative correlation of MgO content with Fa. Figure 13 is a plot of the  $Al_2O_3$  content of orthopyroxene versus its MgO content. These plots reveal the existence of a preferred orthopyroxene composition with approximately 0.75 percent  $Al_2O_3$  superimposed on a possible trend with a negative correlation with respect to MgO.

Figure 14A is a plot of the MgO content of clinopyroxenes versus the Fa content of coexisting olivine from Loewrencia. There appears to be no correlation. Even the plot of MgO content in the clinopyroxene versus MgO content in the coexisting orthopyroxene (Figure 14B) reveals no clear correlation. The plot of  $Na_2O$  content versus  $Al_2O_3$  content in the clinopyroxene from Loewrencia (Figure 14C) shows a positive correlation with considerable scatter to the data.

Probe analysis of the pyroxenes in some cases revealed heterogeneties for the minor elements and occasionally heterogeneties for the major elements. These data suggest lack of equilibration between the coexisting phases. Also, the plot of the mole percent of Ca, Mg and Fe of coexisting pyroxenes that show the total range in chemistries (Figure 15A) gives clear evidence of differences in environmental temperature. That is, the most Ca-rich clinopyroxenes coexist with Ca-poor orthopyroxenes (lowest temperature) and vice-versa (highest temperature).

Fifty-nine of the inclusions from Loewrencia contained garnet, twenty-two contained spinel and eighteen inclusions contained both phases. Six of the latter type appear to have both primary spinel and garnet coexisting, whereas the other twelve inclusions contain secondary spinel. The spinels have an interesting chemistry in that they are very chromium-rich and aluminium-poor and contain up to 5.6%  $TiO_2$  (Table 2). Figure 15B shows the plot of mole percent  $Al_2O_3-Cr_2O_3-Fe_2O_3$  and a line showing the simultaneous variation in FeO-MgO of these spinels. Those spinels that are the most ferric-rich contain the highest percentages of  $TiO_2$  and have the lowest FeO/mgO ratios.

The garnets from Loewrencia are pyropes with mole ratios of  $Mg/(Mg + Fe)$  ranging from 0.87 to 0.78. The grossular component ranges from 0.0 to 9.0 and those analyses showing

the total variation are plotted in terms of the three components pyrope, almandine and grossular, are shown in Figure 15C. Chromium content is high and varies from 1.8 to 8.3% (Table 2). Comparison of these data from Loewrencia to those of Reid and Hanor (1970) and Table 1 on garnets of inclusions from Kimberly and surrounding mines shows that the Loewrencia garnets in general have higher pyrope ratios and higher chromium contents than those from the Kimberly area.

One interesting aspect of the garnets from Loewrencia is their high content of hanelite ( $\text{Mg}_3 \text{Cr}_2 \text{Si}_3 \text{O}_{12}$ ) that varies up to 6 mole percent in those garnets containing the highest percentages of chromium. The chemistry of the spinels and garnets and the coexistence of primary spinel and garnet in some inclusions is consistent with the experiments of MacGregor (1970) on the effects of calcium and the trivalent cations iron, chromium and aluminum on the stability of the spinel-garnet reaction boundary. The presence in some nodules of reaction rims containing spinel around garnets demonstrates that the inclusions were transported to a lower pressure environment and partially reequilibrated.

From the data of Irvine (1965) the partial pressure of oxygen in equilibrium with these spinels is probably in the range of  $10^{-4}$  to  $10^{-7}$  atmospheres which may suggest high temperature formation. This is in contrast with the spinels studied by Carter (1969) from inclusions in basaltic rocks where the partial pressure of oxygen is possibly in the range  $10^{-8}$  to  $10^{-11}$  atmospheres.

Conclusions about the origin of the inclusions from these localities must await attainment of complete probe data for major and minor elements for all the coexisting phases. However, several observations and inferences about their origin may be made at this time.

1) The average fayalite content of the olivine of inclusions from the several localities are different especially comparing inclusions of Loewrencia with those from the Kimberly area and when compared with inclusions from basaltic rocks (Carter, 1966).

2) The orthopyroxenes from Loewrencia have a slightly lower MgO content than those from the Kimberly area, which is reflected in the higher FeO content in the olivines from Loewrencia.

3) There is a preferred concentration of about 0.75%  $Al_2O_3$  in the orthopyroxenes and possibly a negative correlation of  $Al_2O_3$  with MgO, especially in the Loewrencia inclusions.

4) Lack of a clear-cut correlation between MgO in the clinopyroxene and MgO in the coexisting orthopyroxene and the fayalite content in the coexisting olivine.

5) Ca-rich clinopyroxenes coexist with Ca-poor orthopyroxenes and vice-versa.

6) Garnet in the Loewrencia inclusions is rich in the pyrope, uvavorite and hanleite molecules.

7) Spinel is chromium-rich and alumium-poor and sometimes titanium-rich in the Loewrencia inclusions.

8) Variable distribution of aluminum, chromium, titanium and sodium in some of the pyroxenes and low contents of titanium and sodium in the pyroxenes.

9) The presence of reaction rims around garnets that contain spinel and mica, and the ubiquitous occurrence of serpentine.

These data suggest as a working hypothesis that the inclusion phase assemblage originally crystallized at moderate pressures and temperatures, possibly residuum from partial fusion as reflected by the low fayalite contents of olivine and by the low clinopyroxene, spinel, garnet and orthopyroxene contents and by the low titanium and sodium contents in the pyroxenes (Carter, 1966). Incorporation of inclusions in magma and partial reequilibration at shallower depth resulted in variable composition of the pyroxenes and formation of secondary mica, spinel and serpentine.

## REFERENCES

- Bowen, N.L., 1928, The evolution of the igneous rocks:  
Princeton University Press, 332 p.
- Boyd, F.R., and J.L. England, 1960, Apparatus for phase-equilibrium measurements at pressures up to 50 kilobars and temperatures up to 1750°C: Jour. Geophys. Res., v. 65, p. 741-748.
- Boyd, F.R., and J.L. England, 1962, Effect of pressure on the melting of pyrope: Carnegie Inst. Washington Year Book 61, p. 109-112.
- Boyd, F.R., J.L. England, and B.T.C. Davis, 1964, Effects of pressure on the melting and polymorphism of enstatite, MgSiO<sub>3</sub>: Jour. Geophys. Res., v. 69, p. 2101-2109.
- Carter, J.L., 1966, Chemical composition of the primitive upper mantle: abstract in program of 1966 Annual Meeting, Geol. Soc. America, p. 35-36.
- Carter, J.L., 1969, Chemistry of spinels from ultramafic and mafic nodules from Kilbourne Hole, New Mexico: Trans. Am. Geoph. Union, v. 50, p. 345 (Abstract).
- Green, T.H., D.H. Green, and A.E. Ringwood, 1967, The origin of high-alumina basalts and their relationships to quartz tholeiites and alkali basalts: Earth Planet. Sci. Letters, v. 2, p. 41-51.

- Irvine, T.N., 1965, Chromian Spinel as a Petrogenetic Indicator, Part 1. Theory: *Can. J. of Earth Sci.*, v. 2, p. 648-672.
- Kushiro, I., 1969, The system forsterite-diopside-silica with and without water at high pressures: *Am. Jour. Sci.*, v. 267-A, p. 269-294.
- Lindsley, D.H., 1967, Melting relations of plagioclase at high pressures: *Carnegie Inst. Washington Yearbook* 65, p. 204-205.
- MacGregor, I.D., 1968, Mafic and ultramafic inclusions as indicators of the depth of origin of basaltic magmas: *Jour. Geophys. Res.*, v. 73, p. 3737-3745.
- MacGregor, I.D., 1970, The effect of  $\text{CaO}$ ,  $\text{Cr}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$  and  $\text{Al}_2\text{O}_3$  on the stability of spinel and garnet peridotites: *Phys. Earth Planet. Interiors*, v. 3, p. 372-377.
- Reid, A.M., and J.S. Hanor, 1970, Pyrope in Kimberlite: *Amer. Min.*, v. 55, p. 1374-1379.
- Rodgers, K.A., and R.N. Brothers, 1969, Olivine, pyroxene, feldspar, and spinel in ultramafic nodules from Auckland, New Zealand: *Min. Mag.* v. 37, p. 375-390.
- Yoder, H.S., Jr., and C.E. Tilley, 1962, Origin of basalt magmas: an experimental study of natural and synthetic rock systems: *Jour. Petrology*, v. 3, p. 342-582.

Table 1. Partial chemical composition of olivine (ol), orthopyroxene (Opx), clinopyroxene (Cpx), garnet (Gt) and mica (Mi) of inclusions from Bultfontein (B), Dutoitspan (D), Wesselton (W), De Beer's (DB) and Kampfersdam (K).

Wt. %	B-OL	D-OL	W-OL	DB-OL	K-OL
SiO <sub>2</sub>	37.5-39.4	37.5-40.0	39.1-40.2	38.4-40.4	39.0-39.9
Al <sub>2</sub> O <sub>3</sub>	0.0- 0.0	0.0- 0.0	0.0- 0.0	0.0- 0.0	0.0- 0.0
MgO	45.2-51.6	48.5-51.7	46.8-52.2	46.8-52.3	47.3-56.0

Wt. %	B-OPx	D-OPx	B-Cpx	B-GT	D-GT	B-Mi
SiO <sub>2</sub>	56.0-58.5	55.2-58.4	56.4-58.2	41.4-42.4	40.5-42.4	56.4-58.2
Al <sub>2</sub> O <sub>3</sub>	0.2- 0.3	0.1- 3.2	1.5- 4.5	19.4-21.6	16.9-21.9	1.5- 4.5
MgO	32.9-36.2	33.5-36.5	15.1-18.5	17.4-22.1	19.4-23.2	15.1-18.5

Table 2. Chemical composition of olivine (ol), orthopyroxene (Opx), clinopyroxene (Cpx), garnet (Gt), spinel (Sp) and mica (Mi) of inclusions from Loewrencia.

Wt. %	ol	Opx	Cpx	Gt	Sp	Mi
SiO <sub>2</sub>	37.9-39.3	55.6-58.0	53.5-57.7	41.0-42.1	0.0- 0.1	39.5-42.1
Al <sub>2</sub> O <sub>3</sub>	0.0- 0.0	0.8- 1.9	1.4- 2.9	18.4-21.0	5.4-31.5	12.8-15.3
Cr <sub>2</sub> O <sub>3</sub>	-	0.1- 0.7	0.6- 2.6	1.8- 8.3	34.8-56.4	0.1- 1.8
Fe <sub>2</sub> O <sub>3</sub>	-	-	-	0.0- 1.8	6.0-11.0	-
TiO <sub>2</sub>	-	0.0- 0.3	0.0- 0.6	0.0- 1.3	0.1- 5.6	0.1- 2.1
MgO	46.4-51.5	32.0-35.6	16.1-19.1	18.6-21.0	10.3-16.5	21.6-24.5
FeO	-	4.7- 6.5*	1.9- 3.6*	5.4- 7.8	3.0-17.5	1.8- 4.7*
CaO	-	0.2- 1.2	16.6-22.4	4.6- 7.3	0.0- 0.0	0.0- 0.2
Na <sub>2</sub> O	-	0.0- 0.3	0.3- 1.9	0.0- 0.0	0.0- 0.0	0.1- 0.4

## FIGURE CAPTIONS

- Figure 1. The system  $Mg_2SiO_4$ - $MgSiO_3$  at 15 kb.
- Figure 2. Liquidus surface of the system  $MgO$ - $Al_2O_3$ - $SiO_2$  at 15 kb. Light lines are liquidus boundary lines with arrows showing the directions of decreasing temperature. Heavy lines are liquidus isotherms with temperatures indicated in degrees C. Solid dots are compositions studied. Abbreviations are as follows: En = enstatite,  $MgSiO_3$ ; Fo = forsterite,  $Mg_2SiO_4$ ; Sp = spinel,  $MgAl_2O_4$ ; Sill = sillimanite,  $Al_2SiO_5$ ; Sa = sapphirine,  $Mg_4Al_{10}Si_2O_{23}$ .
- Figure 3. Liquidus and solidus relationships in the system  $MgO$ - $Al_2O_3$ - $SiO_2$  at 15 kb. Light lines with arrows are liquidus boundary lines as in Figure 2. Heavy straight lines show phases in equilibrium at solidus temperatures. The compositions of aluminous enstatites are only approximately known. The dashed lines show the positions of the forsterite-spinel and forsterite-enstatite boundary lines at one atmosphere pressure.
- Figure 4. The tetrahedron  $CaO$ - $MgO$ - $Al_2O_3$ - $SiO_2$  shown with the  $SiO_2$  apex in the rear. The smaller tetrahedron  $Fo$ - $Di$ - $An$ - $SiO_2$  shows the region of interest in the present study. Abbreviations are as follows: Fo = forsterite,  $Mg_2SiO_4$ ; En = enstatite,  $MgSiO_3$ ; Di = diopside,  $CaMgSi_2O_6$ ; An = anorthite,  $CaAl_2Si_2O_8$ ; CaTs = Ca Tschermak's molecule,  $CaAl_2SiO_6$ ; Sill = sillimanite,  $Al_2SiO_5$ ; Sa = sapphirine,  $Mg_4Al_{10}Si_2O_{23}$ ; Sp = spinel,  $MgAl_2O_4$ .

- Figure 5. Liquidus surface of the join enstatite - anorthite,  $\text{MgSiO}_3\text{-CaAl}_2\text{Si}_2\text{O}_8$ , at 7, 10, and 15 kb.
- Figure 6. Liquidus surface of the join forsterite-diopside-anorthite,  $\text{Mg}_2\text{SiO}_4\text{-CaMgSi}_2\text{O}_6\text{-CaAl}_2\text{Si}_2\text{O}_8$ , at 7 kb. Light lines are liquidus isotherms with temperatures indicated in degrees C. Heavy lines with arrows indicating decreasing temperatures are boundary lines separating the various primary phase fields. Solid circles are compositions that have been studied. The solid square is a composition studied by Kushiro (1969).
- Figure 7. Same as Figure 6 except at 10 kb.
- Figure 8. Same as Figure 6 except at 15 kb.
- Figure 9. Liquidus relationships in the system  $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$  at 15 kb. Liquidus relationships in the base,  $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ , are after the work of Taylor (see Figure 2) and those in the left hand face  $\text{CaO-MgO-SiO}_2$  are interpolated from Kushiro (1969). Heavy lines with arrows are inferred liquidus univariant lines within the tetrahedron, and the arrows indicate directions of decreasing temperatures. A field of Ca-poor clinopyroxene, recently reported by Kushiro (1969) has been omitted because its limits have not been determined within the tetrahedron.
- Figure 10. Sample location. Dot labeled L is Loewrencia; Solid rectangle labeled K is Kimberly area. Enlarged view shows relationship of mines in the Kimberly area.
- Figure 11. Histogram of fayalite contents of olivine of inclusions from Loewrencia (L), Bultfontein (B), Dutoitspan (D), Wesselton (W), De Beer's (DB) and Kamfersdam (K).

- Figure 12. MgO content in orthopyroxene versus fayalite content of coexisting olivine of inclusions from Loewrencia (L), Bultfontein (B) and Dutoitspan (D).
- Figure 13.  $\text{Al}_2\text{O}_3$  content versus MgO content in orthopyroxene of inclusions from Loewrencia (L), Bultfontein (B) and Dutoitspan (D).
- Figure 14. A. MgO content in clinopyroxene versus fayalite content of coexisting olivine of inclusions from Loewrencia. B. MgO content in clinopyroxene (CpX) versus MgO content in orthopyroxene (OpX). C.  $\text{Al}_2\text{O}_3$  content versus  $\text{Na}_2\text{O}$  content in clinopyroxene from Loewrencia.
- Figure 15. A. Plot of mole per cent Ca, Mg and Fe of clinopyroxenes and orthopyroxenes from Loewrencia. B. Plot of mole per cent  $\text{Al}_2\text{O}_3$ - $\text{Cl}_2\text{O}_3$ - $\text{Fe}_2\text{O}_3$  of spinels from Loewrencia, combined with a linear scale expressing simultaneous variation in FeO and MgO. C. Plot of molecular proportions of pyrope, almandine and grossular in garnets from Loewrencia. D. Plot of molecular proportions of pyrope, almandine and uvarovite plus hanleite.

Fig. 1

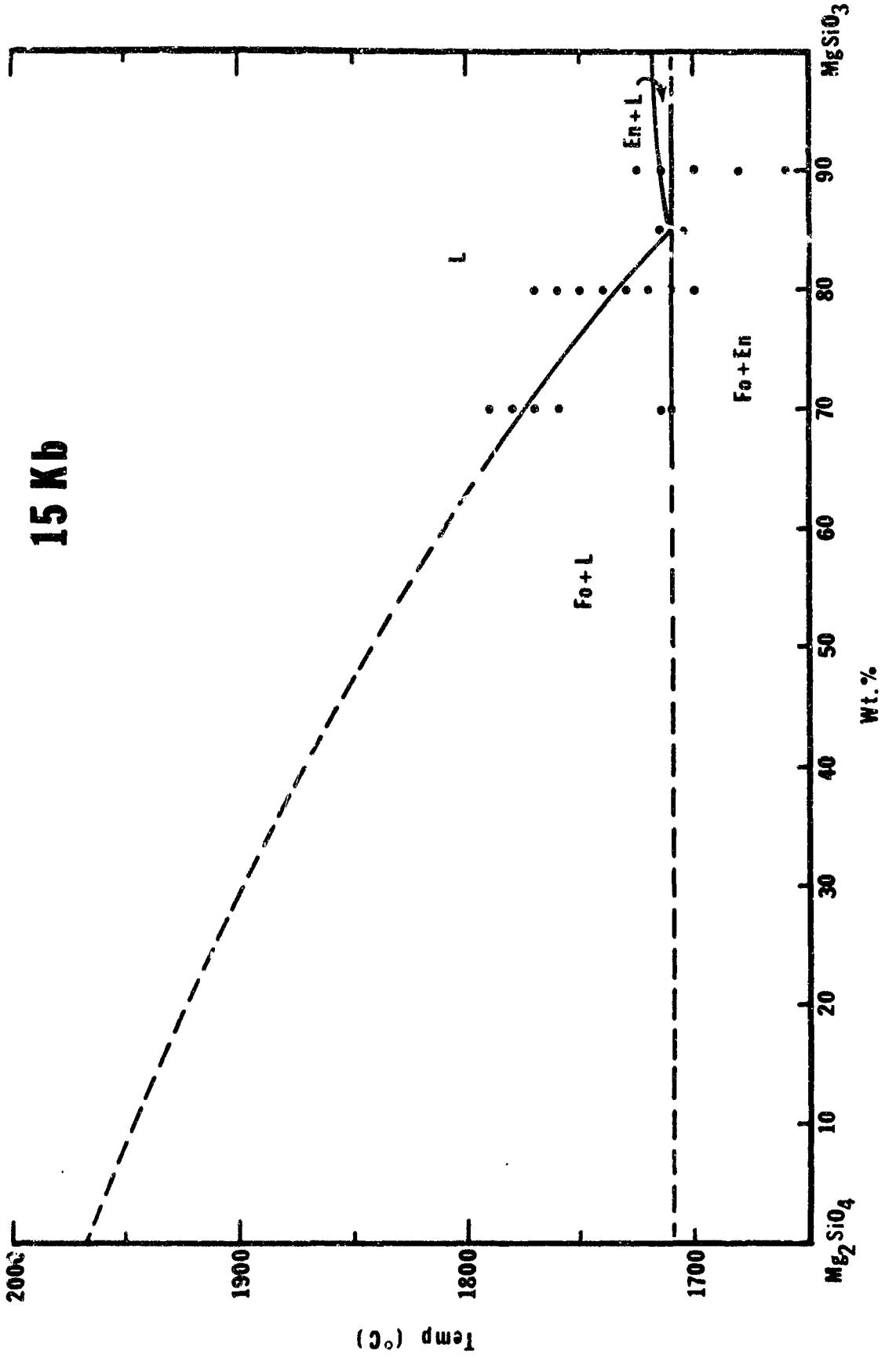


Fig. 2

15 Kb

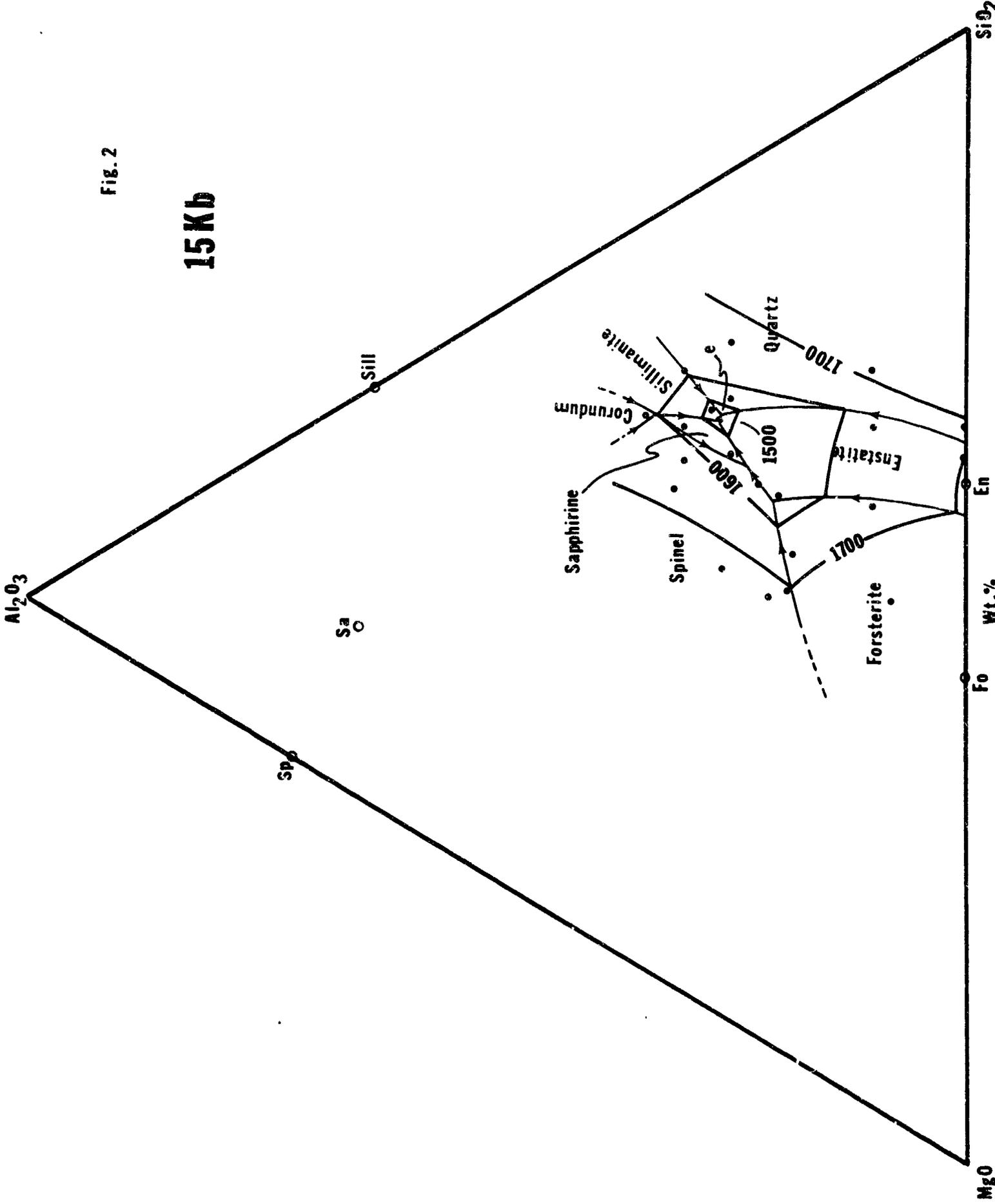


Fig. 3

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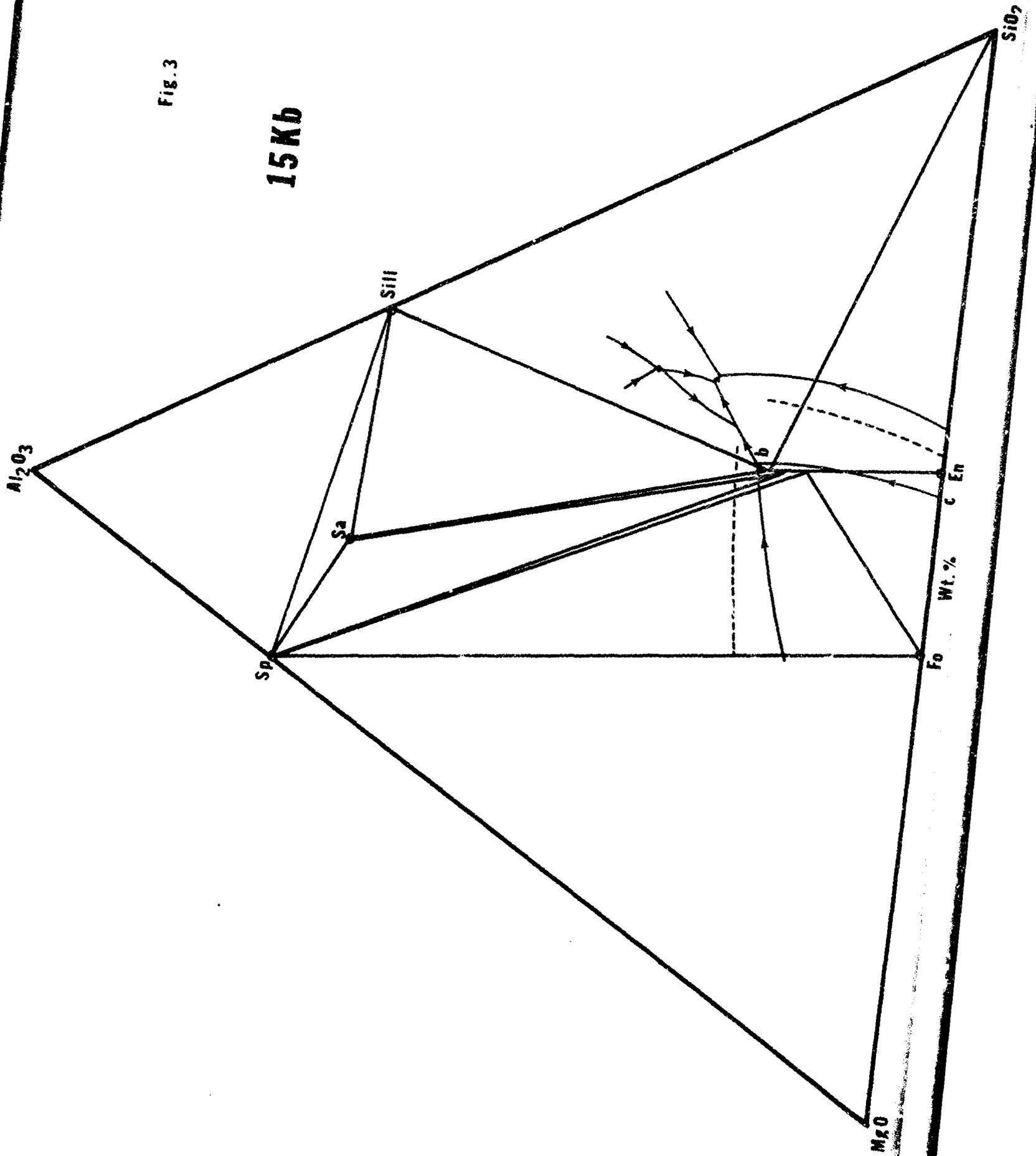


Fig. 4

Wt. %

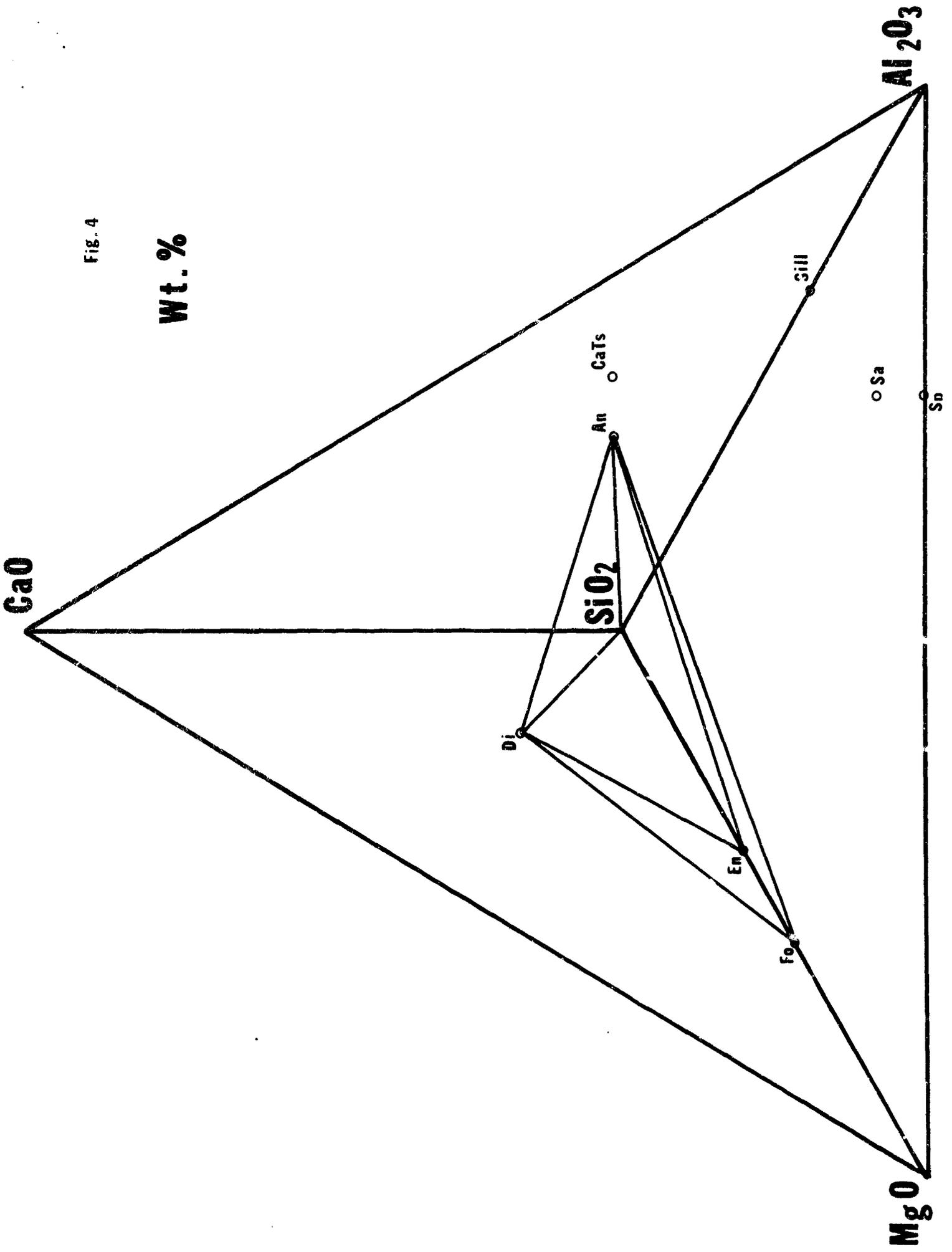


Fig. 5

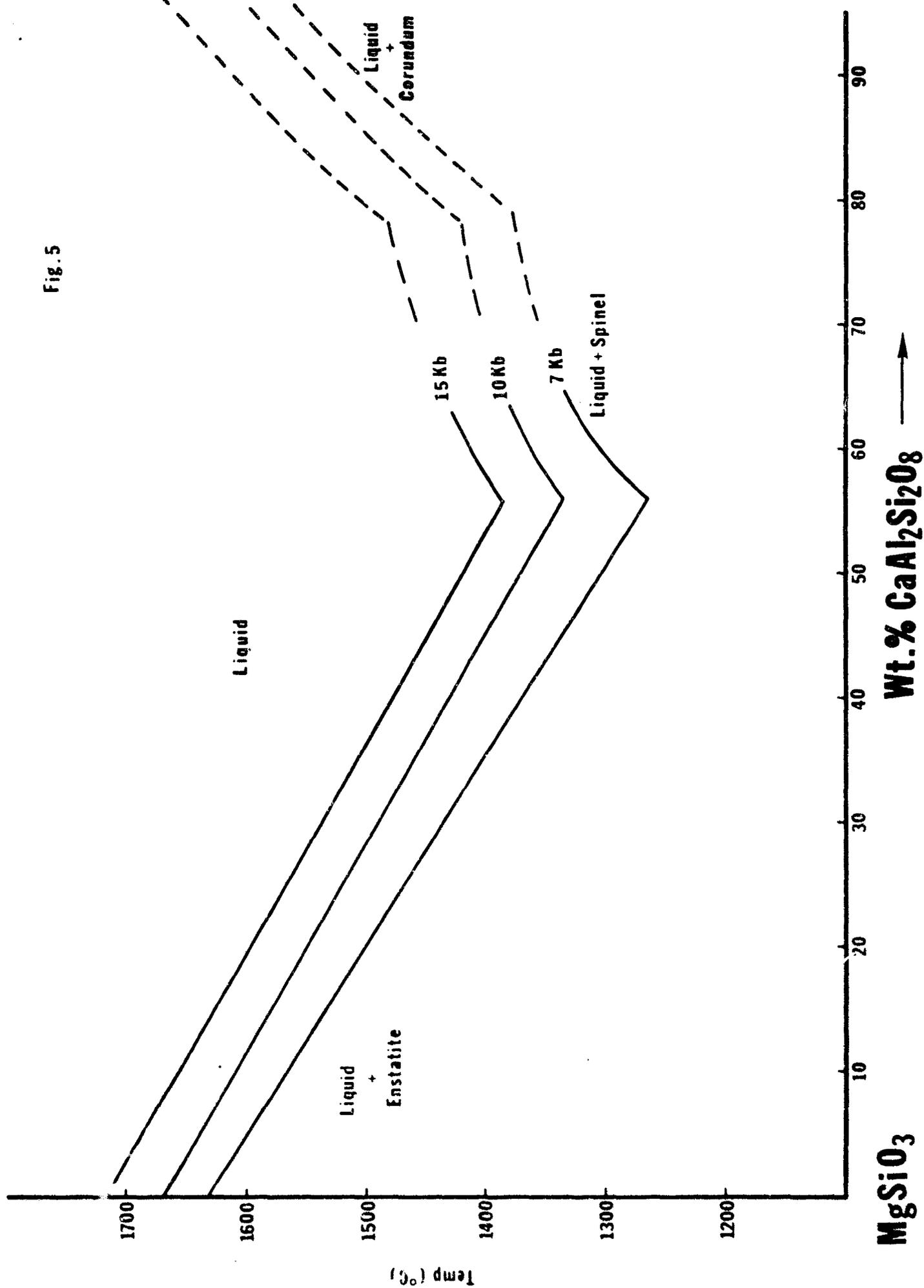


Fig. 6

7 Kb

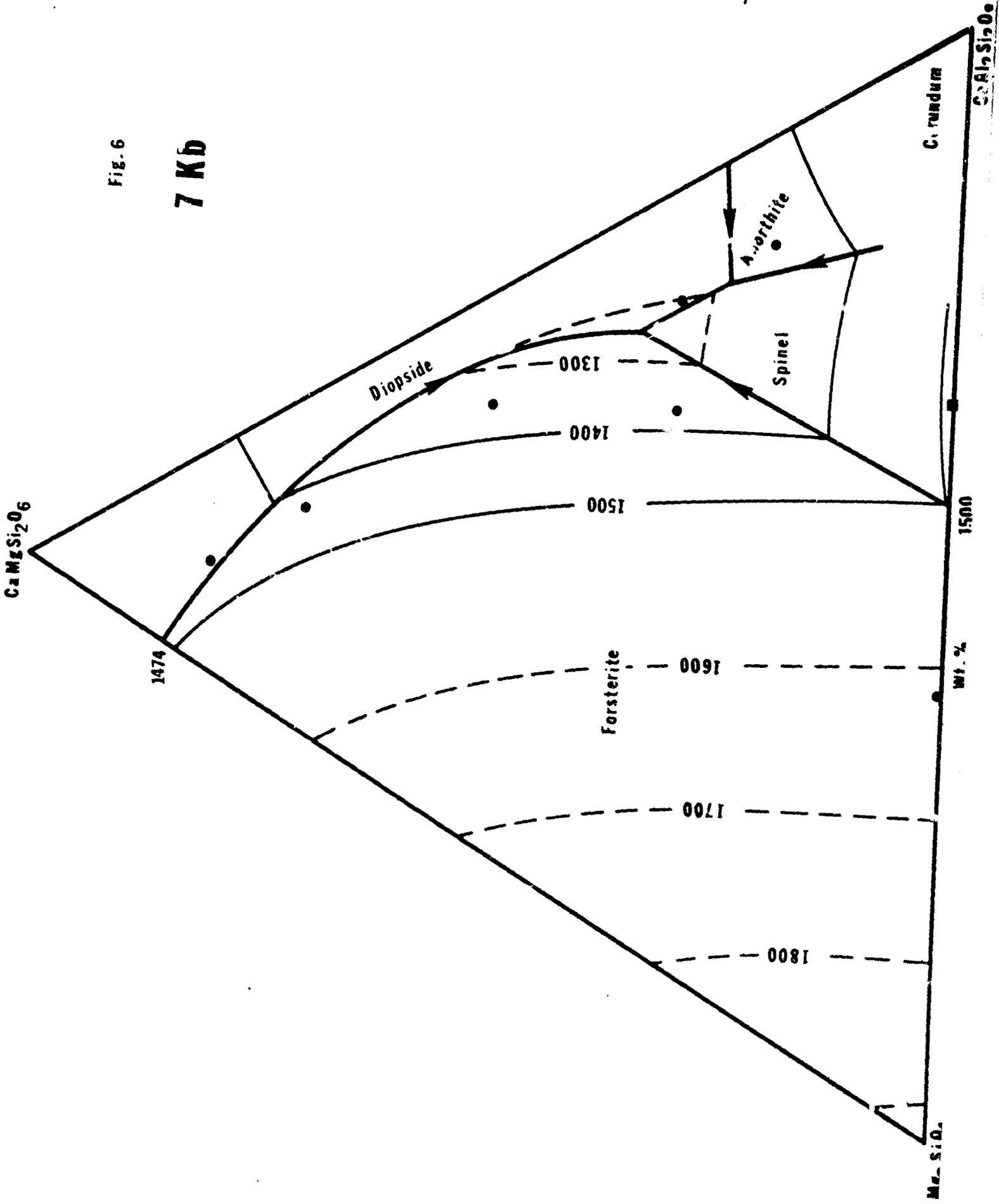




Fig. 8

15 Kb

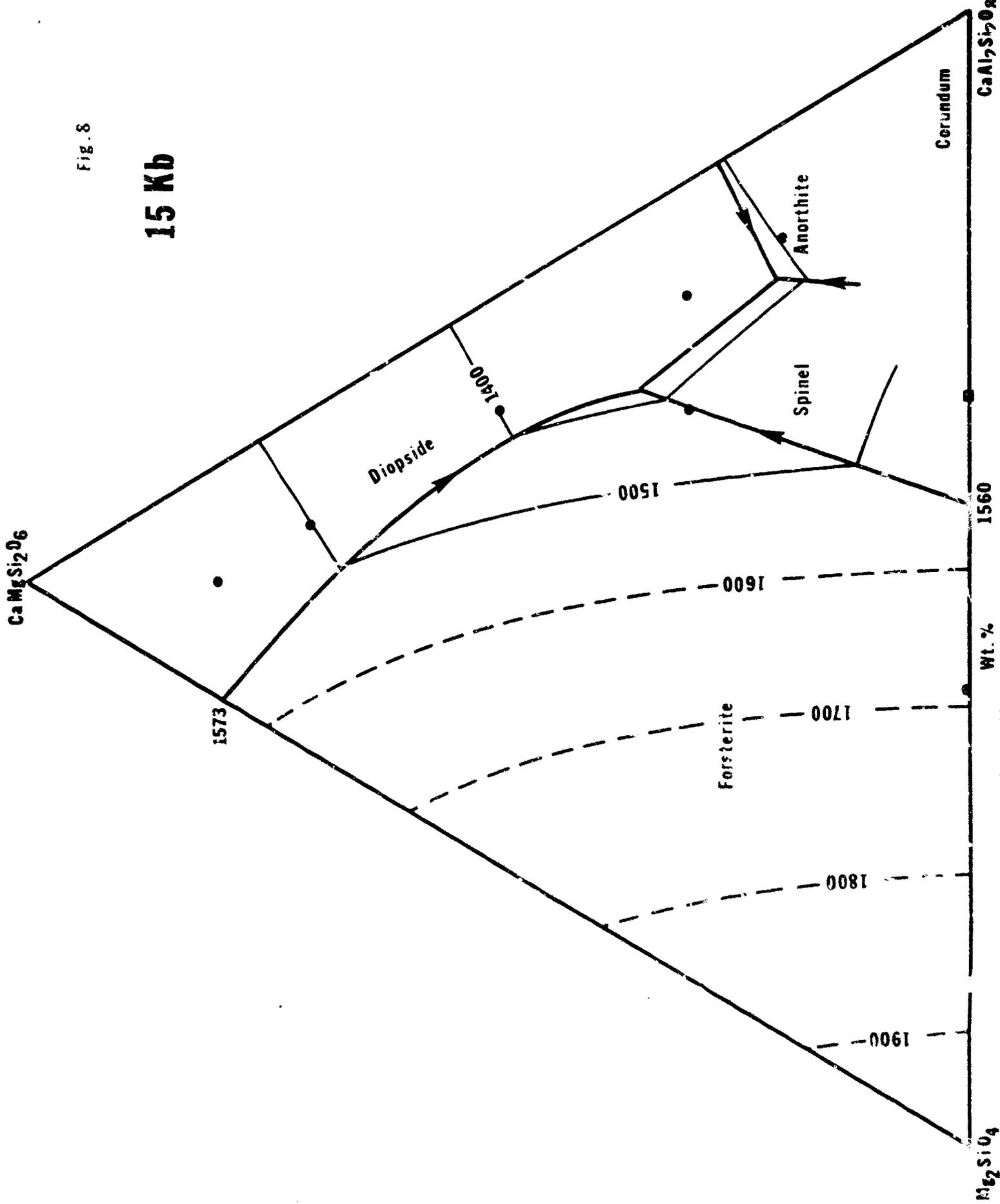


Fig. 9

15 Kb

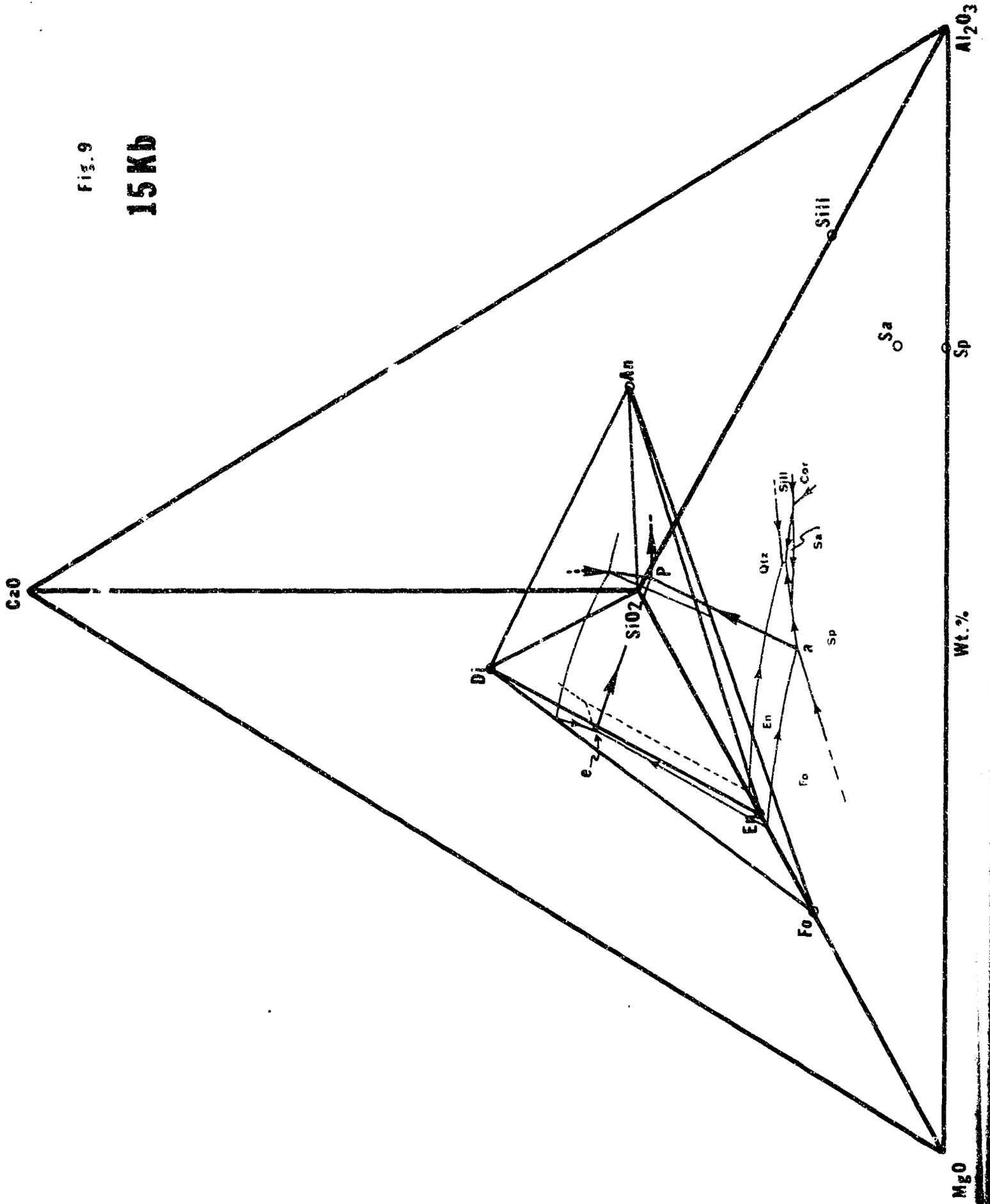


Fig. 10

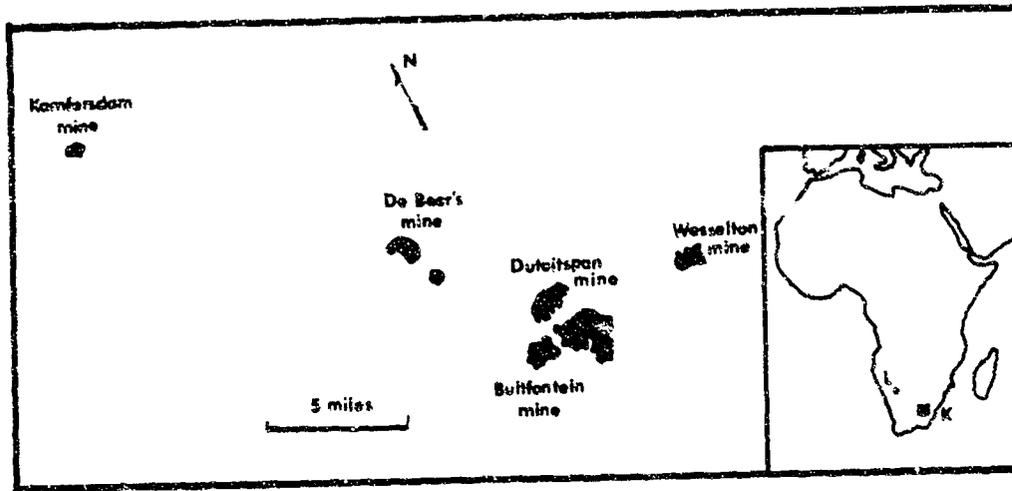


Fig. 11

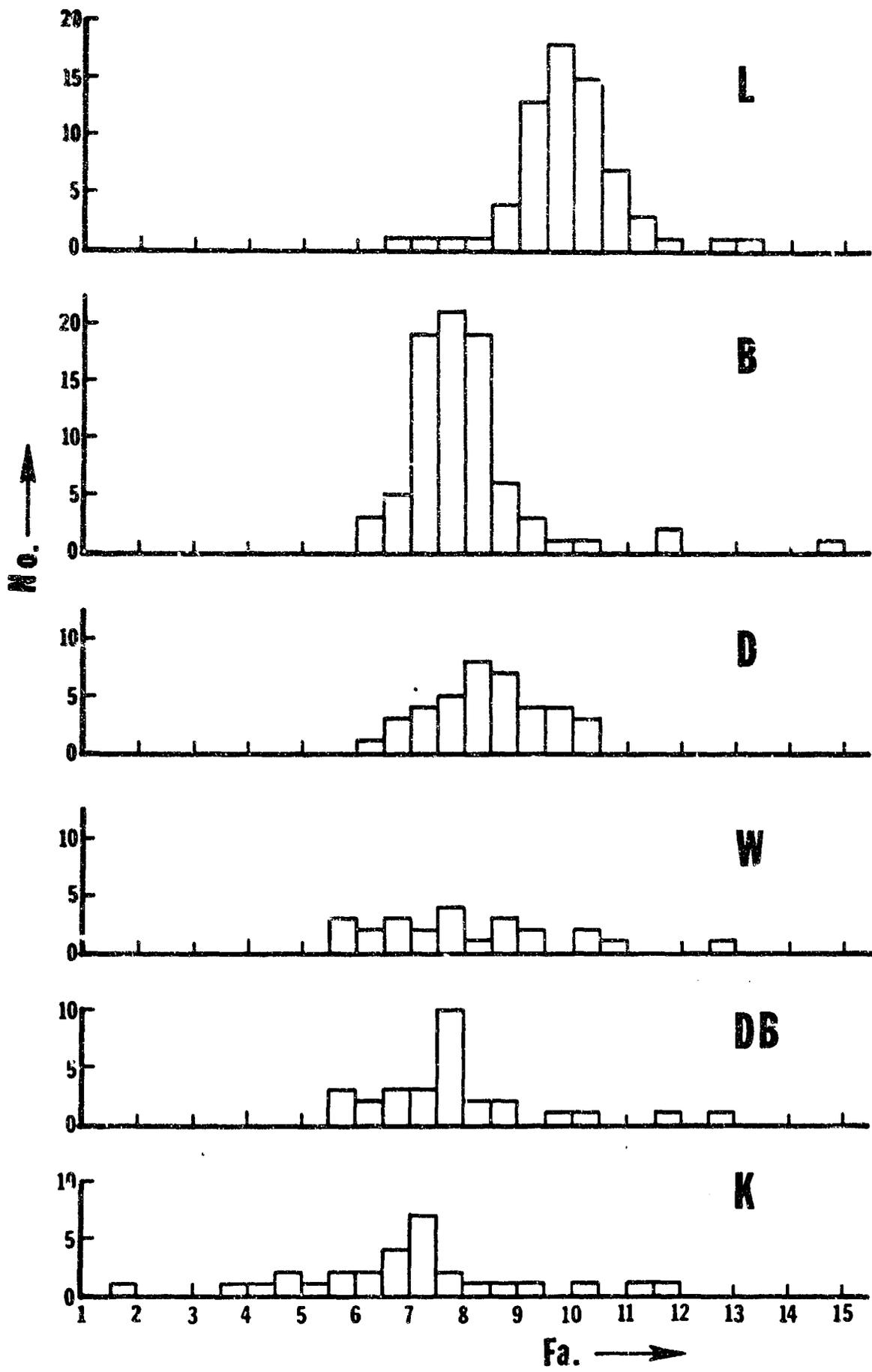


Fig. 12

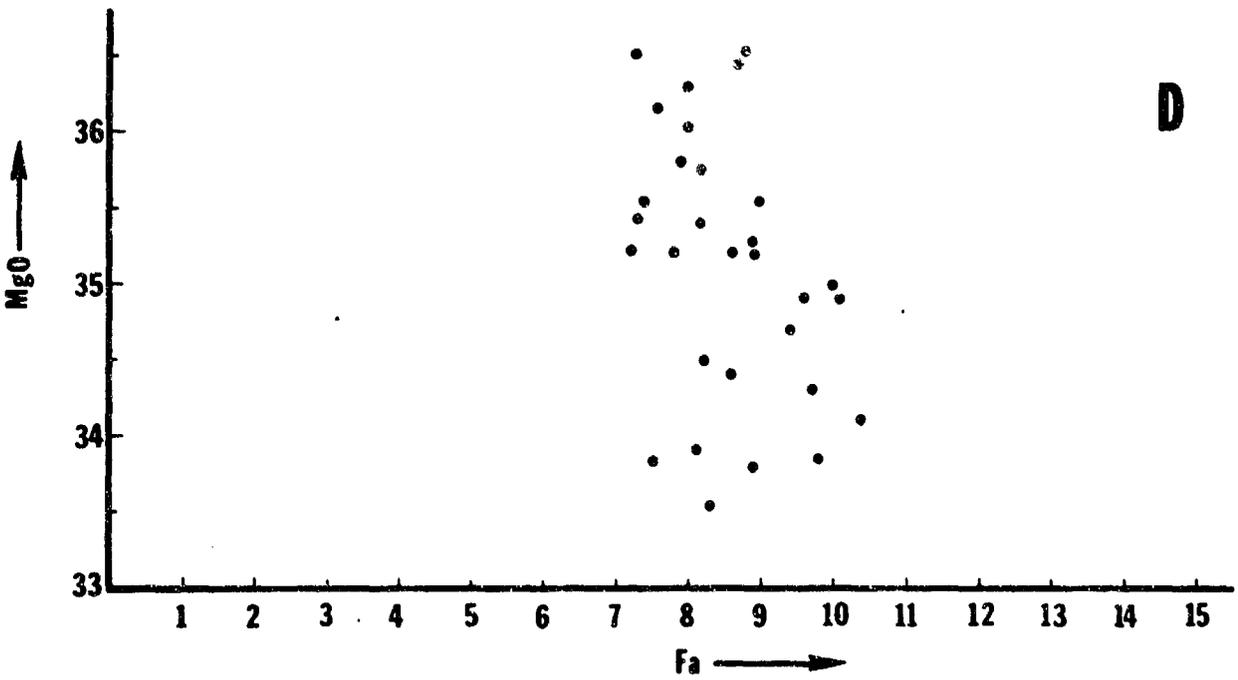
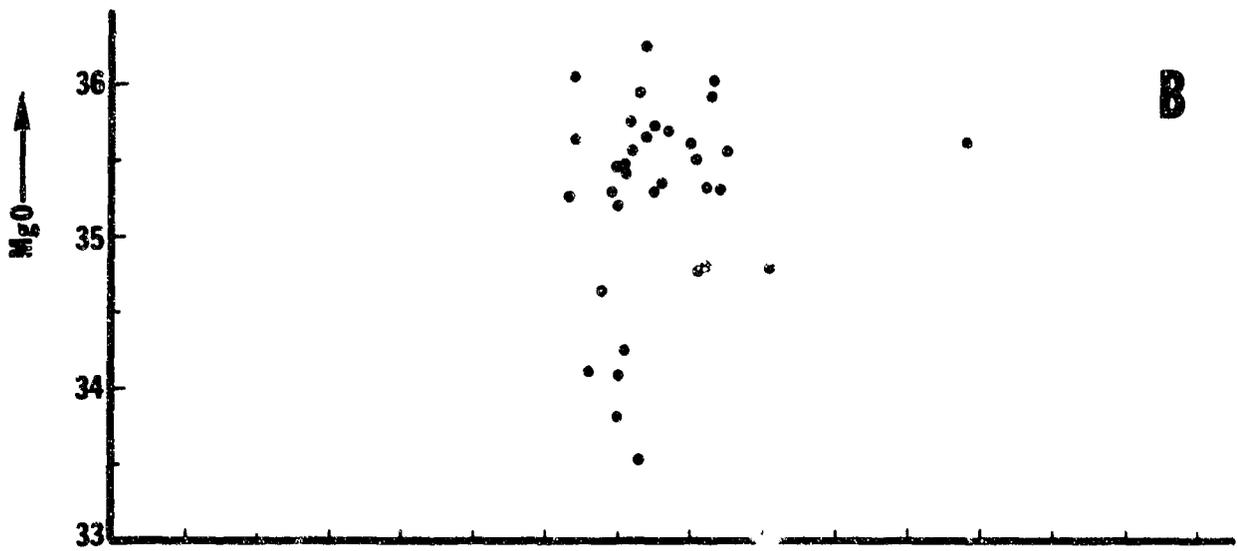
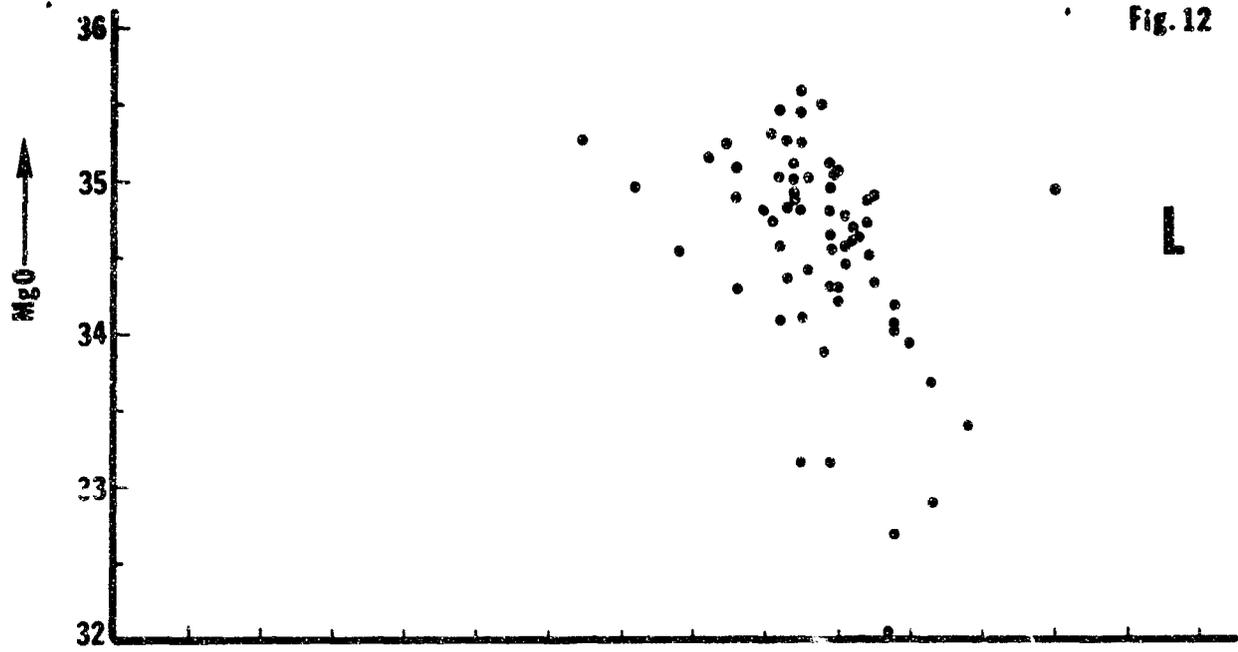


Fig. 13

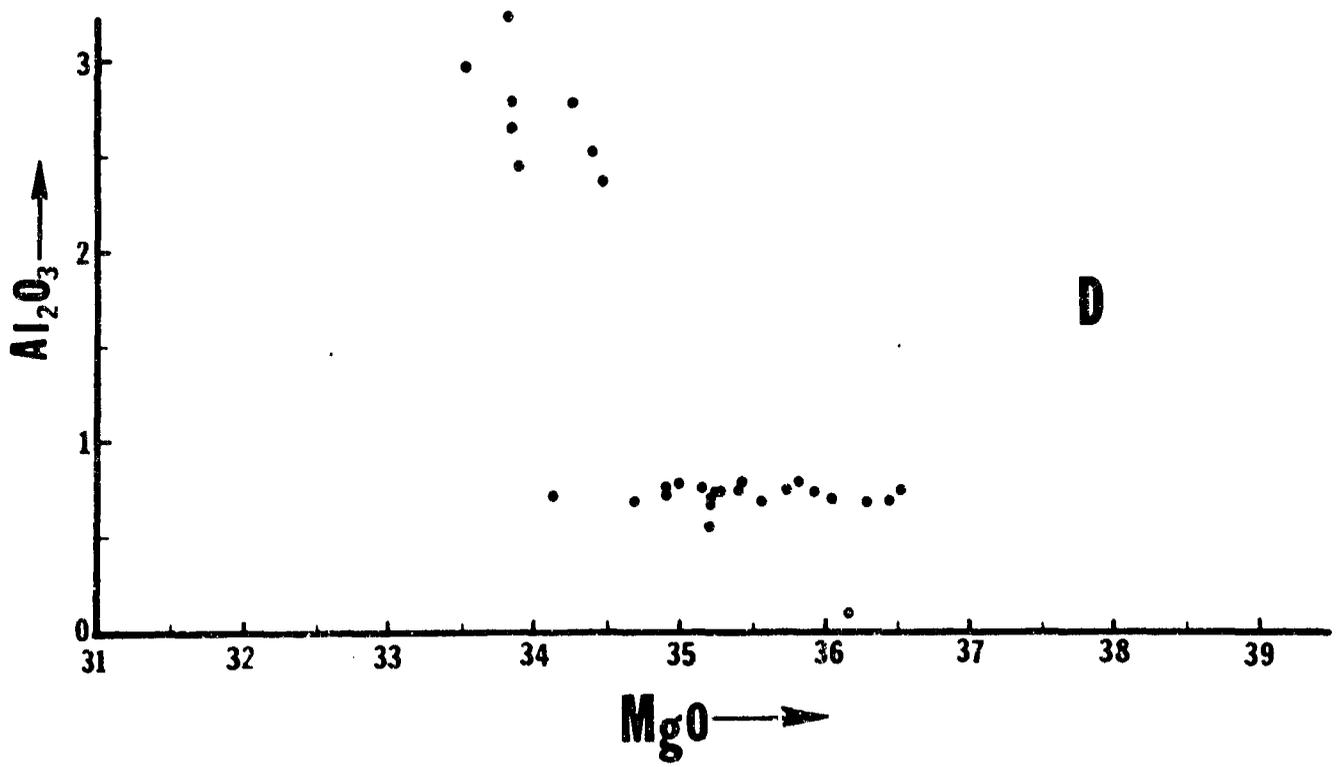
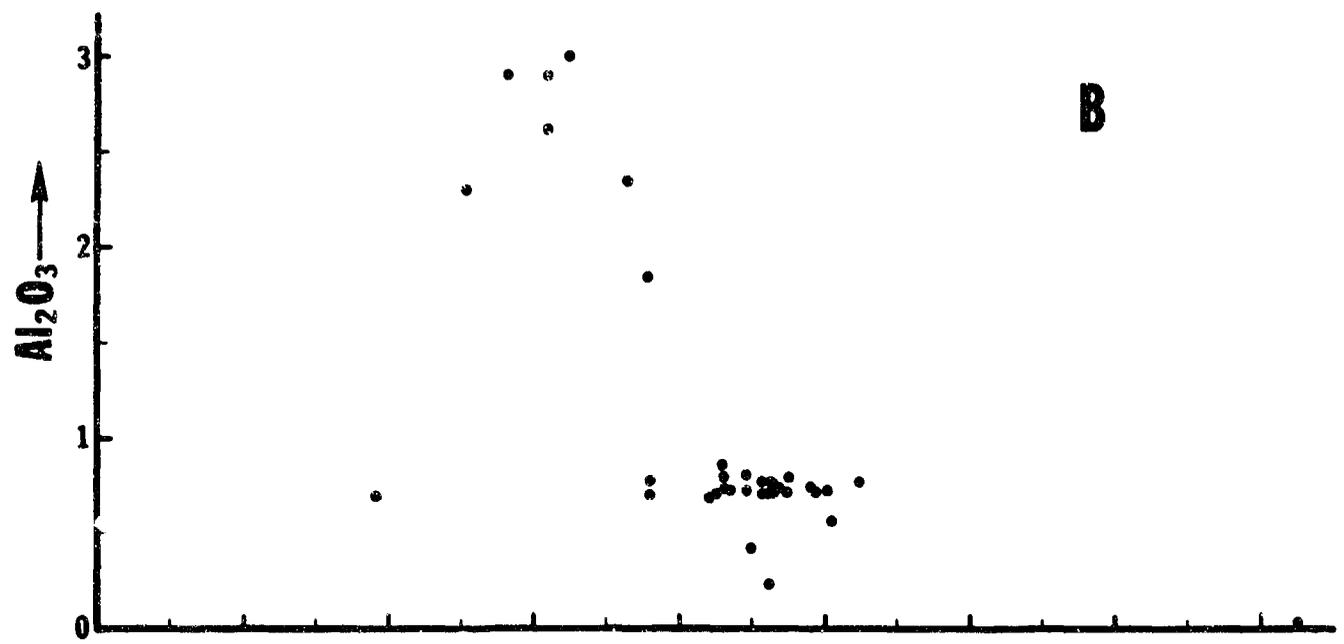
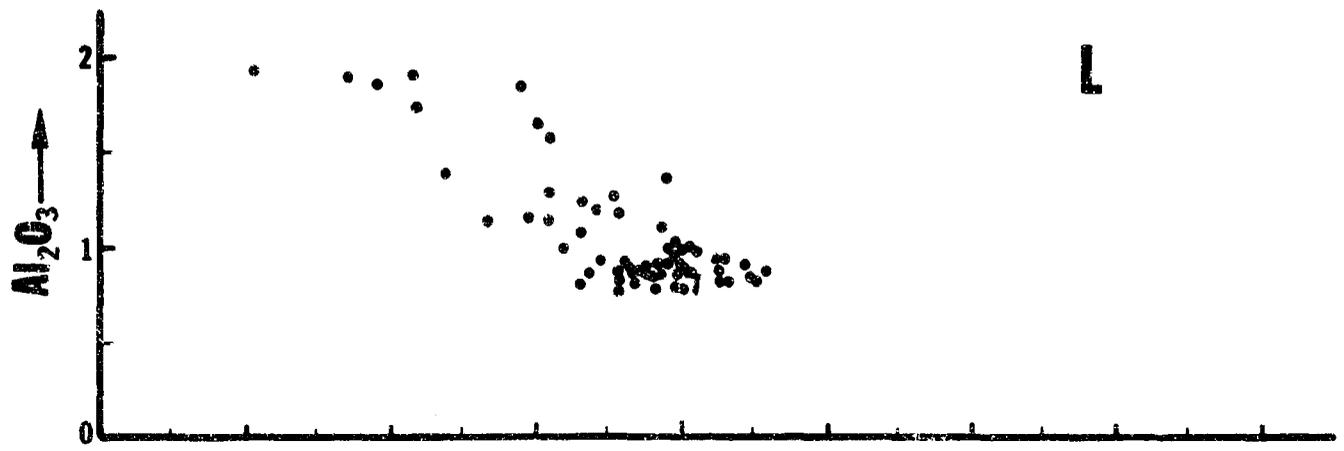


Fig. 14

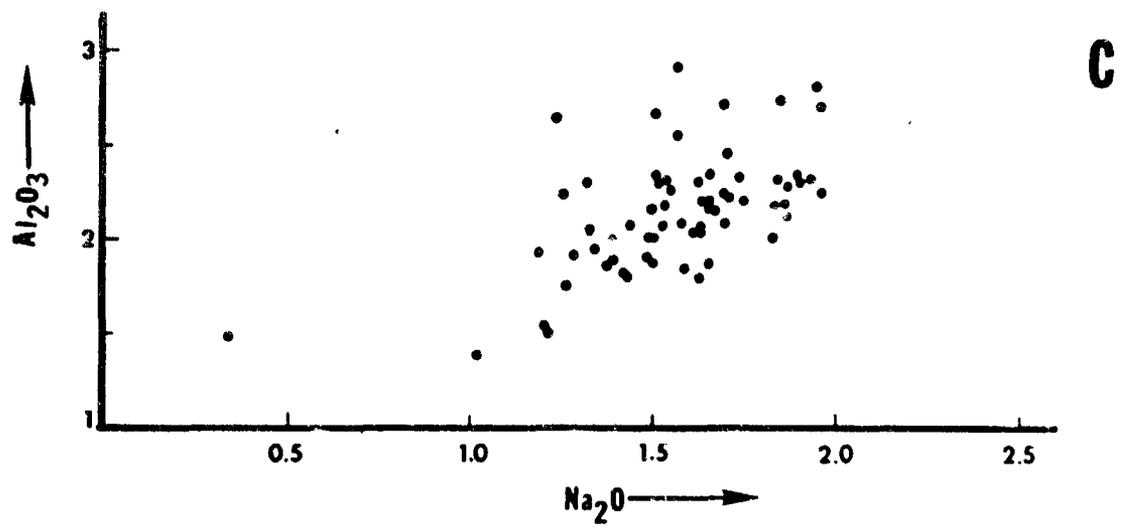
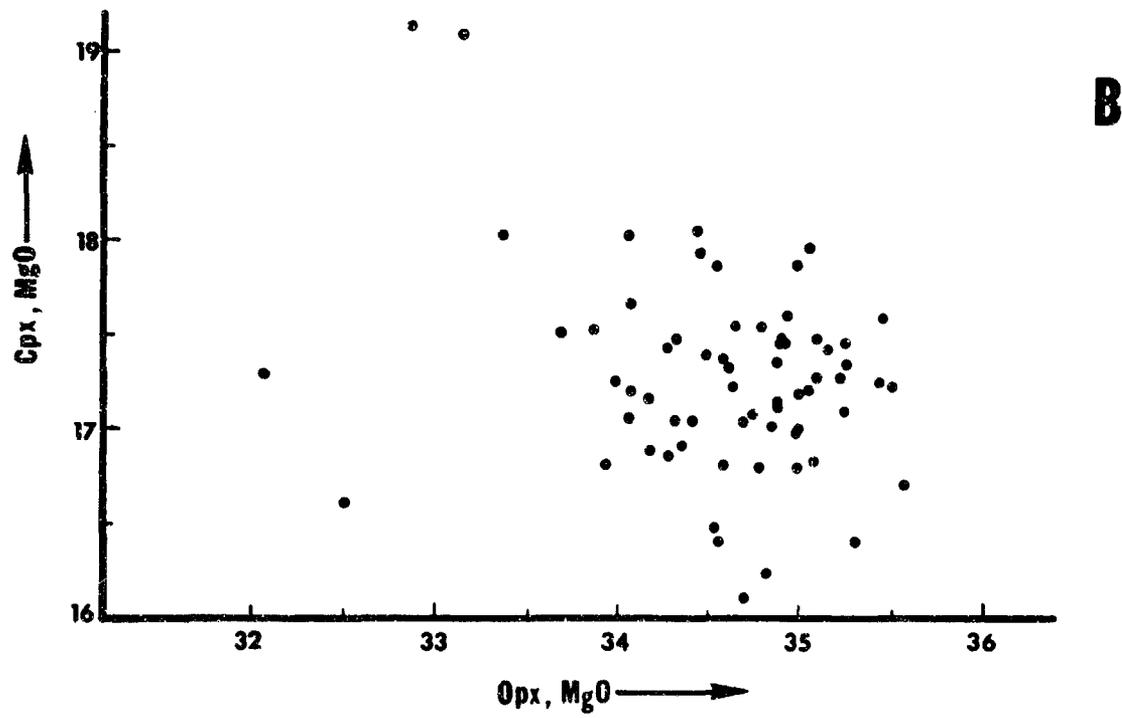
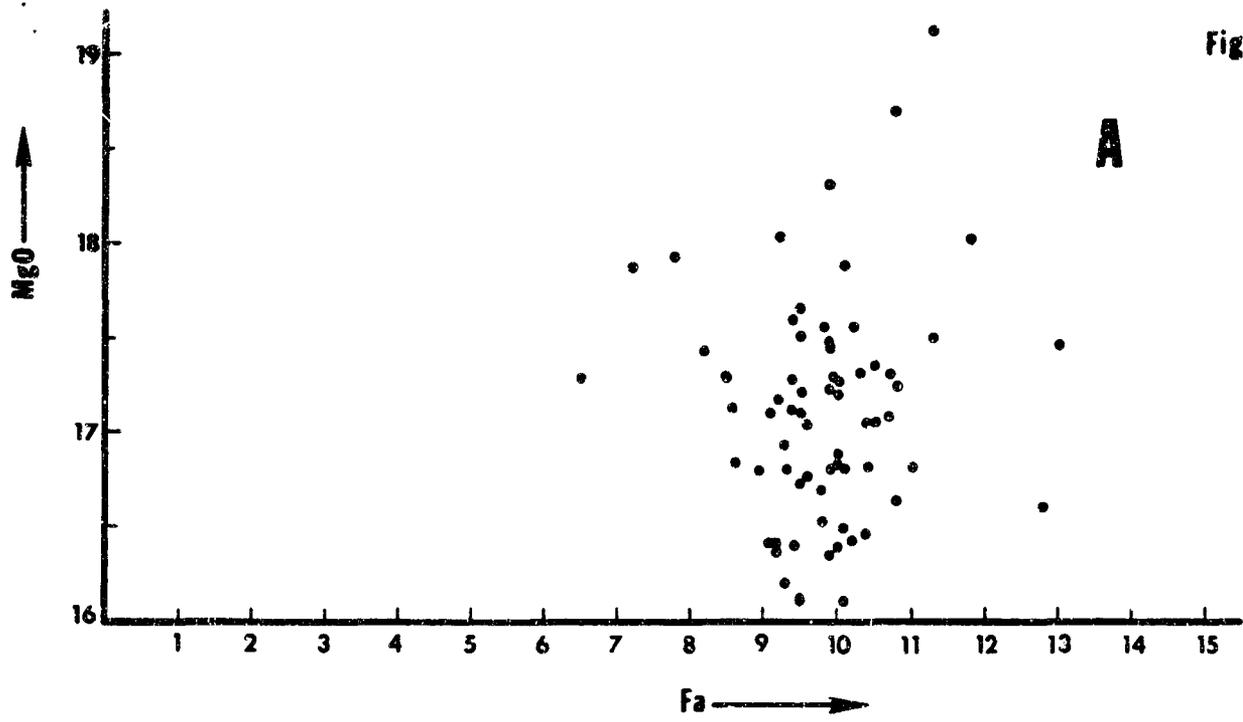
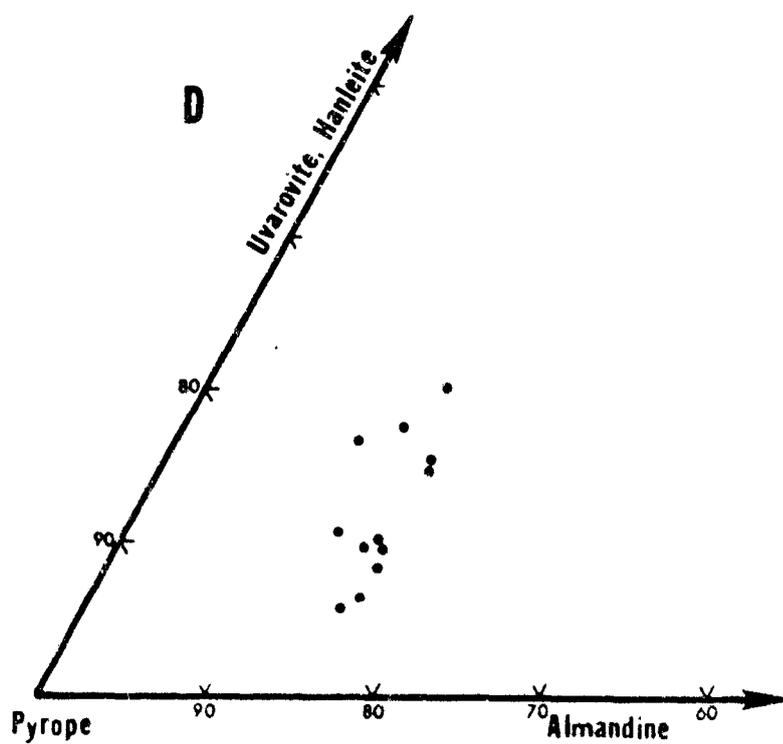
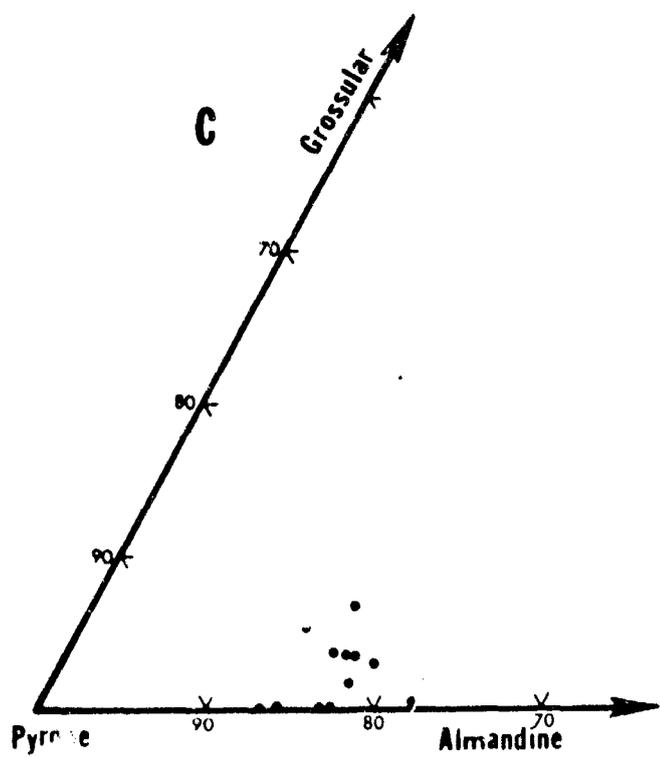
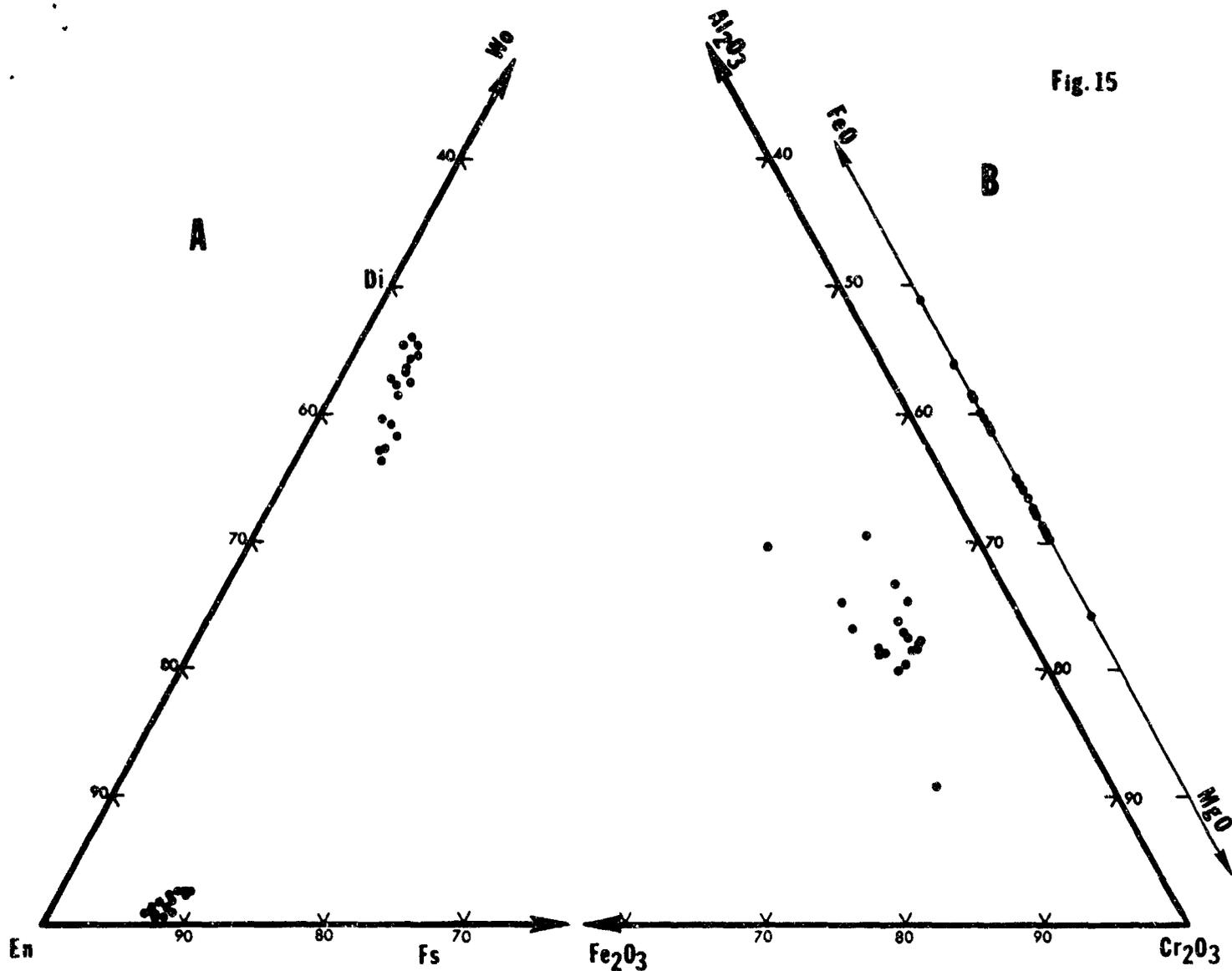


Fig. 15



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- I.D. MacGregor, assistant professor and later associate professor, supported from May, 1966 to August, 1969.
- J.L. Carter, research associate and later assistant professor, supported from May, 1967 to September, 1970.
- D.C. Presnall, assistant professor, supported from May, 1969 to September, 1970.
- H.C. Taylor, graduate student, supported from June, 1968 to August, 1969.

Advanced degrees granted

- H.C. Taylor will complete his thesis on the system  $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$  at 15 kilobars and will receive his M.S. degree in the fall, 1970.

Publications Supported by Contract DA-31-124-ARO-D-463

- MacGregor, I.D., 1966, Stability fields of spinel- and garnet-bearing peridotites, abstract in program of 1966 Annual Meeting, Geol. Soc. America, p. 129-130.
- Presnall, D.C., 1969, The geometrical analysis of partial fusion, Am. Jour. Sci., v. 267, p. 1178-1194.
- MacGregor, I.D., 1970, The effect of CaO, Cr<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub> on the stability of spinel and garnet peridotites, Phys. Earth Planet. Interiors, v. 3, p. 372-377.
- Porath, H., and D.C. Presnall, Changes in electrical conductivity of a synthetic basalt during melting, (submitted for publication to Jour. Geophys. Research).
- \*Carter, J.L., 1966, Chemical composition of the primitive upper mantle, abstract in program of 1966 Annual Meeting, Geol. Soc. America, p. 35-36.
- \*Carter, J.L., 1969, Chemistry of spinels from ultramafic and mafic nodules from Kilbourne Hole, New Mexico, Trans. Am. Geoph. Union, v. 50, p. 345. (Abstract)

\*These papers were inadvertently omitted from previous semi-annual reports. Reprints are not available but Xerox copies are enclosed with this final report.

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<p>This report presents the results of studies of the nature and composition of the earth's upper mantle, using petrography, analytical, and synthetic techniques. The theoretical basis for these studies was established and subsequently high pressure liquidus studies were carried out using the system <math>\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2</math>. This system was chosen to model a composition of the upper mantle because (1) it contains all the major minerals thought to exist in the upper mantle and about 90 percent of the composition of the mantle can be represented by this system, and (2) it contains the maximum number of components that can be handled geometrically with complete rigor and generality. Detailed accounts of the work are contained in the publications which were prepared during the course of the investigation.</p>			
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