

GPO PRICE \$

CFSTI PRICE(S) \$

Hard copy (HC)

Microfiche (MF)

853 July 65

Lunar Differentiation Processes

Dr. Louis S. Walter
NASA, Goddard Space Flight Center
Greenbelt, Maryland

INTRODUCTION

The chemical and mineralogical composition of the lunar surface will be known in the near future. It may therefore be of interest to consider the processes of igneous rock differentiation as they may apply to the moon. Such speculations may aid in making the extrapolations from such preliminary data which will be necessary in order to define more completely the nature of the surface and the processes by which it was formed.

The following discussion is based on the following major assumptions:

1. the increase in total (lithostatic) pressure as a function of depth beneath the surface is less for the moon than for the earth.
2. the moon, at some time in its history has been hot enough, at least locally, to melt the silicate material of which it is composed.
3. This melting process, although local at any one time, has taken place throughout a large portion of the upper part of the moon so that presently there are few places which have escaped igneous activity since the moon was formed.
4. Because of the ubiquitous nature of the melting (in place rather than time) and the gravitative attraction of the moon, the rocks of the moon have lost much of the material which, at standard temperature and pressure are

FACILITY FORM 508

N66 33169

(PAGES)

TMX-54903
(NASA CR OR TMX OR AD NUMBER)

(THRU)

(CODE)

30
(CATEGORY)

considered volatile. Water and oxygen are such materials of particular interest to this discussion.


It turns out that several chemical processes which are suspected of controlling differentiation processes on earth may be affected by the factors discussed above. Furthermore, it seems that these physico-chemical parameters all drive the trend of differentiation in the same direction.

Discussion of the Assumptions

The most likely assumption, indeed, it is almost a fact, is that the increase in lithostatic pressure with depth for the moon is less than that for the earth. Calculations based on a mean density of 3.34 gms/cm^3 and allowing for the variation of gravity with depth have been made by Lowman (1963). The pressure-depth relations thus derived are presented in figure 1. Figure 1 also shows the depth vs. pressure curve derived from data presented by Howell (1959).

There are several present indications that the moon is not a cold body. Heating due to the decay of radioactive isotopes, by meteorite impact and other methods (Kopal, 1962) are considered to have increased the heat content of the moon with time. It is however, impossible to be certain about the thermal gradient at depth and the possibility of localized heating in the moon. Widespread rock melting on the moon is therefore questionable.

MacDonald (1961) has calculated the rise in the temperature of the moon due only to radioactive decay. Assuming that the average content of radiogenic heat producers found in chondrites obtains for the moon, he finds that



temperatures at the center of the moon approach or exceed the melting temperatures of basic rocks, even if the moon were initially cold. It is more important to the present work that these melting temperatures are approached since if they are exceeded, no fractionation occurs. This process takes place when melting is localized in "hot spots" or when the melting points of the more refractory constituents are not attained. Once such a process is begun, it is abetted due to the fact that the radiogenic heat producers (potassium, uranium and thorium) are concentrated in the lighter, more siliceous fraction.

The lunar P-T gradient determined from MacDonald's data and the data presented in figure 1 is shown in figure 2. Opik (1962), considering the insulating properties of the moon's surface layer, estimates a temperature of 600°C at a depth of 10 km (= 0.6 kilobars). Although Opik considers this value to be qualitative, the indication is that the lunar P-T curve of figure 2 is not unrealistic. The terrestrial P-T curve as presented by Turner and Verhoogen (1951) is also shown in figure 2.

It appears from the data in figure 2 that the temperatures of igneous rock fractionation and the partial melting temperature of basic rocks, 1100°C , would normally be attained at a depth of about 300 km beneath the lunar surface, even if the moon were originally a cold body. There is thus a good possibility that localized melting of silicate material has occurred on the moon. It seems likely that such melting has taken place randomly in time and space after the initial build-up of heat and before the loss of volatiles increased the melting temperatures appreciably. The latter stages of igneous

activity would be restricted to those rock types and localities which had the proper combination of low-melting constituents, high radioactive heat generation, low lithostatic pressure and/or high water pressure.

O'Keefe and Cameron (1962) have presented evidence for melting and differentiation of the moon. They suggested that the surfaces of the maria were covered by welded tuffs. Lowman (1963) discussed the nature of igneous activity on the moon. He argues that the emplacement of the great granite batholiths and the basalt flows on earth are generally associated with orogenic or sedimentary cycles. Since it is unlikely that such activity has occurred on the moon, he proposes that igneous rocks on the moon were emplaced as lopoliths which, on earth, are not associated with such cycles. He suggests that these lunar lopoliths, represented by the maria, are largely the result of repetitive extrusive volcanism and that they are capped by their own differentiates.

Such a picture seems a bit more coherent than that proposed by Salisbury (1962) which involved the extrusion of the maria in one stage shortly followed by the formation of a crust over the still-molten maria. Salisbury suggests that the volatiles released by this sub-crustal lava was trapped by the crust at the edge of the maria. Such a process of vapor collection seems unlikely for several reasons. The crusts of terrestrial lava flows are generally disturbed and broken by movements of the lava underneath. Assuming, however, that a continuous cap could form in some way and the original water, comprising 6 weight percent of the magma, is trapped in the volume resulting from the increased density as the magma cools to form crystalline rock, the cap would have to retain a pressure of four kilobars at the temperature of crystallization of the rock.

In an attempt to explain the origin of the lunar domes, Salisbury (1961) further suggests that the reaction between peridotite and water at 500°C which results in a significant volume increase of the resulting serpentine causes the lunar domes to be punched up. It is suggested that this reaction takes place at the 500° isotherm beneath the surface of the moon which, according to figures 1 and 2, lies at a depth of approximately 90 km. It is difficult to imagine how the domes, which have a maximum diameter of about 10 km, could originate from a reaction which takes place at 90 km. Furthermore, the process of serpentinization might often result in elongated or imbricate uplifts and thus fails to explain the generally circular outlines of lunar domes.

The final assumption of depletion of volatiles in the moon hinges on the earlier assumptions. If widespread igneous activity has occurred on the moon, the volatiles originally contained in the lunar material must have been, to a large extent, brought to the surface and then released into space. A very small fraction of these volatiles may have collected in cold traps in shaded areas or in cold layers beneath the surface, but many of these regions would be subject to later periods of volcanic activity. There seems to be no strong mechanism for returning volatiles to depth such as the sedimentary cycles on earth. In addition, since the volatiles, particularly water, generally serve to lower the melting point of rocks, those regions in the moon with higher volatile content would be most susceptible to melting. The mobility of volatiles in aureoles of contact rock on earth strongly suggests that diffusion, coupled with magmatic reworking of lunar rocks would be effective in removing a great deal of volatiles from the moon.

Petrogenetic Processes Affecting Lunar Magmatism

The effect of total pressure. Two principal trends of differentiation of igneous rocks have been recognized by petrologists for many years. The tholeiitic series begins with a primary differentiate of basalt which is rich in augite and poor in olivine. This trend terminates with a rhyolitic end-product and is therefore characterized throughout by a relative abundance of the SiO_2 constituent. On the other hand, the primary precipitate of the alkalie basalt trend is a basalt rich in olivine and the final product is trachyte which is silica-deficient.

Yoder and Tilley (1962) have recently argued that these two magma types could be derived from the same (more basic) parent material by fractional crystallization or partial fusion of this parent under contrasting pressure conditions. Their discussion seems to have considerable bearing on the in our investigation of differentiation trends of lunar rocks.

The composition of the final liquid remaining after the crystallization of a rock melt, or the first liquid to form when a rock is melted is, of course, a function of the mineralogical composition of the rock. This mineralogical composition, however, may not be constant for a given bulk composition since phase transformations in the solid state may occur before the rock melts. Many such reactions have been deduced from metamorphic rocks and have often been found, in the laboratory, to be dependent on pressure. Thus, the pressure conditions which exist during rock melting will be a determining factor in the composition of the primary or the residual liquid.

F163 Fig. 3, a, b and c illustrates ternary relationships of such high pressure solid state phase transformations which Yoder and Tilley have shown

and which they feel have some effect on the differentiation trends of the parent material. Figure 3a indicates that, at high pressures, jadeite becomes stable and albite and forsterite react to form enstatite and jadeite. When crystallized at high pressure, compositions in the field, forsterite-x-enstatite yield a residual liquid which lies in the field forsterite-jadeite-enstatite and is relatively deficient in silica compared with the residuum produced by crystallization at low pressures. Figure 3b illustrates the high pressure reaction of leucite and enstatite to form forsterite and sanadina. In this case, those residual liquids resulting from crystallization of mixtures in the field forsterite-x-enstatite are relatively depleted in silica if crystallization occurs at high pressures. Similarly figure 3c indicates the reaction of anorthite and forsterite to form pyrope and grossularite. Upon fractional crystallization at high pressures, mixtures in the field forsterite-x-pyrope become relatively depleted in silica.

Fig 4 In figure 4 the pressure-temperature conditions of melting in the high-pressure "eclogite" field and low pressure "basalt" according to a diagram by Yoder and Tilley (1962) are illustrated. Superimposed on these relations are the P-T gradients for the earth and moon.

Since partial melting and differentiation result from local heating (corresponding to a horizontal movement to the right from the P-T gradient curves is figure 2) it is evident that terrestrial differentiation can occur from either the basalt or eclogite field, resulting in either tholeiitic or alkaline trends. On the moon, however, it is more likely that local heating

will result in partial melting in the basalt field. This indicates that the lunar igneous rocks will follow a tholeiitic trend and be generally higher in silica.

The effect of water deficiency. Several effects of water vapor pressure on the melting relations of granites have been discussed by Tuttle and Bowen (1958). Increased water pressure lowers the melting point of f6.5 granite (figure 5) and changes the composition of the eutectic in the ternary "granite" system¹ (figure 6).

The higher temperatures at lower pressures occurring on the moon which was just discussed will also affect the composition of the granite differentiate through the change in the position of the eutectic in the "granite" system. Granites on the moon will be formed by local heating at pressures which will generally be lower than the pressures involved in the formation of terrestrial granites causing the lunar granites to be more siliceous and higher in quartz content.

Lower water abundance during the formation of granites will tend to diminish the amount, but not the composition, of the granite formed. Let us imagine the following isolated system: crystalline rock of granite composition with 2% total water at a depth of 80 km beneath the lunar surface and consequently at a pressure of approximately 4 kilobars (see figure 1). The ordinary temperature at this depth would be about 350°C (see figures 2, 3) but local heating results in a rise in temperature of the system. At approximately 660°C (see figure 5) water vapor will combine

¹Since granites are composed essentially of quartz (SiO_2), orthoclase (KAlSi_3O_8) and albite ($\text{NaAlSi}_3\text{O}_8$), extrapolation of the phase relations determined for this simplified system to natural systems is justified.

with crystalline rock to form a silicate melt. This melt will have the equilibrium amount of water for a granite melt under these P-T conditions, namely 9 weight percent. This relationship will be maintained as heat is added to the system until all the vapor is consumed. The system now consists of about 25% melt (silicate + water) and 75% crystalline granite. Further melting is impossible unless temperature increases. If this occurs, more rock gradually melts until, at 820°C a granitic liquid with 2% water is the only phase in the system. If the assumption of decreased water abundance on the moon is correct (and this follows directly from the assumption of widespread volcanism) the above illustration indicates the mechanism by which lunar volcanism may have been self-limiting. The requirement that lunar rocks be heated to considerably higher temperatures may have considerably slowed down the pace of volcanic activity in the later history of the moon.

If we generalize the previous illustration somewhat by choosing a basaltic composition instead of a granitic composition we may investigate the effect of decreased water abundance of the composition of the differentiate. In this case, the first melt to form will be approximately of granite composition but as additional material melts, the composition of the liquid will become more basic. In short order, however, melting ceases because the water is consumed. The result is a melt which diverges much less from the granite minimum composition than would a melt formed under conditions of greater water abundance. It thus appears that the later products of lunar magmatic activity should, in general, lie closer to granitic composition than they do on earth. In other words, the intermediate dacites and

andesites should be relatively less abundant on the moon, compared with rhyolites, than they are on earth. These rocks should, in general, be richer in SiO_2 than their terrestrial counterparts.

The effect of oxygen deficiency. Investigation of the Skaergaard intrusion of Greenland has pointed up the difference between two differentiation trends in igneous rocks. The difference between these trends is best shown in a ternary diagram which shows the variation of the components

Fig 7. $(\text{CaO} + \text{MgO})$, $(\text{FeO} + \text{Fe}_2\text{O}_3)$ and $(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{SiO}_2)$ as in figure 7. The rocks of the normal sequence (as shown by the analytical results of Tahitian rocks) follow a trend in which CaO , MgO , FeO and Fe_2O_3 progressively decrease while Na_2O , K_2O and SiO_2 increase. The other trend (as shown by analyses of Skaergaard rocks) is characterized by an initial, extreme, enrichment in iron. Kennedy (1955) has shown that such a sequence may be caused by primary precipitation of fayalitic olivine (Fe_2SiO_4) at low oxygen pressures resulting in a relative depletion of SiO_2 in the magma. On the other hand, work by Osborn has shown that the primary precipitation of magnetite (Fe_3O_4) due to high oxygen pressures results in silica enrichment in the residual magma.

Differentiation of lunar magmas, especially in the later stages of magmatic activity, would take place under lowered partial pressure of oxygen. Progressive degassing of the moon may have lowered the availability of oxygen to such an extent that instead of divalent iron coming out in Fe_2SiO_4 , metallic iron would separate as an immiscible liquid or as a

crystalline phase. In this case the trend would be characterized by depletion of iron, magnesium and calcium in the magma and consequent concentration of alkalies and silica.

Conclusions

We have started with the assumption that the build-up of radiogenic heat in the moon has resulted in ubiquitous magma generation. Such igneous activity should have occurred sporadically over the surface of the moon resulting in the differentiation of a lunar crust (if it did not already exist at the time of the formation of the moon). Such differentiation served not only to concentrate the radioisotopes in the more acidic crustal fraction tending to increase the amount of volcanic activity at the surface and further degassing and dehydrating the surficial rocks. Loss of volatiles, however has had the opposite effect of decreasing the generation of magmas. Lack of water and sedimentary recycling may be the reason why the moon seems to be a cold body since volcanic activity may have been greatly curtailed in the recent selenological past.

It is with the products of the most recent stages of lunar magma generation with which this paper deals. Three factors affecting terrestrial magmatic trends which have been studied in the laboratory and in the field have been discussed in terms of their effect on lunar differentiation trends. Two factors, the lower pressure gradient with depth and the supposed water deficiency of the moon would tend to cause lunar magmas to be acidic or silica-rich. An extremely low abundance or fugacity of oxygen would tend to have the same effect.

While such a priori reasoning may be quickly and certainly invalidated by analyses of the lunar surface, it is hoped that consideration of theoretical petrology will enable full utilization and greater understanding of the significance of the first remote instrumental analyses of the surface of the moon.

Acknowledgements

I would like to thank Drs. Paul Lowman and John A. O'Keefe for thoughtful and helpful discussion of the substance of this paper.

REFERENCES

- Howell, B. F., 1959, Introduction to Geophysics: 399 pp. McGraw-Hill, New York.
- Kennedy, G. C., 1955, Some aspects of the role of water in rock melts: Geol. Soc. Amer. Special Paper 62, pp. 489-504.
- Kopal, Z., 1962, The internal constitution of the moon: Planet. Space Sci., v. 9, pp. 625-638.
- Lowman, P. D., Jr., 1963, The relation of tektites to lunar igneous activity: Icarus, v. 2, pp. 35-48.
- MacDonald, G. J. F., 1961, Interior of the moon: Science, v. 133, pp. 1045-1050.
- O'Keefe, J. A., and Cameron, W., 1962, Evidence from the moon's surface features for the production of lunar granites: Icarus, v. 1, pp. 271-285.
- Opik, E. J., 1962, Surface properties of the moon: Prog. Astronautical Sci., v. 1, pp. 219-260.
- Salisbury, J. W., 1961, The origin of lunar domes: Astrophys. J., v. 134, pp. 126-129.
- Salisbury, J. W., 1962, Natural resources of the moon: Nature, v. 195, pp. 424-427.
- Turner, F. J., and Verhoogen, J., 1951, Igneous and Metamorphic Petrology: 601 pp., McGraw-Hill, New York.
- Tuttle, O. F., and Bowen, N. L., 1958, Origin of Granite in the Light of Experimental Studies in the System $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 - H_2O : Geol. Soc. Amer. Mem. 74, 153 pp.
- Yoder, H. S., and Tilley, C. E., 1962, Origin of basalt magmas: An experimental study of natural and synthetic rock systems: J. Pet., v. 3, pp. 342-532.

FIGURE CAPTIONS

Fig. 1 Pressure-depth relationships for the earth (after Howell, 1959) and the moon (after Lowman, 1963)

Fig. 2 Pressure-temperature relationships for the earth (after Turner and Verhoogen, 1951) and the moon (after MacDonald, 1961)

Fig. 3 Ternary representations of low-pressure phase relations (in solid lines) and high-pressure reaction products (joined by dashed lines).

(After Yoder and Tilley, 1962.) The reactions represented are:

a: albite + forsterite \rightleftharpoons enstatite + jadeite

b: leucite + enstatite \rightleftharpoons forsterite + sanadine

c: anorthite + forsterite \rightleftharpoons pyrope + grossularite (Ca--Thermal's molecule)

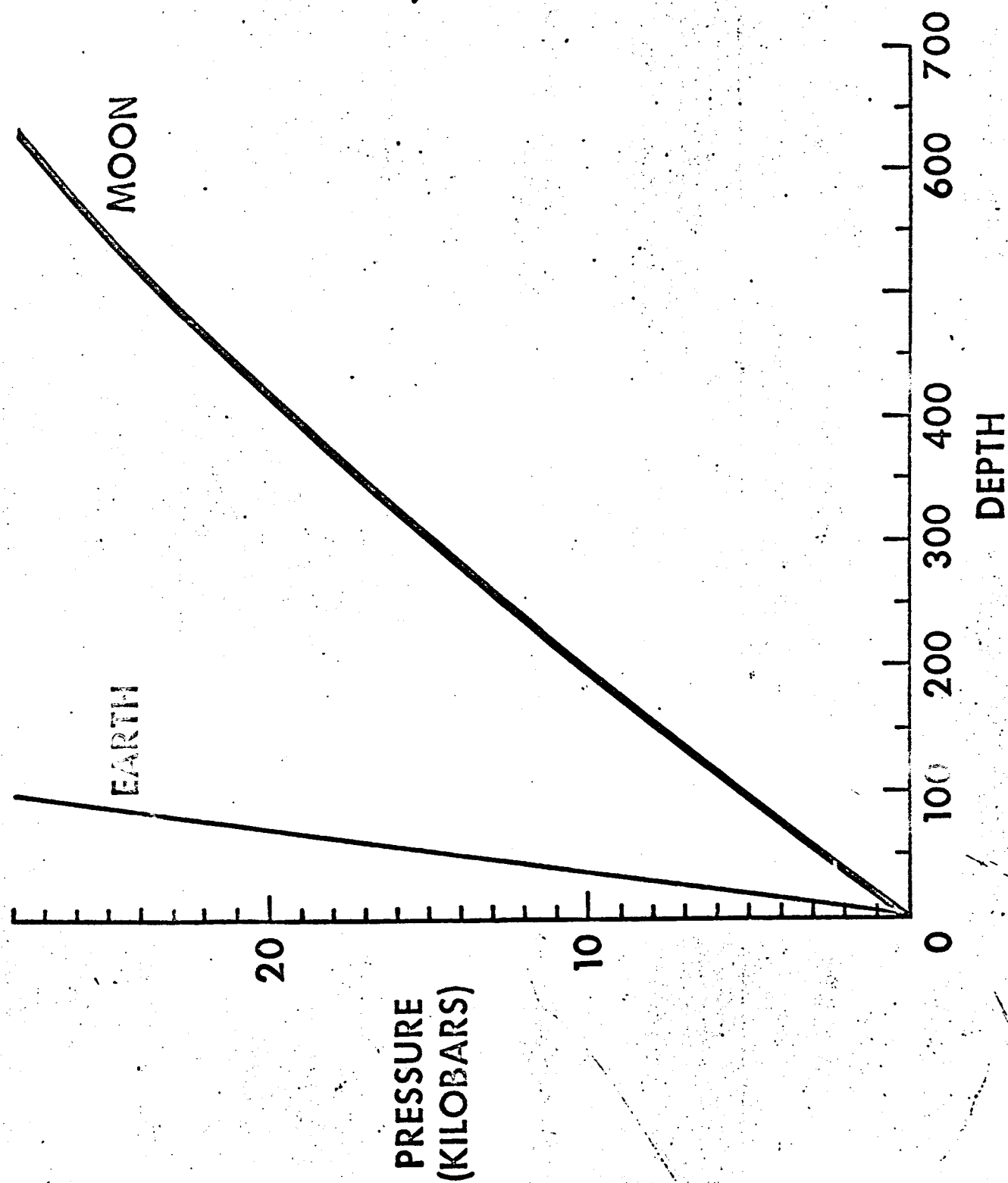
Fig. 4 Pressure-temperature phase relations of material of basaltic composition (after Yoder and Tilley, 1962). Superimposed are the P-T curves of figure 2.

Fig. 5 Pressure-temperature phase relations in the system granite-water (after Tuttle and Bowen, 1958). The P-T curve assumes excess water vapor while the curve labeled "2% H₂O" indicates the conditions under which a granite melt will contain two weight percent water.

Fig. 6 Position of the minimum in the system albite-orthoclase-silica as a function of water pressure (after Tuttle and Bowen, 1958).

Fig. 7 Igneous differentiation trends of Skaergaard and Tahiti rocks in terms of the components (CaO MgO), (FeO Fe₂O₃) and (Na₂O K₂O SiO₂).

Data from Turner and Verhoogen (1951) are schematically represented.



NEPHELINE

KALSILITE

JADEITE

LEUCITE

ALBITE

SANIDINE

a

b

FORSTERITE ENSTATITE SiO_2 FORSTERITE ENSTATITE SiO_2

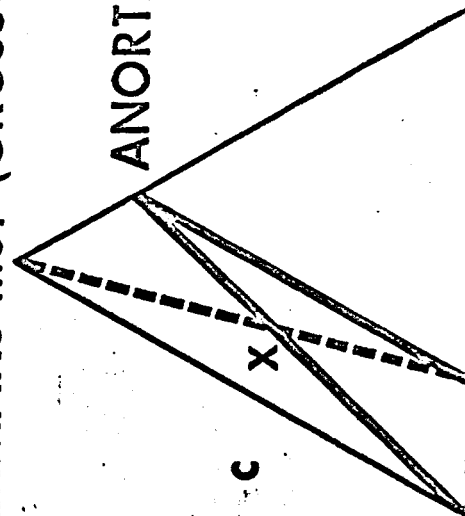
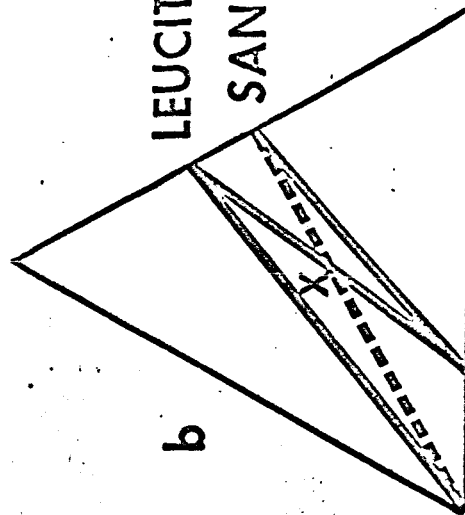
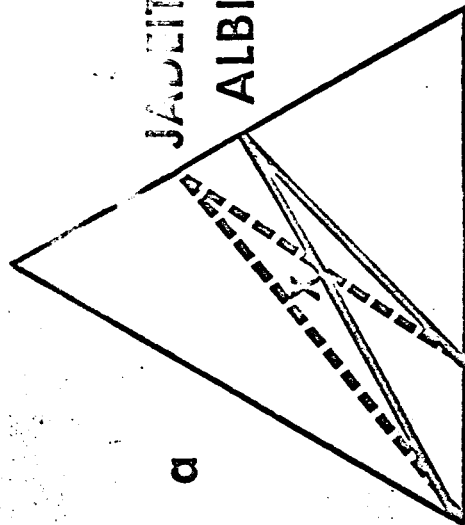
CA-TSCHERMAKS mol (GROSSULARITE)

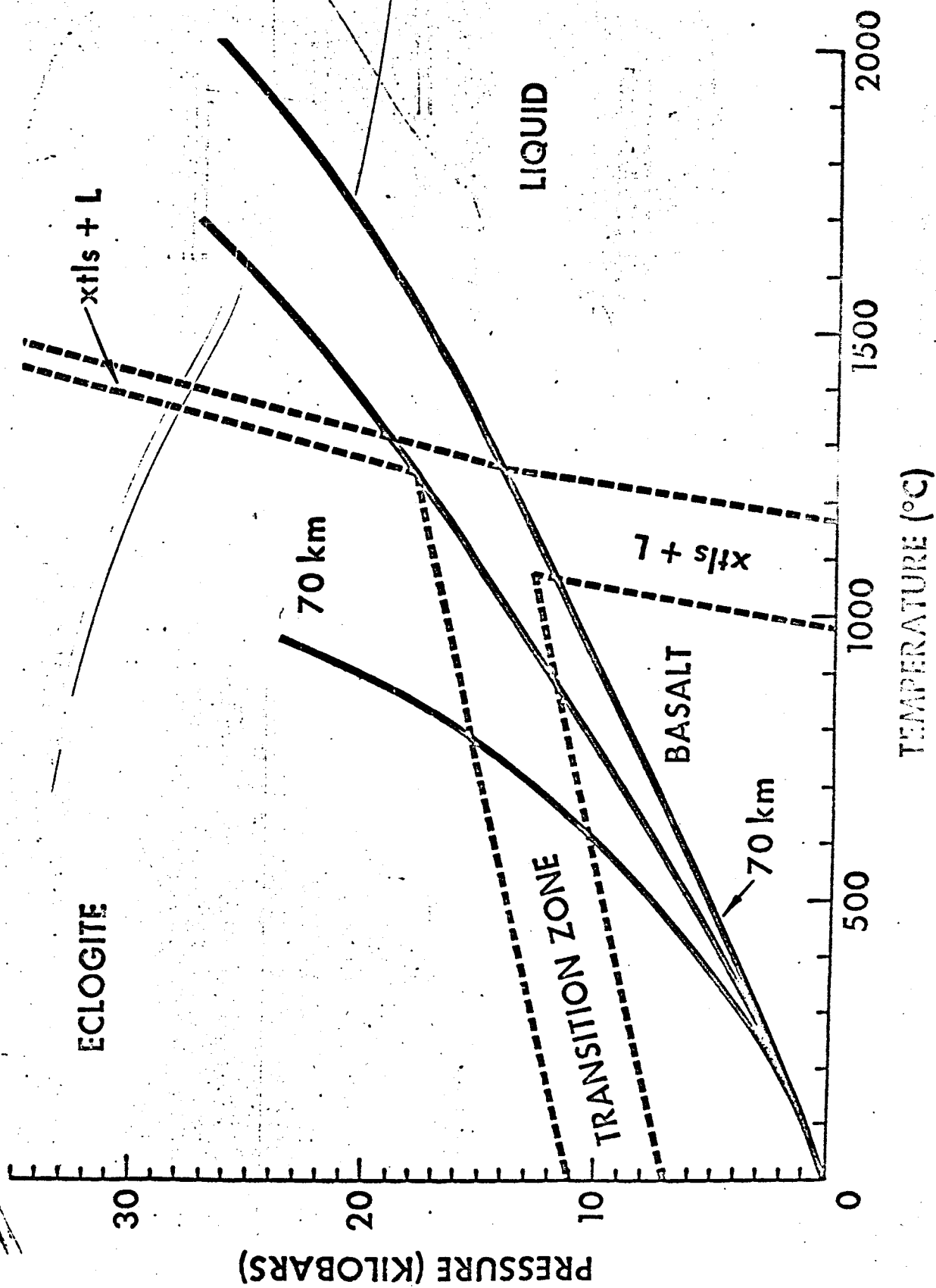
(YODER & TILLEY)

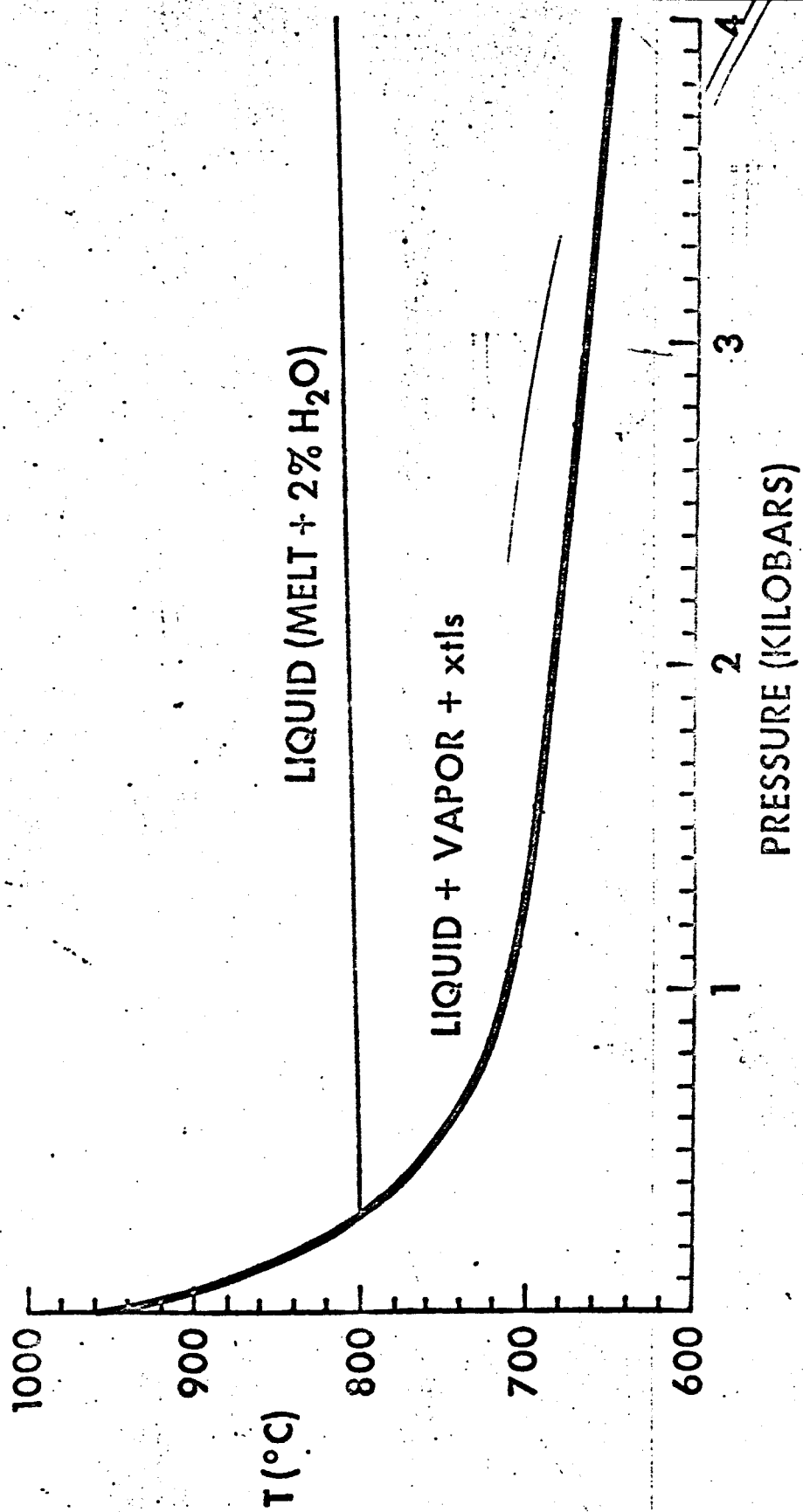
ANORTHITE

c

FORSTERITE ENSTATITE SiO
(PYROPE)







SiO₂

Or

Ab

500
1000°
2000°
3000°
4000°

