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# A NEW MODEL FOR THE LUNAR INTERIOR TO 250 km

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# A NEW MODEL FOR THE LUNAR INTERIOR TO 250 km

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## ABSTRACT

A new model for the structure of the lunar interior to about a 250-km depth is proposed. It is suggested that this region is composed of plagioclase-bearing rocks, and that the 65-km seismic discontinuity represents the appearance of garnet. A variety of rock types mainly composed of plagioclase, pyroxene, olivine and garnet is envisioned, with at least half of the outer 250 km of the moon made of plagioclase, which dominates the electrical conductivity. This model agrees with recent petrological and electrical conductivity results and does not violate velocity-depth profiles obtained from elastic-wave studies of lunar and terrestrial materials.

# INTRODUCTION

Contemporary petrologic and seismic investigations have indicated that the lunar crust is largely feldspathic. It appears to be composed of a cortege of rock types ranging from anorthosite through norite to troctolite, and are commonly called the ANT suite (Keil *et al.*, 1972) or ANTS. Weight percent plagioclase in the norm in ANTS from the lunar highlands varies from approximately 40-100 percent (Wood, 1974). Anorthite content of the plagioclase feldspar ranges from $An_{78}$ to $An_{95}$ (Taylor *et al.*, 1972) in the norites (see Fig. 1).

Toksöz *et al.* (1972) reported a preliminary structure of the moon having velocity discontinuities at 25 and 65 km. They further noted that the gradual increase in the low seismic velocities present to 25 km is caused by compaction of loose material as well as closure of cracks and pores in dry rocks under elevated pressure. Compressional wave velocities in lunar anorthosites (Mizutani and Newbigging, 1973) and terrestrial gabbros (Anderson and Kovach, 1972) are compatible with those deduced for the lunar interior between 21 and 55 km (Toksöz *et al.*, 1974) (see Fig. 2).

Toksöz *et al.* (1972) attribute the 65 km discontinuity to the boundary between the lunar crust and mantle. However, there is no direct evidence for this discontinuity from P-wave velocities (Toksöz *et al.*, 1974). Recent seismic data (Toksöz *et al.*, 1974) demonstrate that lunar upper mantle P-wave velocities are not that well constrained, varying between 7.7 and 9.0 km/sec (see Fig. 3). This allows a wide range of compositional models to fit the seismic constraints. At least four petrologically viable models have been proposed: (1) olivine (Smith *et al.*, 1970), (2) pyroxenite (Ringwood and

Essene, 1970), (3) peridotite (Biggar *et al*., 1971; O'Hara *et al*., 1970), and (4) high-pressure analogue of anorthosite (Anderson and Kovach, 1972).

In this paper, we propose a new model for the structure of the lunar upper mantle (to about 250 km), which we feel agrees with recent petrological and electrical conductivity results. It does not violate velocity-depth profiles obtained from elastic-wave stuides of lunar and terrestrial materials, and fits fundamental constraints of total mass and moment of inertia.

PRESENTATION OF DATA

Experimental data on the phase equilibrium relationships of a gabbroic anorthosite reported by Green (1970) are presented in Fig. 4. He found that plagioclase feldspar is stable to approximately 2.2 GPa at 1173 K and that a series of complex mineralogical reactions occur amongst plagioclase feldspar, pyroxene and garnet solid solutions over this pressure interval. Green further noted that "prior to the first appearance of garnet there is a small decrease in the proportion of plagioclase relative to pyroxene...This effect is attributed to reactions of the type (i) and (ii) resulting in the formation of aluminous pyroxene and quartz, *with coexisting plagioclase becoming more sodic* (italics are ours):

(i) $$\underset{\text{orthopx}}{m(Mg, Fe)SiO_3} + \underset{\text{anorthite}}{CaAl_2Si_2O_8} \rightarrow \underset{\text{cpx}}{Ca(Mg, Fe)Si_2O_6} + \underset{\text{aluminous opx}}{(m-2)(Mg, Fe)SiO_3 \cdot MgAl_2SiO_6} + \underset{\text{quartz}}{SiO_2}$$

(ii) $$\underset{\text{orthopx}}{m\ Ca(Mg, Fe)Si_2O_6} + \underset{\text{anorthite}}{CaAl_2Si_2O_8} \rightarrow \underset{\text{aluminous cpx}}{m\ Ca(Mg, Fe)Si_2O_6 \cdot CaAl_2SiO_6} + \underset{\text{quartz}}{SiO_2}$$

The first appearance of garnet, and its subsequent increase in amount with increasing pressure may result from the reaction of pyroxene with the anorthite component of plagioclase...

$$\text{(iii)}\quad \underset{\text{orthopx}}{4\,(Mg,\ Fe)SiO_3} + \underset{\text{anorthite}}{CaAl_2Si_2O_8} \rightarrow \underset{\text{pyrope-almandine garnet}}{(Mg,\ Fe)_3Al_2Si_3O_{12}} + \underset{\text{clinopx}}{Ca(Mg,\ Fe)Si_2O_6} + \underset{\text{quartz}}{SiO_2}$$

$$\text{(iv)}\quad \underset{\text{clinopx}}{Ca(Mg,\ Fe)Si_2O_6} + \underset{\text{anorthite}}{CaAl_2Si_2O_8} \rightarrow \underset{\text{grossular-almandine-pyrope}}{Ca_2(Mg,\ Fe)Al_2Si_3O_{12}} + \underset{\text{quartz."}}{SiO_2}$$

In addition to Green's results, Fig. 4 presents pressures for the lunar interior taken from Walker et al. (1973); they are approximately 60 percent greater than those reported by Kushiro et al. (1972) at any particular depth. The pressure scale of Walker et al. (1973) is consistent with a simple $\rho gh$ calculation where $\rho = 3.33$ mg/m$^3$, $g = 1.62$ m/sec$^2$ and $h$ = depth. Included in Fig. 4 are the range of temperatures estimated from recent electrical conductivity data for pyroxene and olivine (Heard et al., 1975; Duba and Ringwood, 1973; Duba et al., 1973) under controlled oxygen fugacity and electrical conductivity-depth profiles of Sonett, et al., (1972) and Dyal and Parkin (1973). The uncertainty in temperature is quite large (above 200 km) because of the increased uncertainty in the electrical conductivity-depth profile as well as in the mineralogy.

The most provocative feature of the original lunar $\sigma$-depth profile is the "spike" centered at a depth of approximately 250 km (Sonett et al., 1971) (see Fig. 5). In less than 50 km, the $\sigma$ increases almost three decades. Although detailed analyses indicate that the data may be fitted with a more traditional monotonic profile, the σ spike still represents the mathematically preferred solution (Sonett *et al.*, 1972). The absolute σ at depth and the shape of the σ-depth profile is subject to large uncertainty as indicated in Fig. 5.

Recent σ investigations on albite (Piwinskii and Duba, 1974; Duba and Piwinskii, 1974) provide an explanation for the σ spike and also suggest a method of reconciling diverse petrologic and seismic constraints on the composition of the lunar interior. These studies indicated that the σ of single crystal Amelia albite increased approximately four decades isothermally at temperatures greater than 1253 K and times up to 3200 hr (see Fig. 6). This dramatic increase in σ spike depends on order-disorder phenomena in plagioclase feldspar.

## DISCUSSION OF THE MODEL

We propose that the outer 250-300 km of the moon is composed of plagioclase-bearing rock. If this model is correct, the temperature at the σ spike may be uniquely determined as that temperature where significant disorder commences in the plagioclase feldspar. However, it has yet to be determined if the σ of intermediate plagioclase and anorthite behaves similarly to the albite used in the study reported above.

Extrapolating Green's (1970) data on the gabbroic anorthosite to lower pressures and temperatures suggests that the 65 km seismic discontinuity represents the appearance of garnet as a stable phase. Thus, we suggest that within the upper 250 km of the moon a series of related mineralogical reactions occur amongst coexisting plagioclase, pyroxene, olivine and garnet solid solutions. We envisage a variety of rock types primarily composed of these phases with plagioclase stable until it disappears either by melting or transformation into the high-pressure assemblage via equations (i) to (iv) listed above.

Our model requires at least half of the outer 250 km of the moon be composed of plagioclase feldspar to dominate the $\sigma$. It is assumed that the albitic component of the plagioclase acts as an impurity conductor and thus controls the $\sigma$ of the plagioclase, even if it is only 5 or 10 percent, up to the position of the $\sigma$ spike. We suggest that the $\sigma$ maximum at approximately 250 km marks the point where disorder in the plagioclase increases the $\sigma$ by approximately three to four decades. As depth increases, plagioclase decreases in the amount shown by the reactions mentioned. In this interval, the mafic phases dominate the $\sigma$. We suggest that this type of reaction occurs in the range 250-400 km. Further increase in depth results in the following: (1) plagioclase reaction to form denser mafic phases, and (2) $\sigma$ increases as a result of increasing temperature with depth.

The petrological associations described above are consistent with the range of compressional-wave velocities recently reported by Toksöz et al. (1974). We have calculated P-wave velocities for phase assemblages discussed above using the following equation:

$$V_p = \sum (V_{pi})(\phi i),$$

where $\phi_i$ = volume fraction and $V_{pi}$ = velocity of ith component. This assumes that the velocity in the aggregate is the sum of the product of the volume fractions of the single crystal constituents ($\phi$) and their Voigt-Reuss-Hill average velocities ($V_p$). Voigt-Reuss-Hill averages were obtained from Simmons and Wang (1971) for the minerals in the assemblages listed in Table 1.

The Voigt-Reuss-Hill averages for compressional wave velocities in plagioclase feldspars as a function of anorthite content are plotted in Fig. 7. The linear relationship between $V_p$ and anorthite content is obvious; it is consistent with the linear relationship between elastic constants calculated from $V_p$ and $V_s$ by Ryzhova (1964). We have used this linear variation as license to extrapolate the P-wave velocities to 90% anorthite content, a plagioclase composition more likely to be present in the lunar interior (Wood, 1974). Figures 7 and 8 illustrate the variation in $V_p$ for plagioclases along the join albite-anorthite, and for the assemblages (plagioclase + diopside) and (plagioclase + olivine and/or garnet).

Data presented in Table 1 and displayed in Figs. 7 and 8 indicate the ranges of P-wave velocities that can be expected in plagioclase, pyroxene, olivine, and garnet assemblages. In general, $V_p$ increases with increasing anorthite content of plagioclase and increasing amounts of pyroxene, olivine, or garnet. In lunar anorthosite, compressional wave velocity is about 7.1 km/sec. The addition of garnet and olivine increases $V_p$ from 7.1 km/sec to 8.25 km/sec as the volume fraction of these mafic phases increases to one. These data indicate a regular, monotonic increase in P-wave velocities as plagioclase is consumed in reactions producing ferromagnesian phases. Densities of these assemblages similarly increase in a regular fashion; plagioclase-pyroxene-olivine-garnet assemblages possess densities of 3.3 to 3.4 mg/m$^3$. These are certainly permissible for lunar upper mantle rocks. Thus, we see that rocks containing plagioclase feldspar, pyroxene, olivine, and garnet solid-solution assemblages exhibit compressional wave velocities reported for the lunar crust and upper mantle.

The model presented above is not in conflict with petrogenetic schemes outlined by various investigators for the origin of ANTS, Fra Mauro rocks, and mare-type basalts. Walker <u>et al</u>. (1972) presented experimental data indicating that partial melting of plagioclase, olivine, and Ca-poor pyroxene "will tend to produce significant quantities of liquid having a major element chemistry resembling that of certain Apollo 14 materials," i.e., Fra Mauro igneous rocks and soil glasses. These investigators (Walker <u>et al</u>., 1973) also have shown that plagioclase-rich members of ANTS could be generated by partial melting of plagioclase-spinel-corundum assemblages at approximately 300 km. Also, regarding the petrogenesis of mare-type basalts, Hodges and Kushiro (1973) state that if they can be formed by partial melting then "the source materials were probably ...plagioclase-bearing periodotites for Apollo 12 basalts."

## ACKNOWLEDGMENTS

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Table I. Calculated compressional wave velocities for lunar rocks.

| Mineral assemblage (Volume % in parenthesis) | Mineral composition | $V_p$ (km/sec) |
|---|---|---|
| plagioclase (90) + pyroxene (10) | $An_{90}$; diopside | 7.1 |
| olivine (50) + plagioclase (50) | $Fo_{90}$; $An_{50}$ | 7.5 |
| olivine (50) + plagioclase (50) | $Fo_{90}$; $An_{90}$ | 7.8 |
| plagioclase (50) + pyroxene (40) + garnet (10) | $An_{50}$; diopside; almandine-pyrope | 7.3 |
| plagioclase (80) + pyroxene (10) + garnet (10) | $An_{90}$; diopside; almandine-pyrope | 7.3 |
| plagioclase (60) + pyroxene (20) + garnet (20) | $An_{90}$; diopside; almandine-pyrope | 7.6 |
| plagioclase (50) + pyroxene (25) + garnet (25) | $An_{90}$; diopside; almandine-pyrope | 7.7 |
| plagioclase (50) + olivine (25) + pyroxene (25) | $An_{90}$; $Fo_{90}$; diopside | 7.8 |
| plagioclase (10) + olivine (45) + pyroxene (45) | $An_{70}$; $Fo_{90}$; diopside | 8.1 |
| plagioclase (10) + olivine (60) + pyroxene (30) | $An_{70}$; $Fo_{90}$; diopside | 8.2 |
| pyroxene (70) + olivine (20) + garnet (10) | diopside; $fo_{90}$; almandine-pyrope | 8.2 |
| pyroxene (50) + olivine (30) + garnet (20) | diopside; $fo_{90}$; almandine-pyrope | 8.3 |

# LIST OF FIGURE CAPTIONS

Fig. 1. Whole rock and lithic fragment analyses of lunar highlands materials. Rocks plotting in region between A and B: norite; those between B and C: anorthosite gabbro to anorthosite. Data from Wood (1974).

Fig. 2. Compressional wave velocity of lunar anorthosite 15415, 96 and a terrestrial anorthosite as functions of pressure. Data from Mizutani and Newbigging (1973).

Fig. 3. Compressional wave velocity for the lunar crust and upper mantle.

Fig. 4. Experimental runs on gabbroic anorthosite after Green (1970). Curved full and dashed lines straddling appearance of garnet curve represent the estimated P-T regime for the lunar interior. See text for complete discussion.

Fig. 5. Lunar electrical conductivity profiles as a function of depth (lower abscissa) and lunar radius (upper abscissa). $A_z$, $\bar{A}$ and $A_y$ are individual transfer functions. After Sonett *et al*. (1971).

Fig. 6. Electrical conductivity as a function of time for the Amelia high albite at 1353, 1373 and 1384 K at a frequency of 1.6 kHz. Run durations at 1353, 1373, and 1384 K are 526, 1199 and 1486 hr, respectively. Data are from Piwinskii and Duba (1974).

Fig. 7. Compressional wave velocity as a function of anorthite content for plagioclase feldspars. Open circles and squares are Reuss and Voigt values, respectively. See text for complete discussion.

Fig. 8. Compressional wave velocity as a function of volume % plagioclase for the assemblages: (1) plagioclase ($An_{50}$) + diopside; (2) plagioclase ($An_{100}$) + diopside; (3) plagioclase ($An_{50}$) + olivine and/or garnet; (4) plagioclase ($An_{90}$) + olivine and/or garnet; and (5) plagioclase ($An_{100}$) + olivine and/or garnet. For any particular assemblage, the ordinate gives the volume percentage of plagioclase with the remainder either being diopside (Assemblage 1 or 2), or olivine and/or garnet (Assemblage 3, 4, or 5).

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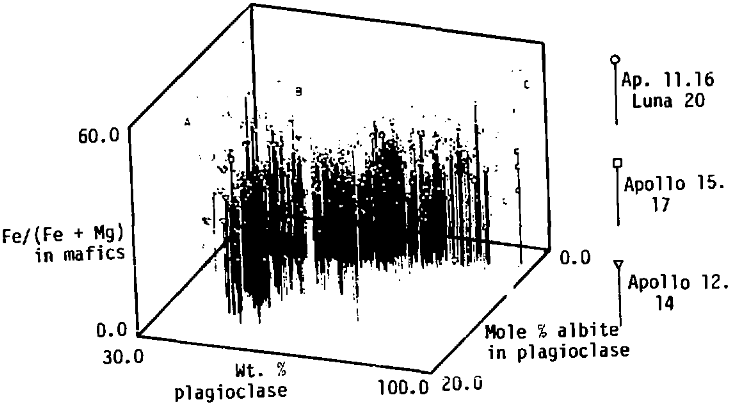

**Piwinskii -**
**Fig. 1**

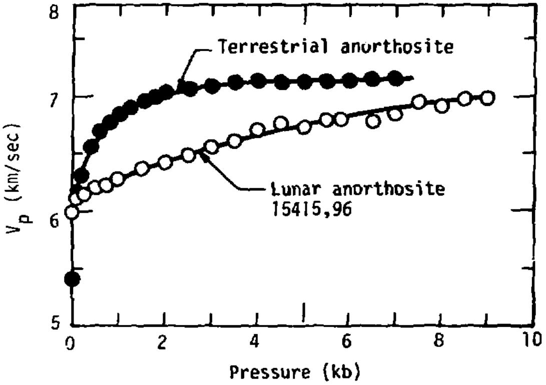

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**Fig. 2**

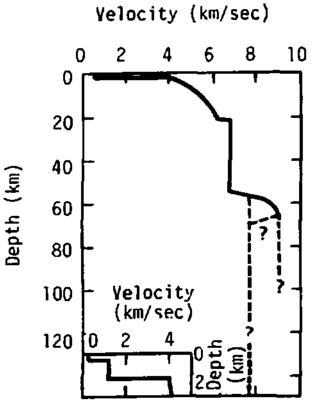

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Fig. 3

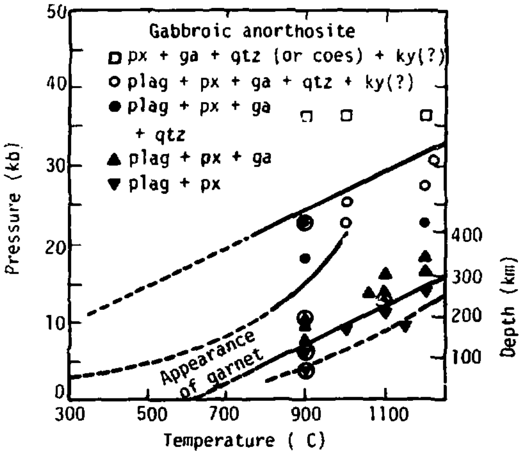

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Fig. 4

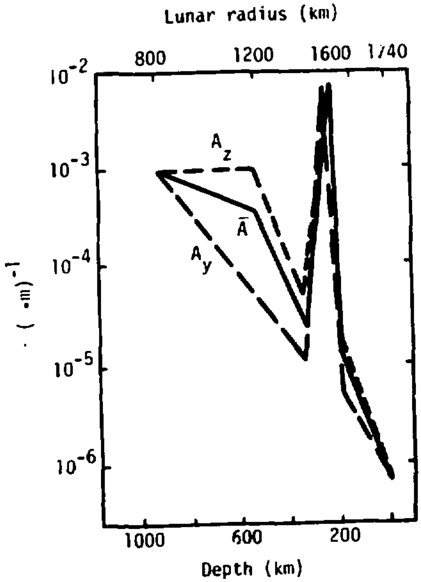

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Fig. 5

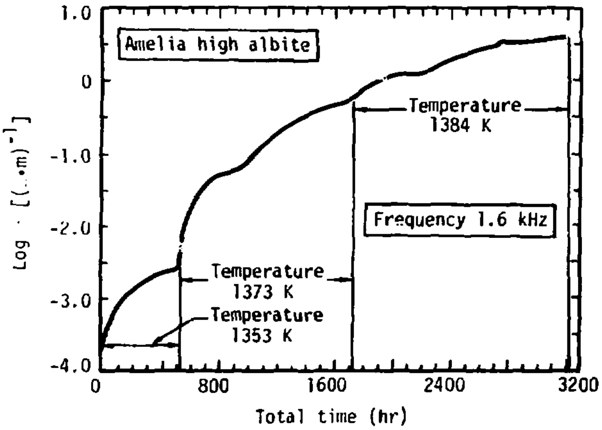

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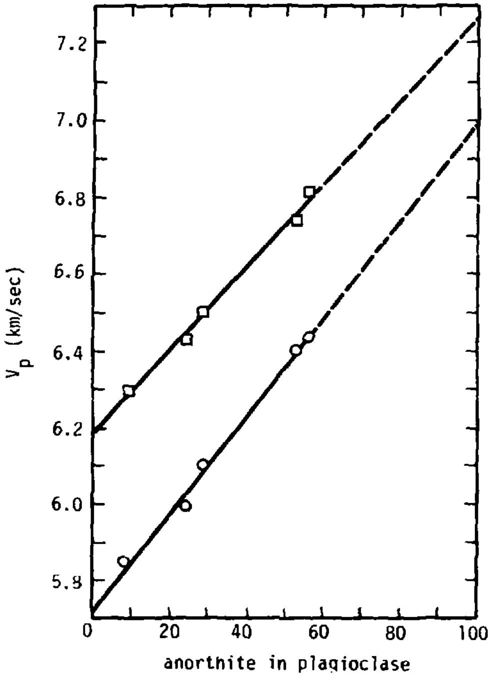
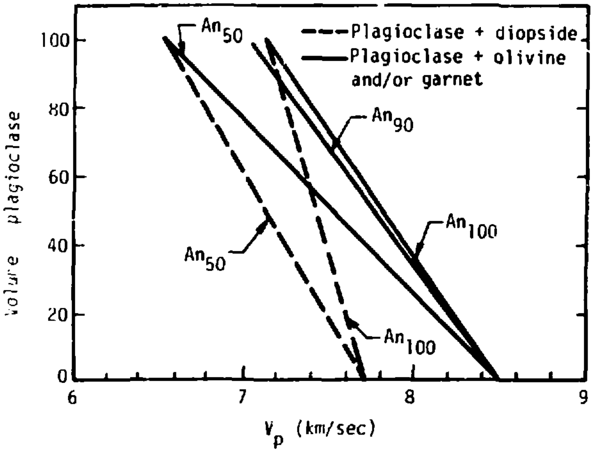
Fig. 6**



Piwinskii -
Fig. 7



**Piwinskii -**
**Fig. 8**

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