The compositions of several lunar oxide minerals--most armalcolites and ilmenites, and some ulvöspinelss--fall essentially in the system FeO-MgO-TiO₂. Phase relations in this system can thus aid in the interpretation of the para-
genesis of these minerals. Most armalcolites (Arm) are essentially solid so-
lutions between FeTi₂O₅ (ferropseudobrookite, Fpb) and MgTi₂O₅ (Karrooite, Kar); Fe/(Fe+Mg) is variable but tends to approach 0.5. Both textural re-
actions (many armalcolites are mantled by ilmenite) and melting experiments on lunar basalts (1) strongly indicate that armalcolite is stable at high temper-
atures but tends to disappear by reactions of the type:

\[
(\text{Mg,Fe})\text{Ti}_2\text{O}_5 \text{ (Arm)} + \text{FeO (from melt)} = 2(\text{Fe,Mg})\text{Ti}_3\text{O}_5 \text{ (ilmenite)}
\]

Analogy with the Fe₂TiO₅-FeTi₂O₅ system suggested that armalcolite might be
inherently unstable with respect to magnesian ilmenite plus rutile at low tem-
peratures (2). This is confirmed by experiments in the join FeTi₂O₅-MgTi₂O₅
(Fig. 1): for example, Fe₀.₅Mg₀.₅Ti₂O₅ is not stable below 1030 ± 10⁰C. Note
that extrapolation of data obtained at high pressures (Fig. 2) suggests that
the breakdown of pure MgTi₂O₅ will occur near 600⁰C. The partial break-
down of armalcolite to rutile plus FeO-enriched ilmenite (3) is in accord with Fig. 1.

Fig. 1 shows the lowest temperature at which armalcolite of a given composi-
tion is stable: reaction with liquid or another phase will tend to increase
the minimum temperature of stability. On the other hand, if components other
than FeTi₂O₅ and MgTi₂O₅ enter into armalcolite, it may be stabilized to lower
temperatures than indicated in Fig. 1. An important example of such stabil-
ization is shown by experiments on Fpb (or Arm) plus FeO at temperatures
40-50⁰C below the minimum stability for each pure phase. The Fpb (or Arm) re-
acted with 2 wt% FeO to form ilmenite + Fpb (or Arm) with unit cell different
from that of the starting material, and no rutile. The reaction for FeTi₂O₅
appears to be: 4FeTi₂O₅ (Ppb) + FeO = 5Fe₃O₅ (Ilm) + Ti₃O₅ (in solid solu-
tion with Fpb). The reaction of approximately 2% FeO corresponds to 10-15%
Ti₃O₅ entering into the solid solution. The exact reaction for Fe₀.₅Mg₀.₅Ti₂O₅
is more difficult to determine, but the absence of rutile from the products at
980⁰C strongly suggests that Ti₃O₅ component also enters into solid solution
with armalcolite. These results show that it is risky to melt high-Ti basalt
in iron containers without evidence that it was saturated with FeO throughout
its melting interval.

Molar volumes of armalcolites are approximately 10% greater than those of
compositionally equivalent ilmenite + rutile (50.51 ± 0.09 cm³/mole) and gei-
kielite + rutile (49.68 ± 0.08 cm³/mole) (Fig. 3); thus, it is expected that
armalcolite will become less stable with increasing pressure.

The schematic T-fO₂ section for part of the system Fe-O-TiO₂ serves as a
model for several important reactions in high-Ti lunar basalts (Fig. 4). The
reaction Usp + Fpb = Ilm (Curve A), which is metastable with respect to oxide
melting, is analogous to reaction (A) in basalts, with Usp proxying for FeO
from the silicate melt at lower temperatures. Curve B is the lower stability
limit for FeTi₂O₅. Curve C is the reaction Ilm = Usp + Rut and point D repre-
sents the combined breakdown and reduction reaction $\text{Ilm} = \text{Usp} + \text{Rut} + \text{FeO}$; both reactions are observed in Apollo 17 basalts (4) with the important difference that the presence of Cr in the spinel undoubtedly stabilized the breakdown assemblage to higher temperatures.

Fig. 1. Stability of Armss. All experiments in evacuated silica-glass capsules, except for pure MgTi$_2$O$_5$ ($P_{H_2O} = 1$ kbar in welded Pt capsules).

- $\text{Ilm}_{ss} + \text{Rut} \rightarrow \text{Arm}_{ss}$;
- $\text{Arm}_{ss} + \text{Ilm}_{ss} + \text{Rut};$
- $\text{Arm}_{ss} + \text{Arm}_{ss} + \text{Ilm}_{ss} + \text{Rut};$
- $\text{Arm}_{ss} + \text{Arm}_{ss} + \text{Ilm}_{ss} + \text{Rut}$ and $\text{Ilm}_{ss} + \text{Rut} + \text{Arm}_{ss} + \text{Ilm}_{ss} + \text{Rut}.$

Fig. 2. P-T stability of MgTi$_2$O$_5$ (Kar). Geik = MgTiO$_3$, Rut = TiO$_2$.

Fig. 3. Molar volumes of synthetic armalcolite$_{ss}$. 

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Fig. 4. T-$f\text{O}_2$ stability of phases in the system Fe-O-TiO$_2$ (0<P<1 atm) based on (5) and analysis of 70 isobarically invariant (4-phase) points. $f\text{O}_2$ scale is schematic; temperatures are known in the range 1000-1500°C, but are only schematic at higher and lower values.

References


