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National Aeronautics and Space Administration
Office of Scientific and Technical Information (Code US)
Washington, D.C. 20516

Dear Gentlemen:

Enclosed is my final report of the research conducted under NASA Grant NGR 15-005-164. The report consists in large part of the Progress Report which accompanied my renewal application on October 1, 1972.

I recently presented two papers and extended abstracts at the Fourth Lunar Science Conference along with a paper and abstract on my recent Apollo 17 findings. I am in the process of writing this up now for the Proceedings Volume.

I hope that this report suffices as a final report although the research is continuing under my new NASA Grant NGR 15-005-175.

Sincerely,

Lawrence A. Taylor

Lawrence A. Taylor
Assistant Professor

LAT/mf

APPENDIX 4

PROGRESS REPORT

A considerable amount of research has been conducted under N.A.S.A grant NGR 15-005-164. Our various investigations have produced many important and significant results concerning the cooling histories of the lunar rocks. In this report I will briefly discuss some of the more important findings.

<u>Publications Resulting from N.A.S.A. grant NGR 15-005-164</u>

Four papers are currently in press for Oct. and Nov. publication, at least one and possibly 2 more will be submitted before the end of 1972, and 3 papers will be presented at national meetings during the remainder of this year.

These papers are:

Taylor, L.A. and R.H. McCallister, 1972, An experimental investigation of the significance of zirconium partitioning in lunar ilmenite and ulvöspinel, Earth Planet. Sci. Lett., Vol. 18, 105-109.

Taylor, L.A., R.J. Williams and R.H. McCallister, 1972, Stability relations of ilmenite and ulvöspinel in the Fe-Ti-O system and application of these data to lunar mineral assemblages, Earth Planet. Sci. Lett., Vol. 16, , 282-288.

Taylor, L.A., and R.H. McCallister, 1972, Opaque mineralogy of Apollo 15 rocks: Experimental investigations of elemental partitionings and subsolidus reduction, Lunar Science Institute, , The Apollo 15 Lunar Samples, 169-73

McCallister, R.H. and L.A. Taylor, 1973, The Kinetics of ulvöspinel reduction: synthetic study and applications to lunar rocks, Earth Planet. Sci. Lett., Vol 17, 357-364.

In the original proposal, the experimental projects outlined included:

1) the partitioning of Zr between ilmenite and ulvöspinel, as well as Ti between ilmenite and troilite and Cr between native Fe and chromian ulvöspinel;

2) the kinetics and mechanism of ulvöspinel reduction to ilmenite + native Fe.

The ideas for these projects originated from observations which I (L.A. Taylor) had made during previous studies of Apollo 11, 12 and 14 samples.

Partitioning Studies

The partitioning of Zr between $FeTiO_3$ and Fe_2TiO_4 in the presence of Fe + ZrO_2 was experimentally investigated (see Taylor and McCallister, 1972). The partitioning is a strong function of temperature. Although the phases in the synthetic study did not have compositions similar to those in the lunar rocks (e.g. Cr, Al, etc. are absent in synthetic ulvöspinel), certain assumptions can be made based on dilute solution models which allow for direct application of the partitioning data.

The Zr partitionings between coexisting ilmenite and ulvöspinel were determined in 18 Apollo 14 and 15 rocks. Application of the experimental data indicates that these Zr partitionings can possibly be used as sensitive indicators of differences in cooling histories of lunar rocks. For example, whereas the mineralogies and textures of several rocks are similiar, certain rocks have Zr ratios of the coexisting oxides indicating high temperature formation (i.e. 1200-1250°C) and others (e.g. 15065 and 15475) have reequilibrated to subsolidus temperatures of 800-850°C, a result of slow subsolidus cooling. These rocks which show this reequilibration to low temperatures are also the only Apollo 15 rocks examined which show good evidence for subsolidus reduction of ulvöspinel to ilmenite + Fe. It is therefore suggested that the presence of ulvöspinel reduction is not evidence a priori that these rocks have undergone more reducing conditions than the other Apollo 15 rocks. It may only indicate that the cooling rates were slower in that subsolidus temperature range (<900°C) where f_{O_2} values were favorable for ulvöspinel reduction. The deciphering of the cooling histories of lunar rocks has tremendous scientific ramifications of which the evolution of the moon is one.

It was anticipated that heating experiments would be performed on some of the Apollo 16 samples in order to check the validity of certain of our assumptions. However, the samples which we have recieved to date are "notably" low in opaque mineral content, but we hope to be able to obtain suitable samples in the not too distant future.

The investigations of Zr partitioning have been very gratifying from a scientific standpoint; however, several additional studies will be conducted with both synthetic (e.g. pressure effects) and lunar materials (applications to suites of lunar rocks).

The investigation of Ti partitioning between coexisting ilmenite and troilite has also progressed well. We have gathered data from several lunar rocks. The data from the experimental study, which should be completed in approximately 2 months, indicate that the troilites in many of the lunar rocks have reequilibrated to low temperatures (i.e.<500°C); however, several rocks contain troilites which have not undergone extensive reequilibration. Thus, the Ti partitioning between troilite and ilmenite also may be of significance in detailing cooling histories of lunar rocks, particularly at temperatures below 1000°C.

A study of the partitioning of Cr between native FeNi and chromian ulvöspinel is still in progress. The Cr contents of FeNi grains in most of the rocks studied, with the exception of 15536, do not show any systematic variations. The poor polishing behavior of the FeNi grains lends itself to contamination by minute particles of ulvöspinel and thus may directly contribute to erroneous Cr contents. The experimental portion of this study also continues at present. Some of our results are presented within the L.S.I. Apollo 15 preprint accompanying this report.

Ulvöspinel Reduction

The reduction of ulvöspinel to ilmenite + native Fe has occurred extensively in lunar rocks (e.g. Haggerty, 1971; El Goresy *et al.*, 1971; Taylor *et al.*, 1971). We studied the reaction $Fe_2TiO_4 = FeTiO_3 + Fe + \frac{1}{2} O_2$ within the Fe-Ti-O system and were concerned with the kinetics of this reduction. In order to be confident about the position of our experiments relative to this univariant curve and that of ilmenite reduction to rutile + native Fe, the position of both curves were carefully redetermined (Taylor *et al.*, 1972) and found to be substantially different from those present in the literature. The oxygen fugacity limits already in the literature for lunar rocks (e.g. Haggerty, 1971) based on the older data are in need of revision. The thermodynamic parameters for reactions involving these oxide phases were also determined. In addition, the first direct determination of the free energy of formation of $FeTi_2O_5$ was performed. This phase is one of the end-members of the armalcolite series (magnesian ferropseudobrookite).

These new data provide a ready explanation for the common occurrence of ulvöspinel reduction, yet the apparent stable nature of fayalite in the lunar rocks. Prior to this study (Taylor et al., 1972), the absence of fayalite reduction to Fe + SiO_2 in all lunar rocks, except in 14053 and 14072 (a new find by us), could only be explained by means of complex models. This study also pointed out that the "complete" reduction of ulvöspinel to rutile + Fe proceeds in a stepwise manner, first to ilmenite + Fe and then, however more slowly, the ilmenite is reduced to rutile + Fe. Thus, the presence of ulvöspinel reduction to ilmenite + Fe can occur anywhere below the univariant curve for this reaction, even below the ilmenite stability curve. Because of this stepwise process, no lower limit can be given for this reduction since the kinetics of ilmenite reduction are considerable slower than those of ulvöspinel. This will necessitate the revision of certain principles and fugacity estimates currently in the literature (e.g. Haggerty, 1971).

The kinetics and mechanism of $\underline{Fe_2TiO_4}$ reduction were then determined (McCallister and Taylor, 1972). The mechanism is one of nucleation and growth, where the growth stage may be controlled by diffusion of reactants through the product. The activation energy determined by runs at f_{O_2} of 0.5 log units below the ulvöspinel curve is 46±4 kcal/mole, and our results indicate that ulvöspinel reduction in lunar rocks may have taken place at relatively low temperatures (i.e. less than 600°C).

Although the lunar ulvöspinels are not pure Fe_2TiO_4, many observations from our study can be applied to textures observed in lunar rocks. Lunar ulvöspinels commonly contain ilmenite lamellae but lack native Fe in close association. This has been interpreted as mutual intergrowths of ulvöspinel and ilmenite. In our experiments, slow reduction of ulvöspinel produces blades and lamellae of ilmenite parallel to {111} of the host. The native Fe diffuses very rapidly through the ulvöspinel and tends to coalesce into large grains. In fact, an ulvöspinel can contain ilmenite lamellae with no Fe phase in the immediate vicinity. Thus, we have shown experimentally that these composite inter-growths present in lunar rocks can and probably are developed by slow reduction processes. Various other textures involving lunar ulvöspinels can now be interpreted based on the speed on reduction.

Here again, the Apollo 16 samples which we have been allocated and received have not proven to be suitable for heating experiments due to the paucity of opaque mineral grains.

<u>Other Studies in Progress</u>

Besides the investigations discussed above, portions and extensions of which are still in progress, other studies have been initiated. These include:

1) Examination using the electron microscope of chromian ulvöspinels in rocks 12018 and 12051 which have compositions in the middle of the "Apollo 12 gap" (Haggerty and Meyer, 1970). It is suspected that although the analyses give every indication of being a single phase, the grains are actually very fine-grained intergrowths of chromian ulvöspinel and titanian chromite as suggested by Taylor _et al_. (1971).

2) Study of the kinetics of the reduction of fayalite to native Fe + SiO_2 first observed by El Goresy _et al_. (1971). These data will have a bearing on the subsolidus cooling histories of certain lunar rocks (e.g. 14053 and 14072).

<u>Publications Relevant to the Lunar Sample Program</u>

1. <u>Abstract</u>: Amer. Geophys. Union Ann. Mtg., Wash., D.C. (1970).
2. <u>Abstract</u>: Deutsche Min. Gesellschaft Ann. Mtg., Germany (1970).
3. <u>Abstract</u>: Geol. Soc. Amer. Ann. Mtg., Milwaukee (1970)
4. Carnegie Inst. Wash. Year Book <u>69</u>, 238-243 (1971).
5. Proc. Second Lunar Sci. Conf., Vol. 1, 219-235 (1971).
6. Proc. Second Lunar Sci. Conf., Vol. 1, 855-871 (1971).
7. <u>Abstract</u>: Meteoritical Soc. Ann. Mtg., Germany (1971).
8. <u>Abstract</u>: Geol. Soc. Amer. Ann. Mtg., Wash., D.C. (1971).
9. Earth Planet. Sci. Lett., vol. 13, 121-129 (1971).
10. Lunar Sci. Institute, No. 88, 254-256 (1972).
11. Proc. Third Lunar Sci. Conf., Vol. 1, in press (1972).
12. <u>Abstract</u>: COSPAR, Madrid, Spain (1972).
13. <u>Abstract</u>: Deutsche Min. Gesellschaft, Germany (1972).
14. <u>Abstract</u>: Geol. Soc. Amer. Ann. Mtg. - accepted (1972).
15. <u>Abstract</u>: Geol. Soc. Amer. Ann. Mtg. - accepted (1972).
16. Lunar Sci. Institute, Apollo 15 Volume, in press (1972).
17. Earth Planet. Sci. Lett., Vol. 16, in press (1972).
18. <u>Abstract</u>: Meteoritical Soc. Ann. Mtg. - submitted (1972).
19. <u>Abstract</u>: Meteoritical Soc. Ann. Mtg. - submitted (1972).
20. Earth Planet. Sci. Lett., Vol. 16, in press (1972).
21. Earth Planet. Sci. Lett., Vol. 17, in press (1972).
22. Earth Planet. Sci. Lett., in press (1972).
23. Earth Planet. Sci. Lett., submitted (1972).

The complete reference for each of these publications can be found in L.A. Taylor's publication lists.