ISSN 0029 - 3865

Geochim. Cosmochim. Acta, in press.

CBPF-NF-083/85

NUCLEAR TRACKS, Sm ISOTOPES AND NEUTRON CAPTURE EFFECTS IN THE ELEPHANT MORRAINE SHERGOTTITE

by

R.S. Rajan[2], G.Lugmair[3], A.S. Tamhane[4]
and G. Poupeau[1,5]

[1]Centro Brasileiro de Pesquisas Físicas - CBPF/CNPq
Rua Dr. Xavier Sigaud, 150
22290 - Rio de Janeiro, RJ - Brasil

[2]Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Passadena, CA

[3]Scripps Institute of Oceanography
University of California at San Diego
La Jolla, CA 92093

[4]Tata Institute
Bombay, India

[5]CNRS, Paris, France

ABSTRACT

Nuclear track studies, uranium concentration measurements and Sm-isotope studies have been performed on both lithologies A and B of the Elephant Morraine Shergottite, EETA 79001. Track studies show that EETA 79001 was a rather small object in space with a preatmospheric radius of 12 ± 2 cm, corresponding to a preatmospheric mass of 28 ± 13 kg. U-concentrations measurements indicate that phosphates have concentrations ranging from 0.3 to 1.3 ppm. There are occasional phosphates with excess fission tracks, possibly produced from neutron induced fission of U and Th, during the regolith exposure in the shergottite parent body (SPB). Sm-isotope studies, while not showing any clear cut excess in ^{150}Sm, enable us to derive meaningful upper limits to thermal neutron fluences of 2 to 3×10^{15}n/cm^2, during a possible regolith irradiation. These limits are consistent with that required to explain the track data and also enable us to derive an upper limit to the neutron exposure age of EETA 79001. of 55 Myr in the SPB regolith.

Key-words: Meteorites; Cosmic ray tracks; Meteorite cosmic ray exposure; Fission tracks; Plutoniun 244 in meteorites; Sm isotopes in shergottites; Neutron capture effects in meteorites.

INTRODUCTION

Shergottites are an extremely important group of meteorites to study because of their possible origin from Mars, e.g. Shih et al. (1982). The chronologies and exposure histories of these meteorites are extremely complex. The finding of rare gases and nitrogen with elemental and isotopic compositions similar to those measured in Martian atmosphere in glassy phases of the Elephant Morraine shergottite has lent strong support to the Martian origin hypothesis (Bogard and Johnson, 1983; Becker and Pepin, 1984). The Rb-Sr systematics of shergottites indicates a major resetting event at 180 ± 4 Myr (Shih et al., 1982). This has been interpreted by them as dating the time of shock metamorphism when plagioclase was partially converted into maskelynite. The U-Th-Pb study of Shergotty by Chen and Wasserburg (1985) confirms a significant event at that time. However, in a recent work Jagoutz and Wanke (1985) have suggested that the linear array observed in the Rb-Sr systematics could be due to a mixing line effect. They have inferred a Sm-Nd crystallization age of 343 ± 46 Myr, which would represent a strong constraint in the permissible track retention age.

NUCLEAR TRACK STUDIES

We have carried out nuclear track studies and uranium concentration measurements on samples from the Elephant Morraine shergottite EETA 79001. Preliminary report was published as an abstract in Meteoritics (Rajan et al. 1984). Nuclear tracks in pyroxenes were revealed by etching in 37.5 N NaOH for 25 minutes. Based on track density measurements in over 100 pyroxenes, the range of track densities observed is given below:

79001.58	lithology A	3 to 6 $\times 10^5/cm^2$
79001.44	lithology B	5 to 8 $\times 10^5/cm^2$

Based on the short exposure age determined for this meteorite of 0.6 Myr (Pepin and Becker, 1984; Bogard et al. 1984), we infer that the samples had undergone little ablation and were very close to the preatmospheric surface. In fact, the preatmospheric depths of the samples are tightly constrained by the measured track densities and are only weakly dependent on the preatmospheric radius. The deduced preatmospheric depths are 3 ± 0.5 cm and 2 ± 0.5 cm respectively. Recently, Bhandari et al. (1985) reported track densities of 1 ± 0.2 $\times 10^5/cm^2$ in olivines from EETA 79001.95. Their data, when corrected for the lesser sensitivity of the olivines, yields a preatmospheric depth of 5.0 cm. Taking into consideration the location of all the three samples inside the meteorite, the ablation seems to be rather uniform around 2 to 3 cm. We derive a preatmospheric radius of 12 ± 2 cm, corresponding to a preatmospheric mass of 15 to 40 kg.

We have also analyzed about 800 phosphate grains from lithology B. The phosphates were etched with 0.25% HNO- for 45 seconds. Most of the phosphates in our sample were heavily shocked, as was expected. However, there is a small fraction of the phosphates (1-2%) where the tracks can be observed clearly. The track densities seen in these crystals range from $3 \times 10^6/\text{cm}^2$ to $9 \times 10^6/\text{cm}^2$. A study of the neighboring pyroxenes, discussed earlier, indicates that cosmic ray tracks can account for only 10 to 25% of the observed tracks. Accordingly, the majority of the tracks are indeed due to fission in the phosphates.

Uranium contents have been determined for over 50 phosphate grains and several of those have also been analyzed with the electron microprobe. All the phosphates analyzed were whitlockites and their uranium concentrations range from 0.3 to 1.3 ppm. Figure 1 shows the distribution of uranium concentrations measured. Electron probe measurements also showed that there is no major compositional differences between phosphates containing tracks and others.

Using the highest uranium concentration measured, we can calculate that the number of fission tracks expected over 180 Myr is only $0.15 \times 10^6/\text{cm}^2$. It is known that phosphates are somewhat more sensitive than pyroxenes, but no quantitative data exists. If we conservatively assume that they may be as much as 1.5 times more sensitive, then the track density expected from cosmic rays is 0.8 to $1.2 \times 10^6/\text{cm}^2$. So the expected track density from both cosmic rays and fission over 180 Myr is 0.95 to $1.35 \times 10^6/\text{cm}^2$. It is thus clear that the measured densities in phosphates are two to three times higher than what is expected.

There are basically three possible explanations for these results and we discuss them below: The first is that the features observed in phosphates are either dominated by spallation recoils or are some kind of shock induced artifacts.

The track density of $3 \times 10^6/\text{cm}^2$ is conveniently observable in the optical microscope. Our track density measurements refer to counting of all tracks greater than 1 micron in length. If spallation recoils were significantly contributing to the observed track density, then one would expect a lot more tracks in the 1-2 microns region than that nominally expected from the population of longer tracks. Based on our microscope observations, we deduce that they are not a dominant source and estimate the contribution from spallation recoils to be less than 10%. This is also confirmed by a theoretical estimate of recoil tracks expected over the cosmic ray exposure age, based on simulation studies. Using about 1 spallation track per cm per year as the production rate and 0.6 Myr exposure age, the spallation recoils expected would be about $6 \times 10^5/\text{cm}^2$, which is only 20% of that observed.

It is much more difficult to rule out shock-induced artifacts, considering the extreme sensitivity of the phosphates to shock and the rarity of phosphates with tracks. In the case of phosphates from lunar breccia 14321, Pellas and Storzer (1975) showed that shock features similar to tracks do get revealed after a 45 sec etching with 0.25% HNO_3. However, in our study there were two crystals where tracks were well etched with small cone angles (10^0) and lengths of up to 10 μm. Because of these reasons, we feel that all our observations cannot be dismissed as due to shock-induced artifacts and the excess fission tracks are indeed the main cause for our observations in some of the phosphates.

The second hypothesis would be to attribute time signif icance to the different phosphate grains based on the measured track densities and uranium concentrations in the different phosphate grains. Such data, which exist only for four grains, yield nominal fission track ages ranging from 2.5 to 4.0 Gyr. However, there are a number of problems associated with this hypothesis. The most serious objection would be in understanding how these grains managed to retain their tracks in spite of the documented major metamorphic events at times as recent as 180 Myr, which was successful in totally resetting the Rb-Sr systematics. For this reason we think that it is unlikely that they could be interpreted as representing relict grains with older ages, though it cannot be totally ruled out.

The third hyphothesis, which we prefer as the most likely one at this time, is that the additional tracks were acquired due to neutron induced fission of U and Th during residence in the parent body. Clearly, there are several unresolved problems relating to a Martian origin, particularly in regard to the time of ejection and the ejection mechanisms involved. Treating it as a reasonable model, the neutron effects would be accumulated over at least 180 Myr and possibly up to 340 Myr. The burial depths will have to be constrained around a few meters in order to satisfy the requirements of the short cosmic ray exposure age and the possibility of neutron effects. While a precise estimate of the neutron fluence on the Martian regolith as a function of the burial depth is a non-trivial calculation, it is possible to make an order of magnitude estimate of the neutron fluence required to explain the observed track excess if we make several assumptions. 1) We will use the measured neutron profile from Apollo 15 (Russ et al., 1972) as a starting point; 2) Our sample was located at the corresponding peak depth; 3) We will assume that the Th/U ratio in our phosphates is 10. Based on the above, we calculate that a fluence of about $3 \times 10^{15}/cm^2$ would be able to produce the observed track excess, within a factor of two or so. From the lunar analogy, we should be able to test this hypothesis by looking for neutron capture effects in the form of increases in isotopic ratios of $^{150}Sm/^{149}Sm$ and $^{150}Gd/^{157}Gd$. A neutron fluence of $3 \times 10^{15}/cm^2$ wil increase the $^{150}Sm/^{149}Sm$ ratio by about 5 parts in 10^4 and the $^{150}Gd/^{157}Gd$ ratio by about 4 parts in 10^4.

Sm ISOTOPE STUDIES

Because of the potential pitfalls associated with the study of phosphates in such a heavily shocked meteorite, we decided to independently verify and possibly quantify such a neutron exposure history. We have performed Sm isotopic studies on samples of both lithologies A and B, in order to look for possible increase in the Sm/Sm ratio due to neutron capture effects. The Sm isotopic measurements were performed on about 60 mg of lithology A and 100 mg of lithology B. The experimental techniques and details are similar to that previously described in Lugmair et al., (1975), where it is presented in great detail. Our results are summarized below in Table 1.

TABLE 1

Sample	$^{150}Sm/^{149}Sm$	δ (ε units)
Terrestrial Std	0.53400 ± 2	$\equiv 0$
Lithology A	0.53411 ± 14	2 ± 3
Lithology B	0.53405 ± 12	1 ± 3

From the above data, it is clear that there is no evidence for an excess Sm, within the experimental uncertainties. However, it is possible to derive upper limits to the thermal neutron fluences experienced by these samples. From the ratios measured in samples and standard in Table 1, we calculate the neutron fluence ϕ from:

$$\phi = \frac{(^{150}Sm/^{147}Sm)_{sample} - (^{150}Sm/^{149}Sm)_{std}}{\left[1 + (^{150}Sm/^{149}Sm)_{sample}\right] <\sigma_{149}> (< 0.2\,eV)}$$

(Russ et al., 1971) where $<\sigma_{149}>$ is the capture cross section of ^{149}Sm averaged over the neutron energy spectrum below ~ 0.2 eV suffered by the shergottites. $<\sigma_{149}>$ cannot be calculated precisely, since the neutron energy spectrum below ~ 0.2 eV in the shergottites parent body regolith is not known. To a first approximation, using $<\sigma_{149}>$ derived from the lunar energy spectrum of 5.0×10^4 barns, we derive upper limits to the thermal neutron fluences which are:

Lithology A	$\leq 3.3 \times 10^{15} n/cm^2$
Lithology B	$\leq 2.2 \times 10^{15} n/cm^2$

DISCUSSION

We can now try to see how these upper limits to neutron fluences compare with that estimated for explaining the observed track data in phosphates. We do not know the exact Th/U ratios in our phosphate samples, except that it could be as much as 10 or more based on the work of Crozaz (1979). In such a case, the contribution from induced fission of Th, could be as much as 40% of that expected from the induced fission of U. There is also the contribution from high energy proton induced fission, where the contribution from Th may be as high as twice that from U (Hutcheon. priv. comm.). If we take the highest values of uranium concentration measured,$\sim$ 1.5 ppm, with all the above effects (several of which are difficult to quantify), our track data would require a thermal neutron fluence of $3.0 \times 10^{15}/\mathrm{cm}^2$ to explain the observed track excess. We estimate the uncertainty in our calculated neutron fluence to be at least a factor of two because of the uncertainties mentioned above.

Another way to infer neutron fluences is by looking at neutron effects in rare gases. Specifically, excesses in ^{60}Kr and ^{62}Kr due to neutron capture reactions in ^{79}Br and ^{91}Br have already been oberved in lithology C (Becker and Pepin, 1984; Swindle et al. 1984; Swindle et al., 1985). An excess of ^{80}Kr of 8.6 ± 2.3% has been observed in EETA 79001, which is probably due to neutron capture effects on bromine (Swindle et al., 1985). Their measured ^{82}Kr excess, and to a lesser certainty, the $^{128}\chi$e excess (from ^{127}I) are consistent with the ^{80}Kr observations. There are major uncertainties in estimating the fluences from the rare gas data using Kr and Xe. Between fluences inferred from Kr and Xe, there is an uncertainty of a factor 4 (thermal spectrum) or a factor of 9 (a special spectrum, where thermal to 1 MeV neutrons are captured). If one uses the thermal spectrum, the neutron fluences required for explaining the observed effects in Kr and Xe in lithology C is about (5 ± 3) x 10^{15} n/cm^2 (Swindle et al., 1985). The chemistry of lithology C seems closest to that of lithology A (Smith et al., 1984). The major question is to decouple the observed neutron effects into those which occurred in the regolith 'in situ' and those which may have occurred in the atmosphere of the parent body (e.g. Mars). Swindle et al. (1985), based on comparison of rare gas results of lithologies A and C have convincigly argued that the substantially larger effects in lithology C, indicates that most of it was probably produced in the atmosphere. Based on lithology A, the neutron fluence corresponding to the 'in situ' production is estimated by them to be more than 0.7 ± 0.5 x 10^{15}n/cm^2.

CONCLUSIONS

1. Nuclear track studies of pyroxenes showed that EETA 79001 was a rather small object in space with preatmospheric mass of 28 ± 13 kg.

2. The study of phosphates show that there are occasional phosphates with fission tracks in excess of that expected from spontaneous fission of ^{238}U over 180 Myr. The most likely explanation for this is that the additional tracks were pro-

duced due to neutron induced fission of U and Th, while the sample resided in the top few meters of the shergottite parent body (SPB).

3. In order to verify the above hypothesis, Sm isotope studies were performed on both lithologies of EETA 79001. Within the uncertainties, there is no evidence for neutron-induced effects in samarium. However, the derived upper limits of the thermal neutron fluences of 2 to 3×10^{15}n/cm^2 are consistent with that needed to explain the excess tracks observed in occasional phosphate grains.
4. Finally, taking the measured upper limits of neutron fluences and comparing them to the lunar rock 75075 (Lugmair et. al., 1975), we also infer an upper limit to the neutron exposure age of Elephant Morraine in the regolith of 55 Myr.

ACKNOWLEDGEMENTS

We are extremely grateful to the Antarctic Meteorite Working Group and the Geological Survey of India. Drs. H.A. McSween and J.C. Laul are to be thanked for arranging excellent consortia. We would like to thank Drs. C.M. Hohenberg, I.D. Hutcheon, J.D. Macdougall and T. Swindle for extremely helpful discussions. This paper has greatly benefitted from the excellent and detailed reviews by Drs. L. Nyquist, P. Pellas and T. Swindle. Finally, the skilled help of Ms. G. Cline and Mrs. S. Prather in preparing this manuscript is gratefully acknowledged. The work reported here was partially supported by NASA grants to UCSD and to the Jet Propulsion Laboratory, California Institute of Technology.

FIGURE CAPTION

Fig. 1 - Measured uranium concentrations (in ppm) of 52 phosphate grains.

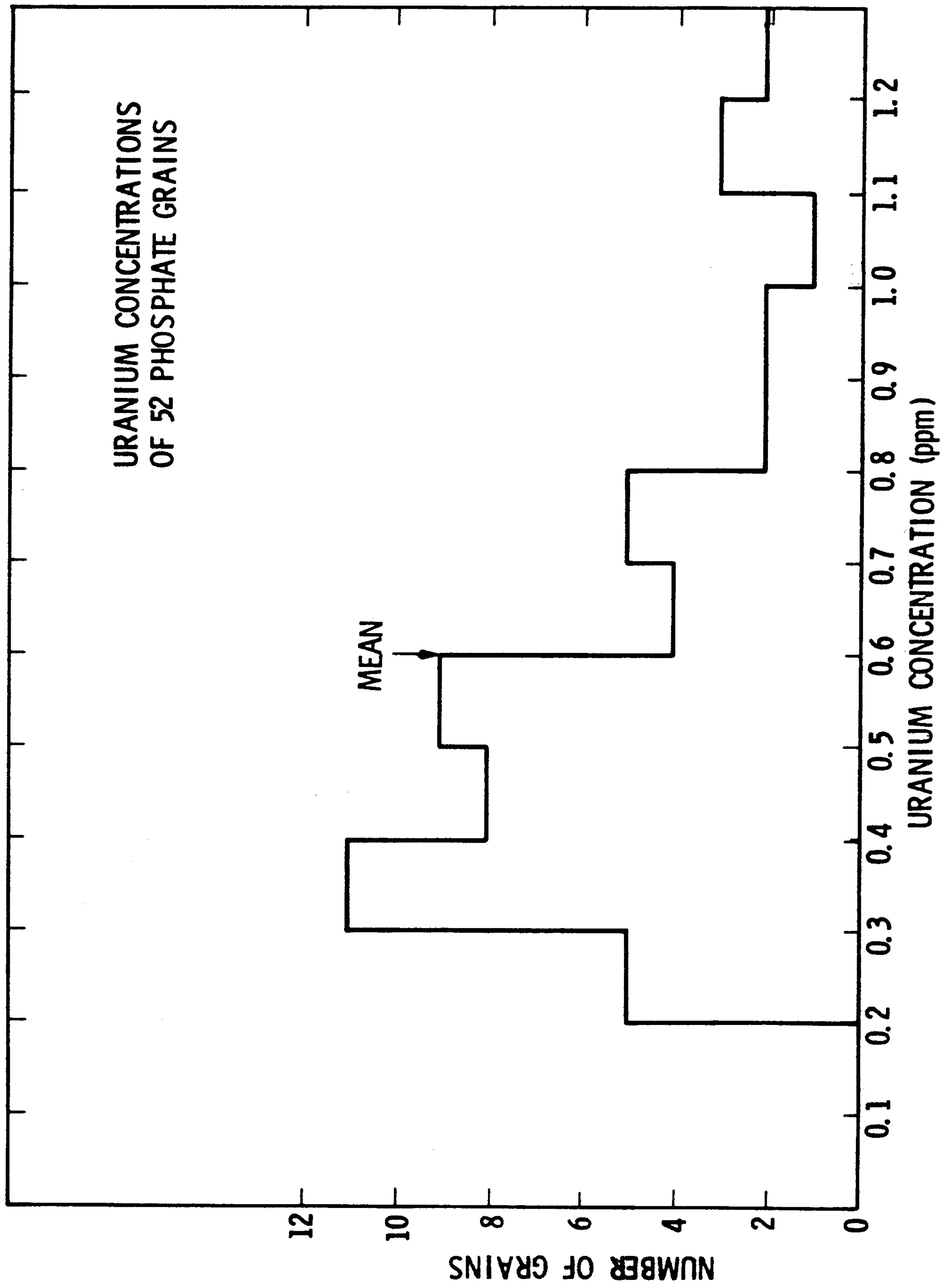
URANIUM CONCENTRATIONS
OF 52 PHOSPHATE GRAINS
MEAN
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
URANIUM CONCENTRATION (ppm)
0
2
4
6
8
10
12
NUMBER OF GRAINS

FIG. 1

REFERENCES

Becker R.H. and Pepin R.O. (1984) The case for a Martian origin of the shergottites: nitrogen and noble gases in EETA79001. Earth Planet. Sci. Lett, 69, 225-238.

Bhandari N., Sengupta D., Jha R. and Goswami, J.N. (1985). TL and nuclear track studies in Shergotty and other SNC meteorites (abstr.). Lunar and Planet. Sci. XVI. Suppl. A, 3-4.

Bogard D.D. and Johnson P. (1983) Martian gases in an Antarctic meteorite? Science 221, 651-654.

Bogard D.D., Nyquist L.E. and Johnson P. (1984), Noble gas contents of shergottites and implications for the Martian origin of SNC meteorites. Geochim. Cosmochim. Acta, 48, 1723-1739.

Burghele A., Dreibus H., Palme H., Rammensee W., Spettel B., Wecheworth, G. and Wanke, H. (1983) Chemistry of the shergottites and the shergottite parent body (SPB): Further evidence for the two component model of planet formation (abstr.). Lunar and Planetary Science XIV, 80-81.

Crozaz, G. (1979) Uranium and thorium microdistributions in stony meteorites. Geochim. Cosmochim. Acta 43, 127-136.

Jagoutz, E. and Wanke H. (1985) Sm-Nd and Rb-Sr studies on shergotty meteorite (abstr.). Lunar and Planet. Sci. XIV, Suppl. A, 15-16.

Lugmair, G.W. Schnein, N.B. and Marti, K. (1975) Sm-Nd age and history of Apollo 17 basalt 75075: Evidence for early differentiation of the lunar exterior. Proc. Lunar Sci. Conf. 6th 1419-1429.

Pellas P. and Storzer D. (1975). Plutonium 244 fission tracks: An alternative explanation for excess tracks in lunar whitlockites. Science 187. 862-863.

Pepin R.O. and Becker R.H. (1984) Galactic cosmic ray exposure ages of the Antartic shergottite EETA 79001. Lunar and Planet. Sci. XV, 637-638.

Rajan, R.S., Rambaldi, E., Tamhane, A.S. and Poupeau, G. (1984) Possible neutron effects in the Elephant Morraine shergottite (abstr.). Meteoritics, 19, 293-294.

Rajan, R.S. and Lugmair G.W. (1985) Search for neutron effects in the Elephant Morraine Shergottite (abstr.). Lunar and Planet Sci. XVI, 681-682.

Russ, G.P. III. Burnett D.S., Lingenfelter R.E., and Wasserburg, G.J. (1971) Neutron capture on ^{147}Sm in lunar samples. Earth and Planet Sci. Lett. 13, 53-60.

Russ G.P. III, Burnett, D.S. and Wasserburg, G.J. (1972) Lunar stratigraphy. Earth and Planet Sci. Lett. 15, 172-186.

Shih, C.Y.,Nyguist, L.E. Bogard, D.D., Mckay, H.A., Wooden, J. L., Bansal, B.M., and Weissman, H. (1982). Chronology and petrogenesis of young achondrites, Shergotty, Zagami and ALHA 77005; late magmatism on a geologically active planet. Geochim. Cosmochim. Acta 46 2323-2344.

Smith, M.R., Laul, J.C., Ma M.S.,Huston, Verkouteren, T., R.M., Lipschutz, M.E. and Schmitt, R.A. (1984). Petrogenesis of the SNC meteorites: Implications for their origin from a large dynamic planet, possibly Mars. Proc. Lunar and Planet. Sci. Conf. 14th. in J. Geophys. Res. 89, B612-B630.

Swindle, T.D., Caffee, M.W., Hohenberg, C.M., Hudson, G.B. and

Rajan, R.S. (1984). Noble gases in SNC meteorites. Meteoritics 19, 318-319

Swindle T.D., Caffee M.W. and Hohenberg C.M. (1985). Xenon and other noble cases in shergottites. To be published in Geochim. Cosmochim. Acta.