

LEAD VOLATILIZATION AND VOLATILE TRANSFER PROCESSES ON THE MOON

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The striking differences in Pb-U-Th systematics and apparent ages between individual Apollo 11 basalt fragments and lunar regolithic debris presumably derived from them, led Silver (1970a) to infer the presence in the soil of lead components with unusually high Pb^{207}/Pb^{206} radiogenic ratios and suggested the possibility of unexpected fundamental lunar processes. A combination of leaching and volatilization experiments established the extraordinary heterogeneity and lability of lead isotope systems in 10084 (Silver, 1970b) and identified the presence of parentless leads which Silver concluded were produced by volatile transfer reflecting the numerous thermal events recorded on the lunar surface. Tatsumoto (1970 and 1971) showed that Pb^{207} -rich leads tended to be concentrated in the finer-size fractions of the Apollo 11 and 12 soils and concluded that volatilization indeed had enriched the dust in an older component of surface-related lead. Silver (1971) and Huey et al. (1971), reporting initial systematic studies of volatilization of lead from Apollo 11 and 12 soils, identified the presence of a significant volatile lead component mobile at quite low temperatures (below $700^{\circ}C$). The lowest temperature yields were, indeed, most enriched in Pb^{207} .

This work abstracts comprehensive studies on the vacuum volatilization of eight soils and two soil breccias from all four Apollo sites. A technique of extended step-heating in vacuum has been used to define lead sites in the soil with characteristic release activation energies. In every sample (see Silver, 1970b, for 10084 data), 70-80% of all the total lead can be volatilized at temperatures less than $1000^{\circ}C$. The most interesting lead yield occurs in all samples at temperatures between 475° and $600^{\circ}C$, peaking in yield at about $550^{\circ}C$.

In Figure 1, the release of data for 14163 soil is plotted against exposure time in a vacuum furnace. The lead extracted at $555^{\circ}C$ shows an abrupt release and decline and represents 9% of the total Pb in the soil. Two successive increments (1 and 2 hours), differing by a factor of 2 in quantity, gave Pb^{207}/Pb^{206} values 1.272 and 1.267 indicating a lead component in a unique low activation energy site characterized by a uniform value of about 1.27. The very small lead release at $595^{\circ}C$ ($\sim 0.1\%$) for 20 hours probably is a relict of the same site and has a Pb^{207}/Pb^{206} ratio of 1.255.

This accessible lead has been shown to be surface-area correlated by several independent experiments we have performed. Most important is the fact that it is precisely related to the slope of the line fitted through the entire family of Apollo 14 soils which is shown in Figure 1 of the accompanying paper by Silver. Parentless lead of this general composition is unambiguously the major variable responsible for the linear array. In comparing yield against isotopic composition, it is clear that while there may be one or two small intermediate release sites, the next major release takes place above $800^{\circ}C$, below and close to $970^{\circ}C$ at which temperature more than 18% of the lead was released in one hour and 45% more in the next 20 hours.

The leads released in these increments have Pb^{207}/Pb^{206} ratios of 0.76 and 0.69, close to and below the values typical of the total sample. This second major site clearly

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has a very different type of lead as well as activation energy. We believe this site to be within the silicate phases and we have performed several experiments on ground lunar basalt to demonstrate this. At the end of 85 cumulative hours of heating up to the 970° C temperature, the 14163 sample is still an incoherent powder showing almost no sintering or any other effects as drastic as the lunar events which have converted at least half of the 14163 soil to various glasses in the lunar environment.

The existence of these two major lead sites in soils have been confirmed in all of the samples we have studied. The higher temperature site (hts - probably peaking at 900+° C) yields 60-75% of all the lead in each soil sample. Still higher temperature site(s) release essentially all remaining lead as fusion temperatures are approached at 1100-1200° C. Quantities of lead in the lower temperature site (lts <600° C) vary with each sample and appear to be related to the local lead concentrations and regolith history. In all samples, Pb^{204} is preferentially concentrated in this site over higher temperature sites.

The isotopic compositions of the lts leads extracted from each sample are extremely variable from mission site to mission site. They are variable in a much more restricted range among different samples from the same mission site and do not tend to overlap values from other sites. The following data shows the best maximum value for the radiogenic Pb^{207}/Pb^{206} value (corrected for contamination of Pb^{204}) of the low temperature lead from a soil from each mission site: 10084 ($207/206 = 0.97 \pm .02$); 12070 (0.78 ± 0.03); 14163 (1.27 ± 0.02); 15021 (0.81 ± 0.02). It is clear that there is a positive correlation between the ages generally assigned to the surfaces on which these soils were developed and the isotopic composition of the accumulated low temperature lead. A more subdued variation and correlation also occurs in the 900+° C site.

The low temperature volatile lead observations reported here have major implications and remarkable potential for understanding and explaining lunar surface history. (1) They clearly support volatile transfer as a major geochemical process on the lunar surface. They imply that many other volatile elements (we have some direct observations on Bi and Rb migration, for example) must be redistributed in this manner and that all geochemical distinctions reported between lunar soils and rocks must explicitly consider the possible effects of volatilization. (2) The provinciality observed for the lts composition of samples studied so far establishes unequivocally that there has been no moonwide comprehensive mixing or saturation by "magic component" for the Pb-U-Th systems since these regolithic sites formed. However, one can reasonably expect some moonwide volatile transfer effects from very large surface thermal events on the moon. The earliest lunar history with its enormous flux of cratering impacts and profound magmatic events may well have produced moonwide atmospheres which were recorded in the quantities and isotopic properties of volatile lead. (3) The lts lead, because of its peculiar isotopic properties and origins can be a major geographic and temporal tracer of all types of surface lunar thermal events and the transient atmospheres produced by them. (4) The earliest records of lunar history possibly may be found by exploring the volatile leads in deep drill cores on the oldest lunar surfaces we can sample. This is because some recycling of the enormous quantities of lead released to the surface in the early stages of lunar history probably continued long after access to their sources have been buried or modified by subsequent lunar events. For example, the value of 1.27 observed in the 14163 lts lead could not have formed instantaneously more recently than 4.05 b.y. ago and undoubtedly includes some much older contributions.

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Continuous Pb Volatization 14163, 184 Expt # 7 Series

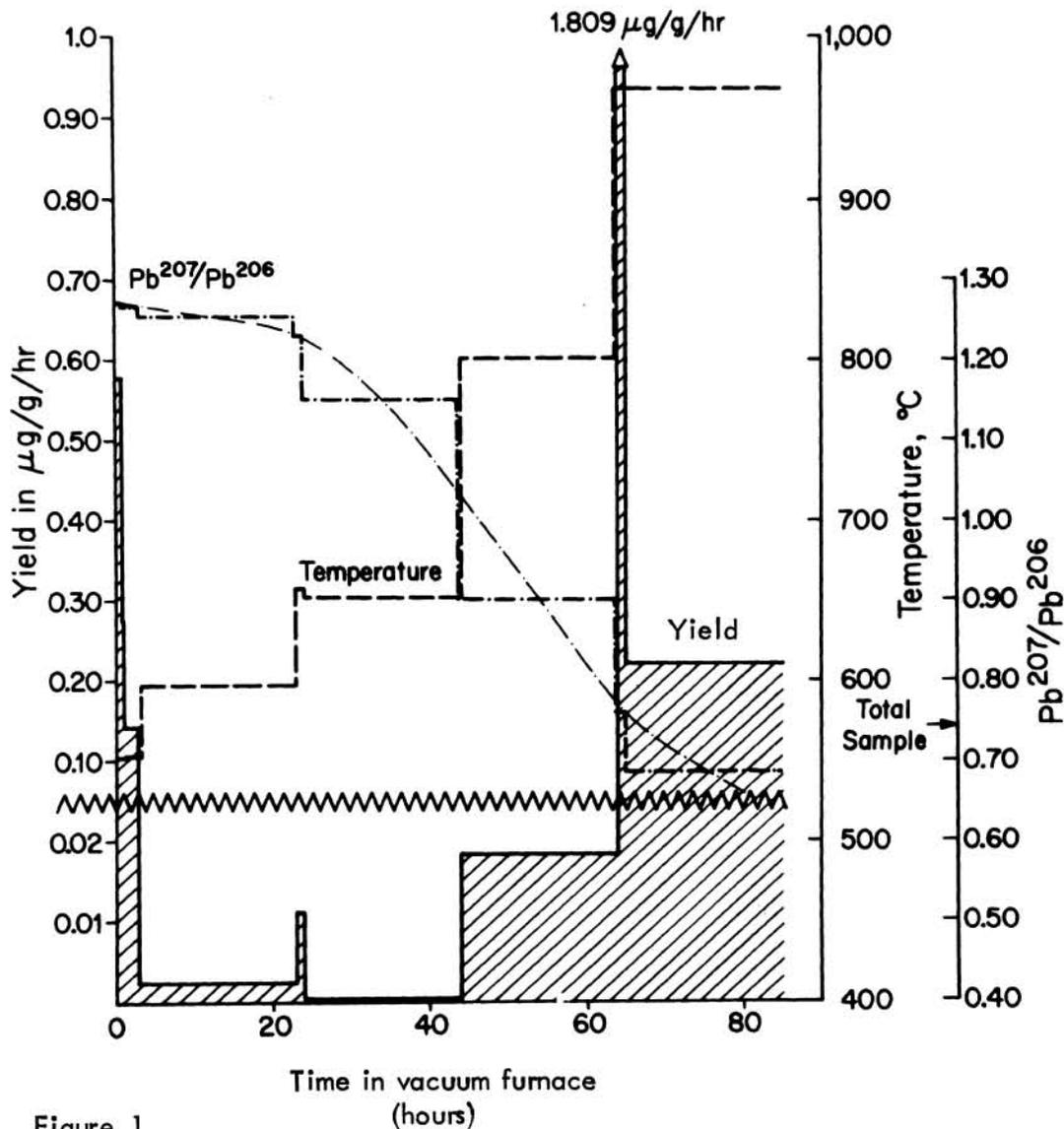


Figure 1

Step-heating vacuum extraction of volatile lead in Apollo 14 bulk soil, plotting release temperature; yield per unit time; and radiogenic $\text{Pb}^{207}/\text{Pb}^{206}$ ratio corrected with contamination lead. Note broken scale for yield curve. $\text{Pb}^{207}/\text{Pb}^{206}$ data is shown as observed increments, and as a smoothed curve for projection to zero yield.