Abstract. The internal temperatures, heat fluxes, and rates of evolution of volcanic liquids for lunar models with initial radioactivities and temperatures that decrease going downward in the Moon are calculated. These conditions lead to a volcanism concentrated very early in lunar history even when other heat sources, e.g. melting due to accretion, are excluded.

1. Introduction

A great deal of effort has been directed towards the development of models for the thermal history of the Moon in order to understand its evolution. Early calculations by Urey, MacDonald, and others were based primarily on the assumption of an initially uniform model of either 'chondritic' or 'terrestrial' composition and assumed a thermal conductivity in which radiative transfer played a large role. As it was recognized that melting of the lunar interior could significantly influence the thermal history, several attempts were made to take this into account. Fricker et al. (1967) allowed for upward diffusion of radioactive elements and assumed that once complete melting had taken place, convective transfer would dominate. McConnell et al. (1967), on the other hand, neglected convective transfer in the conventional sense, but allowed for transfer to the surface of radioactive elements with the melt, thus simulating differentiation.

More recently, new information has been obtained which demonstrates that better models are required. In the first place, analysis of lunar samples shows that an initial uniform chemical composition is no longer tenable, and that neither the 'chondritic' nor the 'terrestrial' models is suitable for an initial starting composition (Papanastassiou and Wasserburg, 1971a; Hubbard and Gast, 1971; Gast, 1972). Furthermore, recent experimental and theoretical studies show that radiative conductivity is unlikely to dominate heat transfer from the lunar interior (Aronson et al., 1967, 1970; Fukao et al., 1968). Accordingly, Wood (1972), Hays (1972) and Toksöz et al. (1972) have incorporated more realistic compositions and thermal conductivities into their models and have attempted to allow for the redistribution of radioactivity at the time of melting.

Even with these improvements, however, there are no published calculations which intimately associate movement of the radioactive elements with movement of a melt, whose migration is controlled by reasonable mechanical and thermal considerations. Such a model should be capable of predicting a wide variety of properties which could be compared with field observations. Some of these observations are discussed in more detail in the following section.
2. Observational Constraints on Successful Models

With the rapidly increasing knowledge of the geological, geophysical, and geochemical properties of the Moon, the constraints imposed on successful models become more and more stringent. The most important are those related to present interior temperatures, present heat flow composition, density and velocity distributions, strength of the interior, and thermal properties such as specific heat, thermal conductivity, and heat of fusion. In addition, the model must predict times, rates, and volumes of volcanic extrusives consistent with those observed or inferred for the planet.

One of the most difficult factors to determine is the present interior temperature. From magnetic observations, Sonett et al. (1971a, b) have inferred temperatures as low as 800 K at 500 km and 1200 K at 1000 km below the surface. Such temperatures are most easily explained by very low uranium concentrations in the deep interior, as pointed out by Hays (1972). Tozer (1972) believes that the equilibrium temperature for convection by means of solid state creep would not be much different than that postulated by Sonett. It should, however, be noted that convection requires an increasing temperature as a function of depth and would, thus, be limited for lunar models with inverted gradients much cooler at depth than near surface; i.e. Tozer's convective transport mechanism is only likely to become effective at those times and in those regions where temperature increases faster than the adiabatic gradient. In the calculations discussed below, the effects of solid convection are neglected, although we do not believe they should be dismissed.

Some qualitative constraints for the thermal evolution of the Moon have recently been summarized by Papanastassiou and Wasserburg (1971a). Their summary can be augmented by other data or observations. We suggest that the following characteristics must be explained by any comprehensive model of the thermal history of the Moon:

1. Widespread igneous liquids (KREEP basalts) occurred 4.5–4.4 billion years ago. The major chemical characteristics of these liquids imply that they are formed by partial melting of a plagioclase-rich lunar interior (Hubbard and Gast, 1971; Papanastassiou and Wasserburg, 1971b);
2. The source of the KREEP basalts had at least 5 times the uranium concentration of normal chondrites (Hubbard and Gast, 1971);
3. Extensive volcanism between 3.3 and 3.8 billion years ago implies a partially molten interior as recently as 3.3 billion years ago;
4. The post 3-billion year old volcanism is probably limited to small volcanic events such as the dark halo craters of the Alphon- sus and the post-Copernican dark halo crater, Copernicus H; (5) the outer 100–150 km of the Moon must be rigid enough to support mascons 3.5–4.0 billion years ago. In order to maintain the implied stresses of 100 bars (Kaula, 1969), temperatures in the range of 900–1100 K or less are required at these depths;
6. The present lunar interior is cold, i.e. substantially below the melting point of silicates (Sonett et al., 1971b; Dyal and Parkin, 1971);
7. The present-day heat flux is substantially higher than that of the Earth (Langseth et al., 1971); and
8. Uranium is the prime radioactive heat source in the outer part of the Moon.

As a first step in developing a more realistic and complete thermal model, we modi-