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II. THE EARLIEST EVOLUTION OF THE CRUST

The early chronology of the Moon: evidence for the early collisional history of the solar system

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A major aim of lunar science has been to understand the early evolution to the lunar crust in the period prior to the extrusion of the mare basalts. There are two aspects to this early period of evolution about which age determinations provide information. On the one hand is the magmatic activity which led to the chemical differentiation of the outer regions of the Moon, while on the other is the bombardment of the Moon by large objects in the period immediately following its formation. The two aspects are probably not unrelated in that the bombardment may represent the final stages of the accretion of the Moon, and the heat source responsible for the initial differentiation was possibly the gravitational energy released during the major accretion phase. ^{40}Ar–^{39}Ar ages have been largely reset by the final stages of the bombardment and therefore most of the information obtained from argon measurements pertains to the chronology of the bombardment. Information on the magmatic activity is obtained from Rb-Sr, U, Th-Pb and Sm-Nd studies.

The major results of argon dating of highland samples are by now well known as a result of age determinations made on more than a hundred distinct rocks in seven laboratories. The results may be summarized as follows:

(1) The major proportion of highland ages ($\sim$ 90 %) show a strong clustering in the interval 3.85–4.00 Ga. The clustering has been referred to as the lunar cataclysm by Tera *et al.* (1973) and its significance will be discussed in detail later. It is apparent however, in a few instances where precise ages have been obtained from samples irradiated and analysed in the same batch and in the same laboratory, that within this cluster there are real age differences between samples (Turner *et al.* 1971; Jessberger *et al.* 1974). A comparison of Apollo 17 and Apollo 14 ages for example shows clear age differences at the two sites. The majority of published ages from Apollo 17 cluster strongly at 3.98 Ga while several high alumina basalts from Apollo 14 (14310 type) yielded well defined ages by the ^{40}Ar–^{39}Ar and Rb-Sr methods close to 3.88 Ga. These differences are significantly in excess of experimental uncertainty and must imply that the 3.85–4.00 Ga cluster represents at least two events.

(2) A significant proportion of rocks (around 10 %) from Apollo 16 and 17 have apparently well defined ages in the range 4.2–4.3 Ga, with a suggestion of a hiatus between this group and the major 3.9–4.0 Ga cluster, if only samples with well defined 'plateau' ages are considered (Turner & Cadogan 1975). The possibility of excess argon affecting the measured ages of some of these 'high age' rocks has been raised by Huneke & Wasserburg (1975), as a result of mineral studies on troctolite 76535, and this is an important question still to be settled. If the ages are substantiated then the observed distribution of highland ages required a *minimum* of three outgassing events, at around 3.9, 4.0 and 4.25 Ga.

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(3) Although the great bulk of the highland ages are older than 3.85 Ga a very few examples show evidence of extensive outgassing more recently than 3.8 Ga but for the most part the argon release patterns of these rocks do not yield well defined ages. Rocks 14318 (Reynolds *et al.* 1974), 61016 (Stettler *et al.* 1973) and 63335 (Alexander & Kahl 1974) all yield ages less than or equal to 3.7 Ga from disturbed systematics. There is at present just a single example of a rock, a glass coated cataclastic anorthosite (60015), which had yielded a well defined and very low plateau age (3.50 ± 0.05 Ga, Schaeffer & Husain 1974). The significance of these observations of young highland ages is in the constraints they place on attempts to relate the older ages to the times of basin-forming impacts. Presumably 60015, which yields an age younger than many mare basalts, has been reset by an impact but it could not have been reset at 3.5 Ga by a basin-forming impact.

(4) The surfaces of the lunar maria show a much lower crater density than the lunar highlands which they therefore post-date. In consequence an absolute age for the oldest mare surface provides an absolute lower limit to the termination of intense bombardment of the highlands. At the present time the oldest mare surface to have been dated is that at the Apollo 17 site. Several basalt boulders excavated from near the surface there yield ages of 3.78 ± 0.04 Ga. The major lunar impact basins and most of the lunar highland craters must be older than this.

The $^{40}Ar-^{39}Ar$ ages of the mare basalts are almost universally interpreted as indicating the time of onset of argon retention immediately following the initial crystallization of the basalt, i.e. they are taken to indicate the crystallization age. Such a simple interpretation is rarely possible for the more complex highland samples. In broad terms the ages are taken by the majority of authors to indicate at least four types of event:

(1) Argon loss as a result of heating during the formation of an impact crater. In its extreme form such heating would lead to complete melting followed by crystallization and the generation of a rock with an igneous texture. Possible examples are 14310 (Dence & Plant 1972; Green *et al.* 1972), 62295 (Agrell *et al.* 1973).

(2) Argon loss as a result of annealing in the hot ejecta blanket of an impact crater or basin (e.g. Turner *et al.* 1971). Argon diffusion is strongly temperature dependent and loss may occur in a short time at high temperatures (situation (1)) or over a longer time at lower temperatures. Thus milder heating episodes may produce low grade thermal metamorphism and argon loss provided a thermal blanket is available to maintain a high ambient temperature for a sufficient time.

(3) Commencement of argon retention following uplift and cooling of plutonic rocks as a result of major impacts (Huneke *et al.* 1973; Turner *et al.* 1973). This mechanism, which requires that the material be excavated from depths where the ambient temperature is sufficient to cause continuous argon loss, may only be appropriate to the ejecta from the large impact basins.

(4) Argon retention following crystallization from a (primary) igneous melt. There are thought to be few, if any, examples in the category. The highland samples with relatively straightforward igneous textures (e.g. 14310, 68415) are more likely to be impact melts, particularly in view of the presence of 'meteoritic' trace elements (Morgan *et al.* 1974). In the few cases where relict plutonic textures have been possibly identified (e.g. troctolite 76535, Gooley *et al.* 1974) it may not be assumed that the $^{40}Ar-^{39}Ar$ age refers to the time of crystallization, since the samples have been incorporated (with possible reheating) in breccias.

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It is quite probable then that most, if not all, of the ^{40}Ar–^{39}Ar ages of highland rocks are related to impact events. At the present time however there has been remarkably little systematic effort directed to quantifying the effect of the impact process on dating methods. Three of the basic questions to be answered are (*a*) how effective are craters of a given size in causing argon loss? (*b*) Where are the samples, outgassed by a cratering event of a given size, distributed in the ejecta blanket of the resulting crater? (*c*) What is the relation between argon loss and petrological effects? Without definitive answers to these questions it is hardly surprising that major difficulties arise when attempts are made to determine which events have been responsible for argon loss in specific samples and there is little agreement between chronologists on detailed interpretations of the ages.

Several authors (see for example Turner *et al.* 1971, 1973; Turner & Cadogan 1975; Jessberger *et al.* 1974; Schaeffer & Husain 1974) have made the assumption that, to a first order, the age distribution of the rocks at the sites samples is dominated by a relatively small number of major basin forming events, specifically the impacts which produced the Imbrium, Serenitatis and Nectaris basins, and, at the Luna 20 site, the Crisium basin. The basic justification for these interpretations is to be found in the proximity of most of the landing sites to one or more of the impact basins and in the extent to which the local geological features are the direct result of the basin forming events.

A number of photogeological arguments have guided these interpretations. The interpretation of the Fra Mauro formation as Imbrium ejecta was a prime reason for the choice of the Apollo 14 landing site (see Sutton *et al.* 1972) and has been a feature of virtually all interpretations of the Apollo 14 age data.

A view of the massifs at the Apollo 17 site as fault blocks uplifted by the Serenitatis event and covered by Serenitatis ejecta (Muehlberger *et al.* 1973) has similarly dominated many of the interpretations of the Apollo 17 data. With several large impacts capable of contributing ejecta at each landing site theoretical (or semi-empirical) calculations of the distribution of basin ejecta (McGetchin *et al.* 1973) have also played a prominent role in attempts to estimate the relative contributions of different impacts at a particular site. More recently Oberbeck *et al.* (1974) have stressed the importance of the mixing of the ejecta from basin and other impacts with locally derived material. It is argued that the proportion of locally derived material increases with distance from the source of the ejecta and so the process is likely to be particularly significant at the Apollo 14 and Apollo 16 sites. Wilhelms (1970) and Stuart-Alexander & Howard (1970) have proposed *relative* chronologies of the basin forming impacts based on photogeology and these have been used to constrain the assignment of *absolute* ages of events.

Because of the complexity of the highland breccias petrological considerations have been of more limited use in attempts to assign ages to particular basin impacts. Bulk chemistry is likewise of limited significance to most basin interpretations apart from the clear distinction between 'kreep' rich and anorthositic samples and the association of the kreep with the Oceanus Procellarum and Imbrium region (Metzger *et al.* 1974). The significance of the siderophile trace element chemistry in attempts to correlate material from different impacts has been stressed by Morgan *et al.* (1974). Some experimental justification for this approach has recently been obtained from studies of the trace element chemistry of ejecta from terrestrial impact craters (Morgan *et al.* 1975).

In any attempt to establish a lunar impact basin chronology Imbrium and Serenitatis assume

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roles of prime importance; Imbrium because its ejecta has been well sampled and because, apart from Orientale, it is the *youngest* major basin; Serenitatis because of the excellent sampling by Apollo 17 and because on photogeological grounds it is the *oldest circular* mare basin (in the sequence; Orientale, Imbrium, Crisium, Humorum, Nectaris, Serenitatis; Stuart-Alexander & Howard 1970). An important assumption made by most authors, in connection with Imbrium, is that the Apollo 14 site is dominated by Imbrium ejecta (Turner *et al.* 1971. 1973; Huneke *et al.* 1973; Kirsten *et al.* 1973) which generally leads to the conclusion that the age of 3.95 Ga typical of the Apollo 14 breccias represents an upper limit to the time of the Imbrium event. There exists the possibility that one or other of the age groups defined by the crystalline rocks (Turner *et al.* 1971) represents the time of the Imbrium event rather than a limit, but such interpretations must make further assumptions about the relationship of the crystalline rocks to the breccias, i.e. whether or not they are clasts from the breccias, and about the extent of annealing resulting from the Imbrium event. Crystalline rock 14310 has been interpreted by a number of authors as a possible impact melt, both on the basis of petrology (Dence & Plant 1972; Green *et al.* 1972) and meteoritic trace element abundances (Morgan *et al.* 1972). Dence & Plant argue that 14310 is probably an impact melt rock but because of the great distance of the Fra Mauro site from the Imbrium basin it cannot be an Imbrium melt. They therefore argue that it is *pre*-Imbrium and on this assumption the younger age of 3.88 ± 0.04 Ga becomes the upper limit for the Imbrium event.

Chao (1973) has discussed the petrology of the Apollo 14 rocks with reference to their interpretation as Imbrium ejecta and concludes, because of the presence of annealed and unannealed fragments within the same rocks and from a comparison with the distribution of annealed material around terrestrial impact craters, that little annealing occurred as a result of the Imbrium event. He further argues that the relationship of the 14310 group of crystalline rocks to the breccias is unclear and that it is the age of the youngest clast, 3.95 ± 0.04 Ga, should be taken as the upper limit of the Imbrium event.

The prime site for sampling Serenitatis ejecta is Apollo 17. Ages around 3.98 Ga obtained on massif breccias have been associated with the Serenitatis event by many authors (Turner *et al.* 1973; Huneke *et al.* 1973; Morgan *et al.* 1974). The basic arguments used to support this interpretation include: the preponderance of 3.98 Ga ages obtained for the strongly annealed noritic boulder samples and the relative absence of 3.90 Ga ages, which contrasts with the situation at other highland sites; the association of the boulder samples with major lithic units of the Taurus-Littrow massifs and the association of the massifs with the Serenitatis event; the presence of distinctive trace element groupings in the 3.98 Ga old rocks which suggest a common impact event for these samples.

Relative to Imbrium and Serenitatis the ages of the Orientale, Crisium, Humorum and Nectaris are constrained by the stratigraphic sequence. The proportion of Orientale ejecta at the Apollo landing sites is very small and there is therefore no obvious candidate for Orientale ejecta among the lunar samples. The low radioactivity of the Orientale ejecta blanket (Metzger *et al.* 1974) suggests that Orientale ejecta is not particularly rich in kreep material. Since Orientale is younger than Imbrium but older than the Apollo 17 mare surface most authors estimate an age in the interval 3.8–3.9 Ga.

Crisium, Humorum and Nectaris are intermediate in age between Imbrium and Serenitatis and therefore probably fall in the interval 3.9–4.0 Ga if the age of (3.98 ± 0.03) Ga is accepted for Serenitatis. The dates of (3.90 ± 0.05) Ga for the two metaclastic norites from

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the Luna 20 site have been tentatively associated with the Crisium event by Podosek *et al.* (1972).

Schaeffer & Husain (1973) have associated the 4.25 Ga ages from Apollo 16 light matrix breccia fragments with the Nectaris event. The arguments in support of this association relate to calculated distribution of basin ejecta (McGetchin *et al.* 1973) and the postulated excavation by North Ray crater of an underlying Nectaris layer. In the present author's opinion the arguments associating the massif boulders at Taurus Littrow with the Serenitatis event are stronger than those associating a minor component of the Apollo 16 soil with Nectaris. Nevertheless it is clear that at present there is no definitive way of deciding which (if any) hypothesis is correct. If the view that the 3.98 Ga old samples date Serenitatis is correct then the older ages of 4.2–4.3 Ga must arise from pre-Serenitatis (and pre-Nectaris) cratering or basin events.

Kirsten & Horn (1974*a*) have stressed an alternative view of the highland age distribution namely that the ages reflect the outgassing resulting from the very large number of medium sized cratering events in addition to major basin events. Since there is clear evidence of at least one sample (60015) being reset by a post basin cratering event it is clear that this view must be given serious consideration.

If a large number of events is represented in the age histogram and if the sampling is not biased to specific events then the form of the histogram could be interpreted in a statistical way. The form of the histogram would depend on two major factors (Turner & Cadogan 1975): (1) The cratering rate as a function of time would determine the number of samples reset at a particular time. (2) The time integral of the cratering rate from that time to the present would determine the proportion of the samples reset which survive on the surface to the present day to be dated. In principal it should therefore be possible to infer cratering rate as a function of time from the form of the age histogram provided the above assumptions are valid. Unfortunately this seems unlikely to be the case. The Apollo sites were chosen specifically to sample major basin ejecta and it is probable that a significant proportion if not all of the ages reflect a small number of events. It seems fairly certain for example that the strong clustering of the Apollo 17 boulder sample ages at 3.98 Ga represents a single event whether that event is the Serenitatis impact or not.

The clustering of most lunar highland ages in the interval 3.9–4.0 Ga has impressed all involved in the measurement of these ages. It has been referred to by Tera *et al.* (1973) as the lunar cataclysm and interpreted broadly in terms of the termination of the intense bombardment of the lunar highlands. What is not yet clear is whether this 'cataclysm' represents simply the effective termination of an approximately monotonic decrease in the early cratering influx or whether it represents a period of increased influx to close to 4.0 Ga. The solution of this problem is currently a major aim of lunar chronologists.

If the ages represent the termination of a decreasing influx then mechanisms must be found to account for the implied capture lifetime of the colliding solar system debris. This problem has been discussed recently by Wetherhill (1974, 1975) in terms of orbital dynamics. If on the other hand the 'cataclysm' represents a real and significant increase in influx then some catastrophic event is implied, for example a major collision between two asteroids providing a source of new impacting objects. Alternatively the cataclysm could be related to the capture of the Moon by the Earth if the capture mechanism involved collision of the Moon with a circumterrestrial debris swarm.

While the correct interpretation of the cataclysm is unclear at the moment the problem does

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appear to be open to solution and several lines of investigation are indicated. Turner & Cadogan (1975) have argued that a possible hiatus in ages between 4.0 and 4.2 Ga could be used to argue in favour of an increased influx of bombarding objects at 4.0 Ga. The strength of this argument is dependent on the number of events actually represented in the age histogram since the smaller the number of events the more likely an apparent minimum may occur purely on statistical grounds.

A second line of argument may follow from a comparison of radiometric basin ages with crater densities on the ejecta blankets of the basins. Neukum *et al.* (1975) have determined crater densities in areas of the highlands identified with ejecta of several major basins and have interpreted their results in terms of an exponentially decreasing influx of bombarding objects. Interpreted in this way their results appear to be most consistent with a high age (~ 4.2 Ga) for Serenitatis. On the other hand the arguments may be inverted and a low age (4.0 Ga) for Serenitatis used to argue in favour of an increased cratering flux at 4.0 Ga. It is clear then that *the unambiguous determination of an age for the Serenitatis basin is of crucial importance in any attempt to interpret the lunar cataclysm.*

A third method of attacking the problem is to search for evidence of collisions in other parts of the solar system by applying the ^{40}Ar–^{39}Ar method to meteorites. Outgassing events in the interval 4.2–3.8 Ga have been detected in at least three meteorites (Turner & Cadogan 1974; Kirsten & Horn 1974*b*) but at the present time the amount of ^{40}Ar–^{39}Ar data on meteorites is minimal. This situation will probably be rectified in the next few years.

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