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[summary in 7], indistinguishable from the age of Imbrium. The Rb-Sr ages are slightly older (slight Rb loss?) but within uncertainty of a 3.85-Ga age. KREEP basaltic material of other character or age has not been identified in the region, thus these basalts appear to represent a unique event in the region.

**Apollo 15 KREEP = Apennine Bench Formation:** The morphology of the Apennine Bench Formation indicates subsidence of a fluidlike material, consistent with volcanic flows [5,6]. The deconvolved orbital geochemistry shows the formation to be chemically very similar to the Apollo15 KREEP fragments. The formation occurs very close to the Apollo 15 landing site (Fig. 1), and is inferred to underlie the mare basalts near Hadley Rille; it may even be exposed at the North Complex, intended to be visited on the Apollo 15 mission but missed because of time delays. The Apollo 15 KREEP basalts are ubiquitous at the Apollo 15 site, and most must represent a local, not an exotic, component. The age of the KREEP fragments is consistent with requirements for the Apennine Bench. The correlation of the Apollo 15 KREEP basalts with the Apennine Bench Formation is almost inescapable.

**Apollo 15 KREEP Basalts Are Volcanic:** The basalts are free of clasts or meteoritic siderophile contamination, and have a range of compositions indicating crystal separation (unlike impact melts) and lying along the plagioclase-low Ca pyroxene cotectic [2]. Some demonstrate nonlinear cooling rates inconsistent with cooling of impact melts [8]. They cannot represent an average crustal composition such as would be represented by the Imbrium impact melt because they are so radiogenic.

With such a coincidence in age of a giant impact basin and a unique flood basalt eruption, the most reasonable conclusion is cause and effect: The unloading and heat input from the Imbrium Basin impact was directly responsible for the partial melting of a hot crust producing the Apollo 15 KREEP basalt floods. The chemical and isotopic evidence suggest that a large amount of partial melting of a crustal source is required to produce these basalts. The small gravity field on the Moon shows that the pressure relief of unloading even 100 km is only 0.5 GPa, and brings a mass of suitable rock only 60 K closer to its melting point [1]. The unloading of the lunar lower crust would have been less than that, and with latent heat of melting to take into account, not much melting can be expected. Thus, if impact-induced crustal melting is responsible for the Apollo 15 KREEP basalts, the source must have been at or very close to its melting temperature anyway, or melts induced by pressure release of the mantle added their heat to the source by upward movement without actually reaching the surface.

The oldest Earth rocks of any significant volume have an age similar to that of the lunar cataclysmic bombardment. Older crust either did not exist, or was essentially annihilated at that time. A hotter Earth at 3.86 Ga ago was perhaps very susceptible to impact-induced partial melting, causing very extensive recycling even of nonsubductable granitic crust. Even larger planetesimals would have hit the Earth than the Moon, traveling even faster; the effects of pressure release would have been greater because of the stronger gravity field, and more material close to its melting temperature. Such melting could have had drastic effects in remixing and assimilating old crust into upper mantle material to add to an assumed plate-tectonic recycling that could not by itself be very efficient for granitic material.

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## APOLLO 15 IMPACT MELTS, THE AGE OF IMBRIUM, AND THE EARTH-MOON IMPACT CATACLYSM.

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The early impact history of the lunar surface is of critical importance in understanding the evolution of both the primitive Moon and the Earth, as well as the corresponding populations of planetesimals in Earth-crossing orbits. Two endmember hypotheses call for greatly dissimilar impact dynamics. One is a heavy continuous (declining) bombardment from about 4.5 Ga to 3.85 Ga. The other is that an intense but brief bombardment at about 3.85 (±?) Ga was responsible for producing the visible lunar landforms and for the common 3.8–3.9-Ga ages of highland rocks.

No impact melts among lunar samples have been found with an age greater than 3.9 Ga [1]. A heavy continuous bombardment requires such melts to have once been common, and their absence requires either that they are present but have not been sampled, or that they have been reset continuously or terminally at dates later than 3.9 Ga. The chemical variety of dated impact melts suggests that at least several impacts have been dated, not just a limited sample reset by Imbrium and Serenitatis. Most ejecta in an impact is deposited cold and is not radiometrically reset even for Ar (although it can be disturbed), as shown by studies of both experimentally and naturally shocked materials [2–4]. Resetting should be accomplished only or nearly only by making a new impact melt, yet lunar samples clearly show that not all of the lunar crust has been so converted; old melt should remain if it once existed. Furthermore, the existence of old basalts and plutonic rocks suggests that old impact melts should have been preserved, had they existed. These arguments should be persuasive that no heavy bombardment in the period from at least 4.3 to 3.9 Ga occurred [1]. Apparently, for various reasons they are not persuasive [e.g., 5]. Thus reliable ages for impact melt rocks of even more varied composition (hence potentially distinct origins) are needed to further test the various early impact hypotheses, and particularly to establish the relative abundance of old impact melts.

The Apennine Front, the main topographic ring of the Imbrium Basin, was sampled on the Apollo 15 mission. The rocks in the massif represent two main sources: (1) pre-Imbrium masses that have been uplifted by the event itself, and consist of pre-Imbrium rock units, and (2) ejecta from the Imbrium event, consisting of material melted in the Imbrium event and older material [6]. Either way, if impact melts existed in the region prior to the Imbrium event, they should now be part of the Front. Material formed in impacts younger than the Imbrium Basin must be minor, of very local origin, and from small craters (which tend to produce glassy melt products). The Apollo 15 impact melts show a diversity of chemical compositions, indicating their origin in at least several different impact events [e.g., 7,8,9]. The few attempts at dating them have generally not produced convincing ages, despite their importance. Thus we chose to investigate the ages of melt rock samples from the Apennine Front, because of their stratigraphic importance yet lack of previous age definition.

Using a continuous laser system, we have obtained high-resolution $^{40}Ar/^{39}Ar$ age spectra on single fragments of 12 melt rock samples from the Apennine Front. The melt rocks, all fine-grained, are essentially aluminous basalts, but with a variety of compositions, e.g., MgO 9 to 21%, Sm 2 to 25 ppm. We believe they must represent at least several different impact events. A few milligrams of each sample were crushed to submillimeter sizes and individual fragments, visibly free of clasts and weighing 62 to 620 mg, were irradiated. They were analyzed with a continuous Ar-ion laser extraction system and mass spectrometer [10,11]. Individual particles were incrementally heated, with temperature measured with an infrared radiometer. We have obtained 26 age spectra on the 12 melt samples. Some of these results have been previously published [11].

Of the 12 rocks analyzed, 7 have age spectrum plateaus that we interpret as crystallization (impact) ages. Individual plateaus have 2-sigma uncertainties of ±16 Ma. The $^{40}Ar/^{39}Ar$ plateaus are generally well defined in the intermediate temperature range with 40% to 70% of the $^{39}Ar$ released. Six of these ages fall within the narrow range of 3879 Ma and 3849 Ma, more or less within uncertainty of a common age. Spectra on five fragments of one sample gave a range from 3856 Ma to 3879 Ma. The seventh sample gave a plateau age of 3836 Ma. The total span of ages is less than 1%, a very narrow range. The remaining five samples show spectra that clearly indicate disturbance by post-3.8-Ga events, and lack plateaus. None of the 26 age spectra for the 12 melt rocks show any indication of older melt components. A conventional $^{40}Ar/^{39}Ar$ age of 3.85 ± 0.05 Ga for a different impact melt from the Apollo 15 landing site was reported by [12].

We believe that these data provide ages for a variety of impact melts that are coeval with or predate the Imbrium event. Thus a first-order conclusion is that the Imbrium event is no older than about 3870 Ma, and probably no older than 3940 Ma. Independent evidence suggests strongly that Imbrium is not younger than this (because of the later KREEP basalts), hence is indeed very close to 3840 to 3850 Ma. In that our data show a variety of melts at or just before this time but not older melt, we believe it to be consistent with a very tightly constrained bombardment of the Moon. Serenitatis (about 3.87 Ga) falls in this same period. We have still no tangible evidence for significant bombardment prior to 3.9 Ga.

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## SEARCH FOR THE 700,000-YEAR-OLD SOURCE CRATER OF THE AUSTRALASIAN TEKTITE STREWN FIELD.

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Many tektite investigators have hypothesized that the impact crater that was the source of the extensive Australasian strewn field lies somewhere in or near Indochina. This is due to variations in abundance and size of tektites across the strewn field, variation of thickness of microtektite layers in ocean cores, nature of ablation characteristics across the field, and, above all, the occurrence of the large, blocky, layered Muong Nong-type tektites in Indochina. A recent study of the location and chemistry of Muong Nong-type and splash-form tektites suggests that the source region can be further narrowed to a limited area in eastern Thailand and southern Laos [1].

There are four lines of evidence that point toward this area. The first is the observation that tektite sites in Indochina are nonrandomly distributed. Many sites seem to be located along linear trends or "rays" separated by areas relatively sparse or devoid of samples. These rays converge to a small area along the Thailand-Laos border between 15.5°N and 17°N latitude. Second, there is a somewhat larger region, enclosing the area delineated by the rays, where Muong Nong tektites predominate and/or there is no mention of splash-form-type tektites. Third, a high proportion of the reported sites containing super-sized (>1 kg) Muong Nong tektites are in this area. Lastly, Muong Nong tektites with this area show the largest chemical inhomogeneity in sites, and there is a high chemical gradient across the region; these are characteristics one would expect proximal to the source. The area defined by the above evidence is centered at 16°N/105°E, with a radius of approximately 125 km.

Satellite multispectral imagery, a digital elevation dataset, and maps showing drainage patterns have been used to search within this area for possible anomalous features that may be large degraded impact craters. Four interesting structures have been identified from these datasets:

1. An approximately 30-km-diameter, quasicircular structure in Laos, resembling a partially infilled impact structure, centered at 16.35°N/106.15°E. It has a relatively flat floor surrounded by hills rising 70 m to several hundred meters above the floor, and a central elevated area rising about 100 m above the floor (Fig. 1). The structure is breached at approximately the cardinal points by rivers.

2. An approximately 25-km-diameter circular feature on the east side of the Mekong River, slightly east of Savannakhet, Laos (16.55°N/104.90°E). This feature is not an obvious depression or crater, but is an approximately circular area enclosing hummocky terrain of very low relief.

3. A 90-km-diameter area, centered at 16.6°N/105.5°E (directly to the east of structure 2). This broad south-sloping feature is rimmed by high hills on the north and east, rising to 450 m above the floor, but only low lying hills to the west and south. The area is drained by two rivers flowing to the south.

4. An oblong depression on the west side and in a curve of the Mekong River, approximately 80 km northeast of Ubon Ratchathani, Thailand. It is approximately 30 km long northwest-southeast, and about 20 km wide southwest-northeast. Hills rise about 75 m in the southwest to over 300 m in the southeast above the flat floored plain.

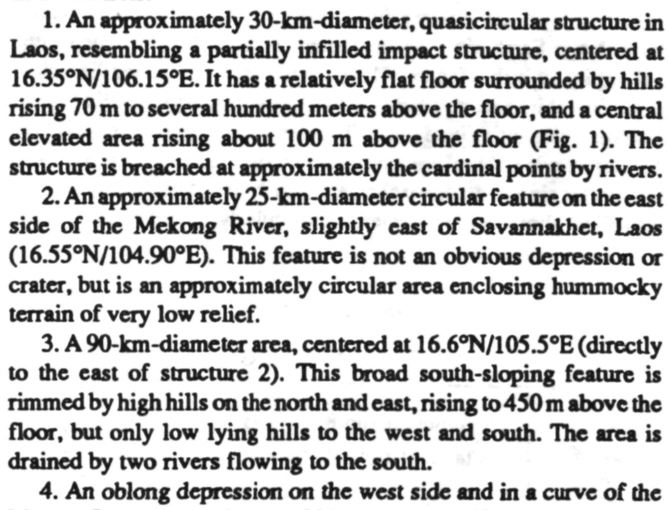

**Fig. 1.** Profiles across structure 1, centered at 16.35°N/106.15°E, in southern Laos. From top to bottom, southeast-northwest, southwest-northeast, west-east, south-north.