the (sub)planar deformation structures in quartz represent PDFs or planar fractures? It is our contention that they generally resemble planar fractures rather than the shorter and closer-spaced PDFs (compare Figs. 7b,c of [4] with Vredefort microdeformation).

Other unresolved problematics regarding Vredefort pt are the nature and origin of the enigmatic granophyre that, besides being regionally homogeneous in composition, displays a number of characteristics similar to those of pt. Major shortcomings in the pt database are (1) absolute ages for the several phases of pt development and of structural deformation, (2) understanding of the geological structure in the zones of major pt development and (3) of the internal structures of pt-rich (fault?) zones, (4) P-T-x conditions at pt formation—also with regard to HP SiO_2 polymorph generation, and (5) the relationships between Vredefort and Witwatersrand pt and Witwatersrand fault structure.

References: [1] Schwarzman E. C. et al. (1983) *Bull. GSA, 94,* 926–935. [2] Dietz R. S. (1992) *Earth, 1,* 22. [3] Reimold W. U. et al. (1987) *JGR, 92,* 747–758. [4] Stöffler D. et al. (1992) *GCA, 55,* 3845–3867. [5] Killick A. M. and Reimold W. U. (1990) *S. Afr. J. Geol., 93,* 350–365. [6] Reimold W. U. et al. (1990) *Geol. Soc. Austral. Abstr., 27,* 82. [7] Allsopp H. L. et al. (1991) *S. Afr. J. Sci., 87,* 431–442. [8] Reimold W. U. (1991) *N. Jhrb. Miner. Abh., 162,* 151–184. [9] Martini J. E. J. (1991) *EPSL, 103,* 285–300. [10] Reimold W. U. (1990) *S. Afr. J. Geol., 93,* 645-663.

COINCIDENCE IN TIME OF THE IMBRIUM BASIN IMPACT AND APOLLO 15 KREEP VOLCANIC SERIES: IMPACT-INDUCED MELTING? Graham Ryder, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058, USA.

On the Earth there may be no firm evidence that impacts can induce volcanic activity [1]. However, the Moon does provide a very likely example of volcanism induced by an immense impact: The Imbrium Basin-forming event was immediately succeeded by a crustal partial melting event that released KREEP lava flows over a wide area. These two events are at present indistinguishable in radiometric age. The sample record indicates that such KREEP volcanism had not occurred in the region prior to that time, and never occurred again. Such coincidence in time implies a genetic relationship between the two events, and impact-induced partial melting appears to be the only candidate process.

This conclusion rests essentially on the arguments that (1) the Imbrium Basin event took place 3.86 ± 0.02 Ga ago; (2) the Apennine Bench Formation postdates Imbrium; (3) the Apollo 15 KREEP basalts are 3.85 ± 0.03 Ga old; (4) the Apollo 15 KREEP basalts are derived from the Apennine Bench Formation; and (5) the Apollo 15 KREEP basalts are volcanic. Thus the Apollo 15 KREEP basalts represent a unique volcanic unit that immediately postdates the Imbrium event (within 20 Ma, possibly much less).

This abstract sketches the evidence for the links in the argument, describes some implications for initial conditions, and briefly explores ramifications of the process for the early history of the Earth.

The Age of Imbrium: Samples collected at the Apennine Front must be dominantly isotopically reset either by the Imbrium event or by older events. Analyses by laser argon release methods [3,4] of varied impact melts from the rubble that forms the Apennines constrains the basin to be probably no older than 3.836 Ga, and extremely unlikely to be older than 3.870 Ga. Imbrium must also be younger than Serenitatis, reliably dated at 3.87 Ga. A younger limit set by the Apennine Bench Formation arguments is within uncertainty the same age.

The Stratigraphic Age of the Apennine Bench Formation: This extensive plains unit inside the Imbrium Basin underlies Imbrium-age craters and mare units (Fig. 1). However, it overlaps basin topography, hence is at least slightly younger than the basin itself [5,6].

The Age of Apollo 15 KREEP Basalts: This distinct group of intersertal igneous fragments, widespread at the Apollo 15 landing site, gives Ar-Ar and Sm-Nd crystallization ages of 3.85 ± 0.05 Ga

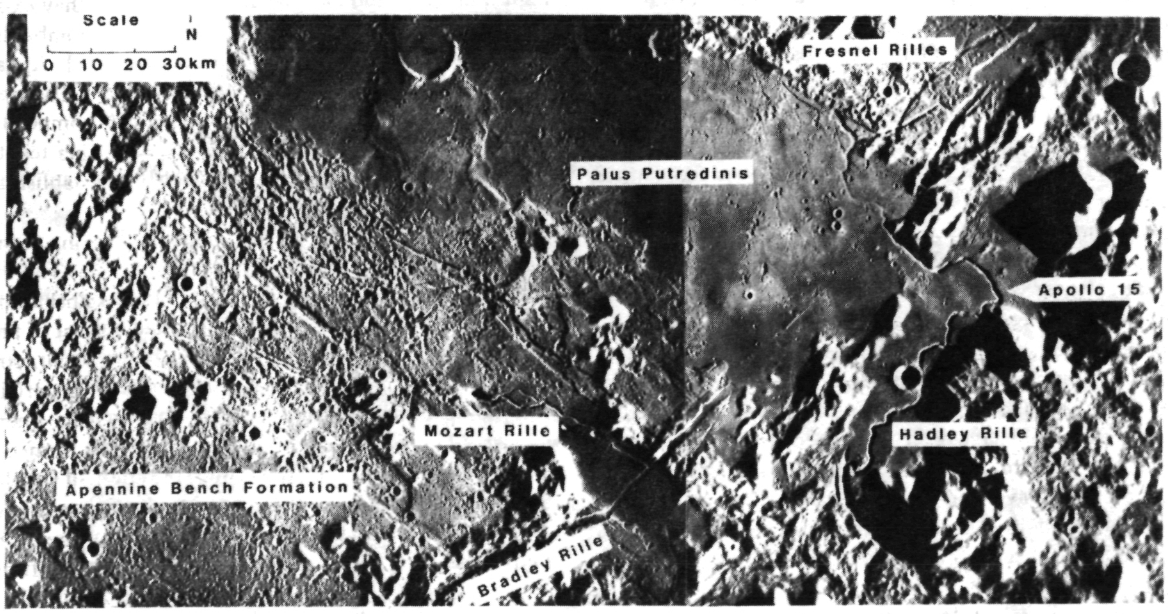

Fig. 1. Orbital photograph of the Apollo 15 landing site and relevant environs. Apart from the large area to the left of the picture, Apennine Bench Formation occurs at the area of the Fresnel Rilles. It probably also underlies the mare near the Apollo 15 landing site and may even be exposed at the North Complex (a dimple just to the north of the landing site) and elsewhere nearby. The mountains to the right are the Apennines, a prominent ring of Imbrium.

475217

[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.

References: [1] Melosh H. J. (1989) *Impact Cratering*, Oxford, 245 pp. [2] Ryder G. (1989) *LPSC XX*, 936. [3] Dalrymple G. E. and Ryder G. (1991) *GRL, 18*, 1163. [4] Dalrymple G. B. and Ryder G. (1992) *Trans. AGU 14 Suppl.*, 362. [5] Spudis P. D., *Proc. LPSC 9th*, 3379. [6] Wilhelms D. (1987) *U.S. Geol. Surv. Prof. Pap. 1348*, 302. [7] Shih C.-Y. et al. (1992) *EPSL, 108*, 203. [8] Ryder G. (1987) *Proc. LPSC 17th*, in *JGR, 92*, E331.

S64-91 N93-10176-2

APOLLO 15 IMPACT MELTS, THE AGE OF IMBRIUM, AND THE EARTH-MOON IMPACT CATACLYSM. Graham Ryder[1] and G. Brent Dalrymple[2], [1]Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058-1113, USA, [2]U.S. Geological Survey, 345 Middlefield Road, Menlo Park CA 94025, USA.

L-86189-29 GN 717886

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.