granophyre as melt rock. (8) Shock metamorphism occurs in the form of shock-characteristic planar microdeformation features (PDFs) in quartz.

Contra Impact: (1) The structure is asymmetrical and polygonal. (2) The southern equivalent to the collar in other sectors shows subhorizontal stratigraphy. (3) The "crust-on-edge" model is only valid for the northern part of the dome. (4) There is only limited structural evidence for 2-Ga deformation. (5) Deformation intensity does not increase toward the center, and deformation in the central area is generally poorly developed. (6) Deformation is magnified along northeast-southwest-trending lineaments. (7) Several phases of deformation have been identified. (8) Vredefort deformation phenomena are also observed in the northern Witwatersrand basin. (9) Temporal relationships between MSJS/shatter cones and pseudotachylite are complex and multiple. (10) Microdeformation is restricted to controversial "features" in quartz and kinkbanding of mica and occasionally hornblende. No other characteristic shock effects have been described from other minerals. (11) Temporal relationships between the various deformation and structural/magmatic events are complex and as yet not sufficiently resolved.

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THE PSEUDOTACHYLITES FROM THE VREDEFORT STRUCTURE AND THE WITWATERSRAND BASIN.

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Pseudotachylite (pt) from both the Sudbury structure in Ontario and the Vredefort Dome in South Africa have been widely cited as the result of shock(impact)-induced brecciation. In the scientific [e.g., 1] and popular [2] literature pt has been described as "shock melt" or even as "impact melt rock" [2, p. 22]. In contrast, others have for years requested that a clarification of the definitions for "pseudotachylite" and "impact melt rock" be pursued [e.g., 3]. We have suggested that, until that time when well-defined criteria for genetically different melt rock types (e.g., generated by impact or tectonic processes) will have been established, the term "pseudotachylite" should only be used as a descriptive one and that, wherever genetic implications are discussed, other terms, such as impact melt (rock) or friction melt, should be applied. It is obvious that these suggestions are not only of value for the discussion of terrestrial melt rocks of controversial origin, but also apply to the characterization of melt veins in extraterrestrial materials [1,4].

The majority of planetologists currently support the impact hypothesis for the origin of the Vredefort Dome. However, those workers that have actively pursued research in the structure still feel uncomfortable about the severe limitations of the Vredefort database and the widely held belief that a few particular observations should hold the key to the understanding of the origin of the Dome. When the whole database is considered, there is a lot of (mainly structural or pt-related) evidence that is not readily explained by the impact hypothesis. Unfortunately, in recent years these workers have been ridiculed in a quite unscientific way, e.g., as "academic dinosaurs" or "reactionary diehards."

In this paper important observations on Vredefort and Witwatersrand pseudotachylite are summarized (for more detail, cf. [5]).

Distribution and Styles of Development: Major pt occurrences on the Dome are concentrated along the transition zone between Outer Granite gneiss and Inlandsee Leucogranofels, as well as along a northeast-southwest-trending zone just south of the Inlandsee. Brecciation in the central core region is extremely limited. Within the collar strata, pt mainly occurs in the form of <30-cm-wide veins along bedding faults, but up to several-meter-wide zones comprised of intercalated networks of narrow veinlets and more massive melt breccia have recently been observed in mafic intrusives in the collar. Throughout the Dome and the northern part of the Witwatersrand basin pt is also found as thin melt films on slickenside and shatter cone (MSJS) surfaces. In the granitic core one finds either massive development (network breccia) or up to 50-cm-wide veins. Network breccias are occasionally seen to be delimited at one side by a thick, straight vein that possibly represents the initial generation vein. Several new quarry exposures indicate subhorizontal internal structures within major breccia developments, but individual large-scale breccia zones appear to have overall vertical attitude. Thin veins generally resemble tectonic pt occurrences. Displacement is usually variable in dm to m intervals and ranges normally from <1 mm to >50 cm (but <1 m). Sense of movement is found to be equally variable along a given vein (but only rarely can three-dimensional geometries be studied). Frequently orthogonal pairs of veins—at 90° angles—are observed. Most veins trend parallel to the main orientations (northwest-southeast and northeast-southwest) defined by the pervasive Archean fabric. Other veins are generally injection veins off master veins or network breccia.

Pt in the Witwatersrand basin has been described from the north and northwest portions—the remainder is barren. Most pt here is bound to important bedding faults (dipping generally at low angles to the south) and to a few north-south-trending normal faults. Drilling has revealed several up to 40-m-wide breccia zones with up to 60% melt development. Steeper pt veins are thought to represent injection veins. As in the Vredefort case, several generations of fault rocks (including pt) have been recognized. Ages for Vredefort pt range from 2.2 to 1.1 Ga. Further support for some of the lower ages has recently been presented by [6,7]; for one occurrence of Witwatersrand pt, ages of 2.0 Ga have been established (Trieloff et al., this volume). This could possibly mean that formation of at least some of the Witwatersrand pt could be linked with either Bushveld or Vredefort activity.

Mineralogical data are still scarce and no quantitative micropetrographic results are available yet. The limited data at hand have, however, shown that at least some of the Vredefort pt was formed by cataclasis prior to melting. Chemical results for Vredefort pt [8] show that most of the analyzed pt was formed locally and that lateral mixing, probably not exceeding distances of a few meters, is restricted to network breccias. Comparative analysis of host rock and pt pairs illustrated that the same melting processes apply to Vredefort pt and to tectonic occurrences. A discussion of Vredefort pt would be incomplete if Martini's [9] findings of HP SiO_2 polymorphs in narrow veinlets from the outer collar were to be ignored (discussion of this aspect is in press elsewhere). Also of importance is the debate about the nature of mineral deformation associated with host rock contact zones and clasts within pt: e.g., do 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.

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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

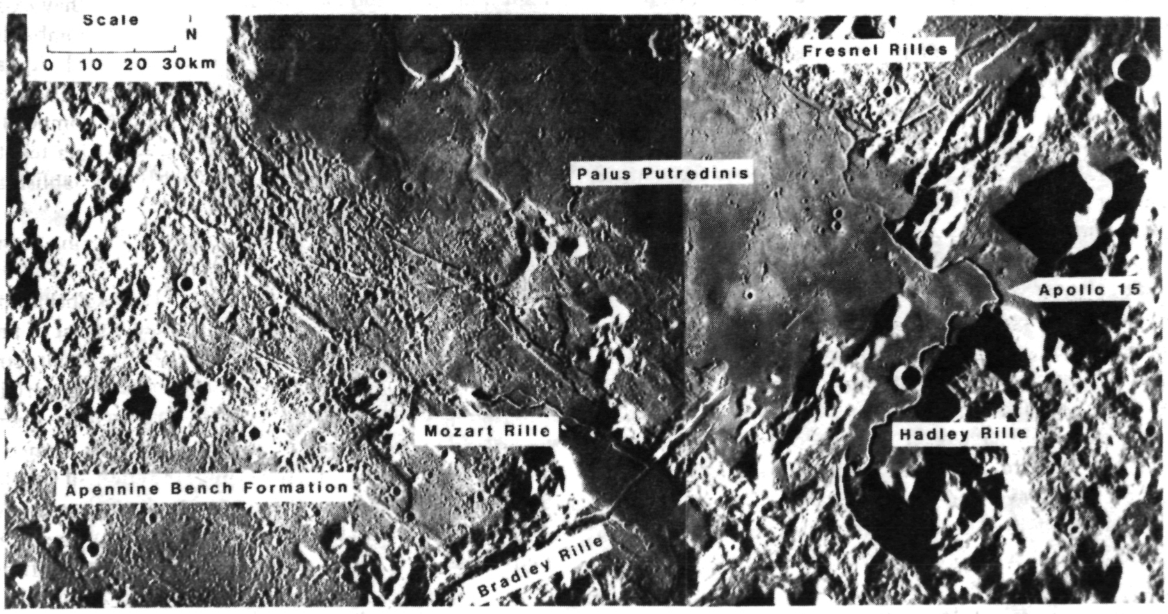

Fig. 1. Orbital photograph of the Apollo 15 landing site and relevant environs. Apart from the large area to the left of the picture, Apennine Bench Formation occurs at the area of the Fresnel Rilles. It probably also underlies the mare near the Apollo 15 landing site and may even be exposed at the North 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.