Metamorphism on the Moon: A terrestrial analogue in the Vredefort dome, South Africa?

Roger L. Gibson* W. Uwe Reimold Andrew J. Ashley

Impact Cratering Research Group, School of Geosciences, University of the Witwatersrand, WITS, Johannesburg 2050, South Africa

Institute of Geochemistry, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria

ABSTRACT
A new model is proposed to explain the origin of enigmatic fine-grained granulitic facies rocks sampled from the Moon, based on observations from the Vredefort dome, South Africa. The dome is the deeply eroded central uplift of the ~300-km-diameter Vredefort impact structure. In the dome, fine-grained granulites displaying poikilitic or granoblastic microstructures were formed by relatively slow cooling of shock ± friction melts derived at T > 1350 °C. Slow cooling was achieved owing to the >7 km depth of burial of the rocks following the impact. At least some of the lunar granulitic impactites may also have formed by shock heating and slow cooling at deep levels within the central uplifts of large impact structures, without the need for additional heating by younger intrusive or impact melt bodies.

Keywords: breccia, granulite facies, impactite, Moon, shock metamorphism.

INTRODUCTION
Lunar rocks displaying extremely fine grained (typically <100 μm) high-temperature metamorphic microstructures—the so-called lunar granulitic impactites (Cushing et al., 1999)—form a significant component of the Apollo and Luna sample suites (Stöffler et al., 1979). The origin of such metamorphic rocks within the context of the evolution of the lunar lithosphere has engendered much debate. General opinion favors high-temperature metamorphism of older impact-generated fragmental and/or melt breccias (Cushing et al., 1999; Warner et al., 1977). This metamorphism has been attributed to local effects adjacent to or within large igneous intrusions or impact melt bodies (Cushing et al., 1999; Stöffler et al., 1979), to regional heat sources such as the early lunar magma ocean or to an elevated early lunar lithospheric geotherm (Warren et al., 1990, 1991). However, the lack of in situ geologic control on the samples, their small size (commonly <10 cm), and their complex, reworked nature caused by their polyphase history hamper further elucidation of this problem.

An investigation in the central parts of the Vredefort impact structure has revealed rocks that display many of the complex microstructural features described in the lunar granulitic impactites. Here we describe the salient features of the Vredfort granulitic impactites that provide clues to their origin and discuss the significance of these findings for the origin of the lunar granulitic impactites.

GRANULITIC IMPACTITES IN THE VREDEFORT DOME
The Vredefort dome, a 75-km-wide feature centered ~120 km southwest of Johannesburg, South Africa (Fig. 1), is the deeply eroded central uplift of a large (~300 km diameter), complex impact structure formed 2.02 Ga (Kamo et al., 1996; Gibson and Reimold, 2000). The dome comprises a 40-km-wide core of predominantly granitic to tonalitic Early Archean high-grade gneiss that is surrounded by a subvertically dipping sequence of Late Archean to Paleoproterozoic supracrustal rocks and intrusions (Fig. 1). The rocks display a variety of impact-related features, including shatter cones, coesite and stishovite, planar deformation features in quartz, dikes of impact melt breccia (Vredfort Granophyre, Fig. 1), and voluminous pseudotachylytic breccias (Gibson and Reimold, 2000). The absence of both a definitive crater rim and a coherent impact melt body indicates substantial erosion of the impact structure, estimated as between 7 and 10 km (Gibson et al., 1998).

In much of the core of the dome, the Archean gneisses preserve their coarse-grained (1–5 mm average grain size) preimpact mineral assemblages and fabrics, which formed during upper amphibolite to granulite facies regional metamorphism ca. 3.1 Ga (Hart et al., 1991). Within 5 km of the center, however, the rocks have a fine-grained character caused by selective replacement of the coarse Archean minerals by fine-grained (typically <100 μm) granoblastic assemblages. For the most part, this replacement is pseudomorphic, and the Archean fabric is preserved; hence the rocks are identified as granofelses rather than granulites. In places, however, polymict breccia veins to 50 cm wide that contain lithic and mineral clasts set in a fine-grained matrix (Fig. 2A) cut the granofelses. Many clasts display fine-grained rims with flow microstructures that are interpreted as evidence of melting and partial assimilation into the breccia matrix (Fig. 2A). Some breccias are located along slip surfaces that display offsets of as much as several centimeters.

In the granofelses, the coarse precursor plagioclase and alkali feldspar grains are almost always completely replaced by fine-grained granoblastic aggregates. The local development of plume-like radiating textures in these aggregates (Fig. 2B) suggests that this replacement involved melting and subsequent rapid crystallization. Quartz typically occurs as glomerocrystalline aggregates of polygonal to rounded grains with granophyric rims developed along margins adjacent to feldspar (Fig. 2B). Where feldspar forms the bulk of the rock, the quartz aggregates have the appearance of clasts within the finer grained matrix. Biotite and hornblende have been largely replaced by pseudomorphs consisting of fine-grained aggregates of clinopyroxene, orthopyroxene, quartz, plagioclase, alkali feldspar, magnetite, and/or ilmenite. Only pyroxene grains lack evidence of recrystallization or replacement by fine-grained aggregates, although they commonly display mechanical twinning and subplanar intragranular fractures.

The breccia veins are dominated by plagioclase (60–95 vol%), and have subsidiary alkali feldspar, biotite, orthopyroxene, clinopyroxene, quartz, magnetite and/or ilmenite, and zircon (Fig. 2C). Grain sizes are similar to those in the granofelses, and vein margins are commonly indistinct. Mineral clasts include coarse angular grains of pyroxene displaying mechanical twins and fractures (Fig. 2C), opaque minerals, quartz, and zircon. Some quartz grains are noticeably smaller than those in the wall rocks, and display irregular, scalloped edges indicating reaction with the breccia matrix (Fig. 2C). Orthopyroxene and clinopyroxene also occur as small, interstitial, polygonal to subangular grains in the breccia matrix (Fig. 2D). Zircon clasts display planar shock features, but small authigenic zircons are also found (Kamo et al., 1996). Both alkali feldspar and biotite form large (to 1–2 mm) poikilitic grains, within which plagioclase is the dominant inclusion type (Fig. 2C and D).
The breccias display highly variable major and trace element bulk-rock compositions that fall between those of the host Archean granitoid and mafic gneisses, and are thus consistent with variable mixing of these mafic and felsic gneiss precursors (Gibson et al., 2001). Trace element data (Gibson et al., 2001) indicate no siderophile element enrichment in the breccias relative to the host gneisses; therefore, these veins are not a meteorite-contaminated impact melt. Mineral compositions are homogeneous within individual samples, but vary between samples in a range between the granitic and mafic host gneisses.

ORIGIN OF THE GRANOFELSES AND GRANULITIC BRECCIAS

The mineral assemblages and microstructure of the granofelses and breccias confirm the existence of an unusually short lived, static, high-grade (granulite facies) metamorphic overprint in the central parts of the Vredefort dome. The synimpact timing of this metamorphism has been confirmed by a U-Pb SHRIMP age of 2023 ± 4 Ma obtained on an authigenic zircon from a breccia (Kamo et al., 1996; Gibson, 2002). The partial assimilation of clasts in the breccias, and the poikilitic, granophyric, and plume-radiating microstructures in the granofelses and breccias confirm that this impact-related metamorphism involved melting. However, apart from the granophyric quartz-feldspar intergrowths, the microstructures in the rocks are not consistent with equilibrium (eutectic) melting. In particular, the initial breakdown of individual minerals in the granofelses appears to have occurred without reaction between adjacent grains (Fig. 2B). Such selective mineral breakdown and the formation of clast-laden melt breccias are, however, well-known features of shock melting associated with impact events (French, 1998).

Shock melting occurs at high shock pressures (typically >45–50 GPa; French, 1998) when sufficient heat is imparted to a mineral such that the shock to postshock temperature of the mineral exceeds its dry melting point. Postshock heating occurs because of the nonsentropic nature of shock-pressure release and is proportional to both the shock pressure and the compressibility of the mineral (Raikes and Ahrens, 1979). Unlike eutectic melting, which involves reaction between adjacent minerals, shock melting occurs independently of the mineral paragenesis and is virtually instantaneous. In order to melt minerals such as biotite, hornblende, alkali feldspar, and andesine-oligoclase plagioclase, but not pyroxene and quartz, at low pressures typical of shallow-crustal levels, temperatures would have to be between ~1350 °C (dry melting of andesine) and 1400 °C (dry melting of orthopyroxene; Deer et al., 1976).

Recent two-dimensional hydrocode modeling results (Ivanov and Deutsch, 1999) have demonstrated that postshock temperatures in excess of 1000 °C are readily attained over large vertical intervals within the cores of central uplifts of large impact structures (Fig. 3). These high temperatures are primarily the result of shock heating but, with increasing depth, the contribution of the preimpact geotherm increases. The final geometry of the postimpact isotherms shown in Figure 3 reflects distortion of the broadly hemispheric shock-heating isotherms and the subhorizontal preimpact crustal isotherms because of the differential inward and upward movement of the subcrater basement to produce the central uplift (Ivanov and Deutsch, 1999). The high postshock temperatures and the strong, radially outward temperature decrease in the central uplift predicted by the model have been confirmed by postshock mineral parageneses in metapelites in the Vredefort dome (Gibson et al., 1998; Gibson, 2002; Fig. 1). Initial cooling from the isotherm pattern shown in Figure 3 is likely to have been rapid, hence the unusually fine grain size of the granulite assemblages in the center of the dome. We propose that, after shock melting and uplift of these rocks, temperatures fell rapidly, leading to quenching or crystallization of the shock melts. High temperatures were, however, sustained long enough to produce small-volume eutectic melts and to facilitate the attainment of textural equilibrium at lower temperatures, producing the granoblastic microstructures.
The granulitic breccias and their microstructures indicate that melting was enhanced at specific sites. The association of some of the breccias with slip surfaces suggests that this enhanced melting may reflect an additional component of heating due to friction along these surfaces (Kenkmann et al., 2000). The higher melt temperatures, together with differential stresses in the vicinity of these surfaces, would have facilitated melt mobility and mixing and allowed injection of clast-laden melts into the surrounding granofelses prior to crystallization.

In summary, the granofelses and breccias in the center of the

Figure 2. A: Section of borehole core showing granulitic breccia with aligned lithic clasts and melting (m) along clast margins. B: Photomicrograph showing radiating (top left) and columnar (center) aggregates of intergrown plagioclase and alkali feldspar in granofels, with granophyric rims developed against quartz. Note polygonal-rounded quartz grain shapes. Crossed polarizers. C: Backscattered-electron image of granulitic breccia vein showing poikilitic biotite (bt) and K-feldspar (ksp) as well as fine-grained granoblastic pyroxene and coarser pyroxene clasts (opx) in plagioclase-rich matrix (pl). Note needlelike biotite grains and irregular interstitial quartz (arrow), and finer K-feldspar and quartz (qtz) grain size in breccia compared with wall rock (top right). D: Backscattered-electron image of poikilitic K-feldspar (ksp) in breccia containing subhedral plagioclase (pl) and orthopyroxene (opx) grains. Note interstitial quartz (qtz) and acicular and poikilitic biotite (bt). Scale bar = 500 µm.
Vredefort dome were derived by shock melting, followed by crystal-
ization under granulite facies conditions. Owing to the involvement
of shock processes in their evolution, the rocks are best described as
granulitic impactites (French, 1998), rather than contact-metamorphic
hornfelses.

LUNAR GRANULITIC IMPACTITES—AN ALTERNATIVE
ORIGIN?
There are several hundred impact craters on the Moon with di-
ameters similar to or greater than that of the Vredefort structure. It is
thus inescapable that granulitic impactites of similar origin to those in
the Vredefort dome also exist in the lunar crust within the cores of
large central uplifts. What is less clear, however, is whether the lunar
granulite samples represent such rocks or whether they formed in con-
tact aureoles adjacent to magmatic or impact melt bodies, as has been
suggested previously.

Like the Vredefort granulitic impactites, the lunar granulites are
polymict breccias with lithic and mineral clasts set in extremely fine
grained granoblastic to poikilitic matrices dominated by plagioclase (±
pyroxene, olivine, ilmenite; Heiken et al., 1991; Cushing et al., 1999).
Their bulk compositions also indicate mixing of rocks believed to con-
stitute the pristine lunar crust, and geothermometry indicates minimum
temperatures of formation of 1000–1100 °C (Heiken et al., 1991; Cushing
et al., 1999). Such temperatures are difficult to achieve in large
volumes of the shallow crust, even where impact melts (T ≥ 2000 °C;
French, 1998) are the heat source (e.g., Ivanov and Deutsch, 1999).
Conversely, if the lunar granulites formed by shock melting in the same
manner as the Vredefort impactites, then temperatures would have been
even higher (anorthite melts at ~1500 °C and olivine at ~1650 °C;
Deer et al., 1976). Such temperatures would require shock pressures
in excess of 50–60 GPa (French, 1998), which are not uncommon in
the central parts of giant impact craters.

The main argument against a single cycle of shock melting and
slow cooling to generate the lunar granulites is the apparent enrichment
of the granulites in siderophile elements relative to their inferred crustal
protoliths (Lindstrom and Lindstrom, 1986; Heiken et al., 1991). Al-
though both the reliability and representativeness of the siderophile
data for samples of so-called pristine lunar crust are debatable (Heiken
et al., 1991), this pattern, if correct, implies contamination of the
granulite precursors by meteoritic sources (i.e., formation of impact melt:
Fig. 3). The near-surface location of impact melts would not be con-
ductive to the slow postimpact cooling needed to produce the granulite
microstructures. If the lunar granulitic impactites formed in a way simi-
lar to those in the Vredefort dome, it would first be necessary to bury
the impact melt rocks beneath younger ejecta prior to renewed shock
melting and incorporation into a large central uplift. Whereas the his-
tory of intense bombardment on the Moon might permit deep burial
of early-formed impact melts, such complexity in the model would be
redundant if new data were to establish that the pristine lunar crust
contains a siderophile component.

CONCLUSIONS
Granulitic breccias and granofelses from the central parts of
the Vredefort Dome display textures that strongly resemble those from
the lunar granulitic impactite suite. The Vredefort granulitic impactites are
attributed to a single impact event, in which shock melting of gneissic
precursors in the crust beneath the transient impact crater was followed
by comparatively slow cooling at depths of 7–10 km within the core
of the central uplift. Initial temperature distribution in these rocks may
have locally been heterogeneous due to variation in peak shock pres-
sures and localized shock frictional heating along slip surfaces. A simi-
lar origin is proposed for at least some of the lunar granulites.

ACKNOWLEDGMENTS
Funding for this research was provided by the University of the Witwa-
tersrand Research Committee and the Austrian Science Foundation. We thank
M. Brown and P. Schultz for their reviews. H. Czekanowska and D. du Toit
assisted with the photographs and diagrams.

REFERENCES CITED
impactite suite: Impact melts and metamorphic breccias of the early lunar
Institute, 120 p.
Gibson, R.L., 2002, Impact-induced melting in Archaean granulites in the Vre-
defort dome, South Africa: I. Anatexis of metapelitic granulites: Journal of
Metamorphic Geology, v. 20, p. 57–70.
Gibson, R.L., and Reimold, W.U., 2000, Deeply exhumed impact structures:
A case study of the Vredefort structure, South Africa, in Gilmour, L., and
Koeberl, C., eds., Impacts and the early Earth: Berlin, Springer-
Verlag, p. 249–277.
signature of an impact event in the Vredefort dome, South Africa: Geol-
melt breccias in the Vredefort Impact Structure, South Africa—A terres-
trial analog for lunar granulites?: Houston, Texas, Lunar and Planetary
of the dynamic and thermal metamorphic history of the Vredefort crypt-
explosion structure: Implications for its origin: Tectonophysics, v. 192,
p. 313–331.
Ivanov, B.A., and Deutsch, A., 1999, Sudbury impact event: Cratering me-
chanics and thermal history, in Dressler, B.O., and Sharpton, V.L., eds.,
Large meteorite impacts and planetary evolution II: Geological Society of
Ga age for the Vredefort impact event and a first report of shock meta-
morphosed zircons in pseudotachylitic breccias and granophyre: Earth and
Kenkmann, T., Hornemann, U., and Stöfler, D., 2000, Experimental generation
of shock-induced pseudotachylites along lithological interfaces: Meteor-
Lindstrom, M.M., and Lindstrom, D.L., 1986, Lunar granulites and their pre-
cursor anorthositic norites of the early lunar crust: Journal of Geophysical
Raikes, S.A., and Ahrens, T.S., 1979, Post-shock temperatures in minerals: Roy-
breccias and the classification of lunar highland rocks: Lunar and Planetary
Science Conference Proceedings, 10th, p. 639–675.
granulitic impactites and pre-final bombardment lunar evolution: Lunar
alkali anorthosite with coarse augite exsolution from plagioclase, a mag-
nesian harzburgite, and other oddities: Lunar and Planetary Science Con-
and the duration of cooling to isotopic closure within differentiated aster-

Manuscript received August 20, 2001
Revised manuscript received January 22, 2002
Manuscript accepted February 6, 2002

Printed in USA