TABLE 1. Noble gases in lunar meteorites.

	Trapped Gas			
	^{4}He	^{36}Ar	^{132}Xe	^{40}Ar/^{36}Ar
Calcalong Creek	30,000	11,000	0.61	4.9
QUE 93069	700,000	70,000	2.4	2.2
	Spallation-produced Gas			
	^{3}He	^{38}Ar	^{126}Xe	^{131}Xe/^{126}Xe
Calcalong Creek	27	67	0.012	4.8±0.3
QUE 93069	50	*	0.004	*

All amounts in 10^{-4} cm^{3}STP/g.
* Not measurable.

unlikely that they come from the same event.

It is difficult to determine the amount of spallogenic gas in QUE 93069 because of the huge solar wind signature. However, a few isotopes that are normally dominated by spallation (^{3}He, ^{21}Ne, ^{80}Kr, and ^{126}Xe) are enhanced by >1σ over solar wind values, although in every case the spallogenic gas is <25% of the total. The exposure ages derived [4,7] are comparable to those for Calcalong Creek, consistent with extensive near-surface lunar exposure. However, ^{131}Xe is within 1σ of solar wind, so we cannot constrain the average shielding depth. Measurements on separated clasts would probably be required.

In summary, both meteorites have typical exposure histories for lunar meteorites. Both contain solar wind gases and high cosmogenic noble gas contents suggesting ejection from near the lunar surface. We cannot adequately constrain the ejection event for QUE 93069, but Calcalong Creek appears to be the only meteorite from its impact event.

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A THERMAL HISTORY TALE OF TWO BODIES: WHAT DID THE HED PARENT BODY HAVE THAT THE MOON DIDN'T?

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Impact, brecciation, and regolith working are important processes in the history of small planetary bodies in the solar system. All classes of meteorites contain breccias, particularly the basaltic achondrites, and all returned lunar samples are breccias. We have examined the induced thermoluminescence (TL) properties of lunar and meteoritic samples as a means of comparing the surface properties of the Moon and the HED parent body. Both types of material are basalts originating on airless bodies that have suffered considerable reworking by impact, and our study may provide insights into the differences in impact and related surface processes on large and small bodies.

Hartmetz and Sears have shown that TL peak temperature is a sensitive indicator of the degree of order in the feldspar framework, highly ordered feldspars having TL peak temperatures of ~120°C compared with ~200°C for disordered feldspars [1]. Figure 1 compares TL peak temperatures for basaltic meteorites and lunar samples. In many respects the TL properties of these samples are similar, calcic feldspar being the source of TL in both types of material [2,3]. The major difference is that TL peak temperatures for the meteorites are all ~120°C, and the TL sensitivity of these samples correlates with metamorphic indicators [2]. This is in contrast to the lunar samples, which show a much wider spread in values, as well as having a large population exhibiting peak temperatures in excess of 170°C.

The observed TL peak temperatures and a series of heating experiments on four petrographically diverse eucrites, as well as a lunar highland soil, suggest that the basaltic meteorites have experienced a period of post brecciation metamorphism with temperatures ≤800°C [2]. Assuming this temperature was typical of metamorphic conditions, the thermal model of Miyamoto et al. suggests burial depths of >350 m for the equilibrated eucrites [4]. The high TL peak temperatures of the lunar samples, however, suggests a large population of disordered feldspar and the lack of any appreciable thermal metamorphism.

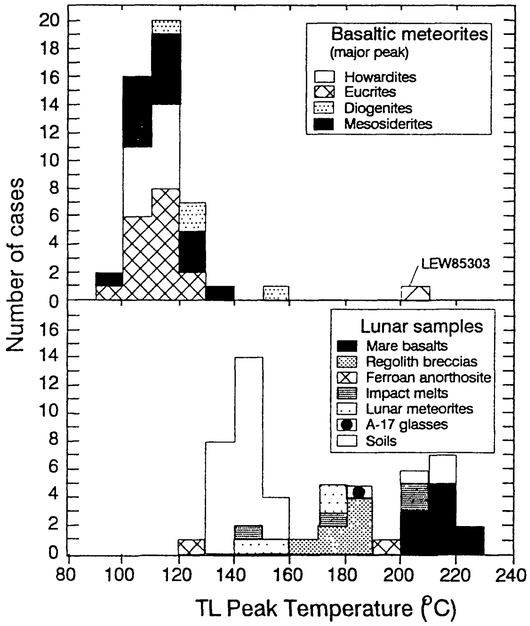

Fig. 1.

Since many of the HEDs contain regolith components [e.g., 5], the history of these samples involves both deep burial and regolith processing. In addition, the regolith history must postdate the metamorphism since metamorphism would have destroyed many of the regolith properties. One possibility is that following the metamorphic episode, the HED parent body suffered large, nearly catastrophic impact events that exposed deeply buried material that then experienced a regolith history. Consistent with this, Binzel and Xu have discovered a family of basaltic asteroids that are most likely multikilometer-sized fragments excavated from Vesta through one or more impacts [6].

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LUNAR METEORITE QUEEN ALEXANDRA RANGE 93069: HISTORY DERIVED FROM COSMIC-RAY-PRODUCED AND TRAPPED NOBLE GASES.

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We obtained lunar meteorite QUE 93069,7 (0.304 g) from the NASA/MWG for the determination of its noble gas isotopic abundances and exposure history. The data relevant for the discussion of the exposure history and trapped noble gases are given in Tables 1 and 2.

Exposure History: The duration of Moon-Earth transfer was determined by Nishiizumi et al. [1]. Based on ^{10}Be these authors obtained 1.9 ± 0.4 Ma for a 4π model (all radionuclides produced in 4π space) and <0.1 Ma for a 2π model (most radionuclides produced on the Moon). Adopting these times we find that <1% of the cosmogenic noble gases were produced during

TABLE 1. Cosmogenic and trapped solar wind noble gases (concentrations in 10^{-8} cm^3 STP/g).

Meteorite	$^{21}Ne_c$	^{38}Arc	$^{20}Ne_{tr}$	$^{36}Ar_{tr}$
QUE 93069	53.1	179	111000	34600
	±6.8	±60	±7300	±1600
MAC 88105,24	10.8	33.2	215	146
	±0.5	±3.0	±20	±15
ALHA 81005	41.3	64	55900	19500
	±4.0	±30	±3100	±1200

Moon-Earth transfer. The overwhelming amounts of $^{21}Ne_c$ and $^{38}Ar_c$ must have been produced during residence in the lunar regolith. Using lunar regolith production rates [2] at 5–10 g/cm^2 shielding [1], we calculated the exposure times, T (2π), on the Moon. Table 2 gives the results and compares them with the exposure times for other anorthositic lunar meteorites (MAC 88105 and ALHA 81005). Queen Alexandra Range 93069 shows the longest exposure to cosmic rays (1100 ± 400 Ma) of all lunar meteorites if we compare the T_{38} values. Based on $^{21}Ne_c$ we obtain 420 ± 60 Ma. Typically for lunar surface material the T_{21} are lower than those based on $^{38}Ar_c$, $^{83}Kr_c$, and $^{126}Xe_c$ due to ^{21}Ne loss. This effect is also observed for MAC 88105 and ALHA 81005.

Characteristics of the Trapped Noble Gases: The long lunar surface residence time and the shallow shielding depth are consistent with the very large amounts of trapped solar wind particles (^{20}Ne and ^{36}Ar, Table 1) for QUE 93069. The concentration of trapped ^{36}Ar is quite similar to that of Y 791197: Takaoka [3] and Ostertag et al. [4] obtained 33,900 and 36,600 × 10^{-8} cm^3 STP/g respectively. The trapped ratio $^{40}Ar/^{36}Ar$, an antiquity indicator for lunar soil, yields information on the time when the breccia was compacted from regolith material [5]. For QUE 93069 we obtain $(^{40}Ar/^{36}Ar)_{trapped} = 1.9 \pm 0.1$, indicating exposure of the breccia material on the lunar surface about 600 Ma ago.

Conclusions: Based on $^{38}Ar_c$ the lunar surface exposure to cosmic rays for QUE 93069 lasted about 1100 ± 400 Ma, similar to Y 791197, about twice as long as for ALHA 81005, and about 7× longer than for MAC 88104/5. The trapped $^{40}Ar/^{36}Ar$ ratio of 1.9 ± 0.1 suggests that exposure to solar particles occurred around 600 Ma ago. Since relatively large amounts of solar wind particles were accumulated, it is reasonable to assume that most cosmogenic noble gases were also produced during this exposure period. Krypton and Xe analysis are in progress with the main purposes to determine ^{81}Kr, T_{83}, T_{126}, and the shielding in the lunar regolith based on $(^{131}Xe/^{126}Xe)_c$.

Acknowledgments: We thank the NASA/MWG for the meteorite sample. This work was supported by the Swiss N.S.F.

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TABLE 2. Exposure ages, lunar surface exposure ages T(2π), Moon-Earth transfer time (all ages in m.y.).

Meteorite	T_{21}	T_{38}	$T(2\pi)_{Moon}$	$T_{Transfer}$
QUE 93069	420	1100	1100	<0.1[1]
	±60	±400	±400	
MAC 88105	110	150	150	<0.24[6]
	±30	±40	±40	
ALHA 81005	270	460	580	<0.1[7]
	±200	±200	±180	

HOW BIG IS VREDEFORT?

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Consisting mainly of uplifted crystalline basement, the 40–50-km Vredefort Dome is in a near-central position within the Witwatersrand Basin [1,2] (Fig. 1). The Vredefort impact structure (27°00'S, 27°30'E) consists of the Vredefort Dome and a wide "collar" of metasediments and metavolcanic rocks. Prior to the 1970s the diameter of the Vredefort structure was estimated at 60 km, and possibly up to 200 km [3,4]. In the 1970s and 1980s, the diameter was estimated at 100–120 km, while in the early 1990s 170–180 km was preferred.

In relation to the outer edge of the Dome, the radial limit of shatter cones (26–37 km), PDFs (~13 km), and downfaulted Transvaal outliers (45–55 km) yield an estimate of 192–300 km for the final crater diameter [5] (Fig. 2). These spatial indicators are subject to erosional effects. At the Sudbury Structure, a 45-km-thick impact melt sheet has been preserved, under which PDFs have been annealed from the target rocks for at least 1 km. At Vredefort, the granophyre is the only remnant of this melt sheet [6], and PDFs are observed in the Dome. The Vredefort Structure, therefore, has been eroded below the crater floor and, comparing it to Sudbury, the area has undergone at least 6 km of erosion. This corresponds with the regional erosion estimate of 5–10 km [7].

To better define an original crater diameter estimate, an indicator relatively independent of erosional effects is needed. The exposed 36-km "crust-

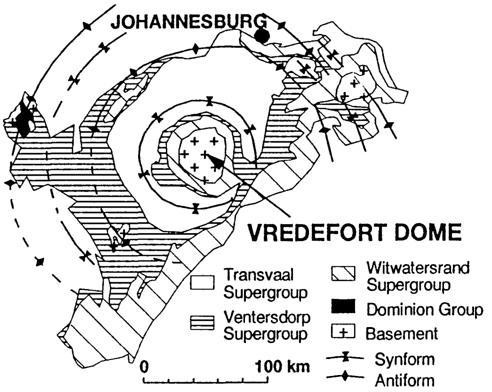

Fig. 1. General geology of the Witwatersrand Basin with major fold pattern.

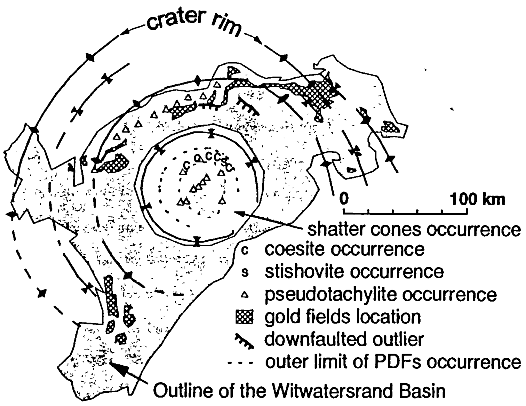

Fig. 2. Shock metamorphic features and crater information superposed on an outline of the Witwatersrand Basin and major fold pattern (cf. Fig. 1).