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Constraints on the thermal and mixing history of lunar surface materials and comparisons with basaltic meteorites

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Abstract. We have measured the induced thermoluminescence (TL) properties of mare basalts, highland rocks, glasses, regolith breccias, soils and core samples. We also performed a series of heating experiments and made cathodoluminescence (CL) observations of Apollo 16 soils. The data are readily interpreted in terms of feldspar being the dominant source of TL and CL, the known luminescence properties of feldspar and history of the samples. For example, the TL sensitivity of the mare basalts is lower than that of the highland basalts by about an order of magnitude, probably due to the differing FeO content of their feldspars. Similarly, the TL properties of regolith breccias can readily be explained in terms of thermal processes similar to those experienced by the soils and by mixing of highland and mare components. Our major new observations and interpretations include (1) that there are maturity-dependent variations in the TL and CL properties of the core samples which reflect thermal annealing and melting during regolith working, (2) that the most "primitive" material in lunar samples in terms of their thermal histories is located in the immature lunar soils, and (3) that there is no TL evidence for widespread long-term thermal metamorphism of lunar samples, TL being particularly sensitive to low-level metamorphism in extraterrestrial materials. In this latter respect, lunar samples differ from basaltic meteorites which otherwise have very similar properties and histories. We argue that this reflects a greater tendency toward thick regoliths on asteroid-sized bodies.

1. Introduction

Impact, brecciation and regolith working (perhaps with associated metamorphism) are important surface processes in the histories of the Moon and other small planetary bodies [*Bunch and Rajan*, 1988; *Scott et al.*, 1989; *Batchelor and Sears*, 1991b; *McKay et al.*, 1991; *Hörz et al.*, 1991; *Melosh*, 1989]. In the case of the Moon, craters range from the 1000-km scale multiring basins to the meter-scale bowls, and large areas of the lunar surface (including some of the Apollo sites) are covered with ejecta excavated from depth by large impacts. Thus all rocks from the heavily cratered highland regions of the Moon are breccias, either clastic fragmental breccias of the primary igneous rocks (ferroan, Mg-rich or KREEP anorthosites) or impact melt breccias derived from these rock types.

Impact also results in the formation of a surface regolith of the order of several meters thick and a several kilometer thick megaregolith [*Toksöz et al.*, 1973]. Shock heating is especially effective when the target is porous [*Schaal et al.*, 1979]. About 30-50% of the Apollo hand samples and ~50% by volume of the lunar soil were produced from melts [*Hörz et al.*, 1991, p.78]. Important constituents of the soils are agglutinates, dust grains bonded by a vesicular glass [*McKay et al.*, 1991], and impact-produced glassy spherules [*Delano et al.*, 1981]. As the surface "matures," the proportion of agglutinates increases, grain sizes decrease, the ferromagnetism of the soils increases (as FeO is reduced to metallic Fe), and the abundance of trapped solar wind gases and charged-particle tracks increases. Thus surface exposure ages can be calculated, and unless the layers have been disturbed, soil maturity increases with depth because grains from deeper depths tend to spend less time on the surface [*Langevin and Arnold*, 1977; *McKay et al.*, 1991].

The mare and highland regolith breccias are coherent rocks of soil or soil-like components in a glassy matrix [*Simon et al.*, 1984]. Most of the lunar meteorites are highland regolith breccias, some containing significant amounts of mare material [*Palme et al.*, 1991].

Mixing of target and impactor is so extensive on the lunar surface that low abundances of chondritic siderophile elements can be used to locate rocks that, while clearly brecciated and texturally altered by surface processing, at least retain a chemical fingerprint of their petrogenesis [*Warren and Wasson*, 1977]. We suggest that it is also possible for material to be "primitive" in terms of thermal history. If a sample displays evidence for cooling rates that are too slow to be consistent with impact processes, or closure temperatures that are too low, then (1) that sample experienced metamorphism after impact or, (2) where this is unlikely, impact and associated surface processing was too mild to change the apparent cooling rates or closure temperatures and the samples retain a memory of preimpact conditions. We suggest that such thermally primitive material is present in the soils.

While metamorphic effects due to shock heating of rocks and individual grains are abundant, evidence for wide scale long-term (~10^6-year timescale) metamorphism subsequent to formation of the rocks is relatively rare [*Williams*, 1972; *Stewart*, 1975]. However, it is clearly important to locate and possibly quantify

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long-term metamorphic effects because of their relevance to the physical conditions following formation or burial depths following impact.

The closely related luminescence phenomena displayed by certain minerals, cathodoluminescence (CL) and thermoluminescence (TL), have proved to be uniquely suited to the quantitative study of thermal histories of a variety of planetary materials. We thought it probable that measurement of the TL and CL properties of lunar samples might help us address whether there is any evidence for widespread metamorphic effects that are too mild to detect by other means. We also thought that such studies might provide a new quantitative means of exploring maturation processes in the regolith and perhaps identify mineralogical changes not previously discussed or assign temperatures to the processes. Finally, we wanted to compare the TL properties of different types of lunar sample to see if we could identify materials that were primitive in terms of their thermal histories.

An example of a metamorphically induced change in TL properties is the 10^5-fold increase in TL sensitivity caused by the crystallization of feldspar in the chondrule glass of ordinary chondrites [*Sears et al.*, 1980, 1991a]. These changes are difficult to detect and impossible to quantify by mineralogical and petrographic techniques. TL measurements are now the best means of assigning ordinary chondrites to petrologic type. The mineralogical and textural changes wrought by metamorphism can also be followed using mosaics of CL images [*Sears et al.*, 1989; 1995]. Such studies have been successfully extended to the CO chondrites [*Sears et al.*, 1991b] and the little-metamorphosed CV chondrites [*Guimon et al.*, 1995]. The eucrites can also be quantitatively assigned to petrographic types using TL sensitivity and CL intensity, but in this case the increase in luminescence is thought to reflect the migration of FeO out of the feldspar [*Batchelor and Sears*, 1991a, b; *Batchelor*, 1992]. There are very few data for terrestrial basalts that one can use for "ground truth" in studies of lunar samples. In a study of TL dating, *May* [1979] reported that Hawaian lavas showed a decrease in TL sensitivity on the 10^4-year timescale and then an increase on the 10^5-year timescale which he attributed to the short-term annealing and long-term creation of TL traps. He did not report induced TL peak temperature data.

Induced TL peak temperature provides a crude but independent indicator of metamorphic temperatures. Heating experiments on ordinary chondrites, basaltic meteorites, and terrestrial feldspars cause TL peak temperature to increase from ~120°C to ~220°C [*Guimon et al.*, 1985; 1995; *Keck and Sears*, 1987; *Batchelor and Sears*, 1991a, b]. This increase in TL peak temperature is associated with increases in structural disordering as determined by X ray diffraction [*Pasternak et al.*, 1976; *Pasternak*, 1978; *Hartmetz and Sears*, 1987]. Independent observational evidence for a link between thermal history and TL peak temperature is that type 3.2-3.5 ordinary chondrites have peaks at ~120°C, while type 3.6-3.9 have peaks at ~240°C. *Van Schmus and Ribbe* [1968] have shown that feldspar in

Table 1. Induced Thermoluminescence and Other Data for Lunar Rocks

Sample	Split Number	Mass, mg	Description	TL Sensitivity (Dhajala=1000)	TL Peak Temperature, °C
			Mare Basalts		
10020	222	533	high-Ti, low-K	15±8	220±20
10049	89	494	high-Ti, high-K	11±2	200±10
12002	240	527	low-Ti, olivine	17±7	210±6
12005	46	419	low-Ti, ilmenite/ol	35±10	206±10
12011	25	413	low-Ti, pigeonite	10±9	215±20
12021	574	449	low-Ti, pigeonite,	28±5	225±10
			$\mathrm{An}_{94.7},\mathrm{Ab}_{5.2}\mathrm{Or}_{0.1}$	24±5[a]	124±4[a]
12052	330	440	low-Ti, pigeonite	8±4	218±4
15058	239	468	low-Ti, pigeonite	28±12	212±10
15499	13	484	low-Ti, pigeonite	8±4	200±10
EET 87521	36	25	very low-Ti, meteorite	44±10	214±3
			Highland Rocks		
60025	48	280	ferroan anorthosite	230±20	198±2
			$\mathrm{An}_{96.3}\mathrm{Ab}_{3.7}\mathrm{Or}_{0.0}$	210±10	127±5
60015	755	269	cataclastic anorthosite	2010±150	210±5
14310	631	486	clast-poor impact melt, $\mathrm{An}_{86.0},\mathrm{Ab}_{12.7},\mathrm{Or}_{1.3}$ $\mathrm{An}_{95.1},\mathrm{Ab}_{4.6},\mathrm{Or}_{0.3}$	210±30	210±25
60315	30	518	clast-poor impact melt	720±100	204±2
			rock,	940±130	144±4
68415	200	40	clast-poor impact melt, $\mathrm{An}_{94.6},\mathrm{Ab}_{2.4},\mathrm{Or}_{0.1}$ $\mathrm{An}_{90.7},\mathrm{Ab}_{8.8},\mathrm{Or}_{0.5}$	1110±70	170±2
			Lunar Pyroclastic Deposits		
74220	758	409	Apollo 17 orange glass	11±4	185±20

Uncertainties in thermoluminescence are 1σ on triplicate measurements. Descriptions of other data are from *Heiken et al.* [1991], who give primary references.

[a] Peak due to quartz. Data are not included in the figures.

equilibrated ordinary chondrites is structurally disordered, but observations on the trace amounts of crystalline feldspar in type 3.2-3.5 chondrites are not possible. The transition from low-temperature feldspar to high-temperature feldspar occurs 500-600°C for sodic feldspars like those in ordinary chondrites, but this transition temperature is dependent on the Ca content of the feldspar and would be higher for lunar feldspars.

Early work on the TL properties of lunar samples was prompted by an unsuccessful attempt to explain transient lunar phenomena [*Blair and Edgington*, 1970; *Nash and Greer*, 1970]. However, most work concerned the identification and characterization of the minerals responsible for the luminescence through studies of individual grains [*Hoyt et al.*, 1972; *Walker and Zimmerman*, 1972] and, more especially, through studies of their CL or related measurements [*Geake et al.*, 1977; *Sippel and Spencer*, 1970].

In the present study we have examined a wide variety of lunar surface materials [*Benoit et al.*, 1994; *Symes et al.*, 1992, 1994, 1995] with a view to searching for (1) evidence of low-level metamorphic effects, (2) thermally primitive material, and (3) new regolith maturation processes. We also discuss the wider implications of these results for understanding surface processes on basaltic atmosphereless planetary surfaces.

2. Experimental Procedure

2.1. Samples

The samples we studied are listed in Tables 1-3. The mare basalts are those of the *Basaltic Volcanism Study Project* (BVSP) [1981] reference suite, while the highland samples include lunar meteorites, a ferroan anorthosite, and clast-poor highland impact melts. We also obtained regolith breccias and core samples in order to explore effects related to regolith maturity. Finally, we obtained a sample of Apollo 17 orange glass to represent pyroclastic glasses.

2.2. Thermoluminescence Measurements

The rocks were crushed to 100-mesh, while powders (which were of similar grain size) were used in the "as-received" state. Three 4-mg aliquants were placed in shallow copper pans for TL measurement, drained of their natural TL by briefly heating to 500°C, given a ~20 grey beta dose from a 250 mCi ^{90}Sr source, the short-lived TL allowed to decay for 5 min, and the induced TL measured at 7.5°C/s with Daybreak Nuclear and Medical TL apparatus fitted with blue and IR filters (Corning 7-59 and 4-69). Previous work has shown that the spectra of feldspars change from blue to blue-green and yellow as the Na/Ca ratio decreases, so that TL apparatus whose sensitivity is at a maximum for blue wavelengths will underestimate the TL sensitivities of the calcic feldspars. However, the effect is relatively small, readily quantifiable, and easily correctable [*Huntley et al.*, 1988; *Prescott and Fox*, 1993; *Batchelor and Sears*, 1989]. The Dhajala meteorite (H3.8) was used as a long-term stability check for the apparatus. The data were reduced in the manner of previous studies [*e.g.*, *Sears and Weeks*, 1983], with the quoted uncertainties being 1σ for the three 4-mg aliquants. "TL sensitivity" refers to the level of induced TL when it reaches maximum production (usually normalized to that of the Dhajala meteorite). The temperature at which TL production reaches a maximum is referred to as "peak temperature." We refer to samples displaying the ~120°C peak as "low-temperature" feldspars and those displaying the ~220°C peak as "high-temperature" feldspars.

Table 2. Induced TL and Other Data for Lunar Regolith Breccias

Sample	Split Number	Mass, mg	Agg, vol%	C, μg/g	^{20}Ne, 10^{-8} cm^3 STP/g	N, μg/g	HC, %	TL s, (Dhajala= 1000)	$T_{p,}$, °C
					Lunar Maria				
10018	101	52	13.5	375	4.8	105.4	0.8	4.5±0.3	176±4
10019	85	55	12.8	--	~0	~0	0.6	5.7±0.7	179±4
10021	90	58	--	--	7.5	~0	--	3.2±0.3	183±6
10046	231	54	--	180	3.06	~0	--	2.7±0.4	186±6
10048	198	50	9.5	150	3.2	118.8	0.7	2.8±0.4	183±7
10060	136	60	--	120	3.3	95.1	--	3.6±0.1	186±4
10065	145	60	10.2	--	4.62	104.1	1.5	6.2±0.5	167±5
					Lunar Highlands				
ALHA 81005	83	62			50000			220±20	167±6
	84	56						240±40	169±6
Y-82192^a	64	214			4.4			270±20	164±3
MAC 88104^b	2	326			~200			137±4	197±4
MAC 88105^b	4	270						128±9	172±4

Abbreviations and references for mineralogical, petrographic, compositional and isotopic data are as follows: Agg Agglutinates, and HC, highland components, modal from *Simon et al.* [1984] and *Chao et al.* [1971]; carbon from *Friedman et al.* [1971], *Filleux et al.* [1978], and *Becker and Epstein* [1981]; ^{20}Ne from *Funckhauser et al.* [1970], *Kirsten et al.* [1970], *Heymann and Yaniv* [1971], *Hintenberger et al.* [1970; 1975], *Bogard and Johnson* [1983], *Takeda et al.* [1987], and *Eugster et al.* [1991]; total nitrogen from *Thiemens and Clayton* [1980]; TL s, TL sensitivity; T_p, TL peak temperature. Uncertainties on the TL data are 1σ on triplicate measurements of the homogenized powder.

[a] Y-82192 is paired with Y-82193 and Y-86032 [*Takeda et al.*, 1989].

[b] MAC 88104 and 88105 are paired meteorites [*Lindstrom et al.*, 1991].

Table 3. Induced Thermoluminescence and Other Data for Lunar Soils and Cores

Sample	Split Number	Depth, cm	Mass, mg	I_s/FeO	TL Sensitivity	T_p, °C
12025	352	0-0.5	51	--	73±5	210±6
12025	351	6.0-7.0	102	--	63±3	212±2
12028	835	32.2-33.2	101	--	100±7	209±2
60010	1265	0.5-1.0	153	86	90±20	153±6
60010	1263	3.5-4.0	154	71	80±10	147±3
60010	1261	11.0-11.5	151	70	80±20	147±1
60010	1259	14.0-14.5	159	62	140±30	137±4
60010	3238	20.0-20.5	169	47	200±20	135±2
60010	1257	24.5-25.0	165	46	120±10	141±3
60009	619	28.8-29.3	152	47	110±10	139±5
60009	621	48.4-49.0	156	44	100±20	140±2
60009	623	53.3-53.8	156	26	280±20	138±2
60009	625	58.3-58.8	155	49	120±20	141±1
60014	197	5.0-5.5	53	100	66±7	158±6
60014	199	15.0-15.5	52	92	96±9	144±4
60013	319	34.7-35.2	51	85	84±7	142±6
60013	321	54.7-55.2	53	38	118±10	142±2
70009[a]	550	4.1-4.5	54	45	24±5	146±1
70008[a]	513	29.8-30.3	52	12	25±1	138±2
70008[a]	515	49.3-50.3	50	14	32±4	133±6
70007[a]	452	79.9-80.4	55	36	20±1	139±5
70006	505	120.7-121.2	57	80	27±9	145±8
70005	485	159.8-160.3	54	73	19±2	158±3
70004	574	199.7-200.2	54	69	19±7	145±3
70003	537	239.7-240.2	51	44	28±4	139±1
70002	461	269.2-269.7	51	66	26±6	144±9

Abbreviations, mineralogical and petrographic descriptions as follows: 12025,12028, *Fryxell and Heiken* [1974];. 60009,60010, *McKay et al.* [1977]; .60013,60014, *Basu and McKay* [1995];. 70002-70009, *Vaniman et al.* [1979] and *Taylor et al.* [1979]; TL sensitivity is relative to Dhajala = 1000; T_p, TL peak temperature. Uncertainties are 1σ on triplicate measurements of the homogenized powder. I_s/FeO data (arbitrary units): 60009/10, *Morris and Gose* [1976]; 60013/14, *Korotev et al.* [1993]; 70002-70009, *Morris et al.* [1979] *and Morris and Lauer* [1992].

[a] Very low-Ti mare basalts according to *Vaniman and Papike* [1977].

2.3. Heating Experiments

Twenty-milligram samples of powder from an 8.5-g sample of Apollo 16 lunar soil 61501 were placed in quartz vials which were three-times filled with high-purity N_2 and evacuated and then finally filled with N_2 to ~0.3 bar. The vials were then heat sealed and heated for the times and at the temperatures indicated in Table 4. They were allowed to cool to room temperature without quenching. Triplicate vials were run at each time and temperature. We did not measure oxygen fugacity, but since the same results are obtained with a variety of feldspar-bearing rocks, terrestrial and extraterrestrial, some containing carbon, and some containing water (see *Sears et al.* [1997] for a summary), we doubt that oxygen fugacity is important for these studies.

2.4. Cathodoluminescence Observations

Mosaics of the CL of polished thin sections from lunar core 60009/10 were produced using a Nuclide Corporation (now MAAS) "Luminoscope" attached to a standard petrographic microscope. A 15±1 keV and 0.7±0.1 mA, 1.0 x 0.7 cm electron beam was used and the CL recorded with Fujicolor 1600 film, ~1 min exposures and a 50X magnification. The luminescent grains were analyzed using the Cameca Camebax electron microprobe at Johnson Space Center using the usual standard block and data reduction methods [see, *e.g.*, *Zhang et al.*, 1995].

3. Results

3.1. Induced TL Properties of Lunar Rocks

The mare basalt samples have very low TL sensitivities with relatively little spread in the data, ~8 to ~44, lunar meteorite EET 87521 having the highest value. The samples also have very similar TL peak temperatures, 200-230°C (Figure 1). There are no significant differences in the TL properties of the various Ti mare basalt groups (Table 1). There is a tendency for the mare regolith breccias to show a decrease in TL sensitivity as the peak temperature increases, with 10065 lying at the top of the TL sensitivity range and 10046 (along with 10060, 10021, and 10048) lying at the bottom of the range (Table 2 and Figure 1). The Apollo 17 orange glasses have very low TL sensitivity (11±4) and peak temperatures intermediate to those of the mare and highland samples.

The highland samples have TL sensitivities ~10 times those of the mare basalts and also show a factor of ~5 spread in values, i.e. ~210 to ~1110 (Figure 1 and Tables 1 and 2). The TL sensitivity of the lunar highland meteorites (and ferroan anorthosite 60025) lies at the lower end of the range displayed by the impact melt rocks. Peak temperatures among the meteorites are generally similar, 165-200°C, whereas 60025 has two resolvable peaks, one at 127±5 and one at 198±2 °C. Two of the three clast-poor highland impact melt rocks show peak temperatures slightly, but significantly, higher than highland meteorite samples and comparable with those of the mare basalts.

3.2. Induced TL Properties of the Lunar Cores

Depth profiles are shown in Figure 2 and TL sensitivities are compared with peak temperatures in Figure 3 (Table 3). The TL sensitivities of samples from the three cores decrease with increasing maturity, while peak temperatures generally increase with increasing maturity. Although still present, the relationship between TL sensitivity and maturity is weaker for the Apollo 17

Table 4. Induced TL Sensitivity and Peak Temperature Data for Heated Samples of Apollo 16 Soil 61501

Temperature, °C	Time, hours	TL Sensitivity (Dhajala=1000)	T_p, °C
500	10	206±33	137±4
	100	280±56	139±4
700	10	251±53	146±4
	100	257±44	140±4
800	10	226±63	146±7
	100	424±108	157±9
900	1	223±55	149±10
	2	302±36	154±4
	10	436±85	188±7
	20	394±53	208±4
	100	606±48	206±4

Uncertainties are 1σ on triplicate measurements of the homogenized powder.

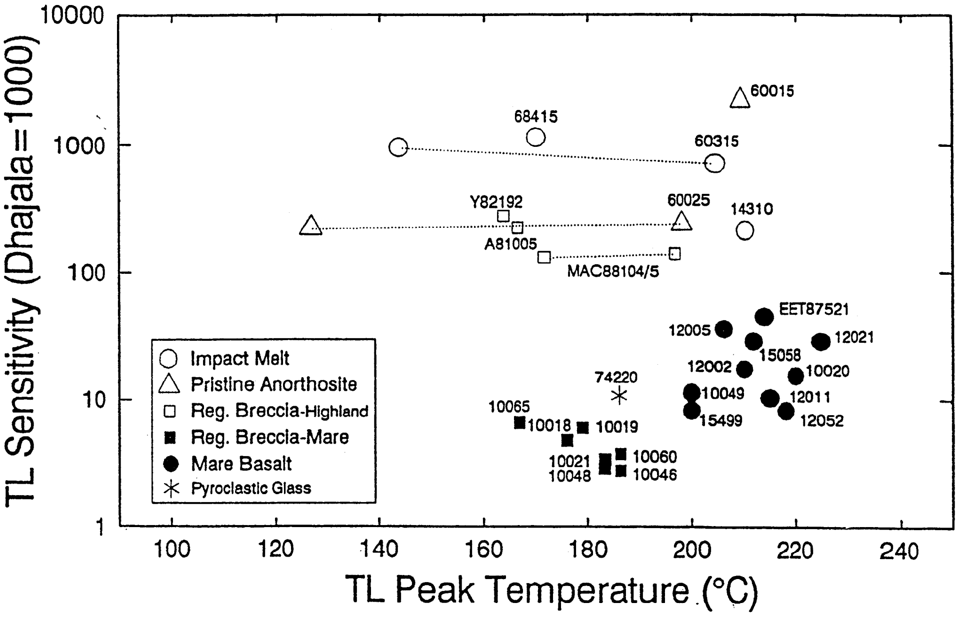

Figure 1. Thermoluminescence sensitivity against TL peak temperature for mare basalts (solid circles), Apollo 11 regolith breccias (solid squares), clast-poor impact melt rocks (open circles), pristine anorthosites (open triangles), highland regolith breccias (open squares), and a pyroclastic glass (asterisk). Data points linked by dotted lines indicate the presence of multiple TL peaks. Highland samples have TL sensitivities 1-2 orders of magnitude higher than mare basalts and with slightly lower peak temperatures. The Apollo 11 regolith breccias show a tendency for TL sensitivity to decrease with increasing peak temperature.

core, probably because of the especially low TL sensitivity values.

3.3. Cathodoluminescence Properties of the Lunar Cores

The major luminescent phosphors in Apollo 16 soils are (1) monomineralic feldspar grains in the matrix that display yellow-green CL and (2) feldspar grains in the clasts that display blue CL. Feldspar grains exhibiting strong shock features, such as undulatory extinction or diaplectic glass, were nonluminescent. The modal abundance of yellow-green luminescing grains decreases as a function of maturity, while the abundance of nonluminescent grains increases and the abundance of blue-luminescing feldspar remains reasonably constant (Figure 4).

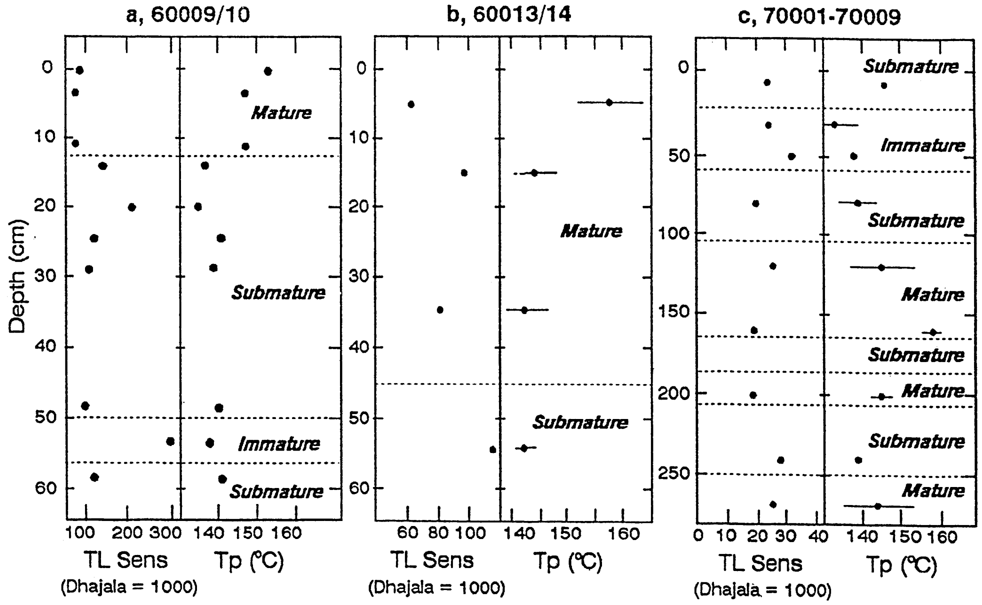

Figure 2. Depth profiles for TL sensitivity and peak temperature for three lunar cores. In each case, low TL sensitivity and high peak temperatures are associated with high maturity. Maturity assignments are from *Morris and Gose* [1976], *Morris et al.* [1979] and *Morris and Lauer* [1992].

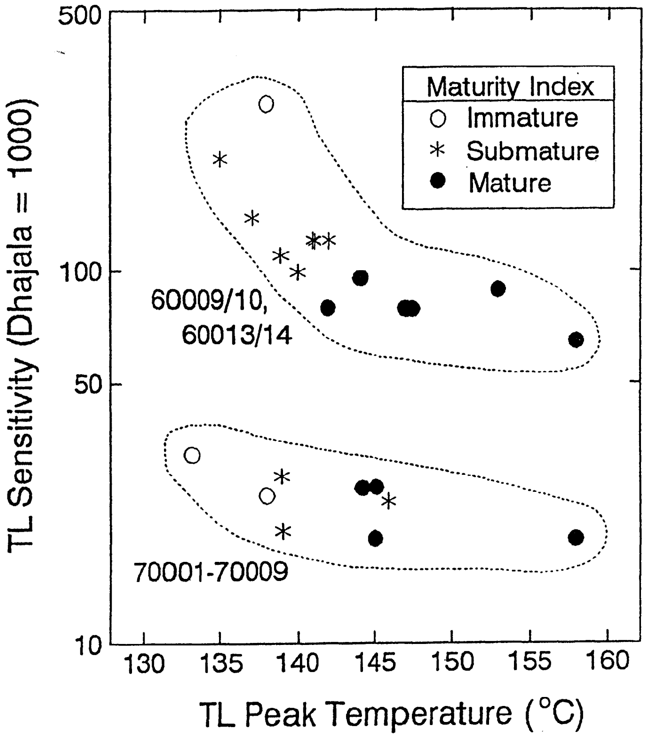

Figure 3. Thermoluminescence sensitivity against peak temperature for the Apollo 16 and 17 cores, data being coded according to maturity. The Apollo 16 cores show about an order of magnitude higher TL sensitivity than the sample from the mare region, and within each core, TL peak temperatures increase and TL sensitivity decreases as a function of maturity, although only slightly in the case of the TL sensitivity of the Apollo 17 core.

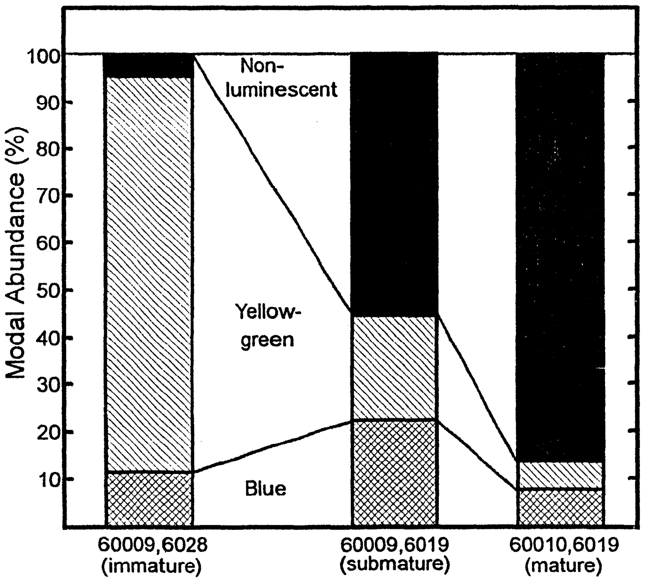

Figure 4. Modal abundance of the major phases in terms of CL color in three Apollo 16 lunar soil samples from the 60009/10 core. Phases which exhibit luminescence (yellow-green or blue) are feldspar, while nonluminescent phases include heavily shocked feldspar, glass, pyroxene, olivine, and metal. The abundance of nonluminescent grains increases rapidly as a function of soil maturity in these samples at the expense of yellow-green luminescing grains.

3.4. Induced TL Properties of a Heated Lunar Soil

Samples of the Apollo 16 soil 61501 showed increases in both TL sensitivity and peak temperature with increasing heating temperature. Peak temperatures increased from ~140°C to ~200°C (Table 4 and Figure 5). In both cases, changes started to occur after the 800°C heating and slightly greater changes occurred with longer heating times.

4. Discussion

4.1. The Thermoluminescence Properties of Lunar Materials

4.1.1. The TL sensitivity differences between highland and mare samples. The major CL and TL phosphor in lunar samples is feldspar [*Dalrymple and Doell*, 1970; *Geake et al.*, 1977; *Hoyt et al.*, 1972; *Nash and Greer*, 1970; *Sippel and Spencer*, 1970] and the present CL mosaics of the Apollo 16 drive tube confirm this. In feldspars, the abundance of transition metal impurity ions is the major factor in determining their TL and CL properties [*Marshall*, 1988], Mn^{2+} often being the major activator, while Fe^{2+}, Ti^{4+},and the rare earth elements are also sometimes important. Most activators can become quenchers at concentrations above about 0.5 wt %.

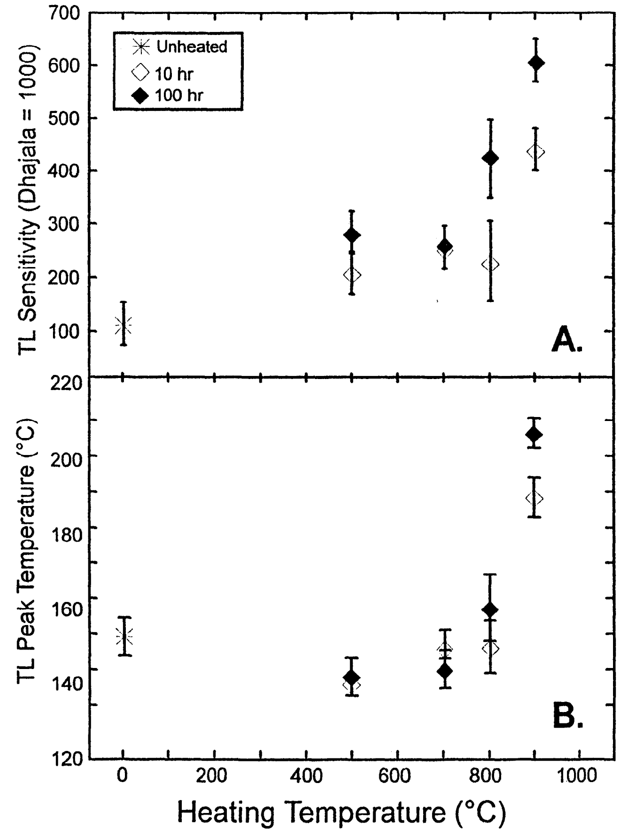

Figure 5. (a) TL sensitivity versus heating temperature for lunar soil 61501 heated at the times and temperatures indicated. Thermoluminescence sensitivity increases after heating at 800°C and 900°C and the increase is greater for the longer time. (b) Peak temperature versus heating temperature for lunar soil 61501 heated at the times and temperatures indicated. Like TL sensitivity, TL peak temperature increases after heating at 800°C and 900°C, and the increase is greater for the longer time.

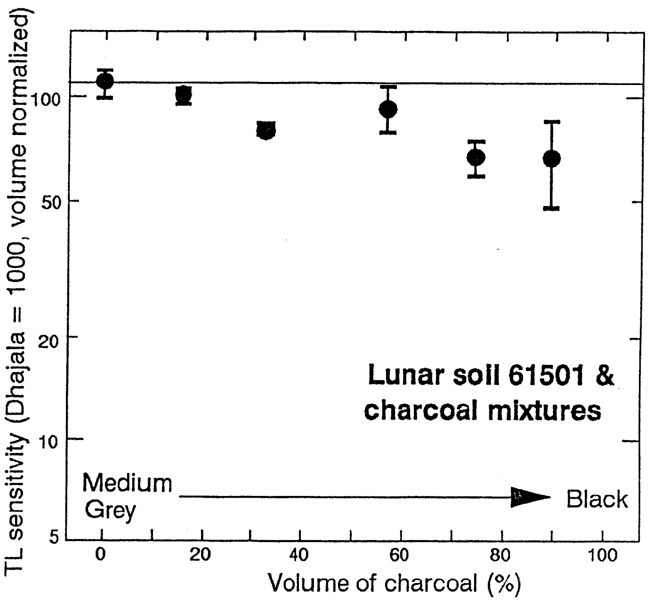

Figure 6. Thermoluminescence sensitivity, normalized to the volume of the soil in the soil/charcoal mixture against the amount of charcoal in the mixture, this being a measure of the albedo of the mixture. The normalization corrects for dilution but means that the curve does not go to zero when only charcoal is present. The decrease in normalized TL sensitivity is not enough for differences in albedo to explain the difference in TL sensitivity between highland and mare samples. The indicated error bars are one-sigma values for the TL measurement.

In principle, the difference in TL sensitivity between highland and mare rocks could be explained in terms of feldspar abundance, sample albedo, or feldspar composition. Highland samples normally contain more feldspar than mare samples, but the difference is only twofold to fivefold (20-40 vol % compared with 80-100 vol %) and not enough alone to explain the order of magnitude difference in TL sensitivity. Albedo potentially affects TL sensitivity measurement since light undergoes multiple scattering between grains prior to reaching the detector in the TL apparatus (J. F. G. Garlick, personal communication, 1978). We try to avoid this by using monolayers of powder, but we checked this by measuring the TL sensitivity of mixtures of soil 61501 with charcoal (Figure 6). The 40% decrease in TL sensitivity as the mixture changes from midgrey to black is comparable to experimental uncertainty and insignificant compared to the order of magnitude difference between highland rocks and mare basalts. We conclude that albedo is not a major factor in explaining the difference in TL sensitivity of highland and mare samples.

Mare feldspars are typically >An_{75} while highland feldspars are >An_{90} (see Figure 7), but this difference is not sufficient to account for an order of magnitude difference in TL sensitivity [*Batchelor*, 1992]. There is also no systematic difference between highland and mare feldspars in the abundance of potential activator ions Ti, Mn, and rare earth elements. However, Fe^{2+} is present in much higher levels in mare plagioclase than it is in highland plagioclases (Figure 7), and the abundance of Fe in mare feldspars is sufficient for Fe to behave as a quencher of TL and CL. Thus TL sensitivity should be a sensitive indicator of metamorphism for basalts with the diffusive loss of FeO from feldspar being related to an increase in TL sensitivity and CL intensity. This is probably also the case for the eucrite meteorites [*Batchelor and Sears*, 1991b].

4.1.2. The significance of TL peak temperatures of lunar samples. As discussed above, TL peak temperatures depend largely on the thermal history of the feldspar, regardless of the composition of their feldspars. Thus unlike the XRD method that is not well-suited to the more calcic compositions [*Smith*, 1974], TL can provide evidence for structural disordering (or associated processes) in even the most calcic feldspars. The activation energy for the TL peak change is only ~80 kJ/mol, whereas complete structural disordering requires breaking the Si-O bond, whose energy is ~330 kJ/mol, so the TL change is probably detecting only one step of a multistep process. *Pasternak et al.* [1976] suggested that the changes in TL peak temperature were caused by changes in defect structure that preceded disordering.

The increase in peak temperature upon heating to ~800°C displayed by the lunar soils (Figure 5) is very similar to that displayed by chondrites [*Guimon et al.*, 1985], basaltic meteorites [*Batchelor and Sears*, 1991b] and terrestrial feldspars [*Hartmetz and Sears*, 1987]. Plagioclase samples heated to temperatures above ~700°C have a TL peak at ~220°C, while unheated samples and samples heated below ~700°C have a TL peak at ~120°C. However, experimental uncertainty and other effects produce a certain amount of variance in these values, so we take a single value of ~160°C to discriminate between "high"- and "low"-temperature samples. The equilibrium temperature for disordering is 800-1000°C, depending on the composition of the feldspar [*Smith*, 1974]. The transition temperature for lunar feldspar is expected to be higher than for chondritic meteorites because of their different feldspar compositions. However, in all cases we expect the temperatures determined in the laboratory to be slightly low because of kinetic difficulties. It is also well-known that while the order-disorder transition is facile and can be observed among samples heated on the laboratory timescale, this is not true of disorder-order transition which is sluggish even on geological timescales.

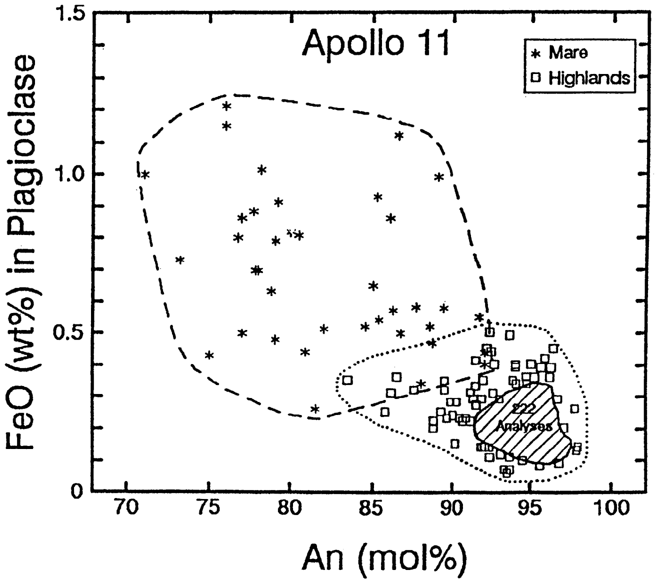

Figure 7. FeO in plagioclase against the An content of the plagioclase found in Apollo 11 mare basalts and highland lithics from the Apollo 11 coarse fines (data from *Simon* et al. [1984]). There is a fairly clear separation between mare and highland feldspars.

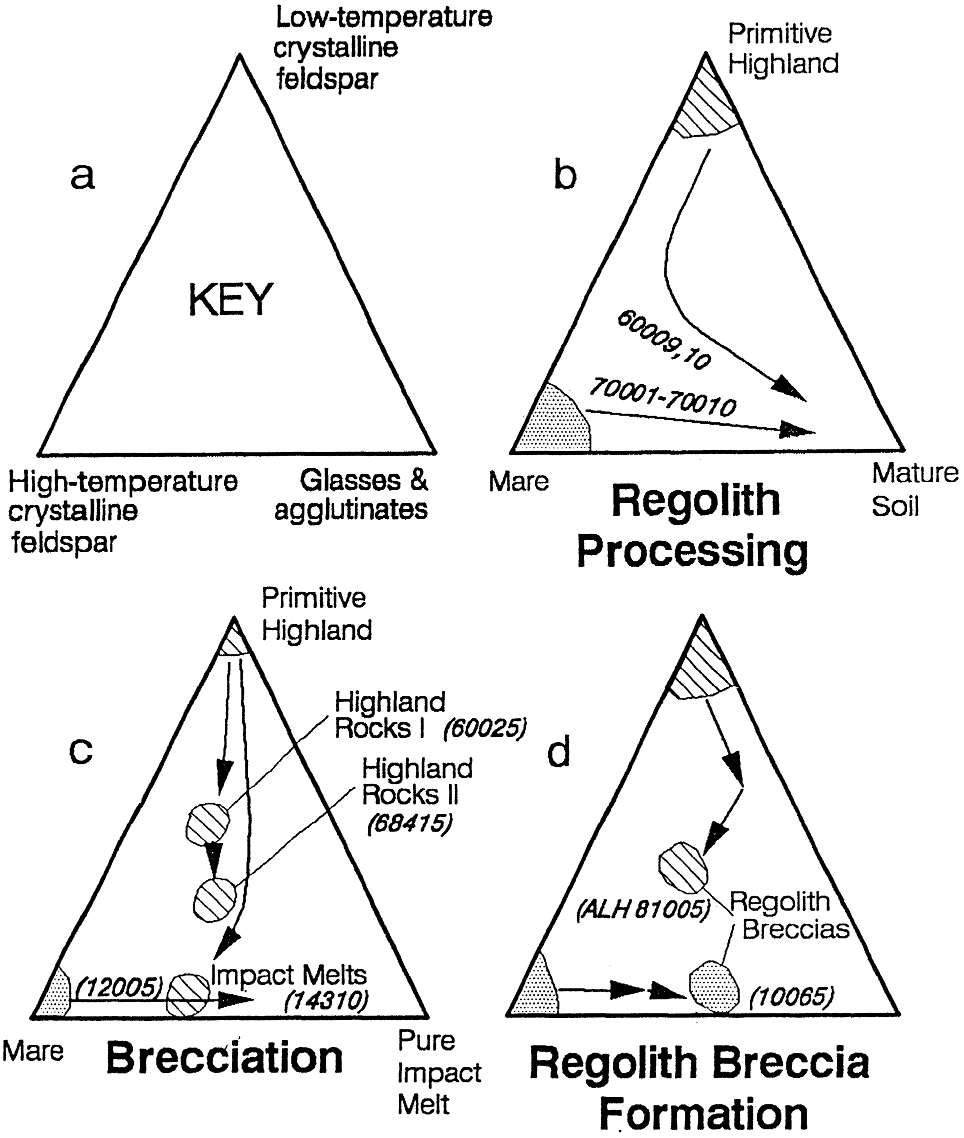

Figure 8. Schematic diagrams summarizing the effects of brecciation, shock melting and regolith "gardening" on the feldspar of lunar samples and its TL properties. TL sensitivity decreases from the left side of the triangle to the lower right corner of the triangle as crystalline forms of feldspar are converted to agglutinates and glasses. The terms "high-" and "low-" temperature state refer samples displaying TL peaks above and below 160oC. Samples with TL peaks at ~120°C can have their TL peak moved to ~220°C by laboratory heating, and in the case of terrestrial oligoclase and albite this change in peak temperature has been shown by X ray diffraction measurements to be associated with structural disordering. (Calcic plagioclases also display structural disordering but this is not readily measured by XRD.) Only large-scale impacts are capable of converting feldspar originally in the low-temperature state in highland rocks to the high-temperature state either through solid-state conversion or by melting and rapid crystallization. Regolith processing causes a change in the ratio of feldspar in the low- to high-temperature state in soils largely because of the preferential destruction of feldspar in the low-temperature state. The feldspar population in mare rocks is already in the high-temperature state, but some of the feldspar will be rendered nonluminescent during impact. The formation of regolith breccias involves both processes.

4.1.3. TL properties in the light of the known histories of lunar samples. We can summarize some of the expected TL properties for lunar samples as a ternary with amount of feldspar in the high- and low-temperature forms on two axes and amount of glass and agglutinates on the third axis (Figure 8). Thus each apex refers to a different temperature regime determined by the state of the feldspar: low-temperature crystalline (upper apex), high-temperature crystalline (lower left apex), and high-temperature partially or completely fused (lower right apex). The two extremes in thermal history would then be igneous rocks with an origin involving slow cooling at depth; these would plot at the upper apex, and rapidly cooled rocks would plot at the lower left apex. Regolith processing converts the crystalline material to glasses and agglutinates, forming trends toward the lower right apex. Since regolith processing involves impact heating and rapid cooling, it also converts low- to high-feldspar (a process facilitated by the high pressures associated with impact [*Hartmetz et al.*, 1986; *Goldsmith*, 1987]). Thus the trends might be curved towards the lower left apex.

All of the mare samples have induced TL peak temperatures in excess of 160°C (Figure 1), and X ray diffraction studies indicate that feldspar from Apollo 11 mare basalts is disordered [*Stewart et al.*, 1970]. This is consistent with the rapid cooling (~0.1°C to ~30°C/h and <10 m thick lava flows [Brett, 1975]) inferred from dynamic crystallization [e.g., *Lofgren*, 1974] and theoretical studies [e.g., *Onorato et al.* 1978]. Thus mare samples (like 12005) plot in the lower left corner of the ternary.

The highland rocks are more diverse in their TL peak temperatures than the mare samples (Figure 1). The moderately shocked but chemically "pristine" anorthosite 60025 [*Ryder*, 1982] exhibits two peaks of about equal intensity, while pristine sample 60015 is a coarsely crystalline shock-melted anorthosite [*Sclar and Bauer*, 1974]. These would plot in the middle of the diagram. The remaining highland rocks (impact melts 68415, 60315, and 14310 and regolith breccias Y-82192, ALH 81005, and MAC 88104/5) display middle to high TL peak temperatures and are thus dominated by high-temperature feldspar and would plot in the central region of the plot trending toward the horizontal axis and the right corner. The TL data might then suggest that 68415 was the most slowly cooled sample in the present study, while 14310 cooled the most rapidly, since 68415 has the highest TL peak temperature and 14310 has the lowest. The high TL sensitivity of the clast-poor impact melt rocks is consistent with their high crystallinity, 60315 having a particularly coarse texture [*Taylor et al.*, 1991]. Their high peak temperatures are consistent with fairly rapid cooling, suggesting that the postformation cooling was not fast enough to prevent crystallization but it was fast enough to leave the feldspar in the high-temperature state.

The Apollo 17 orange glass has low sensitivity, but higher than the regolith breccias in which the feldspathic material is glassy. One interpretation is that the glass is about 0.1% crystallized (since the pure feldspar has a TL sensitivity of about 1000) which is perfectly consistent with petrographic and chemical arguments for small amounts of crystallization [*Delano et al.*, 1981].

The combined process of regolith and breccia formation can thus move data over most of the ternary (Figure 8d). The tendency for TL sensitivity of the Apollo 11 regolith breccias to decrease as peak temperature increases might mean that they represent a sequence of increasing maturity (10065 —> 10018, 10019 —> 10060, 10021, 10048, 10046), but there is little or no evidence to support this interpretation (Table 2 and Figure 1). More likely, the series represents mixing. As the modal abundance of highland components increases, TL sensitivity increases and TL peak temperature decreases. The lunar meteorites (like ALH81005) and Apollo breccia 10065 are also examples of regolith breccias.

The TL properties of a wide variety of lunar samples may thus be readily explained in terms of current understanding of the luminescence mechanisms of geological materials and the relative abundance of these three components. Most significant is the lack of material corresponding to the top corner of the ternary. The closest candidate material is to be found in the immature soils.

4.1.4. Maturity-related variations in core samples. Thermoluminescence peak temperature increases and TL sensitivity decreases with increasing maturity in the Apollo 16

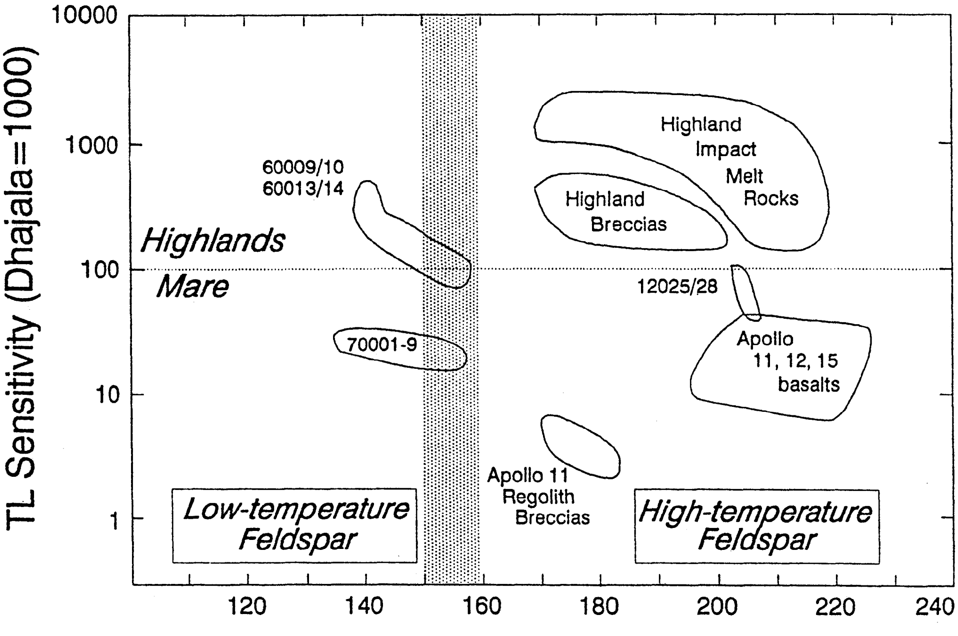

Figure 9. Schematic diagram showing the fields for lunar rocks and soils on a plot of TL sensitivity against peak temperature, compared with proposed boundaries for mare/highlands and low- to high-temperature state, which is related to order/disorder. The lunar highland materials have TL sensitivities about an order of magnitude higher than the mare materials, but two soil cores have much lower peak temperatures than rocks from the same region. Regolith breccias are displaced to lower TL sensitivities and peak temperatures relative to other rocks of similar lithologies. The only pristine highland sample in our study and one of the clast-poor impact melt rocks have a second peak at low temperatures.

and 17 cores (Figure 3). The CL observations (Figure 4) and laboratory heating data (Figure 5) provide fairly straightforward interpretations of these trends. The CL observations indicate that the TL signal is produced primarily by feldspar and that the decrease in TL sensitivity is a result of the feldspar becoming nonluminescent as it is converted to glass and agglutinates. Thus TL sensitivity, like CL intensity, decreases with increasing regolith maturity. The increase in peak temperature displayed by the core samples would seem to indicate that the soil samples are being thermally processed in a manner similar to the samples heated in the laboratory; they are apparently undergoing a thermally induced conversion from the low- to the high-temperature state. Thus peak temperature increases with increasing regolith maturity.

The Apollo 12 core has induced TL properties similar to the mare rocks but with slightly higher TL sensitivities (Figure 9). This probably results from the presence of some highland feldspar. Because the peak temperature is not affected, this feldspar must be present as quickly cooled highland impact melt fragments. The Apollo 12 site is some distance from the lunar highlands, in contrast to the Apollo 16 and 17 sites.

4.1.5. Thermally primitive material on the Moon? In terms of its relative lack of chondritic contamination, ferroan anorthosite 60025 is one of the most pristine highland samples [*Warren and Wasson*, 1977; *Ryder*, 1982]. This rock is unusual in containing a significant amount of feldspar in the low-temperature state (Figure 1), which is presumably original, surviving igneous feldspar. However, the rock also has a significant amount of feldspar in the high-temperature state, which we attribute to the granulated feldspar present in this rock that was produced during shock [*Dixon and Papike*, 1975]. Thus, although 60025 is very pristine compared to the impact melts, or regolith breccias dominated by feldspar in the high-temperature state, it is still far from being a truly unaltered sample of igneous rock.

In at least one sense, the most primitive samples in our current database are the immature regolith soil samples in which feldspar is present as predominantly low-temperature monomineralic grains. The comminution process that produced these grains was obviously gentler than the large-scale impact and excavation events that placed large rocks like 60025 on the lunar surface [*Benoit et al.*, 1994]. Other primitive highland minerals are probably also present in the Apollo 16 and 17 soil samples.

4.1.6. Low-level long-term metamorphism on the Moon? Probably the best way to address the question of whether there is any TL evidence for metamorphism among the lunar samples is to compare them with a very similar suite of samples from a parent body on which there is good evidence for low-to-moderate levels of metamorphism, namely, the basaltic meteorites [*Batchelor and Sears*, 1991a, b]. The major difference between the TL properties of lunar materials studied in our laboratories to date and basaltic meteorites is that with one notable exception, the basaltic meteorites all have a strong TL peak at 120°C (Figure 10), the intensity of which varies with metamorphic equilibration. The thermal history that was proposed for the eucrites was as follows. On the basis of cooling rates deduced from textures of basaltic meteorites we would expect eucrites to have similar TL peak temperatures as the lunar mare basalts (200-240°C). However, the observed TL peak at lower temperatures suggests that the initial high-temperature peak must have been erased by some heating, most plausibly impact heating (see below), followed by slow cooling by rapid burial under a thick insulating ejecta blanket. During slow cooling, pyroxenes became homogenous in composition, exsolution lamellae appeared and Fe diffused out of the feldspar causing TL sensivity to increase. Using the intensity of this peak, *Batchelor and Sears* [1991b] divided the eucrites into "petrologic types" and found good agreement with classifications based on mineralogical data [*Takeda et al.*, 1983]. The minor peak in Figure 10 probably reflects remnant igneous high-temperature feldspar. The possibility that the minor peak is shock-produced cannot be entirely excluded, but the naturally shocked LEW 85300 eucrite has a very much broader high-temperature peak.

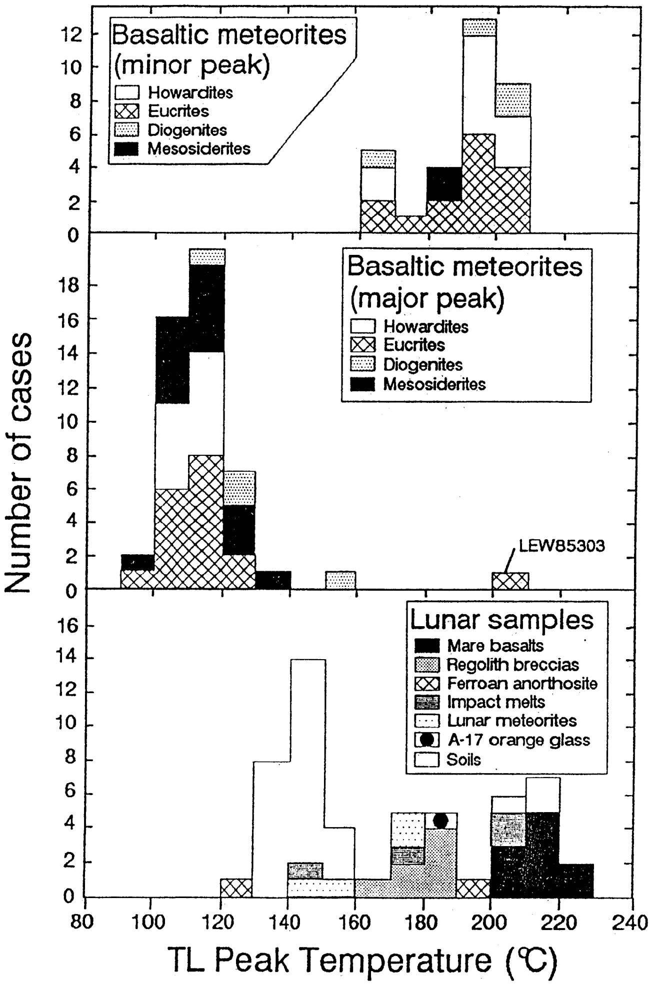

Figure 10. Histograms of TL peak temperatures for lunar samples compared with those of basaltic meteorites (data from *Batchelor and Sears* [1991b]). Basaltic meteorites normally have a TL peak at 120°C, whose intensity is related to metamorphism (as determined from petrographic and mineralogical data), and a weaker peak at ~200°C. The 120°C peak is either weak or absent in the shocked eucrite LEW 85303. In the Apollo samples the 120°C peak is weak or absent. Lunar soils have a peak at 140°C. Two lunar samples (the ferroan anorthosite 60025, and one of the impact melts 60315) have both 120°C and 200°C peaks.

The exceptional basaltic meteorite, LEW 85303, and several samples thought to be fragments of the same original mass and collectively termed LEW 85300, did not show this low-temperature peak but instead showed a broad high-temperature peak which could be reproduced in the laboratory by heating normal eucrite powder at temperatures ~800°C for ~100 hours. This meteorite appears to have been shock-heated and, unlike the other eucrites, not metamorphosed at low temperature.

Petrographic data are consistent with this scenario [*Kozul and Hewins*, 1988a, b]. Its TL properties and history are much more similar to those of the lunar samples than are those of any other basaltic meteorite.

4.2. Comparison of Two Planetary Basaltic Parent Bodies and Their Surfaces.

Several possible heat sources for metamorphism of most lunar samples and basaltic meteorites are possible, but in view of the brecciation and shock evident in these materials, impact heating is clearly the most likely. It has recently been argued that the metamorphism of the basaltic meteorites occurred during initial igneous processes 4.6 Gyr ago and the thermal event that reset the K-Ar system 3.5 Gyr ago did not leave any petrographic effects in the meteorites [*Yamaguchi et al.*, 1996]. However, the early metamorphism is inconsistent with chronological and cooling rate data. The textures of the eucrites suggest very rapid cooling during solidification, consistent with extrusion as lavas onto the surface [*Miyamoto et al.*, 1985]. However, this would result in cooling rates several orders of magnitude faster than calculated from the composition and size of exsolution lamellae in the pyroxene. Slowing the cooling rate by multiple lava flows requires prohibitively large numbers of flows and also creates into mass balance problems, and insulation by regolith requires prohibitively fast regolith formation [*Sears et al.*, 1997]. *Bogard and Garrison* [1995] has pointed out other difficulties involving Ar closure temperature, cooling rates, and Ar-Ar age for an unmetamorphosed eucrite. Metamorphism in ejecta blankets of varying thicknesses following the widespread impact heating 3.9 Gyr ago is more plausible [*Sears et al.*, 1997], notwithstanding the *Yamaguchi et al.* [1996] argument that impact heating is inadequate to cause metamorphism. Metamorphic temperatures for eucrites calculated from mineral pairs are actually similar to Ar degassing temperatures, and impact melts are common on heavily impacted surfaces. The varying levels of metamorphism experienced by the eucrites must have been governed by the extent of burial by ejecta and other regolith materials following the impact heating. *Batchelor and Sears* [1991b] showed that for the most highly metamorphosed eucrites, burial under several hundred meters of loosely consolidated regolith would be required, while the least metamorphosed eucrites may have been buried to depths of less than 50 m. In contrast, the lunar mare and impact materials cooled essentially on the lunar surface with only minimal regolith covering.

It is possible that these differences in metamorphic history of basaltic meteorites and lunar samples simply reflect a sampling artifact, since only surface materials were sampled by the Apollo astronauts, while the basaltic meteorites may have been excavated by large impacts. However, major impacts have distributed material on the Moon on a global scale and ejecta constitutes discrete geological units with stratigraphic and temporal implications. Much of the surface material on the Moon has been excavated from depth by major impacts, for instance, the Fra Mauro region is largely ejecta from the Imbrium impact. The presence of highland material in the mare soils indicates considerable transport of material [*McKay et al.*, 1991, p. 306]. The apparent difference in metamorphic history of the basaltic meteorites and the lunar materials probably reflects significant differences in the regolith thicknesses of the two parent bodies.

The thickness of a planetary regolith depends on the size of the body, the flux and velocity distribution of impactors, and the original nature of the surface being impacted [*e.g.*, *Housen et al.*, 1979a, b]. Several authors have argued that Vesta was the basaltic meteorite parent body [McCord et al., 1970; Drake, 1979], with fragments excavated by impact and sent to Earth on orbits like those of the small Vesta-like asteroids observed by *Binzel and Xu* [1993]. *Housen et al.* [1979a, b] calculated that after 1 Gyr a 500 km asteroid like Vesta should acquire a 500 m regolith. Most of the impact events experienced by the basaltic meteorites occurred, according to Ar-Ar dating, around 3.4-4.1 Ga, a range which is not unlike that of lunar samples, 3.7-4.1 Ga [*Bogard*, 1995]. In the case of the lunar samples, the impact events were severe enough to reset chronometers more robust than Ar-Ar. *Housen et al.* [1979a, b] also point out that asteroids should have thicker regoliths than the Moon, because the meteorite flux is lower at 1 AU and ejecta stays closer to the crater on the Moon due to its stronger gravity, reducing the average deposition rate per unit area. Recent calculations show that even smaller objects, like the Vesta-like asteroids observed by *Binzel and Xu* [1993], probably also have thick regoliths [*Asphaug and Nolan*, 1992; *Asphaug and Melosh*, 1993]. Thus it has long been argued by some theorists that asteroids should have thick regoliths, and the difference in thermal histories of the basaltic meteorites and lunar samples is consistent with that theory.

5. Conclusions

1. The induced TL properties of a large suite of lunar samples and CL images of centimeter-sized thin sections of several soil samples have been examined. In agreement with a great many previous studies, feldspar is found to be the dominant mineral responsible for the CL and TL. Most of the TL properties of the lunar rocks can be readily interpreted in terms of the feldspar being present in two forms, a high-temperature state and a low-temperature state (which are thought to be related to ordered and disordered forms), the amount of feldspar present, and, in some cases, its FeO content. Most lunar rocks, including most highland samples in our collection, are dominated by feldspar in the high-temperature state. Highland samples have higher TL sensitivities than mare samples partly because their feldspar has lower FeO contents.

2. Regolith maturation processes affect the TL and the CL properties of the soils and therefore provide a new means of exploring these processes. Highland soil samples are dominated by feldspar in the low-temperature state, but with increasing degrees of soil maturity, high-temperature feldspar becomes dominant. Maturation also causes some of the feldspar to become nonluminescent (by conversion to glass), and the surviving feldspar, located mainly in clasts, is increasingly in the high-temperature form. The proportion of feldspar in the low- and high-temperature states, and the TL sensitivity for samples from a given core, can be used as an indicator for the degree of maturity.

3. In terms of thermal history feldspar in the Apollo 16 regolith is more "primitive" than that of the "pristine" highland rock 60025 or feldspar from any of the major lunar rock types.

4. The lunar samples have TL properties very similar to those of the basaltic meteorites (the howardites, eucrites and mesosiderites, LEW 85300 aside) but unlike basaltic meteorites show no evidence for small amounts of metamorphism since formation in their present form. This might reflect the greater ease of forming large blankets of ejecta on asteroid-sized bodies.

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