DEFINITIONS

Anorthosite: Rock containing 90% plagioclase [(Ca,Na)(Al,Si)Si_2O_8]by volume.

Basalt: Volcanic lava rock containing silicate minerals rich in magnesium and iron plus plagioclase.

CI or chrondritic standard: elemental and isotopic abundances in the sun and in carbonaceous chrondrites are the same except in some very special details.

Differentiation: creation of chemical differences in magma by processes that separate minerals from it, usually as a result of contrasting densities in a gravitational field.

Gabbroic and noritic: Contains clinopyroxene or orthopyroxene, respectively, greater than ~10% by volume.

Granulite: Rock composed of even-sized, interlocking mineral grains.

Immiscible: Property of liquid phases that cannot dissolve completely in one another.

Incompatible element: elements whose ions are incompatible with incorporation into the crystal lattices of common rock forming silicate minerals.

Isochron age: radiometric age determined by extrapolation of the apparent ages of distinct phases or physical components in a rock. After Glossary of Geology, American Geological Institute. In the case of extinct parent radioisotopes, the isochron age relates to the time before the disappearance of measurable parent.

Model age: radiometric age determined by analysis of the total proportion of parent and daughter isotopes in a given isotopic system. After Glossary of Geology, American Geological Institute. In the case of extinct parent radioisotopes, the model age relates to the time before the disappearance of measurable parent.

Pressure release melting: denotes a process by which rocks very near to their initial melting point melt as a consequence of the removal of the pressure or weight of overlying rocks. Sometimes referred to as "decompression melting."

Siderophile: Elements that tend be enriched in iron-rich metallic phases produced in nature.

IMPACT CRATERING

Almost everything we think we know relative to the Moon must be viewed through the mask of impact cratering effects (figure 5) that have dominated lunar history from its origin to the present ([i], [ii], [iii], [iv], [v], [vi]). The impact of comets, asteroids, meteors, micrometeors, dust, and energetic atomic and nuclear particles have modified the surface and near-surface expression of all the internally generated processes contributing to the present physical nature of the Moon. The secondary effects of each impact have magnified the importance of these impacts. Most comet, asteroid, meteor, and micrometeoroid impact velocities are between 13 and 18 km/sec with some as high as 70km/sec, giving associated target pressures at the point of impact of several hundred Gpa (gigapascal). Extraordinary amounts of heat per unit mass are released as conversion of kinetic energy into forward and rearward shock waves takes place almost instantaneously. The amount of extra-lunar material that can be identified in regolith samples returned to Earth indicates that about 98% ([vii]) to 99.7% ([viii]) of all but the larger projectiles is melted, vaporized or ionized, and returned to space. The general characteristics of lunar impact craters as a function of diameter are summarized in Table 1.

Processes associated with cratering and space radiation have created a well-defined zone of debris that covers essentially the entire Moon, the thickness of which depends on the length of exposure of a specific geological unit or feature. This zone is called the "regolith," a terrestrial term also used relative to the Moon. Essentially all the samples returned from the Moon by Apollo have come from the regolith or from rocks incorporated within it. It has been defined as "the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers bedrock. It includes rock debris of all kinds, including volcanic ash...lunar regolith consists [largely] of particles <1 cm in size although larger cobbles and boulders, some as much as several meters across, are commonly found….much of the pulverized material is melted and welded together to produce breccias (fragmental rocks) and impact melt rocks, which make up a significant portion of the regolith ..." ([ix], [x]). A particularly important part of the lunar regolith consists of aggregates of rock, mineral, and glass fragments, called agglutinates, held together by impact melt glass. Recently, it has been shown that at the nanometer scale, iron metal blebs accreted on and formed in the rims of regolith grains significantly affect optical and magnetic properties ([xi, xii], [xiii]). Further, the lunar regolith contains imbedded solar wind gases, meteoritic material, and the isotopic products and crystal structure damage produced by solar and cosmic radiation. The average depth of the regolith in a given area reflects the age of the underlying bedrock. Lateral mixing of material derived from adjoining bedrock units is a function of the age of the separating contact.

Table 1. General characteristics of lunar craters as a function of size ([xiv]).

DIAMETER RANGE Examples	GENERAL CHARACTERISTICS
<10m	➢ Craters normally do not penetrate the regolith.

	➢ Depth to diameter ratio variable. ➢ Glass discontinuously lines shallow pits in the center of fresh craters. ➢ Mineral grains shattered around small craters on solid rock **(**zap pits**).** ➢ Deep pits **(**~1/3 the crater diameter**)** in the center of some craters.
~10m to ~100m Van Serg and Shorty Craters in Taurus-Littrow	➢ Craters normally penetrate mare regolith if above 20-m diameter. ➢ Depth to diameter ratio about 1:3 to 1:4 for fresh craters. ➢ Inner benches common if target material stratified. ➢ Regolith breccias present inside and on the ejecta blankets of young craters. ➢ Ejecta blankets extend to about one crater diameter. ➢ Target strata are overturned but original vertical sequence is preserved in ejecta blanket.
~100m to ~10km Taruntius Camelot Crater in Taurus-Littrow	➢ Both transient and initial steady state craters are hemispherical with circular and raised rim. ➢ Depth to diameter ratio about 1:3 to 1:4 for fresh craters ➢ Impact breccias present inside and on the ejecta blankets of

	young craters. ➢ Ejecta blankets extend to about one crater diameter. ➢ Secondary impact cratering significantly modifies surface features out to many crater diameters from the edge of continuous ejecta. ➢ Target strata are overturned but their original vertical sequence is preserved in ejecta blanket.
~10km to <300km Copernicus	➢ Transient crater approaches hemisphere with circular raised rim and probably is lined with a shell of impact melt. ➢ Initial steady state crater has a flat floor with central mound or peak. ➢ Initial steady state crater walls have many stepwise benches (slump landslides) on walls. ➢ Hummocky crater floors and the depressions on wall benches and near-rim ejecta blankets of larger craters have indications of pools and flows of impact melt. ➢ Ejecta blankets extend to about one crater diameter ➢ Target strata are overturned but their original vertical sequence is preserved in ejecta blanket. ➢ Secondary impact craters, crater clusters, and crater chains, and herringbone crater chains, extend several thousand

	kilometers beyond edge of continuous ejecta.
>300km (basin) Orientale	➢ Transient crater depth to diameter ratio decreases with increasing size as lithostatic pressures compete with explosive pressures. ➢ Transient crater has an increasingly flat trapezoidal cross-section with increasing diameters. ➢ Transient crater has a flat floor, a circular raised rim, and probably is lined with a thick shell of impact melt. ➢ Initial steady state crater has a fractured, flat floor with central ring or partial ring of peaks. ➢ Initial steady state crater walls have many wide, stepwise benches (slump landslides) on walls. ➢ Floors and depressions on wall benches and near-rim ejecta blankets have indications of large pools, mantles, and flows of impact melt. Impact melt also injected into target materials. ➢ Ejecta and debris flow blankets extend to beyond one crater diameter. ➢ Two to six rings of mountains outside transient crater rim around basins >400 km in diameter. ➢ Target strata sequence is not well preserved in ejecta blanket

	due to extensive mixing of ejecta during flow. ➢ Within one crater diameter of the final steady state rim there is a continuous deposit of melt breccia possibly several hundred meters thick at the rim of the larger basins. ➢ Secondary impact craters, crater clusters, and crater chains, and herringbone crater chains, extend beyond the edge of continuous ejecta and debris flows and reach thousands of kilometers and probably around the entire Moon to the basin antipode.

i Pike, R. J., *Earth and Planetary Science Letters*, 23, 1974, pp 265-274.

ii See summary in Wilhelms, D. E., *The Geologic History of the Moon*, U.S. Geological Survey Professional Paper 1348, 1987, pp 27-53.

iii See summary in Heiken, G. H., and co-workers, *Lunar Sourcebook*, 1991, pp 47-56, 62-84.

iv Croft, S. K., in P.H. Schultz and R. B. Merrill, Eds., *Multi-ring Basins, Lunar and Planetary Science Conference 12*, Pergamon, New York, 1981, pp 133-148.

v Melosh, H. J., *Journal of Geophysical Research*, 87, 1982, pp 371-380.

vi Cintala, M. J., and R. A. F. Grieve, *Meteoritics and Planetary Science*, 33, 1998, pp 889-912.

vii See summary in Heiken, G. H., and co-workers, *Lunar Sourcebook*, 1991, p 151-152.

viii Ryder, G., *Lunar and Planetary Science Conference 30*, Abstract #1362, 1999.

ix Heiken, G. H., and co-workers, *Lunar Sourcebook*, 1991, p 285.

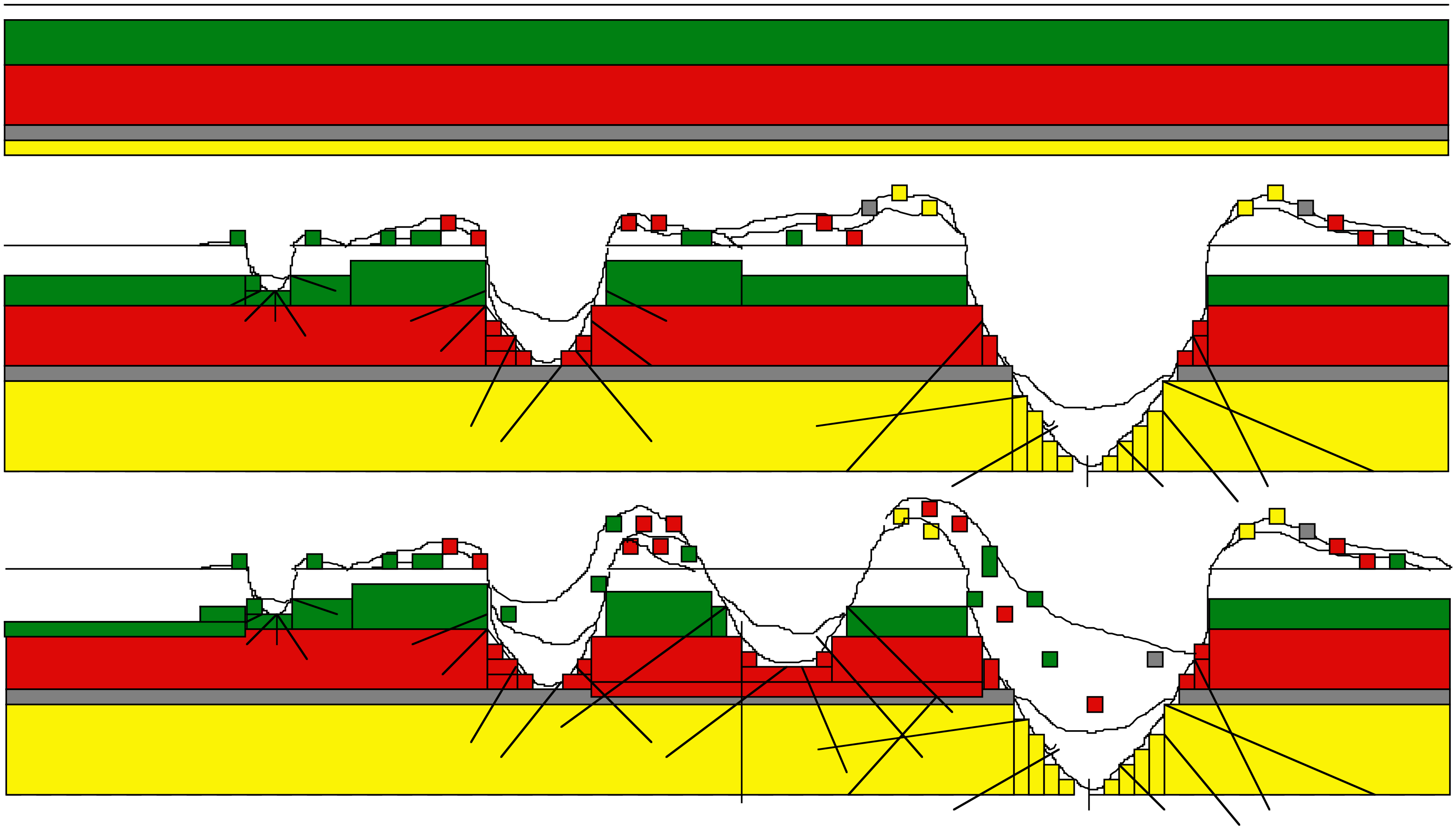
x Shoemaker, E.M., and co-workers, in *Surveyor Project Final Report*, Part II, JPL Technical Report 32-1265, NASA SP-146, 1968, pp 21-136.

xi Taylor, L. A., and co-workers, *Lunar and Planetary Science Conference 30*, Abstract #1885, 1999.

xii Noble, S. K., and co-workers, *Lunar and Planetary Science Conference 31*, Abstract #1810, 2000.

xiii Taylor, L. A., and co-workers, *Lunar and Planetary Science Conference 32*, Abstract #2196, 2001.

xiv see Heiken, G. H., and co-workers, *Lunar Sourcebook*, 1991, p 65-73.



SCHEMATIC REPRESENTATION OF THE FIRST FEW STAGES OF REGOLITH DEVELOPMENT.

(NONQUANTITATIVE VERTICAL EXAGGERATION)

(1) NOTE REVERSAL OF LAYERING SEQUENCE IN EJECTA OF NEW CRATERS, HOWEVER, MIXING OF EJECTA WILL BE RELATIVELY RAPID.
(2) NOTE ALSO THAT THE BASE OF THE REGOLITH IS AN IRREGULAR AGGREGATION OF THE FLOORS OF IMPACT CRATERS ON FRACTURED BEDROCK.