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A GLOSSARY OF TERMS RELATED TO CRATERING, SHOCK METAMORPHISM, AND LUNAR GEOLOGY

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A GLOSSARY OF TERMS RELATED TO CRATERING, SHOCK METAMORPHISM, AND LUNAR GEOLOGY

(Prepared for inclusion in the American Geological Institute *Glossary of Geology and Related Sciences*, revised edition)

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A GLOSSARY OF TERMS RELATED TO CRATERING AND SHOCK METAMORPHISM

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INTRODUCTION

The definitions here were compiled for inclusion in the forthcoming revised edition of the Glossary of Geology and Related Sciences being prepared by the American Geological Institute. The fields of shock metamorphism and cratering studies are relatively new, but their great importance to geological investigations of the earth and other planetary bodies has been impressively demonstrated in numerous studies of terrestrial meteorite impact structures (French, 1968) and by the shock-metamorphic features so strikingly displayed in the returned lunar samples (LSPET, 1969).

Some compilations of terminology in these areas already exist (e.g., Flanders and Sauer, 1960; Nordyke, 1962; Hansen et al., 1964; Fairbridge, 1967), and numerous articles on shock metamorphism have recently appeared (e.g., Short, 1966b; Chao, 1967a, 1967b; French and Short, 1968). However, no specific glossary or dictionary of terms in these new fields has as yet been compiled, particularly for the terms dealing with the striking and unique petrographic effects of shock metamorphism.

These definitions are intended to provide a useful collection for use, discussion, and possible modification by workers in these fields. They are not intended to be definitive, exhaustive, or final. Even in a new and fairly unpopulated field of research, different workers tend to develop and use different terms. I have attempted to construct definitions that correspond to current usage and understanding by most investigators in these fields, without attempting to seek unanimous agreement on any particular term. In several cases, meanings and usages differ significantly among different investigators, particularly for such terms as "planar features", "fallout breccia" et al. In such cases, I have added to the definitions themselves a commentary which I hope will illuminate the diversity without creating additional confusion.

Similarly, I have not attempted an exhaustive literature search to trace down the original sources of many terms, particularly those already in the geological lexicon which have acquired new meanings as a result of cratering and shock metamorphism studies (e.g., "kink band," "crater"). The references cited are intended to provide guides toward current usage of the terms rather than to provide rigorous original definitions.

Any attempt to construct a dictionary for a new field will tend to reflect in a small but unavoidable degree the personal usages and opinions of the compiler. The responsibility for the terms contained here is my own, and I hope that the usefulness of the compilation will exceed the problems caused by the unavoidable disagreements and uncertainties about the terms themselves. I am very grateful to F. Hörz, D.E. Gault, and N.M. Short, whose comments and criticisms helped remove a number of the more serious defects, and to Mary-Hill French for her criticism of the manuscript itself. I thank the American Geological Institute Glossary Revision Project, particularly C.E. Raley and R. McAfee, for their help and for permission to present these terms as a separate publication. I also thank my colleagues in advance for their anticipated comments, criticisms, and disagreements, since this interchange will be essential to improving the definitions presented here.

This glossary is a first and incomplete attempt to catalogue a field whose scope, importance, and activity are increasing at an incredible rate. If it is soon followed by more improved and comprehensive versions, it will have more than fulfilled its original intent.

GLOSSARY

allochthonous breccia: A fragmental unit composed of material ejected from an impact or explosion crater during formation and subsequently deposited in and around the resulting crater. In meteorite impact craters, such units contain numerous shock-metamorphosed rock fragments and may contain meteoritic material. In general geological usage, the term designates rocks composed of material that did not form in situ (= allogenic breccia) (see fallback breccia; fallout breccia; suevite) (Dence, 1964, p. 249).

allogenic breccia (= allochthonous breccia) (Shoemaker, 1963, p. 312).

apparent crater: The depression of an impact or explosion crater, as it appears after modification of the original shape by postformational processes such as slumping and deposition of material ejected during formation. The apparent diameter and apparent depth are measured using the highest points on the rim crest and the deepest part of the observable depression (see true crater) (Nordyke, 1962, p. 3447; Baldwin, 1963, p. 128).

asterism: Elongation of Laue X-ray diffraction spots produced by stationary single crystals as a result of internal crystalline deformation. The size of the Laue spot is determined by the solid angle formed by the normals to any set of diffracting lattice planes. This angle increases with increasing crystal deformation, producing progressively elongated (= asterated) spots. Asterism measurements are used as indicators of deformation in crystals subjected to slow stress or to shock wave action (Guinier, 1952, p. 192-194; Dachille et al., 1968, p. 559; Hörz and Ahrens, 1969).

astrobleme: (Gk. = star-wound) An ancient scar on the earth's surface caused by the impact of a cosmic body; an eroded or "fossil" meteorite crater. The structure is usually circular and its rocks are highly disturbed and show evidence of intense shock. The term is generally applied to structures of great age in which any associated meteorite fragments have been destroyed (= fossil meteorite crater) (see cryptoexplosion structure) (Dietz, 1961, p. 53).

astrogeology: A general term for a field of research characterized by the use of geological, geochemical, and geophysical methods to study the nature, origin, and history of the condensed matter in the solar system, particularly of bodies other than the earth. The field includes. (1) remote sensing observations and in situ manned exploration of other planetary bodies (the moon, Mars); (2) the study of returned extraterrestrial material (lunar samples, meteorites); (3) investigation of the effects of extraterrestrial processes (meteorite impacts, solar energy changes, tides, etc.) on the earth in the present and past.

authigenic breccia (= autochthonous breccia) (Shoemaker, 1963, p. 311).

autochthonous breccia: A fragmental unit in an impact or explosion crater which is composed of shattered and brecciated material that was not ejected from its original position during crater formation. Such units generally occur in the crater walls and below the original crater floor. They are generally monomict, and their component fragments exhibit only minor rotation or translation (= authigenic breccia) (see rupture zone) (Dence, 1964, p. 249).

base surge: A ring-shaped basal cloud that sweeps outward as a density flow from the base of a vertical explosion column accompanying volcanic eruption or the formation of a crater by explosion or hypervelocity impact. "This horizontally moving cloud has an initial velocity of more than 50 meters per second and can carry clastic material many kilometers," to form distinctive bedded dune-shaped or blanket-like base surge deposits (Moore, 1967, p. 337-338; Fisher and Waters, 1969, p. 1349).

blast: "The violent effect produced in the vicinity of an explosion that consists of a wave of increased atmospheric pressure followed by a wave of decreased atmospheric pressure" (Gove, 1967, p. 230).

blast wave: "A sharply defined wave of increased pressure rapidly propagated through a surrounding medium from a center of detonation or similar disturbance" (Baker et al., 1966, p. 22).

central peak: In large craters, a central area that is topographically higher than the surrounding crater floor, commonly observed in lunar craters. In terrestrial impact and explosion craters, a central peak may form by uplift of material originally below the crater floor as part of the crater formation process.

central uplift: A central high area produced in impact and explosion craters by inward and upward movement of material below the crater floor. Formation occurs during the crater-forming event at a relatively late stage and apparently is not due to long-term slow isostatic adjustment. Central uplifts are characteristic of many cryptoexplosion structures believed produced by meteorite impact (see cryptoexplosion structure; central peak) (Bucher, 1936, p. 1055; Dence, 1968, p. 180; Wilshire and Howard, 1968, p. 258).

(NOTE: As used here, the term central peak refers to surface topography and implies no specific mechanism of origin. A central peak may form by volcanic processes or by transport of slump blocks from the rim as well as by central uplift. The term central uplift implies both

a specific mechanism of formation and a specific structural arrangement in and beneath the crater, i.e., the rocks now found in the central uplift were located deep beneath the original crater floor at the time of impact.)

coesite: A monoclinic high-pressure polymorph of SiO_2, produced at static pressures above about 35 kb and found naturally in shock-metamorphosed quartz-bearing rocks associated with definite and probable meteorite impact craters (Meteor Crater, Arizona; Wabar, Arabia; Ries basin, Germany). Its occurrence in such near-surface rocks indicates high-pressure shock-wave action and provides a criterion for meteorite impact (see stishovite) (Frondel, 1962, p. 310-316).

complex crater: A meteorite impact crater of large diameter and relatively shallow depth, characterized by formation of a central uplift and a peripheral ring depression which apparently develop during the late stages of the crater-forming event as a result of yielding of rock beneath the crater (see simple crater; central uplift) (Dence, 1968, p. 182).

crater: A topographic depression, formed by the explosive release of volcanic, chemical, or kinetic energy, generally of considerable size, and typically bowl-shaped with steep slopes (AGI, 1957; p. 67).

crater, explosion (= explosion crater): (1) A volcanic crater formed by violent explosion commonly developed along rift zones on the flanks of large volcanoes and occasionally at the summit of volcanoes. Distinguished from ordinary craters at the top of volcanoes and from pit craters, which are produced largely by collapse. The term explosion pit is synonymous (AGI, 1957, p. 102); (2) A crater produced experimentally by detonation of nuclear or chemical explosive (Nordyke, 1962, p. 3439).

crater, volcanic: (= volcanic crater): A steep-walled depression at the top of a volcanic cone or on the flanks of a volcano, directly above a pipe or vent that feeds the volcano and out of which volcanic materials are ejected. In its simplest form, usually a flat-bottomed or pointed inverted cone more or less circular in plan. The diameter of the floor is seldom over 1000 feet; the depth may be as much as several hundred feet. Primarily the result of explosions or collapse at the top of a volcanic conduit (AGI, 1957, p. 67).

crater, meteorite impact (= meteorite impact crater): A crater formed by impact of a meteorite onto a surface. On the earth, small meteorites are retarded by the atmosphere and strike at low velocities to form penetration structures, while larger meteorites strike at their original geocentric velocities, releasing their kinetic energy as shock waves and forming larger structures (see penetration funnel; hypervelocity impact).

crater, impact (= impact crater): A crater formed on a surface by the impact of an unspecified terrestrial or extraterrestrial projectile. Particularly applied to structures where the nature of the extraterrestrial body (meteorite, asteroid, comet, etc.) is not known (see crater, meteorite impact; hypervelocity impact).

(NOTE: The term meteorite impact crater is rather broadly used to include structures of great size and age for which there is no direct evidence as to the nature of the impacting body.

Further, there is no definite distinction in size between meteorites and larger bodies of asteroidal dimensions (several miles in diameter) presumed to have formed the larger terrestrial structures, and there is debate as to whether such structures have formed by asteroidal or cometary impact. The term impact crater has no connotations about either the nature of the impacting body or the velocity of impact. The term hypervelocity impact crater implies no particular type of body but is restricted to structures formed at impact velocities high enough to cause extensive shock-wave production.)

crater d: The maximum depth of a crater, measured from the deepest point of the depression to the original ground level (Flanders and Sauer, 1960, p.5).

crater fill: A term for all material deposited within an impact or explosion crater at any time after formation, including fallback breccia, slump and talus deposits, and later sediments.

crater radius: The average radius of a crater, measured at the level corresponding to the original ground surface (Flanders and Sauer, 1960, p.6).

cratering: The process or mechanism of crater formation. (1) The dynamic process of formation of an individual crater. (2) The process of modification of a planetary surface by continuous or repeated crater formation (Gault et al., 1968, p. 87).

cryptoexplosion structure: A nongenetic term designating a structure formed by the sudden release of energy and exhibiting intense, often localized, rock deformation with no obvious relation to volcanic or tectonic activity. The structures typically exhibit some or all of the following: (1) an approximately circular outline; (2) wide variation in diameter (from less than one mile to more than 30 miles); (3) a central dome-shaped uplift with intense structural deformation, often surrounded by a concentric ring depression; (4) complex faulting and subordinate folding; (5) widespread brecciation and shearing; (6) occurrence of shatter cones. Many of the structures are believed to be the result of meteorite impact. The term, as presently used, largely replaces the earlier term, cryptovolcanic structure (see cryptovolcanic structure; astrobleme) (Dietz, 1959, p. 496-497; Bucher, 1963, p. 599).

crytovolcanic structure: (1) A term originally applied to highly deformed, generally circular structures believed to have been produced by volcanic explosions but lacking any direct evidence of volcanic activity (type example: Steinheim Basin, Germany). Many of these structures are now believed to have formed by meteorite impact, and the nongenetic term cryptoexplosion structure is used instead. (2) A circular structure lacking evidence of shock metamorphism or of meteorite impact origin and therefore presumed to be of internal origin, but lacking exposed igneous rocks or other obvious volcanic features (e.g., Richat, Maruitania) (see cryptoexplosion structure).

deformation lamellae: Planes of finite width formed in minerals, notably quartz, produced by active slip within mineral grains during tectonic deformation. They occur naturally in metamorphic quartz and have also been produced in static experiments. The term has sometimes been applied to similar features of presumed shock origin (see planar features) (Christie and Raleigh, 1959; Carter, 1965, p. 786).

diaplectic (from Gk. diaplesso = to destroy by beating or striking): A term designating "all products produced by shock waves in such a way that the characteristics of the liquid state are lacking. The term diaplectic minerals thus applies to all disordered and deformed mineral crystals modified by shock waves without melting. . . Diaplectic glasses (of quartz, feldspar, or other minerals) are amorphous phases produced by shock waves without melting. . . [They] represent intermediate stages of structural order between the crystalline and the normal glassy phases." (see thetomorphic) (Engelhardt and Stöffler, 1968, p. 163).

ejecta: (1) Material thrown out of a volcano or volcanic structure, e.g., lapilli, ash, bombs (AGI, 1957, p. 93); (2) Material thrown out of an explosion or impact crater, particularly glass and shock-metamorphosed rock fragments. Such material forms an ejecta blanket around the crater and may be deposited in distinctive patterns such as ejecta rays and ejecta loops (see ejecta blanket; fallback breccia; fallout breccia) (Shoemaker, 1962, p. 325; Milton and Michel, 1965, p. 5-11).

ejecta blanket: The deposit surrounding an impact or explosion crater formed by material ejected from the crater during formation, including base surge deposits, throwout, fallout breccia, etc. (Shoemaker, 1962).

fallback: In crater formation studies, a term which designates "material fallen inside the true crater and includes: (1) slide blocks; (2) breccia and stratified fallback—ballistic trajectory; (3) dust—aerosol transport; (4) talus, etc." (Hansen et al., 1964, p. 773).

fallback breccia: A unit composed of fragmental material ejected from an impact or explosion crater during formation and deposited within the crater almost immediately afterwards.

fallout: "A term applied to both the process of deposition of solid material on the earth's surface and to the deposited material itself. It may be used in such a sense as to signify only 'dry deposition' (mainly the result of gravitational settling); in such a sense it is used in contrast to the term washout. The term fallout is, however, used mainly in respect to the radioactive debris which is associated with a nuclear explosion." (McIntosh, 1963, p. 93).

fallout breccia: A fragmental deposit produced around explosion or impact craters by deposition of material ejected from the crater during formation. The material may have undergone extensive atmospheric sorting before deposition. The deposit is characteristically a "multiple-rock type breccia that contains small amounts of glass fragments and a limited range of fragment sizes" (see allochthonous breccia; suevite) (Chao, 1968, p. 136, 139).

(NOTE: There is considerable overlap and confusion in the terms applied to material removed from impact and explosion craters and the deposits formed from it. One set of terms is a horizontal classification derived chiefly from experimental studies, in which deposits are defined on the basis of location with respect to the crater. Other terms, which derive generally from geological and petrographic studies of the deposits, have vertical (stratigraphic) connotations which reflect relatively different histories and different times of deposition of separate units.

As used here, ejecta designates all material removed from a crater during formation which may be redeposited in response to gravity and (on the earth) atmospheric effects. The deposition of such material occurs almost immediately after formation of the crater before the normal processes of erosion and sedimentation have a significant effect on the newly-formed crater. Ejecta is divided into two types on the basis of horizontal location: fallback designates ejected material which falls within the crater, and throwout designates ejected material deposited outside of the crater rim. The term ejecta blanket includes all deposits formed by throwout. Deposits within the crater, made of fallback, are called fallback breccia or the fallback breccia lens (or breccia lens). The term crater fill refers to all material found in the presently exposed crater, including fallback breccia, but also including slump and talus deposits, later sediments and alluvium, etc.

The presence of an atmosphere strongly affects the behavior of ejecta from terrestrial impact and explosion craters. The term fallout breccia is strictly applied to deposits formed by throwout outside the crater. However, the terrestrial rocks so designated show such conspicuous atmospheric effects (sorting, aerodynamic sculpturing of glassy fragments) that the term fallout breccia is often used to imply the presence of observable atmospheric effects as well as location outside of the crater. Such terrestrial fallout breccias are usually finer-grained and richer in glassy fragments than other ejecta units. They are usually the last ejecta units to be deposited as part of the crater-forming process itself, before normal erosional effects become dominant in affecting the crater and its surroundings.)

Fladen (= Flädle; Germ. for "pancake"): (1) A local term for individual bodies resembling volcanic bombs and composed of mixtures of glass and rock and mineral fragments, found in the suevite breccias at the Ries basin, Germany. The bodies have distinctive, generally flat, shapes and exhibit flow structure and surface sculpturing apparently produced by aerodynamic forces; (2) Any similar glass-rich, aerodynamically shaped body, formed by meteorite impact, and found associated with other meteorite impact structures (see suevite; impactite) (Hörz, 1965, p. 621; Engelhardt and Stöffler, 1968, p. 166).

fossil meteorite crater: An ancient, deeply eroded, meteorite impact structure (= astrobleme) (Beals et al., 1963, p. 253).

horsetailing: A feathery or frondlike structure produced on the surfaces of shatter-coned rocks by the distinctive striations which radiate from the apex of each shatter cone and extend along its length. The presence of multiple nested and parasitic shatter cones produces a distinctive horsetail-like effect (see shatter cone) (Manton, 1965, p. 1020-1021; Dietz, 1968, p. 268).

Hugoniot (= Hugoniot curve, Rankine-Hugoniot curve): "The locus of pressure-volume-energy states that may be achieved within the material by shocking it from a given initial state. If the initial state is the standard laboratory state (25° C and 1 atm), the curve is called the principal Hugoniot" (Ahrens and Rosenberg, 1968, p. 59).

(NOTE: Pressure, specific volume, internal energy, particle velocity, and shock velocity are five variables describing the "equation of state" of any given material under shock. From

the requirement that mass, momentum, and energy are conserved across the shock front, the Rankine-Hugoniot relations are derived. These equations allow all five parameters to be calculated if two are known. Combining the Rankine-Hugoniot relations with the equation of state of a material allows specification of all five parameters if only one is known. A graphical presentation of the relation between pressure and specific volume for any material is generally known as the Hugoniot curve, although similar graphs using the other parameters are equally valid. The term is also used more generally as "Hugoniot experiments," "Hugoniot work," etc. for any equation-of-state investigations involving shock-wave generation (Duvall, 1961, p. 171-172; 1968, p.24).

hydrodynamic "jetting": Directional ejection of molten or vaporized material at very high velocities as a result of shock-wave interactions at the interface between projectile and target in the early stages of hypervelocity impact. Such a process may operate to form tektites by meteorite impact (Gault et al., 1968, p. 90).

hypervelocity impact: The impact of a projectile onto a surface at a velocity such that the stress waves produced upon contact (peak stress waves) are orders of magnitude greater than the static bulk compressive strength of the target material. The minimum required impact velocities vary for different target and projectile materials, but are generally 1-10 km/sec, and about 4-5 km/sec for most crystalline rocks. In such an impact, the kinetic energy of the projectile is transferred to the target medium in the form of intense shock waves whose interactions with the surface produce a crater much larger in diameter than the projectile. Meteorites striking the earth at speeds in excess of about 5 km/sec are examples of large hypervelocity impacts and produce correspondingly large craters (Dietz, 1959, p. 499; Gault et al., 1968, p. 87).

impact: "A forceful contact, collision, or onset; the degree or concentration of force in a collision (Gove, 1967, p. 1131).

impact bomb: (see Fladen; impactite).

impact glass (= impactite glass) : (see impactite).

impactite: (1) Vesicular glassy to finely-crystalline material produced by fusion of target rock during a meteorite impact, ejection during crater formation, and deposition in and around the resulting crater, typically as individual bodies composed of mixtures of melt and rock fragments, often with traces of meteoritic material. Some bodies show flow structures and aerodynamic sculpturing produced during their passage through the atmosphere (impactite bombs) (see Fladen) (Nininger, 1954, p. 277). (2) (Incorrect) Any shock-metamorphosed rock.

impact lava: (see impact melt).

impact melt: Molten material produced by fusion of target rock during a meteorite impact and emplaced in and around the resulting crater as: (1) discrete partly - to completely- crystalline dike- and sill-like bodies; (2) the matrix of fragmental breccias; (3) discrete fragments ejected from the crater (Dence, 1968, p. 172; French, 1969, p. 6); the term impact lava is equivalent (Beals, 1965, p. 908-910).

impact metamorphism: A field of geology which "describes the changes in minerals and rocks resulting from the hypervelocity impact of a body such as a meteorite," Equivalent to the term shock metamorphism, except restricted to changes caused by shock waves produced naturally by meteorite impact (Chao, 1967b, p. 192).

impact slag: (see impactite).

impact structure: A generally circular or crateriform structure produced by impact (usually extraterrestrial) on a planetary surface. Neither degree of erosion of the structure nor the nature and impact velocity of the impacting body are specified (see astrobleme; crater, meteorite impact).

injection breccia: A fragmental rock formed by the introduction of largely foreign rock fragments into veins and fractures in the host rock by a process such as igneous intrusion, gas fluidization, or shock-wave action. Some examples, notably the Sudbury breccias at Sudbury, Ontario, Canada, are associated with structures of probable meteorite impact origin and may have formed as a result of the impact process itself (Speers, 1957, p. 497).

isotropization: The solid-state conversion of a mineral such as quartz or feldspar into an isotropic phase at temperatures below its normal melting point, as a result of the destruction of the crystallinity by shock-wave action, neutron bombardment, etc. (see diaplectic; thetomorphic) (Short, 1966b, p. 160).

kink-band: A thin band or plate, in a crystal or foliated rock, transverse to the foliation, bounded by the subparallel axial surfaces of a pair of angular folds of opposite sense. Kink-bands in micas may form during normal metamorphism and are also common products of shock-wave action (Cummings, 1968, p. 211; Anderson, 1969, p. 201; Hörz and Ahrens, 1969, p. 1213).

lechatelierite: Natural glass close to pure silica in composition, formed by the high-temperature fusion of quartz or siliceous materials by lightning strikes or by meteorite impact (see also impactite) (Frondel, 1962, p. 325).

lip height (= rim height): "The height above the surface to which the earth is piled around the crater formed by an explosion" (Flanders and Sauer, 1960, p. 13). Also, the maximum height of the crater rim above the original ground surface.

maskelynite: An isotropic or nearly isotropic phase exhibiting the composition and morphology of plagioclase feldspar, found in some meteorites (e.g., Shergotty) and in terrestrial shock-metamorphosed rocks, and generally regarded as the product of shock-wave action on original plagioclase (Bunch et al., 1967, p. 244).

(NOTE: The material was first described and named from the Shergotty meteorite (Tschermak, 1872; and it was originally interpreted as a possible fusion product. It has recently been produced experimentally by high-pressure shock-wave experiments on plagioclase and has been identified in several terrestrial impact structures.)

meteor crater (= meteorite crater): (see crater, meteorite impact or meteorite impact crater).

penetration funnel: An impact crater formed at relatively low velocity, generally funnel-shaped and containing nearly all the impacting mass within it (Cassidy, 1968, p. 117).

planar features (= shock lamellae, planar elements): Distinctive, multiple, closely-spaced, parallel planes a few microns or less in width, which occur in shock-metamorphosed minerals (particularly quartz) and which are regarded as unique and important indicators of shock metamorphism. They are characteristically multiple (often more than five distinct sets per grain) and are oriented parallel to specific planes in the host crystal lattice. They have been produced experimentally by shock pressures of about 80-250 kb. The related term planar structures is nongenetic and also includes structures of possible nonshock origin, e.g., cleavage, deformation lamellae (Robertson et al., 1968, p. 433; Engelhardt and Bertsch, 1969, p. 203).

(NOTE: Some confusion, by no means resolved at present, attends the use of the terms deformation lamellae, planar features, planar structures, planar elements, and shock lamellae. The term deformation lamellae (often called Böhm lamellae) has long been used for features developed in tectonically metamorphosed quartz. Carter (1965) suggested that the occurrence of deformation lamellae parallel to {0001} in quartz (basal deformation lamellae) in rocks from impact structures was an indicator of shock metamorphism and described the optical characteristics of these lamellae.

In the same article he described other structures in quartz which were multiple, oriented parallel to ω $\{10\bar{1}3\}$, and optically distinguishable from the deformation lamellae. These structures, given the nongenetic term planar features, were also suggested as shock-metamorphic criteria and presently constitute the most widely-used shock-metamorphic effect. (The term planar fractures was used briefly and then discarded when it became evident that the features in question were not open cracks but definite lamellae of a phase with different properties than the host quartz.) The shock-metamorphic origin of planar features has since become widely accepted because of their occurrence at known meteorite impact craters and their experimental production in shock-wave experiments, and the genetic term shock lamellae has been used interchangeably with planar features.

In present usage, the term planar structures is nongenetic and designates planiform structures in quartz and other minerals, regardless of origin. It includes cleavage, inclusion arrays, shock-induced planar features, etc. The term deformation lamellae is generally reserved for features produced during normal metamorphism where no shock-wave origin is implied, and whose optical characterisitics are well known (e.g., Christie and Raleigh, 1959; Carter, 1965, 1968). Basal deformation lamellae refers to similar features in a unique orientation which may result from shock-wave action (Carter, 1965, 1968). Planar features (= shock lamellae) designates shock-produced lamellar structures whose optical properties in fresh material are distinct from those of deformation lamellae (Carter, 1965, 1968); the term planar elements has also been applied to these shock-produced features (Engelhardt and Bertsch, 1969).

The exact mechanism of formation of planar features (= shock lamellae) by shock-wave action is not yet definitely established. It is also not yet possible to say whether low-pressure shock waves of a few tens of kb will form basal deformation lamellae while higher shock pressures produce the mechanically and optically distinct planar features. Until these uncertainties are resolved, some uncertainty in the terminology is unavoidable.)

pressure decay: "The decline, usually gradual, from a temporary, abnormal pressure condition, toward a normal pressure which is more nearly in balance with permanent or steady-state conditions" (W.H. Roberts, personal communication to AGI, 1968).

primary crater: (see true crater).

pseudotachylite: (1) A term applied to an unusual intrusive breccia found at the Vredefort structure, South Africa (Shand, 1916, p. 199). The type material is "a black rock externally resembling tachylite and occurring in irregularly branching veins. The material carries fragmental enclosures and shows evidence of having been at a high temperature; miarolitic and spherulitic crystallization took place in the extremely dense base. Pseodotachylite differs from flinty crush rock (q.v.) in its intrusive habit, and in the absence of any structures referable to local crushing" (Holmes, 1920). Virtually identical rocks are found at Sudbury, Ontario (Sudbury breccias; Speers, 1957). These rocks contain shock-metamorphic effects and may be injection breccias emplaced in fractures formed during a meteorite impact. (2) A dense rock produced in the compressive and shear conditions associated with intense and extensive fault movements, involving extreme mylonitization and/or partial melting; see also Flinty Crush Rock; Hartschiefer; Mylonite; Trap-shotten Gneiss; Ultramylonite (AGI, 1957, p. 235). Such fault movements may be associated with normal tectonism or with the formation of the central uplifts of large meteorite impact structures (Dence, 1968, p. 170).

(NOTE: At present, the term pseudotachylite is applied in three diverse senses: (1) curious intrusive breccias associated with probable impact structures (Shand, 1916; Speers, 1957); (2) highly sheared and partly melted rock produced during fault movements (mylonite and ultramylonite) with no relation to impact structures (AGI, 1957, p. 235); (3) similar sheared and melted rock produced in impact structures by movements connected with formation of the central uplift during crater formation (Dence, 1968, p. 170, 192).

The original pseudotachylite from the Vredefort structure, South Africa (Shand, 1916) is virtually identical to the Sudbury breccias from Sudbury, Ontaric, Canada (Speers, 1957). They conform to the definition of Holmes above and are clearly tensional in character as indicated by the netlike and pervasive intrusion into the wallrock, by the rotation of contained fragments, by the streaky flow structure occasionally observed, and by the lack of relative movement of the wallrock. At Sudbury, both inclusions in the breccias and the enclosing wall rock exhibit shock-metamorphic features. This material, which is the type pseudotachylite (Shand, 1916) is apparently an injection breccia composed of material introduced into fractures surrounding the crater at the time of impact, either by the shock-wave impulse or by transport by gas fluidization.

The subsequent application of the term to rocks produced by intense shearing associated with fault-plane movements, both in normal tectonic environments (AGI, 1957, p. 235) and in the substructure of impact craters (Dence, 1968, p. 170, 182) implies a distinctly different environment in which compression and shear forces are dominant. In using the term pseudotachylite it is necessary to keep the distinctions clear. In terms of priority, the term should be retained for the distinctive injection breccias associated with impact at Vredefort and elsewhere. In terms of present usage, it may be more practical to retain the term for rocks produced by extensive crushing and melting by compression and shear, and use the term injection breccia to designate the material from Vredefort, Sudbury, and other structures, for which a tensional environment is clearly indicated.)

release adiabat: A curve which defines the succession of states through which a mass element shocked to a high pressure state passes upon being monotonically returned to zero pressure. This process operates in times that are short compared with the characteristic time for heat flow in the material (see also Hugoniot) (Ahrens and Rosenberg, 1968, p. 59).

ring depression: The annular, structurally depressed area surrounding the central uplift of a cryptoexplosion structure (Bucher, 1936, p. 1055). This depression may in turn be surrounded outward "by other ring-shaped uplifts and depressions of rapidly diminishing amplitude, forming a 'damped-wave structure'" (Dietz, 1959, p. 496-497). Both faulting and folding may be involved in formation of the ring depression. The terms ring syncline and peripheral depression are equivalent.

ring syncline: (see ring depression).

rupture zone: "The zone immediately adjacent to the crater boundary in which the stresses produced by the explosion have exceeded the ultimate strength of the medium" (see also autochthonous breccia) (Flanders and Sauer, 1960, p. 19).

shatter cone: A distinctive striated conical surface along which fracturing has taken place, generally found as nested or composite groups in the rocks of cryptoexplosion structures, and generally believed to have been formed by shock waves generated by meteorite impact. "Shatter cones are striated cup-and-cone structures, most common in carbonate rocks, but also known from shale, sandstone, quartzite, granite, and other lithologies. The striated surfaces radiate from small parasitic horsetail-like half-cones on the face of the master cone—a pattern which serves to differentiate these structures from the parallel grooving of slickenslides. . .Shatter cones also have positive faces on the cone and negative faces on the cup. The apical angle varies but is close to 90 degrees" (Dietz, 1968, p. 268). Shatter cones are often associated with other shock-metamorphic effects indicative of meteorite impact (Dietz, 1959, p. 496; Manton, 1965, p. 1020-1021).

shatter cone segment: Part of an incompletely developed shatter cone, consisting of a single curved, striated surface, generally "10 to 45° of cross section, of cones with apical angles ranging from 90 to 120°" (Manton, 1965, p. 1021). Most shatter-coned rocks display only segments.

shatter coning: A mode of rock failure characterized by the development of shatter cones (Manton, 1965, p. 1021).

shock: "The impact of an earth vibration (as of an earthquake)" (Gove, 1967, p. 2099).

shock lamellae: (see planar features).

shock-lithification: The conversion of originally loose fragmental materials into coherent aggregates by the action of shock waves generated by explosions or meteorite impacts. The process apparently involves such mechanisms as fracturing, compaction, and intergranular melting (Short, 1966a, p. 382).

shock loading: The process of subjecting material to the action of high-pressure shock waves generated by artificial explosion or by meteorite impacts.

shock melting: Fusion of material as a result of the high temperatures produced by the action of high-pressure shock waves (see impact melt).

shock metamorphism: The production of permanent physical, chemical, mineralogical, and morphological changes in materials as a result of the passage of transient high-pressure shock waves. Characteric shock-metamorphic conditions involve extremely high pressures, short pressure pulse durations (unusually high stress and strain rates), and unusually high temperatures. Shock-metamorphic effects are characterized by selective mineralogical changes and by long-term preservation of physical and chemical disequilibrium as a result of rapid quenching. The only natural mechanism for producing shock-metamorphic effects is the hypervelocity impact of large meteorites, but the term also includes identical effects produced by shock waves generated in small-scale laboratory experiments and in nuclear and chemical explosions (French, 1966, p. 903; French, 1968, p. 2).

shock wave: "A compression wave formed whenever the speed of a body relative to a medium exceeds that at which the medium can transmit sound and characterized by a disturbed region of small but finite thickness within which very abrupt changes occur in the pressure, density, and velocity of the medium" (Gove, 1967, p. 2099).

shock zone: A volume of rock in or around an impact or explosion crater in which a distinctive shock-metamorphic deformation or transformation effect indicative of the zone is present (Dence, 1968, p. 170).

silica glass: (see lechatelierite).

simple crater: A meteorite impact crater of relatively small diameter, characterized by a uniformly concave-upward shape and a maximum depth in the center, and lacking a central uplift. Meteor Crater, Arizona is an example (see also complex crater) (Dence, 1968, p. 171).

spalling: "Chipping or fracturing of rock due to the interaction of a compression wave (shock) at a free surface" (Flanders and Sauer, 1960, p. 21).

stishovite: A tetragonal high-pressure polymorph of SiO_2, produced under static conditions at pressures above about 100 kb and found naturally only in shock-metamorphosed quartz-bearing

rocks (e.g., Meteor Crater, Arizona and the Ries basin, Germany). Its occurrence provides a criterion for meteorite impact. Stishovite forms at higher pressures than coesite and is apparently less stable at lower pressures after formation (see coesite) (Frondel, 1962, p. 317-318).

suevite: A depositional breccia associated with meteorite impact craters, which contains both shock-metamorphosed rock fragments and glassy inclusions. The latter occur typically as aerodynamically sculptured bombs. Suevite closely resembles volcanic tuff-breccias, but it can be distinguished by the presence of shock-metamorphic effects. The term, originally applied to material from the Ries basin, Germany, now designates similar deposits found at other impact structures (see allochthonous breccia; fallout breccia).

thetomorphic: (from Gk. thetos = adopted; morphe = form): A term applied to glassy phases formed by solid-state alteration of originally crystalline minerals by shock-wave action (Chao, 1967b, p. 211-212). A relatively high-pressure and low-temperature history is implied. The phases formed (thetomorphs), commonly of quartz and feldspar, retain such original textures as fractures, twin lamellae, and grain boundary shapes (see also diaplectic).

(NOTE: The related term diaplectic implies a shock-metamorphic history and is used as an adjective to designate materials displaying distinctive shock-metamorphic effects, e.g., diaplectic quartz (with planar features, lowered refractive indices, etc.), diaplectic feldspar, etc. The term diaplectic quartz glass is applied to quartz made isotropic by shock-wave action. The terms diaplectic quartz glass and thetomorphic quartz are thus equivalent and designate the same material. The terms thetomorphic and thetomorph are applied only to isotropic phases for which a shock history is presumed.)

throwout: "The material thrown out of a crater and deposited on the outside of the crater lip" (Flanders and Sauer, 1960, p. 23) (see also allochthonous breccia; fallback; fallout).

true crater: The primary depression formed by impact or explosion before modification by slumping or by deposition of ejected material. "The true crater is defined as the boundary between the loose, broken fallback material and the underlying material that has been crushed and fractured but has not experienced significant vertical displacement" (Nordyke, 1962, p. 3447) (see also apparent crater).

welded breccia: A fragmental rock containing a high proportion of originally molten material, deposited at high temperature at or near the ground surface, and converted by sintering and recrystallization during cooling into a tough compact rock which is strongly resistant to erosion and which may exhibit jointing and subconchoidal fracturing. Such units occur both in extrusive volcanic deposits (e.g., welded tuffs) and in meteorite impact craters. In impact craters, such units are generally found at or near the base of the breccia deposit within the crater, where welding is promoted by the insulating and compressive effects of the overlying fragmental ejecta (Dence et al., 1968, p. 353-354).

venting: "The escape through the earth to the atmosphere of gases or radioactive products from an underground high explosive or nuclear detonation" (Flanders and Sauer, 1960, p. 24).

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A GLOSSARY OF TERMS RELATED TO LUNAR GEOLOGY AND SURFACE FEATURES

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INTRODUCTION

The brief list of terms presented here is not intended to be exhaustive, but it will hopefully serve to describe some of the lunar features of present geological interest. More general references which discuss lunar nomenclature, geology, and surface processes in more detail are available (e.g., Spurr, 1944; Shoemaker, 1962; Green, 1965; Fielder, 1965; Hess et al., 1966; Fairbridge, 1967; McCauley, 1967; Kaula, 1968; Lowman, 1969; Mutch, 1970). The rapid expansion of knowledge about the moon in the last few years, including the results of the recent manned landings, makes it difficult to construct a glossary or encyclopedia which does not run the risk of being soon out of date. I hope that this list will be of use until a more extensive and detailed compilation can be made. I thank the American Geological Institute Glossary Revision Project, particularly C. F. Raley and R. McAfee, for their permission to present the terms here.

GLOSSARY

Cayley Formation: A unit of material with a relatively high albedo and mare-like topography, which occupies highland craters of pre-mare age (e.g., Ptolemaeus) and which is interpreted as pre-mare volcanic flows and pyroclastics.

crater chain (= chain craters): A series of relatively small, linearly aligned, lunar craters. Some are located along rills (e.g., Hyginus Rille). These craters are generally thought to be of internal (i.e., volcanic) origin and are perhaps analogous to maars. Crater chains are considered distinct from secondary craters, which sometimes occur in lines or arcs, but which are believed to form by impact of ejecta (see secondary crater).

dark halo crater: A crater surrounded by dark material, generally relatively small and sometimes (as in Alphonsus) aligned along rills. Some dark halo craters penetrate the ejecta blankets of ray craters such as Copernicus. Possible explanations for the origin of dark halo craters include volcanism or the penetration of a dark substratum by meteorite impact.

dimple crater: A small, nearly rimless crater, generally less than 200 m in size, characterized by inner walls that steepen toward the center, producing a deep, button-like center and a distinctive

dimple-like shadow. Proposed origins include: (1) collapse of the roofs of lava flow and tunnels; (2) drainage of fragmental material into sub-surface fissures or cavities; (3) postformational erosion of concentric meteorite impact craters by continuing subsequent meteorite impacts (Oberbeck, 1970).

dome (lunar): A term originally applied to telescopically resolvable, dome-shaped hills in mare regions, which frequently exhibit summit craters and are thought to be shield volcanoes; the Marius Hills are a good example. The term is now also applied to other similar elevations of possible volcanic origin which have been resolved with high-resolution orbital photography.

Fra Mauro Formation: A unit characterized by relatively high albedo, fairly hummocky topography, and arcuate distribution around Mare Imbrium. It is older than the mare material and is interpreted by the U.S. Geological Survey as ejecta from the Imbrium Basin, which is in turn considered to be a large impact crater (Hackman, 1966).

highland: (see terra)

Imbrian sculpture: A series of ridges and valleys radiating to the southeast and northeast from Mare Imbrium for distances of tens to hundreds of kilometers. The term was coined by G.K. Gilbert, who considered the sculpture to be gouges produced by fragments flying from the impact that he thought had formed the Imbrium Basin. An alternative theory favored by many modern astrogeologists is that the Imbrian sculpture consists of horst and graben structures formed when the Imbrium Basin was excavated by meteorite impact.

lunar grid: A term used by Spurr (1944) and Fielder (1965) to designate series of moon-wide fractures. Fielder considers that there are two distinguishable sets on the earthward face, in addition to regional sets of radiating fractures.

lunar transient phenomena (LTP): A term commonly applied to short-lived color changes, brightenings, flashes, and similar events observed telescopically or otherwise on the moon. The best-known example is the sighting of "red spots" near Aristarchus by Greenacre and Barr in 1963 (Cameron and Gilheany, 1967).

lunar varnish: A hypothetical substance coating subsurface lunar particles, suggested to explain the fact that the lunar subsoil is darker than the surface material (Rennilson et al., 1966).

mare (pl. maria): A dark, relatively level lunar plain, with a smaller number of large craters (larger than a kilometer or so in diameter) per unit area than the terrae (highlands). Some maria occupy well-defined, roughly circular basins (e.g., Mare Imbrium), while others, which have irregular boundaries, do not (e.g., Mare Tranquillitatis). Where investigated by manned landings, the maria have proven to be lava fields of basic to ultrabasic rock with crystallization ages of between 3 and 4 billion years, overlain by a fragmental regolith a few meters thick. Some highland areas with relatively high albedo also appear to be mare-like in topography (see terra).

mare basin: A circular or elliptical topographic depression of regional extent occupied at least partly by mare material. Not synonymous with mare, which term is generally applied only

to the areas of mare material itself. Mare basins cannot be clearly distinguished from large craters filled with mare material (e.g., Archimedes), and there appear to be all gradations between mare basins and craters. Examples of mare basins include the Imbrium, Crisium, and Orientale Basins (see mare).

mare material: A nongenetic term for the rock and soil underlying the surface of the maria. The material is now known from two areas to be heavily-impacted volcanic rock with ages of several billion years. Some relatively high-albedo areas, such as the floor of Ptolemaeus, may also be mare material whose albedo has increased with age. Some parts of the terrae (highlands) may also be underlain by old mare material (see mare, mare basin, terra).

mare ridge (= wrinkle ridge): A two-sided linear hill on a mare surface. Mare ridges frequently occur in chains or linear groups that may be several hundred kilometers long and a few hundred meters high. Theories proposed for their origin include: (1) as pressure ridges on lava flows; (2) as anticlines; (3) by intrusion or extrusion of lava, with the ridges marking the vents from which the mare lavas were erupted.

mare scarp: A local steepening of grade on a mare surface, possibly the expression of an underlying fault or the front of a lava flow.

mascon: Contraction of "mass concentration"; a term coined by Muller and Sjogren for high density bodies suggested by them as responsible for the positive gravity anomalies which they discovered existing over circular maria, using analysis of the orbits of lunar orbiting spacecraft. Theories as to the origin of mascons include: (1) buried asteroidal or meteoritic bodies; (2) unusually dense mare rocks; (3) intrusions of dense subcrustal rock beneath the maria (Muller and Sjogren, 1968).

patterned flow: A structured surface which consists of irregular low hills and depressions, marked with low linear grooves and ridges. The type area, north of the crater Tycho, on which Surveyor VII landed, is interpreted as having been formed by the ejection of extremely viscous impact melt from Tycho (Shoemaker et al., 1968).

patterned ground (lunar): A surface characterized by parallel ridges and grooves, frequently with lengths of several meters, on the lunar surface. The precise nature of such a surface is not known, but parallelism of the ridges and grooves with regional structures suggests that they may be lines along which fine-grained material has sifted down into underlying joints in the bedrock (Heacock et al., 1966).

playa (lunar) (synonymous with "lakes," "ponds"): Relatively small (up to a few kilometers in size) enclosed basins located on the flanks and inner walls of large lunar ray craters (e.g., Tycho) and filled with mare-like material. Two explanations have been proposed for the origin: (1) accumulation of impact melt in low spots shortly after formation of the main crater; (2) eruption of lavas through fractures around the crater.

Procellarum group: A collective mapping unit in U.S. Geological Survey lunar stratigraphic nomenclature that includes mare lavas and mare domes (Hackman, 1966).

ray, ray system (lunar): Light-toned streaks radiating from lunar craters and visible at high sun angles. Some rays are of regional extent, extending several hundred kilometers in extreme cases. The rays are known to fade with time, since craters without rays are invariably much more eroded and more heavily impacted than are ray craters. Clusters of satellitic (secondary) craters are frequently found along rays, indicating that the rays may be composed of light material excavated from the craters. The rays may also consist partly of finely-divided ejecta from the main crater. Typical ray craters are Tycho and Copernicus.

ray crater: A lunar crater with visible rays; synonymous with Copernican crater in the U.S. Geological Survey lunar stratigraphic nomenclature. Rays appear to fade with time, implying that ray craters are relatively young (see ray).

regolith (lunar): The unconsolidated fragmental layer covering most of the moon's surface, except for very recent features, to a depth of several meters in most places. It is believed to have formed over long periods of time (i.e., post-mare in age) by a combination of meteoritic and secondary ejecta impact and mass wasting. The regolith consists of a complex mixture of rock fragments, breccia, glass, shock-metamorphosed materials, a minor meteoritic component, and possibly volcanic ash. The regolith on the maria is relatively thin (probably less than 100 m) and apparently overlies harder bedrock such as lava flows. On the terrae the fragmental material overlying bedrock is probably much thicker (about 1 km) and largely pre-mare in age.

rill (alternate spelling rille): A valley-like depression in the lunar surface. Rills range in length from a few kilometers to over 200 km in length, and in width from a few meters to 4 km. They are typically a few tens of meters to a hundred meters deep. Most rills are relatively straight and are called "normal" rills; they are generally considered as fault-bounded depressions which have evidently localized volcanic activity in the form of chain craters in some localities (e.g., Hyginus Rille). "Sinuous" rills, which are much less common, have winding courses superficially resembling meandering streams. Their origin has been variously attributed to: (1) lava drainage; (2) erosion by running water; (3) erosion by volcanic ashflows (nuées ardentes); (4) subsidence, sometimes accompanied by maar eruptions, along lines controlled by complex subsurface fracture patterns (Cameron, 1967).

ring-structure (lunar): A collective term (e.g., Fielder, 1965) for a wide variety of lunar craters and basins of varying morphology, size, and age.

satellitic crater (= secondary crater): A relatively small, circular or elliptical crater formed by the low-velocity impact of fragments ejected during the formation of a larger crater. Such craters range in size from a few kilometers down to less than a meter in diameter and typically form a halo around the larger (primary) crater.

secondary crater: (= satellitic crater).

Sulpicius Gallus Formation: A unit of relatively thin material with low albedo, blanketing both mare and terra near Mare Serenitatis and Copernicus. The unit is interpreted as pyroclastic deposits, possibly with some lava flows, of similar age as the mare lavas (Carr, 1966).

terra (pl. terrae) (= highlands, uplands): The part of the moon's surface characterized by: (1) relatively high albedo; (2) greater elevations than adjacent maria; (3) greater number of larger craters (over a kilometer or so in diameter) than adjacent maria. Typical terrae are found in the southern part of the earthward face; most of the far side is terra. These parts of the moon are thought to be a complex of overlapping impact craters with a superficial fragmental breccia layer more than a kilometer thick, together with volcanic rocks and landforms. The terrae are apparently in isostatic adjustment on a regional scale. The high crater density indicates that the terrae are older than the maria, and for this reason the terrae may be, in part, the primordial lunar crust, in which the oldest craters may represent the last stages of the moon's accretion from planetesimals (see mare).

thalassoid: A term proposed by Russian scientists for large lunar basins similar to those occupied by circular maria, but which contain little or no mare material. The best example is the basin partly occupied by Mare Nectaris and bounded on the west by the Altai scarp; others are found on the far side of the moon (Walter and Lowman, 1967, p. 326).

Vitello Formation: hilly terrain with moderate albedo (0.075 to 0.085) surrounding Mare Humorum and interpreted as ejecta from the Humorum basin, which is considered to be a large impact crater (Trask and Titley, 1966).

wrinkle ridge: (= mare ridge).

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