11. Impactites

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Introduction

A Study Group, under the leadership of D. Stöffler (Berlin) has formulated this proposal for the classification and nomenclature of impactites. The following scientists have participated actively in the Study Group: W. von Engelhardt (Tübingen), V. I. Feldman (Moscow), F. Hörz (Houston), K. Keil (Honolulu), and R. A. F. Grieve (Ottawa). Contributions were also made by B. M. French (Washington) and W. U. Reimold (Johannesburg). After having evaluated proposals by the members of the Study Group and by scientists working with impactites, this work presents a classification and nomenclature of such rocks.

Classification

The term 'impactite' is a collective term for all rocks affected by one or more hypervelocity impact(s) resulting from collision(s) of planetary bodies. A classification scheme is proposed for products of single and multiple impacts (Table 11.1). It is applicable to terrestrial and extraterrestrial rocks, such as lunar rocks and meteorites of asteroidal, lunar, and Martian provenance. The basic classification criteria are based on texture, degree of shock metamorphism, and lithological components. Shock metamorphism is the irreversible changes in (geologic) materials resulting from the passage of a shock wave (Fig. 11.1). Additional criteria for a subclassification of the main types of impactites relate to the mode of occurrence with respect to the parent impact crater and to the geological or structural setting of the impactites (Fig. 11.2, Table 11.2). The proposed classification has made use of previous recommendations (Stöffler et al., 1979, 1980; Stöffler & Grieve, 1994, 1996).

Impactites from a single impact are classified into 3 major groups (Table 11.1) irrespective of their geological setting which is not known for most extraterrestrial rocks such as meteorites and lunar rocks:

Shocked rocks are defined as non-brecciated rocks, which show unequivocal effects of shock metamorphism, exclusive of whole rock melting. They are subclassified into progressive stages of shock metamorphism (Tables 11.3 to 11.7);

Impact melt rocks are subdivided into three subgroups, according to the content of clasts. These three subtypes may be subclassified according to the degree of crystallinity into glassy, hypocrystalline, and holocrystalline varieties. The first two subtypes include 'impact glass' as well as 'tektites';

Impact breccias fall into three subgroups, according to the degree of mixing of various target lithologies and their content of melt particles. *Lithic breccias* and *suevites* are generally polymict breccias except for single lithology targets. The matrix of lithic breccias is truly clastic and consists exclusively of lithic and mineral clasts whereas the matrix of suevite additionally contains melt particles and may therefore be better called *particulate matrix.* This primary matrix of suevite may be altered by secondary (mostly hydrothermal) processes.

Impactites from multiple impacts, as known from the Moon and from meteorites, as samples of the meteorite parent bodies, are subdivided into two main groups (Table 11.1):

Impact regolith (unconsolidated clastic impact debris), and;

Shock lithified impact regolith (consolidated clastic impact debris). This group is subclassified into *Regolith breccias* (with matrix melt and melt particles) and *Lithic breccias* (without matrix melt and melt particles)**.** The term lithic breccia is synonymous with 'fragmental breccia' which has been used for lunar rocks and meteorites (Stöffler et al., 1980; Bischoff & Stöffler, 1992). Note that the matrix melt is formed in situ by intergranular melting induced by the shock lithification process (Table 11.7).

Irrespective of the geological setting of a specific rock type *progressive stages of shock metamorphism* (Stöffler, 1966, 1971; Chao, 1967; Tables 11.3 to 11.7) can be identified in all target rocks affected by the shock wave. They are defined on the basis of shock effects of the constituent minerals and of the shock-induced changes of the primary rock texture. The definition of progressive stages of shock metamorphism depends on the mineralogical composition and on the primary texture (e.g. porosity) of the material shocked. Therefore, the shock classification is different for different lithologies. Since quartz, plagioclase, and olivine (Chao, 1967; Stöffler, 1972, 1974; Stöffler et al., 1991; Stöffler & Langenhorst, 1994; French, 1998) are the most sensitive shock indicators, separate classification schemes have been proposed for quartzofeldspathic rocks (Table 11.3), basaltic-gabbroic rocks (Table 11.4), dunitic and chondritic rocks (Table 11.5), sandstone (Table 11.6), and particulate rock material, for example,. sand and regolith (Table 11.7). Shock metamorphism of carbonates and shales is difficult to recognise on a macroscopic and microscopic scale and reasonable classifications have not yet been established.

Discussion

The process which results in the formation of impactites is related to the interplanetary collisions that all planetary bodies have undergone since their formation. The term '*impact*' or more correctly '*hypervelocity impact*' is defined as the collision of two (planetary) bodies at or near cosmic velocity, which causes the propagation of a shock wave in both the impactor and target body (Melosh, 1989). A shock wave is a compressional wave with material transport (whereas seismic waves are compressional waves without material transport). It can be defined as a step-like discontinuity in pressure, density, particle velocity, and internal energy, which propagates in gaseous, liquid or solid matter with supersonic velocity. Shock compression is non-isentropic and results in the production of post-shock heat (waste heat), which increases with increasing pressure and eventually results in the melting or vaporisation of the shocked material (Duvall & Fowles, 1963; Asay & Shahinpoor, 1993; Graham, 1993).

The material engulfed by the shock wave is affected by what is collectively called *impact metamorphi*sm. Impact metamorphism should be applied only for natural rocks and minerals and it includes solid state deformation, melting and vaporisation of the target rock(s) and their constituents minerals. The term *shock metamorphism* is a more general term that can be used irrespective of the process which generates a shock wave: Natural impacts or artificial hypervelocity impacts or explosions of chemical or nuclear explosive devices (French & Short, 1968; Stöffler, 1972, 1974, 1984; Roddy et al., 1977; French, 1998). Unequivocal residual shock effects in minerals of shocked rocks are generally formed above the so-called Hugoniot elastic limit (HEL), which is in the order of several GPa for silicate minerals. Consequently, the typical range of shock pressures resulting in remanent or residual shock effects is between 5 and 100 GPa for solid state effects and melting, and above 100 GPa for vaporisation. Typical maximum pressures and temperatures at the point of impact are in the order of several 100 GPa or greater and several tens of thousands degrees for all impacts within the inner solar system (terrestrial planets).

Impactites are formed during a complex but very short sequence of processes: Shock compression of the target rocks (compression stage), decompression and material transport (excavation stage), and deposition upon ballistic transport and upon collapse of the central ejecta plume which takes place during or after the collapse of the transient crater cavity (modification stage) (Fig. 11.1). Consequently, shock metamorphosed material (shocked rocks and impact melts) commonly displays disequilibrium and can be mixed with unshocked lithic and mineral fragments forming polymict breccias in and around the parent crater: *layered* impact formations, such as *impact melt rocks* or *impact breccias*, and *dyke breccias,* which both occur inside the crater and as part of the continuous ejecta blanket extending some 2 to 3 crater radii (proximal impactites) and continuous *airfall beds* or discontinuous ejecta deposits, such as *tektites* (distal impactites) (Table 11.2). The geological setting of shocked rocks or impact melts is, therefore, variable (Fig. 11.2). *Impact melt lithologies* occur as (1) allochthonous coherent melt sheets, (2) inclusions in polymict impact breccias (suevite), (3) dykes and veins in the autochthonous crater basement, in displaced shocked rock fragments and in displaced (unshocked) megablocks, (4) individual melt particles on top of the ejecta blanket, glassy or crystallised spheres in global air fall beds, and (5) glassy tektites. *Shocked minerals and rocks* are found as allochthonous clasts within polymict

impact breccias, impact melt rocks and air fall beds and as (par)autochthonous material of the crater basement. *Monomict breccias* formed during shock compression and dilatation are characteristic of the crater basement but are also common constituents of polymict breccias. Displaced megablocks within the continuous ejecta blanket are usually monomictly brecciated. *Dyke breccias* can be related to all major phases of the crater formation process and up to 4 generations of dykes have been observed in a single impact event (Lambert, 1981; Stöffler et al., 1988; Spray, 1998). *Shock veins and vein networks* (previously termed 'pseudotachylites') are formed during the compression stage, since they commonly occur as clasts within later formed breccia dykes. The injection of dykes of polymict lithic breccias starts during the compression stage and continues during the excavation stage. A final generation of dykes (polymict or monomict breccias) is produced during the modification stage, while the transient crater collapses and more conventional (but still very high strain rate) faulting takes place.

The time for the formation of the final crater and of some early formed impactites (shocked rocks, melt, dykes) is in the order of seconds to minutes for craters ranging from about 1 to 100 km and the total time for the deposition of the proximal ejecta ranges from minutes to hours (Melosh, 1989; Ivanov & Artemieva, 2002). This time is very short compared to all other geological processes. Despite this, superposition contacts between layered impact formations or contacts at discordant dykes are quite common at impact craters, for example, sharp contacts of sheets of impact melt to the monomictly brecciated, unshocked or mildly shocked crater basement or contacts between the continuous ejecta deposits (polymict lithic breccias) and the overlying suevite are characteristic, as are discordant dykes intersecting displaced megablocks.

Impactites from planetary bodies with a thin or non-existent atmosphere and with very low intensity of endogenous geological activity, such as the moon, the asteroids and, in part, Mars, show evidence of multiple impacts. This is most conspicuous for the moon and the asteroids, where the outer zone of the crust is reworked by multiple impacts of all sizes with impactors ranging in size from hundreds of kilometres to micrometres. Because of the inverse proportionality between impactor size and impact frequency (Neukum et al., 2001) the fraction of very small impactors is so large that a fine-grained *regolith* is formed in the upper few metres (5 to 15 m in the case of the moon). This regolith rests on top of a megaregolith, which is composed of the ejecta blankets from larger impact craters superimposed on each other (Hartmann, 1973, 2003). This megaregolith was essentially formed during the so-called 'early heavy bombardment' of the terrestrial planets (4.5 to 3.8 Ga ago); whereas, the fine-grained regolith was built up during the past 3.5 Ga when the impact rate had declined by a factor of about 1000 (Taylor, 1982; Heiken et al., 1991; Neukum et al., 2001; Stöffler & Ryder, 2001). Impactites from the megaregolith display all the characteristics found at single terrestrial craters (Stöffler et al., 1980); whereas, impactites from the *regolith* are either represented by unconsolidated clastic impact debris or by shock lithified consolidated *regolith breccias,* as sampled on the moon during the Apollo and Luna programmes (e.g. Heiken et al., 1991; see Table 11.1). Among *asteroidal meteorites* regolith breccias, lithic breccias, impact melt rocks, and shocked rocks are represented in proportions, which reflect the multiple cratering of asteroids and the relatively lower impact velocity in the asteroid belt. The lower impact velocity explains the scarcity of impact melt lithologies (Bischoff & Stöffler, 1992; Keil et al., 1997). According to expectations, *Martian meteorites* are exclusively shocked rocks or monomict breccias of basaltic, gabbroic and peridotitic

provenance (Nyquist et al., 2001; Fritz et al., 2005). In some of the Martian plutonic rocks, now occurring as meteorites, more than one shock or impact event is recorded.

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FIGURES

Figure captions

Fig. 11.1: Schematic representation of the shock zoning and particle motion in an impact crater based on various data and models, e.g. Dence et al. (1977), Grieve et al. (1977), O'Keefe & Ahrens (1978), Stöffler (1977), Croft (1980), Kieffer & Simonds (1980), and Orphal et al. (1980)

Fig. 11.2: Geological setting of impactites on Earth: a) proximal and distal impactites, b) proximal impactites at a simple impact crater (diameter range on Earth: ~30 m to about 2-5 km); c) proximal impactites at a complex impact crater with central uplift (diameter range on Earth: ~5 km to 50-60 km); shock pressure isobars are shown in the parautochthonous crater basement.

Fig 11.1

a)

PROXIMAL IMPACTITES

DISTAL IMPACTITES

Polymict lithic breccia

Fall back breccia (suevitic)

Coherent layer of impact melt rocks

Polymict lithic breccia

Suevite

Suevite

Tektites

Air fall beds

Impact melt dykes

veins and vein networks

Impact breccia dykes
a) lithic breccia
b) suevitic

b)

Crater rim

Center of crater

megablocks with breccia dikes

lithic breccias

lithic breccias with melt particles (suevite)

fallback breccia

melt rock

uplifted shocked basement

30 GPa

25 GPa

20 GPa

intrusive melt dykes

lithic breccia dykes

veins and vein networks

ca. 10 GPa

monomictly brecciated basement

ca. 0.2 - 0.5 GPa

c)

Crater rim

Center of Crater

melt splashes

megablocks with breccia dykes

lithic breccias

lithic breccias with melt particles (suevitic)

fallback breccia

melt rock

25 GPa
5 GPa

~ 0.2-0.5 GPa

monomictly brecciated basement

veins and vein networks

Fig 11.2

Table 2: Classification of impactites from single impacts according to geological setting, composition, texture, and degree of shock metamorphism (see text for details)

* Typically monomict; **Generally polymict but can be monomict, e.g. in a single lithology target; ***Includes glassy, hypocrystalline and holocrystalline varieties

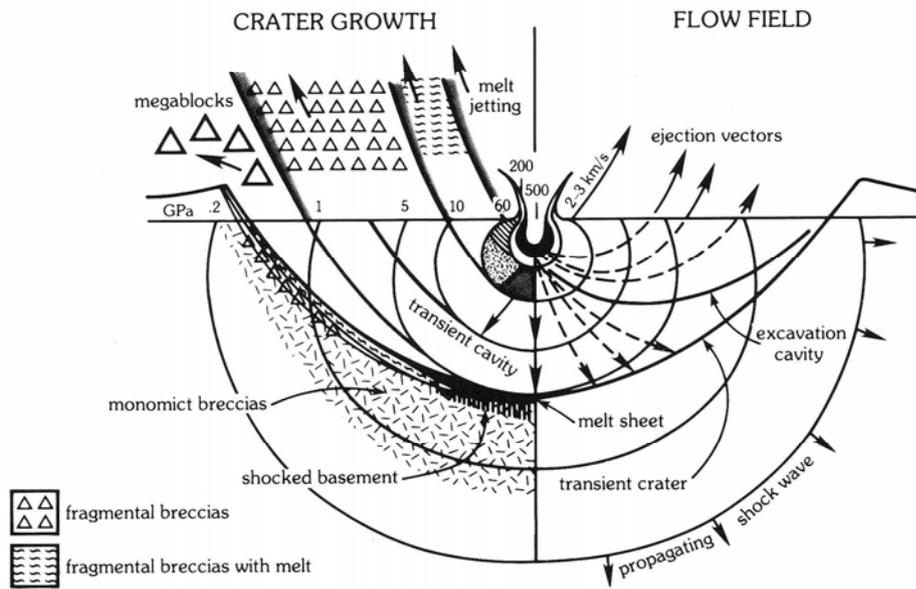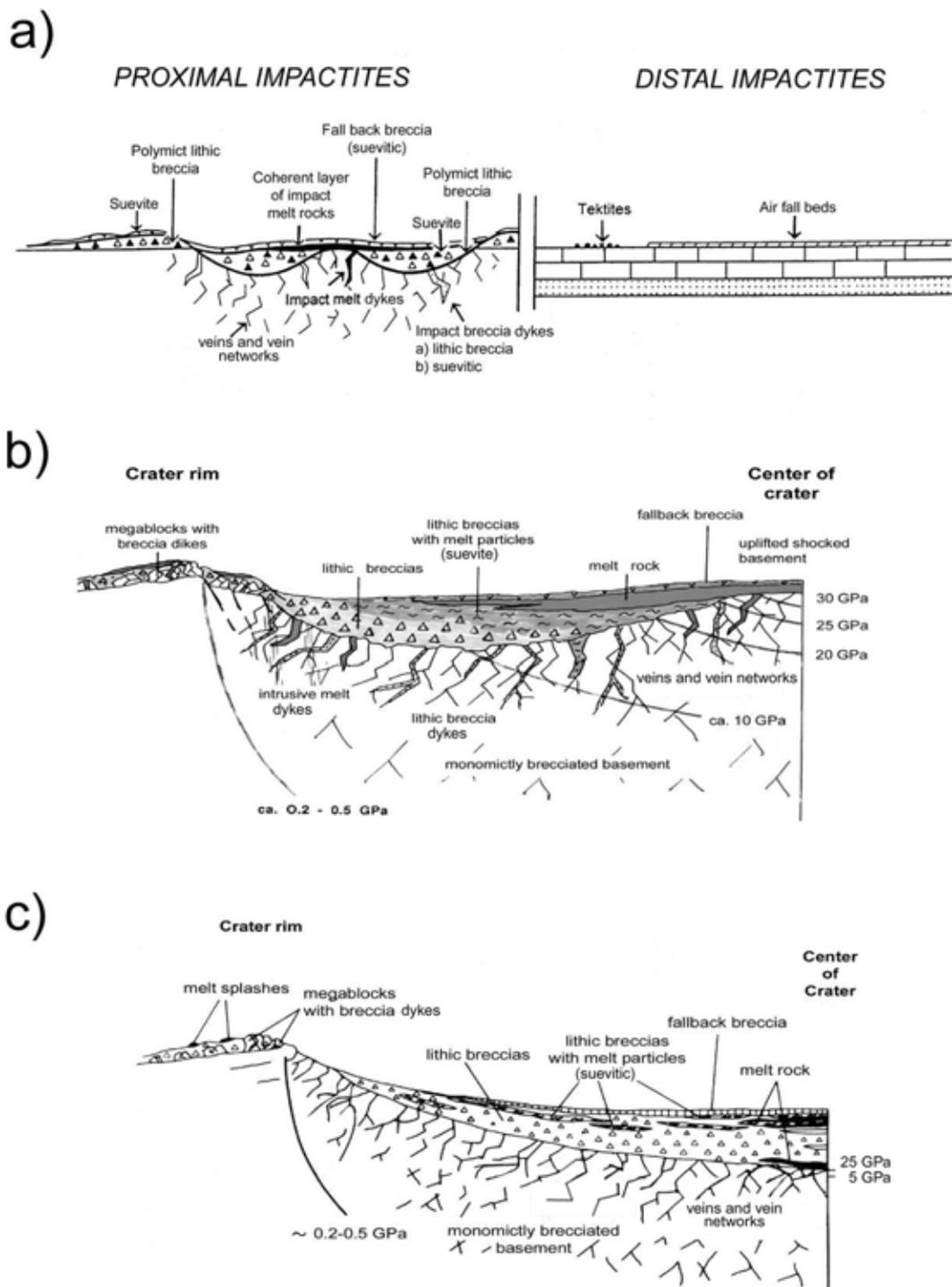Table 11.2

Table 2.11.3: Classification of shocked quartzofeldspathic rocks (progressive stages of shock metamorphism); modified from Stöffler (1971, 1984); post shock temperatures are relative to an ambient temperature of 0 °C.

Shock stage	Peak pressure (GPa)	Post-shock temperature (°C)	Shock effects
0	~5-10	~100	Fractured minerals
Ia	~20	~170	Quartz with planar fractures and planar deformation features: feldspar with planar deformation features
Ib	~35	~300	Quartz and feldspar with planar deformation features and reduced refractive index; stishovite and minor coesite
II	~45	~900	Diaplectic quartz and feldspar glass; coesite and traces of stishovite; cordierite glass
III	~60	~1500	Normal feldspar glass (vesiculated) and diaplectic quartz glass; coesite; cordierite glass
IV	~80-100	>2500	Rock glasses or crystallised melt rocks (quenched from whole rock melts)
V			Rock glasses (whole rock melts condensed from silicate vapour)

Table 2.11.4: Classification of shocked basaltic-gabbroic rocks (progressive stages of shock metamorphism); based on data of Kieffer et al., 1976; Schaal & Hörz, 1977; James, 1969; Ostertag, 1983; Stöffler, 1984, and Stöffler et al, 1986; post-shock temperatures are relative to an ambient temperature of 0 °C and in part based on Raikes & Ahrens (1979); (?) uncertain values with errors of ~ ±50 °C

Shock stage	Equilibration shock pressure (GPa)	Post-shock temperature (°C)	Shock effects and textural characteristics	Accompanying disequilibrium shock effects
0			Unshocked (no unequivocal shock effects)	none
	~1-5	~0		
1			Fractured silicates; mechanical twinning on pyroxene and ilmenite; kink bands in mica; rock texture preserved	none
	~20-22	~50-150		
2a			Plagioclase with planar deformation features and partially converted to diaplectic glass	Incipient formation of localised 'mixed melt' and glassy veins
2b	~28-34	~200-250	Diaplectic plagioclase glass; mechanicl twinning in pyroxene and ilmenite; mosaicism in olivine and other silicates	Localised 'mixed melt' and melt veins (glassy or microcrystalline)
	~42-45	~900 (?)		
3			Melted plagioclase glass with incipient flow structure and vesicles; mafics and ore as in stage 2	
	~60	~1100 (?)		
4			Melted plagioclase glass with vesicles and flow structure; incipient contact melting of pyroxene; incipient recyrstallisation of olivine	

Table 2.11.5: Classification of shocked chondritic meteorites and olivine-rich crystalline rocks (progressive stages of shock metamorphism) modified after Stöffler et al. (1991); shock pressure data are based on experimental data given in Stöffler et al. (1991); pressures given in columns 4 – 6 indicate the upper limit of the shock stage in question; temperature data refer to the ambient temperature before shock compression; *from Stöffler et al. (1991); **from Schmitt (2000)

Shock stage	Effects resulting from equilibration peak shock pressure		Effects resulting from local P-T-excursions	Pressure GPa* (293 K)	Pressure GPa** (293 K)	Pressure GPa** (920 K)
	Olivine	Plagioclase				
Unshocked S1	Sharp optical extinction Irregular fractures	Sharp optical extinction Irregular fractures	none			
Very weakly shocked S2	Undulatory extinction Fractures Angular variation of extinction position: Low grade: < 1° High grade: 1° – 2°	Undulatory extinction Irregular fractures	none	< 4-5		
Weakly shocked S3	Planar fractures (PF) Undulatory extinction Irregular fractures Angular variation of extinction position: < 2° Low grade: maximum of 2 sets of PF High grade: 3 or more sets of PF	Undulatory extinction	Opaque shock veins, incipient formation of melt pockets (sometimes interconnected)	5 - 10		
Moderately shocked S4	Mosaicism (weak) Low grade: incipient mosaicism, PF and PDF High grade: mosaicism, PF, and PDF	Low grade: undulatory extinction High grade: partially isotropic, PDF	Melt pockets, interconnected melt veins, opaque shock veins	15 - 20	10 - 15	10 – 15
Strongly shocked S5	Mosaicism (strong) Planar fractures Planar deformation features (PDF)	Maskelynite (diaplectic glass)	Pervasive formation of melt pockets, veins and dykes, opaque shock veins	30 - 35	25 - 30	20 – 25
Very strongly shocked S6	_Restricted to local regions in or near melt zones_ Recrystallisation; yellow-brown staining; ringwoodite and wadsleyite; high pressure phases of pyroxene (e.g. majorite, akimotoite)	Shock melted (normal glass)	as in stage S5	45 - 55	45 - 60	35 – 45
Shock melted	Whole rock melting and formation of melt rocks			75 - 90	45 - 60	45 - 60

Table 2.11.6: Classification of shocked sandstone (progressive stages of shock metamorphism); modified after Kieffer (1971) and Kieffer et al. (1976); ranges of pressure estimates are given in parentheses; post-shock temperature are relative to an ambient temperature of 0 °C

Shock stage	Equilibration shock pressure, GPa	Post-shock temperature, °C	Shock effects
0			Undeformed sandstone
1a	0.2-0.9	~25	Compacted sandstone with remnant porosity
1b	~3.0 (2.2-4.5)	~250	Compacted sandstone compressed to zero porosity
2	~5.5 (3.6-13)	~350	Dense (non-porous) sandstone with 2-5% coesite, 3-10% glass and 80-95% quartz
3	~13	~950	Dense (non-porous) sandstone with 18-32% coesite, traces of stishovite, 0-20% glass and 45-80% quartz
4	~30	>1000	Dense (non-porous) sandstone with 10-30% coesite, 20-75% glass and 15-45% quartz
5			Vesicular (pumiceous) rock with 0-5% coesite, 80-100% glass (lechatelierite) and 0-15% quartz

Table 2.11.7: Classification of unconsolidated sediments and particulate materials (progressive stages of shock metamorphism); based on data from shock recovery experiments and theoretical models (e.g. Kieffer, 1975)

Equilibrium shock pressure (GPa)	Particulate basalt	Lunar soils			H5 Chondrite powder		L6 chondrite powder	Quartz sand
	75035*	15101* 45-150 µm	Model soil	65101* <150 µm	16% porosity <150 µm	<5% porosity <150 µm	ALH 85017* 125 – 250 µm	63-125 µm
40	vesiculated glass	vesiculated glass			?	?	Vesiculated glass (50 % melt at ~ 65 GPa)	vesiculated glass
30	lithification by	lithification by						
20	glass cement	minor intergranular glass	vesiculated glass	glass bonding	lithification by glass cement		intergranular glass (starting at ~ 25 GPa)	minor intergranular glass
10	lithification and compaction	lithification and compaction	minor intergranular glass; lithification compaction	lithification compaction; lithification	minor intergranular glass; lithification and compaction	minor intergranular glass; lithification and compaction	lithification and compaction (complete at 14.5 GPa)	minor intergranular glass; lithification and compaction
	Schaal et al. (1979)	Schaal & Hörz (1980)	Kieffer (1975)	Christie et al. (1973)	Bischoff & Lange (1984)	Bischoff & Lange (1984)	Hörz et al. (2005)	Stöffler et al. (1975)

* Refers to lunar sample numbers and meteorite names