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.

References

Asay J.R. and Shahinpoor M., 1993. High-pressured shock compression of solids. Springer, New York, Berlin, Heidelberg, 393pp.

Bischoff A. and Lange M.A., 1984. Experimental shock-lithification of chondritic powder: Implications for ordinary chondrite regolith breccias. Lunar Planet. Sci. Conf. 15th, Abstracts, 60-61.

Bischoff A. and Stöffler D., 1992. Shock metamorphism as a fundamental process in the evolution of planetary bodies: Information from meteorites. Europ. J. Mineral. 4, 707-755.

Chao E.C.T., 1967. Impact metamorphism: In Researches in Geochemistry, Wiley J. and Sons, New York, New York, 204-233.

Christie J.M., Griggs D.T., Heuer A.H.,Nord GL., Radcliff S.V., Lally J.S., and Fisher R.M., 1973. Electron petrography of Apollo 14 and 15 breccias and shock-produced analogs. Proc. 4th Lunar Sci. Conf., 365-382.

Croft S.K., 1980. Cratering Flow Fields: Implications for the excavation and transient expansion stages of crater formation. Proc. Lunar Planet. Sci. Conf. 11th, 2347-2378.

Dence M.R., Grieve R.A.F., and Robertson P.B., 1977. In Roddy D.J., Pepin R.O. and Lerrill R.B. (Ed.) Terrestrial impact structure: Principal characteristics and energy considerations. Impact and Explosion Cratering, New York, 247-275.

Duvall G.E. and Fowles G.R., 1963. Shock waves, in High Pressure Physics and Chemistry (R. S. Bradley, ed.), Academic Press Inc., New York, Vol. II, 209-291.

French B.M. and Short N.M. (eds.), 1968. Shock metamorphism of natural materials, Mono Book Corp., Baltimore, Maryland, 644pp.

French B.M., 1998. Traces of catastrophe: A handbook of shock-metamorphic effects in terrestrial meteorite impact structures. LPI Contribution No. 954, Lunar and Planetary Institute, Houston, 120pp.

Fritz J., Greshake A. and Stöffler D., 2005. Ejection of Martian meteorites. Meteoritics and Planetary Science 40, 1393-1411..

Graham R.A., 1993. Solids under high-pressure shock compression - mechanics, physics and chemistry. Springer, New York, Berlin, Heidelberg, 221pp.

Grieve R.A.F., Dence M.R. and Robertson P.B., 1977. Cratering processes: As interpreted from the occurrence of impact melts. In Roddy D.J., Pepin R.O. and Merrill R.B. (eds.) Impact and Explosion Cratering, New York, 791-814.

Heiken G., Vaniman D. and French B.M. (eds.), 1991. The lunar sourcebook. A user's guide to the moon, LPI and Cambridge Univ. Press, New York, pp. 736.

Hartmann W.K., 1973. Ancient lunar mega-regolith and subsurface structure. Icarus 18, 634-636.

Hartmann W.K., 2003. Megaregolith evolution and cratering cataclysm models – Lunar cataclysm as a misconception (28 years later). Meteoritics and Planetary Science 38, 579-593.

Hörz F., Cintala M.J., See T.H., and Le L., 2005. Shock melting of ordinary chondrite powders and implications for asteroidal regoliths. Meteoritics and Planetary Science 40, 1329-1346.

Ivanov B.A. and Artemieva N.A., 2002. Numerical modelling of the formation of large impact craters. In Catastrophic Events and Mass Extinctions: Impact and Beyond. GSA Spec Paper 356, 619-630.

James, O. B., 1969. Shock and thermal metamorphism of basalt by nuclear explosions, Nevada Test site. Science 166, 1615-1620.

Keil K., Stöffler D., Love S.G., and Scott, R.D. 1997. constraints on the role of impact heating and melting of asteroids. Meteoritics and Planetary Science 32, 349-363

Kieffer S.W., 1971. Shock metamorphism of the Coconino sandstone at Meteor crater, Arizona. J. Geophys. Res. 76, 5449-5473.

Kieffer S.W., 1975. From regolith to rock by shock. The Moon 13, 301-320.

Kieffer S.W., Schaal R., Gibbons R., Hörz F., Milton D., and Duba A., 1976. Shocked basalt from Lonar impact crater, India, and experimental analogues. Proc. Lunar Planet. Sci. Conf. 7th, 1391-1412.Kieffer S.W. and Simonds C.S., 1980. The role of volatiles and lithology in the impact cratering process. Rev. Geophys. Space Phys. 18, 143-181.

Lambert P., 1981. Breccia dikes: geological constraints on the formation of complex craters. In Multi-ring basins: formation and evolution (Schultz P.H. and Merril R.B., eds.), Proc. Lunar Planet. Sci. 12A, 59-78, Pergamon, New York.

Melosh H.J., 1989. Impact cratering: A geologic process. Oxford University Press, New York, 245p.

Neukum G., Ivanov B. and Hartmann W.K., 2001. Cratering records in the inner solar system in relation to the lunar reference system. Space Science Rev., 96, 55-86.

Nyquist L.E., Bogard D.D., Shih C.-Y., Greshake A., Stöffler D. and Eugster O., 2001. Ages and geologic histories of Martian meteorites. Space Science Rev., 96, 105-164.

O'Keefe J. and Ahrens T.J., 1978. Impact flows and crater scaling on the Moon. Phys. Earth Planet. Interiors 16, 341-351.

Orphal D.L., Borden W.F., Larson S.A. and Schultz P.H., 1980. Impact melt generation and transport. Proc. Lunar Planet. Sci. Conf. 11th, 2309-2323.

Ostertag R., 1983. Shock experiments on feldspar crystals. Proc. Lunar Planet. Sci. Conf. 14th, J. Geophys. Res. 88 Suppl., B364-B376.

Raikes and Ahrens, 1979. Post-shock temperatures in minerals. J. Royal Astron. Soc. 58, 717-747.

Roddy D.J., Pepin R.O. and Merril R.B. (eds.), 1977. Impact and explosion cratering: Planetary and terrestrial Implications. Pergamon, New York, 1301pp.

Schaal R.B. and Hörz F., 1977. Shock metamorphism of lunar and terrestrial basalts. Proc. Lunar. Planet. Sci. Conf. 8th, 1697-1729.

Schaal R.B. and Hörz F., 1980. Experimental shock metamorphism of lunar soil. Proc. 11th Lunar Planet. Sci. Conf., 1679- 1695.

Schaal R.B., Hörz F., Thompson T.D. and Bauer J.F., 1979. Shock Metamorphism of granulated lunar basalt. Proc. 10th Lunar Planet. Sci. Conf., 2547-2571.

Schmitt R.T. and Stöffler D., 1995. Experimental data in support of the 1991 shock classification of chondrites. Meteoritics 30, 574-575.

Schmitt R.T., 2000. Shock experiments with the H6 chondrite Kernouvé: Pressure calibration of microscopic shock effects. Meteoritics and Planetary Science 35, 545–560.

Spray J.G., 1998. Localised shock- and friction-induced melting in response to hypervelocity impact. In Meteorites: Flux with time and impact effects (Grady M.M., Hutchinson R., McCall G.J.H., and Rothery D.A. (eds.). Geol. Soc. Spec. Publ., London, 140, 195-204.

Stöffler D., 1966. Zones of impact metamorphism in the crystalline rocks of the Nördlinger Ries crater. Contr. Mineral. and Petrol. 12, 15-24.

Stöffler D., 1971. Progressive metamorphism and classification of shocked and brecciated crystalline rocks at impact craters. J. Geophys. Res. 76, 5541-5551.

Stöffler D., 1972. Deformation and transformation of rock-forming minerals by natural and experimental shock processes: I. Behavior of minerals under shock compression. Fortschr. Miner. 49, 50-113.

Stöffler D., 1974. Deformation and transformation of rock-forming minerals by natural and experimental shock processes: II. Physical properties of shocked minerals. Fortschr. Miner. 51, 256-289.

Stöffler D., Gault D.E., Wedekind J. and Polkowski G., 1975. Experimental hypervelocity impact into quartz sand: Distribution and shock metamorphism of ejecta. J. Geophys. 80, No. 29, 4062-4077.

Stöffler D., 1977. Research drilling Nördlingen 1973: polymict breccias, crater basement and cratering model of the Ries impact structure. Geologica Bavarica 75, 443-458.

Stöffler D., Knöll H.D. and März U., 1979. Terrestrial and lunar impact breccias and the classification of lunar highland rocks. Proc. 10th Lunar Planet. Sci. Conf., 639-675.

Stöffler D., Knöll H.-D., Marvin U.B., Simonds C.H. and Warren P.H., 1980. Recommended classification and nomenclature of lunar highland rocks, In Proc. Conf. Lunar Highland Crust (Papike J.J. and Merrill R.B., eds.), Pergamon Press, New York, 51-70.

Stöffler D., 1984. Glasses formed by hypervelocity impact. J. Non-Crystalline Solids, 67, 465-502.

Stöffler D., Ostertag R., Jammes C., Pfannschmidt G., Sen Gupta P.R., Simon S.B., Papike J.J., and Beauchamp R.M., 1986. Shock metamorphism and petrography of the Shergotty achondrite. Geochim. Cosmochim. Acta 50, 889-903

Stöffler D., Bischoff L., Oskierski W. and Wiest B., 1988. Structural deformation, breccia formation, and shock metamorphism in the basement of complex terrestrial impact craters: Implications for the cratering process, In: Deep Drilling in Crystalline Bedrock (A. Boden. and K.G Eriksson, eds.), Vol. 1, Springer Verlag, 277-297

Stöffler D., Keil K. and Scott E.R.D., 1991. Shock metamorphism of ordinary chondrites. Geochim. Cosmochim. Acta 55, 3845-3867.

Stöffler D. and Langenhorst F., 1994. Shock metamorphism of quartz in nature and experiment: I. Basic observation and theory. Meteoritics 29, 155–181.

Stöffler D. and Grieve R.A.F., 1994. Classification and nomenclature of impact metamorphic rocks: A proposal to the IUGS Subcommission on the Systematics of Metamorphic Rocks. Lunar and Planetary Science XXV, The Lunar and Planetary Science Institute, Houston, Texas, 1347-1348.

Stöffler D. and Grieve R.A.F., 1996. IUGS classification and nomenclature of impact metamorphic rocks: Towards a final proposal. International Symposium on the Role of Impact Processes in the Geological and Biological Evolution of Planet Earth, Postojna, Slovenia, 27.9.-2.10.1996, Abstract.

Stöffler D. and Ryder G., 2001. Stratigraphy and isotope ages of lunar geologic units: Chronological standard for the inner solar system. Space Science Rev., 96, 9-54.

Taylor S.R., 1982. Planetary science: A lunar perspective. Lunar and Planetary Institute, Houston, 481pp.

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.

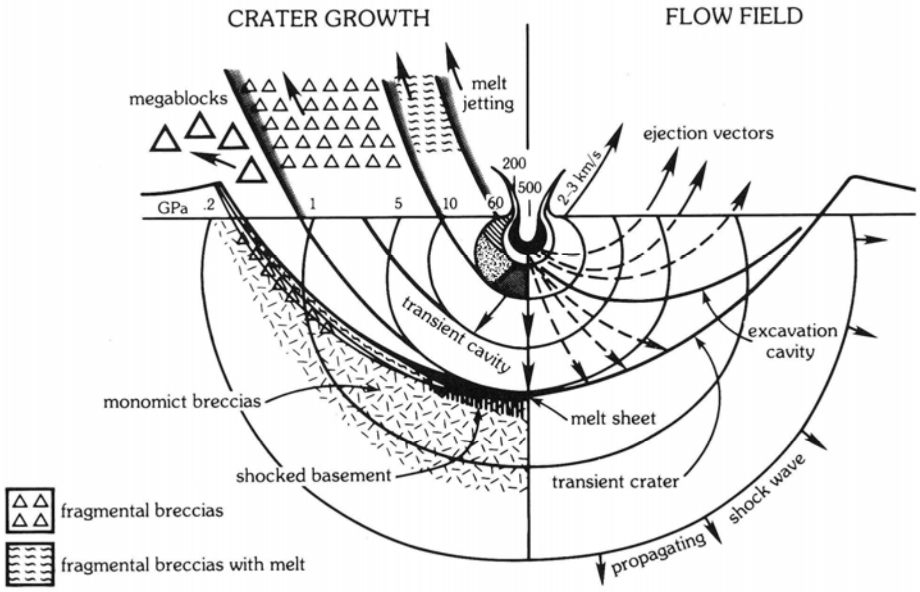

CRATER GROWTH
FLOW FIELD
megablocks
melt
jetting
ejection vectors
200
500
2-3 km/s
GPa
.2
1
5
10
60
transient cavity
excavation
cavity
monomict breccias
melt sheet
shocked basement
transient crater
shock wave
propagating
fragmental breccias
fragmental breccias with melt

Fig 11.1

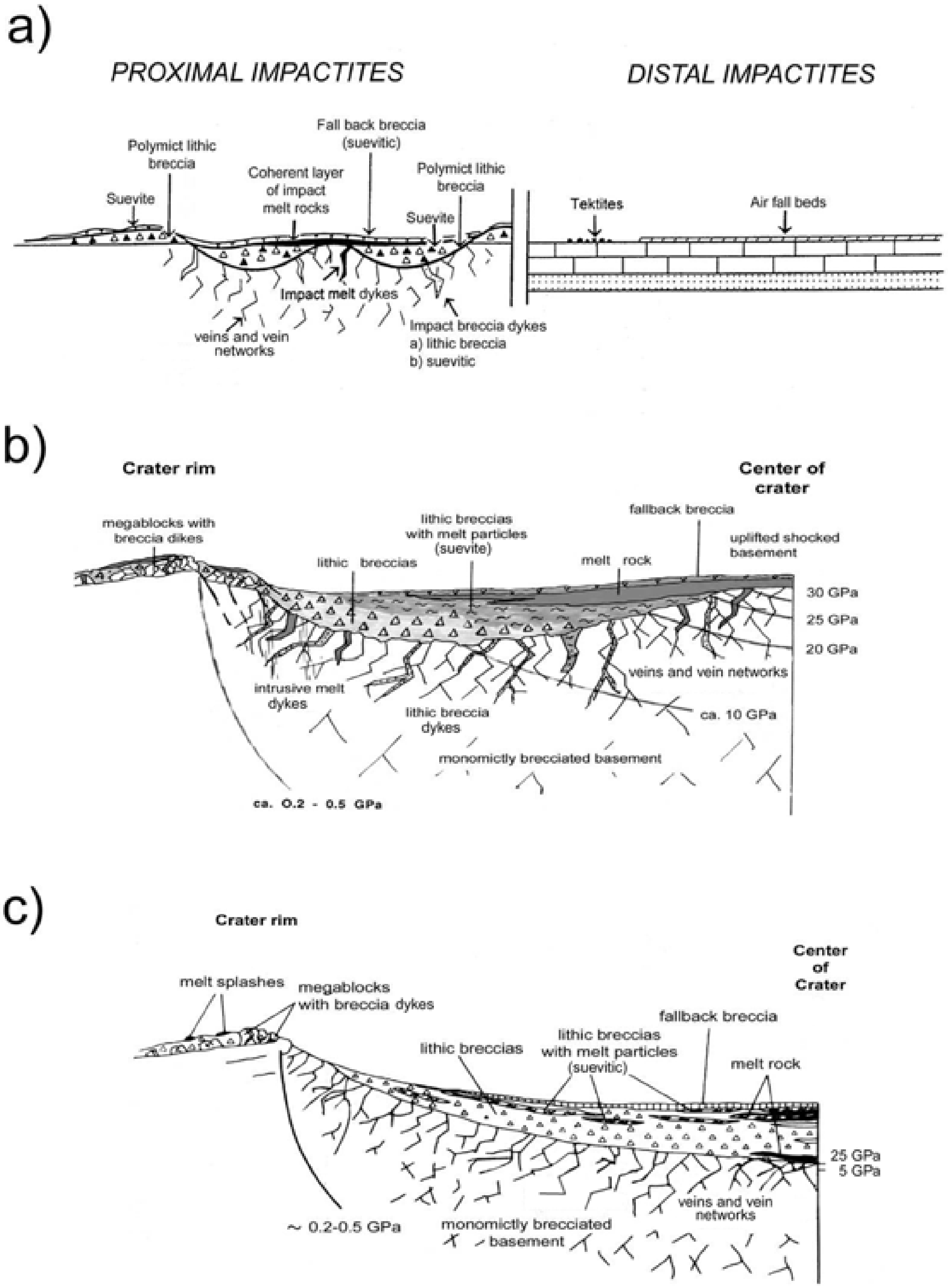
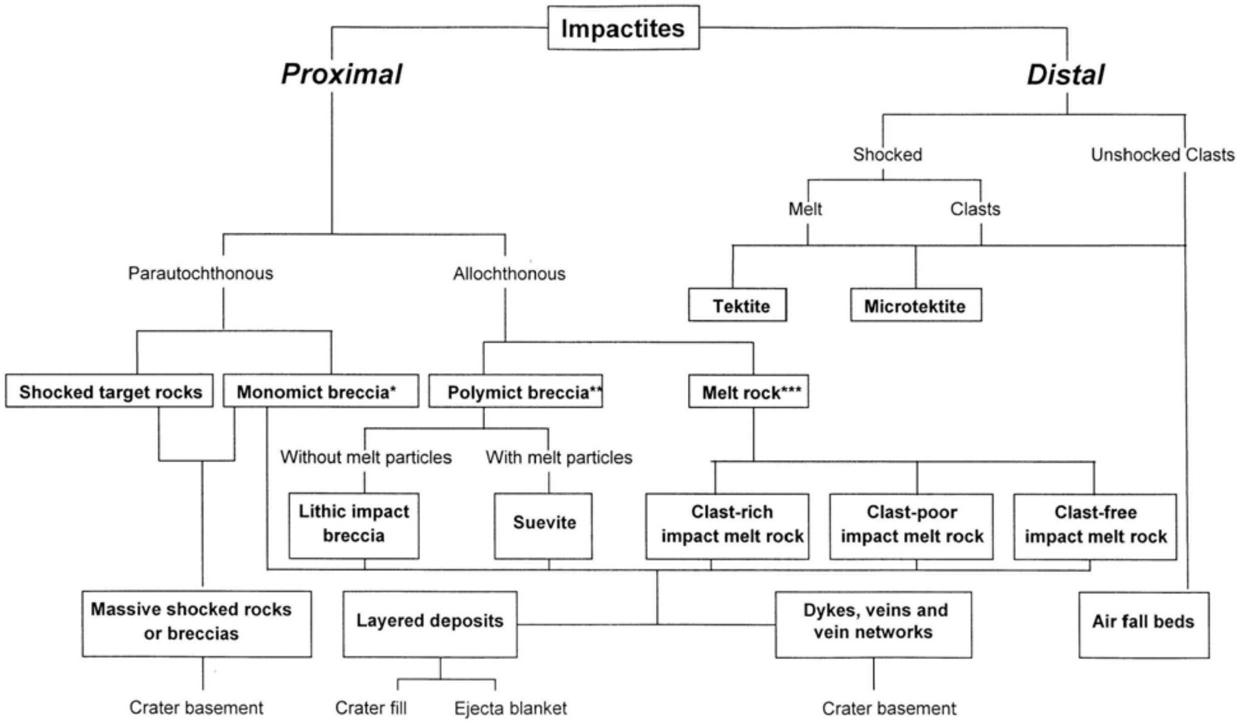

a)
PROXIMAL IMPACTITES
DISTAL IMPACTITES
Polymict lithic breccia
Suevite
Coherent layer of impact melt rocks
Fall back breccia (suevitic)
Polymict lithic breccia
Suevite
Tektites
Air fall beds
Impact melt dykes
veins and vein networks
Impact breccia dykes
a) lithic breccia
b) suevitic
b)
Crater rim
Center of crater
megablocks with breccia dikes
lithic breccias
lithic breccias with melt particles (suevite)
melt rock
fallback breccia
uplifted shocked basement
30 GPa
25 GPa
20 GPa
veins and vein networks
intrusive melt dykes
lithic breccia dykes
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
veins and vein networks
~ 0.2-0.5 GPa
monomictly brecciated basement

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 (^{o}C)	Shock effects
0			Fractured minerals
	~5-10	~100	
Ia			Quartz with planar fractures and planar deformation features: feldspar with planar deformation features
	~20	~170	
Ib			Quartz and feldspar with planar deformation features and reduced refractive index; stishovite and minor coesite
	~35	~300	
II			Diaplectic quartz and feldspar glass; coesite and traces of stishovite; cordierite glass
	~45	~900	
III			Normal feldspar glass (vesiculated) and diaplectic quartz glass; coesite; cordierite glass
	~60	~1500	
IV			Rock glasses or crystallised melt rocks (quenched from whole rock melts)
	~80-100	>2500	
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 (^{o}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 2b	~28-34	~200-250	Plagioclase with planar deformation features and partially converted to diaplectic glass Diaplectic plagioclase glass; mechanicl twinning in pyroxene and ilmenite; mosaicism in olivine and other silicates	Incipient formation of localised 'mixed melt' and glassy veins 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 equlibration 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	Angular variation of extinction position: Low grade: < 1° High grade: 1° – 2°	Sharp optical extinction Irregular fractures	none	< 4 -5		
Very weakly shocked S2	Undulatory extinction Fractures	Angular variation of extinction position: < 2°	Undulatory extinction Irregular fractures	none	5 - 10		
Weakly shocked S3	Planar fractures (PF) Undulatory extinction Irregular fractures	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)	15 - 20	10 - 15	10 – 15
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	30 - 35	25 - 30	20 – 25
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	45 - 55	45 - 60	35 – 45
	Restricted to local regions in or near melt zones						
Very strongly shocked S6	Recrystallisation; yellow-brown staining; ringwoodite and wadsleyite; high pressure phases of pyroxene (e.g. majorite, akimotoite)		Shock melted (normal glass)	as in stage S5	75 - 90		45 - 60
Shock melted	Whole rock melting and formation of melt rocks						

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, ^{o}C	Shock effects
0			Undeformed sandstone
	0.2-0.9	~25	
1a			Compacted sandstone with remnant porosity
	~3.0 (2.2-4.5)	~250	
1b			Compacted sandstone compressed to zero porosity
	~5.5 (3.6-13)	~350	
2			Dense (non-porous) sandstone with 2-5% coesite, 3-10% glass and 80-95% quartz
	~13	~950	
3			Dense (non-porous) sandstone with 18-32% coesite, traces of stishovite, 0-20% glass and 45-80% quartz
	~30	>1000	
4			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)

Equilibration shock pressure (GPa)	Particulate basalt 75035*	Lunar soils			H5 Chondrite powder		L6 chondrite powder	Quartz sand 63-125 µm
		15101* 45-150 µm	Model soil	65101*	16% porosity <150 µm	<5% porosity <150 µm	ALH 85017* 125 – 250 µm	
	vesiculated glass	vesiculated glass					Vesiculated glass (50 % melt at ~ 65 GPa)	
40					?	?		
	lithification	lithification						vesiculated glass
30	by	by						
	glass cement	glass cement			lithification by glass cement	lithification by glass cement	intergranular glass (starting at ~ 25 GPa)	
20		minor intergranular glass	vesiculated glass	glass bonding	minor intergranular glass	minor intergranular glass		minor intergranular glass
10	lithification and compaction	lithification and compaction	lithification compaction	lithification	lithification and compaction	lithification and compaction	lithification and compaction (complete at 14.5 GPa)	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