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Invited Review

Shock metamorphism of planetary silicate rocks and sediments: Proposal for an updated classification system

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Abstract—We reevaluate the systematics and geologic setting of terrestrial, lunar, Martian, and asteroidal “impactites” resulting from single or multiple impacts. For impactites derived from silicate rocks and sediments, we propose a unified and updated systematics of progressive shock metamorphism. “Shock-metamorphosed rocks” occur as lithic clasts or melt particles in proximal impactites at impact craters, and rarely in distal impactites. They represent a wide range of metamorphism, typically ranging from unshocked to shock melted. As the degree of shock metamorphism, at a given shock pressure, depends primarily on the mineralogical composition and the porosity of a rock or sediment sample, different shock classification systems are required for different types of planetary rocks and sediments. We define shock classification systems for eight rock and sediment classes which are assigned to three major groups of rocks and sediments: (1) Crystalline rocks with classes F, M, A, and U, (2) Chondritic rocks (class C), and (3) Sedimentary rocks and sediments with classes SR, SE, and RE. The abbreviations stand for felsic (F), mafic (M), anorthositic (A), ultramafic (U), sedimentary rocks (SR), unconsolidated sediments (SE), and regoliths (RE). In each class, the progressive stages of shock metamorphism are denominated S1 to Sx. These progressive shock stages are introduced as: S1–S7 for **F**, S1–S7 for **M**, S1–S6 for **A**, S1–S7 for **U**, S1–S7 for **C**, S1–S7 for **SR**, S1–S5 for **SE**, and S1–S6 for **RE**. S1 stands for “unshocked” and Sx (variable between S5 and S7) stands for “whole rock melting.” We propose a sequence of symbols characterizing the degree of shock metamorphism of a sample, i.e., F-S1 to F-S7 with the option to add the tabulated pressure ranges (in GPa) in parentheses.

INTRODUCTION AND GOAL OF THIS CONTRIBUTION

In this introduction, we shall first remind the reader of the fundamental concept of progressive shock metamorphism and its historical development since about 1965 and finally present strong arguments for the need of an updated and unified concept for the systematics and nomenclature for shock classification systems.

Basic Principles of Shock Metamorphism

Shock-metamorphosed rocks are characteristic constituents of impact formations produced by interplanetary collisions on all terrestrial (“rocky”) planetary bodies and moons of the solar system. So far, they are well known and documented from impact craters on Earth, from returned lunar rocks of the Apollo and Luna missions, and as meteorites from the Moon, Mars, Vesta, and many other types of asteroids.

Natural shock metamorphism is the physical consequence of hypervelocity impacts of planetary projectiles (e.g., asteroids and comets) into solid target rocks and sediments exposed on planetary bodies. The impact process leads to a quasi-hemispherically propagating shock wave whose energy is decaying with propagation into the target until it reaches the ambient hydrostatic pressure of the target at some radial distance from the point of impact (Fig. 1).

Considering the weakest recognizable shock effects at a certain radial distance from the point of impact, temporarily existing zones of continuously increasing shock pressure and shock temperature can be defined if one approaches the impact center. The “fictive” central point of these zones is at the stagnation point of the penetrating projectile where the pressure–temperature (P - T) condition is at its maximum (Fig. 1). The material in these zones is exposed to shock compression on extremely short time scales because rarefaction waves propagate down into the compressed target when the shock wave reaches the free surface of the target and the rear side of the projectile. This scenario is the basis of the principle of progressive shock metamorphism that was first recognized and defined at terrestrial impact craters in Canada and Germany around 1965. The driving force for this fundamental discovery was the first experimental synthesis of two high-pressure polymorphs of quartz, coesite and stishovite, in static high-pressure devices (Coes 1953; Stishov and Popova 1961). This stimulated the discovery of coesite and stishovite in a terrestrial impact crater, the Barringer crater (Arizona), by Chao et al. (1960) and later in the Ries crater (Germany) by Shoemaker and Chao (1961) and Chao et al. (1962).

For a general characterization of the P - T conditions of *shock metamorphism*, it seems to be helpful to compare them with the conditions of *endogenous metamorphism* in the case of the Earth as shown in Fig. 2. The P - T field for static metamorphism of rocks is extremely limited with some rocks having experienced in rare cases pressures up to about 1 - 2 GPa and temperatures up to some 10^3 °C compared to roughly 10^3 GPa and some 0.5×10^5 °C, respectively, for shock metamorphism.

It is beyond the scope of this article to discuss the fundamental physics of shock wave propagation in multiphase solid materials in any detail. Clearly, it is necessary for understanding the formation processes of remnant shock effects in rocks or sediments that consist of constituents of rather variable shock impedance (defined as shock wave velocity times density of the mineral) and have variable degrees of porosity. Some background information on these topics has been presented in previous publications (e.g., Stöffler 1972,

1984; Stöffler and Langenhorst 1994). The reader should be aware of the fact that a given impactor velocity will generate very different peak shock pressures and temperatures in different rocks depending on their porosity and shock impedance. An important point is that at a given shock pressure, the shock temperature of highly porous rocks can be up to an order of magnitude higher than those of dense crystalline rocks as shown in Fig. 2.

For more extensive information, we refer the reader to the relevant literature dealing with shock wave physics in general. Basic information can be obtained from books (e.g., Rice et al. 1958; Duvall and Fowles 1963; Zel'dovich and Raizer 1967; McQueen et al. 1970; Melosh 1989; Asay and Shahinpoor 1993; Graham 1993; Ahrens and Johnson 1995a, 1995b), and from general articles on shock metamorphism of minerals and rocks such as Wackerle (1962), Ahrens and Gregson (1964), articles in French and Short (1968), Ahrens and O'Keefe (1972), Stöffler (1972, 1974), Raikes and Ahrens (1979), Grady (1980), Ahrens (1993), Langenhorst et al. (1992), and Sharp and DeCarli (2006).

This contribution represents a manual for the recognition of the intensity of shock metamorphism of a rock or sediment sample based on the microscopic appearance of shock effects in the constituent minerals of this sample and on the potential change of its texture by localized or whole rock melting. Therefore, the physics of the formation processes of certain shock effects are not in the main focus, but rather the mode of identification of shock effects. Sources for information on the former aspect are given above.

Previously Proposed Systematics of Progressive Shock Metamorphism

The principle of progressive shock metamorphism was first defined for quartzo-feldspathic (felsic) rocks, including granites and gneisses, nearly simultaneously by Stöffler (1965, 1966), and Chao (1966). Somewhat later, Kieffer (1971) defined this principle for porous sandstone of the Barringer crater, and still later first attempts to define progressive shock metamorphism for chondritic meteorites were published by Dodd and Jarosewich (1979) although Heymann (1967) had already touched on this topic in 1967. Until the year 2000, shock classification systems had been proposed for various terrestrial rocks (Stöffler 1965, 1966, 1971a, 1984; Chao 1966, 1967; Dence 1968; Kieffer 1971; Kieffer et al. 1976b), for lunar rocks obtained by the Apollo landing missions (Stöffler et al. 1980) (Table 4), for Martian meteorites (Stöffler et al. 1986), and for various groups of chondrites (Stöffler et al. 1988, 1991;

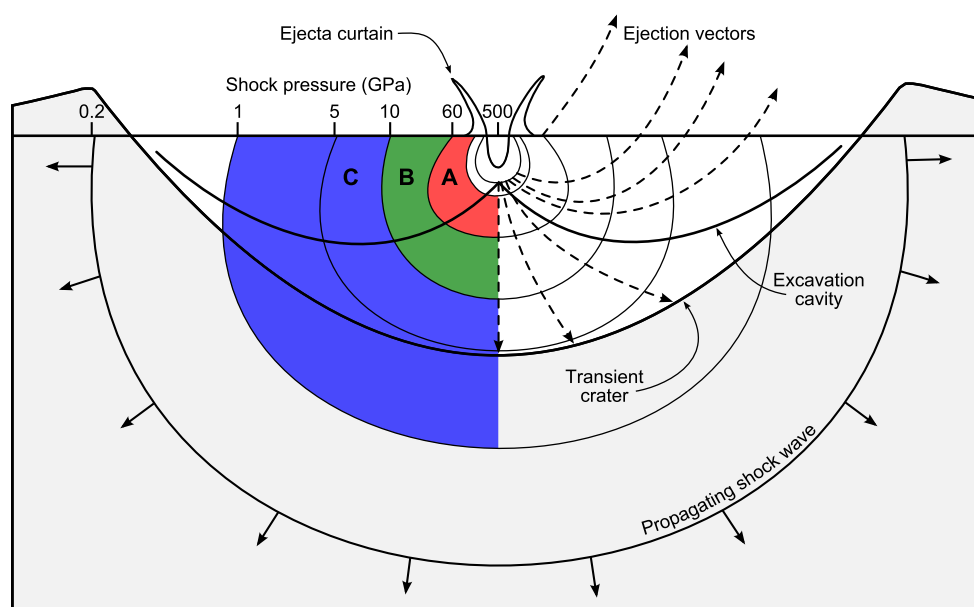


Fig. 1. Schematic representation of the shock zoning and particle motion in an impact crater based on various older models (e.g., Dence et al. 1977; Grieve et al. 1977; O'Keefe and Ahrens 1978; Croft 1980; Kieffer and Simonds 1980; Orphal et al. 1980). For zones A (red), B (green), and C (blue), the main types of shock effects in the major minerals are: A) whole rock melting, B) solid state deformations and phase transitions, and C) mechanical deformations and fracturing. These zones and shock effects are typical for a target composed of crystalline felsic rocks. Maximum shock pressure at the contact of target and projectile (not shown) is assumed to reach 500 GPa corresponding to an impact velocity of about 18 km/s. Graph modified after Stöffler and Grieve (2007).

Bischoff and Stöffler 1992; Scott et al. 1992; Rubin et al. 1997). Shock classification systems for iron meteorites do also exist (e.g., Lipschutz 1968; Jain and Lipschutz 1971; Buchwald 1975), however, these are not subject of this paper.

Around 2000, the International Union of Geological Sciences (IUGS) formed a Subcommittee on the Classification of Metamorphic Rocks (SCMR) that also dealt with "impactites." The work of SCMR was published in a book in 2007 (Fettes and Desmons 2007). This book includes a chapter on "impactites" that contains proposals for the classification of shocked silicate rocks including felsic, mafic, and ultramafic magmatic rocks, chondrites, sedimentary rocks, e.g., sandstone, and unconsolidated sediments (Stöffler and Grieve 2007). In the book "New Views of the Moon" (Jolliff et al. 2006), proposals for the shock classification of lunar rocks by Stöffler (cited in the introductory chapter by Hiesinger and Head 2006) were made for basalts, anorthosites, dunites, troctolites, polymict lithic breccias, impact melt rocks, and regolith.

General Goal of this Contribution

We recognize various problems with the presently available classification systems of planetary silicate rocks and sediments. These are as follows:

1. Separate classification systems have been proposed for shocked rocks or sediments from the Earth, the Moon, Mars, and the asteroids, often leading to unnecessary and confusing duplications regarding specific rock types occurring on all four types of planetary bodies.
2. Classification systems have been published over a long period of time (1965–2007) in various journals and books some of which are not easily accessible.
3. The lack of a compilation of all recommended classification systems in one publication has occasionally led to the incorrect application of a system to a rock type for which it has not been proposed, e.g., application of the shock classification of chondrites to some types of achondrites.
4. In the IUGS classification of impactites (Stöffler and Grieve 2007), Table 2.11.4 is incomplete due to a printing error.

We are convinced that there is an urgent need for a reorganization of the presently existing classification systems of shocked rocks and sediments on the basis of a uniform concept. A compilation of such a reorganized systematics of shocked rocks should be presented in one single publication in which individual classification systems are focused only on rock types *independently* of their source planets or planetoids.

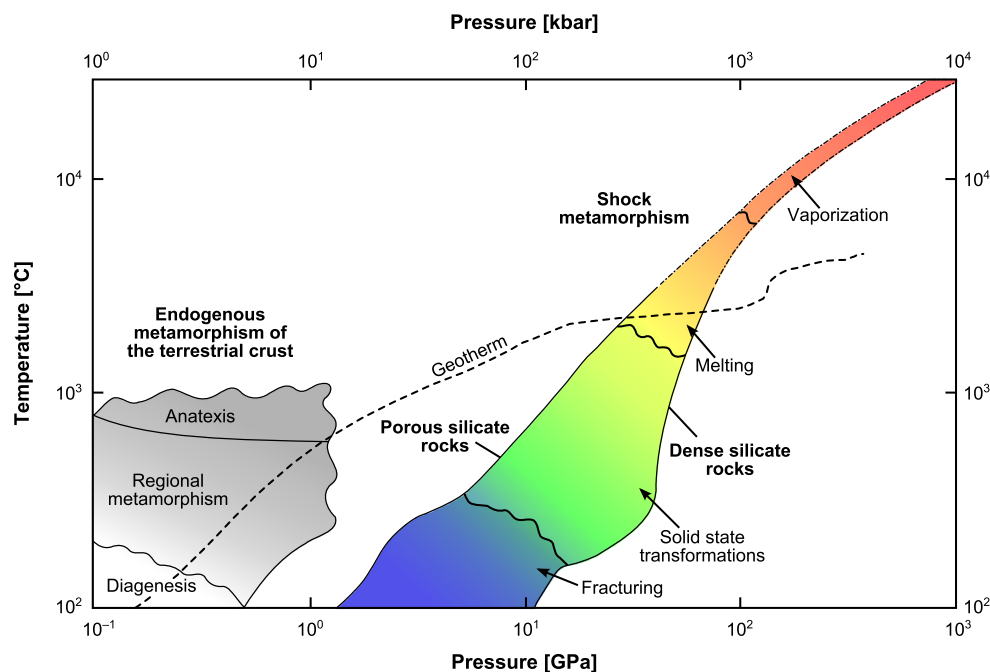


Fig. 2. Pressure–temperature fields for shock metamorphism of silicate rocks in comparison with endogenous metamorphism of the terrestrial crust. The upper curve of the field for shock metamorphism holds for porous silicate rocks, and the lower curve for dense crystalline silicate rocks based on data for quartz (Wackerle 1962) and porous sandstone (Ahrens and Gregson 1964; Kieffer et al. 1976a). The temperature estimates for the slightly dashed boundaries of the P - T field of shock metamorphism (upper part of “melting” and “vaporization”; yellow to orange) are based on theoretical considerations by Davies (1972); the geotherm for continental crust is from Anderson (1981). Modified from Stöffler and Langenhorst (1994).

FORMATION CONDITIONS AND GEOLOGICAL SETTING OF IMPACTITES AND SHOCKED ROCKS

General Aspects of Interplanetary Collisions

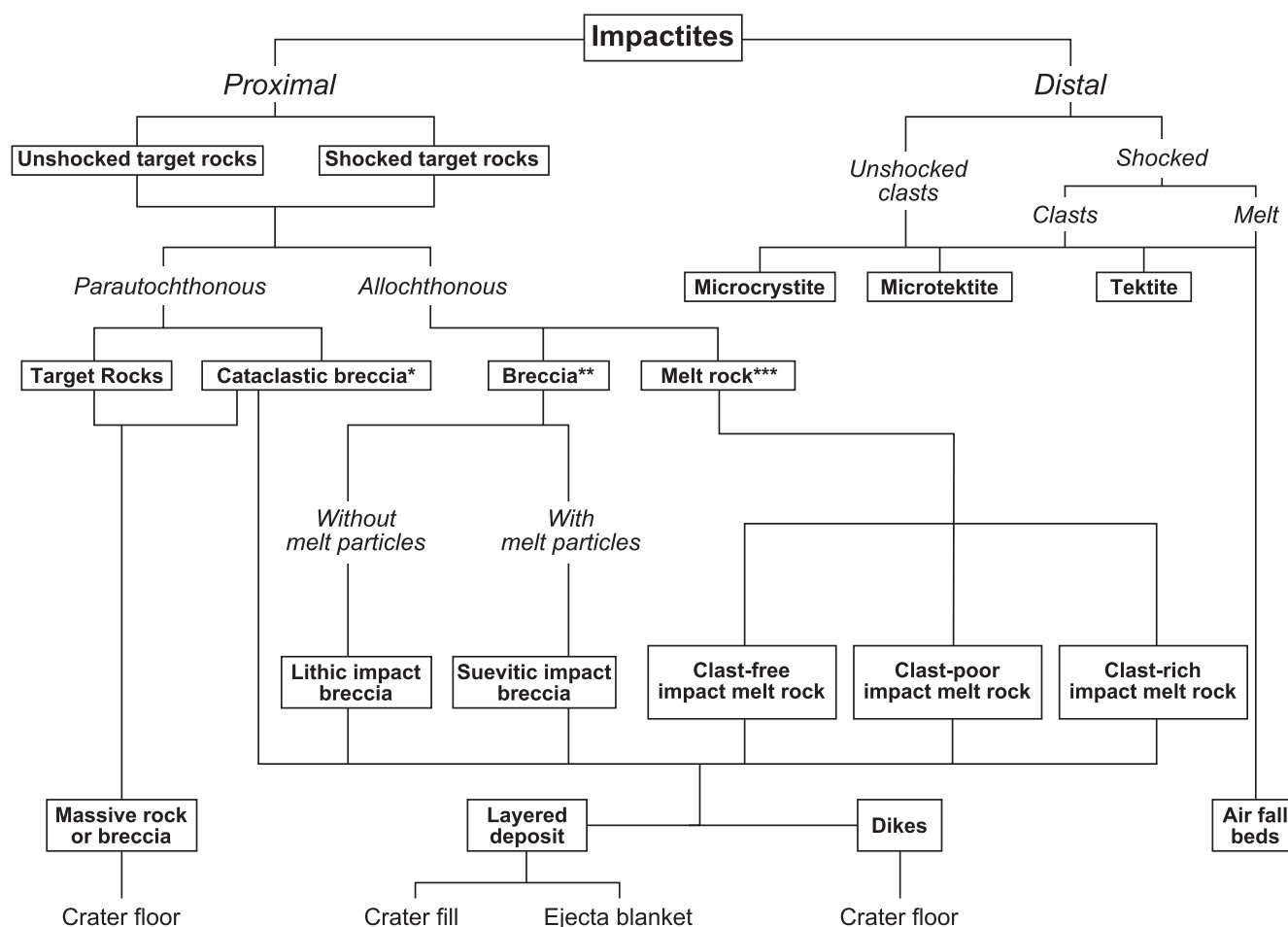
There is a large variety of geological scenarios resulting from interplanetary collisions that need to be considered in order to understand the geological setting of *impactites* in general and of *shocked rocks* in particular on the various types of planetary bodies. The conditions under which impactites (alternatively called “*impact rocks*”) and shocked rocks are formed, depend on

1. size and hence the gravitational properties of the impacted planetary body,
2. relative impact velocities of impactor and target body,
3. relative sizes of the impactor and target body,
4. presence or lack of an atmosphere and water on a planet, and
5. physical properties of impactor and target, e.g., their density, porosity, composition, etc.

We attempt to characterize the different scenarios resulting from the listed conditions in a number of graphs (Figs. 3–6).

Formation of Impactites in Single Impacts and Geological Setting of Shocked Rocks

Most detailed information about the types of impactites and their geological setting with respect to the parent impact crater can be obtained from the Earth and, to some degree, from the Moon and Mars. This is shown in Figs. 3 and 4. The terrestrial case is most clear because the known and accessible impact formations are related to specific impact craters whose ejecta formations are not overlapping. In other words, on Earth we deal with impactites from *single impacts* in contrast to all other planetary bodies, where multiple impact metamorphism has to be taken into account. The systematics of impactites shown in Fig. 3 is fundamental for understanding the geological setting of “shocked rocks.” It is also the basis for understanding the effects of *multiple impacts* that are best known from the impact cratering history of the Moon, as documented by the extensive remote sensing data from the lunar surface and crust and by the analysis of lunar samples from the Apollo missions. For these samples, the geological setting with respect to local small craters and to more distal large craters, including the large multiring basins such as Imbrium and Nectaris, is rather well known in some cases (e.g., Jolliff et al. 2006; Stöffler et al. 2006).



*Typically monomict

**Generally polymict, but can be monomict, e.g., in a single target lithology

***Includes hyaline (glassy), hypocrystalline, and holocrystalline varieties

Fig. 3. Classification of impactites from single impacts based on geological setting, texture, and degree of shock metamorphism as manifested by impact craters on Earth (modified from Stöffler and Grieve 2007); see text for details.

According to Figs. 3 and 4, “shocked rocks” resulting from a *single impact* occur in the following different settings (see also Table 1). In the *proximal impactites*, they are constituents of allochthonous polymict breccias and impact melt rocks, i.e., clasts in polymict breccias (lithic and suevitic breccias) and in clast-bearing impact melt rocks. They are also represented by monomict breccias but only in a very low degree of shock metamorphism. Impact melt rocks are the product of shock-induced whole rock melting, the highest degree of shock metamorphism. In the *distal impactites*, mineral and rock clasts of low degree of shock are absent in the strewn fields of tektites (Koeberl 1994; Stöffler et al. 2002), which represent crater ejecta of the highest degree of shock (i.e., melt particles). In impact-related *air fall beds*, fine-grained material of a wide range of different shock stages is

present such as shocked mineral clasts (e.g., quartz with planar deformation features) as well as melt spherules (Alvarez et al. 1980; Bohor et al. 1987; Grieve et al. 1990). It should be noted here that the main type of terrestrial “suevitic breccias” (“secondary suevite” as defined in Stöffler et al. 2013) are not expected to exist on atmosphere- and water-free planetary bodies, as the formation of this type of suevite requires water or other volatiles and the interaction of hot melt with these components. However, “primary suevite” (fallback material of the ejecta plume) may be possible (see also Artemieva et al. 2013).

The main types of impactites are shown by means of photographs and graphs obtained mainly from various impact formations of terrestrial craters, from lunar samples, and from meteorites (Figs. 7–12).

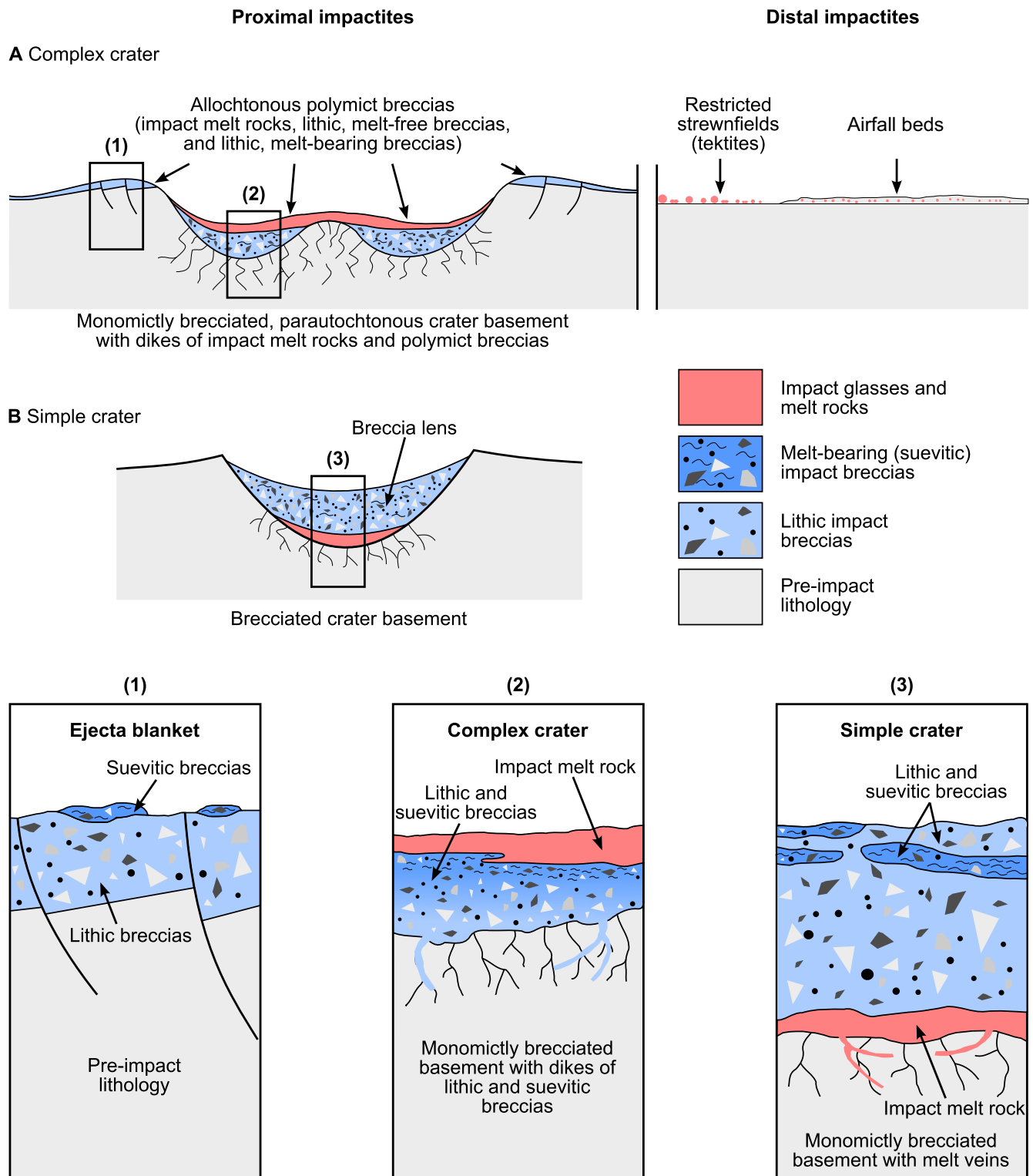


Fig. 4. Generalized sketch of the geological setting of proximal and distal impactites on Earth for simple and complex craters. Diameters of simple craters range from tens of meters to about 5 km, and diameters of complex craters with central uplift from ~5 km to ~60 km. Modified from Stöffler and Grieve (2007).

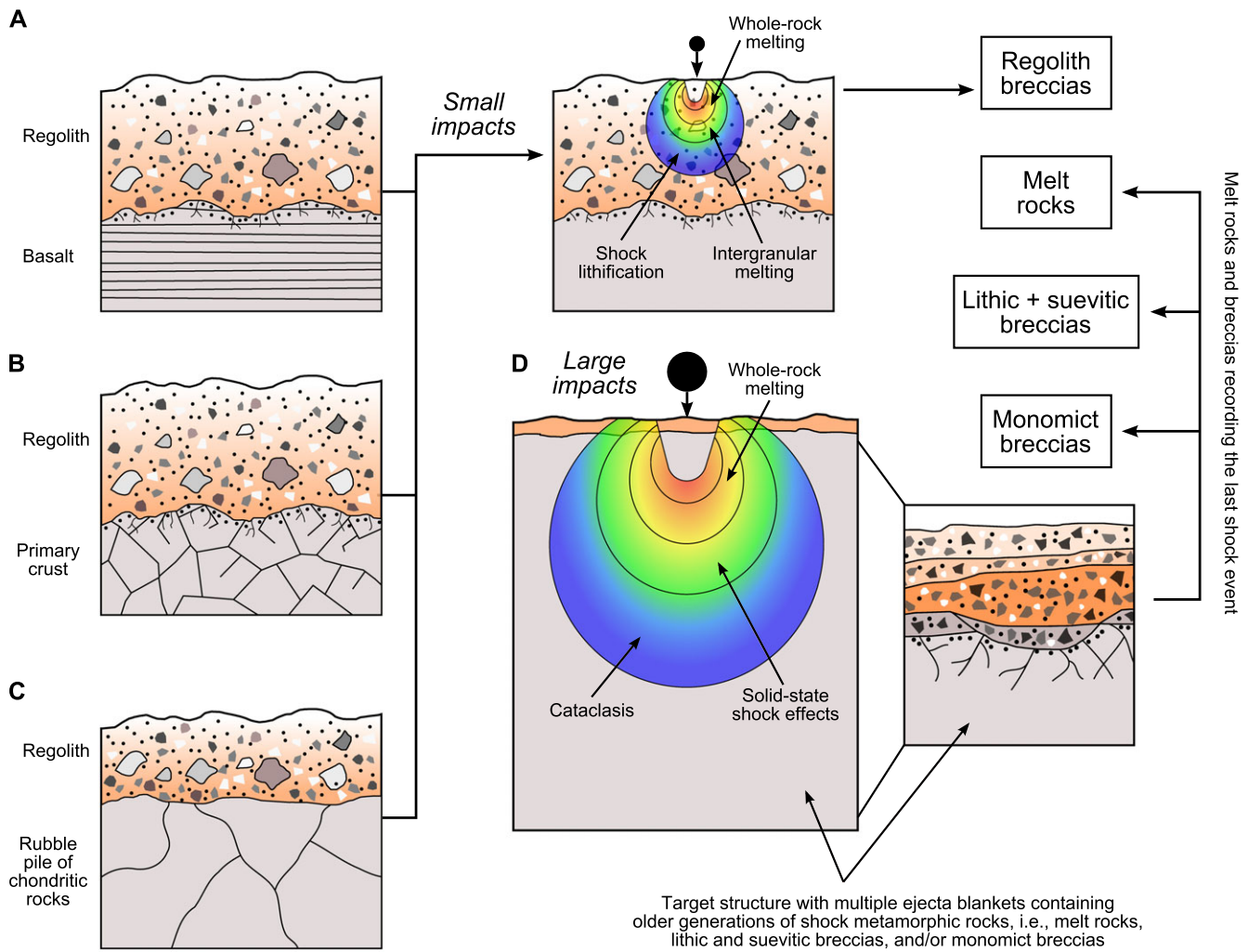


Fig. 5. Scenarios for planetary bodies (Moon, Mars, and asteroids) affected by multiple shock metamorphism. (A), (B), and (C) represent small-scale impacts leading to the formation of regolith breccias on Mars, the Moon, and on asteroids, respectively, and (D) holds for large-scale impacts leading to impact melt rocks, lithic and suevitic breccias, and monomict breccias (cataclastic rocks of very low degree of shock metamorphism), and for multiply shocked rocks embedded in superimposed layers of ejecta blankets in the upper part of the planetary crusts. Suevitic breccias known from craters on Earth may be only present on Mars because the presence of volatiles is required for their formation; they are not known from lunar samples and asteroidal meteorites.

Effects of Multiple Impacts

Scenarios characterizing the effects of *multiple impacts* are shown in Fig. 5 and in a tabulation on the systematics and nomenclature of impactites resulting from multiple impacts (Table 1). *Small impacts* occur on planetary bodies without an atmosphere with a very high frequency and lead to the formation of unconsolidated surface layers called *regolith* (see, e.g., Hörz and Cintala 1997; Jolliff et al. 2006; and references therein). They are best known from the Moon (for references, see Jolliff et al. 2006) and have been confirmed to exist on asteroids. Such regoliths contain a mixture of components formed by repeated

impacts and imply all stages of shock metamorphism, ranging from unshocked mineral and rock clasts to shocked clasts, and to shock-fused material (Fig. 11). The latter is represented by melt particles (so-called agglutinates) and melt spherules. Additional small impacts into regolith lead to the formation of *regolith breccias* (Fig. 11) consolidated by shock lithification (“mechanical compaction” or “sintering”) and intergranular incipient melting of fine-grained material at higher pressures as illustrated schematically in the upper central part of Fig. 5.

If we consider increasingly *larger impacts*, more and more of the deeper planetary crusts, so far unaffected by impact metamorphism, are transformed into shock-

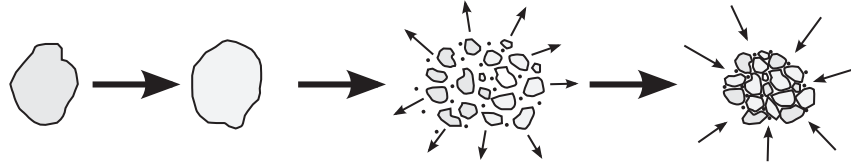
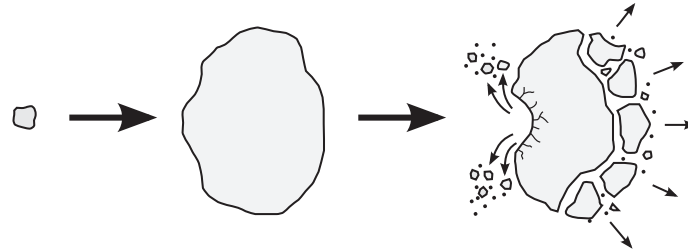
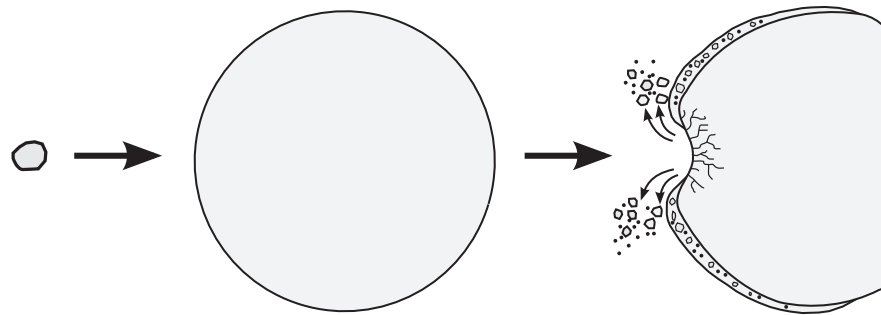
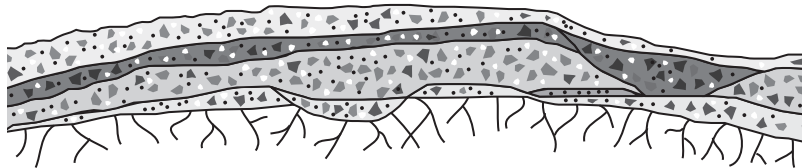
A Low-velocity approach – contact binary asteroid**B** Impact – fragmentation – escape or reaccrction**C** Cratering – ejection – spallation and escape or reaccrction**D** Cratering – ejecta deposition and partial escape of ejecta**E** Multiple cratering, multiple ejecta blankets (megaregolith)

Fig. 6. Effects of interplanetary collisions for variable size ratios of impactor and target bodies; see text for details. Note that the approach velocities increase from (A) to (D). Modified after Stöffler et al. (1988).

metamorphic rocks. These processes lead to the whole range of allochthonous and parautochthonous, polymict and monomict breccias shown in Figs. 3–5: lithic breccias, suevitic breccias, clast-free to clast-rich impact melt rocks, and monomict cataclastic breccias. They are contained in layers of ejecta blankets and breccia lenses inside the craters; some of them are also located in the crater basements as dikes or monomict breccias (compare

Fig. 4). Continuously repeated large impacts on atmosphereless and geologically inactive terrestrial planets, moons, and very large asteroids (e.g., Ceres, Vesta) produce superimposed layered impact formations, sometimes called “megaregolith” (Hartmann et al. 1986; Jolliff et al. 2006). This complex structure of the upper crusts of these bodies contain several generations of shocked rocks (Figs. 5 and 6E). It may be difficult to

Table 1. Systematics and nomenclature of impactites resulting from single impacts (on Earth) and from multiple impacts (on the Moon, Mars, or asteroids); graph modified from Stöffler et al. (2006) and Stöffler and Grieve (2007), see also Fig. 3; see Figs. 7–10 and 12 for impact breccias, impact melt rocks, and shocked rocks, and Fig. 11 for regolith and regolith breccias.

I. Classification of impactites from single impacts			
Proximal impactites			
Shocked rocks ^a	Impact melt rocks ^b	Impact breccias	
5–7 stages of progressively increasing shock metamorphism ^c	Clast-rich	Cataclastic (monomict) breccia	
	Clast-poor	Lithic breccia (without melt particles) ^d	
	Clast-free	Suevitic breccias (with melt particles) ^d	
Distal impactites			
Tektites ^e	Microtektites ^e	Microkrystites ^e	Air fall beds ^f
II. Classification of impactites from multiple impacts ^g			
Impact detritus (unconsolidated impactoclastic debris)	Shock-lithified impact detritus (consolidated impactoclastic debris)		
Regolith ^g	Regolith breccias ^h	Lithic breccias ⁱ	

^aEither as clasts in polymict breccias and impact melt rocks or as zones in the crater basement.

^bMay be subclassified into glassy, hypocrystalline, and holocrystalline varieties.

^cDepending on type of rock.

^dGenerally polymict but can be monomict in a single lithology target.

^eImpact melt with minor fraction of admixed shocked and unshocked clasts.

^fPelitic sediment with melt spherules, shocked, and unshocked clasts (in marine or terrestrial environment).

^gKnown from lunar rocks (Apollo and Luna) and from lunar, Martian, and asteroidal meteorites.

^hBreccias with intergranular melt and melt particles; contain solar wind gases.

ⁱBreccias with intergranular melt and with mineral and lithic clasts of all stages of shock metamorphism except for cogenetic melt particles (previously called fragmental breccias).

identify multiple shock events recorded in a sample that was either collected by space missions or was ejected to an Earth-crossing orbit and found on Earth as a meteorite. The procedures to detect multiple consecutive shock events and their intensity in such a sample will be discussed in detail in the chapter *Manual for the classification of a shock-metamorphosed rock or sediment*.

Impact Processes Recorded in Lunar, Martian, and Asteroidal Meteorites

The final topic of this chapter is devoted to meteorites and their parent bodies. Meteorites are known so far from the Moon, from Mars, and from different types of asteroids as indicated by the major groups of chondritic, achondritic, and iron meteorites. First of all, there is a distinct difference between lunar, Martian, and asteroidal meteorites regarding the impact-induced formation conditions and the geological and lithological characteristics of their source regions. In addition, details of the geological conditions under which a specific meteorite was affected by shock compression are not known in contrast to impactites and shocked rocks resulting from terrestrial impact craters.

Lunar and Asteroidal (Chondritic and Achondritic) Meteorites

Lunar and asteroidal meteorites have in common that they are derived from three main groups of geological formations:

1. surficial regolith layers and *regolith breccias* (Figs. 5 and 11),
2. large-scale impact formations (“megaregolith”) containing small to large clasts of *unshocked to strongly shocked lithologies*, *monomict breccias*, *polymict lithic breccias*, and *impact melt rocks* (Figs. 5 and 7–9), and
3. volcanic (basaltic) to plutonic lithologies exposed at the planetary surface or near-surface, as observed in the case of the Moon and asteroid Vesta (HED meteorites, Fig. 12).

We consider the formation of *regolith breccias* (Fig. 11) in some more detail. As illustrated in Fig. 5, small-scale impacts produce differently shocked regolith materials within the zones of decreasing degree of shock metamorphism if shock pressures above the Hugoniot elastic limit engulf the complete regolith layer or part of it. This leads to shock-lithified, consolidated regolith, i.e., to a regolith breccia by definition. In a theoretical

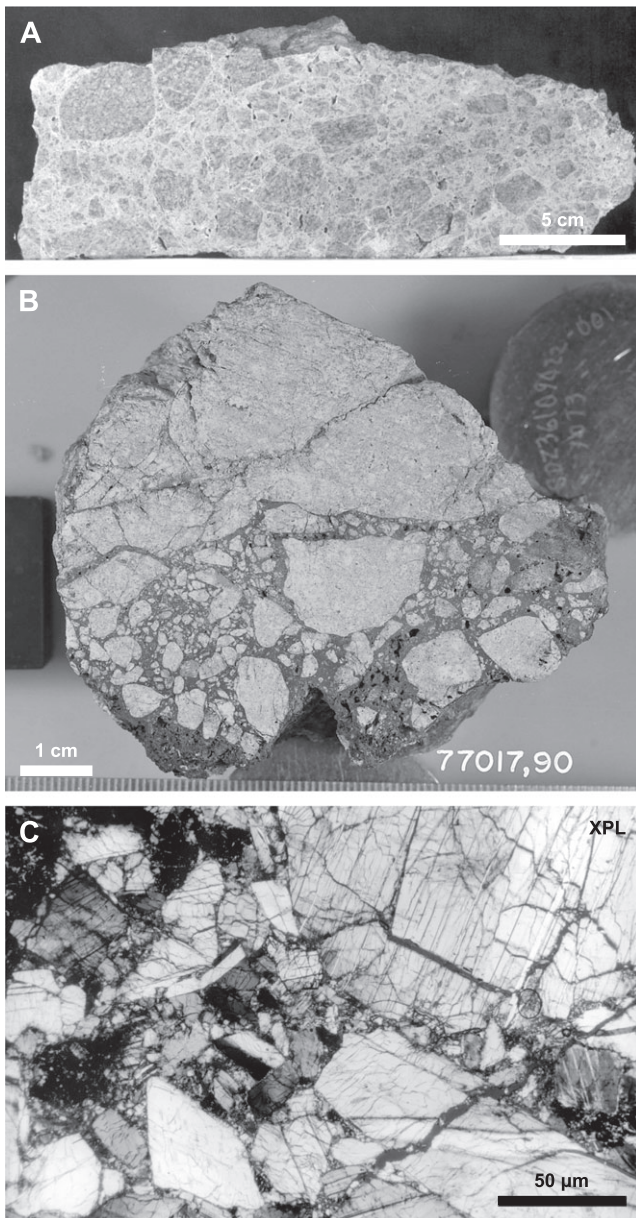


Fig. 7. Terrestrial and lunar monomict impact breccias. A) Monomict granite breccia from Schmähingen, Ries crater, Germany. B) Lunar monomict anorthositic gabbro breccia 77017 (Apollo 17); lower part contains intruded impact melt (black). C) Monomict lunar anorthosite breccia 65015,16 (Apollo 16); microphoto with crossed polarizers. Note intergranular brecciation. Photographs from Stöffler et al. (2006).

scenario that is strongly supported by shock recovery experiments with lunar and chondritic detritus (see Table 13 and references therein), regolith breccias must form in the zones of intermediate shock pressures, in other words predominantly in shock stages S3–S4 of Table 11. At lower shock intensities, the regolith remains unconsolidated, whereas at higher shock

intensities, it gradually undergoes partial or complete melting. Because of the high frequency of small-scale impacts, new melt particles and agglutinates (glass-bonded and melt-dominated aggregates of melts and clasts) are continuously produced over long periods of time. Due to differences in gravitation and distance from the Sun, small particles impact the surface of the Moon with higher velocities than the surface of the Main Belt asteroids (e.g., Vesta). This leads to a much higher formation rate of melt particles (agglutinates and spherules) on the lunar surface compared to asteroids like Vesta. The latter case is reflected by the texture and composition of HED meteorites (howardites, eucrites, and diogenites) that are assumed to originate from Vesta (e.g., McSween et al. 2011). In these meteorites, melt particles are only rarely found and melt-rich regolith breccias of the lunar type are lacking. On the other hand, medium-scale impacts deliver fresh and unshocked or weakly shocked material from the subregolith basement into the regolith. This process also operates differently on the Moon and on Vesta. Vesta appears to represent a rather specific case regarding the formation of impactites. For example, the majority of shocked HED meteorites are affected by subsequent thermal metamorphism. Actually, many HED meteorites are the product of a complex interaction of a magmatic crystallization process and repeated impact processes interrupted by phases of thermal metamorphism as shown by Metzler et al. (1995) (for details see legend of Fig. 12).

For *chondrites* and for all types of *lunar and achondritic meteorites*, such as plutonic and volcanic rocks as well as monomict breccias, polymict breccias, and impact melt rocks, we observe a rather wide range of the intensity of shock metamorphism compatible with the impact and ejection conditions on their parent bodies (e.g., Bischoff and Stöffler 1992). An important fact is that among asteroidal meteorites, we know unshocked samples as well as very strongly shocked samples, as represented by impact melt rocks (although mostly as clasts within polymict breccias, e.g., Lunning et al. 2016). This requires a consideration of the potential collisional scenarios of asteroidal bodies (Hartmann 1979, Stöffler et al. 1988; see Fig. 6). An approach of two bodies with very low velocity leads to a contact binary asteroid and consequently to no ejection of fragments into Earth-crossing orbits (scenario A of Fig. 6). Such ejections are possible in scenarios B, C, and D. In these scenarios, the potential delivery of a meteorite to Earth depends on the approach velocity of the two colliding bodies that we consider to increase from B to D. In case of scenario D, later small-scale impacts may eject a wide range of differently shocked fragments from different locations

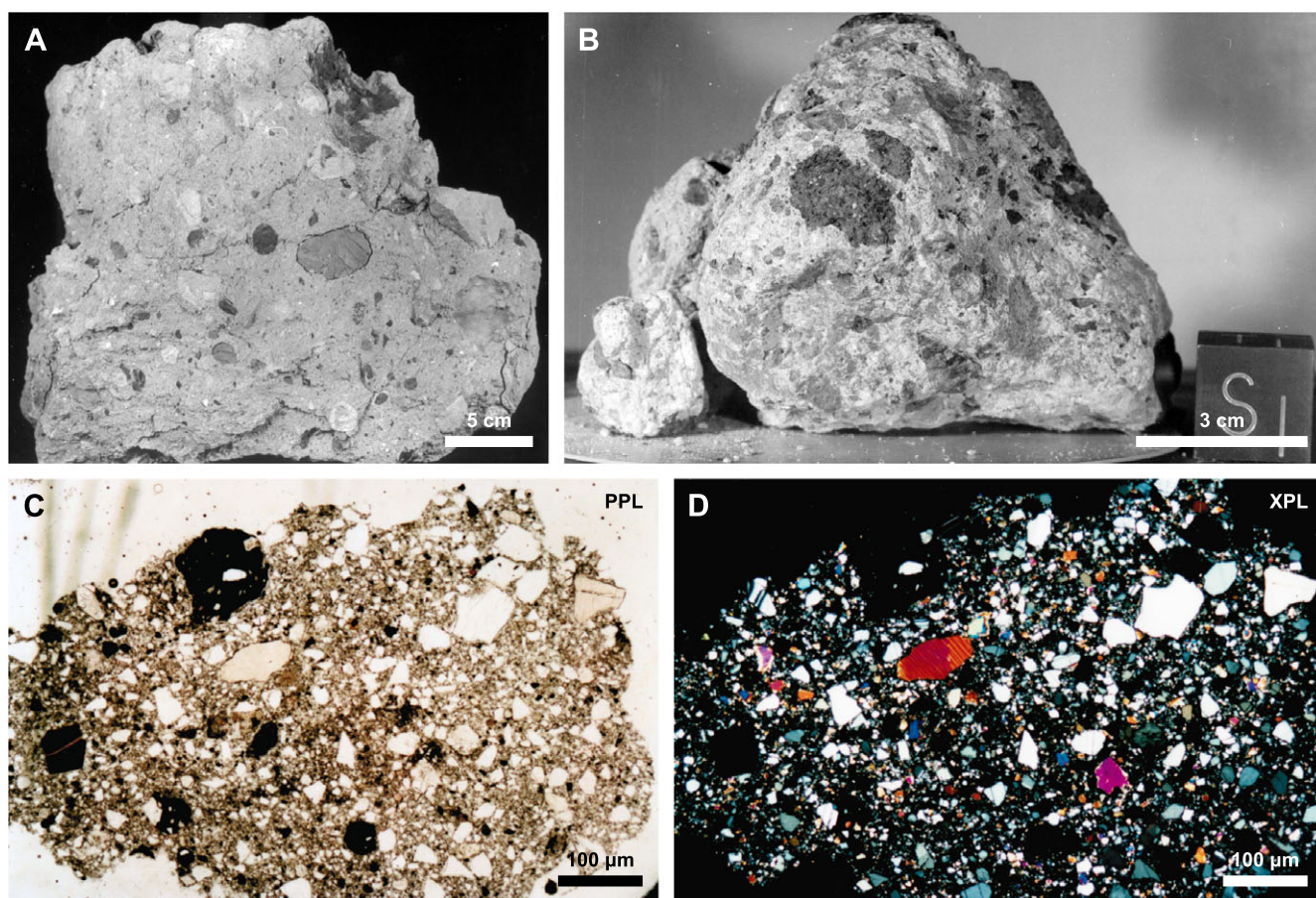


Fig. 8. Terrestrial and lunar polymict lithic impact breccias. A) Sample from the continuous ejecta blanket (Bunte breccia) of the Ries crater (Bschor quarry near Ronheim) with clasts of various sedimentary rocks from the upper 600 m of the target embedded in a clastic matrix. B) Lunar sample 67015 from the rim of North ray crater (Apollo 16) with dark clast of impact melt rocks and light clasts of anorthositic and granulitic rocks. C, D) Thin section images of the lunar lithic impact breccia 14082,46 (Apollo 14) with various types of lithic and mineral clasts (glassy impact melt rocks with dark color, plagioclase, pyroxene, and olivine) in a fine-grained clastic matrix. Left image: plane-polarized light (PPL), right image: cross-polarized light (XPL). (A, B) from Stöffler et al. (2006); (C, D) from Lingner (1989).

of the nearly global ejecta blankets on the target asteroid leading finally to multiple ejecta blankets (scenario E).

Martian Meteorites

Meteorites from Mars represent a special case because of the relatively high escape velocity and the presence of an atmosphere on Mars. The most important observations are as follows.

1. Almost all meteorites are magmatic rocks (mafic and ultramafic), comprising mainly basalts (shergottites), a few pyroxenites (nakhlites and orthopyroxenite), one dunite (chassignite), and so far only one regolith breccia of basaltic provenance (McCubbin et al. 2016; Hewins et al. 2017).
2. All meteorites display shock effects and the related shock pressures range from about 5–10 GPa to 55 GPa (Fritz et al. 2005).

3. Numerical modeling of the ejection process from Mars indicates that the minimum shock pressure for ejection and delivery to Earth is about 10 GPa (Artemieva and Ivanov 2004).
4. Ultramafic meteorites display relatively low shock metamorphism (~5 to ~30 GPa), whereas the mafic types are of a distinctly higher degree of shock metamorphism (~30 to ~55 GPa).

It can be tentatively concluded that the observed shock metamorphism of Martian meteorites is primary and occurred during the impact process that ejected the meteorites. The meteorites were ejected from impact craters formed in the surficial basaltic crust in the case of mafic shergottites and from places where somewhat deeper crustal rocks were exposed in the case of ultramafic meteorites. Moreover, the regions from which these meteorites were ejected appear to lack substantial layers of older impact ejecta formations and obviously

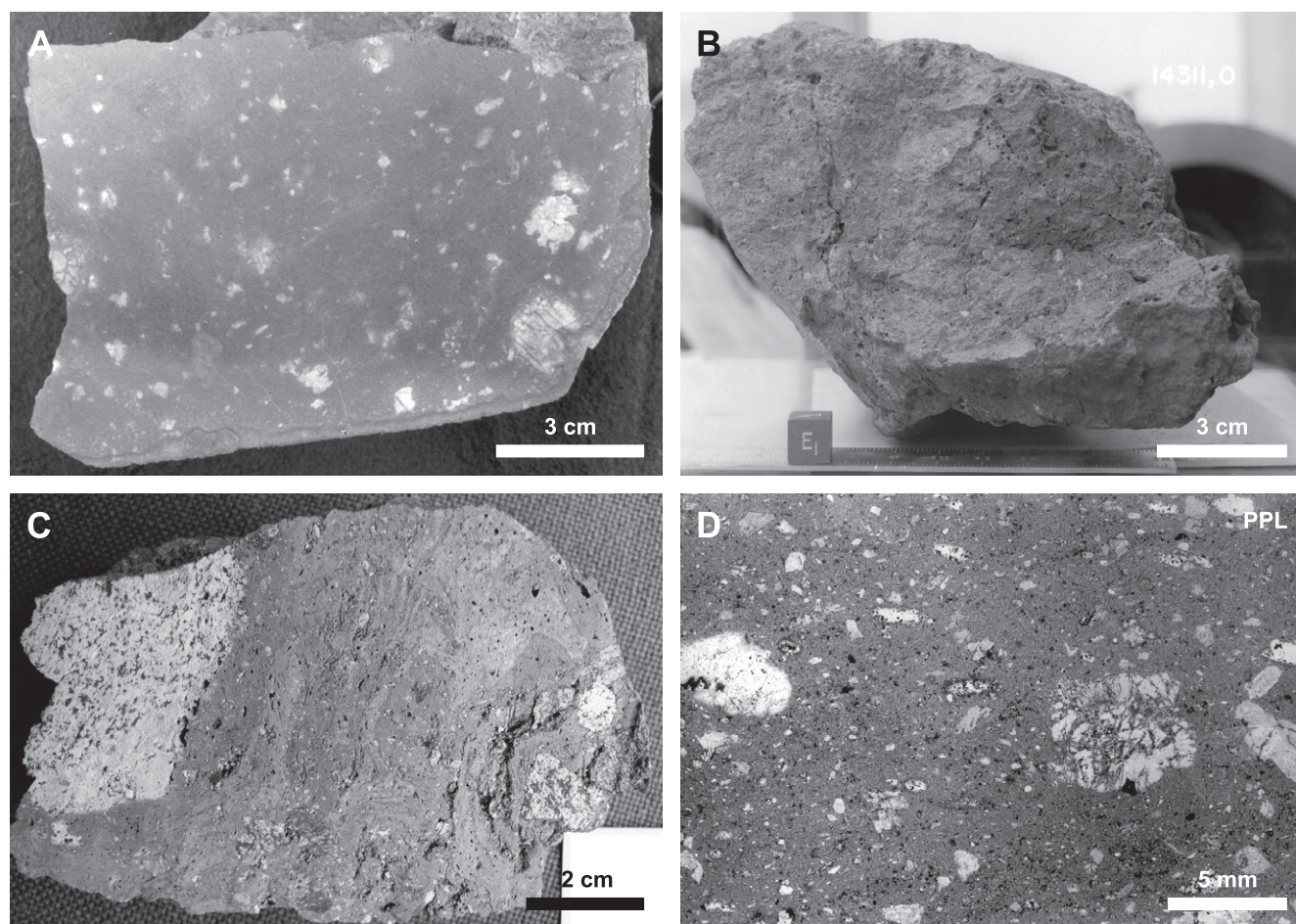


Fig. 9. Terrestrial and lunar impact melt rocks. A) Cut surface of a clast-bearing impact melt rock from Kanta Ahvenieniemi, Kärnä island, Lappajärvi crater, Finland (sample La 41), showing white to gray lithic and mineral clasts in a dark gray aphanitic crystalline matrix. B) Clast-bearing lunar impact melt rock 14311 with aphanitic crystalline matrix (Apollo 14). C) Clast-bearing impact melt rock with flow texture and finely crystallized matrix from Polsingen quarry, Ries crater, Germany. Note strongly shocked, porous granitic clast on the left. D) Thin section image taken in plane-polarized light of clast-bearing impact melt rock with mineral clasts embedded in a fine-grained crystalline matrix from Lappajärvi crater, Finland (sample La 26). (A), (B), and (D) from Stöffler et al. (2006).

were not all covered with regolith, as polymict lithic breccias and regolith breccias are very rare among Martian meteorites (McCubbin et al. 2016). This is compatible with the young ages of the basaltic (mafic) meteorites (Nyquist et al. 2001) and indicates that material from old, heavily cratered Martian highlands seems to be missing so far.

SHOCK EFFECTS APPLICABLE TO THE DEFINITION OF PROGRESSIVE STAGES OF SHOCK METAMORPHISM

Shock Effects in Minerals

Shock waves produce characteristic effects in minerals unknown or different from any effects induced by static high-pressure/high-temperature conditions such

as those observed in terrestrial endogenous metamorphism (Fig. 2). Shock effects are defined as permanent residual effects to be observed after the passage of the shock wave, i.e., after pressure and temperature release to ambient P - T conditions. The main types of shock effects are with increasing shock pressure: mechanical deformations, phase transformations, decomposition, and/or melting.

We present first a brief list of common rock-forming minerals with effects diagnostic of a certain shock pressure level (for more details, see Table 2 and references therein). The shock effects are listed below in a sequence of increasing shock pressure and are tabulated in Figs. 13–19. Typical microscopic images illustrating the different shock effects for each mineral are shown in Figs. S1–S7 of the supporting information.

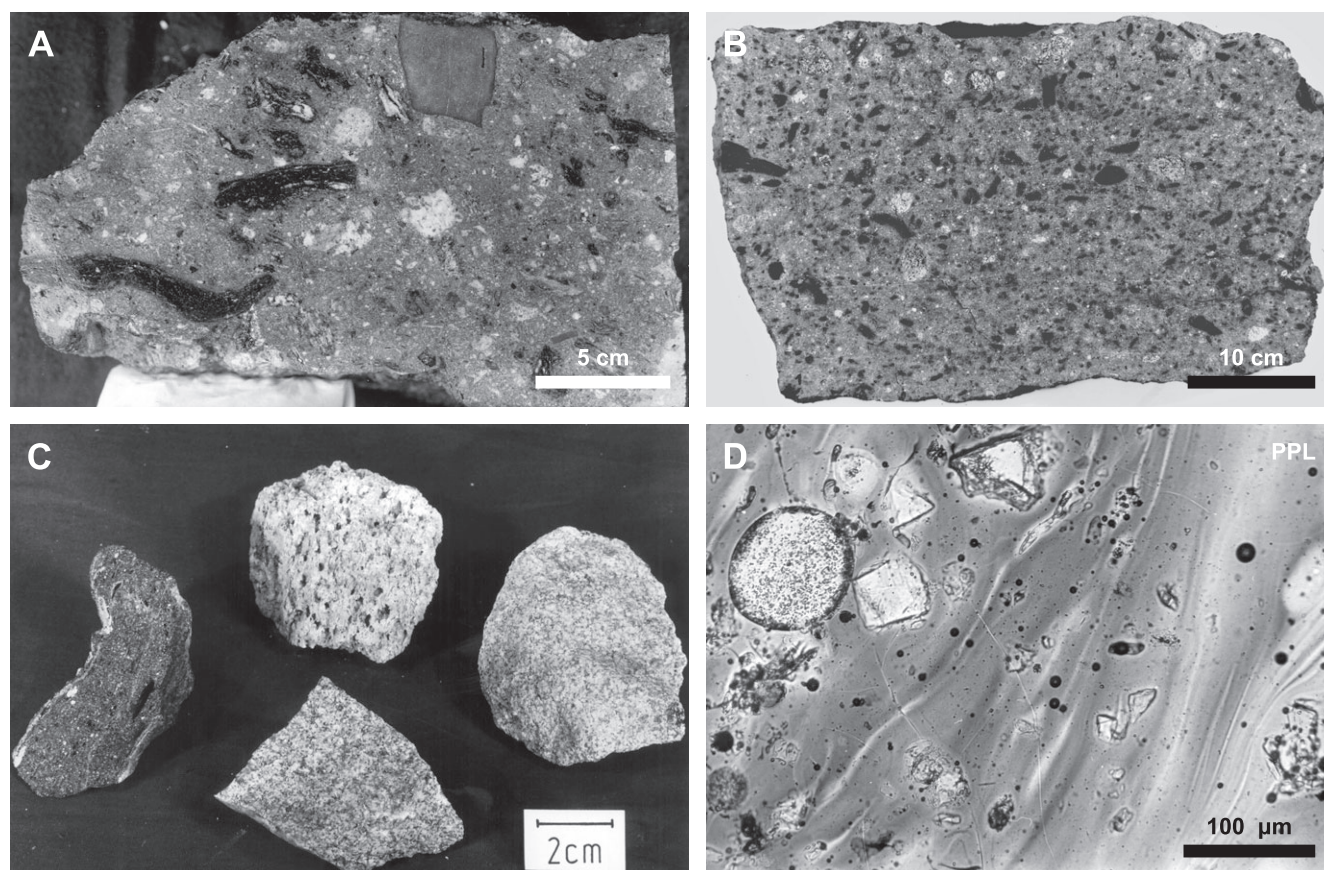


Fig. 10. Suevitic breccias from terrestrial impact craters. A) Suevitic breccia with clastic matrix and melt inclusions (black) and crystalline rock clasts (gray to white) from Mien crater, Sweden. B) Cut surface of a suevitic breccia ("outer suevite" on top of the ejecta blanket), Ries crater, Germany. Dark inclusions are melt particles, and whitish to speckled gray inclusions are predominantly clasts of crystalline rocks representing all stages of shock metamorphism (see C). C) Glassy melt inclusion (black; left side) and three inclusions of lithic clasts of different degree of shock metamorphism from the outer suevite of the Ries crater, Germany. Lower center: unshocked; right side: moderately shocked with diaplectic quartz and feldspar glass; and upper center: strongly shocked with vesiculated feldspar glass, coesite-bearing diaplectic quartz glass, and pumice-like texture. D) Flow-textured and vesiculated glass of granodioritic composition with inclusions of mineral clasts (mainly quartz) from a melt particle of the suevite of Otting, Ries crater, Germany (sample 620a); (A) and (D) from Stöffler et al. (2006) and Stöffler (1984), respectively.

1. *Quartz* (Fig. 13): Undulatory extinction, mosaicism, planar fractures (pf), feather features, planar deformation features (pdf), stishovite, complete isotropization (diaplectic glass), coesite, and normal vesiculated glass (lechatelierite).
2. *Plagioclase* (Fig. 14): Undulatory extinction, mosaicism, planar deformation lamellae (pdf), partial isotropization, complete isotropization (diaplectic glass), hollandite-structured high-pressure phase (lingunite?), jadeite (in case of albitic plagioclase), and normal flow-textured glass.
3. *Alkali feldspar* (Fig. 15): Undulatory extinction, mosaicism, planar deformation lamellae (pdf), partial isotropization, complete isotropization (diaplectic glass), hollandite-structured high-pressure phases (lingunite), and normal flow-textured glass.
4. *Olivine* (Fig. 16): Undulatory extinction, mosaicism, planar fractures, planar deformation features, transformation to wadsleyite, ringwoodite, or ahrensite, partial to complete recrystallization, and melting and subsequent formation of polycrystalline olivine.
5. *Pyroxene* (Fig. 17): Undulatory extinction, mosaicism, mechanical twinning, planar deformation features, loss of pleochroism (if present), transformation to majorite, akimotoite, and bridgmanite, decomposition to oxides, and mixing with flow-textured feldspar glass (if present).
6. *Amphibole* (Fig. 18): Undulatory extinction, mosaicism, mechanical twinning, planar deformation features, loss of pleochroism, transformation to majorite (garnet-structure), decomposition to oxides, and mixing with flow-textured feldspar glass (if present).

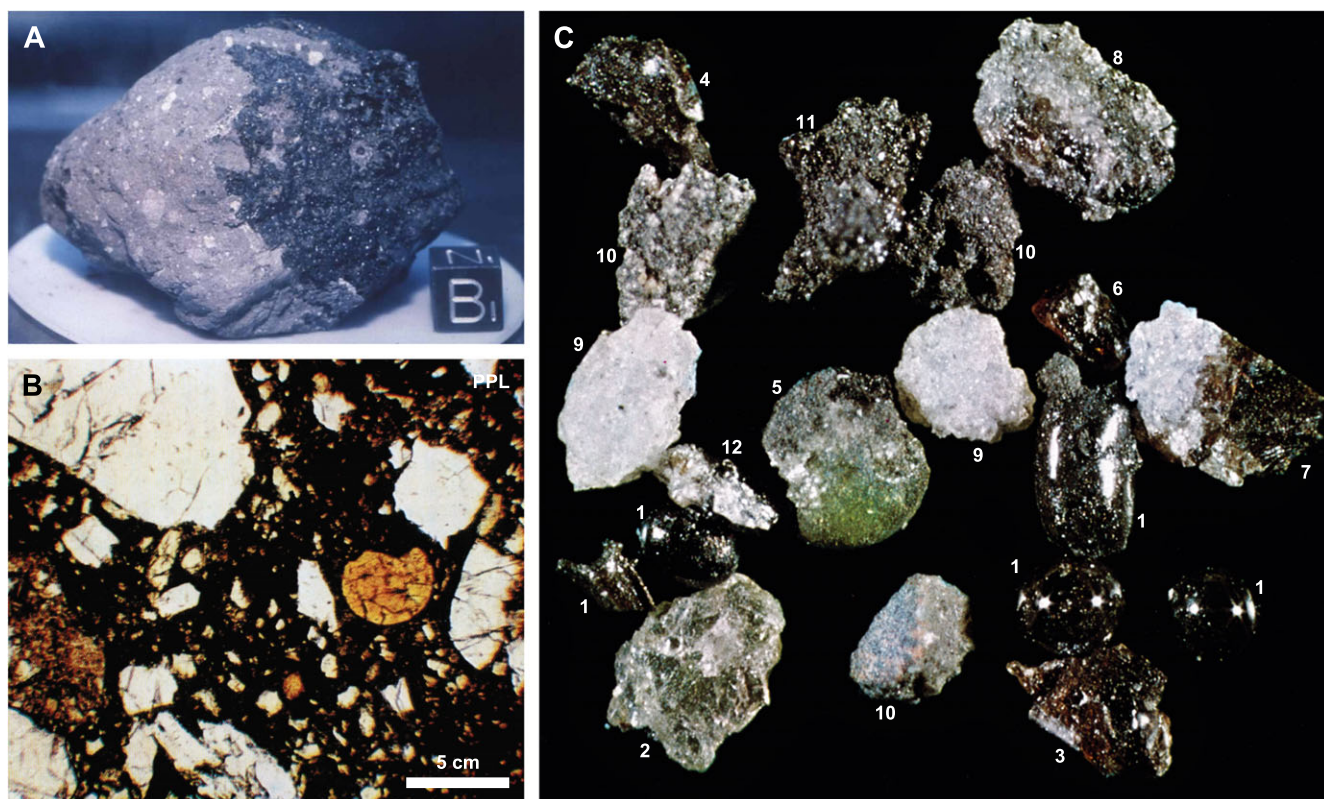


Fig. 11. Lunar regolith breccia and regolith particles. (A) Regolith breccia 14055 (Apollo 14) covered with a splash of impact melt and microimpact craters best visible on the dark melt splash. The sides of the cube are 1 cm in dimension. Photograph from NASA and Knöll (1979). (B) Thin section image taken in plane-polarized light of a regolith breccia from Apollo 11 with mineral and lithic clasts and a melt sphere in a dark, melt-bearing matrix. Photograph from von Engelhardt (1970). (C) Lunar regolith particles from Apollo 11 with particles of glass and of lithic and mineral clasts. The size of particles is in the millimeter range; the photograph is from von Engelhardt (1970). Numbers next to the particles: 1 = spherical and rounded glass bodies, 2 = fragment of green glass, 3 = fragment of red glass, 4 = fragment of dark glass, 5 = fragment of green glass sphere, 6 = pyroxene, 7 = coarse grained basalt, 8 = fine-grained basalt, 9 = anorthosite, 10 = regolith breccia, 11 = regolith breccia with glassy crust, and 12 = feldspar.

7. *Biotite* (Fig. 19): Kink bands together with some undulatory extinction or mosaicism, loss of pleochroism, planar deformation features, decomposition into oxides, and mixing with flow-textured feldspar glass (if present).

8. *Accessory or minor minerals* such as garnet, sillimanite, cordierite, zircon, ilmenite, Fe-sulfides, magnetite, graphite, and others also display shock effects; however, they are not prime criteria for the shock classification of their host rocks.

Regarding “mosaicism” it should be pointed out that there is a strong indication for a variation of its intensity with increasing shock pressure. Especially in minerals (1) to (4), mosaicism seems to first increase with pressure and then decrease before its host mineral transforms to diaplectic glass, or in the case of olivine, before it melts and (re)crystallizes (e.g., Reimold and Stöffler 1978; Bauer 1979).

A further comment concerns “high-pressure phases.” Although the transformation of the listed minerals into high-pressure phases is included in the list, we want to emphasize here that high-pressure phases are not reliable indicators of specific stages of shock metamorphism and are therefore not included in Table 2. They appear to crystallize during the extended phase of shock pressure and temperature release and their formation appears to be strongly dependent on the duration of the peak shock pressure. In other words, they are mostly missing in laboratory-scale shock experiments with very short pressure pulse lengths (see chapter “*Pressure-temperature calibrations for minerals diagnostic of shock metamorphism*”).

It should be also emphasized here that shocked minerals are also affected by the change of physical properties (e.g., decreasing density and refractive indices, or infrared and Raman spectral behavior)

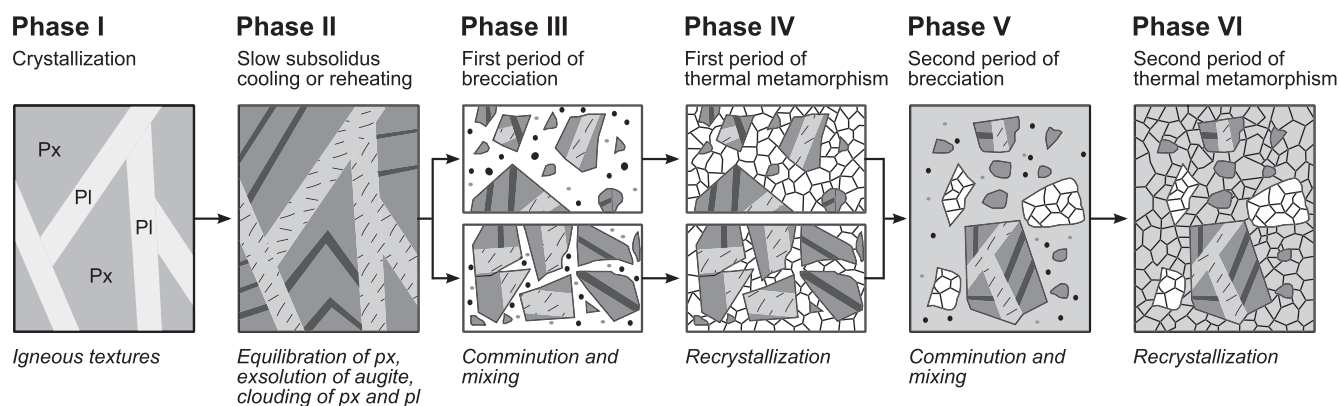


Fig. 12. Complex interaction of magmatic crystallization processes and repeated impact processes as verified by the different types of the howardite, eucrite, and diogenite (HED) meteorites. Phase I: crystallization of primary magmas leading to basalts or ultramafic rocks. Phase II: subsolidus cooling or reheating affecting the texture of pyroxene (Px) and plagioclase (Pl). Phase III: first impact process leading to monomict breccias (eucrites) or polymict lithic breccias (howardites). Phase IV: thermal metamorphism and recrystallization of breccias. Phase V: impact process leading to a second generation of monomict or polymict breccias. Phase VI: second thermal metamorphism and recrystallization of the second generation of breccias. Modified from Metzler et al. (1995).

besides the microscopically recognizable shock effects used here for classification systems of progressive shock metamorphism. The former effects documented in many publications (e.g., data for quartz in Langenhorst and Deutsch 1994; Stöffler and Langenhorst 1994) could be used to establish a fine-scaling of the pressure dependence of progressive shock metamorphism of individual minerals if required. However, this is not necessary for the proposed classification systems.

Shock Effects in Rocks and Sediments Resulting from Localized or Whole Rock Melting

Melt Veins and Melt Pockets

The propagation of a shock wave through a polymineralic rock or sediment that consists of minerals of variable density (i.e., variable shock impedance), and that may have a primary porosity or (secondary) pore space (e.g., cracks) is extremely complex. On the scale of nanoseconds, it leads to an interaction on grain boundaries and produces a “chaotic” system of reflections and rarefaction waves that result in local pressure excursions until the final “equilibration” shock pressure is reached. In the regions of localized pressure excursions, temporary peak pressures and shock temperatures of up to an order of magnitude higher than the equilibration shock pressure and temperature may be achieved (Sharp and DeCarli 2006). In these regions, localized melting takes place and shock veins (melt veins) and melt pockets are formed (Fig. 20; see also Fig. S8 of the supporting information). They occur most frequently in rocks of mafic to ultramafic

composition in which the difference of the shock impedances of the constituents is extremely large, e.g., in chondrites with neighboring minerals displaying a large range of shock impedances such as Fe-metal, olivine/pyroxene, and plagioclase. In felsic rocks that are dominated by feldspars and quartz having almost identical shock impedances, melt veins and melt pockets are usually not observed. The effect of localized melting has been verified in shock recovery experiments in which flat interfaces of quartzite and dunite with minerals of distinctly different shock impedances (olivine and quartz) were oriented at different angles to the shock front (Kenkmann et al. 2000). These experiments cannot serve, however, as a direct model for the formation of melt veins in mafic rocks because of the extremely complicated grain boundary geometry of the constituent minerals of such rocks.

It is important to emphasize that the melt veins and melt pockets described here are formed in situ as documented by their composition. It clearly demonstrates that they result from localized melting of the constituent minerals of the rock sample in question in contrast to so-called pseudotachylites, which are macroscopic features and predominantly formed by the intrusion of impact melt into the basement of impact craters. They typically occur in felsic rocks in terrestrial craters (Riller et al. 2010) and do not contain high-pressure phases formed simultaneously with the melt. However, coesite and stishovite occurs in the wall rocks of rather thin pseudotachylite veins in very large impact craters such as the Vredefort Dome (type A pseudotachylites; Martini 1991).

Table 2. Shock wave barometry for rock-forming minerals and for whole rock melting; data are based on the following references: Hörz (1968); Müller and Hornemann (1969); Hornemann and Müller (1971); Stöffler and Hornemann (1972); Stöffler (1970, 1971b, 1972, 1974); Snee and Ahrens (1975); Kieffer et al. (1976a,b); Schaal and Hörz (1977); Reimold and Stöffler (1978); Schaal et al. (1979); Bauer (1979); Ostertag (1983); Reimold and Hörz (1986); Stöffler et al. (1986, 1988, 1991); Bischoff and Stöffler (1992); Stöffler and Langenhorst (1994); Schmitt (2000); Fritz et al. (2011a,b); Poelchau and Kenkmann (2011); Kowitz et al. (2013, 2016). Shock pressure derived from shock recovery experiments performed at a pre-shock temperature of ~25 °C in most cases; note that planar deformation features in feldspars are also called planar deformation lamellae; for high-pressure phases, see text and Binns et al. (1969), James (1969), Smith and Mason (1970), Stöffler (1971b, 1972), Price et al. (1983), Stöffler et al. (1991), Stöffler and Langenhorst (1994), Tomioka and Fujino (1999), Liu and El Goresy (2007), Ozawa et al. (2009), Tschauner et al. (2009, 2014), Stähle et al. (2011), Agarwal et al. (2016), Ma et al. 2016; see Figs. S1–S9 in the supporting information.

Mineral	Shock effects	Shock pressure (GPa)
Quartz	Undulatory extinction	~5 to ~10
	Mosaicism	~10 to ~34
	Feather features (in conjunction with planar fractures)	~7 to ~10
	Planar fractures (0001) and {10 $\bar{1}$ 1}	~5–10 to 34
	Planar deformation features {10 $\bar{1}$ 3}	~10 to 34
	Planar deformation features {10 $\bar{1}$ 2}	~20 to 34
	Diaplectic quartz glass	34 to 50
Plagioclase	Melting	>50
	Undulatory extinction	~5 to 10–12
	Mosaicism	10–12 to 24/34 ^a
	Planar deformation features	18–22 to 24/34 ^a
	Diaplectic glass	24/34 ^a to ~45
Alkali feldspar ^c	Melting	>45
	Undulatory extinction	~5 to ~14
	Mosaicism	~14 to 32–34
	Planar deformation features	10–14 to 32–34
	Diaplectic glass	32–34 to ~45
Olivine	Melting	>45–50
	Undulatory extinction	4–5 to 10–15
	Mosaicism	10–15 to 60–65
	Planar fractures	15–20 to 60–65
	Planar deformation features	35–40 to 60–65
Pyroxene	Melting and recrystallization	>60–65
	Undulatory extinction	5–10 to 20–30
	Mechanical twinning	~5 to ~70
	Mosaicism	20–30 to ~70
	Planar deformation features	30–35 to ~70
Amphibole	Incipient melting	~>70
	Undulatory extinction	~5–45
	Mechanical twinning	3–5 to ~45
	Planar deformation features	~45 to ~50
Biotite	Loss of pleochroism and decomposition	>~45
	Kink bands	0.5–1 to 40–42
	Planar deformation features	~42 to 45
	Loss of pleochroism	40–42 to 45
Granite/gneiss	Decomposition	>42–45
	Whole rock melting	>60
Basalt/gabbro	Whole rock melting	>60–65
Anorthosite	Whole rock melting	>50–60
Ultramafic rocks	Whole rock melting	>60–70
Chondritic rocks	Whole rock melting	>70–75
Regolith	Whole rock melting	>40
Sandstone/sand	Whole rock melting	>15–30 ^b

^aIncreasing from anorthite to albite from ~24–34 GPa.

^bIncreasing with decreasing porosity from ~40–10% porosity.

^cExperimental data for sanidine and orthoclase.

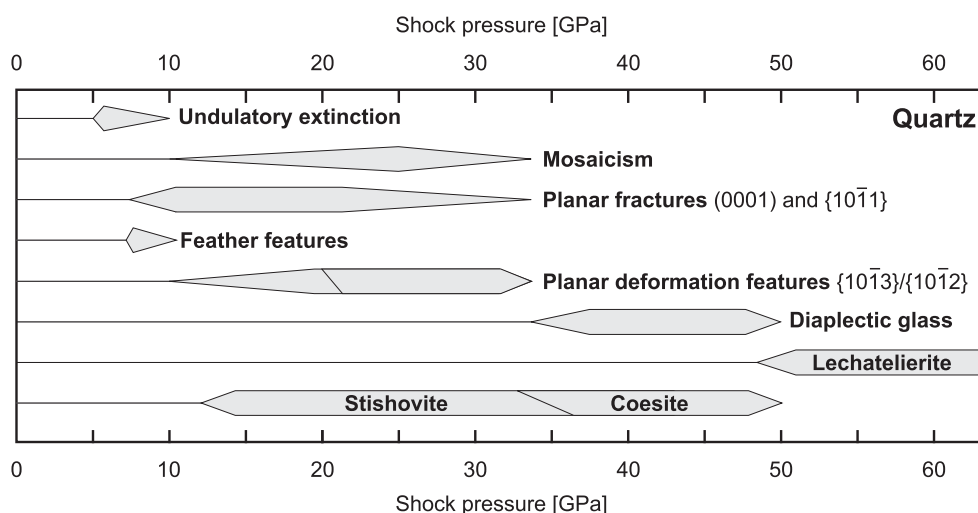


Fig. 13. Shock effects in quartz relative to a shock pressure scale based on data and references contained in Tables 2 and 4 (cf. Fig. S1 in the supporting information).

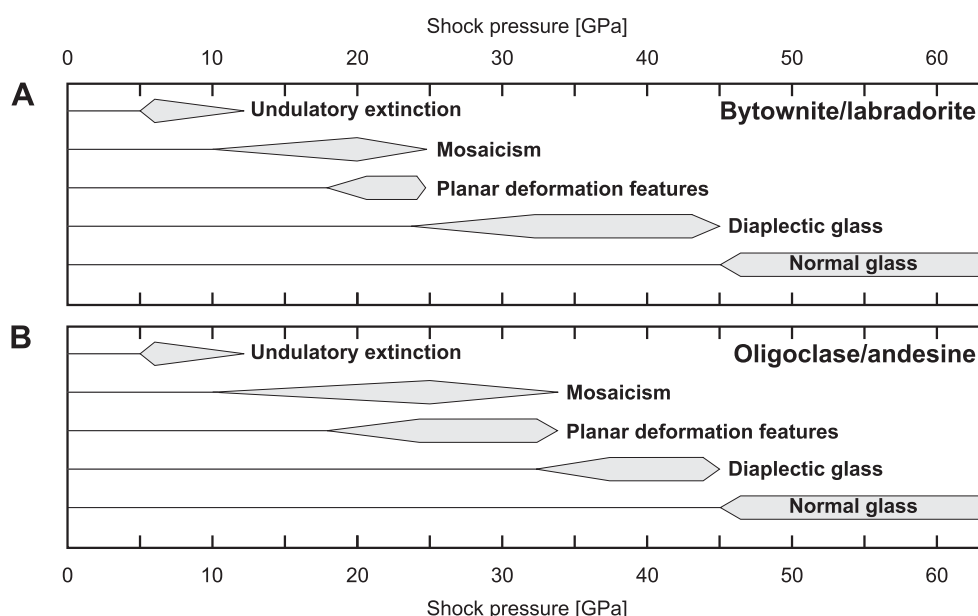


Fig. 14. Shock effects in plagioclase relative to a shock pressure scale based on data and references contained in Tables 2 and 5. A) oligoclase and andesine (An_{10} – An_{50}); B) bytownite and labradorite (An_{50} – An_{90} ; cf. Fig. S2 in the supporting information).

Whole Rock Melts

If a certain shock intensity is reached and the post-shock temperature after pressure release is higher than required for melting of the rock or sediment in question, whole rock melting takes place. This effect is manifested by hyaline (glassy), hypocrySTALLINE, and holocrystalline melt products such as melt particles in suevitic breccias (Figs. 9, 10, and 21; see also Fig. S9 of the supporting information), larger bodies of impact melt rocks, or glassy particles (agglutinates, spheres, etc.) in regolith layers (Fig. 11).

PRESSURE–TEMPERATURE CALIBRATIONS FOR MINERALS DIAGNOSTIC OF SHOCK METAMORPHISM

General Approach

The shock effects in those minerals that are used for shock classification systems should have been studied in detail based on shock recovery experiments (at variable shock pressures). Only from such experiments, a complete sequence of shock effects as

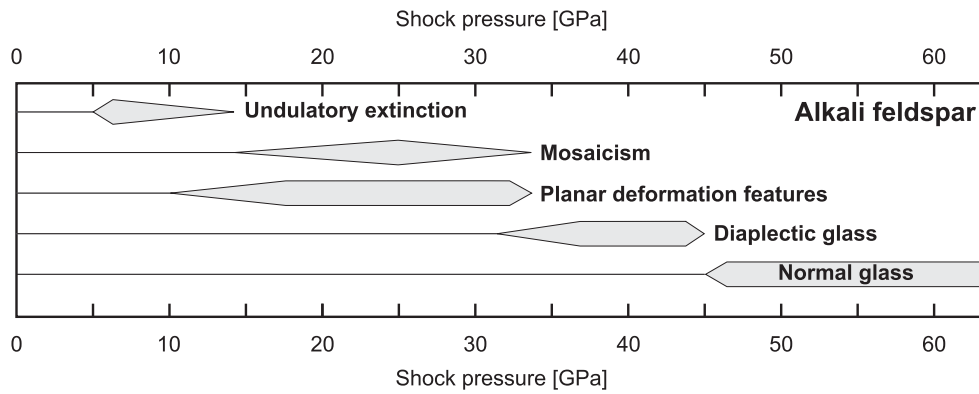


Fig. 15. Shock effects in alkali feldspar (orthoclase) relative to a shock pressure scale based on data and references contained in Tables 2 and 4 (cf. Fig. S3 in the supporting information).

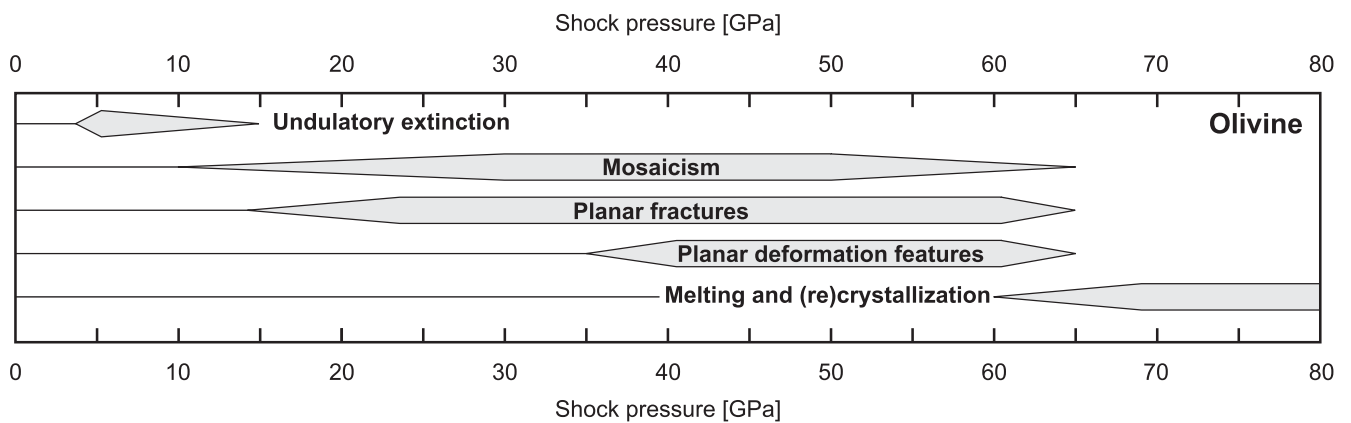


Fig. 16. Shock effects in olivine relative to a shock pressure scale based on data and references contained in Tables 2, 7, and 8 (cf. Fig. S4 in the supporting information).

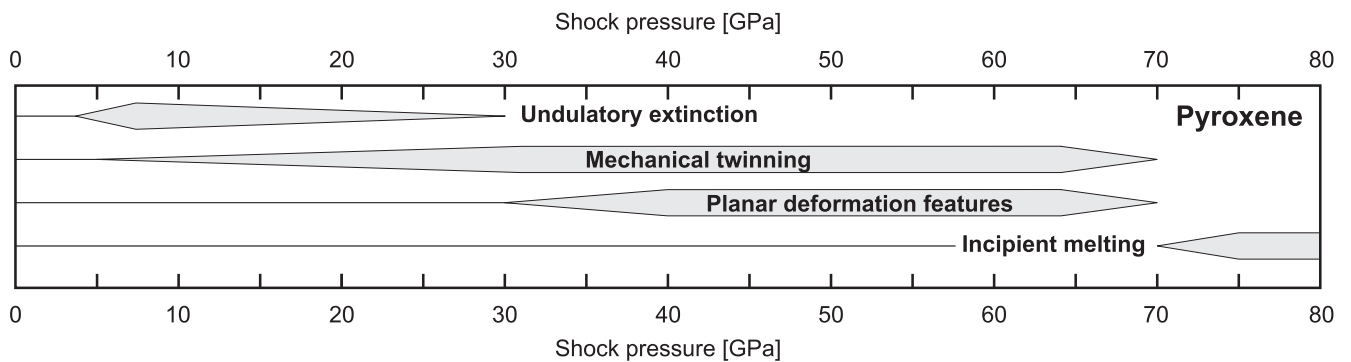


Fig. 17. Shock effects in pyroxene relative to a shock pressure scale based on data and references contained in Tables 2, 5, and 7 (cf. Fig. S5 in the supporting information); note that mosaicism is also present in the 25 to 65 GPa range.

function of progressively increasing shock pressure can be derived. In other words, experimental data for single crystals of any diagnostic mineral and corresponding experimental data for rocks or sediments in which this mineral is a major constituent are essential for establishing shock classifications systems of rocks or sediments. It should be noted that the

natural conditions of shock metamorphism on the different planetary bodies cannot be directly simulated in shock recovery experiments with rather short pressure pulse lengths. This is, however, not a major concern because correct *absolute* pressure and post-shock temperature values are not required to establish a *relative* sequence of shock effects as a

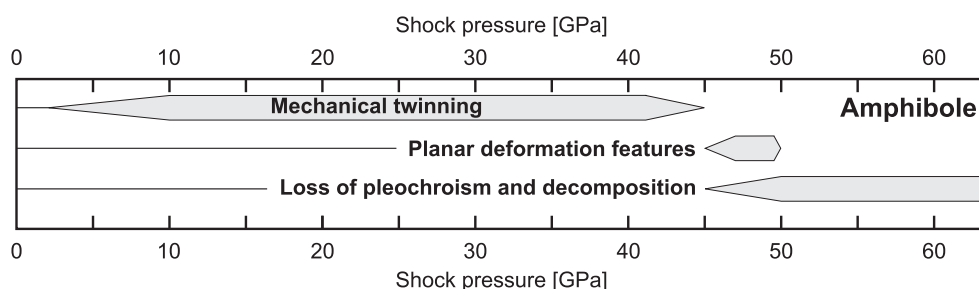


Fig. 18. Shock effects in amphibole relative to a shock pressure scale based on data and references contained in Tables 2, 5, and 7 (cf. Fig. S6 in the supporting information); note that undulatory extinction and mosaicism are also present in the ~ 5 to ~ 45 GPa range.

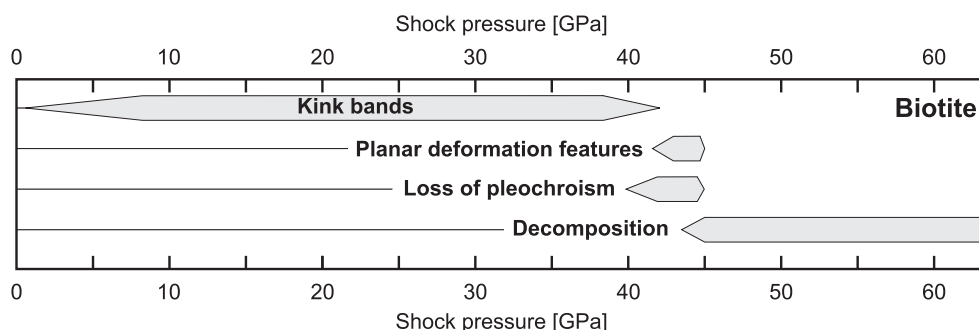


Fig. 19. Shock effects in biotite relative to a shock pressure scale based on data and references contained in Tables 2 and 4. (cf. Fig. S7 in the supporting information); note that also mosaicism is present at pressures below ~ 40 GPa.

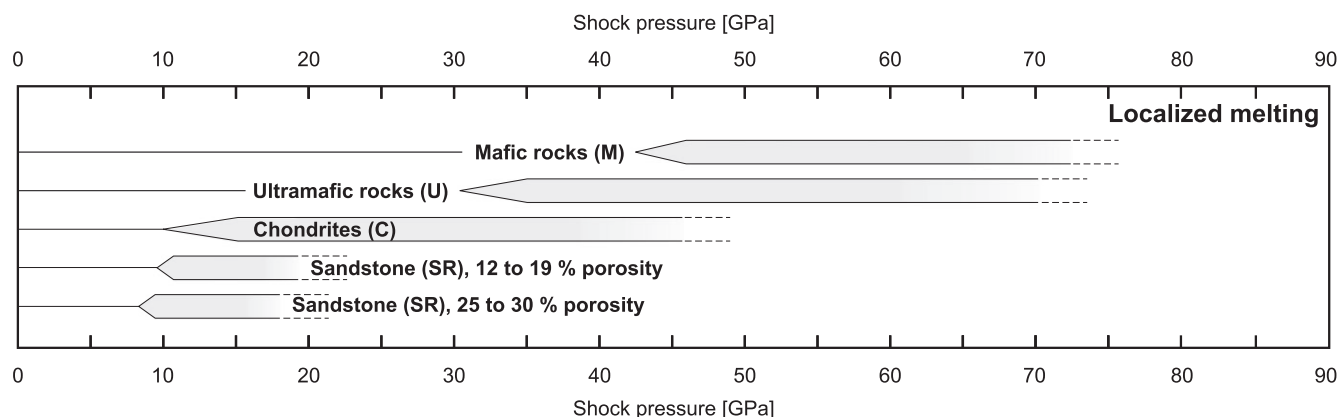


Fig. 20. Localized melting and formation of melt veins and melt pockets, predominantly in mafic rocks including chondrites, relative to a shock pressure scale. Graph based on data and references contained in Tables 2, 5, 7, 8, and 9, and on information contained in chapter “Shock effects applicable to the definition of progressive stages of shock metamorphism” (cf. Fig. S8 in the supporting information).

function of shock pressure as it is needed for establishing a shock classification system.

Variation of Pre-shock Temperature

The shock pressure required to induce a specific shock effect is influenced by the pre-shock temperature, which should therefore be considered in defining shock pressure scales for certain shock effects. Most existing

shock classifications refer to experiments made at room temperature, i.e., at about 295–300 K. Experiments performed at different temperatures indicate that in general, the progressive sequence of shock effects observed with increasing shock pressure does not change with decreasing or increasing pre-shock temperature (Huffmann et al. 1989; Langenhorst et al. 1992; Fritz et al. 2011b). Increasing pre-shock temperature does, for example, lead to a decrease in the minimum shock

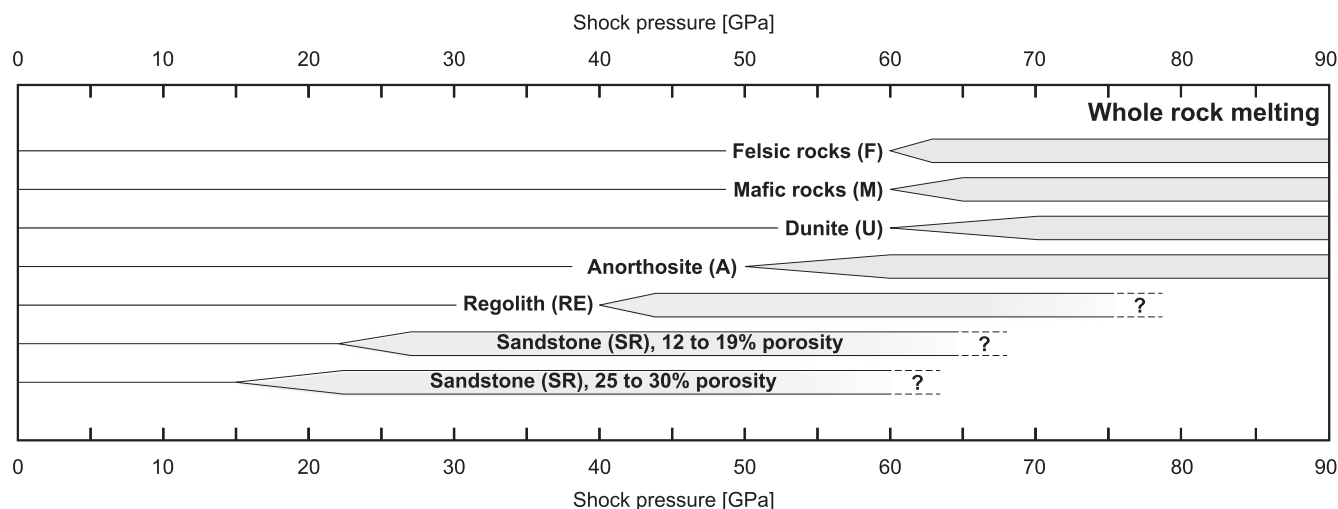


Fig. 21. Shock-induced whole rock melting of various rocks and sediments relative to a shock pressure scale based on data and references contained in Tables 2 and Tables 4–9 and 11 (cf. Fig. S9 in the supporting information).

pressure required to induce a certain shock effect (Langenhorst and Deutsch 1994). Nevertheless, it is still desirable to obtain more data from shock experiments at variable pre-shock temperature for most rock-forming minerals except for quartz that has been studied in some detail (Langenhorst et al. 1992; Langenhorst and Deutsch 1994; Langenhorst 2002; Fritz et al. 2011b).

Duration of the Peak Pressure Pulse

The influence of the duration of the peak pressure pulse (“thickness” of the shock wave) on the type and variability of a specific shock effect induced in the shocked mineral or rock is another important factor to be considered. In nature, the pressure duration increases with the size of the impacting projectile and consequently with the size of the related impact crater. The different effects of short and long pressure pulses are exemplified by the existence of a large variety of high-pressure polymorphs of quartz, pyroxene, olivine, and other minerals present in shocked rocks of terrestrial impact craters or in shocked chondritic meteorites (see discussion in Sharp and DeCarli 2006). Although exceptions exist (DeCarli and Milton 1965; Tschauner et al. 2009; and Mansfeld et al. 2015), most of these high-pressure phases could so far not be produced in shock recovery experiments with short pressure pulses (e.g., Reimold and Stöffler 1978; Schmitt 2000). This observation holds, for example, for the transition of α -quartz to coesite or the transition of pyroxene to bridgmanite.

Consequently, preference in using a particular shock effect in any mineral must be given to shock effects occurring rather independently of pressure pulse duration and to those shock effects that form during

the compression phase. Shock effects produced during the extended pressure release path such as most high-pressure phases are less useful because they are not indicative of the equilibration peak shock pressure achieved in a shocked rock.

BASIC PRINCIPLES FOR THE CLASSIFICATION OF PROGRESSIVE SHOCK METAMORPHISM OF PLANETARY SILICATE ROCKS AND SEDIMENTS

Identification of Shock Effects in Minerals by Thin-Section Microscopy

In order to be able to recognize a certain degree of shock metamorphism in a specific sample of a rock or sediment, two fundamental conditions should be fulfilled:

1. One, two, or three major mineral constituents diagnostic of specific ranges of peak shock pressure should be present in the rock sample in question, e.g., quartz and plagioclase for granite, or plagioclase for basalt/gabbro, or olivine and plagioclase for chondrites.
2. Only well-defined shock effects recognizable with the polarizing microscope should be used for the shock classification in order to provide a relatively easy and fast mode to determine the degree or stage of progressive shock metamorphism of a rock or sediment (Table 2; Figs. 13–21).

Shock effects that can be detected by more sophisticated techniques such as X-ray diffraction, transmission electron microscopy, Raman spectroscopy, or synchrotron radiation are not useful for shock classifications although they can provide important insights into the pressure–temperature–time history of

an impact event. Consequently, the polarizing microscope is the main tool for shock classification of a rock or sediment although it may have to be supported by electron-optical techniques (e.g., scanning electron microscopy, electron microprobe analysis, or electron backscatter diffraction) for a safe identification of a mineral phase in question that exhibits specific shock effects.

Grouping of Rocks or Sediments into “Classes” for which Different Shock Classification Systems are Required

Based on their mineralogical composition, rock samples having the same major mineral constituents can be grouped into one “class” for which one specific shock classification system can be established. As porosity has a strong effect on the type of shock metamorphism (Stöffler and Langenhorst 1994; Kowitz et al. 2016), separate classifications system must be established for nonporous crystalline rocks, such as magmatic and metamorphic rocks; for chondrites; and for porous rocks, such as sedimentary rocks and sediments including lunar and asteroidal regoliths (see Table 3 and more details in chapter “*Identification of major classes of rocks and sediments as basis for shock classification systems*”).

Crystalline rocks have porosities ranging typically from about 0.1 to 1.5%. Porosities of *chondrites* range mostly from ~3.5 to ~8% in the case of ordinary and enstatite chondrites, but can be distinctly higher for C-chondrites (Consolmagno et al. 2008). Porosities below some 10–20% have obviously no major effects on the textural characteristics of shock metamorphism as shown in a comparison of quartzite and low-porosity sandstone (e.g., Kowitz et al. 2016). This is, however, clearly the case for *sedimentary rocks* and *sediments* whose porosities are typically higher than 10–20%, reaching values of 50% in the case of sand and clay.

For the definition of a specific shock stage of *crystalline rocks*, for example, the concept of grouping rocks into classes based on their mineralogical composition means that only one shock classification system is needed for all types of *felsic crystalline rocks* containing abundant quartz and feldspar. For all magmatic rocks of terrestrial, lunar, Martian, and asteroidal origin, as well as for crystalline terrestrial metamorphic rocks, the definition of “specific types of rock” of a well-defined mineralogical composition (as listed in Table 3, see below) should be based on the internationally accepted IUGS classification systems (Streckeisen 1974, 1980; Le Maitre 1989; Fettes and Desmons 2007). The relevant rock types of magmatic origin are shown in Figs. 22 and 23.

For sedimentary rocks and sediments, the definition of “classes” for shock classification systems needs to take not only mineralogical composition but also porosity, grain size characteristics, and eventually water content into account (e.g., Kowitz et al. 2016).

It should be pointed out that rocks or sediments affected by more than one shock event (such as lunar and asteroidal impact breccias and impact melt rocks, as well as lunar or asteroidal regoliths and regolith breccias) will be included in the proposed classification systems (see below).

IDENTIFICATION OF MAJOR CLASSES OF ROCKS AND SEDIMENTS AS BASIS FOR SHOCK CLASSIFICATION SYSTEMS

The rock classes for which different shock classification systems will be defined, can be summarized in three major groups: (1) Crystalline rocks comprising magmatic rocks, metamorphic rocks, and certain impactites, (2) Chondritic rocks represented by chondritic meteorites, and (3) Consolidated and unconsolidated sediments (Table 3). The first group is texturally characterized by full or a high degree of crystallinity and lack of any essential porosity, and the third group is characterized by rather high degrees of porosity and variable grain size. We keep the group of chondritic meteorites separate from crystalline rocks because they are formed primarily by accretionary processes and not by the crystallization of magma or impact melt. Achondritic meteorites belong to the group of crystalline rocks.

We propose the following three major groups subdivided into eight different classes (Table 3):

Crystalline rocks

1. Felsic (quartzo-feldspathic) rocks (**F**)
2. Mafic rocks (**M**)
3. Anorthositic rocks (**A**)
4. Ultramafic rocks (**U**)

Chondritic rocks (**C**)

1. Ordinary chondrites (including rare non-carbonaceous chondrite groups such as R- and K-chondrites)
2. Carbonaceous chondrites
3. Enstatite chondrites

Consolidated and unconsolidated sediments

1. Sedimentary rocks, quartz-bearing (**SR**)
2. Sediments
 - 2.1. Clastic sediments, quartz-bearing (**SE**)
 - 2.2. Regoliths (**RE**)

For each of the eight classes, the capital letter symbols **F**, **M**, **A**, **U**, **C**, **SR**, **SE**, and **RE** are introduced and their application will be described in the next chapter.

Table 3. Proposal for three major groups of planetary silicate rocks and sediments of terrestrial, lunar, Martian, and asteroidal origin to which eight different shock classification systems (F, M, A, U, C, SR, SE, and RE) are assigned; note that in the list of major minerals diagnostic of shock effects only the first two are critical for the definition of shock classification systems (Tables 4–11).

Major rock groups	Crystalline rocks				Accretionary rocks	Consolidated and unconsolidated sediments		
	F	M	A	U		SR	SE	RE
Classification system					C			
Rock classes	Felsic rocks	Mafic rocks	Anorthositic rocks	Ultramafic rocks	Chondrites	Sedimentary rocks		Sediments
Planetary bodies	Earth	Earth, Moon, Mars, Asteroids	Earth, Moon	Earth, Moon, Mars, Asteroids	Asteroids	Earth	Earth	Moon, Asteroids, Mars
Specific types of rocks and sediments	Igneous rocks, metamorphic rocks	Igneous rocks, metamorphic rocks, achondrites, impact melt rocks	Anorthosite	Peridotites, pyroxenite, hornblende, achondrites, impact melt rocks	All types of chondrites	Sedimentary rocks (quartz-rich)	Clastic sediments (quartz-rich)	Regolith
Major minerals diagnostic of shock metamorphism	Quartz, plagioclase, alkali feldspar	Plagioclase, olivine, pyroxene, amphibole	Plagioclase, pyroxene	Plagioclase, olivine, pyroxene, amphibole	Olivine, plagioclase, pyroxene	Quartz	Quartz	Plagioclase, pyroxene, olivine

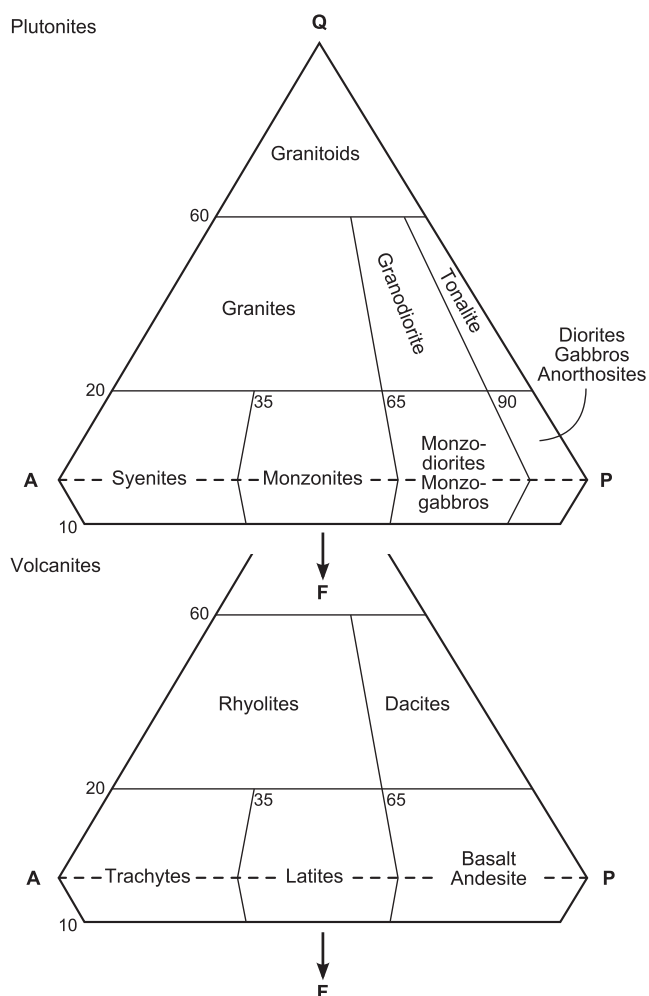


Fig. 22. Simplified Streckeisen diagrams (Streckeisen 1974, 1980; Le Maitre 1989) for the mineralogical composition of plutonic and volcanic rocks representing the most frequently occurring rocks of the crusts of the Earth, Mars, Moon, and achondritic asteroids. Note that feldspathoid-bearing rocks are not considered because they are rare on Earth and not known to occur on all other planetary bodies (in addition, shock effects in feldspathoid minerals are not known). A = alkali feldspar, P = plagioclase, Q = quartz, F = feldspathoids.

PROPOSAL FOR EIGHT MAJOR CLASSIFICATION SYSTEMS OF SHOCK-METAMORPHOSED PLANETARY SILICATE ROCKS AND SEDIMENTS

Main Principles

We propose

1. to adapt the widely accepted denomination system for progressive stages of shock metamorphism of chondrites (Stöffler et al. 1991) to all major classification systems,

2. to delete shock stage 0 for unshocked rocks so far used (Stöffler 1971a,b, 1984; Stöffler and Grieve 2007) and replace it by shock stage S1,
3. to delete a shock stage (highest stage) for material condensed from vaporized rocks (Stöffler 1984; Stöffler and Grieve 2007) as it cannot unequivocally be identified,
4. to use a two-digit nomenclature in compliance with the system for chondrites, e.g., shock stage S1, S2, S3, and so on, and
5. to characterize the rock class by adding a capital letter denominating the rock class, i.e., **F** for felsic, **M** for mafic, **A** for anorthositic rocks, **U** for ultramafic crystalline rocks, **C** for chondritic meteorites, **SR** for sedimentary rocks, **SE** for sediments, and **RE** for planetary regoliths, e.g., **F-S4** for shock stage 4 of the class of felsic rocks or **U-S3** for shock stage 3 of the class of ultramafic rocks.

The option remains to add to the rock class symbols, the related shock pressure range in parentheses, e.g., **F-S4 (20–35 GPa)**, although this makes only sense in those cases where the pressure range is well known.

Lists of Rock Types Belonging to each of the Eight Rock Classes

A short list of all rock types belonging to each class of the eight major classification systems is given in Table 3. A more detailed list of all rock types belonging to each of the eight systems is presented in Table 12. The list covers rocks from all presently known planetary sources including Earth, Moon, Mars, and various types of asteroids from which different types of meteorites originate. For the systematics and nomenclature of magmatic rocks and metamorphic (terrestrial) rocks, we refer to the recommendations by the IUGS (Streckeisen 1974, 1980; Le Maitre 1989; Fettes and Desmons 2007). As the Streckeisen diagrams of plutonic and volcanic rocks contain a lot of rare rock types so far unknown from impact-metamorphic rocks, we present here a diagram in which only the relevant categories of plutonic and volcanic rocks are shown (Figs. 22 and 23).

DESCRIPTION OF THE SHOCK CLASSIFICATION SYSTEMS FOR PLANETARY ROCKS AND SEDIMENTS

The classification systems are presented here in the form of Tables (4–11). The Tables are organized according to the following principles:

The first column contains the proposed nomenclature for the progressive stages of shock

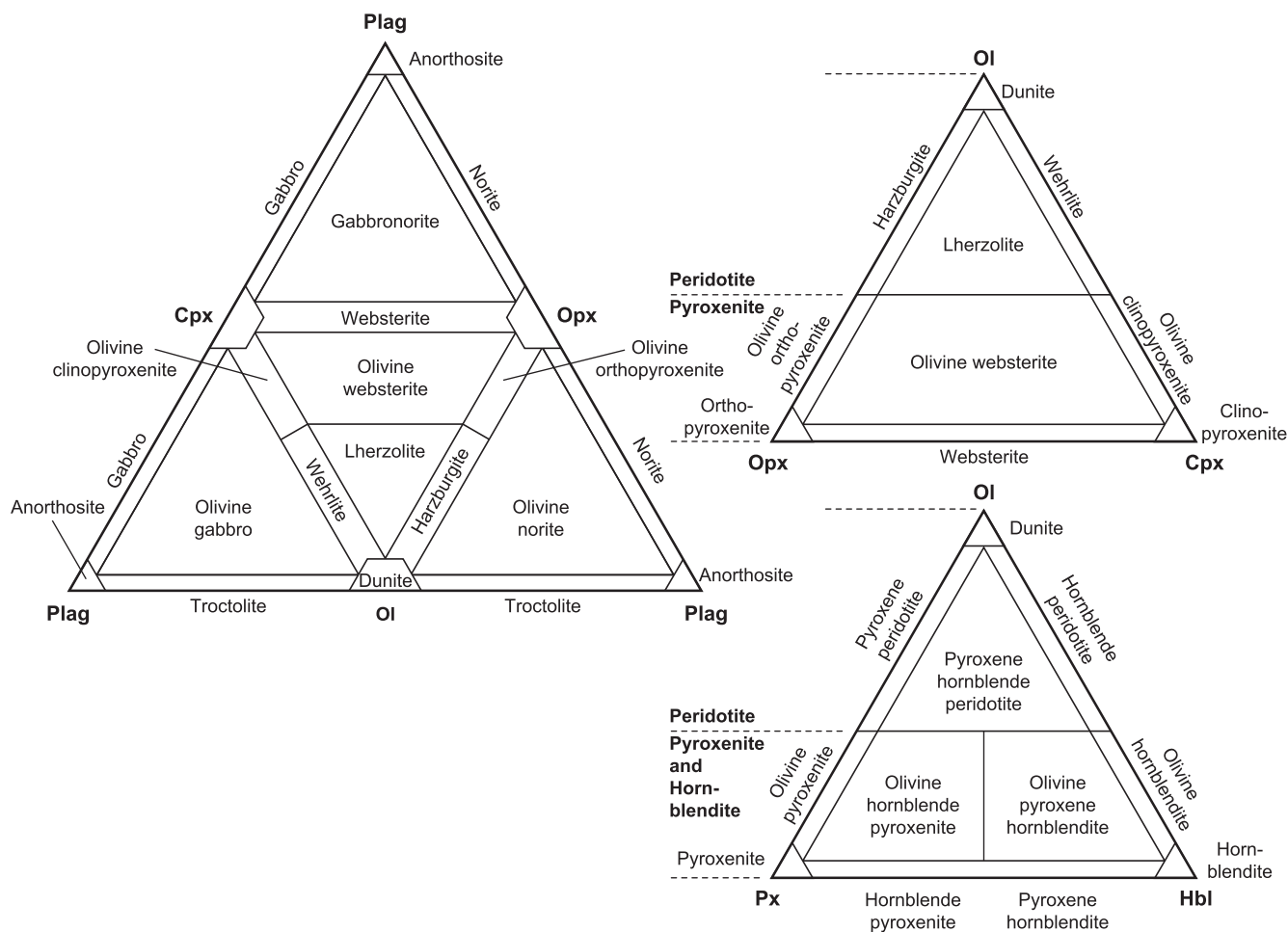


Fig. 23. Streckeisen diagrams (Streckeisen 1974, 1980; Le Maitre 1989) for the mineralogical composition of ultramafic and mafic rocks potentially occurring on Earth, Moon, Mars, and achondritic asteroids.

metamorphism (S1, S2, S3, etc.). The second column called “shock stage IUGS 2007” contains the previously used nomenclature (stages 0, I, II, etc.) for comparison, except for Table 8 and for the newly proposed classifications systems (Tables 6, 7, 10, and 11). In the remaining columns, the relevant diagnostic shock effects are described and shock pressure and post-shock temperature values are given. They are based on Hugoniot data (for references, see chapter on “*Basic principles of shock metamorphism*”) and on data from laboratory shock experiments on the major constituent minerals or on whole rocks containing these minerals (performed mostly at ca. 25 °C; see references in Table 2 and in Tables 4–11).

Felsic Rocks (F)

The system of progressive stages of shock metamorphism of felsic rocks **F** (Tables 3 and 12) is defined in Table 4. It holds for plutonic, volcanic, and (terrestrial) metamorphic rocks and is essentially based

on shock effects of quartz and feldspars. This classification system is most important for terrestrial impact formations because felsic (quartzo-feldspathic) rocks are not known so far from other planetary bodies. Details about the types of magmatic rocks assigned to system F can be derived from Fig. 22 and Table 12.

Mafic Rocks (M)

The system of progressive stages of shock metamorphism of mafic rocks **M** (Tables 3 and 12) is shown in Table 5. It covers a great variety of rocks from all planetary bodies in consideration. They range from plutonic and volcanic rocks to terrestrial metamorphic rocks (e.g., amphibolites), to mafic achondrites, and to first-generation crystalline impactites (impact melt rocks, and eventually strongly shock-lithified polymict breccias of very low porosity) affected by a subsequent impact metamorphism as known from the Moon, the asteroids, and possibly Mars. Details about the types of mafic magmatic rocks are given in Figs. 22 and 23 and in

Table 4. Definition of progressive stages of shock metamorphism for classification system **F** (felsic rocks; see Tables 3 and 12); modified from Stöffler (1971a, 1984), and Stöffler and Grieve (2007); IUGS 2007 = Stöffler and Grieve (2007); shock pressure corresponds to the final equilibration peak shock pressure for polycrystalline rocks (in GPa) derived from shock experiments referenced in Table 2; post-shock temperatures are relative to an ambient temperature of about 25 °C; pf = planar fractures; pdf = planar deformation features; database for experimentally determined shock pressures and post-shock temperatures see Table 2; in case the crystallographic orientation of pdf in quartz is not known, shock stages S3 and S4 can be combined, denominated F—S3/S4; (?) = somewhat uncertain values with errors of $\sim\pm 50$ °C; see Figs. S1–S3 in the supporting information; for additional shock effects in other mineral constituents, see Table 2 and Figs. S5–S7 in the supporting information.

Shock stage Present proposal	Shock stage IUGS 2007	Shock pressure (GPa)	Post-shock temperature (°C)	Diagnostic shock effects in quartz and feldspar ^a	Shock effects in other major minerals
F—S1				No shock effects; sharp optical extinction	No shock effects; sharp optical extinction
F—S2	0	~1–5	~25	Fractured minerals	Fractured minerals; kink bands in biotite
F—S3	Ia	~5–10	~100	Quartz with pf parallel to (0001) and {10 $\bar{1}$ 1} and pdf {10 $\bar{1}$ 3}; plagioclase with pdf; undulatory extinction in all minerals	Kink bands in biotite; mechanical twinning in pyroxene and amphibole
F—S4	Ib	~20	~170	Quartz with pdf parallel to {10 $\bar{1}$ 3} and {10 $\bar{1}$ 2} and reduced refractive index; plagioclase with pdf; mosaicism in all minerals; stishovite; and minor coesite	As in S3
F—S5	II	~35	~300	Diaplectic quartz glass; diaplectic plagioclase and alkali feldspar glass; coesite; and traces of stishovite	As in S3 and increasing loss of pleochroism
F—S6	III	~45	~900 (?)	Normal feldspar glass (vesiculated) and diaplectic quartz glass; coesite	Decomposition of biotite
F—S7	IV	~60	~1500 (?)	Whole rock melts (glassy or crystallized)	

^aFor data on high-pressure phases, see James (1969), Stöffler (1971b, 1972), Stöffler and Langenhorst (1994), Liu and El Goresy (2007), and Agarwal et al. (2016).

Table 12. For various types of mafic achondrites, see Weisberg et al. (2006).

about the definition and occurrence of anorthosite are given in Figs. 22 and 23 and in Table 12.

Anorthositic Rocks (A)

The system of progressive stages of shock metamorphism of mafic rocks **A** (Tables 3 and 12) is shown in Table 6. This system applies for magmatic rocks dominated by plagioclase (>90%) which are so far known only from the Earth and from the Moon and for one type of impactites (monomict breccia). Details

Ultramafic Rocks (U)

The system of progressive stages of shock metamorphism of ultramafic rocks **U** (Tables 3 and 12) is presented in Table 7. Class U comprises ultramafic rocks from all planetary bodies considered here. These are the three major groups of the magmatic suite (peridotites, pyroxenites, and hornblendites) and certain

Table 5. Definition of progressive stages of shock metamorphism for classification system **M** (mafic rocks; see Tables 3 and 12); pdf = planar deformation features; pf = planar fractures; IUGS 2007 = Stöffler and Grieve (2007); classification based on data of Kieffer et al. (1976b), Schaal and Hörz (1977), Ostertag (1983), Stöffler (1984), and Stöffler et al. (1986). Shock pressure corresponds to the final equilibration peak shock pressure for polycrystalline rocks (in GPa) derived from shock experiments referenced in Table 2; post-shock temperatures are relative to an ambient temperature of about 25 °C and in part based on Raikes and Ahrens (1979); (?) uncertain values with errors of $\sim\pm 50$ °C; for high-pressure phases, see text and James (1969), Stöffler (1972), Stöffler et al. (1991) Tschauner et al. (2009, 2014), Liu and El Goresy (2007), Stähle et al. (2011), Agarwal et al. (2016), and Ma et al. 2016; see Figs. S2-S8 in the supporting information.

Shock stage Present proposal	Shock stage IUGS 2007	Equilibration shock pressure (GPa)	Post-shock temperature (°C)	Diagnostic shock effects in plagioclase, pyroxene, olivine, amphibole, and mica	Accompanying disequilibrium shock effects
M—S1	0			Sharp optical extinction of all minerals Irregular fracturing	None
M—S2	1	~1–5	~0	Fractured silicates; mechanical twinning of pyroxene; kink bands in mica	None
M—S3	2a	~20–22	~50–150	Plagioclase with pdf and partially converted to diaplectic glass; mosaicism in plagioclase and mafic minerals; pf in olivine	Incipient formation of localized “mixed melt” and glassy melt veins
M—S4	2b	~28–34	~200–250	Diaplectic plagioclase glass; mechanical twinning in pyroxene; mosaicism in mafic minerals; pf in olivine	Localized “mixed melt” and melt veins (glassy or microcrystalline)
M—S5	3	~42–45	~900 (?)	Melted plagioclase glass with incipient flow structure and vesicles; mosaicism in mafics minerals; pdf in pyroxene and amphibole; loss of pleochroism in mafic minerals	Melt veins and melt pockets
M—S6	4	~55–60	~1100 (?)	Melted plagioclase glass with vesicles and flow structure; incipient and increasing contact melting of pyroxene and olivine and (re) crystallization of olivine	Pervasive melt veins and melt pockets
M—S7	5	>~60–65	~1500 (?)		Whole rock melt

types of achondrites as well as first-generation crystalline impactites (impact melt rocks, and eventually strongly shock-lithified monomict and polymict breccias of very low porosity) originating from the moon,

asteroids, and potentially also from Mars. Details about the types of ultramafic magmatic rocks are given in Fig. 23 and Table 12. For various types of ultramafic achondrites, see Weisberg et al. (2006).

Table 6. Definition of progressive stages of shock metamorphism for plagioclase-rich mafic rocks of classification system **A** (anorthositic rocks; see Tables 3 and 12); pdf = planar deformation features; shock pressure corresponds to the final equilibration peak shock pressure for polycrystalline rocks (in GPa) derived from shock experiments referenced in Table 2; post-shock temperature is the temperature increase (in °C) after pressure release relative to a pre-shock temperature of ~25 °C; (?) uncertain value with an error of $\sim\pm 50$ °C; Table based on various literature and own data as referenced in Stöffler (1984); Stöffler et al. (1980); Stöffler et al. (1986, 1988), and on Table 1.4 in Hiesinger and Head (2006); for high-pressure phases, see text and Stöffler (1972), Stöffler et al. (1991), Tschauner et al. (2014), Liu and El Goresy (2007), and Agarwal et al. (2016); see Figs. S2 and S5 in the supporting information.

Shock stage Present proposal	Shock pressure (GPa)	Post-shock temperature (°C)	Diagnostic shock effects in plagioclase and pyroxene
A—S1	<5	50	Sharp optical extinction of minerals; irregular fractures
A—S2	~26	220	Plagioclase with undulatory extinction; pyroxene with mechanical twinning
A—S3	~28	300	Plagioclase partially isotropic and with pdf; weak mosaicism in plagioclase and pyroxene
A—S4	~40–45	~800–900	Diaplectic plagioclase glass (maskelynite); strong mosaicism and pdf in pyroxene
A—S5	~50–60	~1850 (?)	Plagioclase glass with flow structures and vesiculation; strong mosaicism and pdf in pyroxene; mixed melt of plagioclase and pyroxene
A—S6			Whole rock melt

Chondrites (C)

The system of progressive shock metamorphism of chondritic meteorites **C** (Tables 3 and 12) shown in Table 8 has already been defined in 1991 (Stöffler et al. 1991) and is also part of the 2007 IUGS system (Stöffler and Grieve 2007). It was first established for ordinary chondrites and it has been extended later on to other types of chondrites (Scott et al. 1992; Rubin et al. 1997). It is proposed to apply this system to all chondrites (see Tables 3 and 12). The nomenclature of the progressive stage of shock metamorphism using the symbols S1, S2, S3, etc. is the basis for the current proposal to introduce this nomenclature now to all eight shock classification systems.

Sedimentary Rocks (SR)

The system of progressive shock metamorphism of sedimentary rocks **SR** (Tables 3 and 12) is defined in Table 9 and applicable to terrestrial representatives such as sandstone, arkose, and graywacke. It is based primarily on shock effects of quartz and potentially on accessory feldspar, if present. The petrographic and textural properties of the stages of increasing shock metamorphism are strongly influenced by porosity and/

or water content, as recently shown by Kowitz et al. (2016). Therefore, the system is distinctly different from the systems for crystalline rocks. In general, the shock pressure and post-shock temperature values for a specific shock stage decrease with increasing porosity and/or water content.

Sediments, Quartz-rich (SE)

The system of progressive shock metamorphism of quartz-rich clastic sediments **SE** (Tables 3 and 12) is defined in Table 10. It applies generally to terrestrial sediments such as sand and is therefore based, as in the case of the system **SR**, exclusively on shock effects in quartz and on textural properties resulting from porosity/water content of the sediment.

Sediments, Planetary Regoliths (RE)

The system of progressive shock metamorphism of planetary regoliths **RE** (Tables 3 and 12) is presented in Table 11. It is applicable to all planetary regoliths originating from the Moon, the asteroids, or Mars. The target material is composed of mafic mineral clasts such as plagioclase, pyroxene, and olivine, and lithic clasts (mainly mafic rocks), and it also contains melt particles

Table 7. Definition of progressive shock metamorphism for classification system U (ultramafic igneous rocks; Tables 3 and 12); pdf = planar deformation features; shock pressure corresponds to the final equilibration peak shock pressure for polycrystalline rocks (in GPa) derived from shock experiments referenced in Table 2; post-shock temperature is the temperature increase (in °C) after pressure release relative to an ambient pre-shock temperature ~25 °C; Table based mainly on experimental data from Reimold and Stöffler (1978) and Schmitt (2000) and on various literature and own data as referenced in Stöffler (1972, 1974, 1984), Stöffler et al. (1980), Stöffler et al. (1986, 1988), and Bischoff and Stöffler (1992); for high-pressure phases, see text, Table 8, and Stöffler (1972), Stöffler et al. (1991), Ozawa et al. (2009), Tschauner et al. (2009, 2014), and Ma et al. 2016; see Figs. S2, S4–S6, and S8 in the supporting information.

Shock stage Present proposal	Shock pressure (GPa)	Post-shock temperature (°C)	Diagnostic shock effects in olivine, pyroxene, amphibole, and plagioclase	Accompanying disequilibrium shock effects
U—S1			Irregular fractures, sharp optical extinction of all minerals	None
U—S2	<4–5	20–50	Fractured minerals with undulatory optical extinction	None
U—S3	~5–10	50–100	Undulatory extinction in olivine, pyroxene, and plagioclase; planar fractures in olivine; incipient mechanical twinning in pyroxene ^a	None
U—S4	~15	100–150	Weak mosaicism and planar fractures in olivine and pyroxene ^a ; mechanical twinning in pyroxene ^a ; partially isotropic plagioclase	None
U—S5	~28–30	250–300	Strong mosaicism, planar fractures, and pdf in olivine; mechanical twinning in pyroxene ^a ; diaplectic plagioclase glass	Local melt veins and pockets
U—S6	~50–55	650–850	Incipient melting and (re)crystallization of olivine; incipient melting of pyroxene ^a ; melted plagioclase with vesicles	Pervasive localized melt veins and pockets
U—S7	~60–70	1500–1700	Whole rock melt	

^aThis may also hold for amphibole if the rock is dominated by this mineral, e.g., hornblende (see Fig. 23).

in the form of glassy agglutinates and glass spherules. The system is meant to document the progressive stages of shock metamorphism in which the porosity is steadily decreasing and the lithification by sintering and intergranular melting is gradually increasing. These processes lead to a consolidated *regolith breccia* in an intermediate stage of shock metamorphism (stages S3 and S4) before the regolith is completely (re)melted in the highest stage of shock metamorphism (Table 11).

MANUAL FOR THE CLASSIFICATION OF A SHOCK-METAMORPHOSED ROCK OR SEDIMENT

In Fig. 24, we present an overview of the procedures to establish the degree of shock metamorphism of a sample obtained from any impact formation of the Earth, the Moon, Mars, or the

asteroids. The first three steps need no detailed explanation because they represent standard petrographic techniques. However, it should be pointed out here again that *the main and final tool is the polarizing microscope* that needs of course to be supported by other standard tools for identifying any mineral and its chemical composition. This concept is in concordance with IUGS standards for classifying rocks.

It is highly recommended to use objectives on the microscope with a specific magnification for easy recognition of particular shock effects. For undulatory extinction and mosaicism, a 20× objective, for planar fractures, a 10× or 20× objective, and for planar deformation features, a 40–50× objective should be used. Moreover, when checking the type of shock effect in any of the major diagnostic minerals of a sample, such as quartz, plagioclase, alkali feldspar, olivine, and other mafic minerals, a representative number of grains

Table 8. Definition of progressive stages of shock metamorphism for classification system C (chondrites, Tables 3 and 12) modified after Stöffler et al. (1991); IUGS 2007 = Stöffler and Grieve (2007); shock pressure corresponds to the final equilibration peak shock pressure for polycrystalline rocks (in GPa) derived from shock experiments referenced in Table 2; temperature data refer to the ambient temperature before shock compression; pf = planar fractures; pdf = planar deformation features; hpp = high-pressure phases; note that hpp of olivine, pyroxene, and plagioclase may be present, preferably in or near melt veins/pockets of shock stages S5–S6 (ringwoodite, wadsleyite, ahrensite, majorite, akimotoite, bridgmanite, and lingunite: Binns et al. 1969; Smith and Mason 1970, Price et al. 1983; Stöffler et al. 1991; Tomioka and Fujino 1999; Liu and El Goresy 2007; Ozawa et al. 2009; Tschauner et al. 2009, 2014; Ma et al. 2016); see Figs. S2, S4 and S8 in the supporting information.

Shock stage IUGS 2007 and present proposal	Pressure GPa ^a (293 K)	Pressure GPa ^b (293 K)	Pressure GPa ^b (920 K)	Effects resulting from equilibration peak shock pressure			Effects resulting from local <i>P-T</i> -excursions
				Olivine	Plagioclase		
C—S1				Sharp optical extinction Irregular fractures	Angular variation of extinction position: <2°	Sharp optical extinction Irregular fractures	None
C—S2	<4–5			Undulatory extinction Fractures	Angular variation of extinction position: >2°	Undulatory extinction Irregular fractures	None
C—S3	5–10			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)
C—S4	15–20	10–15	10–15	Mosaicism	Low grade: incipient mosaicism, pf, and pdf High grade: strong mosaicism, pf, and pdf	Low grade: undulatory extinction High grade: partially isotropic, pdf	Melt pockets; interconnected melt veins; opaque shock veins
C—S5	30–35	25–30	20–25	Mosaicism (strong) pf and pdf		Diaplectic glass (maskelynite)	Pervasive formation of melt pockets, veins, and dikes; opaque shock veins
C—S6	45–55	45–60	35–45	Restricted to local regions in or near melt zones: Melting and (re)crystallization and yellow-brown staining of olivine		Shock melted (normal glass)	As in stage S5
C—S7	>70–75		45–60	Whole rock melting			

^aFrom Stöffler et al. (1991).

^bFrom Schmitt (2000).

Table 9. Definition of progressive shock metamorphism for classification system **SR** (sandstone; Tables 3 and 12); IUGS 2007 = Stöffler and Grieve (2007); shock pressure corresponds to the final equilibration peak shock pressure (GPa) derived from shock experiments (e.g., Kowitz et al. 2016); post-shock temperature is the temperature increase after pressure release relative to an ambient pre-shock temperature (~0 °C; Stöffler and Grieve 2007) (?) = uncertain values; Table modified after Kowitz et al. (2016)^a, Kieffer (1971)^b, and Kieffer et al. (1976a)^b; porosity in vol%; ^{c,d,e,f}Estimates of Kieffer (1971) and Kieffer et al. (1976a): ^c3–10% glass, 2–5% coesite; ^d10–20% glass, 18–32% coesite; ^e20–75% glass, 10–30% coesite; ^f80–100% glass, <5% coesite; ^gdiaplectic glass + lechatelierite from Kowitz et al. (2016); ^bdata for Coconino sandstone; see Fig. S1 in the supporting information.

Shock stage Present proposal	Shock stage IUGS 2007	Shock pressure (GPa) ^b ~10% porosity	Post-shock temperature (°C) ^b	Shock pressure (GPa) sandstone with 25–30% porosity ^a	Shock pressure (GPa) sandstone with 12–19% porosity ^a	Shock effects	Vol% of silica glass ^g + coesite and stishovite
SR—S1	0					Undeformed sandstone	0
		0.2–0.9					
SR—S2	1a					Compacted sandstone with fractured quartz; remnant porosity	0
		~3	~25	<1.5	<4		
SR—S3	1b					Compacted sandstone with fractured quartz; no porosity	0
		~5.5	~250	9	11.5		
SR—S4	2					Dense sandstone with fractured quartz and minor intergranular silica glass; traces of coesite ^c	2
		~13	~350	14	16.5		
SR—S5	3					Dense sandstone with fractured quartz and silica glass; coesite and traces of stishovite ^d	20
		~30	~950	16	19		
SR—S6	4					Dense sandstone with relic fractured quartz and a major fraction of silica glass; major fraction of coesite ^e	50
		~30–40 (?)	1000–1500 (?)	18	21.5		
SR—S7	5					Vesicular (pumiceous) melt rock with vesiculated and flow-textured glass (lechatelierite) and minor relics of fractured quartz; traces of coesite ^f	80

randomly distributed throughout the inspected thin section should be checked and these should be of sufficient size (at best exceeding 50–100 µm). For the recognition of planar fractures, which have a rather large interspacing, the inspected grains must be even larger (i.e., >ca. 500 µm).

It is important to note that occasionally the grains of a diagnostic mineral in the thin section of a sample show characteristics of more than one shock stage due to the inherent heterogeneity of shock compression of polycrystalline rocks. As proposed by Stöffler et al. (1991), we recommend choosing the highest shock stage

Table 10. Definition of progressive stages of shock metamorphism for classification system **SE** (quartz-rich sand, Tables 3 and 12); pf = planar fractures; pdf = planar deformation features; shock pressure corresponds to the final equilibration peak shock pressure; post-shock temperature is the temperature increase after pressure release relative to an ambient pre-shock temperature of 20 °C; Table based on Stöffler et al. (1975) and Wünnemann et al. (2016); shock pressures according to Wünnemann et al. (2016).

Shock stage Present proposal	Shock pressure (GPa)	Post-shock temperature (°C)	Shock effects
SE—S1			Unshocked with fully retained porosity
	<0.05–0.1	~25	
SE—S2			Fracturing of a major fraction of sand grains; still distinct porosity; distinctly reduced grain size
	~0.9	~250	
SE—S3			Incipient lithification of fractured and unfractured grains by intergranular melt (glass); zero porosity
	~5.5	~350	
SE—S4			Strong lithification of fractured and unfractured grains by intergranular melt (glass); pf and pdf in quartz; zero porosity
	~13	>1500	
SE—S5			Complete melting and formation of vesiculated melt particles

Table 11. Definition of progressive stages of shock metamorphism for classification system **RE** (regolith, Tables 3 and 12); shock pressure corresponds to the final equilibration peak shock pressure derived from shock experiments referenced in Table 2; post-shock temperature is the temperature increase after pressure release relative to an ambient pre-shock temperature of ~25 °C; (?) = uncertain values; Table based on various literature data (Table 2 and 13) and on data referenced in Table 1.4 in Hiesinger and Head (2006); compare Fig. 11.

Shock stage Present proposal	Shock pressure (GPa)	Post-shock temperature (°C)	Shock effects
RE—S1			Unshocked with fully retained porosity
	~3	~250	
RE—S2			Compaction of regolith to zero porosity
	~5–6	350	
RE—S3			Incipient lithification by intergranular melt (glass) cement; zero porosity
	10	700	
RE—S4			Lithification by intergranular melting and cementation
	20	1500	
RE—S5			Strong intergranular melting and cementation; incipient formation of vesiculated melt
	>40 (?)	>2000 (?)	
RE—S6			Large-scale formation of vesiculated “mixed” melt and whole rock melting

shown by any **significant fraction of grains** in order to establish the shock level of any sample in the lower range of shock stages. In the 1991 paper, “significant fraction” had been defined as “at least 25%” of the inspected grains. We now propose to change this definition to “**at least 50%.**” In all cases where the sample belongs to higher shock stages such as those characterized by diaplectic tectosilicate glass or flow-

textured glass of feldspar composition, it is required that **at least 75% of the grains** should be converted to **diaplectic glass** or to **flow-textured feldspar glass**, respectively. However, these recommendations can only be applied to crystalline rocks and chondritic rocks (classes F, M, A, U, and C) but not to porous rocks such as sedimentary rocks and sediments (classes SR, SE, and RE).

Table 12. List of igneous rocks, metamorphic rocks, and impactites assigned to the proposed eight shock classification systems of planetary silicate rocks; impactites are essentially represented by crystalline impact melt rocks and polymict breccias that experienced multiple shock metamorphism.

CRYSTALLINE ROCKS			
Major rock group	Classification system F		
Shock classification	Quartz, plagioclase, alkali feldspar		
Diagnostic minerals	Earth	Earth	Earth
Planetary bodies	Plutonic rocks	Volcanic rocks	Metamorphic rocks
	Granite	Rhyolite	Felsic gneisses
	Granodiorite	Dacite	Quartzite
	Tonalite	Trachyte ^a	
	Syenite ^a	Latite ^a	
	Monzonite ^a		
	Monzodiorite ^a		
	Monzogabbro ^a		
Shock classification	Classification system M		
Diagnostic minerals	Plagioclase, olivine, pyroxene, amphibole		
Planetary bodies	Earth	Mars	Asteroids
	Diorite	Norite	Basalt (monomict eucrites, most angrites)
	Gabbro	Gabbroonorite	Gabbro (some angrites)
	Norite	Troctolite	Norite (some diogenites)
	Troctolite	Anorthosites	Mafic breccia (polymict eucrites, howardites, mesosiderites type A, type B)
	Anorthosite	(ferroan, alkali, magnesium)	
	Basalt	Mare basalt	
	Andesite	KREEP basalt	
		Al-Basalt	
	Amphibolite	Granulite	
	Mafic gneiss		
	Impact melt rock		
	Lithic breccia		
	Monomict breccia		
Rock type, volcanic			
Rock type, metamorphic			
Rock type impactite ^b			
Shock classification	Classification system A		
Diagnostic minerals	Plagioclase, pyroxene		
Planetary bodies	Earth	Moon	Asteroids
	Anorthosite	Anorthosite	none
		Monomict breccia	none (so far)
			Mars

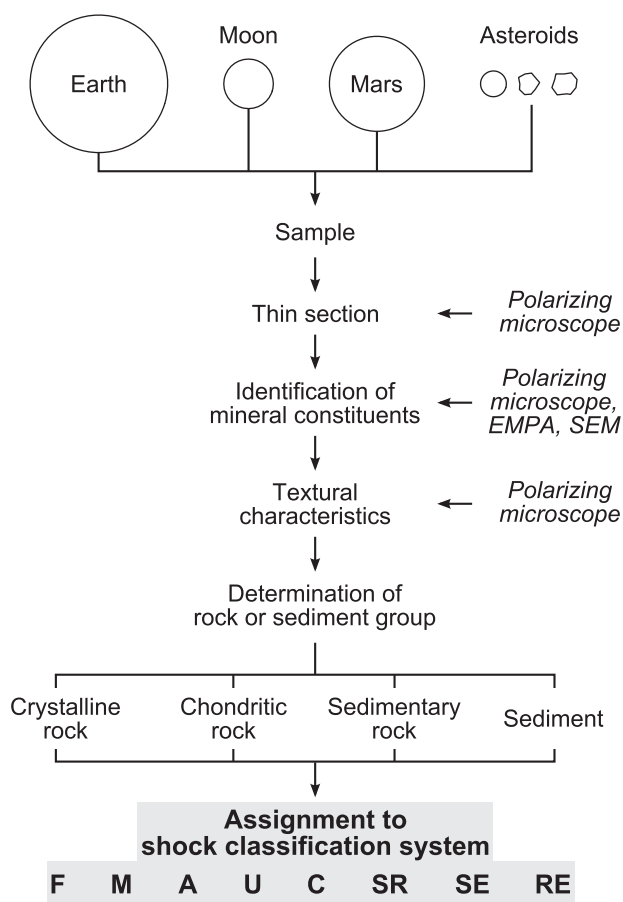


Fig. 24. Manual for the determination of the degree of shock metamorphism of rocks and sediments (see also Table 3); F = Felsic crystalline rocks, A = Anorthositic rocks, M = Mafic crystalline rocks, U = Ultramafic crystalline rocks, C = Chondritic rocks, SR = Sedimentary rocks, SE = Sediments, and RE = Regoliths.

Manual for “Crystalline Rocks” (F, M, A, U = Felsic, Mafic, Anorthositic, and Ultramafic) and for Chondritic Rocks (C)

Introductory Remarks

The following specific steps for determining the degree of shock metamorphism of the sample in question have to be taken. They are applicable to all types of nonporous “crystalline rocks,” i.e., magmatic rocks (felsic, mafic, and ultramafic), including certain achondrites and impactites (crystallized impact melt rocks and eventually low-porosity polymict and monomict breccias), as well as terrestrial metamorphic rocks and lunar metamorphic lithologies (granulitic rocks and breccias). The manual applies also to chondritic meteorites. More details on the shock classification of chondrites can be found in Stöffler et al. (1991) and Stöffler and Grieve (2007). Regarding the diagnostic shock effects, we refer to the descriptions

in Table 2 and Figs. 13–21. For porous rocks, such as polymict breccias, regoliths, sedimentary rocks, and sediments, additional procedures have to be applied which are described separately below.

For identifying the appropriate stage of shock metamorphism of a sample, follow the manual for analyzing the eight categories of sample properties listed below, but first take the following general steps.

1. Record the mineralogical composition, texture, and types of shock effects in one or two thin sections.
2. Decide on the basis of these properties on the type of rock class (F, M, A, U, or C) and on the degree of shock metamorphism by means of Tables 4, 5, 6, 7, or 8.

Detailed Manual

(1) Planar fractures (pf), feather features, and undulatory extinction

Check 10 to 20 of the largest, randomly distributed silicate grains of sufficient size (see introduction to chapter “Manual for the classification of a shock-metamorphosed rock or sediment”) for the presence of either sharp extinction (maximum allowed angle of rotation for complete extinction: 2°), or *undulatory extinction* (angle of rotation for extinction of various positions throughout the grain: $>2^\circ$), or sets of parallel *planar fractures* in addition to undulatory extinction. Either one set of three or more parallel planar fractures or two intersecting sets of two or more planar fractures are typical. Planar fractures are diagnostic of a specific shock intensity in quartz and olivine, and may also occur in feldspars and mafic minerals. Quartz should be checked for the presence of feather features in conjunction with planar fractures. The described effects are the prime criteria for a low degree of shock metamorphism (Tables 4–8).

(2) Mosaicism

Check 10 to 20 of the largest, randomly distributed single silicate grains, at least 50 to 100 μm in size, for the presence of *mosaicism*, which is a supportive criterion for low to intermediate shock stages (Tables 4–8). The differently extinguishing mosaic domains should be smaller than about 3 to 5 μm . In the optimum extinction position, the mineral should not appear homogeneously dark, but rather exhibit interference colors at a small scale. For the distinction between mosaicism and undulatory extinction, see the preceding paragraph.

(3) Kink bands

Check mica crystals (biotite and muscovite), if present, for kink bands. They are indicative of the lowest degree of shock metamorphism together with undulatory extinction in coexisting minerals but they also persist in higher shock stages as seen from Tables 4 and 5.

(4) Planar deformation features

Check 10 or more of the largest mineral grains (quartz, feldspars, and olivine) for the presence of *planar deformation features* (pdf) which are most diagnostic of the shock intensity, although they may be present also in pyroxene, amphibole, and biotite. This is a prime criterion for intermediate shock stages (Tables 4–8).

(5) *Transformation of quartz and feldspar into diaplectic glass*

Check 10 or more of the largest quartz and feldspar grains for the presence of *diaplectic glass* (completely isotropic grains with preserved original crystal shape), often called “maskelynite” in the case of plagioclase. This is the prime criterion for intermediate to high stages of shock (Tables 4–8).

(6) *Transformation of quartz and feldspar into normal vesiculated glass, alteration of mafic minerals, and loss of primary texture*

Check the sample for a visible *loss of the primary crystalline texture and fabric* by shock-induced selective melting of minerals such as plagioclase and alkali feldspar. Record the presence of flow-textured and vesiculated feldspar glass (*normal glass* in contrast to diaplectic glass), coexisting in felsic rocks with diaplectic quartz glass (typically containing also coesite). These shock effects are often accompanied by the gradual loss of pleochroism in biotite, amphibole, and in certain types of pyroxene and by the decomposition of biotite and other mafics into oxides such as magnetite and other phases. These features are the prime criterion for a high shock stage (Tables 4–8).

(7) *Incipient melting of mafic minerals and formation of mixed melts (melt veins and melt pockets)*

Check the presence of incipient melting of mafic minerals and the formation of polymineralic mixed melts that occur with increasing shock intensity, leading to an increasing presence of a network of *melt veins* and *melt pockets*. Note that melt veins and melt pockets usually do not occur in felsic rocks but are typically in mafic and ultramafic rocks. They occur in a broad range of shock intensities ranging from intermediate to high shock stages (only in classes M and C). Therefore, melt veins and melt pockets are not strictly critical for the definition of a specific shock stage (Tables 5, 7, and 8).

(8) *Whole rock melting and formation of glasses and impact melt rocks*

Check whether the sample is derived from a *whole rock melt* and check whether it is in a glassy (hyaline) or finely crystallized state with distinct flow texture and vesiculation, and mixed-in mineral and rock clasts of variable degree of shock (typical for *melt inclusions* in terrestrial suevitic breccias), or whether it represents a *clast-bearing impact melt rock*. In the latter case, it should display a rather homogeneous, mostly fine-

grained crystalline matrix with inclusions of mineral and rock clasts of variable degree of shock and variable degree of thermal alteration (e.g., “checkerboard” and “ballen” textures in feldspars and quartz, respectively, in terrestrial impact melt rocks [see Ostertag and Stöffler 1982; Bischoff and Stöffler 1983; and Ferrière et al. 2010]). Clast-bearing impact melt rocks are characteristic for *impact melt layers* in terrestrial and lunar craters.

Regarding class C (*chondrites*), it should be noted that shock-induced whole rock melts appear to be rather rare but they do occur, although mostly as clasts in polymict breccias (Lunning et al. 2016). Typically, they display a holocrystalline texture due to their mafic composition. Check for the presence of an igneous texture of the whole rock indicating crystallization from a liquid. This will establish the rock as a clast-free impact melt rock. The presence of relic chondrules and of mineral and lithic clasts in an igneous matrix would indicate that the rock is a clast-bearing chondritic impact melt rock.

Manual for Impactites (Classes M, A, and U), Sedimentary Rocks (SR), and Sediments (SE, RE)

Impactites

As explained in Table 1 and Figs. 3 and 5, rocks of planetary bodies without an atmosphere and reduced or lacking internal geological processes in their crusts can be affected by multiple shock metamorphisms. The products to be considered are (1) polymict regolith breccias resulting from lithification by a small-scale impact into regolith and (2) cataclastic and polymict breccias formed in large-scale impact events and deposited as parautochthonous and allochthonous impact formations (ejecta blankets and deposits inside craters) which then are affected by one or more subsequent impacts. Such multiple impact events result in superimposed layers of breccias and coherent impact melt rocks as shown in Fig. 5. In principle, we deal here with (1) *regolith breccias* (2) *cataclastic (monomict) breccias*, (3) *lithic (polymict) breccias*, (4) *suevitic breccias*, and (5) *impact melt rocks* (Figs. 3 and 5). Breccias with cogenetic, rather large, aerodynamically shaped melt particles (*suevitic breccias of the type “secondary suevite”* typical for terrestrial impact craters; Stöffler et al. 2013) will not be considered here as they are restricted to terrestrial craters and cannot be expected on other planetary bodies except possibly on Mars. However, “*primary suevitic breccias*” with small melt particles interpreted as fallback material of the vapor (ejecta) plumes of impact craters, as well documented at the Ries crater (Stöffler et al. 2013), should also be present on all other planetary bodies.

Indications for this were found by one of us (K. M.) in the L3–6 chondritic regolith breccia NWA 869 (Metzler et al. 2010, 2011) and in the polymict eucrite NWA 1644.

The important points are: (1) We cannot assign a certain stage of shock metamorphism to any type of polymict breccia as a whole if it results from a single impact as it is the case in terrestrial impact craters. In the case of lunar, Martian, and asteroidal breccias, we consider therefore these as “first-generation breccias,” and (2) any subsequent impact event affecting such breccias changes their shock stage as a whole by increasing the shock stage of all more weakly shocked constituents to the pressure–temperature level of this secondary shock event.

The following recommendation deals with the effects of a subsequent impact metamorphism of “first-generation breccias” such as regolith breccias and polymict and monomict breccias of lunar and asteroidal provenance (see also Tables 3 and 12). We recommend taking the following steps in determining the degree of shock metamorphism of these breccias:

(1) General petrographic and textural properties

Check the presence or lack of melt particles (glass spherules and agglutinates in the case of regolith breccias) and variably shocked clasts in order to differentiate between regolith breccia and lithic breccia and eventually “primary” suevitic breccia. Examine the nature of the breccia matrix for porosity. The presence of porosity would indicate that the breccia is unshocked or only very weakly shocked. The lack of porosity and the presence of intergranular melt would indicate shock lithification by moderate or strong shock intensity.

Check whether the matrix of the sample is hyaline (glassy), hypocrystalline, or holocrystalline (aphanitic) indicating that the sample is a clast-bearing impact melt rock with mineral and lithic clast of variable degree of shock.

(2) Variation of shock effects among mineral and lithic clasts

In case the breccia sample (monomict or polymict breccias) has retained porosity, check the presence of unshocked mineral clasts forming the breccia matrix, indicating that the breccia is unshocked or only very weakly shocked. Based on Tables 5–7, a breccia sample (including impact melt rocks) can be assigned to a specific higher stage of shock metamorphism if the whole population of clasts in the breccia displays a specific well-defined degree of shock and no primary porosity is present. Keep in mind that more highly shocked inclusions of clasts such as impact melt rocks formed by the first generation of shock metamorphism can still be present in a polymict sample.

At present, a more detailed separate classification system for progressive stages of shock metamorphism of polymict breccias, such as regolith breccias and lithic breccias that retained a primary porosity, is not proposed and to our opinion not needed.

Sedimentary Rocks and Sediments (Terrestrial)

The recommended manual for terrestrial “sedimentary rocks and sediments” is based on the shock classification systems presented in Tables 9 and 10. As the system for progressive shock metamorphism of detrital regolith (Table 11) needs special considerations, we concentrate here first on terrestrial sandstone or other quartz-rich sedimentary rocks and quartz-rich sediments such as sand. The recommendations are supported by a very detailed data set from cratering experiments and shock recovery experiments (references in Tables 9 and 10):

(1) General petrographic and textural properties

Examine first whether you are dealing with an originally porous sedimentary rock or unconsolidated sediment. Check the sample in question for remnant porosity or lack of porosity. The latter is a first indication of shock metamorphism. After having checked additional shock effects described in (2) and (3) below, assign the sample to the appropriate shock classification system presented in Tables 9 and 10.

(2) Planar fractures, planar deformation features in quartz, and quartz glass

Check the presence of mechanical deformations (pf, pdf) and the amount of isotropic quartz grains (presumably diaplectic glass) and intergranular melt (lechatelierite) for proper assignment of the stage of shock metamorphism. Check the volume fraction of quartz glass. If possible, check the presence of high-pressure phases of quartz (coesite and stishovite), and take this as a supportive (but not decisive) tool to assign the appropriate stage of shock metamorphism.

(3) Whole rock melting

Check the texture and composition of the product of whole rock melting. Vesiculated glass and pumiceous texture with inclusions of some relics of crystalline quartz confirms the existence of the highest stage of shock metamorphism of the sample (see Tables 9 and 10).

Planetary Sediments (Regoliths)

The following manual is based on the shock classification system contained in Table 11. This classification system is essentially derived from a set of shock recovery experiments on samples of lunar soil (regolith), particulate lunar basalt, and powdered samples of an H chondrite and an L chondrite as

Table 13. Progressive stages of shock metamorphism observed in shock recovery experiments on lunar and chondritic analog regoliths (based on data from references 1, 2, 4, 5, 6) and on a theoretical model regolith (reference 3); 1 = Schaal et al. (1979), 2 = Schaal and Hörz (1980), 3 = Kieffer (1975); 4 = Christie et al. (1973), 5 = Bischoff and Lange (1984), and 6 = Hörz et al. (2005); note that the plagioclase content decreases from column 1 to column 6; the horizontal boundaries referring to the pressure scale are no sharp boundaries except for column 6.

Shock pressure (GPa)	Regolith analogue samples					
	Lunar samples			Chondritic samples		
	Particulate basalt 75035 ^a	Regolith samples	Model regolith	H5 chondrite powder, 16% porosity <150 µm	H5 chondrite powder, <5% porosity <150 µm	L6 chondrite ALH 85107 ^b
	15101 ^a 45–150 µm		65010 ^a			
0–10	Compaction and lithification	Compaction	Lithification	?	?	Compaction and lithification (complete at 14.5 GPa)
10–20	Compaction and lithification	Lithification		Compaction and lithification with minor intergranular melt	Compaction and lithification	
20–30	Lithification by intergranular melt	Lithification by intergranular melt	Vesiculated melt	Lithification by melt	Lithification by intergranular melt	Intergranular melt (starting at 25 GPa)
30–40						
>40	Vesiculated melt	Vesiculated melt				Vesiculated melt (50% at 65 GPa)
References	1	2	3	4	5	6

^aLunar sample numbers: 75035 = Apollo 17; 15101 = Apollo 15; 65010 = Apollo 16. ^bAntarctic meteorite Allan Hills.

summarized in Table 13. The main goal of this classification system is to define the degree of metamorphism required to obtain a consolidated regolith material (regolith breccia). The following steps have to be taken:

(1) General texture

Check the presence of the essential components defining the sample as regolith, i.e., the presence of variously shocked mineral and rock clasts, of melt particles (agglutinates) and of melt spherules. Examine the presence or lack of porosity and the presence or lack of intergranular melt defining the degree of lithification in order to be able to recognize the sample as a regolith breccia.

(2) Compositional properties (minerals and type of melt)

Determine the types of minerals and of polymineralic components present in the sample, and check for the presence of typical components of chondrites in order to recognize the provenance of the regolith or regolith breccia from a lunar, asteroidal, or Martian source. In order to make a safe distinction between these three sources, additional analytical tools may be necessary such as EMPA and SEM. Decide finally based on Table 11 whether the sample is a regolith breccia (regolith of shock stage S3, S4, or S5).

OPEN ISSUES

Iron Meteorites

We have restricted the topic of this paper to silicate rocks and sediments, but we are aware of the fact that iron meteorites underwent shock metamorphism as well. At present, we do not feel competent enough to deal with this subject in an adequate manner. We hope to stimulate some experts on iron meteorites to provide a review paper on shock metamorphism of iron meteorites and related stony irons. Such a review is overdue because most publications specifying on shock effects in iron meteorites are from the last century (e.g., Lipschutz 1968; Jain and Lipschutz 1971; Buchwald 1975). A recent study is restricted to one group of iron meteorites (IIIE iron meteorites; Breen et al. 2016).

Shatter Cones

Shatter cones are shock-induced deformations of solid rocks formed at low to moderate shock pressures (see papers in a special issue on shatter cones, *Meteoritics & Planetary Science* Vol. 51, No. 8, 2016). They are characteristic macroscopic features with dimensions in the centimeter to decimeter size range and occur in two different geological settings: (1) in parautochthonous

rocks of terrestrial impact craters in a zone of a low degree of shock metamorphism or (2) as rock clasts in allochthonous ejecta deposits, typically with some higher degree of shock metamorphism. Observations in the Ries crater (von Engelhardt and Graup 1977) indicate shock pressures for case (1) of about 5–25 GPa (maximum based on the presence of pdfs parallel to $\{10\bar{1}2\}$) and for case (2) up to a maximum of 45 GPa based on the presence of diaplectic quartz glass. Consequently, in case of felsic rocks (Table 4), such samples belong to shock stages S2 to S4 in case (1) and to shock stages as high as S5 in case (2). The latter types of shatter cones are confirmed by observations on clasts in polymict breccias of the ejecta blanket of the Ries crater. Observations in other craters such as Vredefort indicate a shock pressure range from 2 to 30 GPa (Gibson and Reimold 2008). The complete pressure range for the formation of shatter cones found in the literature is 1–45 GPa as referenced by Zaag et al. (2016).

Shatter cones in parautochthonous formations (1) are very commonly found in most terrestrial impact craters, but those in allochthonous deposits are extremely rare due to erosion. It should be pointed out that shatter cones per se are not suitable for the definition of a shock stage and are therefore not part of the classification systems of progressive shock metamorphism of rocks and sediments discussed in this paper.

Shock Effects in Carbonates

We are aware that carbonates, such as calcite or dolomite, are not discussed in this contribution, although they are abundant in terrestrial impact structures (Osinski et al. 2008), are increasingly discovered on Mars (e.g., Ehlmann et al. 2008; Michalski and Niles 2010), and are even found in meteorites (e.g., Leuw et al. 2010). The response of carbonates to elevated shock pressures is a topic of an ongoing and controversial debate (see recent discussion by Osinski et al. 2008; Langenhorst and Deutsch 2012; Stöffler et al. 2013; Hörz et al. 2015; Osinski et al. 2015; Bell 2016). Although frequently studied in shock recovery experiments, no consensus has been reached so far regarding the onset or even nature of specific shock effects in carbonates. This is illustrated in particular by disagreeing estimates for the shock pressure threshold that governs the onset of calcite decomposition or melting in experiments (see summaries in Osinski et al. 2008; Bell 2016), or by conflicting studies regarding the existence of carbonate impact melts in the impactites from Ries (Graup 1999; Osinski 2003; Stöffler et al. 2013) or Barringer Crater (Hörz et al. 2015; Osinski et al. 2015). At present, we simply do not feel confident enough to advocate a shock classification system for

carbonate rocks, nor for typical carbonate minerals such as calcite or dolomite.

FINAL REMARKS AND RECOMMENDATIONS

Use of the Universal Stage in Polarized Light Microscopy

For the definition of specific shock stages of felsic rocks (Table 4), measurements of the crystallographic orientation of planar deformation features $\{10\bar{1}2\}$ and $\{10\bar{1}3\}$ in quartz are necessary and require the use of the Universal Stage (Berek 1924; Emmons 1943; Medenbach 1985; Kile 2006). It seems that it is getting increasingly difficult to have access to this tool and to be trained in using it. Our recommendation is that any shocked sample of felsic composition displaying planar deformations features of unknown orientation may be classified as “S3 to S4” with the comment “pdf with unknown orientation.”

Polymict Lithic Breccias with Cogenetic Melt Particles

We feel that it is necessary to emphasize that the Subcommittee on the Systematics of Metamorphic Rocks of the IUGS has recommended the terminology for this type of breccia. It is left optional to call it “suevite” or “suevitic breccia” (Fettes and Desmons 2007). These terms cannot be deleted, as has been recently proposed, without any new discussion of the IUGS recommendations. “Suevitic breccia” may be preferable as the other subgroup of polymict breccias is named “lithic breccia” (polymict breccia without cogenetic melt particles). In addition, we recommend keeping in mind that “suevitic breccias” occur on Earth as “primary suevite” and “secondary suevite” according to the presently accepted genetic concept (Artemieva et al. 2013; Stöffler et al. 2013). The latter, representing the main mass of suevite in terrestrial craters, requires an interaction of hot impact melt (melt pool) with water or other volatiles (fuel-coolant interaction). As “primary suevite” represents fallback material from the ejecta plume of an impact crater, it is highly probable that it also occurs on the Moon and possibly on asteroids in contrast to “secondary suevite.” However, we cannot exclude that on Mars the conditions for the formation of the latter type of suevite are favorable although so far none of the Martian meteorites is a suevitic breccia.

Definition of the Shock Stage of a Multiply Shocked Sample

We noticed some confusion in the literature regarding the assignment of a specific shock stage to samples of polymict impactites (lithic breccias and impact melt rocks) of lunar or asteroidal origin, which

typically have been affected by more than one shock event. The shock stage of such samples is clearly defined as the degree of shock metamorphism caused by the shock event that has affected the sample as a whole. It is therefore not acceptable to assign a range of shock stages, e.g., S2–S5 or S2/S5, to such a sample as it has been occasionally done in the literature. We recommend to follow the procedure explained in detail in the section “*Manual for impactites, sedimentary rocks and sediments*,” subsection “*Impactites*.”

General Importance of Shock Classification Systems

In addition to the shock effects described in this article, some other important properties of natural rocks or sediments are affected by shock metamorphism. Besides the microscopically recognizable effects such as mechanical deformations, phase transformations, decomposition into new phases, and melting, essential chemical properties of the sample will be changed. The potential changes are:

1. loss of volatile elements
2. change of the oxidation state of elements (e.g., $\text{Fe}^{2+}/\text{Fe}^{3+}$)
3. change of the isotope ratios of trace elements
4. change of the primary isotope age.

These effects lead to a clearly defined change of the chemical state for samples of the highest stage of shock metamorphism, i.e., by melting. Consequently, the isotopically determined age of impact melts quenched to glass or crystallized impact melt rocks represents the age of the impact event by which the melt was formed. The isotope systems of samples of intermediate stages of shock metamorphism are also affected and their ages are partially reset. These and other chemical effects have been studied in some detail on naturally and experimentally shocked silicate minerals and rocks (e.g., Jessberger and Ostertag 1982; Staudacher et al. 1982; Ostertag et al. 1984; Bogard et al. 1987, 1988; Deutsch and Schärer 1994; Schwenzer et al. 2008).

The general consequence of the described effects is that for any sample, especially for lunar rocks and for all types of meteorites, a clear identification of (1) the type of **impactite** (shocked rock, monomict breccia, polymict breccia, and impact melt rock) and (2) the **degree of shock metamorphism** is mandatory before any detailed chemical analyses are made, and far-reaching conclusions in terms of the genetic origin of a sample are drawn in a cosmochemical or planetary context.

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Editorial Handling—Dr. Oliver Tschauner

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

Fig. S1. Microphotos of shock effects in quartz.

Fig. S2. Microphotos of shock effects in plagioclase.

Fig. S3. Microphotos of shock effects in alkali feldspar.

Fig. S4. Microphotos of shock effects in olivine.

Fig. S5. Microphotos of shock effects in pyroxene.

Fig. S6. Microphotos of shock effects in amphibole.

Fig. S7. Microphotos of shock effects in biotite.

Fig. S8. Microphotos of melt veins and melt pockets in the Martian Tissint meteorite.

Fig. S9. Microphotos of impact glasses.

Appendix S1. Glossary of terms for impactites.
