GEOLOGIC SETTING, PROPERTIES, AND CLASSIFICATION OF TERRESTRIAL IMPACT FORMATIONS

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ABSTRACT

Terrestrial impact formations (impactites) provide the undisputed ground truth for the process and the products of hypervelocity impacts on planetary surfaces. According to [1], *impactites* which are *proximal* to the parent crater, are subdivided into *shocked rocks*, *impact breccias* and *impact melt rocks*. There are 3 types of impact breccias: *monomict breccia*, *suevite* and *lithic breccia*. *Distal impactites* comprise *(micro)tektites* and *global air fall beds*. Based on their geological setting proximal impactites form either allochthonous layered deposits of the crater fill and the continuous ejecta blanket, or appear as (par)autochthonous massive units in the crater basement or as dikes, veins, and vein networks in the basement or in displaced megablocks.

1. INTRODUCTION

Terrestrial impact structures and their associated regional or global deposits provide the fundamental and indispensable data for the interpretation of impact formations on the surfaces of solid planetary bodies, if properly corrected for differences in gravity, target composition (including presence or lack of water), and density of the atmosphere of the various planets or moons. This review deals with all rock types collectively termed “impactites”, which are formed by hypervelocity impacts on Earth, and extends this classification to planetary bodies without an atmosphere. It is based on a yet unpublished proposal [1] by the Subcommission on the Systematics of Metamorphic Rocks (SCMR) of the International Union of Geological Sciences (IUGS).

2. BASIC FACTS AND CAVEATS ABOUT TERRESTRIAL IMPACT CRATERS AND IMPACT FORMATIONS

Some of the most relevant facts resulting from the study of terrestrial and planetary impact structures in the past 50 years can be briefly summarised as follows:

(1) Most of the record of terrestrial impact craters has been lost by erosion and other geological processes (plate tectonics, volcanism); in particular the early Archaean record is lacking but can be inferred indirectly from the moon’s cratering record.

(2) Although the original morphology and the surficial impact formations of individual craters are rarely preserved, the morphological and structural type of a crater changes distinctly with increasing crater diameter in the following sequence: (a) simple bowl-shaped, (b) complex with central uplift, (c) complex with peak ring, and (d) complex with multi-rings (?). This is in clear analogy to what can be recognised on other planetary surfaces except for multi-ring basins for which no undisputed examples exist on Earth.

(3) The crater-forming process on Earth is often complicated by the complexity of the target stratigraphies and target rock compositions and by the presence of a hydrosphere and atmosphere.

(4) Due to the effects of erosion the invaluable advantage of terrestrial craters is that they are accessible at different erosional levels and therefore allow a true three-dimensional analysis unlike craters on other planets and moons.

(5) Comparative studies of craters of the same size class but different target stratigraphy/composition provide an excellent insight into the crater-forming process if properly accompanied by the most-advanced computer code calculation techniques.

3. PRINCIPAL APPROACH FOR THE ANALYSIS OF IMPACT FORMATIONS

The analytical approach to study craters and impactites should be as comprehensive and multi-disciplinary as possible and should include the following steps:

(1) Field mapping and identification/sampling of the different types of impact formations, and assessment of their regional distribution and geological/structural setting.

(2) Petrographic and chemical analyses with respect to texture, modal/chemical composition, and shock metamorphism including radiometric age dating of the appropriate type of impactite (crystallised impact melt rock or impact glass).

(3) Geophysical surveys including seismic, gravity, magnetic and geoelectric analyses to assess the

(4) Exploration by drilling and drill core analyses using methods listed under (2) and (3). Meaningful verification of the regional geophysical signatures and a full understanding of the structural and lithological characteristics of a crater needs focused drilling at several critical sites such as the centre of crater, rim zone, inner ring (peak ring), and ejecta blanket if present. This means that at least 3 drill sites are required for complex craters.

4. WORKING HYPOTHESES FOR THE FORMATION OF CRATERS AND IMPACTITES

Impactites are formed during a complex but very short sequence of processes (Fig. 1): Shock compression of the target rocks (compression stage), decompression and material transport (excavation stage), and material deposition upon ballistic or ground-surging transport and upon collapse of the central ejecta plume (Fig. 2). The first two phases constitute the first of two fundamental working hypotheses in impact cratering: the so-called *transient cavity,* which independently of the size of the crater, has a nearly parabolic shape [2] and collapses to a final crater (modification stage) that becomes more complex (central uplift and ring formation) and less deep with increasing final crater diameter [2]. Although all phases of the cratering process are transitional and partially simultaneous, it is helpful to consider the formation, evolution and collapse of the central *vapour plume* [2] separately in the context of a second working hypothesis.

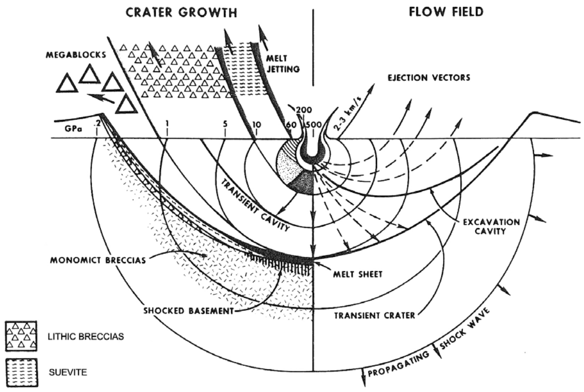


Fig. 1: *Shock wave propagation, crater growth and formation of a transient cavity following a hyper-velocity impact (from [1]).*

The concept of a *transient cavity* (Fig. 1; [2]) includes products formed by highly dynamic transport and by a mixing process driving material (type 1) downward into the growing crater floor (breccia lens formed by ground surging) and ejecting material (type 2) ballistically outside of the cavity forming the ballistically emplaced continuous ejecta blanket. In all craters type 1 material consists of impact melt, shocked lithic clasts, and unshocked lithic clasts from relatively deep levels of the target stratigraphy. As far as we know from the few craters with preserved ejecta blankets, the type 2 material - defined here as material not engulfed in the vapour plume (see below) - appears to include predominantly unshocked lithic clasts, shocked lithic clasts of relatively low degree of shock and no or only rare melt particles. This material originates from relatively shallow levels of the target stratigraphy. Both types of displaced materials are highly polymict except for the type 2 material (ejecta blanket) of small simple craters which may display a layered, inverted stratigraphy.

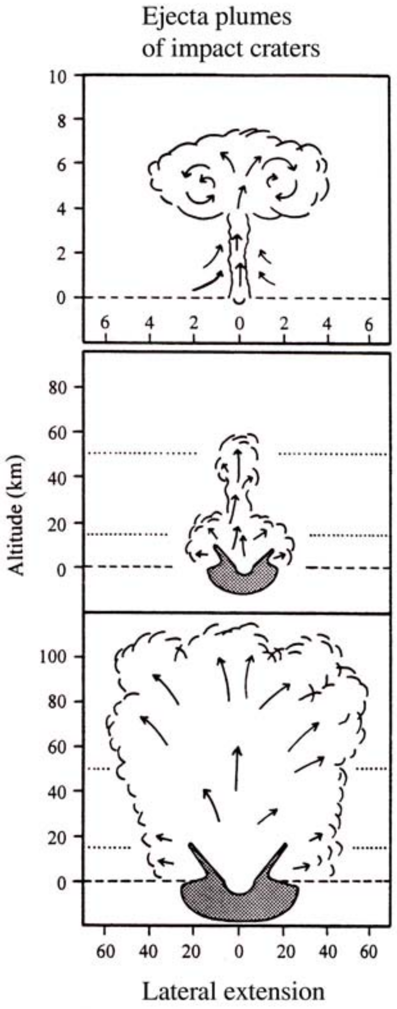


Fig. 2: *Expansion of a vapour plume at impact craters of different size (from [25]).*

The concept of the *vapour plume (or ejecta plume)* considers products resulting from vaporisation, melting, and comminution of target material located in the central part of the target below the penetrating impactor [2]. This material is ejected at very high velocities and is turbulently mixed within the expanding vapour plume that eventually collapses and forms fallback deposits (suevitic polymict breccias) inside the crater and - as we know it from the Ries and Chicxulub craters – also on top of the continuous ejecta blanket. It appears that the tektite and microtektite strewn fields observed at some young impact craters are also part of the vapour plume forming process. Depending on the size of the crater the vapour plume may rise well above the Earth's stratosphere and consequently may distribute material globally. The deposits from the vapour plume are expected to contain condensates of vaporised rocks.

5. CLASSIFICATION AND NOMENCLATURE OF IMPACTITES

The term *"impactite"* is defined as a collective term for all rocks being affected by one or several impact(s) resulting from collision(s) of planetary bodies. A classification scheme is proposed for products of single and multiple impacts ([1], Table 1, Figs. 3 and 4). It is applicable to both terrestrial and extraterrestrial rocks such as lunar rocks and meteorites of asteroidal, lunar, and Martian provenance. The basic classification criteria are based on texture, degree of shock metamorphism, and the type(s) of lithological components.

Table 1: Classification of impactites formed by single and multiple impacts; from [1]

1\. Impactites from single impacts
  1.1. Proximal impactites
    1.1.1. Shocked rocks*
    1.1.2. Impact melt rocks^{1}
      1.1.2.1. clast-rich
      1.1.2.2. clast-poor
      1.1.2.3. clast-free
    1.1.3. Impact breccias
      1.1.3.1. Monomict breccia
      1.1.3.2. Lithic breccia (without melt particles)^{2}
      1.1.3.3. Suevite (with melt particles)^{2}
  1.2. Distal impactites
    1.2.1. Consolidated
      1.2.1.1. Tektite^{3}
      1.2.1.2. Microtektite^{3}
    1.2.2.Unconsolidated
      1.2.2.1. Air fall bed^{4}
2\. Impactites from multiple impacts
  2.1. Unconsolidated clastic impact debris
    2.1.1. Impact regolith^{5}
  2.2. Consolidated clastic impact debris
    2.2.1. Shock-lithified impact regolith^{5}
      2.2.1.1. Regolith breccia^{5} (breccia with in-situ formed matrix melt and melt particles)
      2.2.1.2. Lithic breccia^{5} (breccia without matrix melt and melt particles)

*see Tables 2-4 for further subclassification of some common rocks; for other rocks and sediments see [1]
^{1} may be subclassified into glassy, hypocrystalline, and holocrystalline varieties, ^{2} generally polymict but can be monomict in a single lithology target, ^{3} impact melt (generally glassy) with admixed shocked and unshocked clasts, ^{4} pelitic sediment with melt spherules, shocked and unshocked clasts, ^{5} generally polymict but can be monomict in a single lithology target.

Impactites from a single impact are classified into 3 major groups irrespective of their geological setting: s*hocked rocks* (Tables 2-4), *impact melt rocks*, and *impact breccias.* The latter fall into three subgroups (monomict breccia, lithic breccia, suevite) according to the degree of mixing of various target lithologies and their content of melt particles. *Impact melt rocks* that have a crystalline to glassy matrix, and *lithic breccias* and *suevites* which have a fine-grained particulate matrix, are generally polymict breccias, except for single-lithology targets.

Impactites from multiple impacts, as known from the Moon [3] and from the meteorite parent bodies [4], are subdivided into two main groups: *Impact regolith* and *shock lithified impact regolith*. This group is subclassified into *regolith breccias* (with in-situ formed matrix melt and individual melt particles) and *lithic breccias* (without matrix melt and melt particles). The term lithic breccia is synonymous to the traditional term "fragmental breccia", which has been used also for lunar rocks and meteorites [3, 4].

An important extension of the first-order classification, which is based essentially on texture, modal composition, and shock metamorphism, is achieved if the geological or structural setting of impactites is taken into account (Fig. 4). Structurally, three types of formations have been recognised: (a) Parautochthonous massive *monomict breccias* and *shocked rocks* of the crater basement*,* (b) *layered* impact formations such as *impact melt rocks* and *impact breccias*, and (c) *dyke breccias*. The latter two types occur as proximal impactites both inside the crater and outside as part of the continuous ejecta blanket extending outward for some 2 to 3 crater radii.

6. GEOLOGIC SETTING AND PROPERTIES OF THE MAIN TYPES OF IMPACTITES

The geological setting of the various textural types of impactites (Table 1) is rather variable ([1], Figs. 3 and 4):

Impact melt lithologies [1, 5] occur as (1) allochthonous coherent melt sheets, (2) inclusions in polymict impact breccias (suevite), (3) dykes and veins in the autochthonous crater basement, in displaced shocked rock fragments and in displaced (unshocked) megablocks, (4) individual melt particles on top of the ejecta blanket, glassy or crystallised spheres in global air fall beds, and (5) glassy tektites. Coherent melt sheets in large craters and the related hydrothermal processes may produce extensive ore deposits [6]*Shocked rocks and minerals* (~5–50 GPa) are found as allochthonous clasts within polymict impact breccias, impact melt rocks and air-fall beds, and as (par)autochthonous material of the crater basement [1, 7].

Monomict breccias (< ca. 5 GPa) formed during shock compression and dilation are characteristic of the crater basement but are also common constituents of polymict breccias [1, 7, 8]. Displaced megablocks within the continuous ejecta blanket are usually monomictly brecciated.

Dyke breccias can be related to all major phases of the crater formation process and up to 4 generations of dykes have been observed [8, 9]. *Melt veins* or *shock veins* and *vein networks* [4, 10, 11, 12] described from many terrestrial impact sites [11] and from asteroidal, lunar and Martian meteorites [4, 10, 13] are clearly formed during the early compression stage, as they often occur as clasts within later-formed breccia dykes and sometimes contain high-pressure polymorphs. The category *"Dykes, veins and vein networks"* (Fig. 4) includes also formations that in the past have been collectively labelled *"pseudotachylite"*. This term should be avoided as it includes a variety of formations of melt and purely clastic breccia as well as friction-generated bona fide pseudotachylite [11]. The injection

Table 4: Classification of shocked sandstone; modified after [23 and 24]; ranges of pressure estimates are given in parentheses; post-shock temperature are relative to an ambient temperature of 0°C

Shock stage	Equilibration shock pressure, GPa	Post-shock temperature, °C	Shock effects
0			Undeformed sandstone
	0.2-0.9	~25	
1a			Compacted sandstone with remnant porosity
	~3.0 (2.2-4.5)	~250	
1b			Compacted sandstone compressed to zero porosity
	~5.5 (3.6-13)	~350	
2			Dense (non-porous) sandstone with 2-5% coesite, 3-10% glass and 80-95% quartz
	~13	~950	
3			Dense (non-porous) sandstone with 15-35% coesite, traces of stishovite, 0-20% glass and 45-80% quartz
	~30	>1000	
4			Dense (non-porous) sandstone with 10-30% coesite, 20-75% glass and 15-45% quartz
5			Vesicular (pumiceous) rock with 0-5% coesite, 80-100% glass (lechatelierite) and 0-15% quartz

modification stage while the transient crater collapses with development of an extensional regime; large-scale faulting may take place during this phase.

The time for the formation of impactites ranges from seconds to hours [2, 14] and is extremely short compared to any other geological process. Despite of this, distinct superposition contacts between layered impact formations or contacts at discordant impact breccia dykes are quite common; e.g. sharp contacts of coherent sheets of impact melt to monomictly brecciated, unshocked or mildly shocked crater basement, or contacts between the continuous ejecta deposits (polymict lithic breccias) and the overlaying suevite are characteristic.

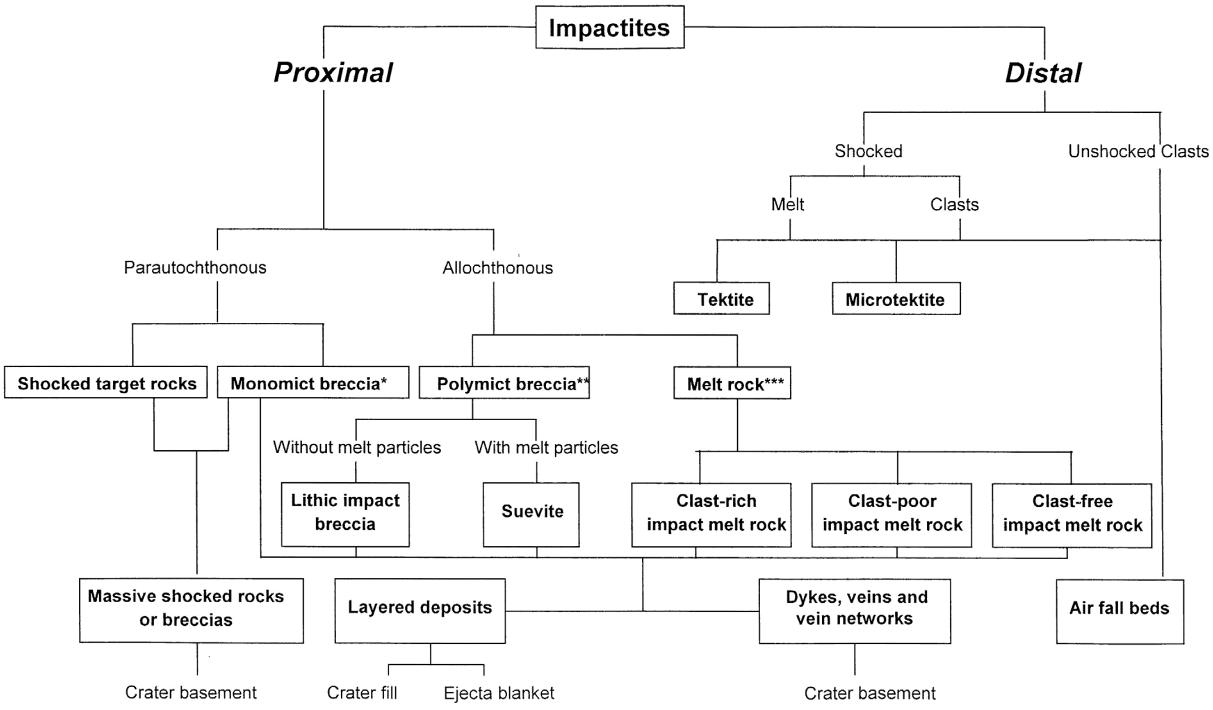
7. OPEN QUESTIONS AND FUTURE PERSPECTIVES

In our view some of the most burning *open questions* in terrestrial impact crater research are:

1. What is the role of target composition and target structure for the cratering process? To answer this question we need more comparative studies of craters of similar size but of different target composition and target stratigraphy. Such studies should be performed in close interaction with numerical modeling of the cratering process.
2. How does the formation and collapse of the vapour (ejecta) plume take place and how does it change as a function of crater size? To make progress in this area one needs more focused analyses of the products of ejecta plumes, in particular suevite breccias, at craters of different size and different target composition. These studies, again, should be accompanied by numerical modeling which should include modeling of the global effects in the case of large impact event such as that at Chicxulub.
3. What is the distribution and state of impactor material in impactites? In a first step the data base should be substantially enlarged, i.e. we need to know the type of impactor for much more craters than we have so far. This requires a comprehensive research effort using platin group elements (PGE) analyses of those impactites which were "contaminated" by projectile material during crater formation, namely impact melt rocks and suevites. This requires that also the data base of the known types of meteorites must be improved substantially. In a second step an attempt should be made to better understand the process of mixing of impactor and target material during the crater-forming process. Such studies may eventually yield a better understanding of the variation of the Earth-crossing impactor flux as a function of time since the formation of the Earth-moon system, if the analysis of melt rocks from the lunar highlands (Apollo samples and meteorites) is included.
4. What are the exact absolute ages of the known terrestrial impact craters? There is a strong need for more high-precision radiometric dating of impact melts in terrestrial craters, as only a fraction of the currently known terrestrial impact structures have been dated at reasonable precision (< 5 Ma error). This is also mandatory with regard to question 3.

Regarding *future strategies* for impact crater research there are certainly conflicting views about the best approach to future research. We do not argue against any effort to discover and describe new craters. However, it is not extremely helpful to produce more "bits and pieces" from unknown or poorly studied craters. There are good arguments for promoting comprehensive and multidisciplinary studies on well documented and well accessible craters in the context of the major issues of cratering mechanics. In this approach any possible effort should be made to favor comparative studies of craters of different size classes and of different target compositions. In any case, a better interaction of field, laboratory, and modeling studies for any crater in question is highly recommendable. In view of the general importance of impact cratering for the geological, climatological and biological evolution of planets and moons in the Solar System, a strong research focus on large complex terrestrial craters such as Vredefort, Sudbury, and Chicxulub is highly promising as such studies do have clear and far-reaching planetary implications. Last not least, a special interdisciplinary effort for learning more about the Achaean cratering record on Earth should be made. In particular, the search for distal ejecta layers (so-called *spherule beds*; [15]) in the Archaean and Proterozoic has the potential to extend the current terrestrial impact record which is strongly skewed to impact ages < 500 Ma.

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



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

Fig. 4: *Classification of impactites and their geological setting (from [1]).*

8. REFERENCES

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