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Morphological, structural and lithological records of terrestrial impacts: an overview

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Impact cratering produces not only craterform topographic features, but also structural disturbances at the site of impact, and a spectrum of transformed and newly formed rocks. The term 'coptogenesis' (from the Greek $\chi o \pi \tau o$, to destroy by shock) may be used collectively to describe the impact process—a process fundamental to all cosmic bodies. Principal coptogenic topographic features of terrestrial impact craters may be subdivided into excavational, structural and accumulative landforms, most of which subsequently experience various processes of degradation. Nevertheless, the original shape of craters may in some cases be reconstructed and compared with fresh craters on other planets. An immediate conformity between the pre-erosional topographic features of complex terrestrial craters, and the morphostructural elements of their erosional remnants, is not a standing rule. Geological observations show that the inner structure of the proximal crater fill and distal ejecta are characterised by pseudo-stratification and that these materials represent a group of facies of impact-derived and impact-related, or coptogenic, lithologies. The study of these facies allows us to distinguish various facies settings of rock-forming processes. Impact lithologies, or coptogenic rocks, may be systematised and classified using the principles adopted by igneous petrology and volcanology. Appropriate geological methods and approaches should be applied to the investigation of terrestrial impact craters, including their identification, mapping, and study of their various physiographic, structural, and lithological features.

KEY WORDS: coptogenesis, ejecta, extraterrestrial, impact crater, impact structure.

INTRODUCTION

Formulation of the concept of impact interactions between cosmic bodies of the Solar System and the understanding of the fundamental geological role of these interactions, is one of the most important achievements of natural sciences during the last century. These interactions are not only responsible for the surface morphology of most solid planets, but ultimately caused their origin and exerted important influences on their evolution (French 1968; Shoemaker 1977; Melosh 1989). The peculiarities of accretion processes and their consequences for the early stages of planet formation are not yet well understood, although different models have been proposed during recent decades (Grieve 1980; Ryder 1990; Glikson 2001). Undoubtedly these processes, in particular accretion, are responsible for the formation of a planet's interior structure, composition of solid, liquid and gaseous shells, and the geological processes of the inner planets. The impacts of small cosmic bodies on the outer solid shells of planets are much better studied. These impact processes started immediately during the origin of the planets and continued throughout their evolution.

The velocity, mass, density and composition of the projectile constitute intrinsic controlling factors in the impact event. The energy of the ensuing impact event is determined by velocity and mass. In the case of a collision between a meteoroid and planet, the gravitational acceleration of the planet, and the composition and structure of its outer shells constitute extrinsic factors. Both the intrinsic and extrinsic factors of individual impact events, as well as the prolonged cumulative result of the influx of cosmic bodies during geological time (Neukum & Ivanov 1994), create the surface appearance of most solid cosmic bodies (Figure 1).

Numerous impact structures, or astroblemes (Dietz 1963) have been discovered on the Earth's surface during the last few decades, both on continents and continental shelves (Grieve & Pesonen 1996; Grieve & Therriault 2004). As a direct result, the study of impact structures has developed as a specific branch of geology. Pioneers in this field included famous natural researchers of the last century such as Robert Dietz and Eugene Shoemaker, who made a valuable contribution to the scientific study of the geological consequences of the interaction between the Earth and space. The data obtained from specific regions has been summarised, among others, by Koeberl (1994), Glikson (1996), Masaitis (1999), Abels *et al.* (2002), Dence (2002) and in the present issue. Although significant results have been achieved, the geological exploration of terrestrial impact structures continues, and many problems remain to be resolved by future research

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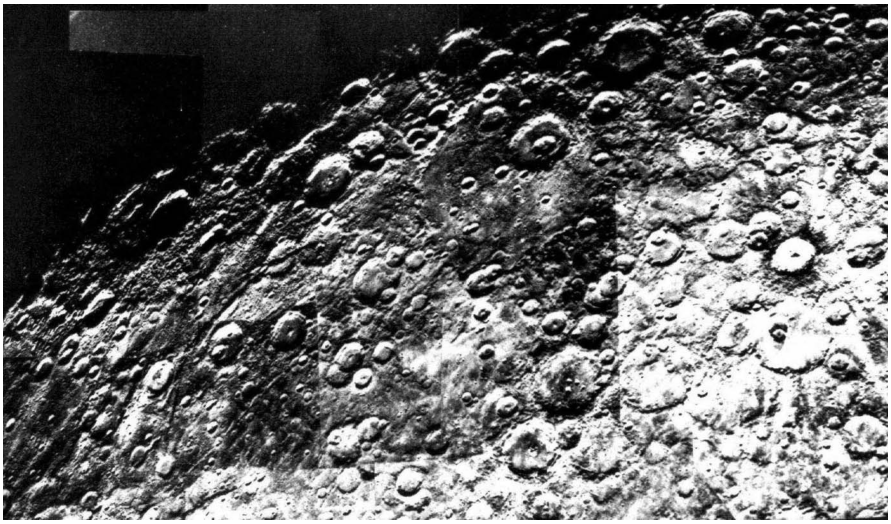

Figure 1 Heavily cratered surface of Mercury (NASA, Mariner)

(French 2004). These studies need to apply systematic approaches such as those adopted by field geology and mapping. However, it has been recently pointed out that comprehensive approaches are still lacking (King & Petruny 2003a; French 2004; Grieve & Therriault 2004). Some papers applying standard geological methods to the investigation and mapping of impact structures, based on studies of large impact structures such as Popigai, Puchezh-Katunki, Kara and some others, were published in Russian (Masaitis 1983; Masaitis *et al.* 1980, and references therein). In the course of these studies various landforms and local structural and lithological features were investigated in relation to factors controlling the distribution of economic minerals in impact craters. As shown by Grieve and Masaitis (1994), some impact-related features may represent traps or favourable zones for localisation of hydrocarbons and ore minerals. Comparisons of various physiographic, structural, and lithological features of terrestrial impact craters demonstrate the necessity of a systematic approach. The principle aim of this paper is to attract attention to this problem and discuss the use and regulation of terms related to impact structures and impact lithologies.

IMPACT GEOLOGICAL PROCESSES

The geological role of impact processes goes beyond cratering. Etymologically, the term 'impact cratering' refers only to formation of a crater by impact, i.e. the production of a circular depression surrounded by a rim (Figures 2, 3), or several rims in the case of large multi-ring impact structures. In the broad sense, impact cratering also embraces significant structural changes and a wide spectrum of rock-forming processes. The idea that impact events produce major geological effects that go far beyond the production of craters has recently been emphasised by French (2004). The term 'coptogenesis' was introduced about two decades ago to collectively designate all these processes: changes in topography, disturbance of preexisting geological structure at the impact site, rock transformation, and formation of new lithologies (Masaitis 1984). The term coptogenesis is derived from the Greek words $\chi o\pi\tau o$ to destroy by shock, and $\gamma\varepsilon\nu\varepsilon\sigma\iota\sigma$ formation. The concept of coptogenesis, in general, is similar, for example, to concepts of magmatism and/or sedimentation, both fundamental terrestrial processes that are responsible for the formation of specific topographic and structural features, and the formation of magmatic, sedimentary and metamorphic rock suites. Coptogenesis occurs during individual impacts as short-term events, but is also a collective term that can be applied to the countless impacts that have occurred during billions of years of planetary history. A study of planetary surfaces has shown that the rate of influx of small cosmic bodies during the early stage of their formation was orders of magnitude higher than observed at present (Taylor 1992; Ryder 1990). Undoubtedly, such bombardment had a strong influence on the evolution of the Earth, including the origin of the early crust and primordial continents (Grieve 1980; Glikson 2001). Various assumptions were made regarding the consequences of impacts on the early Earth's crust, but the geological evidence is largely incomplete in most cases. The main records of early impact events are contained in distal ejecta layers of Archaean and Proterozoic age (*ca* 3.5 – 2.5 Ga) (Glikson *et al.* 2004; Simonson *et al.* 1999; Simonson & Glass 2004; Hassler & Simonson 2001; Lowe *et al.* 2003). Nevertheless, the study of large Proterozoic and Phanerozoic impact craters allows a reconstruction of several important features and possible geological and other consequences of these ancient impacts (Mashchak 1990; Anderson *et al.* 1994; Stöffler *et al.* 1994; Tsikalas *et al.* 2002; Poag *et al.* 1999; Morgan & Warner 1999; Masaitis *et al.* 1999; Masaitis & Pevzner 1999; Gibson & Reimold 2001; Pirajno *et al.* 2003).

A large single impact is characterised by an enormous energy output, which may exceed the annual conductive heat outflow of the Earth, or the annual influx of energy to its surface. Such impacts on the outer shell of a planet could produce effects and products that may be regarded as short-term disturbances to the gaseous and liquid shells of a planet, and

Figure 2 Barringer (Meteor) impact crater, Arizona (35°02′N, 111°01′W) (courtesy of R. A. F. Grieve).

prolonged disturbances of solid outer shells. The shape of the latter, its dimensions, and interior structure depend on the energy of impact. The traces of such impacts, especially large ones, remain preserved for hundreds of millions to billions of years on non-atmospheric planets, which lack significant tectonism, weathering and sedimentation.

The process of impact cratering that causes topographic, structural and lithological transformations is usually subdivided into three stages which follow one another very rapidly: (i) contact and compression stage; (ii) excavation stage; and (iii) modification stage (Melosh 1989). Further, the latter two stages can be subdivided into an early modification stage and a late modification stage, since the geological processes of gravitational adjustment, viscous relaxation and doming, cooling, solidification, and compaction of the hot ejecta may continue for thousands of years or more. In general the final appearance of the impact site is a circular depression surrounded by a rim and filled with brecciated and melted target rocks that together with the fallout ejecta blanket overlie the strongly disturbed and shocked bedrock of the crater. Sometimes the apparent crater floor is buried under subsequently deposited sediments, such as a crater lake or local basin deposits, and the entire area may be overlain by widely distributed younger cover of significant thickness. Consequently four structural–lithological complexes may be distinguished in deeply buried terrestrial impact structures: (i) the bedrock complex that experienced impact disturbances and transformations; (ii) the crater-fill complex (coptogenic) composed of impact breccias and impactites; (iii) the crater-lake complex; and (iv) the overlapping complex (Masaitis *et al.* 1980). Every complex has its own structural features and internal geometry of component geological bodies, as well as specific lithologies. This subdivision may be useful for the adequate identification, correlation and mapping of certain geologic bodies composed of rock units of various origins in impact craters, for the compilation of geological and structural maps, profiles, interpretation

Figure 3 Aerial view of the Shunak impact crater, Kazakhstan (47°12′N, 72°42′E). The crater is 2.8 km in diameter. The annular rim is composed of uplifted Devonian volcanic rocks. The crater fill (flat circular area surrounded by the rim) consists of allogenic lithic breccia overlain by Oligocene–Pliocene lacustrine deposits.

of seismic and other geophysical observations, and for data obtained by drilling.

TOPOGRAPHIC FEATURES

It is very well known that on the Earth's surface the initial impact crater morphological feature degrades very rapidly due to subsequent erosion, denudation, sedimentation, tectonic events, etc. Only relatively young impact craters preserve their original shape including remnants of fallout ejecta, e.g. Meteor or Barringer (Figure 2) (Shoemaker 1963; Roddy 1977b), Henbury (Taylor 1967) and Kaalijarv (Aaloe 1978) craters. Some larger Cenozoic craters preserve remnants of principal topographic features, including an inner crater depression, some relics of the topographic rim and of the ejecta blanket, e.g. Ries (Hörz *et al.* 1977; Pohl *et al.* 1977), Zhamanshin (Boiko *et al.* 1991), Popigai (Masaitis *et al.* 1980, 1998, 1999) and Boltysh (Gurov *et al.* 2003; Valter & Plotnikova 2003). Most terrestrial impact craters, especially those of Mesozoic, Palaeozoic, and late Precambrian age have lost their initial coptogenic landforms completely and are usually referred to as impact structures (Grieve & Therriault 2004). In the case of superposition of erosion, the resulting relief may be considered as structural–denudation features, more or less reflecting the inner structural elements of the crater interior.

Despite some degradation of impact craters on the surfaces of most other planets over geological time, cratered planetary surfaces allow observation of many perfect examples of impact craters. Thus the pristine topography of impact craters of various sizes can be studied in detail. Differences between the shapes and relative altitude of coptogenic relief of craters of the same size on different planets strongly depend on the local gravitational acceleration, as well as properties of the target. The topography of fresh impact craters on the Moon, Mars, Mercury, Venus, on satellites of giant planets, and on asteroids, has been very well explored using remotely sensed images and has been described in numerous reports (Basilevsky *et al.* 1983; Wilhelms 1987; Melosh 1989; Strom *et al.* 1992; Herrick *et al.* 1997; Chapman 2002). Such studies have shown that the landforms of extraterrestrial impact craters are similar in many aspects to those of relatively fresh terrestrial analogues.

Data from impact craters on other cosmic bodies show that their size and shape may vary from microcraters on particles of glass in lunar regolith, up to giant multi-ring impact basins on the surfaces of some planets and their satellites (Melosh 1989). The topography of craters changes in a regular fashion to become more complex as size increases. Relatively small craters on all planets and asteroids are bowl-shaped and flat-floored, being referred to as simple craters (Figure 4). On the Earth the diameter of such craters does not exceed 2–4 km. Larger terrestrial craters possess central peaks or peak rings and are referred to as complex craters (Dence *et al.* 1977; Dence 2002). The difference between these types was originally based on the topography of eroded impact structures (Dence 1968). Such geological studies showed that the difference between simple and complex

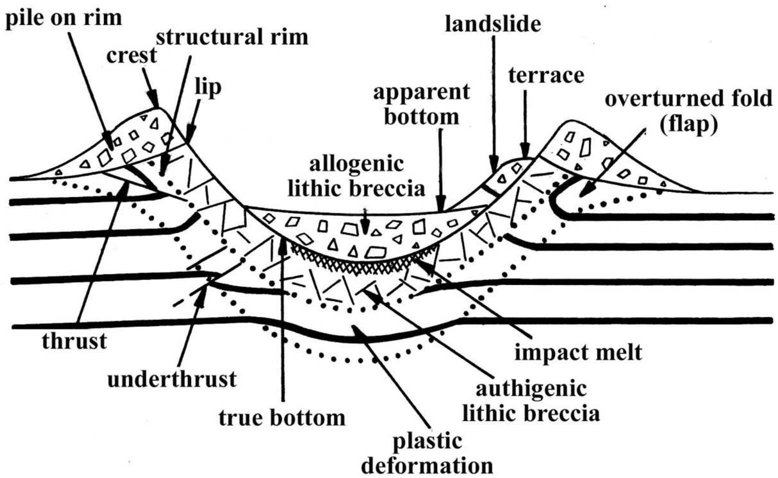

Figure 4 Morphological and structural elements of simple impact crater. Dotted contours outline zones of disturbance and zone of plastic deformation.

craters lies in the morphology of their true bottom. The structural uplift of the crater bottom is not always expressed as topographic relief. The central peak may be buried under crater-fill breccias, such that the complex inner structure of the crater can only be established by drilling or geophysical data. The presence of such buried central peaks, completely or almost completely covered by crater-fill breccia, was established for Zhamanshin, Bigach, Kursk, and Logoisk impact craters (Masaitis *et al.* 1980; Boiko *et al.* 1991; Glazovskaya *et al.* 1991; Masaitis 1999). This shows that the distinction between pristine landforms and structural features (some of the latter being developed due to selective erosion) should be taken into account, and different terms applied to them accordingly.

Complex terrestrial craters with diameters of some tens of kilometres, e.g. Manicouagan, Clearwater West, Shoemaker, Ries, Manson, Puchezh-Katunki, Kara, Popigai, are characterised by central or annular structural uplifts. It is assumed that these uplifts originally corresponded with pristine landforms, e.g. central and/ or ring peaks. There are restricted data regarding the pristine landforms of the largest known terrestrial craters with diameters in the range 150–250 km, which are now deeply eroded (Vredefort, Sudbury), or buried (Chicxulub). In some respects these resemble the structure of multi-ring basins on other planets, but their identity as the latter, especially in terms of pristine topography, cannot yet be proven (French 1998).

The ratios of some crater morphometric elements (diameter, depth, rim and central peak heights, etc.) show regular changes with increasing crater diameter (Basilevsky *et al.* 1983; Pike 1985; Melosh 1989; Grieve & Therriault 2004). These ratios also depend on gravitational acceleration, which varies between planets (Pike 1977, 1985; Melosh 1989; Strom *et al.* 1992; Herrick *et al.* 1997). Moreover, the obliqueness of the projectile trajectory (especially when at a low angle) may strongly influence crater relief, for example the asymmetry of the depression and of the crater rim, and distribution of the ejecta blanket (Melosh 1989; Herrick *et al.* 1997).

Several genetic types of coptogenic relief may be distinguished within and around fresh or slightly eroded terrestrial craters, taking into account all the data regarding the physiography of impact craters on other cosmic bodies: (i) relief produced by excavation during the formation of the transient cavity; (ii) structural relief caused by coherent bedrock displacements during the excavation and modification stages of cratering; and (iii) accumulative relief produced by ejection and deposition of rock debris and impact melt. In most cases these genetic physiographic types may combine to result in complex topography. In general, combinations of certain landforms depend on the crater size, the geological setting of the impact site, on land or water, and on the properties of the target material—strength, water saturation, etc.

The coptogenic topography of terrestrial impact craters has geomorphological meaning only for craters (or pits) with diameter larger then tens of metres. Crater landform groups spanning several orders of magnitude may be distinguished: macrorelief (2nd order, from hundreds to several kilometres across), mesorelief (3rd order, from several kilometres to hundreds of metres), and microrelief (4th order, from a few hundreds of metres to 10–30 m and sometimes less). In other words, these landform groups may be regarded as large, medium, and small (Table 1). In most cases the evaluation of primary altitude of landforms is complicated, but on Earth they will be much lower than for corresponding topographic features on planets with less gravity and lacking an atmosphere.

The main excavated topography of a terrestrial impact crater is a circular depression, which is partly filled with fall-back material, especially if the crater diameter exceeds 1–2 km (Figure 4). In larger craters the depression may be surrounded by a terrace-like annular shelf zone (Melosh 1989). Such a shelf surrounding a deeper inner depression (inner crater), and may be regarded as the 'outer shallow crater'. During excavation, additional morphological features may form. Shallow radial channels, which are excavated by outflow of impact debris, may form in the crater walls and on the shelf zone. Such partly buried excavational landforms were observed at the Puchezh-Katunki (Masaitis & Pevzner 1999) and Popigai (Masaitis *et. al.* 1999)

Table 1 Coptogenic topographic features.

Type of relief	Large landforms	Medium landforms	Small landforms
Excavational relief	Circular depression (flat floor)[a].	Circular depression (flat floor and bowl-shaped)[a]. Crater wall[a]. Annular shelf-zone. Radial channels[a]. Resurge gullies[b].	Pit[a]. External pits (secondary)[a].
Structural relief	Central peak. Peak ring. Outer structural rim. Slump terraces.	Central peak. Peak ring. Outer structural rim. Annular depression[a]. Slump terraces.	Salients. Central pit[a]. Linear trenches (concentric & radial)[a]. Slump terraces.
Accumulative relief	Circular floor plain.	Circular floor plain. Piled on rim. Annular plain. Hummocky terrain.	Resurge valleys[b]. Central mound (built of debris).

[a] Partially modified by successive relief-forming processes.
[b] Caused by resurge wave action.

craters. In marine settings, forceful resurge waves and inward currents produce shallow gullies in the crater shelf zone, e.g. in the Lockne (Ormö & Lindström 2000; von Dalwigk & Ormö 2001) and Kamensk (Movshovich & Milyavsky 1990; Masaitis 1999) craters, but they were formed before the modification stage of cratering. These gullies become filled with reworked fine-grained ejecta. In some cases the gullies may inherit the former radial channels or troughs on the crater edge.

Secondary pits and craters (secondaries) may also be considered as excavation relief features, but their existence on Earth has not been proven. The smallest excavational forms (or nanoforms), that have a similar mode of origin to secondary craters are the radial striations that are produced by large ejected blocks dragged across bedrock surfaces. Such features have been observed in the vicinity of the Ries crater (Chao *et al.* 1978).

In simple terrestrial craters structural relief above the pre-impact land surface is represented by an outer asymmetric rim composed of uplifted and disturbed bedrock (e.g around Meteor crater: Shoemaker 1963; Roddy 1977b). Its inner slope is usually steep, while the outer is gentle. Pristine complex craters sometimes show relics of a similar uplifted structural rim, comprised of overthrusted or overturned blocks. Such relics are observed in the northern sector of Popigai crater, some of which represent deep-seated beds which were uplifted and emplaced over younger sediments (Masaitis *et al.* 1998, 1999).

Reconstructions of the original shape of complex craters, especially large ones, show that they originally had surface relief expression of certain structural components: a central peak, peak ring (annular inner rim), and annular depression. These assumed landforms are present in the relatively well-preserved Boltysh (Gurov *et al.* 2003), Puchezh-Katunki (Masaitis & Pevzner 1999), Popigai (Masaitis *et al.* 1999), Mjølnir (Tsikalas *et al.* 2002) and Manson (Anderson *et al.* 1994) craters, and in many others. In some cases the central peak is complicated by the presence of a small central pit. These former landforms are inferred from the existence of structural central or ring uplifts and ring troughs in more or less eroded terrestrial craters, e.g. Manicouagan (Grieve & Head 1997), Clearwater West and East (Dence *et al.* 1977; Dence 2002), Ries (Pohl *et al.* 1977) and Shoemaker (Pirajno *et al.* 2003).

Other medium- and small-scale structural landforms are represented by slump terraces on the crater wall; they can produce a broad terrace zone with several terrace-like slices. Such buried underground terraces have been revealed by drilling in the Kaluga impact structure (Figure 5) (Masaitis 2002). Linear trenches may occur over radial and concentric fissures that arise due to doming of the crater floor. These forms may be reconstructed based on the presence of thick clastic dykes in the suevite sequence of the Kara crater (Mashchak 1990).

The former presence of some additional elements of structural relief in eroded terrestrial craters may be assumed based on observations from the Moon and other planets (Basilevsky *et al.* 1983; Wilhelms 1987; Melosh 1989). The peak ring of some large craters may initially consist of irregularly distributed hills. Sometimes ring escarpments are also characteristic of such craters, and it can be inferred that such landforms existed outward of the outer rim of some large terrestrial craters. Radial and concentric trenches on the floor of some lunar craters that are covered with impact melt probably were caused by shrinkage of the melt sheet. Similar local forms, filled with debris, may be produced by the dome-like uplifting of the crater floor.

The principal accumulative coptogenic landform of impact craters is a circular flat floor formed above fall-back ejected material (Figure 4). In relatively fresh terrestrial craters of Cenozoic age this flat plain may be partially preserved (initial apparent crater bottom), especially beneath crater-lake deposits if these are deposited immediately after, or only a short time after, the impact event. An annular plain located between the peak ring and the outer rim also existed in some complex craters, e.g. at Popigai. Embankments over the outer rim, or their relics, also represent accumulative landforms; usually such an accumulative rim builds on the structural rim. The remnants of such accumulative deposits over the structural rim have been established around Meteor crater and some others. Resurgent accumulative valleys on the crater edge may occur in the radial gullies, reconstructed, for instance, in the Lockne crater (von Dalwigk & Ormö 2001).

There are no good examples of preserved accumulative landforms of fallout ejecta in the vicinity (1–2 radii) of the terrestrial craters. All known relics of such deposits are strongly modified by erosion, e.g. Meteor, Zhamanshin, Boltysh, Ries, Popigai. In some cases the remnants of the fallout ejecta blanket partially preserve its original form. Such partially eroded ejecta blankets comprised of allogenic breccia form hummocky terrains that in places surround Zhamanshin (Figure 6) and Popigai craters (Boiko *et al.* 1991; Masaitis *et al.* 1998). Small accumulative landforms may be created by resurge currents in the radial valleys, as well as by centripetal debris streams sliding towards the centre of small simple craters. In the last case a low central mound may arise (Melosh 1989).

Contrary to the situation on Earth, numerous accumulative forms of proximal ejecta blankets are preserved around impact craters on the Moon, Mars, Mercury and Venus. For instance, there are rampart craters with ejecta lobes, dune-like proximal ejecta, craters with radial rays or radial grooves and ridges, knobby and hummocky terrains and herringbone patterns (Basilevsky *et al.* 1983; Wilhelms 1987; Melosh 1989; Strom *et al.* 1992; Herrick *et al.* 1997). Some of these features are the result of the joint action of secondary excavation and accumulation of ejected and displaced loose superficial material caused by ballistic sedimentation. All of these landforms are assumed to be composed mostly of solid ejecta, while the lineated and smooth ponds inside the small hollows on the slopes of large crater rims on the Moon, and lineated flows around some Venusian craters, may have formed as the result of ejection and cooling of impact melt (Alexopulos & McKinnon 1994; Herrick *et al.* 1997). It is quite possible that in their pristine state, accumulative relief patterns around terrestrial impact craters were similar to some accumulative landforms observed on the surfaces of other planets. For example, some relics of isolated small sheets of consolidated impact melt found close to the rim

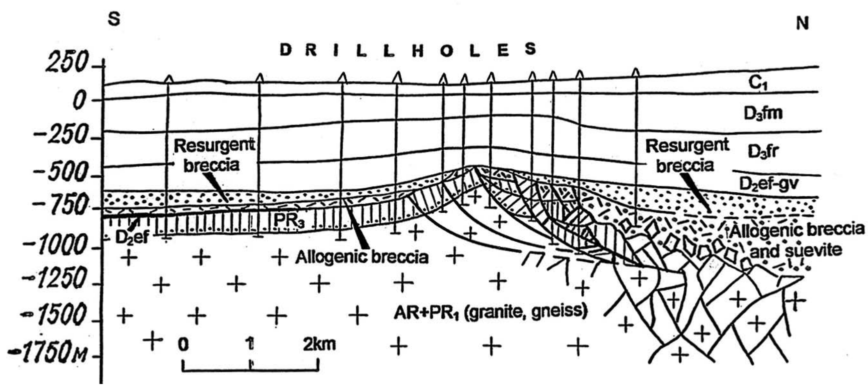

Figure 5 Geological sketch section of the buried southern rim of the Kaluga impact structure, Russia (54°30′N, 36°12′E). The inner structure of the rim shows that it was formed in several stages: (i) uplift and centrifugal displacement of target rocks; (ii) deposition of allogenic breccia and suevite; (iii) slumping; and (iv) erosion by resurge wave; which (v) deposited resurgent breccia. The overlying beds (marked D_2 to C_1) are composed of carbonate and siliciclastic deposits.

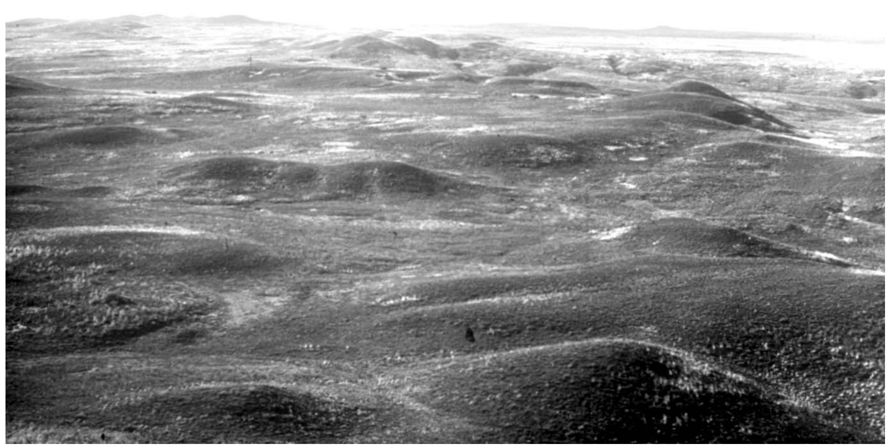

Figure 6 Hummocky relief on the ejecta of the allogenic lithic breccia outside the crater rim. Knolls that are 5–15 m high are made of large blocks of solid rocks partially destroyed by erosion. Zhamanshin impact crater, Kazakhstan (48°24′N, 60°58′E).

crest of Popigai crater (Masaitis *et al.* 1998) may have initially represented such accumulative forms.

Distal ejecta from impact craters on the Earth probably produced some Earth-specific topography, especially in cases where very large craters were formed in a marine setting. The best example are remnants of distal ejecta from Chicxulub crater (Pope *et al.* 1999; King & Petruny 2003b) combined with the extended cover formed by tsunami waves and submarine avalanches caused by the impact. It is possible that several unique accumulative landforms (debris-flow lobes) may be produced by impact onto the coastal plain or adjacent shelf.

In most cases all topographic elements of fresh terrestrial impact craters (Figure 7) are formed by the combined action of excavation, structural disturbance and accumulation of ejected material. On the Earth, erosion, sedimentation and tectonism strongly modify pristine coptogenic relief, producing various combinations of genetic types of relief, e.g. structural – erosional, accumulative – erosional, and some others (Plotnikova 1990), which include impact-induced components and components produced by ordinary geological processes (erosion, sedimentation, etc.).

STRUCTURAL FEATURES

Various structural features within and surrounding impact craters form during penetration of the projectile, and the excavation and modification stages, including ejecta accumulation and its cooling and compaction. Some of structural features may be studied using methods of structural geology, whereas others require sedimentological and structural/petrological studies. Only some structural features directly coincide with the topographic elements, and it is necessary to properly distinguish them. One of the first attempts at a comparison between the structural and morphological features of simple and complex craters was undertaken nearly three decades ago (Roddy 1977a), but only few examples were used.

The main structural features that are revealed within and around terrestrial impact craters are summarised in Table 2. These features are subdivided according to their relative dimensions, although their size depends on the corresponding impact crater. By convention, large impact structures measure from several tens to kilometres across, medium structures from some kilometres to hundreds of metres or less, and small structures from hundreds of metres to one or two metres. The crater-related structural features and internal structures of the composing geological bodies are situated in disturbed bedrocks within and outside of the crater, and in fallback and fallout ejecta. Various impact-induced structural elements may be subdivided according to the dynamic processes which created them, such as outward, inward, and upward displacements. These are accompanied by the processes of compression, extension, shearing, deposition, cooling, etc., which are superimposed on target materials initially having different strengths, layering characteristics, etc. There are further complications because many structural elements arise due to the combined action of different kinds of strain and motion.

The principal structural feature of the target rocks is the hemispherical zone of disturbance and transformation caused by the propagation of shock and rarefaction waves from the point of projectile penetration and ultimate arrest (Dence 1968; Robertson 1975). Close to the original surface, the propagation of these waves and the resulting disturbance is more complex, causing spallation of near-surface layers. At deeper levels, the shock waves and resultant transformations attenuate radially outwards and downwards, forming roughly concentric zones. Transient zones of disruption, melting and evaporation flow outwards and are removed from the crater. Only graded parautochthonous zones of moderate and weak plastic deformation and fracturing that form the true bottom and walls of the final crater may remain (Melosh 1989). The bedrock structure of the final crater results from the outward motion during growth of the transient crater, and the following inward and upward motion of its bottom due to its collapse. These displacements deform the primary shock-metamorphic zonation, especially in the central part of large complex craters. This primary zonation may be complicated due to post-impact thermal annealing and recrystallisation, thus the secondary zonation pattern may occur (Gibson & Reimold 2001).

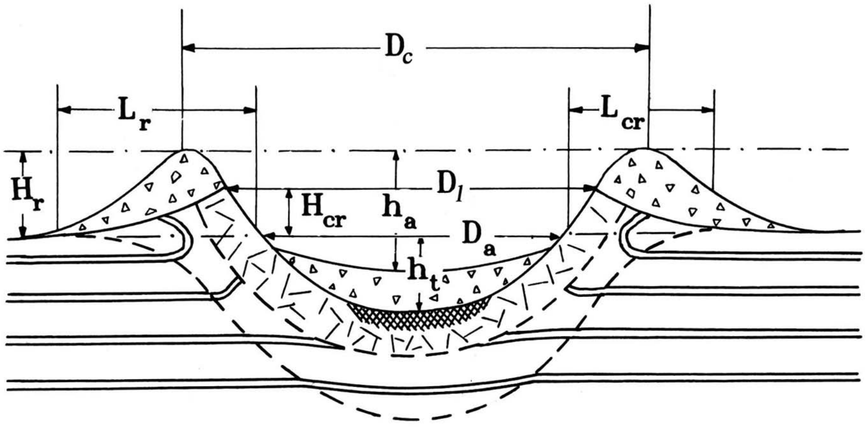

Figure 7 Structural and morphological parameters of simple impact crater. D_c, crest to crest diameter; D_l, lip to lip diameter; D_a, apparent diameter, h_a, rim crest depth; h_t, true depth; H_r, rim height (pile on rim + structural rim); H_{cr}, rim height (structural rim); L_r, rim width (pile on rim + structural rim); L_{cr}, rim width (structural rim).

Table 2 Coptogenic structural features and internal structures of the geological bodies.

Composing rocks	Location	Large and medium forms	Medium forms	Small forms
Bedrocks, non-displaced and partly displaced.	Within the crater.	Zones of fracturing, brecciation and plastic deformation bearing various shock-metamorphic features. Central uplift.	Zones of fracturing, brecciation and plastic deformation bearing various shock-metamorphic features.	Intricate folds and blocks.
		Inner and outer annular uplifts.	Central uplift.	Arcuate (listric) and radial faults.
		Annular subsidence (trough).	Inner and outer annular uplifts.	Basal detachment.
			Annular subsidence (trough).	Thrust slices.
			Shear zones.	Shear zones.
			Annular zone of thrusts (shelf-zone).	Landslide wedges of debris.
			Annular zone of slumped blocks.	Injected breccia and melt dykes.
			Radial transpression zones (folds, thrusts, breccia zones).	Radial and arcuate fissures.
			Intricate folds and blocks.	
			Arcuate (listric) and radial (vertical) faults.	
			Basal detachment.	
	Outside the crater.	Annular and arcuate anticlines and synclines.	Annular anticlines and synclines.	Overturned flap. Folds.
			Arcuate (listric) and radial (vertical) faults.	Uplifted blocks.
Ejecta	Within the crater.	Irregular and lenticular bodies, sheets, bagel-shaped lenses.	Irregular and lenticular bodies, sheets.	Clast-supported zones.
			Central dome-like uplift.	Zones of various crystallinity of melt rocks. Flow-structures. Irregular and obscure bedding. Radial and concentric fissures.
	Outside the crater (fall out, outflowed).	Lenticular bodies and sheets.	Lenticular bodies, flows and sheets.	Clast-supported zones. Zones of various crystallinity of melt rocks. Flow-structures. Irregular and obscure bedding. Gas channels.

Evidence of the distribution of structural elements in simple craters has been collected in the course of detailed study and mapping (Roddy 1977b). The structure of the parautochthonous and autochthonous bedrock of simple bowl-shaped craters is characterised by a graded zone of deformation and shock transformation. Various small folds, faults, thrusts, overthrusts and underthrusts are present (Figure 8). The uplifted structural rim is usually characterised by an overturned flap, and the crater walls are complicated by slump terraces produced by subsidence along listric faults (Figure 4).

Large and medium inner morphostructural features of a complex crater include a central or ring uplift of the true crater bottom, or both, sometimes accompanied by annular subsidence in between (Figure 9). Usually the outer ring uplift forms the structural rim; its remnants have been observed around the Ries (Hörz *et al.* 1977) and Popigai (Masaitis *et al.* 1998) craters. Annular subsidence has been revealed by seismic study in the case of Chesapeake Bay crater (Poag *et al.* 1999) and by drilling in the case of Popigai crater (Masaitis *et al.* 1999). It is assumed that ring uplifts in large craters arise due to the hydrodynamic collapse of the unstable central uplift or central peak (Alexopulos & McKinnon 1994). Geological and petrographic observations in the ring uplift of the Popigai crater show that the composing rocks experienced shock pressures of < 10 GPa (Masaitis *et al.* 1998). This in turn shows that they could not have been displaced due to collapse of the crater centre, where the shock compression reached up to 30 GPa and more. Nevertheless, the internal structure of the central uplift is very complicated. Due to inward and upward motion of the target rocks, accompanied by compression and accretion, the uplift displays a system of intricate small folds, faults and thrusts reflecting mostly the last phase of centripetal motion. Block displacements, shear zones, numerous radial and concentric fissures filled with brecciated and melted material, form the clastic and melt dykes present in the crystalline central uplifts of some craters, e.g. Puchezh-Katunki (Masaitis & Pevzner 1999) and Charlevoix (Rondot 1995) craters. In cases where the target rocks are horizontally layered, it is sometimes possible to reconstruct the altitude of structural uplift, although the core is characterised by thickening of these layers; examples include the Sierra Madera (Wilshire *et al.* 1972) and Gosses Bluff (Milton *et al.* 1996) craters.

As has been shown by geological studies, variations in composition and structure of the target rocks, especially the thickness of the upper sedimentary layer relative to underlying crystalline rocks, leads to significant variations in the shape of the surface of the true crater bottom (Abels 2003). A unique subsurface shape of the true crater bottom occurs in some large craters formed in such two-layered targets. This is a combination of a shallow external crater, excavated in the upper layer (sometimes called the outer flat terrace or shelf zone) and a deeper internal crater with a central uplift, excavated in the crystalline basement (Figure 10). The slope discontinuity between these craters may be slightly uplifted and sometimes regarded as an inner rim. Moreover, this shelf zone may display numerous outward thrusts (Figure 11) and radial faults. In contrast, in the annular subsidence or ring trough, close to the

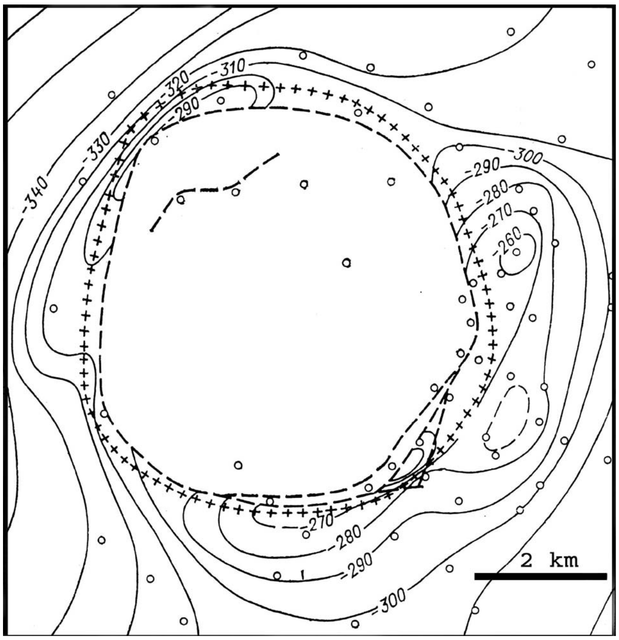

Figure 8 Structural representation of the Vepriaj impact crater, Lithuania (55°05′N, 24°34′E). Contour lines (in metres) of the clay bed of Upper Silurian show the undulatory anticlines in the bedrock. Faults are shown with dashed lines. Multiple faults on the southeastern wall formed due to blocks slumping. The area is covered with Jurassic crater-lake clays which are outlined by crosses. Boreholes are shown as small circles.

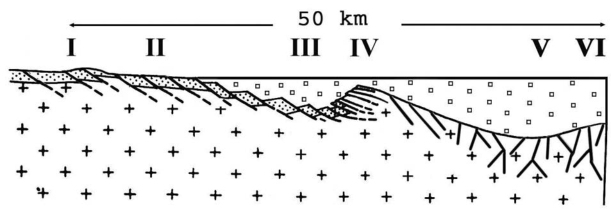

Figure 9 Sketch cross-section of the Popigai impact crater, Russia (71°38′N, 111°11′E). Partially brecciated crystalline basement rocks are marked with crosses, sedimentary cover with dots, and crater fill (impactites and allogenic lithic breccias) with squares. Structural elements: I, outer rim; II, outer flat terrace with numerous overthrusts and other disturbances; III, annular trough, bordered by outer (gentle) and inner (steep) walls; IV, peak ring (inner rim); V, central depression; and VI, flat central uplift.

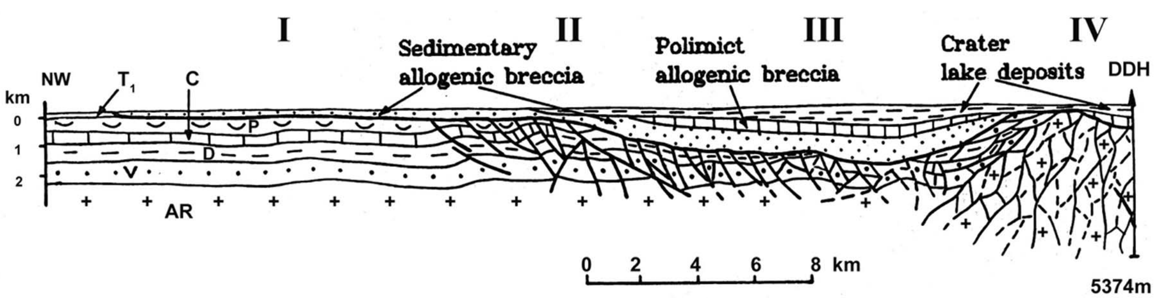

Figure 10 Sketch cross-section of the Puchezh-Katunski impact structure, Russia (56°58′N, 43°43′E). AR, Archaean gneisses and amphibolites; V, Vendian siltstones; D, Devonian siliciclastic and carbonate rocks; C, Carboniferous limestones, dolostones; P, Permian clays, marls, siltstones, sandstones, evaporites; T_1, Lower Triassic clays, siltstones, sandstones. Structural elements: I, annular terrace; II, inner structural rim; III, annular trough; IV, central uplift with the central pit. Crystalline rocks and sedimentary cover are strongly disturbed within the central uplift and bottom of the annular trough. Polymict allogenic breccia incorporates thin beds of suevites and small irregular tagamite bodies. Crater-lake deposits are of Middle Jurassic age. DDH, deep drillhole in the crater centre.

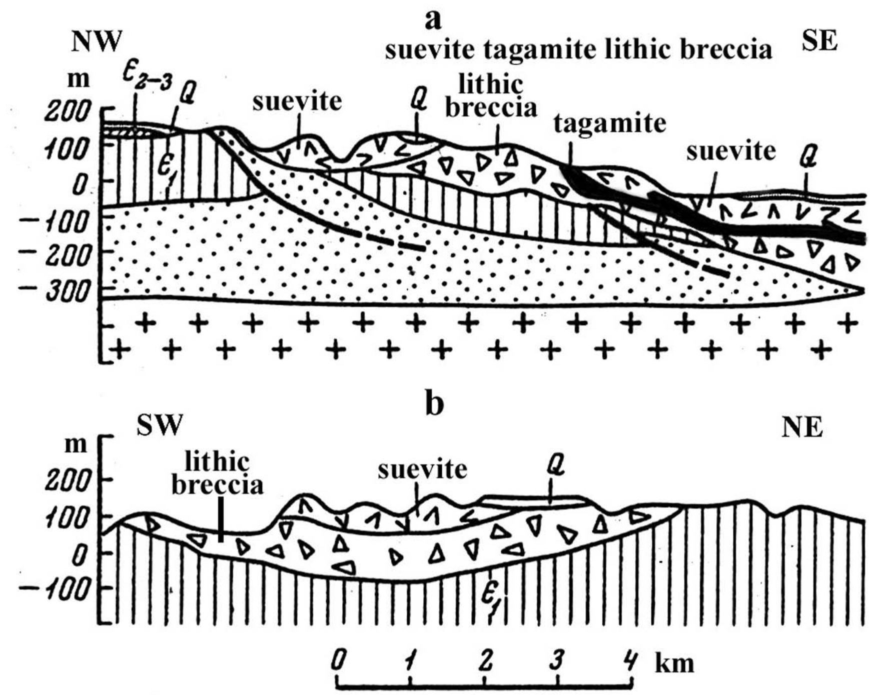

Figure 11 Longitudinal (a) and transverse (b) cross sections through the radial trough at the northwestern outer wall of the annular trough of the Popigai crater, Russia (71°38′N, 111°11′E). Crosses mark Archaean crystalline rocks, dots mark Proterozoic sandstones, vertical shading marks Lower Cambrian marls and siltstones ($Є_1$), diagonal shading marks Mid-Upper Cambrian limestones and dolostones ($Є_{2-3}$), Quaternary sand and gravel beds are left unmarked. Overthrusts indicate displacements outward from the crater centre. Impactites and breccias form a tongue-like complex body which overlies the disturbed sediments.

outer slope, landslide wedges, listric faults and basal detachments occur. In this trough, some specific features were revealed recently that formed due to the radial inward displacement of rock masses and the subsequent reduction of space (Kenkmann & von Dalwigk 2000). The latter produces radial folding, lateral trust ramps, so-called positive flower-structures, and chaotically brecciated ridges, all of which are united under the term 'radial transpression ridges' or 'radial transpression zones' and have been studied in detail at the Siljan impact structure (Kenkmann & von Dalwigk 2000). Similar radial and strongly deformed sharp ridges, probably of the same origin, have been described at the edge of the Kara crater (Mashchak 1990).

Bedrock undergoing plastic deformation outside the impact crater may be locally folded, and show concentric anticlines and synclines (Figure 8), as well as radial and arcuate fissures. Well-known shatter cones (Dietz 1959), which are diagnostic feature of shocked rock, may be regarded as one of the smallest macroscopic structural forms caused by shock compression. Shatter cones in bedrock are usually tilted. Determining their original position and orientation in the parautochthonous layered rocks allows a reconstruct of the original point of impact of the projectile, because the apices of the shatter cones were originally oriented toward this point.

The ejected material that fills the final crater (especially that filling large craters) and is also deposited outside it, displays a type of pseudo-stratification formed by intercalation of flat-laying lens-like and sheet-like bodies of lithic impact breccias and impactites. In turn, the shape of these bodies and the internal structure of the latter, create additional structural patterns, most of them characterised by a combination of radial and concentric ones. The pseudo-stratification of crater-fill deposits may be very complicated, but, in general, coarse allogenic lithic breccias (or megabreccias) comprise the lowermost portion of the ejecta sequence (especially outside the crater depression). Lenses and sheets of tagamite and suevite of various composition and structure occupy the middle portion of the sequence, while the uppermost portion is composed of fine-grained lithic breccia with an admixture of melted material. Rewashed beds may be found on the top as well. The sequence of crater-fill lithologies, and locally proximal ejecta, as described above, has been observed at the Ries (Pohl *et al.* 1977; Hörz *et al.* 1977; Chao *et al.* 1978), Popigai (Masaitis *et al.* 1999), and Puchezh-Katunki (Masaitis & Pevzner 1999) impact structures. A similar internal crater-fill structure was established at the very large Sudbury (Stöffler *et al.* 1994) and Chicxulub (Stöffler *et al.* 2004) impact structures. The total thickness of crater fill, if preserved, varies from some tens of metres in small simple craters, to several kilometres in impact structures having diameters in the range of hundreds of kilometres. The mode of occurrence of the whole complex of lithic breccia, suevite, and tagamite within large craters with central peaks rising above the apparent crater floor, may be defined as a bagel-shaped flat body, or a lens-like body with the hole in the centre, as seen for example at the Manicouagan (Grieve & Head 1997) and Boltysh (Gurov *et al.* 2003; Valter 2003) impact structures (Figure 12).

In some craters, isolated bodies of breccias and impactites in the crater-fill succession sometime possess individual internal structural features caused by the processes of transportation and accumulation of ejected material in different facies settings, or by subsequent cooling and crystallisation. These structural features in lithic breccias and suevites include clusters or bed-like distributions of large blocks and fragments, including

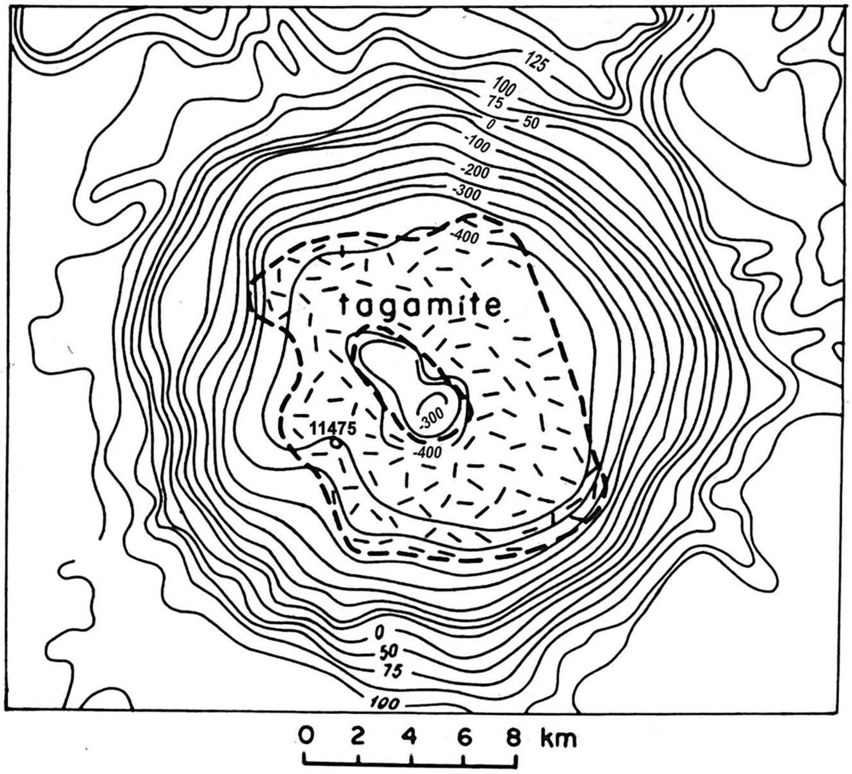

Figure 12 Bagel-shaped lens of tagamite in the Boltysh impact crater, Ukraine (48°45′N, 32°10′E). The contour lines represent the surface of the true crater bottom made of crystalline rocks uplifted in the centr. The location of drillhole (11475) is marked by an open circle.

clast-supported zones, obscure bedding and cross-bedding, or types of fluidal structures (Hörz *et al.* 1977; Mashchak 1990; Masaitis 2003). The coherent bodies of consolidated impact melt may be characterised by a relatively regular bed-like distribution of captured lithic fragments and clasts, by fluidal structure, and by crystal size, which is coarser in the central part of these bodies. Very thick melt bodies, such as at Sudbury, show layering caused by slow cooling and crystal differentiation (Stöffler *et al.* 1994; Dressler & Reimold 2001). Unique internal structures have been observed in the fallout suevites of the Ries crater. These are so-called vertical gas channels (Chao *et al.* 1978; Newsom *et al.* 1986), caused by vapour escaping from the underlying water-saturated sediments, and resemble pipe vesicles in volcanic lava flows. In addition, metasomatic zones may be formed in the brecciated bedrock and crater-fill deposits as a result of post-impact hydrothermal activity (Naumov 2002; Ames *et al.* 2004).

Post-impact movements produced by deep-seated tectonic adjustment and compaction of breccias in large craters may produce additional structural forms, such as block-subsidence faults, open fissures, etc. Such structural changes may affect the bedrocks as well as the crater fill.

LITHOLOGICAL FEATURES

The landforms and structural elements described above are composed of various coptogenic lithologies that were formed contemporaneously, and are now found both inside and outside the impact crater. These lithologies have different environments of formation as reflected in their composition, fabric and inner structure. A very important inherent characteristic is evidence of shock compression and decompression known as shock metamorphism, as described in numerous works (Stöffler & Langenhorst 1994; Deutsch & Langenhorst 1998; French 1998). At mineral-scale these effects include the formation of crystal defects (dislocations, planar fractures and planar-deformation features, mechanical twins, kink bands, mosaizism), transformation to high-pressure polymorphs and diaplectic glass, thermal decomposition and shock melting. The shock effects depend on the degree of compression and on the mineral species, and are unknown in rocks and minerals formed by non-impact terrestrial geological processes.

Shock effects have been intensively explored during the last few decades and are used as diagnostic criteria in identifying impact structures and for the calibration of shock compression of certain minerals and rocks. Less attention has been paid to the systematisation of impact lithologies as geological materials, including the development of a unified classification and nomenclature scheme that may be suitable for different impact craters, large and small, that are superimposed on a variety of geological target environments. Two closely connected approaches may be used in the exploration of impact-generated and impact-related (coptogenic) lithologies: (i) an analysis of rock facies; and (ii) identification of the petrographic rock species and groups.

The concept of facies involves the idea of linking lithological or petrographic features of certain rocks or rock associations to the geological setting of their formation (Bates & Jackson 1987). Some suggestions on the analysis of the rock facies in crater fills were introduced by Masaitis (1983). The whole impact-gener-

Table 3 Coptogenic facies settings.

Location	Transformation facies	Transportation facies	Depositional and settling facies
On the target surface and above it.	Vapour.	Jets.	Tektite strewn fields.
	Melt.	Dust and scorching clouds.	Spherule layers.
	Rock debris.	Ballistic ejecta (debris curtain).	Allogenic lithic breccia sheets & lenses.
		Fluidised flows.	Rock debris wedges.
		Base & ground surges.	Suevite layers, lenses (ash fall, clastic surge & flow).
		Melt flows.	Tagamite & coarse-grained massive impactite sheets & lenses.
		Avalanches.	Resurge breccia layers.
		Resurge waves & currents.	Tsunamite layers
		Tsunami waves.	
Directly beneath the true crater bottom.	Melt. Cataclased massifs.	Moderately moving aggregate of blocks and fragments.	Zones of authigenic lithic breccia, displaced blocks (parautochthon). Fault breccia zones. Zones of cataclasm & mylonitisation. Rock meal zones. Dykes of injected breccia and tagamite.
At the moderate depth beneath the true crater bottom.	Brecciated & fissured massifs.	Moderately displacing coherent massifs	Zones of authigenic lithic breccia (autochthon).
		Injected flows of fragments and melt.	Zones of cataclasm & mylonitisation. Dykes & veins of pseudotachylite. Zones of blastesis.
Deeply beneath the true crater bottom.	Fissured massifs.	Slightly displacing coherent massifs.	Zones of fractured rocks.

ated rock assemblage represents a group, or family, of facies, i.e. a simultaneous continuum of facies formed during a single impact event. Contrary to sedimentary and most volcanic facies, the superposition of coptogenic crater-fill facies in most cases do not reflect on any temporal succession, and do not reflect the duration of the process of formation in a common geological sense. In some aspects, the geological body composed of certain coptogenic rock facies may be attributed to the lithodemic unit (King & Petruny 2003a).

Three groups of facies settings may be distinguished: (i) initial facies of transformation; (ii) transient facies of transportation; and (iii) final depositional and settling facies. The observed impact, or coptogenic, rocks may be attributed to the latter, but rock-forming processes that created them have started in the previous facies setting (Table 3). The transformation facies in the autochthonous (and partially parautochthonous) rocks of the crater bottom may be compared in general with the facies of graded (zonal) metamorphism in some geological regions. On the other hand, similarly to volcanic facies, the coptogenic allochthonous facies is the result of a change in transport mechanism and depositional mechanism. Both autochthonous and allochthonous facies change with increasing distance from the point of impact, and it leads to their lateral variations.

The impact facies settings, during different stages of cratering, have had distinct locations relative to the target ground surface at different moments of crater formation: (i) in the bedrocks at significant and moderate depths below the true crater floor; (ii) directly under this crater floor; and (iii) at various heights above the crater floor. There is a high gradient of continuous variations of communal entropy, enthalpies, transport velocity, etc., and the non-equilibrium nature of rock-transforming and rock-forming processes are typical for these dynamic facial settings.

Facies of transformation occur along with attenuating shock and the propagation of rarefaction waves from the point of impact. A graded series of transient vapour and melt facies, debris facies, and shocked and fractured rock facies arise (Masaitis *et al.* 1980; Melosh 1989; Deutsch & Langenhorst 1994; French 1998). Only the latter, that formed under relatively low shock pressures ($<30-40$ GPa) may remain within the true crater bottom (autochthonous and parautochthonous facies of shock-metamorphosed cataclased, brecciated and fissured rocks). Most of the rocks transformed during shock compression and release are subjected to immediate displacements, mixing and ejection.

A broad spectrum of transportation facies occur: each is distinct in temperature, pressure, velocity, trajectory, clast to melt ratio, gas saturation, viscosity, etc. They form several final outflow products (depositional facies), comprised of various lithic breccias and impactites (Figure 13), that arise from jets, various liquid melt and gas-saturated flows, debris flows and debris curtains, dust and scorching clouds, surges, and plastic flowage of crushed rock debris. Some of these coptogenic depositional facies resemble certain volcanic facies (Fisher & Schminke 1984; Easton & Jones 1986), but have been formed in distinct dynamic and other conditions, including velocity, temperature, etc. Various depositional suevite facies were revealed recently

Figure 13 Allogenic megabreccia is overlain by the erosional remnant of the tagamite sheet. Large blocks and fragments are composed of various crystalline and sedimentary rocks, some of which are shocked. The height of the outcrop is about 80 m. Popigai impact crater, Russia (71°38′N, 111°11′E).

in the Chicxulub crater (Dressler *et al.* 2004; Kring *et al.* 2004; Stöffler *et al.* 2004). In marine settings, the final rock facies may be deposited by tsunami waves, resurge waves and gulley streams (Montanari & Koeberl 2000; Ormö & Lindström 2000). A group of impact-related rocks may be distinguished that originate by reworking of ejected material by such waves. Distal rock facies formed in submarine settings due to the combined action of ejecta deposition and tsunami wave motion differ significantly from proximal coptogenic facies and resemble sedimentary deposits formed in nearshore basin settings due to avalanches of volcanic debris (King & Petruny 2003b).

The systems of parautochthonous displaced blocks (Figure 14) and fragments, as well as avalanches and injections of fragmented material mixed with melt, may be considered as subsurface settling facies resulting from transportation and displacement. In addition, various settling facies may form during cooling, lithification and crystallisation of brecciated and melted materials at the final stage of the crater-forming process. These settings produce several newly formed accessory rocks that can be distinguished in the crater fill and basement, beside coptogenic rocks proper (i.e. formed by shock compression and ejection). These small groups of related rocks are caused by shearing and friction melting (mylonite, and probably so called pseudotachylite), due to pyrometamorphism and additional selective melting and crystallisation (buchite or diatektite, occasionally granophyre), and subsequent blastesis (coptoblastolithes). For instance, some of those rocks were described in Charlevoix (Rondot 1995), Puchezh-Katunki (Masaitis & Pevzner 1999) and Vredefort (Gibson & Reimold 2000) impact structures.

The resultant depositional and settling facies are composed of rocks that may be attributed to three main

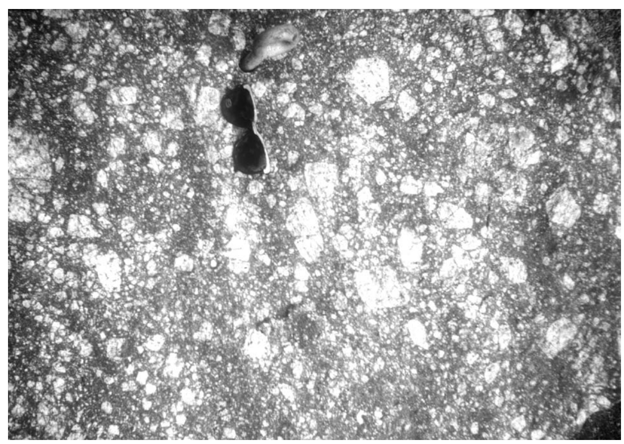

Figure 14 Authigenic mesobreccia that consists of granite fragments cemented with the same comminuted material. Gardnos impact crater, Norway (60°42′N, 9°12′E). Sunglasses for scale.

petrographic groups (Figure 15), similar to that proposed by the IUGS study group on impactites (Stöffler & Grieve 1994). In this context, the impact (or coptogenic) rock type may be considered as equivalent to the type of sedimentary, magmatic and metamorphic rocks. Coptogenic rock types originate, as shown above, from: (i) shock metamorphism, disruption and partial displacement of the target rocks, and occasionally some initial melting, though the primary textures of the precursor rocks may be still discernible; (ii) lithification of deposited mineral and lithic fragments (unshocked and shocked), sometimes with an admixture of a small amount of impact glass (< 10 vol%); and (iii) cooling, crystallisation and lithification of an ejected coherent impact melt mass and dispersed melt particles and bombs, usually deposited together with mineral and lithic clasts (10–90 vol% of impact glass). The corresponding main groups of impact (or coptogenic) rocks are shocked target rocks, impact lithic breccias, and impactites (Figures 15, 16). In Figure 16, the upper two lines display the main classification units of the two subtypes of coptogenic rocks. Shock-metamorphic rocks are distinctly different from shock-metamorphosed ones by total loss of pre-existing structure and sometimes compositions that lead to the formation of new rocks, with their own distinct features, i.e. structure, texture, composition, etc. The lower three lines of the figure represent the diagnostic petrographic features of corresponding groups and subgroups. Their distinctions are based on the composition and aggregate state of the constituents and their quantitative ratios.

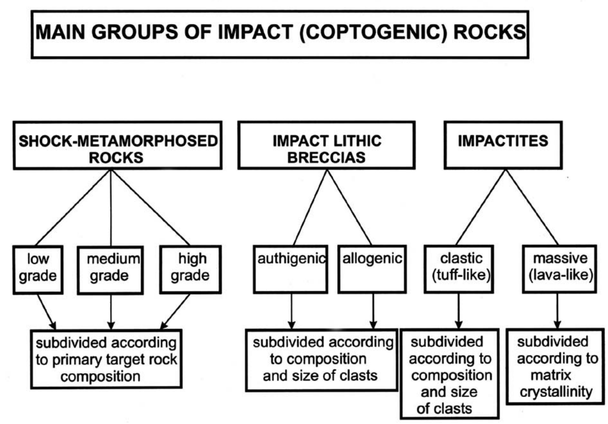

Figure 15 Subdivision of impact (coptogenic) rocks scheme.

The term impactite is applied to that rock subgroup consisting completely, or to a significant extent (conventionally > 10% vol.), of chilled or crystallised silicate impact melt, with (or without) various amounts of lithic and mineral clasts (Masaitis *et al.* 1980; Masaitis 2003). This restricted use of the term is in keeping with its original meaning (Murawsky 1977; Raikhlin *et al.* 1980; Bates & Jackson 1987; Chao & Xiande 1990). Two main species of impactites may be distinguished, the tagamite composed of massive chilled or crystallised impact melt (Figures 17, 18), and suevite, made of lithic, mineral and glass fragments (Figures 19, 20). Further subdivision can be based on such petrographic and lithological criteria as fabric, crystallinity of groundmass, ratio of lithic and mineral clasts to glass particles, grainsize (Figure 21), shape and composition of fragments, type of cementa-

<table>
<tr><th>Subtypes</th><th>Mode of occurrence</th><th>Shocked target rocks</th><th colspan="2">Impact lithic breccias</th><th colspan="4">Impactites</th></tr>
<tr><td>Shock-metamorphosed rocks (initial rock structure is discernible)</td><td>Authigenic, non-ejected (or included as clasts in shock-metamorphic rocks)</td><td>Shocked sedimentary, magmatic & metamorphic rocks</td><td>Breccia-ted rocks, cataclasites</td><td>Glass-bearing brecciated rocks, lithic breccias, cataclasites</td><td colspan="2"></td><td colspan="2">Protoimpactites*</td></tr>
<tr><td rowspan="2">Shock-metamorphic rocks (initial rock structure is indiscernible)</td><td rowspan="2">Allogenic, ejected (or injected in shock-metamorphosed rocks)</td><td rowspan="2"></td><td rowspan="2">Lithic breccias (mega-, meso-, & micro-)</td><td rowspan="2">Glass-bearing lithic breccias (mega-, meso-, & micro-)</td><td rowspan="2">Sue-vites</td><td colspan="2">Tagamites</td><td rowspan="2">Hyalinites (+impact pumices & slags)</td></tr>
<tr><td>Clast-rich</td><td>Clast-poor, clast-free, & their coarse-grained holocrystalline analogues**</td></tr>
<tr><td rowspan="2">Aggregate state</td><td>fragments</td><td>none</td><td>L, C</td><td>L, C, V</td><td>L, C, V</td><td>L. C</td><td colspan="2">L, C (or none)</td></tr>
<tr><td>matrix</td><td>initial</td><td>(C)</td><td>(C, V)</td><td>(C, V)</td><td>G, M</td><td>G, M</td><td>M</td></tr>
<tr><td colspan="2">Content of chilled or crystallized impact melt (vol. %)</td><td>none</td><td>none</td><td><10</td><td>10-90</td><td>30-50</td><td>50-100</td><td>up to 100</td></tr>
<tr><td colspan="9">L - lithoclasts, C - crystalloclasts, V - vitroclasts, G - glass matrix, M - hemi- or holocrystalline matrix. In brackets: dispersed state of minerals and glasses.</td></tr>
</table>

* - protoimpactites contain >10 vol.% of monomineralic impact glasses.
** - coarse-grained holocrystalline impact melt rocks may be named in accordance with their mineral composition, similarly to igneous rocks (e.g. c-granite, c-norite etc., c – caused by cratering).

Figure 16 Classification scheme of main species of coptogenic rocks.

Figure 17 Clast-supported tagamite showing the fluidal structure. Shocked and partially melted schists enclosed in the microcrystalline tagamite matrix represent clasts. Jänisjärvi impact structure, Russian Karelia. Compass is for scale.

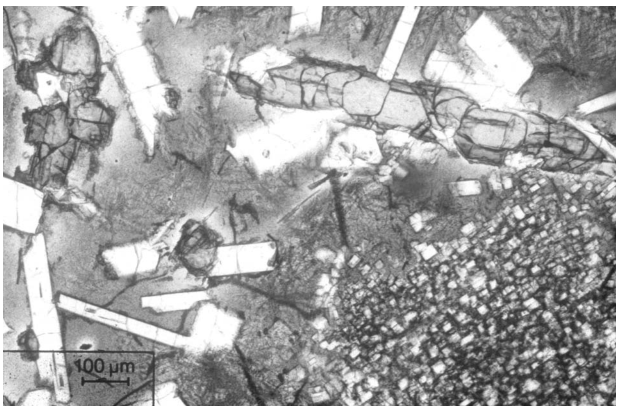

Figure 18 Hemicrystalline tagamite. Microcrystals of plagioclase and hypersthene are submerged into residual glass. The cluster of hypersthene grains (lower right) formed after a quartz clast, dissolved in the impact melt. Photomicrograph of the thin-section, linear polarisers. Boltysh impact crater, Ukraine.

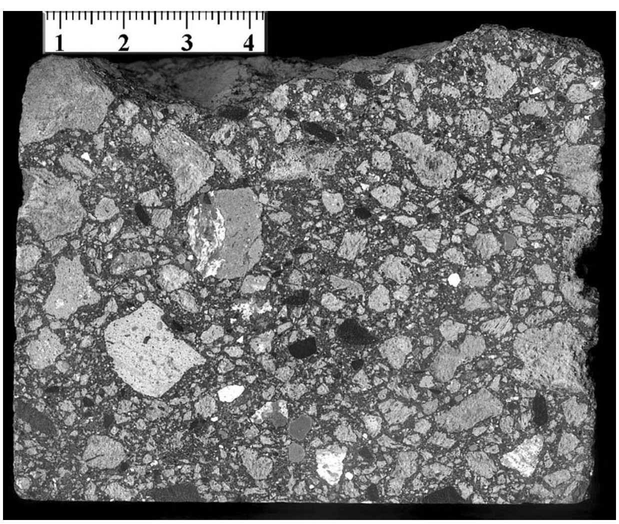

Figure 19 Lapilli crystallo-vitroclastic suevite. Angular clasts are mainly composed of chilled impact glass; matrix consists of partly altered small particles of the same glass and crystal fragments. Popigai impact crater, Russia. Scale in centimetres.

Figure 20 Agglomerate vitro-lithoclastic suevite shows banded and fluidal structure produced by dragging of the mixture composed of brecciated sandstone blocks and shards and lenses of clast-supported impact melt. Kara impact crater, Russia. Hammer for scale.

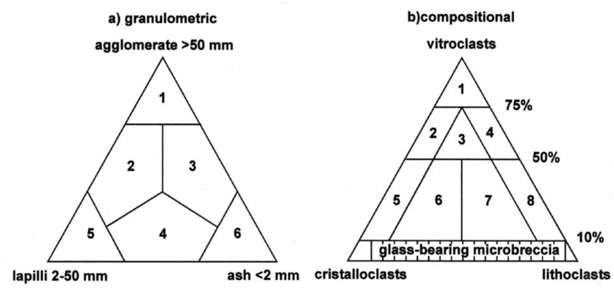

Figure 21 Schemes of the subdivision of suevites based on (a) granulometry of clasts and (b) their composition. Granulometry varieties: 1, agglomerate, blocky; 2, agglomerate–lapilli; 3, agglomerate–ash; 4, lapilli–ash; 5, lapilli; 6, ash. Composition varieties: 1, vitroclastic; 2, crystallo–vitroclastic; 3, crystallo–vitro–lithoclastic; 4, litho–vitroclastic; 5, vitro–crystalloclastic; 6, litho–crystallo–vitroclastic; 7, crystallo–vitro–lithoclastic; 8, vitro–lithoclastic.

tion, etc. A term protoimpactite is proposed for strongly shocked rocks that preserve their initial texture, but are composed mainly of chilled or recrystallised monomineralic shock melts, diaplectic glasses and relics of pristine minerals (Figure 16). The existence of carbonate melt rock (carbonate impactite) is assumed, but requires additional proofs (Stöffler *et al.* 2004), accordingly their nomenclature should be regulated henceforth.

Uniform and internationally accepted systematic petrology, subdivision, and terms for the main impact lithologies do not as yet exist. The approaches presented above are based on the general principles adopted for the classification and nomenclature of igneous and metamorphic rocks, including brecciated varieties (Laznicka 1988; Le Maitre 1989), allowing one to compile discriminating tables to distinguish the rock species. Proper names, rather than descriptive terms, should be preferable used to identify rock species, as is commonly accepted in the petrographic study of igneous rocks. The comparison of classification and nomenclature used in this work with some previous proposals is shown in the Table 4.

Table 4 Comparison of nomenclature of impact rocks proposed by some authors (terms of rocks and rock units) and adopted in this work.

This work[a]	Stöffler *et al.* 1979	French 1998	Deutsch & Langenhorst 1998
1. Shock-metamorphosed rocks (± brecciated and cataclased).	Shocked target rocks.	Shock-metamorphosed rocks.	Monomict brecciated mega-block.
a. Shocked rocks.	Cataclastic breccias.	Lithic breccias.	Paraautochtonous polymict breccia.
b. Brecciated rocks.			
c. Cataclased rocks (coptocata-clasites).			
d. Mylonites (coptomylonites).			
2. Impact lithic breccias.	Clastic matrix breccias.	Lithic breccias.	Fragmental breccia.
a. Megabreccias.	Megabreccias.	Monomict breccias.	
b. Mesobreccias.	Macrobreccias.	Polymict breccias.	
c. Microbreccias (coptoclas-tites).			
3. Impactites	Suevitic breccias.	Suevites (breccias).	Suevitic breccia.
a. Suevites	Impact melt rocks.	Impact melt breccias.	Polymict impact melt breccia.
b. Tagamites	Impact glasses.	Impact melt rocks.	Clast-free melt.
c. Impact glasses (hyalinites or coptohyalinites)			

[a] 1–3 rock groups. Preferably proper root names are used for rock species (in part combined with qualifiers), based on the presence and content of certain mineral (or glassy) components, and on the texture of the rock.

In addition to the proximal allochthonous coptogenic rock species, distal ones can also be distinguished. These are represented by tektite- and microtektite-bearing sediments, by layers that bear impact glass spherules, by tsunamites and slumping breccias with admixtures of such spherules and shocked clasts, and some other sedimentary facies (Warme & Kuehner 1998; Pope *et al.* 1999; Montanari & Koeberl 2000; Hassler & Simonson 2001; King & Petruny 2003b). These rocks are formed only by very large impacts and are mostly found in basin settings. Taking into account their lithologic features, a sedimentological approach to subdivision is required.

CONCLUSIONS

Traces of impact events on the Earth's surface are characterised by broad dimensional range, from lattice deformation in individual crystals to giant circular areas of disturbed, transformed and displaced rocks measuring some tens or hundreds of kilometres across. Macroscopically, these traces are manifested in numerous physiographic, structural and lithological features, but only a restricted number of these may be regarded as sufficiently diagnostic criteria for establishing the existence of a terrestrial impact structure or astrobleme. All of these features arise during a broad spectrum of impact-specific processes that are relief-forming, structure-forming and rock-forming. Not all of these processes are well understood, especially considering the relatively short period that they have been studied, beginning only in the last decades of the twentieth century, as compared to the long duration of investigations in some other fields of geology. New field research using precise methods of rock and mineral study, new data from deep drilling and geophysical observations, as well as new space missions, allow us to compare terrestrial and extraterrestrial impact craters and provide an understanding of the essence and peculiarities of the geological process of impact interactions of solid cosmic bodies in the Solar System, i.e. coptogenesis.

Although the concept of impact interaction between cosmic bodies and its geological role is now accepted by the geological community, not all of the wide arsenal of approaches and methods of the geological sciences, especially of geomorphology, structural geology, lithology and petrography is involved in the study of terrestrial impact structures. The unification and systematisation of all their topographic, structural and lithological elements can provide for more precise correlation and help with compiling maps and cross-sections mirroring various features of impact structures. There is a definite need for this new approach, not only to investigate new and recently discovered impact sites, but also to extend the knowledge of those already identified. Some much wider problems concerning fundamental processes of cratering, global geological evolution, mass extinction, estimation of economic mineral potential of certain impact structures and associated geological regions, and many other problems stand in need of a deepening and widening of the scope of approaches. There are many examples showing that a disregard for analysis of structural position and the interrelationships and correlation of the components of impact craters, including those observed in isolated drillholes in large craters, leads to erroneous interpretations of their inner structure and of rock-forming petrological and lithological processes. Problems likewise arise from the non-systematic usage of terms relating to the physiographic and structural features of impact structures. As a multidisciplinary field, impact geology evolves into the mainstream of the earth sciences (French 2004).

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REFERENCES

Aaloe A. O. 1978. Kaalijarv meteorite craters (in Russian). *Scientific Proceedings of the Tartu University* **473**, 129–133.

Abels A., Plado J., Pesonen L. & Lehtinen M. 2002. The impact cratering record of the Fennoscandia—a new look at the database. *In:* Plado J. & Pesonen L. J. eds. *Impacts in Precambrian Shields*, pp. 1–58. Springer-Verlag, Berlin.

Abels A. 2003. Investigation of impact structures in Finland (Söderfjärden, Lumparn, Lappajärvi) by digital integration of multidisciplinary geodata. Inaugural dissertation for attaining the doctoral degree in natural sciences, Westfalian-Wilhelms University, Münster, Germany (CD–ROM).

Alexopulos J. S. & McKinnon W. B. 1994. Large impact craters and basins of Venus with implications for ring mechanics of the terrestrial planets. *In:* Dressler B. O., Grieve R. A. F. & Sharpton V. L. eds. *Large Meteorite Impacts and Planetary Evolution*, pp. 29–50. Geological Survey of America Special Paper **293**.

Ames D. E., Kjarsgaard I. M., Pope K. O., Dressler B. O. & Pilkington M. 2004. Secondary alteration of the impactites and mineralization in the basal Tertiary sequence, Yaxcopoil-1, Chicxulub impact crater, Mexico. *Meteoritics & Planetary Science* **39**, 1145–1168.

Anderson R., Hartung J. B., Witzke B. J., Shoemaker E. M. & Roddy D. J. 1994. Preliminary results of the US Geological Survey – Iowa Department of Natural Resources Geological Survey Bureau Manson core drilling project. *In:* Dressler B. O.,Grieve R. A. F. & Sharpton V. L. eds. *Large Meteorite Impacts and Planetary Evolution*, pp. 237–248. Geological Survey of America Special Paper **293**.

Basilevsky A. T., Ivanov B. A., Florensky K. P., Yakovlev O. I., Feldman V. I. & Granovski L.B. 1983. *Impact craters on the Moon and Planets*. Nauka Press, Moscow (in Russian).

Bates R. L. & Jackson J. A. (Editors) 1980. *Glossary of Geology* (2nd edition). American Geological Institute, Falls Church.

Boiko Y. I., Mashchak M. S. & Raikhlin A. I. 1991. *Impact crater Zhamanshin. Guide of Geological Excursion*. VSEGEI Press, St Petersburg.

Chao E. & Xiande X. 1990. *Mineralogical Approaches to Geological Investigations*. Science Press, Beijing.

Chao E. C. T., Hüttner R. & Schmidt-Kaler H. 1978. *Principal exposures of the Ries Meteorite Crater in Southern Germany*. Bayerisches Geologisches Landesamt, München.

Chapman C. R. 2002. Cratering on asteroids. *In:* Bottke W. F., Calino A., Paolicchi P. & Binzel R. *Asteroid III*, pp. 315–330. University of Arizona Press, Tucson.

Dence M. R. 1965. The extraterrestrial origin of Canadian craters. *Annals of the New York Academy of Scence.* **123**, 941–969.

Dence M. R. 1968. Shock zoning at Canadian craters: petrography and structural implications. *In:* French B. M. & Short N. M. eds. *Shock Metamorphism of Natural Materials*, pp. 169–184. Mono Book Corporation, Baltimore.

Dence M. R. 2002. Re-examining structural data from impact craters on the Canadian shield in the light of theoretical models. *In:* Plado J. & Pesonen L. J. eds. *Impacts in Precambrian Shields*, pp. 59–80. Springer-Verlag, Berlin.

Dence M. R., Grieve R. A. F. & Robertson P. B. 1977. Terrestrial impact structures: principal characteristicas and energy considerations. *In:* Roddy D. J., Pepin R. O. & Merrill R. B. eds. *Impact and Explosion Cratering*, pp. 247–275. Pergamon Press, New York.

Deutsch A. & Langenhorst F. 1994. Mineralogy of astroblemes—terrestrial impact craters. *In:* Marfunin A. S. ed. *Advanced Mineralogy*, vol. 3, pp. 76–139. Springer-Verlag, Berlin.

Dietz R. S. 1959. Shatter cones in cryptoexplosion structures (meteorite impact). *Journal of Geology* **67**, 650–664.

Dietz R. S. 1963. Astroblemes: ancient meteorite-impact structures on the Earth. *In:* Middlehurst B. M. & Kuiper G. P. eds. *The Moon, Meteorites and Comets*, pp. 285–300.University Chicago Press, Chicago.

Dressler B. O. & Reimold W. U. 2001. Terrestrial impact melt rocks and glasses. *Earth-Science Reviews* **56**, 205–284.

Dressler B. O., Sharpton V. L., Schwandt C. S. & Ames D. E. 2004. Impactites of the Yaxcopoil-1 drilling site, Chicxulub impact structure: petrography, geochemistry, and depositional environment. *Meteoritics and Planetary Science* **39**, 857–878.

Easton R. M. & Johns G. W. 1986. Volcanology and mineral exploration: the application to physical volcanology and facies studies. *Ontario Geological Survey Miscellaneous Paper* **129**, 2–40.

Fisher R. V. & Schminke H-U. 1984. *Pyroclastic Rocks*. Springer-Verlag, Berlin.

French B. M. 1968. Shock metamorphism as a geological process. *In*: French B. M. & Short N. M. eds. *Shock Metamorphism of Natural Materials*, pp. 1–17. Mono Book Corporation, Baltimore.

French B. M. 1998. *Traces of Catastrophe.* Lunar and Planetary Institute, Houston, Contribution **954**.

French B. M. 2004. The importance of being cratered: the new role of meteorite impact as a normal geological process. *Meteoritics and Planetary Science* **39**, 169–198.

Gibson R. L. & Reimold W. U. 2001. The Vredefort impact structure, South Africa. The scientific evidence and a two-day excursion guide. *Council for Geoscience, South Africa, Memoir* **92**.

Glazovskaya L. I., Gromov E. I., Parfenova O. V. & Il'kevich G. I. 1991. *The Logoisk Astrobleme.* Nauka Press, Moscow (in Russian).

Glikson A. Y. (Editor) 1996. Australian impact structures. *AGSO Journal of Australian Geology & Geophysics* **16**, 374–625.

Glikson A. Y. 2001. The astronomical connection of terrestrial evolution: crustal effects of post 3.8 Ga mega-impact clusters and evidence for major 3.2 ± 0.1 Ga bombardment of the Earth–Moon system. *Journal of Geodynamics* **32**, 205–229.

Glikson A. Y, Allen C. & Vickers J. 2004. Multiple 3.47 Ga-old asteroid impact fallout units Pilbara Craton, Western Australia. *Earth and Planetary Science Letters* **221**, 383–396.

Grieve R. A. F. 1980. Impact bombardment and its role in protocontinental growth on the early Earth. *Precambrian Research* **10**, 217–247.

Grieve R. A. F. & Head J. W. 1983. The Manicouagan impact structure: an analysis of its original dimension and form. *Proceedings 13th Lunar Planetary Science Conference*, pp. A807–A818. Journal of Geophysical Research **88** (Suppl.).

Grieve R. A. F. & Masaitis V. L. 1994. The economic potential of terrestrial impact craters. *International Geological Review* **36**, 105–151.

Grieve R. A. F. & Pesonen L. J. 1992. The terrestrial impact cratering record. *Tectonophysics* **216**, 1–30.

Grieve R. A. F. & Therriault A. M. 2004. Observations at terrestrial impact structures: their utility in constraining crater formation. *Meteoritics and Planetary Science* **39**, 199–216.

Gurov E. P., Kelley S. P. & Koeberl C. 2003. Ejecta of the Boltysh impact crater in the Ukrainian Shield. *In:* Koeberl C. & Martinez-Ruiz F. eds. *Impact Markers in the Stratigraphic Record*, pp. 179–202. Springer-Verlag, Berlin.

Hassler S. W. & Simonson B. M. 2001. The sedimentary record of extraterrestrial impacts in deep-shelf environments: evidence from the Early Precambrian. *Journal of Geology* **109**, 1–19.

Herrick R. R., Sharpton V. L., Malin M. C., Lyons S. N. & Feely K. 1997. Morphology and morphometry of impact craters. *In:* Bougher S. W., Hunten D. M. & Phillips R. J. eds. *Venus II—Geology, Geophysics, Atmosphere and Solar Wind Environment*, pp. 1015–1046. Lunar and Planetary Institute Contribution **889**.

Hörz F., Gall H., Hüttner R. & Oberbeck V. R. 1977. Shallow drilling in the 'Bunte Breccia' impact deposits, Ries Crater, Germany. *In:* Roddy D. J., Pepin R. O. & Merrill R. B. eds. *Impact and Explosion Cratering*, pp. 425–448. Pergamon Press, New York.

Kenkmann T. & von Dalwigk I. 2000. Radial transpressive ridges: a new structural feature of complex impact craters. *Meteoritics & Planetary Science* **35**, 1189–1201.

King D. T. & Petruny L. W. 2003a. Application of stratigraphic nomenclature to terrestrial impact-derived and impact-related materials *In*: Koeberl C. & Martinez-Ruiz F. eds. *Impact Markers in the Stratigraphic Record*, pp. 41–64. Springer-Verlag, Berlin.

King D. T. & Petruny L. W. 2003b. Stratigraphy and sedimentology of coarse impactoclastic breccia units within the Cretaceous–Tertiary boundary section, Albion Island, Belize. *In*: Koeberl C. & Martinez-Ruiz F. eds. *Impact Markers in the Stratigraphic Record*, pp. 203–228. Springer-Verlag, Berlin.

Koeberl C. 1994. African meteorite impact craters: characteristics and geological importance. *Journal of African Earth Sciences* **18**, 263–295.

Kring D. A., Hörz F., Zurcher L. & Urruttia-Fucugauchi J. 2004. Impact lithologies and their emplacement in the Chicxulub impact crater: initial results from the Chicxulub Scientific Drilling Project, Yaxcopoil, Mexico. *Meteoritics & Planetary Science* **39**, 879–898.

Laznicka P. 1988. *Breccias and Coarse Fragmentites*. Elsevier, Amsterdam.

Le Maitre R. 1989. *A Classification of Igneous Rocks and Glossary of Terms*. Blackwell Science Publications, London.

Lowe D. R., Byerly G. R., Kyte F. T., Shukolyukov A., Asaro F. & Krull A. 2003 Spherule beds 3.47–3.34 Ga-old in the Barberton greenstone belt, South Africa. A record of large meteorite impacts and their influence on early crustal and biologic evolution. *Astrobiology* **3**, 7–48.

Masaitis V. L. (Editor) 1983. *Textures and Structures of Explosion Breccias and Impactites*. Nedra Press, Leningrad (in Russian).

Masaitis V. L. 1984. The impact reworking of the Earth's crust. *International Geological Congress 27th Session, Comparative Planetology*, Sect.19, pp. 74–80 (in Russian).

Masaitis V. L. 1999. Impact structures of northeastern Eurasia: the territories of Russia and adjacent countries. *Meteoritics and Planetary Science* **34**, 691–711.

Masaitis V. L. 2002. The Middle Devonian Kaluga impact crater (Russia): new interpretation of marine setting. *Deep Sea Research* **49**, 1157–1169.

Masaitis V. L. 2003. Obscure-bedded ejecta facies from the Popigai impact structure, Siberia: lithological features and mode of origin. *In:* Koeberl C. & Martinez-Ruiz F. eds. *Impact Markers in the Stratigraphic Record*, pp. 137–162. Springer-Verlag, Berlin.

Masaitis V. L., Danilin A. N., Mashchak M. S., Raikhlin A. I., Selivanovskaya T. V & Shadenkov E. M. 1980. *Geology of Astroblemes*. Nedra Press, Leningrad. (in Russian). English translation NASA TM-77743, 1984.

Masaitis V. L., Mashchak M. S., Raikhlin A. I., Selivanovskaya T. V. & Shafranovsky G. I. 1998. *Diamond-bearing Impactites of the Popigai Astrobleme*. VSEGEI Press, St Petersburg (in Russian).

Masaitis V. L., Naumov M. V. & Mashchak M. S. 1999. Anatomy of the Popigai impact crater, Russia. *In:* Dressler B. O. & Sharpton V .L. eds. *Large Meteorite Impacts and Planetary Evolution II*, pp. 1–18. Geological Society of America Special Paper **339**.

Masaitis V. L. & Pevzner L. A. (Editors) 1999. *Deep Drilling in the Puchezh-Katunki Impact Structure*. VSEGEI Press, St Petersburg (in Russian).

Mashchak M. S. 1990. Morphology and internal structure of the Kara and Ust'-Kara astroblems. *In:* Masaitis V. L. ed. *Impact Craters of the Mesozoic–Cenozoic Boundary*. pp. 37–55. Nauka Press, Leningrad (in Russian).

Melosh H. J. 1989. *Impact Cratering. A Geologic Process.* Clarendon Press, Oxford.

Milton D. I., Glikson A. Y. & Brett R. 1996. Gosses Bluff—a latest Jurassic impact structure, central Australia. Part 1: Geological structure, stratigraphy and origin. *In:* Glikson A. Y. ed. *Australian Impact Structures*, pp. 453–486. AGSO Journal of Australian Geology & Geophysics **16**.

Montanari A. & Koeberl C. 2000. *Impact Stratigraphy*. Lecture notes in Earth Sciences **93**. Springer-Verlag, New-York.

Morgan J. & Warner M. 1999. Morphology of the Chixculub impact: peak ring or multi-ring basin? *In:* Dressler B. O. & Sharpton V. L. eds. *Large Meteorite Impacts and Planetary Evolution II*, pp. 281–290. Geological Society of America Special Paper **339**.

Movshovich E. V. & Milyavsky A. E. 1990. Morphology and inner structure of the Kamensk and Gusev astroblems. *In:* Masaitis V. L. ed. *Impact Craters of the Mesozoic–Cenozoic Boundary*, pp.110–146. Nauka Press, Leningrad (in Russian).

Murawski H. 1977. *Geologishe Wörterbuch*. Enke Verlag, Stuttgart.

Naumov M. V. 2002. Impact-generated hydrothermal systems: data from Popigai, Kara and Puchezh-katunkim impact structures. *In:* Plado J. & Pesonen L. J. eds. *Impacts in Precambrian Shields*, pp.117–172. Springer-Verlag, Berlin.

Neukum G. & Ivanov B. A. 1994. Crater size distributions and impact probability on Earth from lunar, terrestrial planet, and asteroid cratering data. *In:* Gehrels T. ed. *Hazards due to Comets and Asteroids*, pp. 359–416. University of Arizona Press, Tucson.

Newsom H. E., Graup G., Sewards T. & Keil K. 1986. Fluidization and hydrothermal alteration of the suevite deposit at the Ries crater, West Germany. *Proceedings 17th Lunar and Planetary Science Conference*, E239–E251. Journal of Geophysical Research **91**.

Ormö J. & Lindström M. 2000. When a cosmic impact strikes the sea bed. *Geological Magazine* **137**, 67–80.

Pike R. J. 1977. Size-dependence in the shape of fresh impact craters on the moon. *In:* Roddy D. J., Pepin R. O. & Merrill R. B. eds. *Impact and Explosion Cratering*, pp. 489–510. Pergamon Press, New York.

Pike R. J. 1985. Some morphologic systematics of complex impact structures. *Meteoritics* **20**, 49–68.

Pirajno F., Hawke P., Glikson A., Haines P. W. & Uysal T. 2003. Shoemaker impact structure, Western Australia. *Australian Journal of Earth Sciences* **50**, 775–796.

Plotnikova M. I. 1990. Essay of the Post-Oligocene history of the Popigai impact morphostructure. *Meteoritika* **49**, 154–163 (in Russian).

Poag C. W., Hutchinson D., Colman S. M. & Lee M. W. 1999. Seismic expression of the Chesapeake Bay impact crater: structural and morphological refinements based on a new seismic data. *In:* Dressler B. O. & Sharpton V. L. eds. *Large Meteorite Impacts and Planetary Evolution II*, pp. 1–18. Geological Society of America Special Paper **339**.

Pohl J., Stöffler D., Gall H. & Ernston K. 1977. The Ries impact crater. *In:* Roddy D. J., Pepin R. O. & Merrill R. B. eds. *Impact and Explosion Cratering*, pp. 343–404. Pergamon Press, New York.

Pope K. O., Ocampo A. C., Fisher A., Alwarez W., Fouke B. W., Webster C. L., Vega F. J., Smit J., Fritsche A. E. & Claeys F. 1999. Chicxulub impact ejecta from Albion Island, Belize. *Earth and Planetary Science Letters* **170**, 351–364.

Raikhlin A. I., Selivanovskaya T. V. & Masaitis V. L. 1980. Rocks of terrestrial impact craters: problems of classification. *Lunar Planetary Science 11*, 911–913.

Robertson P. B. 1975. Zones of shock metamorphism at the Charlevoix impact structure, Quebec. *Geological Society of America Bulletin* **86**, 1630–1638.

Roddy D. J. 1977a. Morphological and structural comparisons between bowl-shaped, flat-floored with central uplift and flat-floored with multirings. *In:* Roddy D. J., Pepin R. O. & Merrill R. B. eds. *Impact and Explosion Cratering*, pp. 185–246. Pergamon Press, New York.

Roddy D. J. 1977b. Tabular comparison of the Flynn Creek impact crater, United States, Steinheim impact crater, Germany and Snowball explosion crater, Canada. *In:* Roddy D. J., Pepin R. O. & Merrill R. B. eds. *Impact and Explosion Cratering*, pp. 125–162. Pergamon Press, New York.

Rondot J. 1995. *Les Impacts Meteoritiques*. MNH Inc, Beauport.

Ryder G. 1990. Lunar samples, lunar accretion and the early bombardment history of the Moon. *EOS* **71**, 313–323.

Shoemaker E. M. 1963. Impact mechanics at Meteor crater Arizona. *In:* Middlehurst B. M. & Kuiper G. P. eds. *The Moon, Meteorites and Comets*, pp. 301–336. University of Chicago Press, Chicago.

Shoemaker E. M. 1977. Why study impact craters? *In:* Roddy D. J., Pepin R. O. & Merrill R. B. eds. *Impact and Explosion Cratering*, pp. 1–10. Pergamon Press, New York.

Simonson B. M., Hassler S. W. & Beukes N .J. 1999. Late Archean impact spherule layer in South Africa that may correlate with a Western Australian layer. *In:* Dressler B. O. & Sharpron V. L. eds. *Impact Cratering and Planetary Evolution II*, pp. 249–269. Geological Society of America Special Paper **339**.

Simonson B. M. & Glass B. P. 2004. Spherule layers—records of ancient impacts. *Annual Review of Earth and Planetary Sciences* **32**, 329–361.

Stöffler D., Artemieva N. A., Ivanov B. A., Hecht L., Kenkmann T., Schmitt R. T., Tagle R. & Wittman A. 2004. Origin and emplacement of the impact formations at Chicxulub, Mexico, as revealed by the ICDP deep drilling at Yaxcopoil-1 and by numerical modeling. *Meteoritics & Planetary Science* **39**, 1035–1068.

Stöffler D., Deutsch A., Avermann M, Bischoff L., Brockmeyer P., Buhl D., Lakomy R. & Müller-Mohr V. 1994. The formation of the Sudbury structure, Canada: toward a unified impact model. *In:* Dressler B. O., Grieve R. A. F. & Sharpton V. L. *Large Meteorite Impacts and Planetary Evolution*, pp. 303–318. Geological Survey of America Special Paper **293**.

Stöffler D. & Grieve R. A. F. 1994. Classification and nomenclature of impact metamorphic rocks: a proposal to the IUGS Subcommission on the Systematics of Metamorphic Rocks. *European Science Foundation Network on Impact Cratering Newsletter* **2**, 8–15.

Stöffler D., Knöll H-D. & Maerz U. 1979. Terrestrial and lunar impact breccias and the classification of lunar highland rocks. *Proceedings Lunar and Planetary Conference 10*, 339–375.

Stöffler D. & Langenhorst F. 1994. Shock metamorphism of quartz in nature and experiment: 1. Basic observation and theory. *Meteoritics* **29**, 155–181.

Strom R. G., Croft S. K. & Barlow N. G. 1992. The Martian impact cratering record. *In:* Kieffer H. H., Jakovsky B. M., Snyder S. W. & Mattews M. S. eds. *Mars*, pp. 383–423. University of Arizona Press, Tucson.

Taylor S. R. 1967. Composition of meteorite impact glass across the Henbury strewnfield. *Geochimica et Cosmochimica Acta* **31**, 961–968.

Taylor S. R. 1992. *Solar System Evolution: a New Perspective*. Cambrige University Press, New York.

Tsikalas F., Faleide J. I., Eldholm O. & Dypvik H. 2002. Seismic correlation of the Mjølnir marine impact crater to shallow boreholes. *In:* Plado J. & Pesonen L. J. eds. *Impacts in Precambrian Shields*, pp. 307–321. Springer-Verlag, Berlin.

Warme J. M. & Kuehner H-C. 1998. Anatomy of an anomaly: the Devonian catastrophic Alamo impact breccia of Southern Nevada. *International Geologic Review* **40**, 189–216.

Wilhelms D. E. 1987. The Geologic history of the Moon. *US Geological Survey Professional Paper* **1348**.

Wilshire H. G., Offield T. W., Howard K. A. & Cummings D. 1972. Geology of the Sierra Madera cryptoexplosion structure, Pecos County, Texas. *US Geological Survey Professional Paper* **599-H**.

Valter A. & Plotnikova L. 2003. Biostratigraphic indications of the age of the Boltysh impact crater, Ukraine. *In:* Koeberl C. & Martinez-Ruiz F. eds. *Impact Markers in the Stratigraphic Record*, pp. 163–178. Springer-Verlag, Berlin.

von Dalwigk I. & Ormö J. 2001. Formation of resurge gullies at impacts at sea; the Lockne crater, Sweden. *Meteoritics & Planetary Science* **36**, 359–369.

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