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A deep model of the multi-ring structures formation in the Earth relief*

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Abstract. In order to explain the process of forming the outer rings of an impact crater, a model of an underground explosion of an impactor penetrating into the target is proposed. Intense crushing of the surface rocks is explained by the effect of the primary compression wave if it propagates from a buried source (a camouflage explosion) and when reaching the surface, causes a rapid expansion of compressed rocks at the free boundary (forming the so-called "spalling" cracks). The author's calculations show that the formation of ring spall cracks can occur at all diameters that are multiples of the diameter D of the crater that is visible on the surface (as it is observed in real multi-ring structures) if the compression wave length λ fits an integer number of times (n) on its propagation path up to the first rings on the Earths surface. For the expression obtained under these conditions for $\lambda(n, D)$, it is possible to calculate the depth of a source $H(n, D)$ and to estimate a minimum depth of possible penetration of the impactor as the explosion source $H_{\min} = 0.975D$.

Keywords: Astroblemes, morphostructural elements of the crater, catalog of the impact structures, seismic explosion wave.

1. Introduction

It is known that complex impact structures are often accompanied by a system of concentric rings [1, 2]. Understanding of the mechanism forming many rings is still controversial [2]. For example, the model of "corrugated instability of shock waves" considered and supplemented by the author [2] (for the first time proposed by B.S. Zeylik et al. [3]) assumes that the transverse rarefaction wave excited on inhomogeneities of a medium propagates along circles (parallel to the shock front wave), and its length λ is determined by the condition of resonance on the contour of the crater. However, this model does not take into account the significant attenuation of the rarefaction wave (as a result of refraction) in comparison with the blast compression wave, which transfers the main energy in the radial direction from the source [4]. This paper continues the calculations showing that a much more intense compression wave can form multi-ring structures with a morphology really observed on the surface (a pronounced crater and over-crater rings, the distance between which is determined by the crater diameter D [5]) if it

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propagates from a buried (camouflage) explosion. The source of such an explosion can be the shock-compressed material of a cosmic body penetrating to a considerable depth. A real possibility of such a penetration is indicated by both experimental data [6–8] and some geophysical observations [9].

2. Model description

The classical scheme of the destruction structure [4] (Figure 1a) shows that in a camouflage nuclear explosion, the crushing zone is divided into an external and the internal part. In the near-surface soil zone, a seismic-breaking wave creates a spalling effect, since the rock compressed by the blast wave on the free surface begins to propogate rapidly like a "strongly compressed and suddenly released spring", creating tensile stress by the inertial force [4]. Typical diagrams of the velocity of the soil movement on the day surface in the zone of spalling phenomena have the form shown in Figure 1b. "As soon as the tensile stresses in the unloading wave from the day surface exceed the tensile strength of the soil, the soil is destroyed: spalling" [10]. At the next, geological phase of the development of spall cracks, it is likely that the process of dilatancy (an increase in volume) of rocks destroyed in the zone of cracks leads to their squeezing out and uplift in the form of ring-shaped ridges or out-crater rings.

The formation of a surface crater in this model is also understandable. In the central zone of the explosion, a camouflage cavity is formed, and in the near-surface zone above it, a dome-shaped rise or a swelling zone occurs. Then the camouflage cavity for most soils "turns out to be unstable: the

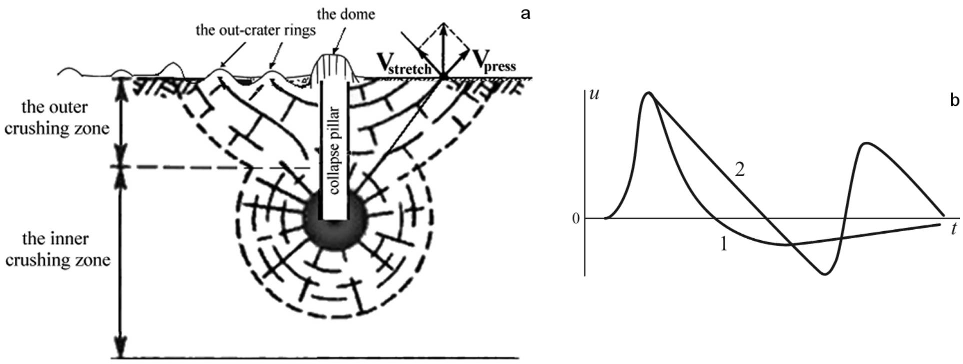

Figure 1. Schemes of the effects of a camouflage nuclear explosion: a) the structure of the rock crushing zones and the schematic direction of soil movements on the surface after an explosion in a low-compressive rock, when the compression wave energy is equal to the rarefaction wave energy (according to [4] with additions by the author); b) typical diagrams of the ground velocity: 1 — in the massif; 2 — on the day surface in the zone of spalling phenomena (according to [10])

roof collapses” [10] with the formation of a collapse column (see Figure 1a), while the central part of the dome sags, forming a crater.

In order to substantiate the reason for forming regular over-crater rings on the surface (with a distance equal to the crater diameter D between them), we assume that the most pronounced spall phenomena arise due to the occurrence in the zone of passage of a seismic-explosive wave of a stable resonant-oscillatory process with a wavelength λ caused by the sharp movement of rocks during the cavity. To calculate the geometry of the model proposed, let us draw the propagation rays of this wave along which the length λ fits an integer number of times in the segment from the explosion center to the Earth’s surface. Let us assume that it is this condition that determines the geometrical position of the most pronounced ring spall cracks on the Earth’s surface. In this case, two empirical conditions must be met: the distance between the outlets of the rays on the surface being equal to the diameter of the visible crater D (Figure 2), and the wavelength λ must be comparable with the diameter of the camouflage cavity (if the steady-state oscillations in the medium occur due to oscillations of the cavity volume, and the high-frequency component of these oscillations is absorbed when propagating over long distances).

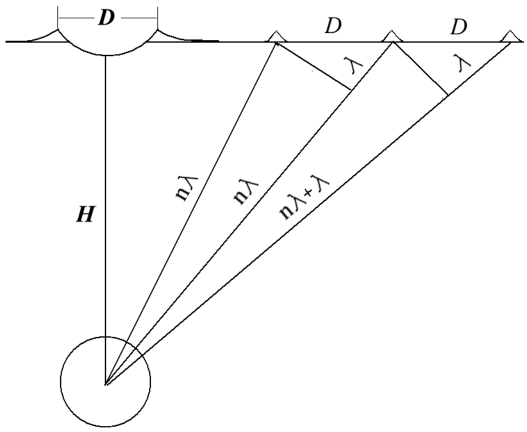

Figure 2. Scheme of the wave propagation from the supposed buried source to the ring uplifts on the surface

From the right-angled triangles formed by the intersection of rays with a surface line and with a depth-segment H, we obtain the equations

$$(3D/2)^2 + H^2 = (n\lambda)^2, \quad (5D/2)^2 + H^2 = (n\lambda + \lambda)^2, \quad \ldots, \tag{1}$$

from which we can find the value of λ, independent of H:

$$\lambda = \frac{2D}{\sqrt{2n+1}}. \tag{2}$$

3. The discussion of the results

Let us consider whether the obtained expression reflects the actually observed pattern for the underground nuclear explosions, on the one hand, and multi-ring structures on the surface, on the other. The observed ratio

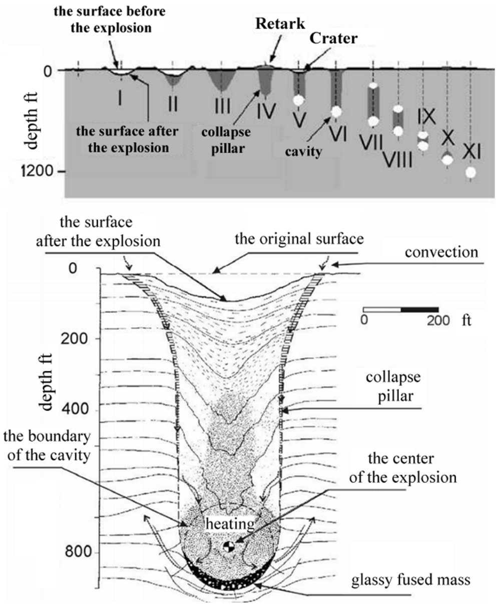

Figure 3. A typical scheme of the structure of destruction zones during underground nuclear explosions (according to [11]): at the top — a model range of structures arising when conducting underground nuclear explosions with a power of 1 ktTNT at different depths in tuffs, at the bottom — a geological vertical section of a typical crater (model V) in alluvium with a rock collapse pillar

of the radii of the surface rings was determined by the condition of a task. As for the classical ratios of the morphological parameters of crushing zones from underground explosions, then, in fact, there are such values of n and D, at which the obtained depth values do not contradict to real observations (Figure 3). And the value of the resonant wavelength corresponds to the size of the camouflage cavity D_0 (which is smaller than the diameter of the crater D in Figure 3). For example, for $n = 4$ and $D = 3$ km, the wavelength $\lambda = D_0 = 2$ km, and $H \sim 6.5$ km. Note that the wavelength also corresponds to the diameter of the collapse column, which is usually equal to the size of the camouflage cavity. Rings at these values, according to formulas (1), can form at radii of 7.5, 10.5, 13.5, ... km.

Indeed, according to theoretical calculations and empirical observations [4] (see Figure 1a), with the camouflage cavity radius R_0, the radius of the inner crushing zone must be $R_D = 4R_0$ [4], the crushing radius in the outer zone (spall processes) must not exceed $R_S = 2R_D$ on the surface, and the depth of the explosion must not exceed $H_{\max} = 2R_D$. Thus, in our case, $R_D = 4$ km, and the resulting explosion depth of 6.5 km does not exceed the limiting $H_{\max} = 8$ km. The theoretically expected radius of the outer crushing zone is $R_S = 8$ km, i.e. it is limited only by one out-crater ring: with a radius of 7.5 km.

With a smaller explosion depth, the number of rings regularly increases. Let us try to estimate a minimum depth of the source H from equations (1) and (2):

$$H = \frac{D}{2}\sqrt{\frac{(8n+3)(2n-3)}{2n+1}}. \tag{3}$$

For the minimum $n = 2$, formula (3) gives the value $H_{\min} = 0.975D$.

For example, in the case of the minimum deepening and $D = 3$ km, the wavelength will be 2.7 km, $H_{\min} = 2.925$ km, $R_S = 10.84$ km, and the radii of the rings: 4.5, 7.5 and 10.5 km. At $D = 5$ km, the wavelength will be 4.47 km, $H_{\min} = 4.875$ km, $R_S = 17.88$ km, and the radii of the rings: 7.5, 12.5 and 17.5 km.

Thus, with a minimum deepening of the impactor and according to the limitation of the theory of nuclear explosions on the size of the zone of spall destruction $R_S \sim 2R_D$, up to 3 out-crater rings with a distance between them equal to the crater diameter can form on the surface. Let us note that the overwhelming majority of proven and probable multi-ring impact structures, in fact, have no more than 3 out-crater rings. However, in [5] the examples of observations were given in which the number of rings is much larger. These are the potential shock geological structures: the "Khibinsky graben", the "Chernorecheskiy" [12], the multi-ring structures of Mercury and Callisto, etc. According to this, we can mention other data on the size of the zone of spall destruction. For example, in [13], the following radii of the observed spall destruction are given: for large-scale underground explosions at the Semipalatinsk test site H = 80–120 m/kt$^{1/3}$, R_S = 800 m/kt$^{1/3}$; and for explosions in the wells of the Balapan site R_0 = 10–13 m/kt$^{1/3}$, $R_D = 24 - 34$ m/kt$^{1/3}$, R_S = 100–200 m/kt$^{1/3}$(in some cases up to 1000 m/kt$^{1/3}$). In the latter observation, the ratio of the radii of the spall destruction zone and the crushing zone: $R_S \sim 4R_D$–$6R_D$, which exceeds the above estimates by 2–3 times (and in some cases— by 20 times). Moreover, at a repeated explosion the estimate of the radius of the zone of irreversible manifestations visible on the surface increases by another third (750 m/kt$^{1/3}$ versus 470 m/kt$^{1/3}$) [13]. When a supercompressed impactor penetrates into the target, the repeated explosions may well occur due to possible subsequent physicochemical reactions in the explosion source. Thus, the number of rings belonging to the zone of spalling disturbances can in real conditions increase by several tens of times.

4. Conclusion

The estimates given in this study show that the formation of the out-crater rings, which characterize many geological structures of the central type on the Earth and other planets, can be explained by the following hypothesis. The most pronounced, ring-shaped spall phenomena on the surface can arise due to the manifestation of a stable resonant-oscillatory process with a wavelength λ in the zone of the passage of a seismic-explosive wave, caused by the movement of rocks during the formation of a camouflage cavity. The hypothesis does not contradict the theory of an underground nuclear explosion. The arrangement of these rings at radii that are multiples of the diameter D of the crater visible on the surface (as is observed in real multi-ring structures) is possible if the compression wavelength fits an integer number of times (n) on the ray of its propagation to the first ring on the Earth's surface and is $\lambda = 2D/\sqrt{2n+1}$. The values of the explosion depth obtained in this model do not contradict to the real observations, and the value of the resonance wavelength corresponds to the size of the camouflage cavity D_0 (smaller than the diameter of the crater D). In this paper, it is shown that at minimum penetration of the impactor and according to the limitation of the theory of nuclear explosions on the size of the spall destruction zone, up to 3 collapsed rings with a distance between them equal to the crater diameter can form on the surface, which corresponds to the data of geological observations in the vast majority of multi-ring structures. The formation of a larger number of rings does not also contradict to the experimental data on nuclear explosions.

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