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The Upper Ordovician dropstones of Central Bohemia and their paleogravity significance

(3 text-figs., 2 pls.

JINDŘICH HLADIL

Abstract. Two layers of diamictites occur in the Kosov Formation (Hirnantian) in the section near Levín W of Prague (Brenchley - Štorch 1989). In the upper layer many dropstones were found which produced well-preserved impact deformations on sandy bottom.

The sedimentation took place in shallower shelf environment where floating and melting icebergs released dropstones. Their fall in quiet water caused deformation of sandy sea-floor. The deformation structures, however, are far more intensive than their counterparts observed in recent seas. To explain this contradiction, numerous experiments were carried out. The author believes that the more intensive Ordovician dropstone impact deformations could be explained by greater fall velocity compared to the recent one. This could be caused by higher gravitational acceleration during the Ordovician (the value about 15 $m.s^{-2}$ could be assumed).

Abstrakt. V kosovském souvrství (hirnant, svrchní ordovik), na profilu u Levína z. od Prahy, jsou známy dvě polohy diamiktitů (Brenchley - Štorch 1989). Ve svrchní z nich byly hojně zjištěny padající eratické klasty, které vytvořily při dopadu na písčité mořské dno velmi dobře zachované impaktní deformace.

Sedimentace probíhala v prostředí mělčího šelfu, kde se zmíněné klasty uvolňovaly při odtávání ledu z plovoucích ledovců. Po pádu několik desítek metrů mocnou vrstvou vody vytvořily impaktní struktury, které jsou však daleko intenzívněji vyvinuté, než ty, které se vytvářejí dnes. Pro vysvětlení tohoto rozporu byl proveden značný počet experimentů. Autor se domnívá, že intenzívnější, ordovické impaktní deformace mohou být vysvětleny vyšší pádovou rychlostí klastů. Ta by měla mít svoji příčinu ve vyšším gravitačním zrychlení (předpokládaná hodnota je přibližně 15 $m.s^{-2}$).

Ústřední ústav geologický, Malostranské nám. 19, 18 21 Praha

Introduction

Two diamictite layers occur in the Upper Ordovician sediments of the Barrandian (Brenchley and Štorch 1989). In the upper layer, P. Štorch found numerous dropstones which by their fall produced well-preserved impact structures on the underlying, originally sandy bottom. Compared to their recent counterparts, the Ordovician dropstone impact structures are far more intensively developed (F, Pl.I). To explain this contradiction, careful examination of dropstones, surrounding sediments and impact structures was carried out. Field study was accompanied by experiments which simulated depositional conditions of dropstone fall in quiet water.

Sedimentological investigation

The layer with dropstones was studied at the Levín section near Beroun. The section is placed 750 m S of the centre of Levín Village, in the central part of the 100 m long road-cut, which is faced to the S, at the left bank of the Litavka Creek Valley. The stratigraphical setting below and above the upper diamictite was given by Brenchley and Štorch (1989). Here, the setting is recapitulated in a summarized form:

On the base of the section, claystones and silty claystones of the upper part of the Králův Dvůr Formation occur with graptolites and benthic fauna. In the topmost part, a so-called "ginger layer" with carbonate admixture is present. The overlying part consists of claystones with Mucronaspis association. The Kosov Formation starts with the lower diamictite (thinner, with greater clayey admixture) and continues with claystones and the upper diamictite (thicker, with prevailing sandstones). The overlying sequence consists of claystone and higher up also of sandstone layers. Some of these exhibit hummocky stratification, ripple marks, washouts and numerous ichnofossils (Cruziana association). These sandstones were deposited in a shallow neritic sedimentary environment.

The presented paper deals with the upper diamictite layer. The layer is 2 m thick, with well-preserved impact structures originating from fall of dropstones on the sandy bottom. The age of this diamictite can be estimated at 440 Ma (GSA Geologic Time Scale, 1988, Boulder - Washington).

Dropstones occur within the sandstone which contains from 9 to 35 per cent of matrix (C, D, Pl.I). Exceptionally, there are some intercalations with more than 40 per cent of clay and silt.

Laminated sandstone was examined carefully, because laminae represent a perfect object for investigation of impact deformational structures. Impact structures registered in the Ordovician sediment could be easily compared to artificially produced impacts during the experiments.

Grain size composition of the dropstone-bearing bed is as follows (dropstones themselves are not included):

125 μm or less	13 %
125 to 250 μm	28 %
250 to 350 μm	6 %
350 to 500 μm	28 %

500 to 710 μm	21.3 %
710 to 1000 μm	3 %
1000 to 2000 μm or larger	0.7 %

Clasts of the fraction 250–2000 μm are mostly quartz whereas in the fraction 62–250 μm also feldspars, lithoclasts of siltstones, sandstones and metasediments are present. Some till pellets (defined by Ovenshine 1970) were also found. In the matrix, silt prevails over clayey fraction.

Dropstones occurring in this layer have generally 0.5–15 cm across, 60 per cent out of them is 2–6 cm large and 52 per cent of out the total number 3–5 cm. As to their shape, they are mostly isometric, sometimes polyhedral; some elongated ones are also present. Rounded dropstones make up 73 per cent of the total population. 5 per cent is represented by isometric plasticlasts of clayey-sandy material (C, Fig. 1). Hard dropstones are composed of sandstones, subgreywackes, silty claystones, silicified volcanites and also of quartz.

Sand-sized clast and dropstone orientations are nearly chaotic, there are no sediment drifts and scours on any side of larger clasts.

Dropstone deformational structures

45 impact deformational structures were registered and studied. The laminae influenced by impacts of dropstones are only bent but not interrupted. Depth of deformation generally corresponds to the dropstone diameter and depth of the impact structure to the 36 per cent of the clast diameter on the average. Wedge-like, circular depression is developed on the bent bottom at the dropstone foot. Impact bending is accompanied by slight, relatively distant ring-like swelling (A, D left, Fig. 1).

The laminated sediment cover of the dropstones exhibits slight doming which could have originated by quiet sedimentation following the dropstone fall, and partly also by diagenetic differential compaction.

About half of our dropstones produced pure primary impact structures without any secondary deformations. The second half exhibits some microfractures and crinkles in the underlying laminae, as well as retirement of sediment to the clast margins.

Plasticlasts clearly exhibit some compaction in their lower parts and expansion in their top parts (C, Fig. 1).

No great heterogenities as agglomeration of sandy, pebbly or clayey materials were found.

Depositional environment

There are many evidences of glacial deposition of dropstones from floating icebergs. Dropstones themselves, impact structure, grain size composition and plasticlasts speak in favour of this assumption. P. Štroch (personal communication) thinks that the clastic material of diamictites was reworked in the near-shore banks and there incorporated into drift ice.

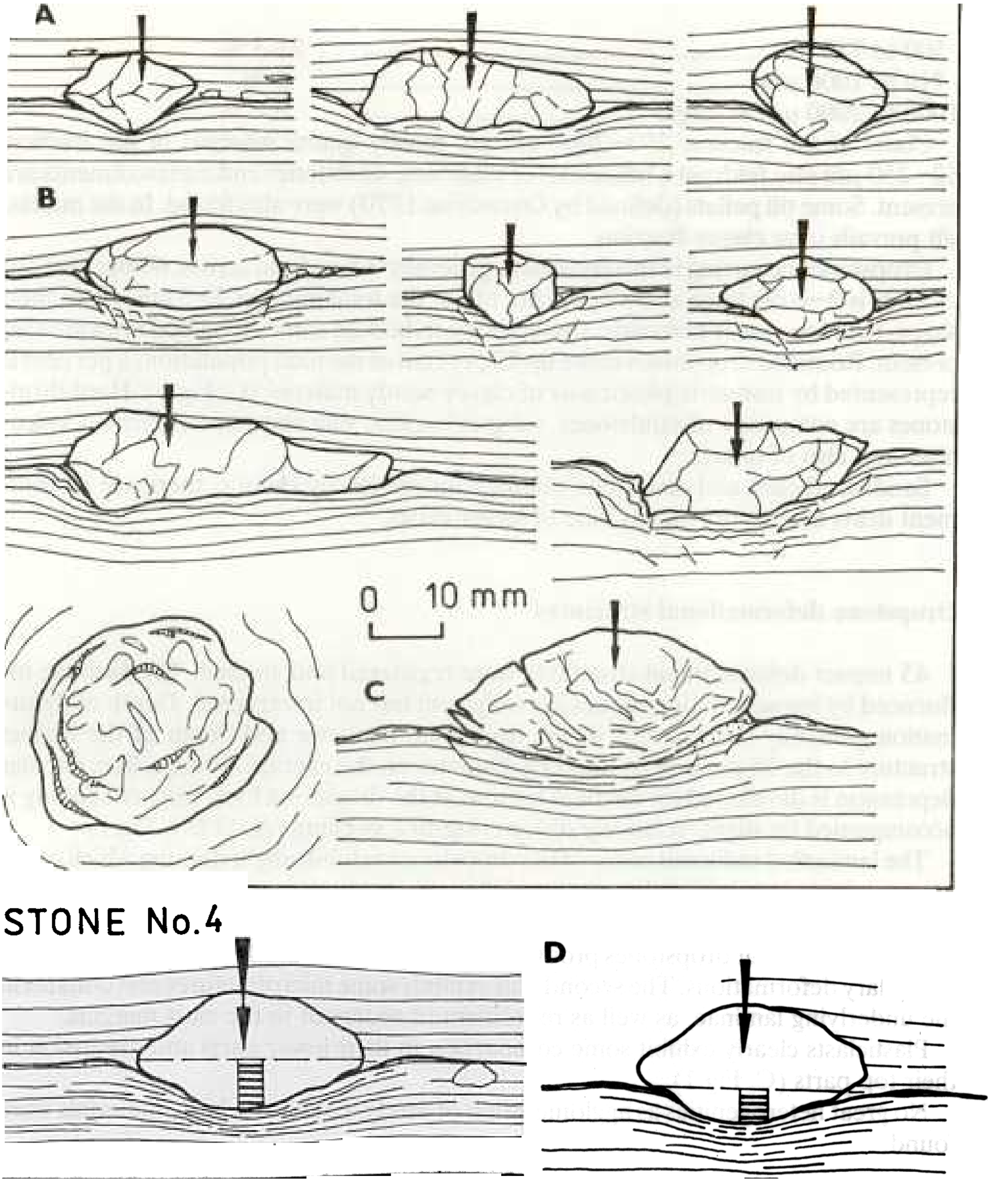

Fig.1. A - examples of undisturbed impact deformations, the upper diamictite of Levín. B - examples of modified structures. C - deformation of the dropped plasticlast. D - low-velocity impact deformations at the clast No.4: in the diamictite of Levín (left), and the highest in recent condition (right)

Absence of flute casts, clast orientation and other current structures speaks in favour of quiet water above the bottom. No grooves or other marks of grounding ice as well as no storm wave structure were found which means that the basin depth could be estimated at several tens of metres. Ichnofossils are absent, diagenetic cement is not present. Thin sections revealed some graptolite tissues consisting of kerogene, pyrite and iron oxide. This fits an idea of deposition in cooler, slightly oligohaline waters.

Factors controlling dropstone deformational structures

This discussion includes the following problems:

1. Was there sufficient water depth for stabilization of dropstone fall? Experiments have shown that sufficient depth for stabilization is only 1.2–7.5 m.

2. What could be the influence of fall velocity oscillations? 8 per cent of tested Ordovician dropstones fell quietly through the water column, 29 per cent alternated quiet and disturbed passages, and 63 per cent exhibited complicated rotations of periods from 0.2 to 1.7 s. The most frequent is the fall and drop position with larger dimensions in horizon. Only the large discs have shown the interrupted lateral slips – "the coin effect". Main care was devoted to the four nearly isometric dropstones, which had been extracted from well-developed impact structures ("key collection" – D, Fig.2). Dropstone No.3 displayed the highest, 3 percentage variance of velocity, but No.4 only 0.3 per cent. While the Ordovician impact position of dropstone No.3 was simulated in 28 per cent of repeated recent experiments, No.4 kept the same position of impact in 93 per cent of experiments.

3. The significance of bulk density of the dropstones. Bulk density of dropstones is between 2.45 and 2.97 $g.cm^{-3}$. In four dropstones tested by the next experiments following bulk densities were found: No.1 – 2.52, No.2 – 2.91, No.3 – 2.68, and No.4 – 2.83 $g.cm^{-3}$. The higher density (specific mass) corresponds with the higher kinetic energy.

4. Lateral currents, upwelling or downwelling could be neglected in the bottom water layer, according to the sedimentological evidence.

5.The effect of fluctuations of water density and viscosity can be also neglected because the expected differences are within the limits of observational error of our experiments. With the rising temperature, the viscosity diminishes only by 4.10^{-4} Po per 1°C (Carlier 1972, Castany 1963). Also the differences in viscosity of fresh and marine waters are low (Houpeurt 1959).

6. The viscosity affected by hydrostatic pressure needs not be taken into consideration. Possible change appears to be lesser than 1 per cent of the viscosity value per 7 MPa (Schneebeli 1966, Tesařík 1977).

7. The resistance of sediment against deformational impact is related to sediment composition, mainly grain size and early cementation. According to the experiments, however, very similar deformational structures are obtained even if the grain-size composition is markedly changed. The same is surprisingly valid for a roundness and shale of clasts. Similar sets of deformational structures originated in different sediments. The experiment was also made with regularly dropped spheres (in one minute intervals) in water-filled cylinder with stiffening plaster on the bottom. The sequence of deforma-

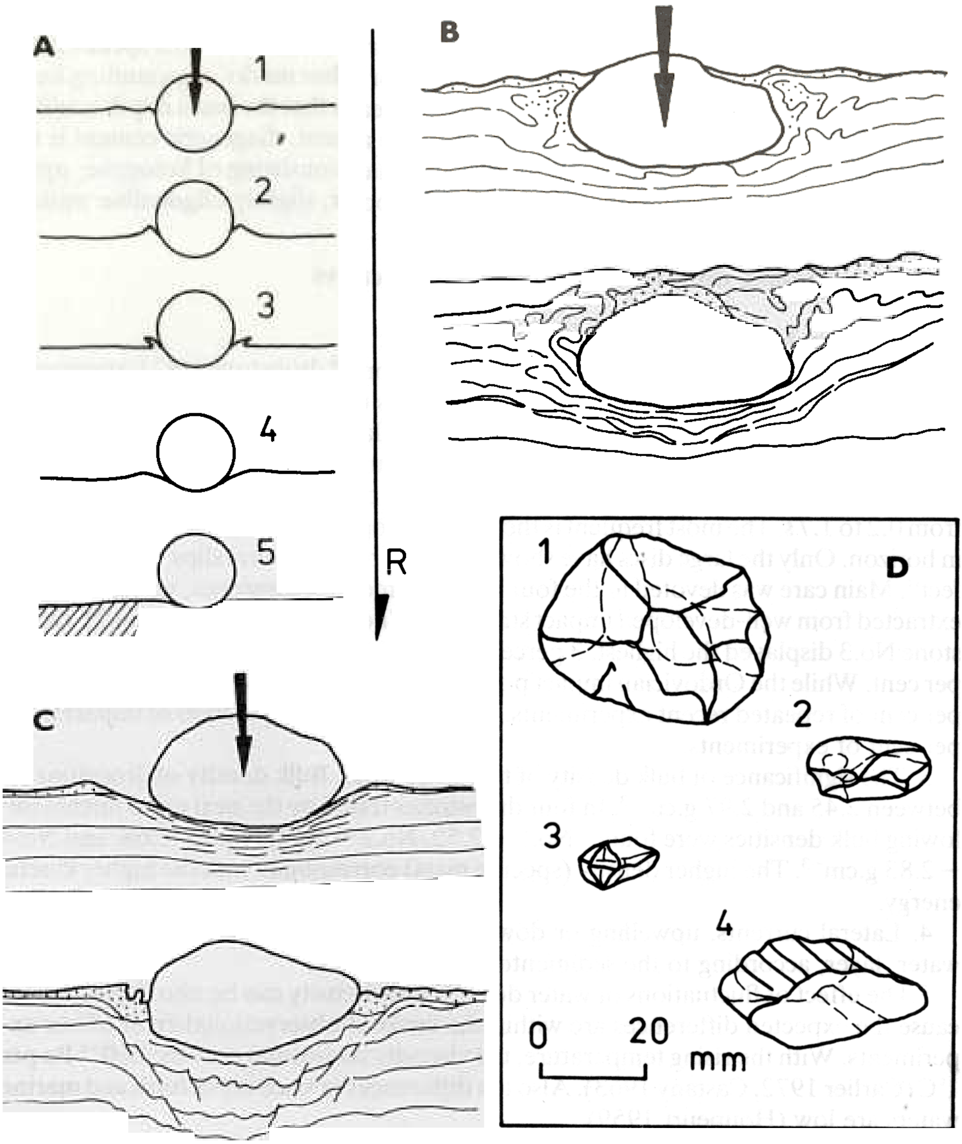

Fig.2. A - deformation styles, beginning from the loose and finishing at the resistant sediment (styles 1 to 5). B - an impact deformation (above) and the secondary sinking (below) in an extremely loose sediment. C - the same, but in more resistant sediment (boundary interval of the 3rd and 4th deformational styles). D - dropstones of the key-collection

tional styles obtained here (A, Fig.2) is very similar to that obtained during experiments with different sediments (from loose to compact ones) and also to well-preserved impact structures observable in fossil state. The less frequent structure of the third style (A, Fig.2) was described for instance by Hardy and Legget (1960). Our Ordovician structures belong to the fourth deformational style (A, D left, Fig.1, A Fig.2).

Some other effects than grain size and early cementation should be taken into consideration; as a sediment lamination, water content, presence or absence of grain coatings (e.g. algae, bacteria, inorganic films). For the "key collection", the structures without sharp discontinuities between the laminae were selected, because the discontinuities diminish the resistance (Maury and Habib 1970). Considering the water content, the experiments showed that at least 25 percentage change of water content or 35 percentage change of pressure in distinct laminae might substantially affect the impact deformation. Against the hypothetic gel with bacterian fibrils speaks the lack of kerogene and iron oxide, as well as the experimental impact simulation with more intensive deformation of upper laminae, radial and concentric wrinkles.

8. Great attention was paid to the post-sedimentation sinking of clasts into the bottom. Secondary sinking can be triggered by water oscillation above the bottom and pore-pressure oscillation in the sediment. According to our experiments, the deformed column is as much as twice as deep as in the low-velocity impact deformation. Conical microfaults and microfolding of laminae is typical for this case (B, Fig.1, and C below, Fig.2). Secondary sinking can be also caused by the deposition of particles on the dropstone. Pure gravitational sinking of the dropstone is also possible. Several-months lasting experiments show that the deformational structures are very similar in all the mentioned cases. Very intensive sinking of clasts occurs when the whole body of sediments is moved. Such structures use to be deep, laminae are often penetrated and sediment is irregularly accumulated at the dropstone margin. Some structures described by Thomas and Conell (1985) and by Hanvey (1989) should be assigned to this case.

9. Vertical diagnetic compaction of sandstone in places of the selected dropstone structures is not more than 5 per cent, generally less.

Recent and ancient impact deformational structures

For these experiments loose sediment was prepared as close to the grain-size composition of the Ordovician one as possible. Ordovician impact structures were compared with experimentally produced using the same dropstones; 18 Ordovician dropstones were used for these experiments.

Dropstone No.4 was namely used for comparison. Here, in the Ordovician sediment, the bending of bottom is 7 mm below surrounding surface, but in recent experiments it cannot exceed 4.5 mm in any of the simulated cases (D, Fig.1).

To obtain similar impact structure as observable in the Ordovician sediment, the mass of dropstone No.4 had to be increased from 0.0359 kg to 0.0446 kg (by production clasts of the same shape and size but of greater bulk density, or by metal insertion into the original pebble). Fall velocity increased in this case from 0.74 to 0.95 $m.s^{-1}$.

The kinetic energy of model with the higher mass and fall velocity ($E = m.v^2/2$) is 0.020126 J. We assume, that this energy was necessary for the impact structure which is observable in Ordovician sediment.

In the next step, we may practice the recalculation using the kinetic energy value, because all the time we are inside the fourth deformational style (comp. D, Fig. 1, A, Fig.2). Considering the original mass of the clast No.4 (0.0359 kg) and the necessary kinetic energy (0.020126 J), the computed fall velocity for the Ordovician dropstone should be 1.06 $m.s^{-1}$ which means by 43 per cent greater than today.

If our assumption is correct this greater fall velocity has to be explained. Greater gravitational acceleration could be considered as a possible reason for that. Approximate estimation of the gravitational acceleration value is based on relations between increasing mass and velocity at constant acceleration (9.81 $m.s^{-2}$) and between acceleration and velocity at the constant mass (0.0359 kg). Regarding the effect, we can correlate the upgrading mass and gravitational acceleration in a short interval, using for instance the ideal Stokes' velocity. Estimation of the Ordovician gravitational acceleration value is about 15 $m.s^{-2}$ (diagram with experimental curve and ideal Stokes' correlation, Fig.3).

An attempt for explanation of the possible higher gravitational acceleration is even far more fetched. We could suggest that either greater gravitational constant or smaller Earth's radius could be responsible for it. Thus, recalculated Ordovician Earth's radius should be only 5540 km and the Ordovician Earth's volume only 66 per cent of the present state at the same Earth's mass. This seems too small number even if we take into consideration several known hypotheses about expanding Earth (Egyed 1957,

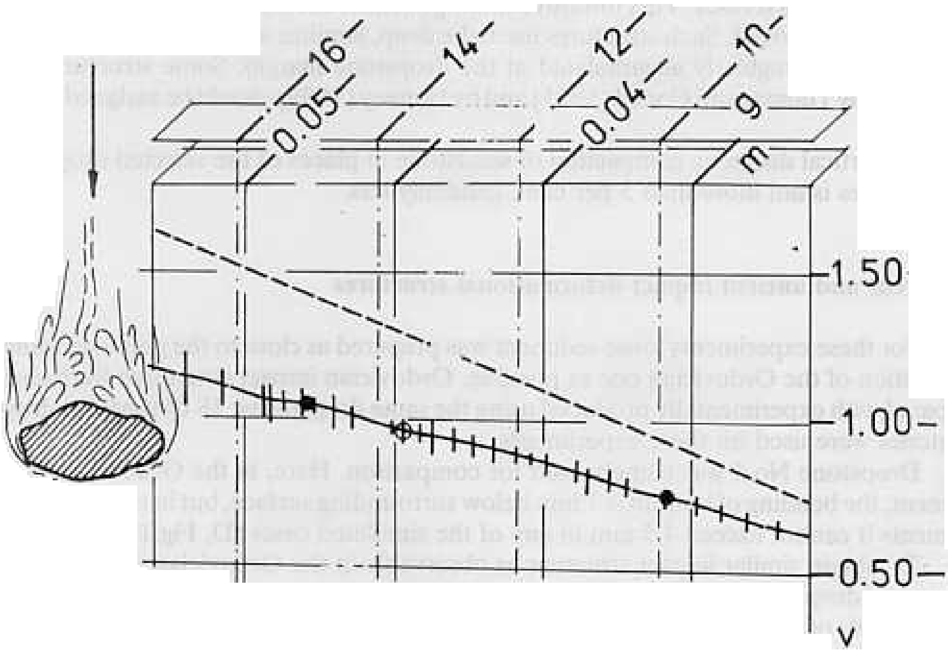

Fig.3 An experimentally found curve for the clast No.4 showing the dependence of fall-velocity on mass (models): for a short interval, indirectly also on gravitational acceleration. Full circles - the recent velocity (right on the curve), and the U. Ordovician one. Broken line - a linear dependence (an ideal Stokes')

Ljubimova 1962, Carey 1975, 1976, King 1983, Owen 1983, Horai 1984) and, of course, also refusing analyses (Smith 1978, Weijermars 1986, 1989). At least with same probability we can speculate about the more expressive changes of gravitational constant.

The well-preserved Ordovician impact structures are so much surprising and clearly visible, that the author finds to be useful to report them, despite the fact, that the presumed historical orbit of the Moon, paleontological-clock data, and image of the historical composition of the atmosphere appear to be controversial to the expansion hypotheses.

Conclusions

1. Ordovician dropstones from Central Bohemia can serve as a tool for paleogravity speculations.

2. Primary impact structures caused by fall of dropstones can be distinguished from the secondary deformations.

3. Several deformational types were recognized which correspond to sediment-resistance stages against the low-velocity impact.

4. Experiments with the same dropstones as found in Ordovician diamictite have shown that the Ordovician impact deformation is more intensive than that obtained in recent conditions.

5. Greater gravitational acceleration of about 15 $m.s^{-2}$ is assumed for the Upper Ordovician time.

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Explanation of plates

Plate I

A - Dropstones of the key-collection; their lower (plunged) parts are whitened. B - clast No.4 during the extraction. C, D - thin sections: vertical cuts of dropstones and surrounding sandstone (Levín). E - an illustration of the impact deformation (left), and the secondary one (right). F - "protected" dropstone, conserved in the section Levín.

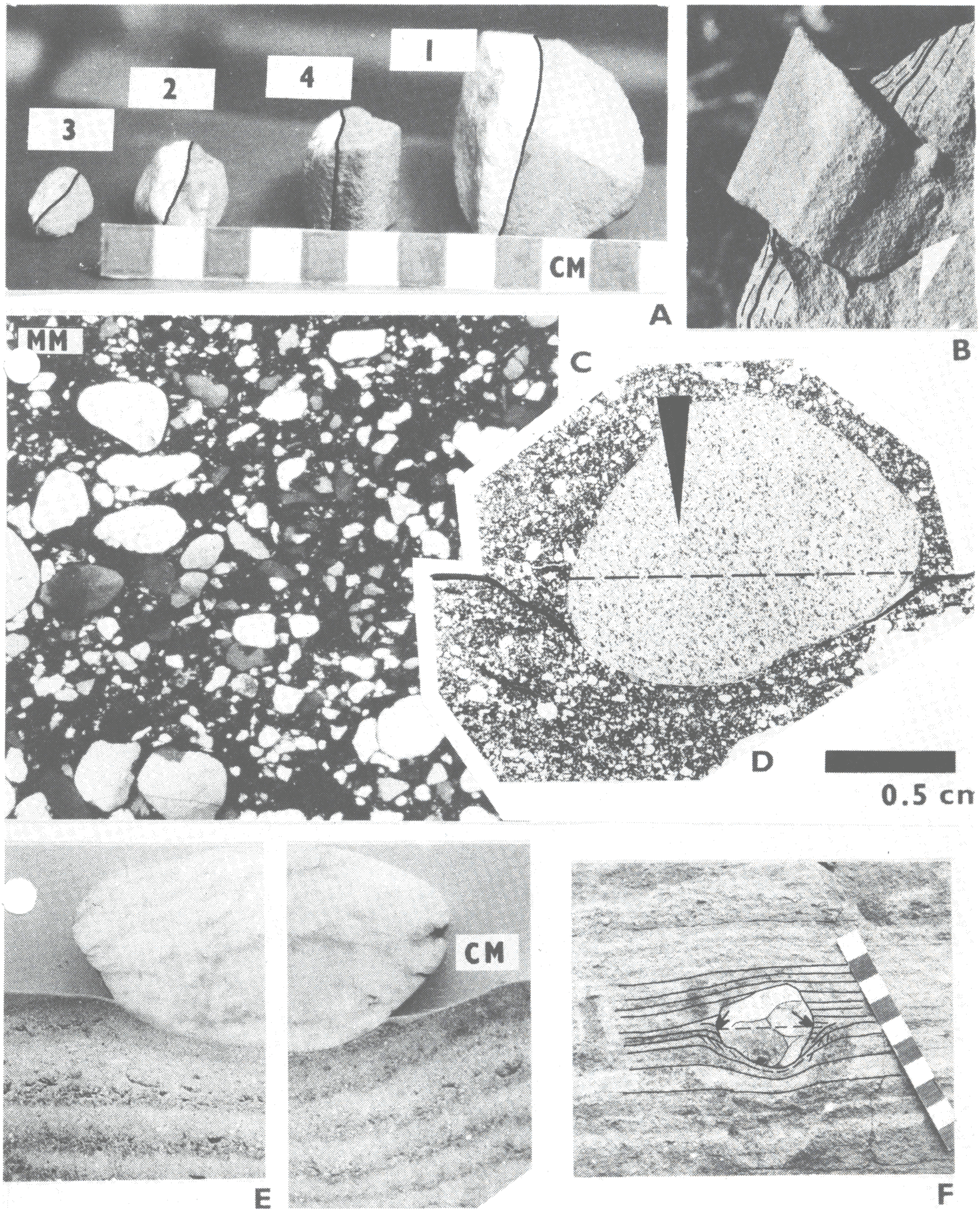
Photo A – E - J. Hladil, F - P. Štorch

Plate II

1 — 3 - Dropstones Nos.1 to 3 during the extraction. Arrows mark the orientation. Dropstone No.3 displays its bottom side.

4 - Draft combined with thin-section photograph: Dropstone No.28, sediment with coarser grains.

Photo J. Hladil



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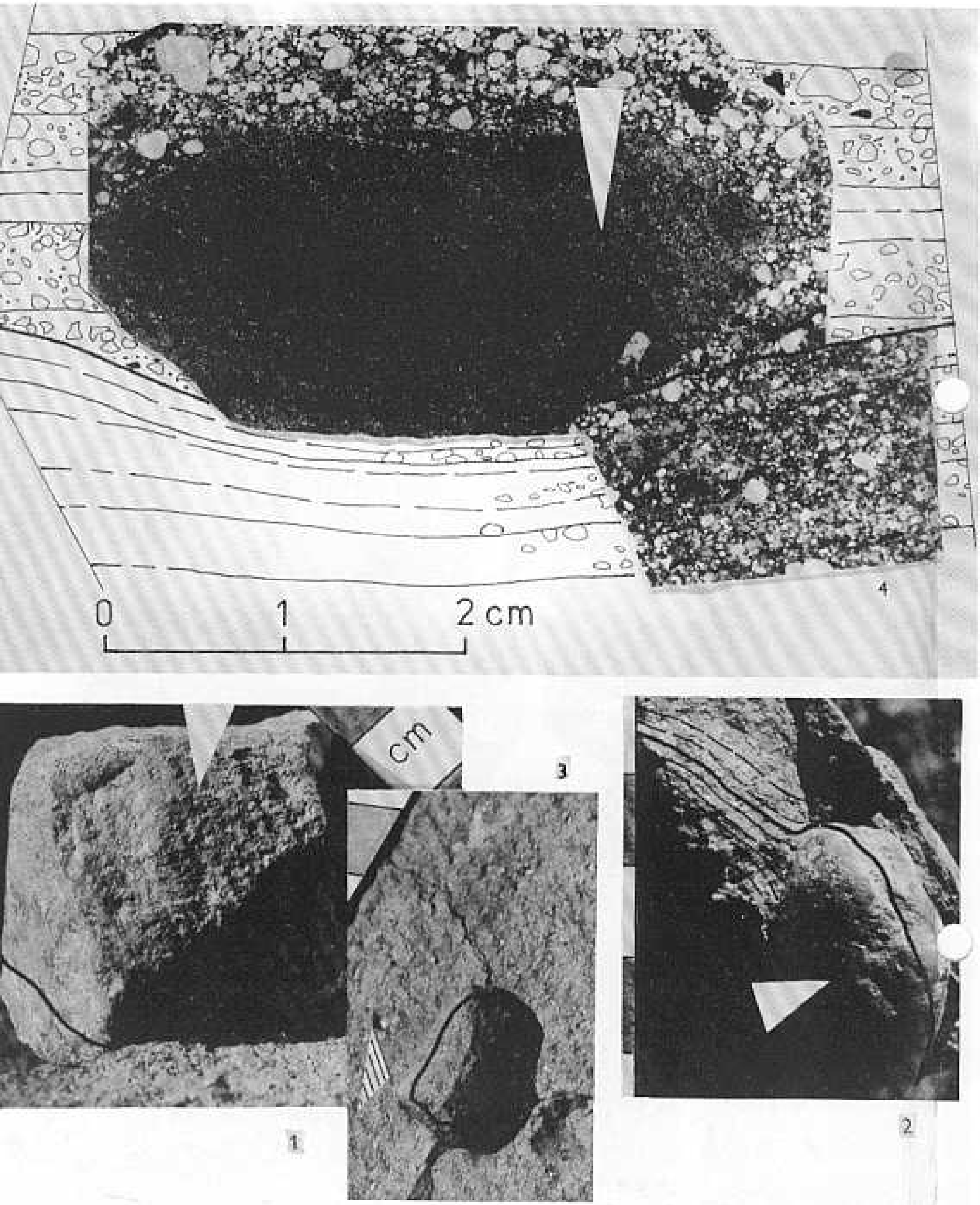
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