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SHORT COMMUNICATIONS

Carboniferous Raindrop Imprints at the Southwestern Margin of the East European Platform

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Abstract—The paper presents data on the distribution of rains during the formation of Carboniferous coal-bearing rocks in the Lvov–Volyn Basin located at the southwestern margin of the East European Platform. They left numerous raindrop imprints that usually occur in the productive Buzhan coal-bearing formation in marginal (repeatedly drained) sectors of maritime lakes, freshened lagoons, bays, and, less commonly, in river floodplains. The raindrop imprints have been recorded for the first time in Carboniferous rocks of the southwestern East European Platform. Their study is of great importance for the interpretation of paleogeographic and paleoclimatic settings.

The paper continues publications dedicated to structural marks at bedding surfaces in coal-bearing formations. In addition to previously discussed fossil gas-seepage marks (Shul'ga *et al.*, 2000), traces left by raindrops on the Earth's surface are also described.

It is well known that hot humid climate with abundant rains is one of the most important factors favoring the intense development of vegetation and the formation of parental matter of coals. Therefore, one should expect wide distribution of raindrop imprints in ancient coal-bearing formations. However, fossil raindrop marks are rarely encountered. Although they were first described more than 150 yr ago (Schrok, 1950), publications dedicated to this phenomenon are still scanty and works describing raindrop imprints in coal-bearing formations are absent at all. They are not even mentioned in fundamental manuals of Zhemchuzhnikov (1948) and Ivanov (1967). At the same time, their study is important for the interpretation of factors determining the formation of coal-bearing sequences.

In this connection, raindrop imprints first discovered in Carboniferous rocks of the Lvov–Volyn coal basin (LVB), which is located at the southwestern margin of the East European Platform near the Ukraine–Poland boundary, are of significant interest (Fig. 1a).

The Visean–early Bashkirian (or Visean–Namurian A, B, C) paralic coal-bearing series of the basin (more than 1400 m thick) is composed of alternating sandstones, siltstones, mudstones, limestones, and coal. The coal-bearing series is divided into the lower (coal-poor) boggy–marine and upper (coal-rich) alluvial–lacustrine–boggy–lagoonal subseries (Fig. 1b). The LVB territory incorporates the Novovolynsk, Chervonograd, and Southwestern coal-bearing districts.

The structural marks, developed at the bedding surfaces of coal-bearing sediments and interpreted as Carboniferous raindrop imprints, have been found over the entire LVB territory in 34 sections of the coal-bearing series and thoroughly described in prospecting borehole cores. In these descriptions, each bed (regardless of its thickness) was considered an individual lithogenetic type with certain primary genetic features (Davydova and Gol'dshtein, 1947; Zhemchuzhnikov *et al.*, 1960). Raindrop imprints were studied at more than 200 bedding surfaces.

MORPHOLOGY OF RAINDROP IMPRINTS

The studied structures (hereafter, imprints) usually occur in clayey siltstones and silty mudstones with discontinuous horizontal, horizontal-sinuous, and lenticular lamination emphasized by interbeds of lighter fine-grained siltstone (1–3 mm) and less common accumulations of plant detritus. The imprints have been detected at the upper surface of mudstone beds at the contact with overlying siltstones. They are observed as oval or round pits up to 3 mm deep (Figs. 2, 3a, 3c, 3e). Edges of the pits are often slightly elevated as small asymmetrical ridges up to 1.5 mm high. The pit diameter ranges from 1–2 to 8–10 mm. In terms of diameter size, the pits can be divided into three groups: <2 mm (73% of the total number), 2–5 mm (26%), and more than 5 mm (1%). At the lower surface of the overlying siltstone bed, the pits are represented by moulds in the form of rounded and less common cone-shaped knobs (Figs. 3b, 3d, 3f–3h). Their diameter and height correspond to similar parameters in structures developed at the upper bedding surface. The imprints are accompanied by worm casts and desiccation cracks filled in with silty material (Fig. 3h). Pits developed at bedding sur-

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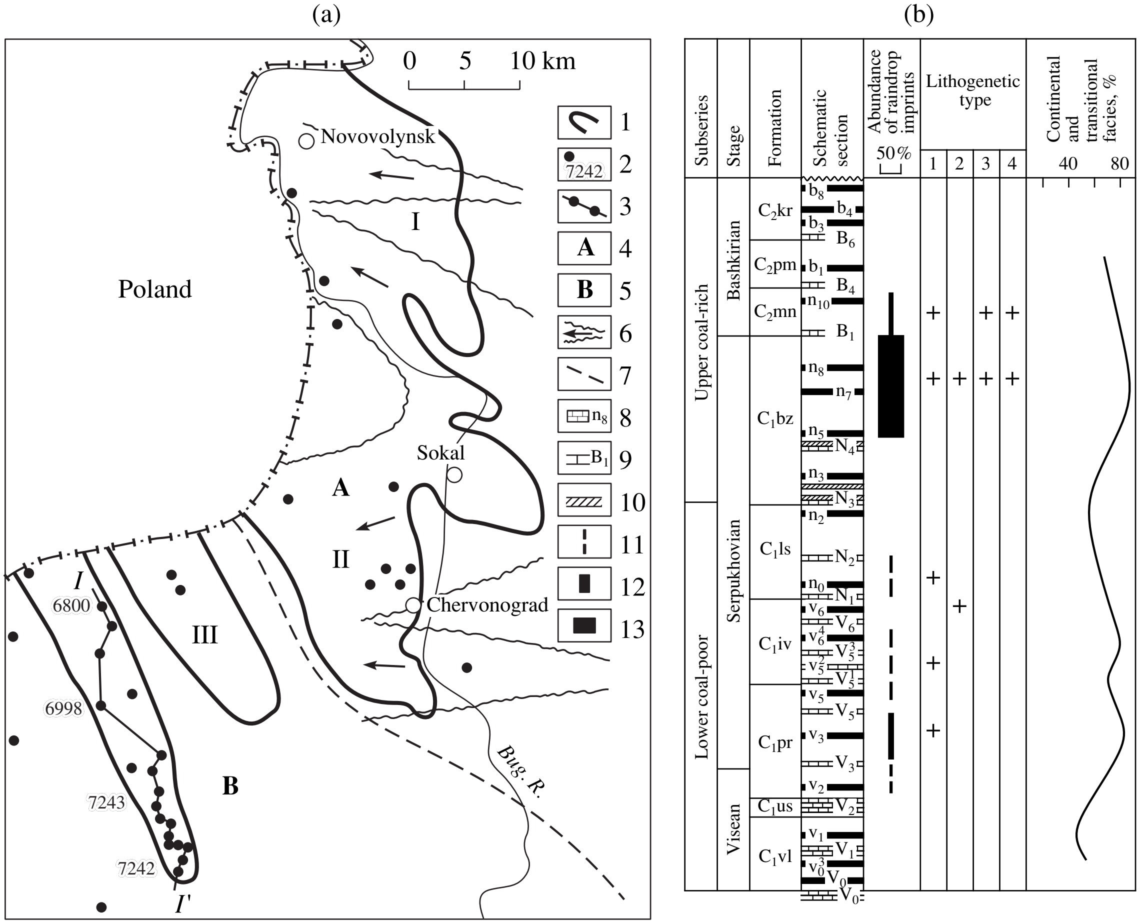

Fig. 1. Schematic lithological–paleogeographic map of the Lvov–Volyn Basin corresponding to timing of the upper coal-bearing subformation showing (a) the location of sections with finds of Carboniferous raindrop imprints and (b) their vertical distribution in the coal-bearing series section. (1) Distribution area of productive coal-bearing series; (2) sections with finds of raindrop imprints; (3) facies profile; lithofacies subzones: (4) with abundance of sandy–silty sediments accumulated in river (mouth and lower course areas) and subordinate development of coaly sediments deposited in peat bogs, as well as silty clayey and calcareous sediments deposited in maritime lakes, lagoons, and shallow seas, (5) with subordinate distribution of sandy–silty sediments accumulated in river (mouth and lower course areas) and abundance of coaly sediments deposited in peat bogs, as well as silty clayey and calcareous sediments deposited in maritime lakes and lagoons; (6) paleohydrographic systems with indication of prevalent current directions; (7) boundary of paleogeographic zones; (8) coal seam and its index; (9) limestone bed and its index; (10) *Posidonia* Horizon; abundance of raindrop imprints (shown in scale): (11) single finds, (12) up to 10%, (13) more than 10%. Coal-bearing areas: (I) Novovolynsk, (II) Chervonograd, (III) Southwestern. Formations: (vl) Vladimir, (us) Ustilug, (pr) Poritsk, (iv) Ivanichi, (bz) Buzhan, (mr) Morozovichi, (pm) Paromov, (kr) Krechev.

faces are variable in size and characterized by chaotic distribution of 1pit/(0.5–7) cm^2, on the average. The pit abundance does not exceed 1pit/(1–2) cm^2 in 64% observations. Figure 3e shows that the long axis of oval pits is usually oriented along a certain direction and imprints of different generations can be superimposed on each other.

The imprints are characterized by distinct diagnostic features. They are similar to raindrop imprints at bedding surfaces of recent and ancient rocks (Chalyshev, 1962; Dmitrieva *et al.*, 1962; Nalivkin, 1955; Pettijohn, 1975; Reineck and Singh, 1975; Richter, 1954; Rukhin, 1961; Shrock; 1948; Shvanov, 1969). They are distinguished from gas-seepage marks by irregular-round and oval forms of pits and from hail imprints by small size. Influence of ice particles in the formation of these structures is hardly possible, because the Lvov–Volyn Basin was located during the Carboniferous in the Westphalian (Euramerian) floral zone of the equatorial belt with hot tropical and subtropical climate (Meyen, 1987).

LITHOFACIES CHARACTERISTIC OF SEDIMENTS

The raindrop imprints are found in rocks of four main lithogenetic types: (1) gray silty mudstone and clayey siltstone with horizontal-sinuous lamination emphasized by silty material with accumulations of

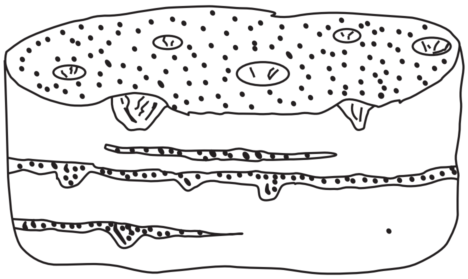

Fig. 2. Distribution of raindrop imprints in core.

plant detritus and large plant fragments; (2) mudstone with thin discontinuous horizontal lamination emphasized by silty material with freshwater bivalve and rare *Lingula* shells; (3) silty mudstone with large ribbon-shaped plant remains at bedding surfaces and rare freshwater bivalve shells; and (4) mudstone with distinct horizontal lamination emphasized by silty material and variable color (faunal and plant remains are absent).

The formation analysis of coal-bearing rocks of the basin (Shul'ga *et al.*, 1992) showed that lithogenetic types 1–3 are sediments of maritime lakes, strongly freshened lagoons, and bays (hereafter, LLB facies). They are characterized by a wide development of horizontal- and sinuous-bedded structures, as well as the presence of abundant euryhaline bivalves *Najadites truemani* forma *normalis, N.* cf. *truemani* f. *samsonowiczi, N. moravicus* f. *lata, Curvirimula belgica* f. *normalis, C. rolandi, C.* cf. *ludmilae*, and *Anthraconaia lenisulcata.* The rocks also include scales of fish species *Elonichthys robinsoni, E. egertoni, E. geikeli, Drydenius* sp., as well as *Lingula* shells. The coalified plant detritus is abundant on the bedding surface. Large (poorly preserved and redeposited) calamite fragments (*Mesocalamites cistiformis, M.* cf. *ramifer, M. roemeri*) are less common. Intact pteridosperm leaves and their fragments (*Cordaites principalis, Neuropteris gigantea, Mariopteris* sp.) are rare. Large ribbon-shaped plant remains, typical of lithogenetic type 3, are probably fragments of stigmaria appendices.

Sediments of the LLB facies (0.3–5.0 m) usually overlie coal seams within the transgressive part of sedimentation cycles of the first order (Fig. 4). Approximately 75% of raindrop imprint finds occur in thinner beds (0.3–1.5 m).

Sediments of lithogenetic type 4 are referred to the silty, sandy and clayey floodplain (FP) facies. They accumulated in small lakes and oxbows that existed in the river mouth and lower course (Shul'ga *et al.*, 1992). These sediments usually form thin (1–1.5 mm) and laterally discontinuous beds within alluvial and floodplain sequences in the regressive part of sedimentation cycles of the first order (beneath the coal seams).

Approximately 95% of raindrop imprint finds are confined to the LLB facies 75% of them belong to the first lithogenetic type. Their abundance is minimal in floodplain mudstones.

DISTRIBUTION AND FORMATION CONDITIONS OF RAINDROP IMPRINTS

The vertical distribution of raindrop imprints in the section was estimated on the basis of the percentage of beds with these structures in sedimentation cycles of the third order (section intervals with a thickness of 80–100 m). It was established that raindrop imprints are rather widespread but irregularly distributed in the coal-bearing series (Fig. 1b). They are most abundant in the coal-rich lagoonal–boggy subseries, i.e., the upper part of the main productive Buzhan coal-bearing formation. The interval between limestones N_4 and B_1 contains more than 60% of the total finds of raindrop imprints. These structures have not been found in the lowermost and upper parts of the coal-bearing series and in the interval between N_2 and N_4.

Raindrop imprints are irregularly distributed within individual beds. They are usually confined to thin (10–30 cm) interbeds. The studied sections are spaced at a distance of 1–3 km. Therefore, we could establish the following facts. In addition to local concentrations of raindrop imprints, they also occur in laterally sustained horizons at the roof of coal seams (Fig. 4). The number of their finds in the upper coal-bearing subseries increases in the southwestern direction from the Novovolynsk area to the Southwestern area (Fig. 1a).

The confinement of the majority of discovered imprints to the LLB facies confirms the assumption of many researchers (Chalyshev, 1962; Gradzinskii *et al.,* 1980; Khvorova, 1957; Popov *et al.*, 1963; Richter, 1954) suggesting that the most favorable conditions for the preservation of raindrop imprints at the surface of wet (clayey and silty) sediments existed in the coastal (shallowest) areas of lakes, lagoons, and bays frequently drained as a result of surge and tidal processes. In floodplains, raindrop imprints occur only in sediments of small lakes (lithogenetic type 4). These structures were not recorded in other continental rocks, because the possibility of their preservation after burial is negligible.

The dependence of the formation and preservation of raindrop imprints on the facies environment is distinctly reflected in their vertical and lateral distribution in the coal-bearing series. The wide development of transitional (paralic) and continental sediments in the upper coal-bearing subseries promoted the maximal abundance of raindrop imprints in the Buzhan Formation, where they occur in four lithogenetic types of the LLB and FP facies (Fig. 1b). In contrast, raindrop imprints are subordinate (or even absent) in the lower coal-bearing subseries because of the wide development of marine conditions o (the imprints have been

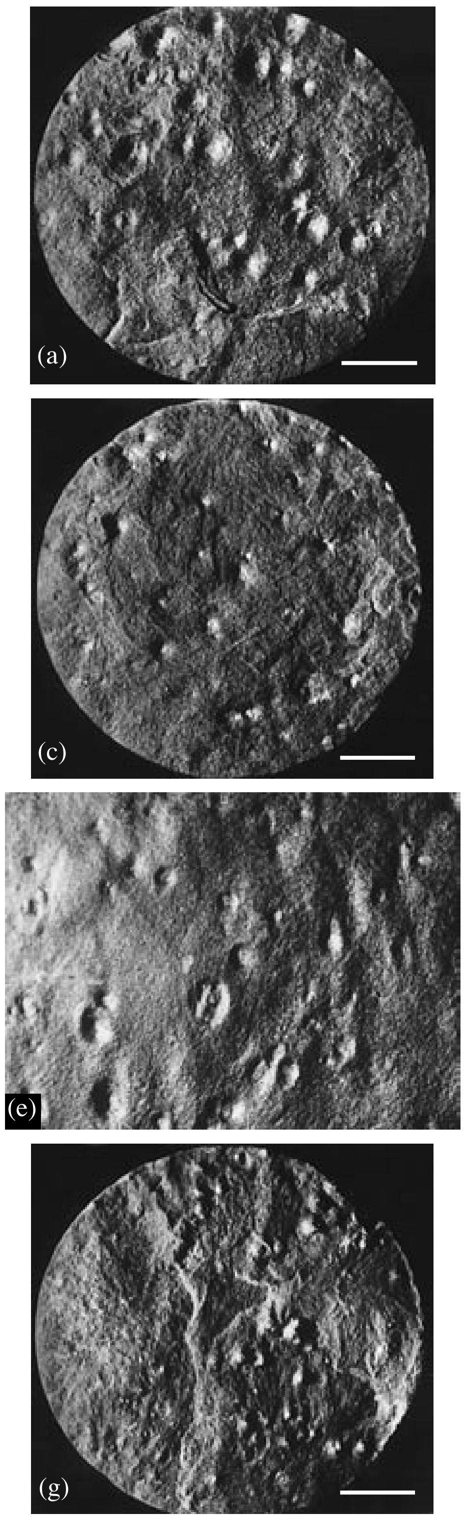

Fig. 3. Raindrop imprints at bedding surfaces in the Buzhan Formation. (a) Borehole 9667 (interval 565.6–566.1 m), upper surface of the bed (Chervonograd area); (b) the same, lower surface; (c) Borehole 9180 (interval 420.7–421.2 m), upper surface of the bed (Chervonograd area); (d) the same, lower surface; (e) Borehole 6044 (interval 1059.8–1060.8 m), upper surface of the bed (Southwestern area), ×2; (f) Borehole 9667 (interval 566.1–566.6 m), upper surface of the bed (Chervonograd area); (g) Borehole 9180 (interval 421.2–421.5 m), lower surface of the bed (Chervonograd area); (h) Borehole 6800 (interval 829.4–830.9 m), lower surface of the bed (Southwestern area). Scale bar corresponds to 1 cm. Illumination from the left.

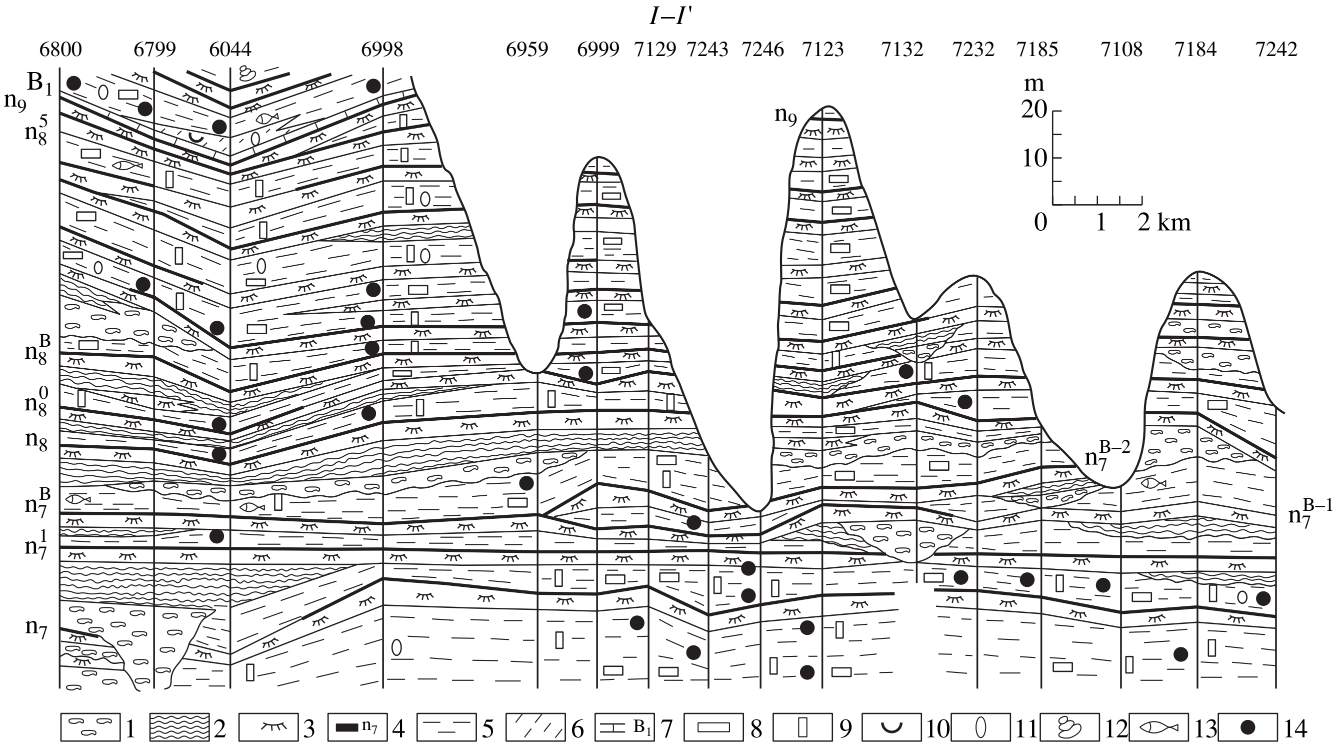

Fig. 4. Facies profile across the upper part of the Buzhan Formation with indication of raindrop imprint finds. Facies: (1) silty and sandy sediments of river mouth and lower course areas, (2) silty and clayey sediments of floodplains, (3) silty and clayey sediments of boggy maritime lowlands, (4) coaly sediments of peat bogs and sapropel lakes (coal seam and its index), (5) clayey and silty sediments of maritime lakes and strongly freshened lagoons, (6) clayey and silty sediments of lagoons, (7) marine calcareous sediments (limestone bed and its index); (8) freshwater bivalves; (9) bivalves; (10) brachiopods; (11) *Lingula* shells; (12) gastropods; (13) fish remains; (14) raindrop imprints. See Fig. 1a for profile position.

found only in a single lithogenetic type of the LLB facies).

When considering specific features of the distribution of raindrop imprints in the Lvov–Volyn Basin, one should bear in mind that the provenance was located 50–60 km northeast of the present-day boundaries of the basin during the formation of the upper coal-bearing subseries (Shul'ga *et al.*, 1992). The southwestern areas were occupied by the spacious maritime lowland intermittently flooded by a sea located further southwest of the study area. Therefore, the region can be divided into two NW-trending lithofacies zones (Fig. 1a). Environments favorable for the formation and preservation of raindrop imprints in the fossil state existed in the second zone with a larger-scale development of the continental-to-marine transitional from settings. This explains the lateral trend of increase in the abundance of raindrop imprints in the Lvov–Volyn Basin in the southwestern direction.

CONCLUSIONS

The materials presented in the paper indicate wide development of rains in the territory of the Euramerian floral zone during the Carboniferous (approximately 320 Ma). They were of variable intensity and frequently accompanied by winds. Simultaneously, the absence of large imprints implies a specific character of rains probably explained by peculiar properties of the atmosphere in the Carboniferous Period. According to Popov *et al.* (1963) and Selley (1976), environments favorable for the formation and preservation of raindrop imprints are probably widespread in arid and other climatic belts. In addition, these structures are abundant in repeatedly drained marginal areas of water basins. Our observations confirm these inferences.

The aim of this work is to attract the attention of geologists to the study of raindrop imprints. Systematic observations will specify their diagnostic features and peculiarities in the vertical and lateral distribution and simultaneously contribute to the knowledge of paleoclimatic and paleogeographic settings favorable for accumulation of coal-bearing formations.

The units with raindrop imprints established in the Lvov–Volyn basin are similar to *raindrop horizons A1, A2, E1, E2* of the Westphalian B Horizon of the Campi mountainous area in Belgium (Paprot *et al.*, 1983) and can be used as additional markers for the correlation of coal-bearing sequences.

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